Precise Point Positioning:
Real-time centimeter accuracy trajectory in peri-urban environment

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Abstract

Reliable centimeter-level positioning in real time remains a major hurdle for Precise Point Positioning (PPP) in peri-urban environments, where frequent signal blockages and multipath corrupt carrier-phase ambiguities. We adapt the strategy previously validated in post-processing to a fully real-time framework. The filter is a forward-only Kalman estimator that (i) keeps all ambiguities as float states, (ii) attempts epoch-by-epoch integer fixing on extra-/wide-lane and gap-bridging combinations in a "continuous ambiguity-resolution" mode, and (iii) embeds an online residual-dispersion test that triggers a restart whenever a run of outliers is detected.

Tests on two dual-frequency, multi-GNSS road trajectories (69 min total) show that the solution converges to a 1 σ horizontal accuracy of 8–10 cm within ~60 s, holds RMS 2-D errors between 12 cm and 16 cm, and maintains ~95 % availability despite short outages. The residual downtime is driven by filter restarts.

Keywords: GNSS · PPP · Ambiguity resolution

1. Introduction

Building on the post-processing approach introduced in [1] for reconstructing Precise Point Positioning (PPP) trajectories in peri-urban environments, where centimeter-level accuracy was demonstrated, we extend the method to a real-time implementation. While real-time operation entails a modest loss in precision, the solution consistently converges to ~10 cm accuracy.

2. Choice of the solution

In [1], we presented two trajectory-estimation strategies, Solution A and Solution B, which differ in that Solution A omits integer-ambiguity resolution for the N1 carrier phase. The present study adopts Solution A, as the performance disparity between the two approaches is marginal and, under real-time conditions, reliable resolution of N1 ambiguities is unlikely.

3. Expected performance

To quantify the real-time accuracy of Solution A, we designed the following Monte-Carlo-style experiment: Sliding-window filtering. A fixed-length window of raw observations was selected and processed; the state at the final epoch of the window represents the solution that would be available in real time.

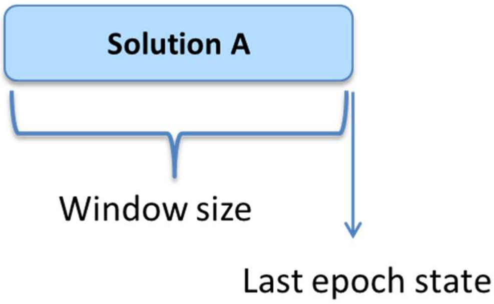

Figure 1: set-up for performance estimation

The estimated position at this final epoch was compared with the reference trajectory, yielding East and North errors. Under the assumption that these components are independent, zero-mean Gaussian variables, the horizontal-error magnitude is Rayleigh-distributed.

Steps were repeated for at least 50 distinct windows, producing an ensemble of horizontal-error magnitudes. A Rayleigh probability-density function was then fitted to this ensemble, and its scale parameter (σ) was taken as the 1-σ horizontal accuracy.

The procedure was carried out for several window lengths to evaluate the convergence performance.

As an illustrative case, executing the procedure with a 60 s window produces the horizontal-error histogram shown in Fig. 2.

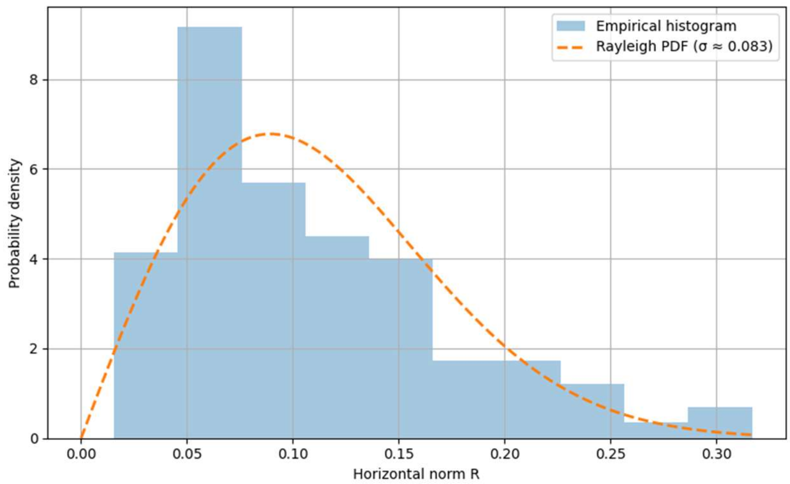

Figure 2: histogram of 2D-errors

And an associated sigma of 8.3 cm

Repeating the experiment across multiple window durations yields the σ-convergence profile shown below.

