Proceedings of the
13th International Conference on Applied Informatics
Eger, Hungary, February 19–21, 2026
DOI: 10.17048/icai.2026.192
pp. 192–201

An Improved Measurement and Visualization System for High Precision Positioning with GPS-RTK

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Abstract. In this work we present a GPS measurement and visualization system that enables real-time tracking, saving, and analysis of measurement data. We performed measurements using a u-blox GNSS receiver (Global Navigation Satellite System) module connected to a `Raspberry Pi 5` microcomputer, to determine whether the out-of-the-box solution can be used for high precision GPS positioning that usually means centimeter level in RTK (Real-Time Kinematic) applications. Besides using the built-in RTK correction of the module we have also applied our own algorithm to further increase accuracy based on repeated measurements. Our test measurements showed that by the use of our algorithm in an optimal setup positioning precision can be increased up to 2-3 cm. We provided a modular user interface for the device supporting graphical visualization, database management and point separation. Based on repeated measurements, the system reproduces the coordinates of measurement locations. Overall, the software assists in handling GPS data and analyzing information collected during experiments. The primary goal is to maximize measurement accuracy and simplify the experimental workflow.

Keywords: GPS, RTK, Positioning software

2020 *Mathematics Subject Classification:* 00A69, 00A79

*Gergely Kocsis was supported by the project TKP 2021 NKTA of the University of Debrecen Project no TKP 2021 NKTA 34 has been implemented with the support provided from the National Research, Development and Innovation Fund of Hungary, financed under the TKP 2021 NKTA funding scheme.

1. Introduction

Real-Time Kinematic (RTK) high precision positioning is widely used in several practical areas [6, 10]. However, its current applications are not viable for low-cost home usage. As a result, its applications focus more on high level agricultural usage. As correction data becomes increasingly accessible, everyday usage of high-precision positioning becomes available. Recently, collaborative low-cost RTK networks such as the Centipede-RTK network have gained attention in the research community [9]. These networks consist of distributed low-cost GNSS base stations providing open RTK correction data and enabling centimeter-level positioning for a wide range of applications. Previous studies investigated the reliability of low-cost GNSS receivers using the Centipede network and demonstrated that such systems can be suitable for land surveying and scientific applications.

The rapid development of low-cost multi-frequency GNSS receivers also contributed to the spread of RTK technology in recent years. Modern receivers are capable of tracking multiple satellite constellations such as GPS, GLONASS, Galileo and BeiDou [4], which improves positioning availability and reliability. This makes low-cost RTK positioning a viable solution not only for agriculture but also for robotics, autonomous vehicles, environmental monitoring and various scientific measurements.

Our first objective is to show how a relatively low-cost RTK device can do positioning while we also try to further improve the positioning accuracy this way. Our results may be used for validating the results of [2] and [9]. Besides we also visualize, store, and analyze data obtained from an RTK GNSS measurement device. As a result of our contribution one can use similar devices as ours out-of-the-box for high level accuracy positioning with even better results than the original software solutions would make possible.

In addition to positioning accuracy, measurement repeatability and data logging are also important aspects of RTK measurements. Therefore, in this work we also focus on measurement data storage, visualization and basic statistical analysis in order to better understand positioning errors and system performance.

2. Methodology

2.1. Measurement Workflow and Software

GNSS positioning has proven to be effective in applications where meter-level accuracy is sufficient. On its own, however, it cannot compensate for atmospheric disturbances, multipath effects, and other error sources, which fundamentally limit its achievable precision.

RTK (Real-Time Kinematic) improves GNSS accuracy by incorporating real-time correction data from a continuously operating reference station [5]. The basic idea behind the technology is that the above mentioned effects limiting the accuracy are almost similar in between distances of 30-50 km. Thus correction data calculated at a fixed base station can effectively be used to tune a moving rover's location data in this radius. In this configuration, the rover receives both the raw satellite observations and the correction stream, enabling it to resolve carrier-phase ambiguities and achieve centimeter-level positioning as described by [11].

In our measurement system (see Figure 1) all computations are performed directly on the rover-side `Raspberry Pi 5`. The Raspberry Pi microcomputer communicates with the `u-blox ZED-F9P-04B-01` receiver, obtains raw GNSS data, and simultaneously retrieves correction messages from the appropriate RTK base station (e.g., `fmtp` in Debrecen or `jrmi` in Mátészalka). The Raspberry Pi fuses these data streams in real time and produces the corrected position solution.

