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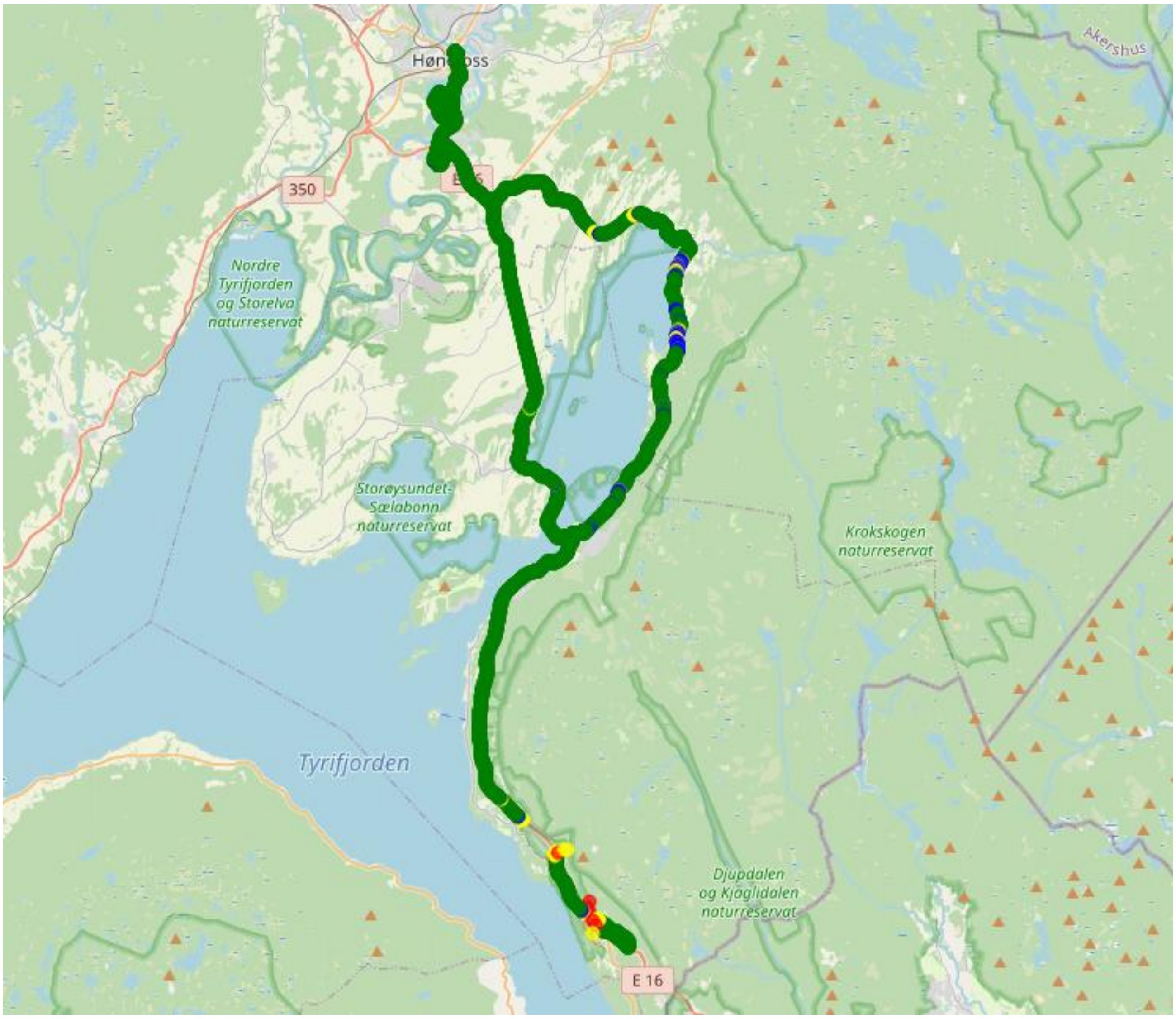
REPORT:

HyPos – Work Package 2: GNSS SSR – Additional analyses



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REPORT:

HyPos – Work Package 2: GNSS SSR – Additional analyses

Project	HyPos - Nasjonal Hybrid Posisjonstjeneste for Fremtidens Digitale og Autonome Samfunn
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1 Introduction

This report is a part of the documentation of Work Package 2, Positioning with distributed GNSS corrections, in the HyPos project. A thorough report was written in 2024, including positioning theory, results from multiple measuring campaigns, thorough discussion and a literature review: Ref. [1]. The current document is a complimentary report, with results from measuring campaigns in 2025.