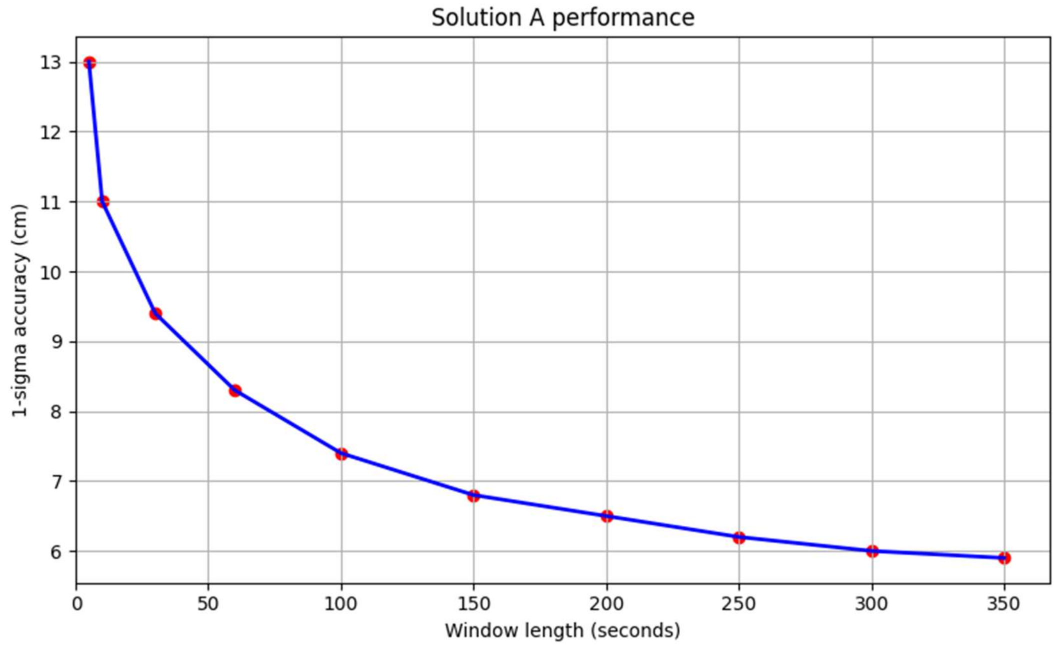

Figure 3: accuracy vs window length

Sub-decimeter accuracy is reached after a few tens of seconds.

4. Adaptation to real-time

To enable real-time operation, Solution A in [1] is implemented as a forward-only Kalman filter that retains carrier-phase ambiguities as float states. At every epoch the algorithm attempts integer fixing, successively on the extra-wide-lane, wide-lane, and gap-bridging combinations, but any successful fix is applied only for that epoch and is **not** held permanently. This "continuous ambiguity resolution" strategy, analogous to RTKLIB's *Continuous AR* mode [2], prevents erroneous fixes from corrupting the main filter estimate.

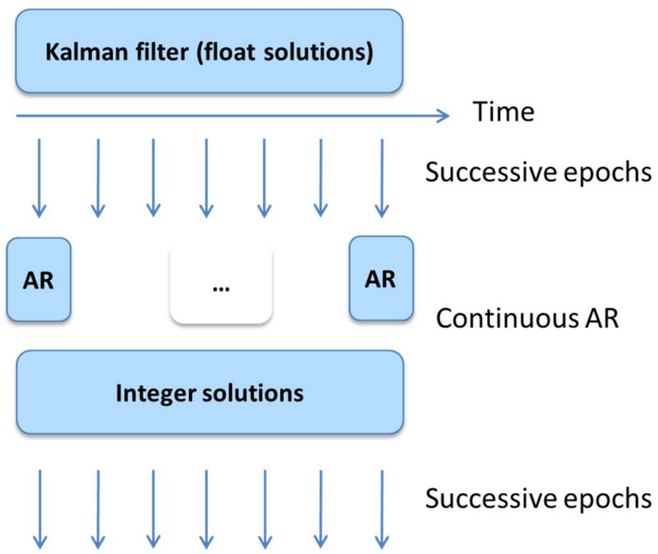

Figure 4: diagram of real-time resolution

5. Robustness and outlier detection

As highlighted in [1], the real-time Kalman filter can diverge when confronted with measurement outliers. We therefore embed an online consistency test that both flags outliers and, when necessary, re-initializes the filter.

After each measurement update, the vector of post-fit residuals $r \in \mathbb{R}^n$ is formed and scaled by the corresponding 1 σ observation noise:

$$\widetilde{r_k} = \frac{r_k}{\sigma_k} \quad \mathrm{k} = 1, \dots, \mathrm{n}$$

A scalar dispersion metric, $D = \sqrt{\frac{\widetilde{r_k}'\widetilde{r_k}}{n}}$ quantifies the overall consistency of the residual set. Because the components $\widetilde{r_k}$ are expected to follow a unit normal distribution, D≈1 denotes consistency, whereas D>1 signals the presence of an outlier.

To distinguish isolated blunders from sustained divergence, an integer counter is maintained: it increments when D>1 and decrements (but not below zero) otherwise. If the counter exceeds a pre-defined threshold, six to eight in this study, the estimator is re-initialized. This strategy effectively suppresses persistent outliers.

