



# Multi-GNSS Precise Point Positioning with Ambiguity Resolution using IGS Products: A Cross-Evaluation of Three Software Packages and Combinations of Constellation Data for Geophysical Investigations

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## Abstract

Precise point positioning (PPP) is a GNSS processing strategy for the estimation of station coordinates, receiver clocks and zenith total delays with high efficiency, precision, and accuracy. However, to achieve the highest quality in PPP solutions, precise satellite orbits and clocks products, and various bias information for code and carrier observations, necessary for PPP integer ambiguity resolution (AR), are essential. These critical products are routinely provided by the International GNSS Service (IGS) and its analysis centers. Due to the undifferenced nature of PPP solutions, they are particularly affected by error sources and in case of insufficient mitigation models, residual errors may propagate into the solutions and contaminate time series of the estimates. Also, inconsistencies between model implementations in software used during product generation and the ones employed by users during product application, lead to artefacts in the PPP solutions. On the other hand, PPP AR does compensate somewhat and improve the solutions despite the frequently inseparable sources of the residual errors.

In this study, we present an analysis of single and multi-GNSS PPP AR solutions using observations from the GPS, GLONASS and Galileo constellations. We employed three independent software packages, the Bernese GNSS Software v5.4, PRIDE v2.2 and GipsyX v2.1, each employing their recommended set of products and processing settings, while attempting to keep settings as consistent as possible between the software packages and processing runs. We processed data from 100 globally distributed IGS stations, carefully selected for known quality and network geometry, for 2019.0 – 2023.5.

In our analysis we evaluate the impact of different single- and multi-constellation GNSS PPP-AR solutions in terms of time series characteristics, mean coordinate differences and solution repeatabilities for the different software packages.

## Introduction

In an era characterized by rapid technological advancements, the need for accurate and reliable coordinate estimates has become paramount across a diverse range of applications. GNSS constellations have revolutionized the geosciences and are fundamental and ubiquitous in everyday life.

Today:

- daily positioning can rely on constellations such as GPS (G), GLONASS (R), Galileo (E) and BeiDou (C), although we did not evaluate the latter constellation here.
- PPP with phase ambiguity resolution (AR) (Geng et al., 2011) has emerged as a highly efficient processing strategy for quick and precise GNSS solutions.
- we assess the precision of coordinate estimates from single- and multi-constellation PPP-AR using three state-of-the-art tools, i.e., Bernese GNSS Software v5.4 (BSW54) (Dach et al., 2015), PRIDE v2.2 (PRIDE) (Geng et al., 2022), and GipsyX v2.1 (GOA) (Bertiger et al., 2020).

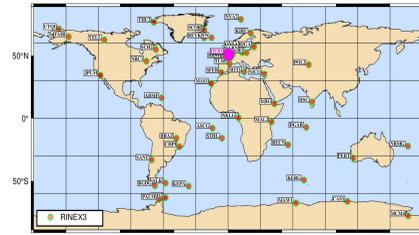
We hypothesize that

- The results of BSW54 are equivalent to those obtained from PRIDE and GOA in single and multi-constellation PPP-AR solutions.
- The combination of multiple constellations improves the precision of coordinate estimates.

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## Data and Methods



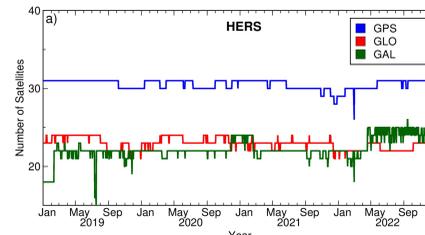
Distribution of GNSS stations.

### Data Sources:

- International GNSS Service (IGS)
- NASA Earthdata Archives
- Tide Gauge Benchmark Monitoring (TIGA)
- British Isles continuous GNSS Facility (BIGF).