The main objective of this work is to explore the current state of GNSS SSR technology, as a part of the larger work on hybrid correction services. In 2023, a GNSS SSR service was established, using the Geo++ GNSMART software. The service was tested using two receivers, a uBlox F9P using SPARTN format for corrections, and a TeriaPYX using SSRZ format for correction. The main reason for conducting an additional measurement campaign in 2025 was the new Alberding A10-RTK receiver. For TeriaPYX, the conversion of SSR to OSR happened on a remote server, before the corrections were sent to the receiver. For the new Alberding receiver, conversion of SSR to OSR happens on the receiver itself. Having the receiver interpret the SSR corrections independently is essential for the scalability of SSR. With a new receiver, new antennas and an updated GNSMART software, a static campaign was performed in May 2025 and a kinematic campaign was performed in June 2025. The kinematic campaign is of limited scope, lasting a couple of hours.

2 Instrumentation and methodology

2.1 Corrections services and GNSS receivers

Three receivers are used for testing: One receiver uses the NRTK service CPOS, while two receivers use the established SSR service. Further details about the positioning methods and formats can be found in the previous report, Ref. [1].

- CPOS (NRTK correction service), using uBlox F9P receiver
- SSR service, on SSRZ format, using Alberding A10-RTK receiver
- SSR service, on SPARTN format, using uBlox F9P receiver

2.2 Static campaign reference positions

The static campaign took place on the rooftop of NMAs office buildings in Hønefoss. There are pillars on the roof, for which we have very accurate ground truth coordinates, and the antennas were placed on these pillars using tribrachs.

2.3 Kinematic campaign reference positions

The kinematic campaign was carried out using NMA's measurement vehicle, as in the previous work [1]. Reference positions are based on the data logs from an inertial measurement unit (IMU) and a high-end GNSS receiver to establish the best possible position accuracy. These reference positions are used as a baseline to compute and analyse KPIs for various GNSS positioning services.

Instrumentation of the reference system consist of the following sensors:

- Apogee-D IMU, SBG-systems
- AsteRx4 GNSS receiver, Septentrio
- Pegasem WSS2 odometer, Pegasem Messtechnik GmbH

During the kinematic data collection campaign, the GNSS receiver is connected to the national NRTK service CPOS, and hence the positions are at the cm level in real time in the Norwegian national reference frame EUREF89. The IMU and odometer ensures that positions are calculated even when GNSS signals are obstructed.

To optimize the accuracy of the reference positions the data logs are processed in the navigation post-processing suite Qinertia.

2.4 Antennas

The uBlox receivers are connected to an Ardusimple antenna, while the Alberding receiver and the reference position unit are connected to Tallysman antennas.

The reference positions are given at the Antenna Reference Point (ARP). The navigation receivers are assumed to output positions for the phase center, and for comparing the positions we subtract the approximate vertical phase center offsets, which are 5.5cm for the ArduSimple antenna and 5.0cm for the Tallysman antenna. These offsets are averages of L1 and L2 offsets, which were reported by a NOAA NGS calibration file for the Tallysman antenna and by a technical drawing for the ArduSimple antenna.

2.5 Reference station network configurations for HyPos_SSR

In the previous campaigns, as described in Ref. [1], three different configs were used, to test the effects of different reference station network densities. In the current campaigns, a single network configuration was used for each campaign. For the static campaign, 16 reference stations were used, as displayed in Figure 1. For the kinematic campaign, 20 stations were used, as displayed in Figure 2, and the most important addition was the reference station in Hønefoss.

(For the CPOS correction service, the Hønefoss reference station was included in the static campaign. This reference station was only meters away from the test setup.)

