Impact of PPP Ambiguity Resolution on Antarctic Glacier GNSS Time Series: Comparison with Network-Based and PPP Ambiguity-Float Solutions

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Abstract

Geodetic observations play a key role in quantifying glacier dynamics and long-term vertical surface changes in Antarctica, where Global Navigation Satellite System (GNSS) techniques are widely used under challenging environmental and logistical conditions. This study investigates the impact of ambiguity resolution in Precise Point Positioning (PPP) processing for glaciological applications through comparisons with both network-based solutions and earlier PPP implementations relying on float ambiguity estimation. Two complementary datasets collected within the Italian National Antarctic Research Program are analyzed: a short-term kinematic GNSS campaign on the rapidly flowing Drygalski Ice Tongue and a long-term continuous time series from the permanent GNSS station DCRU installed at Station Concordia (Dome C, East Antarctic Plateau). The analysis focuses on the consistency of displacement time series, stochastic noise characteristics and long-term velocity estimates derived from different processing strategies. Results indicate that ambiguity-fixed PPP solutions provide displacement and velocity estimates consistent with network-based and float PPP processing, while generally exhibiting reduced short-term scatter and improved temporal stability. This behaviour is particularly evident for the kinematic observations at Drygalski, where the improved signal-to-noise ratio enhances the resolution of small-amplitude glacier motions associated with ocean-tide forcing. Spectral analysis further confirms the tidal origin of the dominant periodic components, with peaks at approximately 25.6 h and 23.4 h. At Dome C, the long time-span observation record confirms the robustness of three-dimensional velocity estimates over more than a decade, with only minor differences between processing approaches. These findings highlight the overall consistency of glacier motion estimates with respect to the adopted processing strategy and demonstrate the benefits of ambiguity-resolved PPP for improving the interpretation and long-term reliability of Antarctic GNSS time series.

Keywords

Antarctica · Glacial monitoring · GNSS · GPS

1 Introduction

High-precision geodetic observations play a fundamental role in investigating glacier dynamics and long-term surface elevation changes in Antarctica. In particular, Global Navigation Satellite System (GNSS) measurements enable the

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quantification of ice-flow velocities, vertical motion associated with firn compaction and ice dynamics, and short-term kinematic variability affecting floating glacier tongues (Danesi et al. n.d.; Vittuari et al. 2023, 2025). In these remote environments, reliable positioning strategies are essential for improving the physical interpretation of cryospheric processes and for ensuring the consistency of displacement estimates derived from heterogeneous datasets and observation periods.

Network-based double-difference (DD) processing has traditionally been regarded as a robust approach for relative positioning in glaciological applications (Negusini et al. 2005). However, owing to its relative nature, DD positioning may partially filter spatially coherent geophysical signals through common-mode error cancellation and network constraint realisation. Depending on network geometry, datum definition and filtering strategies, this mechanism can lead to an apparent attenuation or smoothing of small-amplitude kinematic variability. Such effects are particularly relevant when analysing subtle oscillatory motions on floating ice tongues or in transition zones between grounded and floating ice, where an accurate separation between physical signals and stochastic noise is required.

At the same time, the sparse distribution of permanent reference stations in Antarctica and the logistical constraints associated with field campaigns have often required the adoption of Precise Point Positioning (PPP) strategies (Cappuccio et al. 2024). In several glaciological studies, PPP processing was therefore applied out of necessity, typically relying on float ambiguity estimation as implemented in earlier processing environments such as Bernese GNSS Software v5.2 (Dach et al. 2015, 2024; Steigenberger et al. 2011). Although these solutions enabled the analysis of glacier motion in areas lacking dense regional networks, the resulting time series were frequently characterised by higher stochastic noise levels and reduced capability to resolve subtle kinematic fluctuations.

Recent methodological advances in PPP with integer ambiguity resolution (PPP-AR) have significantly improved positioning precision, convergence behaviour and temporal stability (Cappuccio et al. 2026; Gandolfi et al. 2016). The availability of ambiguity-fixed PPP solutions allows displacement time series to be analysed within a global reference frame without imposing network constraints, thereby potentially enhancing the signal-to-noise ratio and the interpretability of small-amplitude glacier dynamics. These developments also offer new opportunities for the reprocessing of historical Antarctic GNSS datasets originally analysed using earlier PPP implementations (Cappuccio et al. 2024).