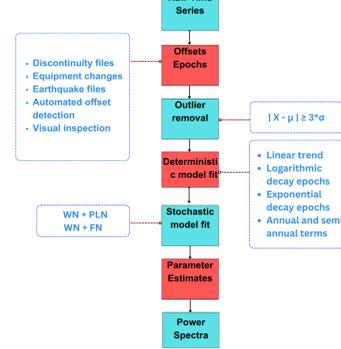
### PPP-AR Processing Strategy

Parameter	Description
Observation	Ionosphere-free code and phase combinations with every 30 seconds
Elevation Cut-off Angle	3°
Subdaily pole model	DESA2016 (Desai & Sibois, 2016)
Data span	4.5 years
Satellite-based Weighting Factor	Equivalent for all
Orbit and Clock	Final REPRO.2020 products produced by CODE
Satellite/Receiver Phase Center	After Nov-2022 from I20.ATX and before I20.ATX (bestmail0401) subject to REPRO.2020 products, (Dach et al., 2019)
Ionospheric Effect	Second order ionospheric effect removed using CODE products (Kolar et al., 2003)
Phase Ambiguities	Fixed for GPS and GAL with CODE products; float for GLO
Ocean Tide Loading	FES2014b model (Carrere et al., 2015, Lyard et al., 2021)
Solid Earth and Polar Tides	IERS conventions 2010 (Petit & Luzum, 2010)
Parameter Differences on the Three Software Tools	
Troposphere	BSW54 and PRIDE use VMF3 (Landskron and Bohm, 2018), while GipsyX employs VMF1 (Ehlig et al., 2006)
Phase ambiguities resolution strategy	Signs for BSW54 (Dach et al., 2022), rounding for PRIDE and GOA



Daily counts of GPS, GLONASS, and Galileo satellites were recorded throughout the analysis period, based on existing RINEX observations.

Time series analysis was performed on the daily solutions using an updated Coordinate Time Series Analysis (CTSAna) software (Teferle, 2013) and Hector (Bos et al., 2013).



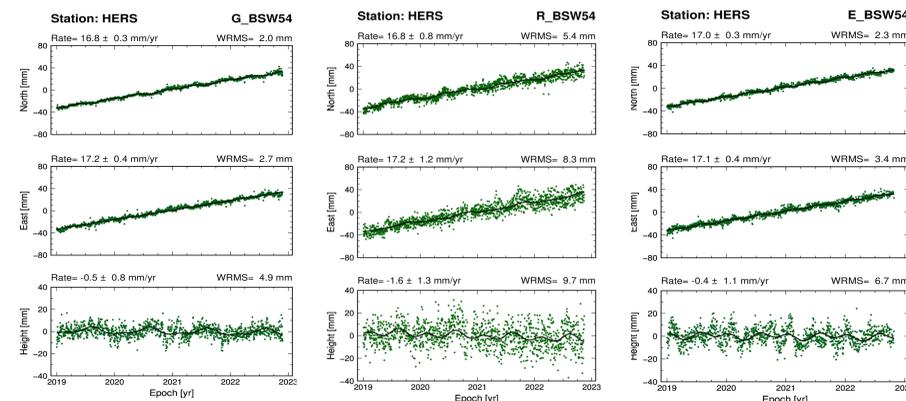
- Single-system and multi-GNSS coordinate precision was assessed as per (Zajdel et al. 2022).
- The Lomb-Scargle periodogram (Scargle, 1982) was employed for power spectral analysis.

### Minimum Frequency Difference ( $\Delta f$ ) for Power Spectra Analysis

- Equation:**  $\Delta f = 365.25 / T_s$  (Rothacher et al., 1999)
- Data Span (Ts):**  $\approx 4$  years (approximately 1643.625 days)
- Calculation:**  $\Delta f = 365.25 / 1643.625 \approx 0.256$  cycles per year (cpy).
- Implication:** The longer the data span (Ts), the finer the resolution of periodic oscillations in the power spectra.