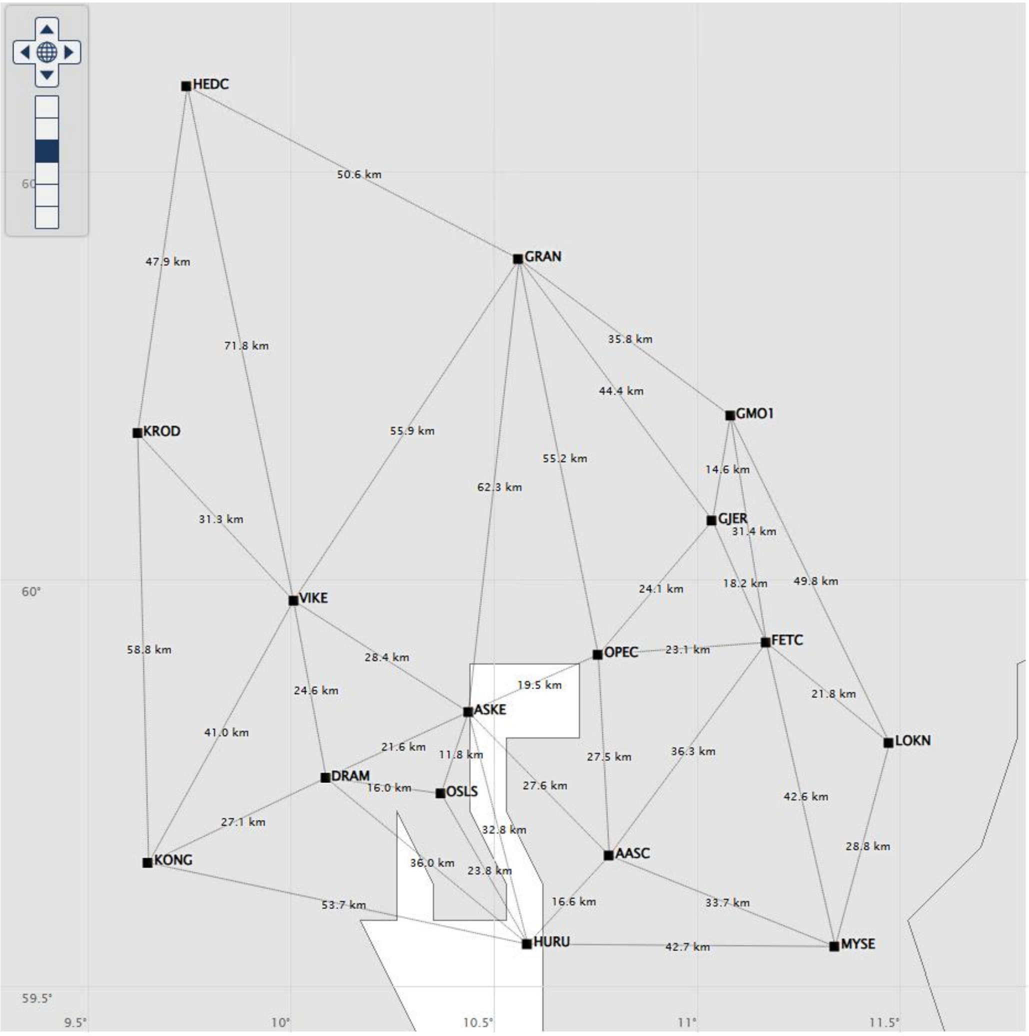

Figure 1: Reference station network used in HyPos SSR, for the static campaign.