In this study, GNSS observations from three Antarctic stations characterised by different dynamic regimes are analysed: the permanent station DCRU at Concordia Station (Dome C, East Antarctic Plateau), the inland ice site ICF1, and the DRY1 station located on the rapidly flowing Drygalski Ice Tongue. At DCRU, a direct comparison between network-based DD solutions and ambiguity-fixed PPP processing is carried out in order to assess the consistency of long-term velocity estimates derived from different positioning strategies. For DRY1 and ICF1, the analysis focuses on the comparison between legacy float PPP solutions obtained with Bernese GNSS Software v5.2 and modern reprocessing performed using the PRIDE PPP-AR (Geng et al. 2019; Jianghui Geng et al. 2010) strategy with ambiguity resolution. Particular attention is devoted to differences in stochastic noise characteristics and to the potential of reduced residual scatter to improve the interpretation of small-amplitude kinematic variability in dynamic glaciological environments.

The main objective of this work is therefore to evaluate the consistency of glacier motion estimates obtained from network-based and PPP processing approaches under representative Antarctic conditions, and to investigate the impact of PPP ambiguity resolution on the reliability, stability and physical interpretability of GNSS time series acquired in Antarctic polar regions.

2 Dataset and Materials

This work is based on two GNSS datasets acquired in Antarctica within PNRA project, representing complementary glaciological environments:

1. the Drygalski Ice Tongue, characterised by rapid flow and tidal influence;
2. the GNSS continuous operating station installed at Concordia Station (DCRU) on the East Antarctic Plateau, where ice flow is extremely slow because it is close to the dome summit.

These datasets were selected both to compare GNSS processing strategies and to investigate how the evolution from classical DD or early PPP methods to modern PPP-AR techniques affects the interpretation of glaciological signals under different dynamic conditions.

2.1 Drygalski Glacier and Ice Tongue Dataset

The first dataset refers to the David Glacier–Drygalski Ice Tongue system, a major outlet glacier of northern Victoria Land discharging into the Ross Sea. The area has been periodically investigated since the early 1990s within PNRA glaciological campaigns. The available GNSS data consist of 24 daily RINEX files collected during the austral summer

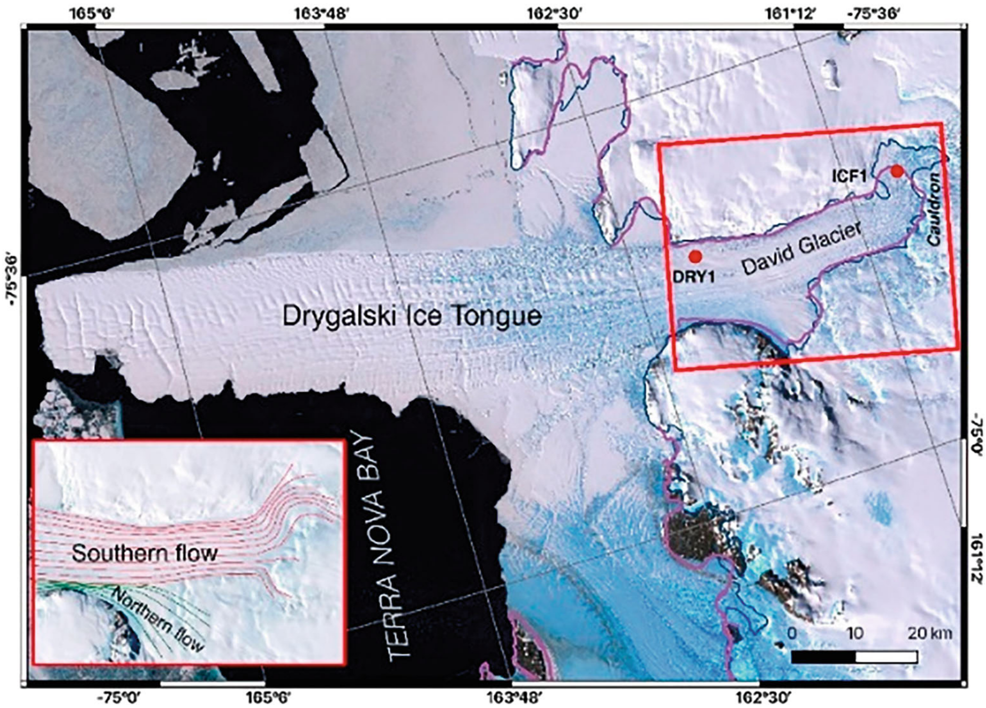

Fig. 1 Location of the temporary GNSS stations DRY1 and ICF1 on the terminal part of the David Glacier–Drygalski Ice Tongue system (northern Victoria Land, Antarctica). The background image shows the ice tongue and the surrounding sea-ice area as observed during the 2006 GNSS campaign (Vittuari et al. 2023)

2006, when two temporary GNSS stations, ICF1 (near the grounding zone) and DRY1 (~40 km downstream on the floating ice tongue) operated simultaneously for 24 days (15 January–7 February 2006) to capture tidal modulation and ice-flow variability (Fig. 1).