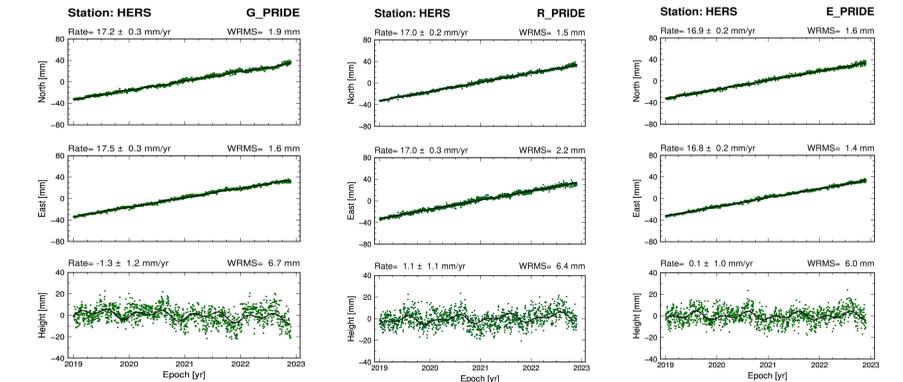
## Results

### Example BSW54 Single Constellation Coordinate Time series for HERS Station

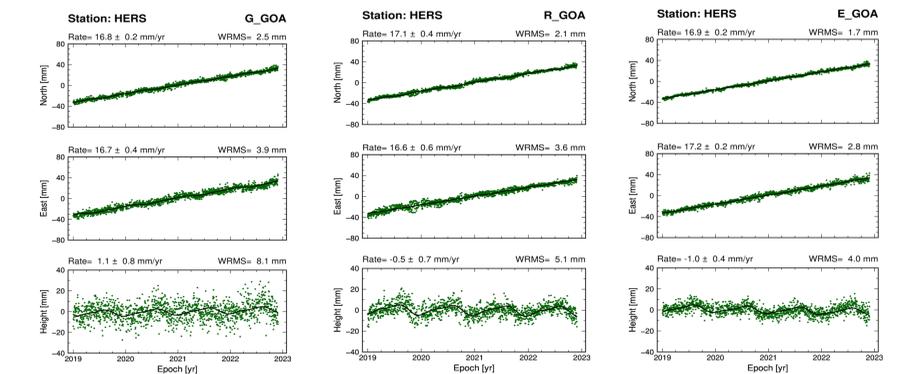


## Results (cont.)

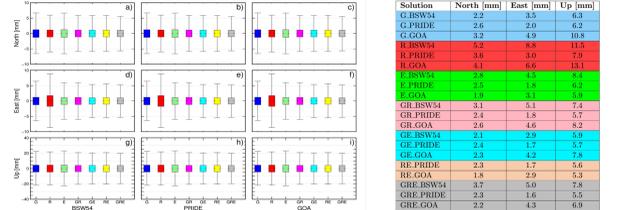
### Example PRIDE Single Constellation Coordinate Time series for HERS Station



### Example GOA Single Constellation Coordinate Time series for HERS Station



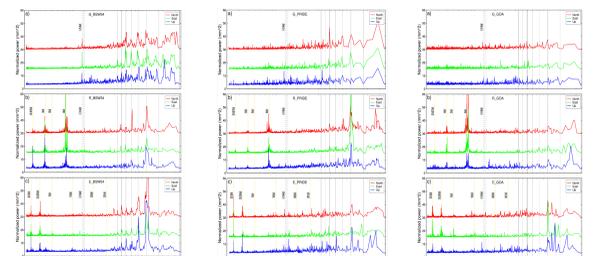
Coordinate precisions (Box-whisker plots and mean WRMS) for single- and multi-constellation solutions for BSW54, PRIDE and GOA.



Mean coordinate differences for single- and multi-constellation solutions for BSW54, PRIDE and GOA.

Solution 1	Solution 2	North [mm]	East [mm]	Up [mm]
G_BSW54	G_GOA	-0.3	-0.3	-0.4
G_BSW54	G_PRIDE	-0.2	0.8	0.0
G_PRIDE	G_GOA	-0.2	-0.6	-0.4
R_BSW54	R_GOA	0.3	0.3	-0.1
R_BSW54	R_PRIDE	0.4	1.9	0.4
R_PRIDE	R_GOA	-0.1	-0.5	-0.4
E_BSW54	E_GOA	0.5	0.4	0.4
E_BSW54	E_PRIDE	-0.1	-0.1	0.1
E_PRIDE	E_GOA	0.3	-0.1	0.1
GR_BSW54	GR_GOA	0.2	0.1	-0.1
GR_BSW54	GR_PRIDE	0.3	1.8	0.3
GR_PRIDE	GR_GOA	-0.1	-0.6	-0.3
GE_BSW54	GE_GOA	-0.1	-0.3	-0.2
GE_BSW54	GE_PRIDE	-0.2	0.7	0.0
GE_PRIDE	GE_GOA	0.1	-0.6	-0.3
RE_BSW54	RE_GOA	0.2	-0.4	0.1
RE_BSW54	RE_PRIDE	0.7	0.2	0.1
RE_PRIDE	RE_GOA	0.6	2.0	0.4
RE_BSW54	RE_PRIDE	0.1	-0.6	-0.2

Single-constellation stacked mean spectra (offset for clarity), for North, East, and Up components. Gray lines show fortnightly signals, golden dashes indicate system-specific signals.



## Conclusions

- The three PPP-AR software tools employed were assessed through cross-evaluation of single- and multi-GNSS solutions from all available data.
- The results from the three tools were highly consistent, with BSW54 slightly worse and PRIDE the best.
- Galileo single-GNSS solutions provide superior coordinate precisions compared to GPS and GLONASS.
- The combined GPS and Galileo solutions provide the most precise coordinate estimates.