External devices such as a smartphone or laptop connect only for control and monitoring purposes, for example to start or stop measurements, adjust configuration parameters, or inspect quality indicators. They do not participate in the positioning computation itself.

The workflow diagram reflects this architecture: satellite signals reach the RTK receiver, the receiver forwards raw observations to the Raspberry Pi, the Raspberry Pi receives correction data over the Internet, and the corrected position is computed locally on the rover.

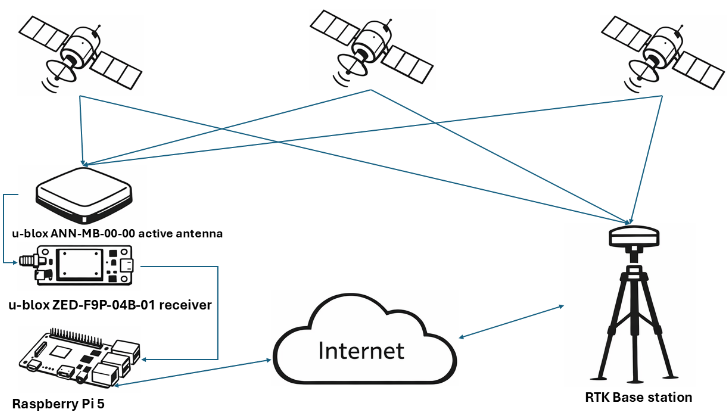


Figure 1. RTK GNSS correction flow diagram in minimalist technical style.

The possible weak point of the system naturally is the availability of RTK correction base stations. The Centipede RTK network is a community-driven GNSS correction network that provides low-cost RTK positioning. It was founded in France around 2019, but today it operates through a distributed network of privately operated base stations that share correction data over the internet, offering an open alternative to commercial RTK services for applications such as precision agriculture, surveying, and robotics [1]. Hungary has a very good coverage of base stations resulting almost 100% availability (see Figure 2). For our measurements in most of the cases we used the base station maintained by University of Debrecen, Faculty of Agricultural and Food Sciences and Environmental Management that has been started operating at March 2025.

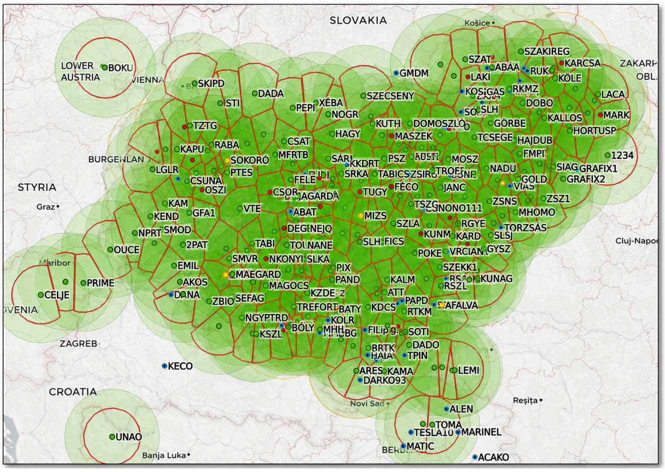


Figure 2. Hungary's Centipede-RTK base station coverage. Red lines show the max. 30 km radii of base stations. (Source: https://www.centipede-rtk.org/maps)

2.2. Hardware setup

Our measurement system is built on reliable, industry-grade GNSS hardware. The RTK processing is performed by the `u-blox ZED-F9P-04B-01` receiver, a high-precision, multi-frequency GNSS module capable of centimeter-level positioning according to its documentation. The `u-blox ANN-MB-00-00` active antenna provides stable multi-band reception, ensuring consistent signal quality even in challenging environments [7].

The antenna connects to the RTK receiver through a standard coaxial RF cable, which minimizes signal loss and preserves the integrity of the multi-band GNSS signals. The RTK module itself interfaces with the `Raspberry Pi 5` via a USB–micro-USB cable, enabling both power delivery and high-speed data transfer without requiring additional interface hardware. The Raspberry Pi provides sufficient computational performance for real-time visualization, database operations, and communication with the GNSS hardware, making the entire setup compact and easily deployable.

For network-based RTK corrections, the choice of reference station depends on the measurement location. In Debrecen, the appropriate correction source is the "fmtp" station, while in Mátészalka the "jrmi" station must be used. Although many services offer a "nearest" virtual reference option, this mode relies on a synthetic baseline and cannot deliver the centimeter-level accuracy required for high-precision geodetic measurements.