The 2006 campaign data were originally processed using the kinematic module TRACK of the GAMIT/GLOBK software suite (Herring et al. 2006), based on double-difference (DD) solutions, using the TNB1 permanent station, located approximately 100 km away at Mario Zucchelli Station, as the reference (Danesi et al. n.d.).

In later studies, the same observations were reprocessed in kinematic PPP mode with Bernese v5.2, using IGS final precise orbits and clocks (Kouba and Héroux 2001) but without explicit ambiguity fixing. In the present work, the dataset was further reprocessed using PRIDE-PPP-AR v3.0, adopting a kinematic PPP-AR strategy based exclusively on GPS observations and employing IGSrepro3 precise orbit, clock, and bias products (Dach et al. 2024). Coordinate solutions were generated every 5 min (15-s sampling) to analyse short-period vertical oscillations and horizontal flow components.

This new PPP-AR reanalysis represents a methodological advancement over the previous Bernese PPP solution, enabling ambiguity resolution and higher temporal resolution while maintaining consistency with the original GPS-only configuration.

2.2 Concordia Station (DCRU) Dataset

The second dataset concerns the permanent GNSS station DCRU, installed on the roof of the Italian French Concordia Station at Dome C (75°06′06″ S, 123°23′43″ E; 3,233 m a.s.l.). Operational since January 2005 with 15-s sampling, DCRU provides one of the longest continuous geodetic time series in the Antarctic interior; metadata on equipment and gaps are documented in the Dome C long-term GNSS archive.

3 Processing Methods

GNSS data from both study sites were processed using two independent workflows based on the Bernese GNSS Software (BSW) v5.2 and PRIDE-PPP-AR v3.0, in order to evaluate the evolution from the classical double-difference (DD) network approach to the ambiguity-resolved Precise Point Positioning (PPP-AR) strategy implemented in PRIDE, lambda method in particular (Jongep and Tiberius 1996).

For this study, a 14-year subset of daily files was processed with both software packages to ensure direct comparability under Antarctic conditions. For Bernese, the DD network processing was carried out using the Bernese Processing Engine (BPE), following the standard automated workflow for daily solutions. The rnx2snx procedure was applied, as recommended for regional GNSS networks (Dach et al. 2015), to generate daily SINEX files and estimate station coordinates in the ITRF2014 reference frame (Altamimi et al. 2016). The adopted products included IGS final orbits, clocks, and code/phase bias corrections provided by the International GNSS Service (IGS).

The positioning time series of DCRU was estimated using an Antarctic GNSS network including IGS permanent stations distributed along the continental margins, as shown in Fig. 2, where the estimation of the Dome C ice summit motion with respect to the bedrock is also illustrated, obtained by combining the observed absolute motion with the expected plate motion at that location.

For PRIDE-PPP-AR v3.0, the processing was implemented through a parallelised workflow controlled by Linux shell scripts for automated batch computation of both static and kinematic solutions. The PPP-AR analyses used the same IGSrepro3 (http://ftp.aiub.unibe.ch/REPRO_2020/CODE) final orbit, clock, Earth orientation and bias products to ensure full consistency with the Bernese configuration. Absolute antenna phase centre variation (PCV) corrections were applied for both satellites and receivers, using individual calibrations for the IGS reference stations. Tropospheric delays were modelled using the VMF1 mapping function (Boehm et al. 2006), while standard IERS corrections for solid Earth tides, pole tides and ocean pole tide were applied. Ocean tide loading was intentionally omitted, as its expected amplitude at the analysed sites is negligible and below 1 mm at DCRU. All PRIDE-derived coordinates were expressed in ITRF2020 (Altamimi et al. 2023).

The kinematic PPP-AR mode was applied to the DRY1 and ICF1 stations (5-min solutions) to capture high-frequency tidal and flow variations, while the static daily mode was adopted for DCRU by processing each 24-h file independently to obtain a homogeneous decadal time series. Standard outlier screening and gap handling were applied without additional smoothing. For the kinematic PPP-AR solutions, ambiguity resolution converged rapidly during the initial epochs and remained stable over the sessions, with average fixing rates close to 95%. The main processing parameters for both software packages are summarised