6. Real life scenarios

The following figure shows the horizontal errors for first trajectory:

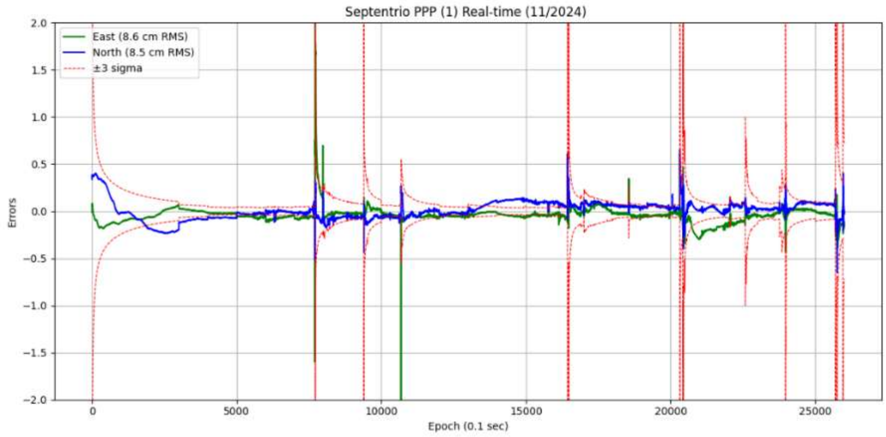

Figure 5: run #1 errors (for stats, epochs where sigma > 15 cm are removed)

The following figure shows the horizontal errors for the second trajectory:

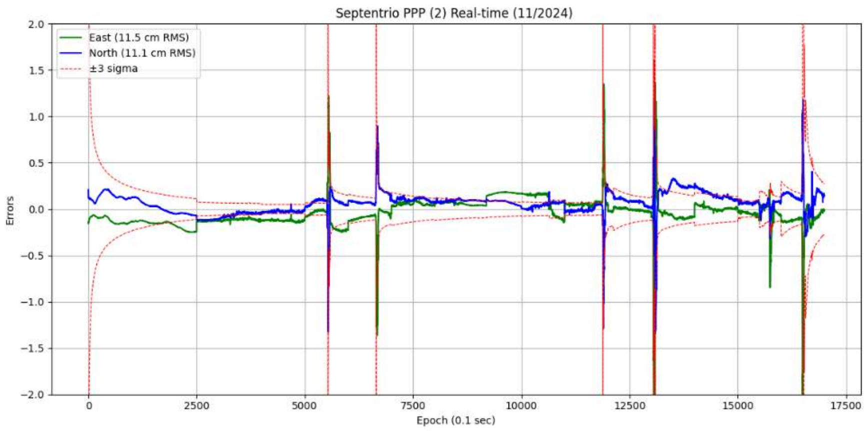

Figure 6: run #2 errors (for stats, epochs where sigma > 15 cm are removed)

7. Synthesis of the solutions

	Run #1	Run #2
Run duration	40 min	29 min
# epochs (10 Hz)	23750	17800
PPP 2D error / avail	12 cm / 96 %	16 cm / 95 %

Table 1: Synthesis of run's main results

8. Possible improvements

The principal limitation of the proposed real-time scheme remains its vulnerability to measurement outliers. Even though the consistency test curtails the frequency of Kalman-filter restarts, each re-initialization still requires a convergence interval and thus lowers overall solution availability. Three complementary mitigations are envisaged:

- **Refined a-priori state and covariance**. The provisional values listed in Table 8 of [1] are intentionally conservative; task-specific tuning of the initial state vector and its covariance, particularly after a cold start, can substantially shorten convergence.
- **Warm rather than cold restarts**. When a reset is triggered, the filter can preserve slowly varying parameters (e.g., tropospheric and ionospheric delay terms) instead of re-estimating them from scratch, thereby accelerating recovery.
- **Outlier suppression at the source**. Integrating an inertial measurement unit (IMU) offers short-term dynamic constraints that mitigate spurious jumps in the GNSS residuals, reducing the likelihood of outlier detection events in the first place.

Collectively, these measures aim to maintain centimeter-level accuracy while boosting availability in challenging real-time environments.

9. Conclusion

This study has demonstrated that centimeter-level Precise Point Positioning can be achieved in real time, even along challenging peri-urban trajectories. By (i) retaining a float-ambiguity forward Kalman filter, (ii) applying a continuous extra-/wide-lane ambiguity-resolution scheme, and (iii) embedding a residual-dispersion test that safely re-initializes the filter when persistent outliers are detected, the proposed implementation converged to a 1 σ horizontal accuracy of 8–10 cm within the first minute of operation. Two representative road tests totaling 69 min confirmed the practical benefits: root-mean-square 2-D errors remained in the 12–16 cm range while maintaining ˜95 % solution availability, despite multipath and signal blockages typical of peri-urban environments.

References

1. **Laurichesse D. (2025)**: Precise Point Positioning: Centimeter accuracy trajectory reconstruction in peri-urban environment
2. **RTKLIB library**: Retrieved from [www.rtklib.com]