2.3. Data correction algorithm

As we will present below, according to our measurements the initial results have not reached the aimed centimeter level accuracy. Thus, we have used a simple correction algorithm to make them more accurate.

Our measurement algorithm selects the coordinates with the smallest error from a set of pre-collected GPS points noted by lat_{best} and lon_{best} respectively for the latitude and longitude. Since in our current measurements they are not needed, height and velocity values are simply averaged. We formalize the above as:

$$lat_{\text{best}} = lat + \min_i \sigma_{lat}(i), \quad lon_{\text{best}} = lon + \min_i \sigma_{lon}(i), \tag{2.1}$$

$$alt_{\text{avg}} = \frac{1}{N}\sum_{i=1}^{N} alt(i), \quad v_{\text{avg}} = \frac{1}{N}\sum_{i=1}^{N} v(i),$$

where $\sigma_{lat}(i)$ and $\sigma_{lon}(i)$ are the accuracy errors in meters of the latitude and the longitude for the measurement i. Since the device remains stationary during a measurement session, the reference point is the same for all collected data. These values are directly received from our measurement device. The total 3D error H_{3D} is:

$$H_{\text{3D}} = \sqrt{(\sigma_{\text{lat}})^2 + (\sigma_{\text{lon}})^2 + (\sigma_{\text{alt}})^2}.$$

Note that according to Eq. (2.1) the latitude and longitude errors are optimized separately. This method simplifies the correction process much compared to trying to find a measurement point with minimal global error. On the other hand, since the error values are strongly correlated in most cases, the same measurement point will typically be selected for both coordinates. To prove the above we ran a test measurement with 1043 measurement points (see Figure 3). As a result of the strong correlation and the fact that the final values of σ_{lat} and σ_{lon} are chosen from 5 independent measurements the probalility of choosing the same measurement point for both values is above 99%.

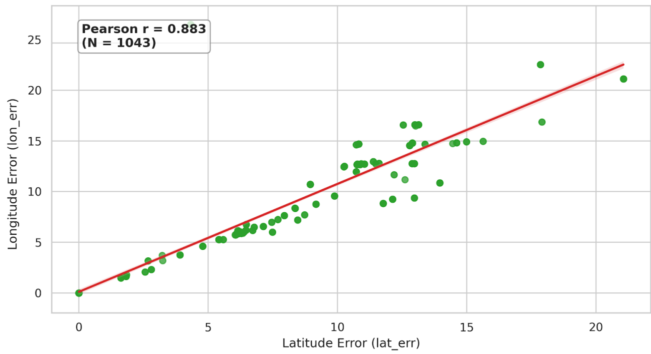


Figure 3. Correlation of σ_{lat} and σ_{lon}.

The above simple correction can indeed increase positioning accuracy, as repeated measurements confirmed that the actual positions lie very close to each other, although the estimated error is typically exaggerated (the real deviation is approximately 5 cm).

2.4. Indoor and Outdoor Accuracy

Similarly to simple GNSS positioning, RTK is also based on satellite data received from one or more supported systems. The problem with this is that the environment highly affects the final results. Weather conditions, signal obstruction and multipath propagation can significantly degrade positioning accuracy, particularly in urban and forested environments [3]. In order to demonstrate this, we performed measurements in different scenarios.

During field tests, ten reference points were marked one meter apart. For each round, 50–100 samples were collected while moving between the points. The results were then summarized to evaluate accuracy under varying conditions.

2.5. Graphical User Interface

In order to easily be able to perform bulk measurements, we have developed a tool in Python with a graphical user interface. A screenshot of the interface is presented on Figure 4.