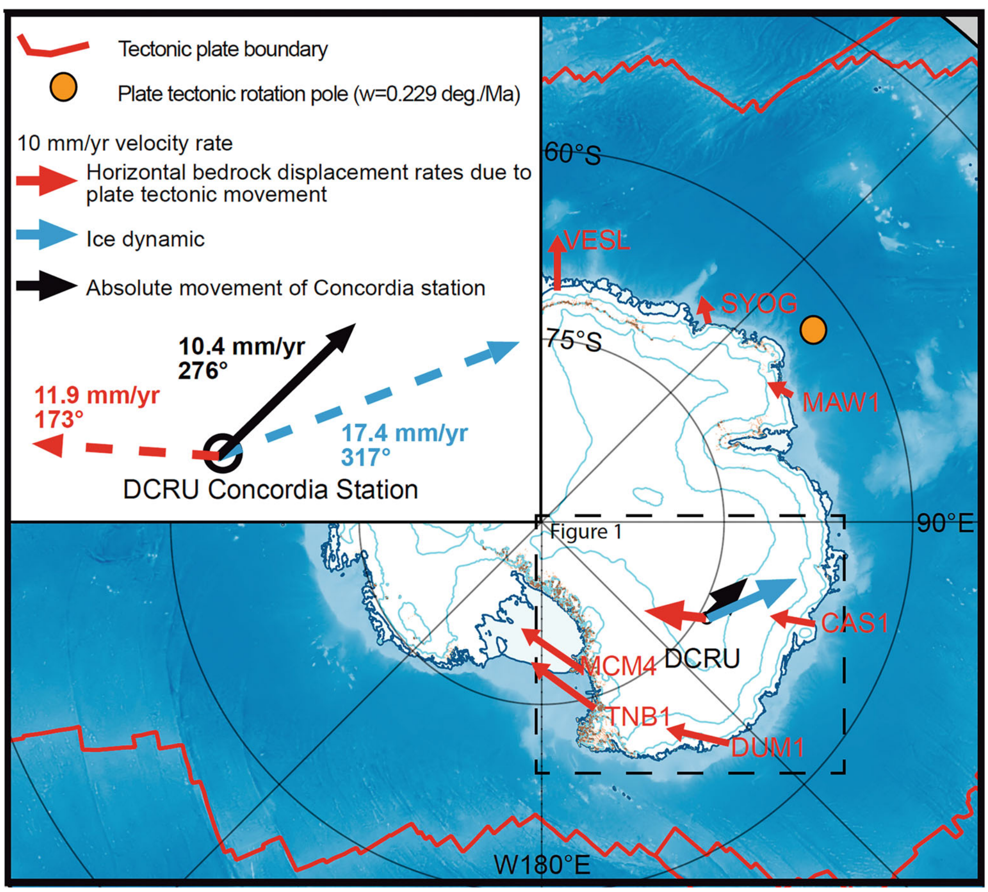

Fig. 2 Map of Antarctica and the Southern Ocean. The map illustrates the horizontal velocity of bedrock movements attributed to plate tectonics, represented by red arrows (in mm year^{-1}). The black arrow indicates the absolute movement measured at Concordia Station (DCRU) due to ice dynamics and plate tectonics at the bedrock. Additionally, the blue arrow represents the estimated movement of the ice summit at DCRU in relation to the bedrock (Vittuari et al. 2025)

Table 1 Main processing parameters adopted for PRIDE-PPP-AR and Bernese GNSS analyses. The table summarizes the key configuration choices applied to both kinematic (Drygalski) and static (DCRU) solutions

Parameter	PRIDE-PPP-AR v3.0	Bernese GNSS v5.2
Processing mode	Kinematic (DRY1, ICF1); static daily (DCRU)	DD static (DCRU), PPP kinematic (Drygalski)
Sampling interval	5 min (kinematic)/24 h (static)	5 min (kinematic)/24 h (static)
Satellite systems	GPS (L1/L2)	GPS (L1/L2)
Reference frame	ITRF2020	ITRF2014
Ancillary products	IGSrepro3 orbits and clocks (30s)	IGS final orbits and clocks (5M)
Tropospheric model	VMF1 mapping function	Dry Niell mapping function
Ionosphere model	Dual-frequency iono-free combination	Dual-frequency iono-free combination
Ocean tide loading	Not applied	Not applied
Ambiguity resolution	Fixed (AR enabled, lambda)	PPP float (no AR) DD QIF fixed
Elevation cut-off	10°	10°
Processing environment	Parallelised Linux scripts	Standard windows/Linux execution

in Table 1, highlighting the key differences in modelling strategy and reference frame definition.

The resulting coordinate solutions were then analyzed to extract displacement time series and velocity components, as described in Sect. 4.

4 Results

The reprocessing of the Antarctic GNSS datasets using PRIDE PPP-AR v3.0 provides solutions that are fully consistent with those obtained with Bernese GNSS Software (BSW), while improving the description of the short-term variability of the coordinate time series. Figure 3 shows the comparison between the two independent processing strategies for station DRY1, located on the floating portion of the Drygalski Ice Tongue. The coordinate time series are expressed in a glacier-oriented reference frame, defined by the along-flow (D), across-flow (T), and vertical (Up) components. The flow direction is oriented at an azimuth of +11.3° with respect to the geographic North.

Across all components, the agreement between BSW and PRIDE solutions is at the millimetre level. The D component confirms the steady downstream motion of the floating tongue, while the Up component clearly reproduces the tidal modulation induced by ocean forcing. In the transverse direction (T), both solutions show a small-amplitude oscillatory signal (on the order of ±0.05 m), already present in the BSW results but more clearly resolved in the PPP-AR solution due to reduced noise. This behaviour is consistent with a secondary transverse response of the floating ice tongue and is likely associated with tidal bending and lateral motion.

The reduced scatter of the PRIDE time series is particularly evident in the D component after detrending, where small-amplitude fluctuations are more clearly resolved. This improvement highlights the capability of ambiguity-fixed PPP processing to enhance the signal-to-noise ratio and to better characterise subtle kinematic features.

A quantitative assessment of the agreement between the two solutions is provided through the analysis of daily coordinate differences. Figure 4 shows the absolute differences between PRIDE and BSW together with the 68% and 95% quantiles for each component. At DRY1, the dispersion of the differences remains within a few centimetres horizontally and below the decimetre level in the vertical component, with the majority of residuals well constrained within the Q68 threshold.

The spectral analysis performed using the Lomb–Scargle periodogram (VanderPlas 2018) confirms that the dominant periodic components correspond to tidal frequencies, with main peaks at approximately 25.6 h and 23.4 h. These periods are consistent between the two processing strategies and are in very good agreement with the nearby tide-gauge observations.

Consistent results are obtained for station ICF1, located closer to the grounding line, where both processing strategies reproduce the same tidal-driven kinematic behaviour without significant discrepancies. In this case, the differences between PPP float and PPP-AR solutions are mainly reflected in a reduction of the stochastic noise, rather than in changes of the signal content.

The comparison of long-term coordinate time series at DCRU (Concordia Station, Dome C) further confirms the robustness and consistency of the two processing approaches (Fig. 3). Daily coordinate differences remain at the millimetre level and do not exhibit any significant systematic trends over the analysed period.

The statistical distribution of the differences at DCRU is shown in Fig. 5, where the Q68 and Q95 quantiles indicate sub-centimetre agreement in the horizontal components and a slightly larger dispersion in the vertical component, as expected. RMS values computed on detrended residuals confirm this behaviour, with comparable noise levels for the two solutions.

The velocities derived from the reprocessed time series are fully consistent with previously published results