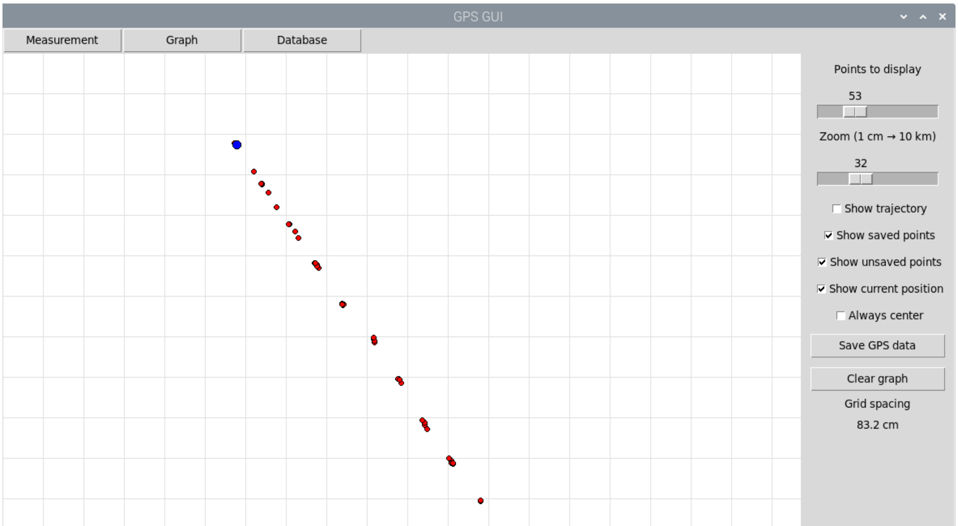


Figure 4. GUI showing measured points, trajectory, and real-time tracking.

The software automatically registers measurement data and persists it using a database. In the database each item describes a measurement registering the below attributes:

```
(id, timestamp, latitude, longitude,
latitude_error, longitude_error,
speed, mode, measurement iteration)
```

The graphical interface displays the measurement points collected during the experiment. The red points represent the measured GPS samples, placed exactly one meter apart on the ground. The isolated point is the control point used for reference. The software correctly visualizes the spatial layout of the points, confirming that the measurement grid was reconstructed accurately.

All data presented in the below section are measured using this tool and the previously described hardware setup.

3. Results

To empirically show the functionality of our system we have performed measurements in the following three environments:

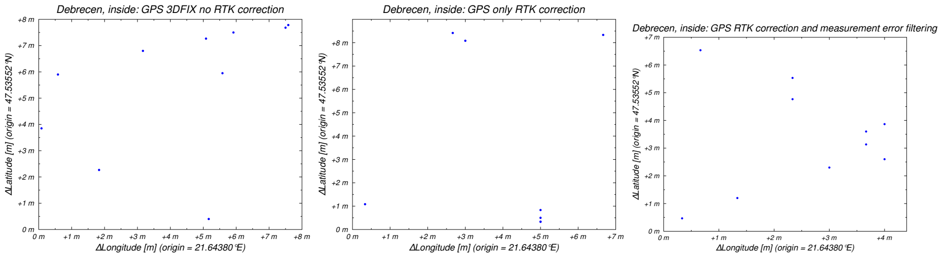
1. Indoor measurements were performed in a flat room in Debrecen residential area.

2. A suboptimal outdoor setup took place at Nagyerdő (Debrecen) that is a classical recreation area of Debrecen city with several high trees and other obstacles.

3. Optimal outdoor measurements were performed in the park of the Faculty of Informatics, University of Debrecen. This relatively new park does not have too many high trees, moreover the measurements were registered in late autumn. In most of the cases the sky was clear.

We have repeated the measurements with simple GNSS positioning, core RTK correction and RTK correction extended with our correction algorithm. The results are summarized on Figures 5, 6 and 7. On the figures it is easy to see how RTK can increase accuracy of GPS positioning in outdoor scenarios. Interestingly, our simple correction algorithm can further increase this accuracy besides really low computational cost. The indoor scenario however proved to be unfeasible for all three positioning variants since no correction can solve the issue of unsatisfactory amount of arriving location data.

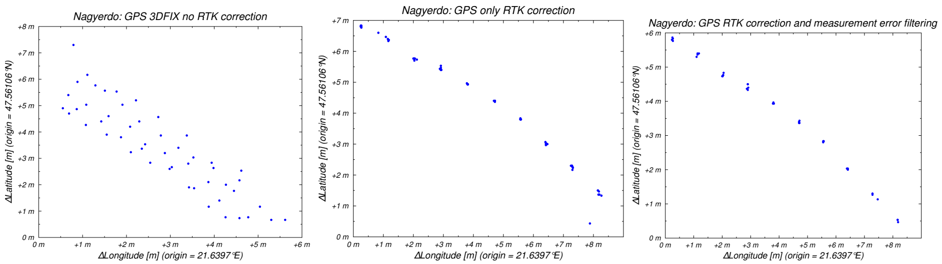
Due to the above mentioned properties of GPS-based positioning, pure GPS indoor measurements without any correction showed large deviations (up to 4 meters), however RTK correction reduced this to approximately 50 cm. With our filtering method, accuracy could be improved to around 35 cm.



(a) 3DFix **(b)** RTKFix **(c)** RTKFix Filtered

Figure 5. GPS positioning results in indoor scenario.