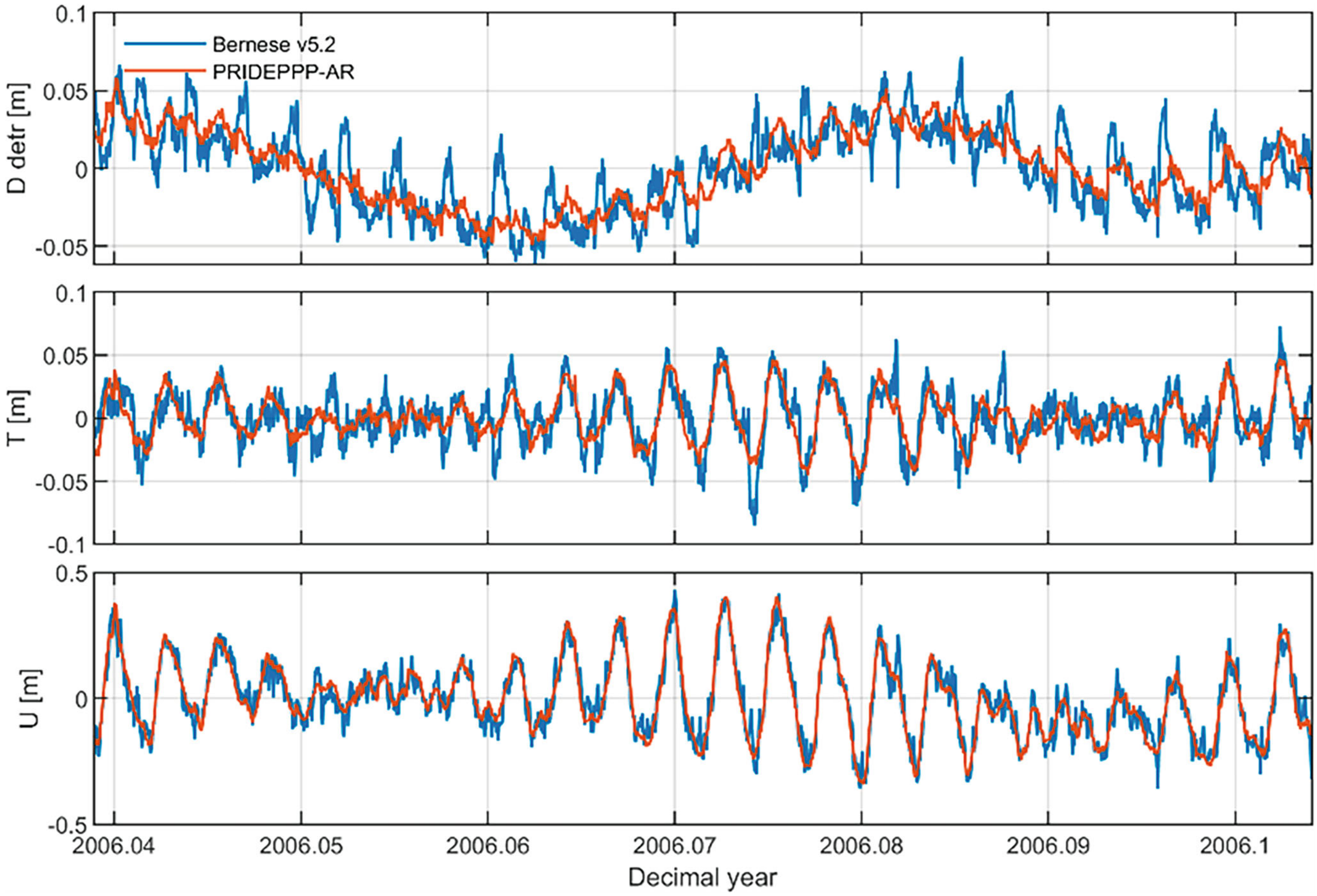

Fig. 3 Comparison between Bernese PPP (blue) and PRIDE PPP-AR (red) coordinate time series at station DRY1, expressed in the glacier-oriented reference frame (D, T, Up). The D component is shown after removal of the linear trend in order to highlight small-amplitude fluctuations

(Vittuari et al. 2025), yielding a horizontal velocity of 10.4 ± 0.4 mm year^{-1} towards 276° and a vertical subsidence of −114 ± 2.6 mm year^{-1}. Differences between BSW and PPP-AR solutions remain below 3.2 mm year^{-1} in all components, indicating that the choice of processing strategy does not affect the long-term kinematic estimates. A complementary coloured-noise analysis performed with Hector (https://teromovigo.com/product/hector/) confirms that the velocity differences between the Bernese and PPP-AR solutions remain of the order of a few millimeters per year (maximum 3.4 mm year^{-1}), fully consistent with the uncertainty range previously reported by Vittuari et al. (2025) for long-term Antarctic GNSS time series.

Overall, the results demonstrate that ambiguity-resolved PPP processing can reproduce the performance of traditional network-based or float PPP approaches, while providing a reduction in noise and an improved capability to resolve small-amplitude kinematic signals. This aspect is particularly relevant in glaciological applications, where subtle variations in transverse or vertical motion may provide insights into ice–ocean interactions and ice dynamics.

A summary of the RMS values computed on detrended residuals for each solution and station is reported in Table 2. These results confirm the comparable noise levels between the different processing strategies, with a slight but systematic reduction of scatter in the PPP-AR solutions.

5 Discussion and Conclusion

This study provides a comprehensive comparison between legacy GNSS processing strategies and modern ambiguity-resolved PPP approaches under representative Antarctic conditions. The results demonstrate that PPP-AR processing achieves a level of accuracy and stability fully comparable with traditional network-based and float PPP solutions, both in short-term kinematic applications and in long-term geodetic monitoring. At the floating DRY1 site, the improved precision of the PPP-AR solution allows a clearer identification of small-amplitude kinematic features, particularly after detrending the along-flow component. The transverse oscillatory behaviour, already present in the legacy solutions,

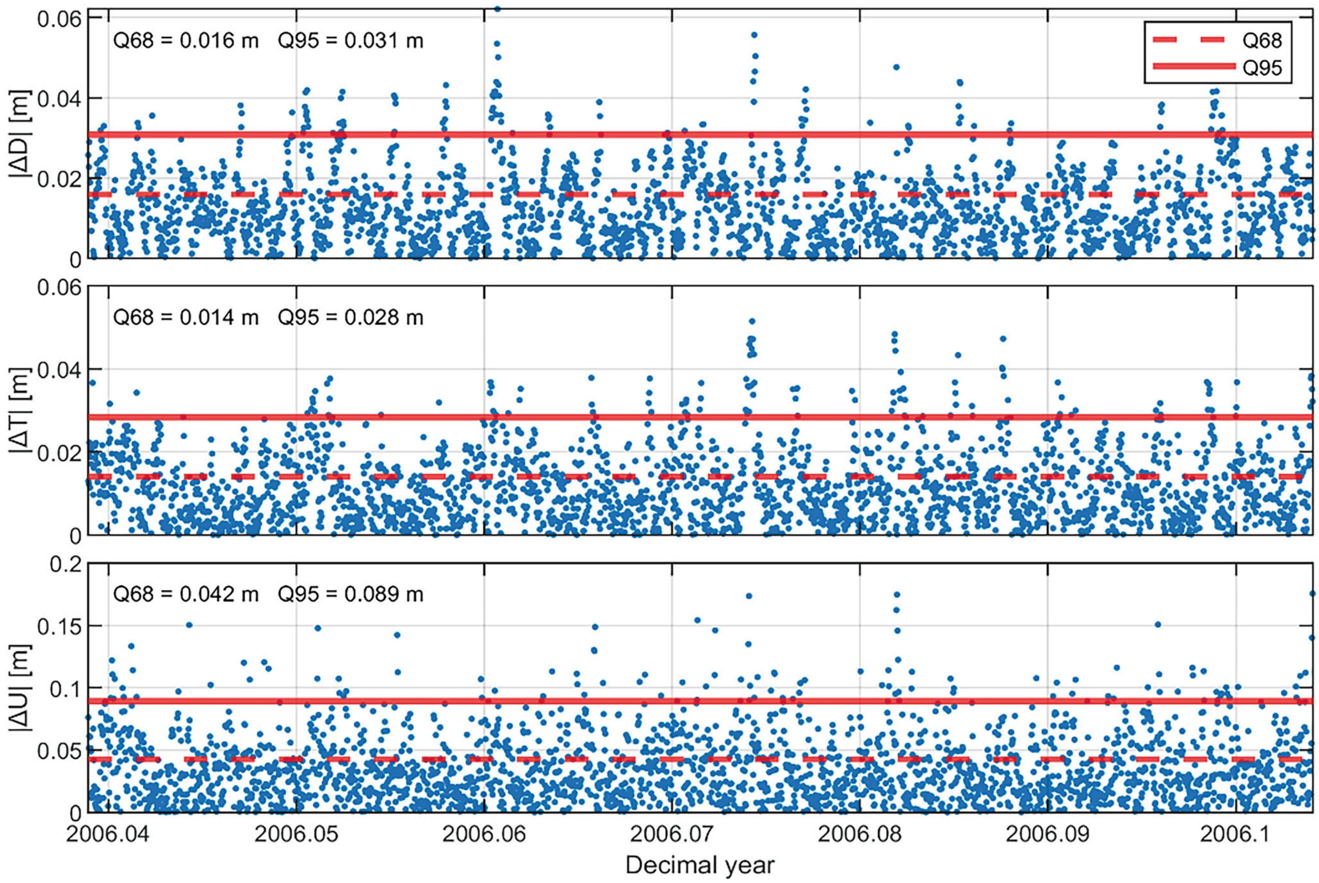

Fig. 4 Absolute differences between PRIDE PPP-AR and Bernese PPP coordinate solutions at station DRY1, shown for the D, T and Up components. The red lines indicate the 68% and 95% quantiles of the residual distribution

is more distinctly resolved and can be consistently interpreted as a tidal-driven response of the floating ice tongue. This highlights the importance of reduced stochastic noise in enhancing the interpretability of glaciological signals. At the inland DCRU station, the comparison confirms the long-term consistency between the two processing strategies, with no significant differences in velocity estimates and only millimetre-level discrepancies in daily positions. The analysis of residuals, including RMS, quantile-based metrics and coloured-noise modelling, further supports the equivalence of the solutions in terms of long-term stability, while indicating a slight reduction of stochastic scatter in PPP-AR. The Hector noise analysis suggests that the differences between Bernese and PPP-AR velocity estimates remain at the level of a few millimetres per year, in agreement with the uncertainty range discussed by Vittuari et al. 2025. This confirms that the observed discrepancies are well within the expected coloured-noise behaviour of long Antarctic GNSS time series and do not affect the physical interpretation of ice motion. Overall, the results indicate that ambiguity-resolved PPP represents a robust and reliable alternative to traditional processing approaches, with the additional advantage of improved sensitivity to subtle kinematic variations and a cleaner stochastic structure of the residuals. This capability is particularly relevant for the reprocessing of historical GNSS datasets and for future applications in polar regions, where the detection of small-scale processes may provide key insights into ice dynamics and ice–ocean interactions.