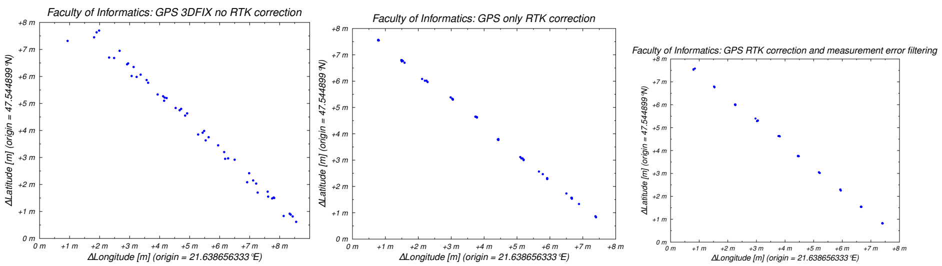
In the Nagyerdő park area, despite unstable signals, the pure GPS positioning showed around 70 cm accuracy that coincides with literature values [8]. RTK correction improved this to around 20 cm, while the full system reached 10 cm accuracy with filtering.



(a) 3DFix **(b)** RTKFix **(c)** RTKFix Filtered

Figure 6. GPS positioning results in suboptimal outdoor scenario.

In optimal outdoor environment measurements yielded significantly better results. At the Faculty of Informatics University of Debrecen, even the pure GPS reached around 30 cm accuracy. RTK correction improved this to ~ 10 cm. Finally the corrected and filtered method achieved 2–3 cm accuracy.



(a) 3DFix **(b)** RTKFix **(c)** RTKFix Filtered

Figure 7. GPS positioning results in optimal outdoor scenario.

Figure 8 sums up our measured accuracy results. The bars indicate the average accuracy.

Initial measurements showed errors of 100-170 cm, while the improved algorithm typically achieves around 70 cm, with best cases reaching 30-40 cm. Measurements were performed in Debrecen under various environmental conditions (forest, open sky, cloudy and clear weather). In order to further improve accuracy we plan refinement of the algorithm, particularly the averaging of coordinates while incorporating error metrics.

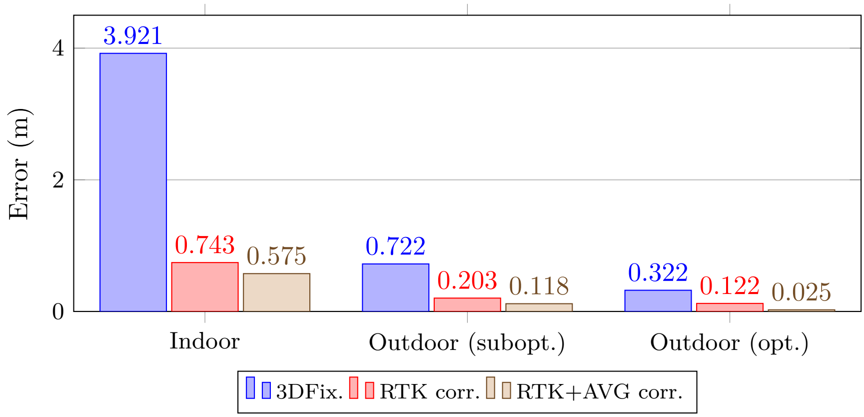


Figure 8. Comparison of GPS measurement errors across locations and correction methods. Our simple correction algorithm can further increase RTK accuracy.

3.1. Conclusion

This paper presented a measurement and visualization system for high-precision positioning based on a low-cost RTK GNSS setup. The system integrates GNSS hardware, real-time data acquisition, visualization, and database management into a unified software environment. The primary objective was to evaluate the achievable positioning accuracy of an out-of-the-box RTK solution and to investigate whether simple post-processing methods can further improve accuracy.

Experimental results demonstrated that RTK correction significantly improves positioning accuracy compared to standalone GNSS positioning, particularly in outdoor environments with good satellite visibility. Furthermore, the proposed filtering and measurement selection method provided additional accuracy improvement with minimal computational overhead. In optimal outdoor conditions, the system achieved centimeter-level positioning accuracy, while suboptimal environments resulted in decimeter-level accuracy. Indoor measurements confirmed the known limitations of satellite-based positioning due to signal attenuation and multipath effects.

The results indicate that reliable high-precision positioning can be achieved using relatively low-cost hardware when combined with appropriate measurement strategies and data processing methods. Future work will focus on advanced filtering techniques, statistical error modeling, and long-term measurements under varying environmental conditions.

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