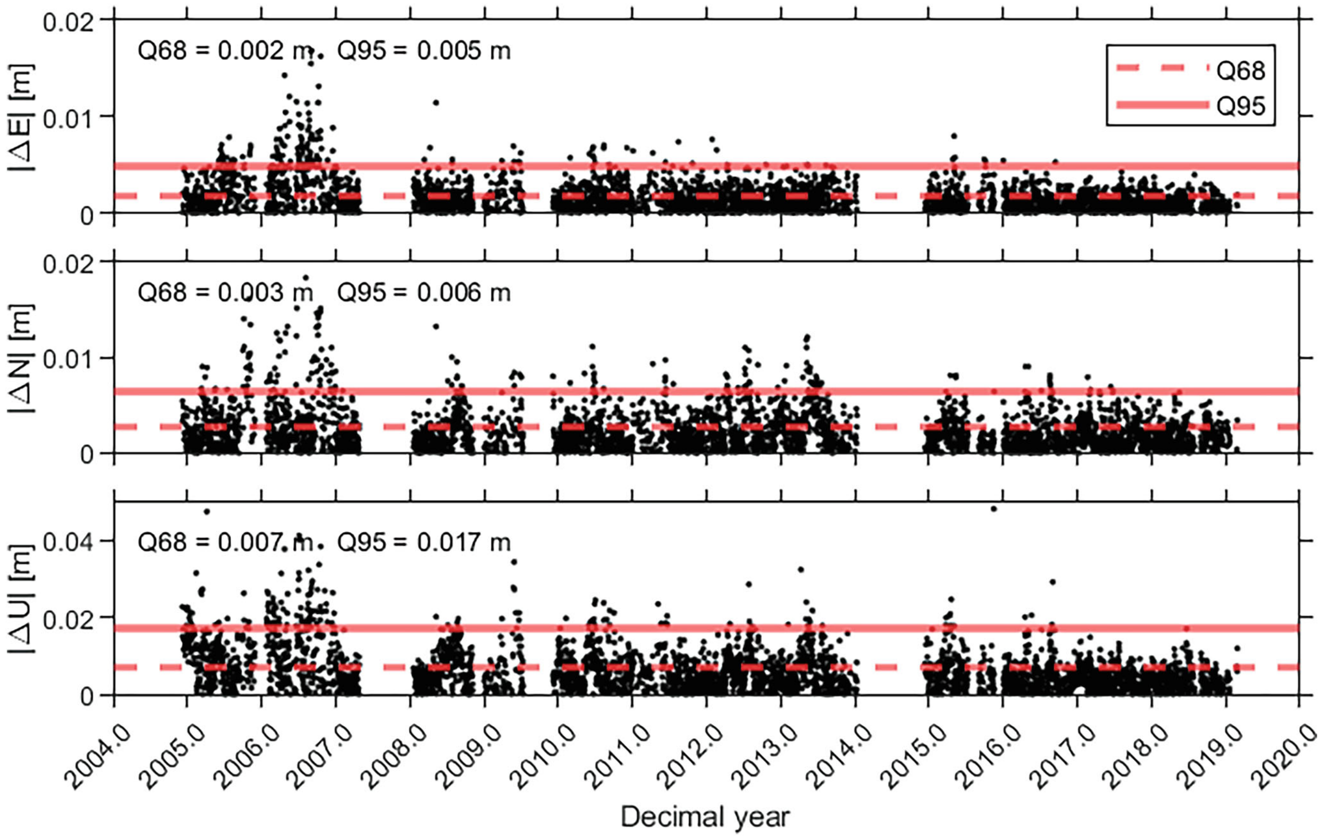

Fig. 5 Absolute differences between PRIDE PPP-AR and Bernese coordinate solutions at station DCRU (Concordia Station) for the North, East and Up components. The red lines indicate the 68% and 95% quantiles of the residual distribution

Table 2 Root mean square (RMS) values of the coordinate time series for each station and processing strategy, computed on detrended residuals

Station	Software	RMS N [m]	RMS E [m]	RMS U [m]
DCRU	Bernese v5.2 (DD)	0.004	0.004	0.051
	PRIDEPPP-AR	0.003	0.004	0.050
ICF1	Bernese v5.2 (PPP-float)	0.029	0.024	0.051
	PRIDEPPP-AR	0.026	0.022	0.046
Station	**Software**	**RMS D [m]**	**RMS T [m]**	**RMS U [m]**
DRY1	Bernese v5.2 (PPP-float)	0.027	0.022	0.148
	PRIDEPPP-AR	0.023	0.018	0.143

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Competing Interests The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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