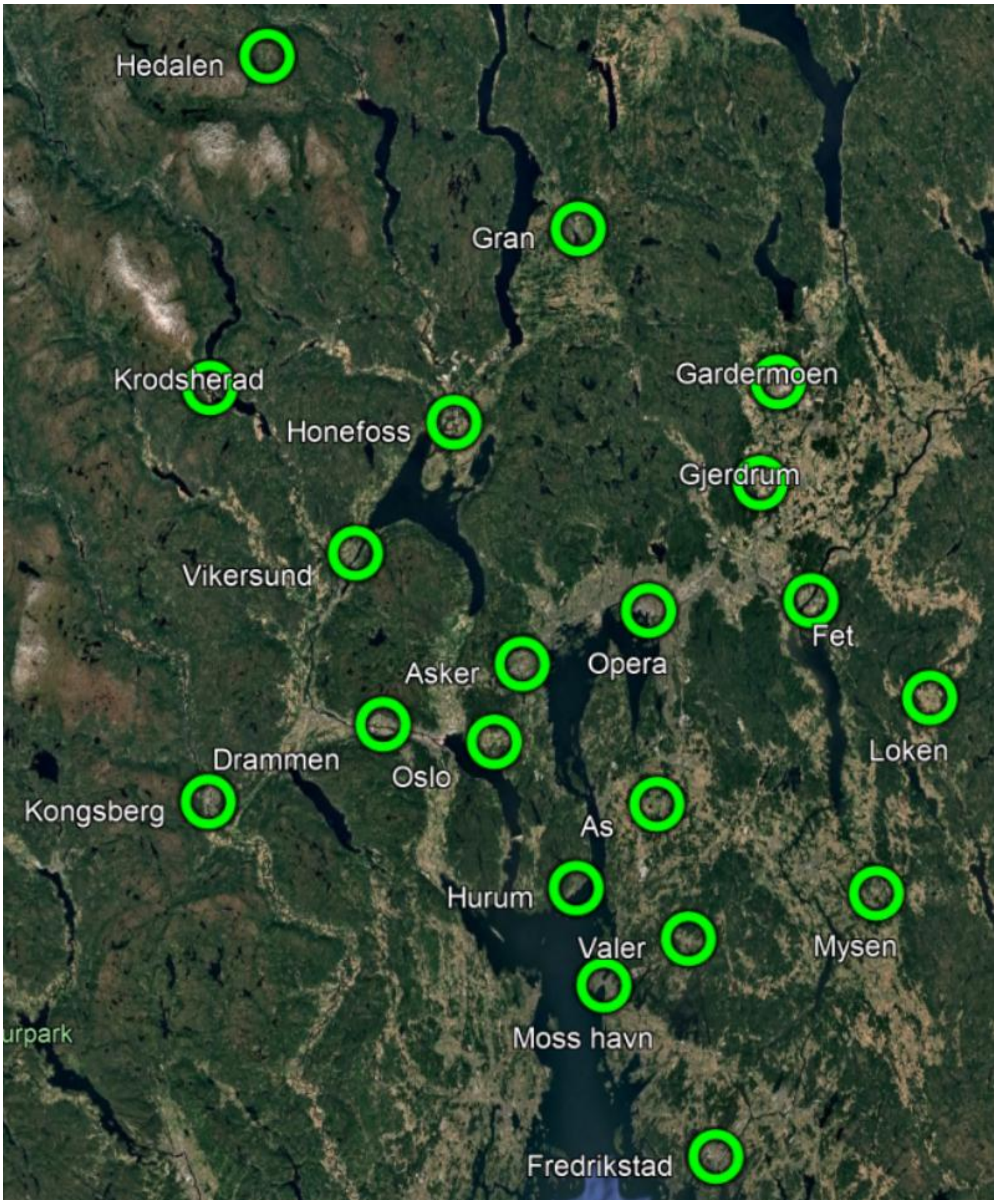

Figure 2: Reference station network used in HyPos SSR, for the kinematic campaign.

2.6 Kinematic campaign routes

Figure 3 and Figure 4 shows the routes taken during the kinematic campaign. The route encompasses a lake, among other things. On the west side of the lake there is a lot of open road and clear view of the sky. On the east side of the lake there is a lot of forest and hilly terrain, which affects the service availability in this area. In the southmost part of the route, there are two long tunnels.

Figure 3: Route of the kinematic campaign on June 11, where position is plotted for each epoch, colored according to position solution type. (Green is RTK-fix, blue is RTK-float, yellow is Differential and red is autonomous solution.)

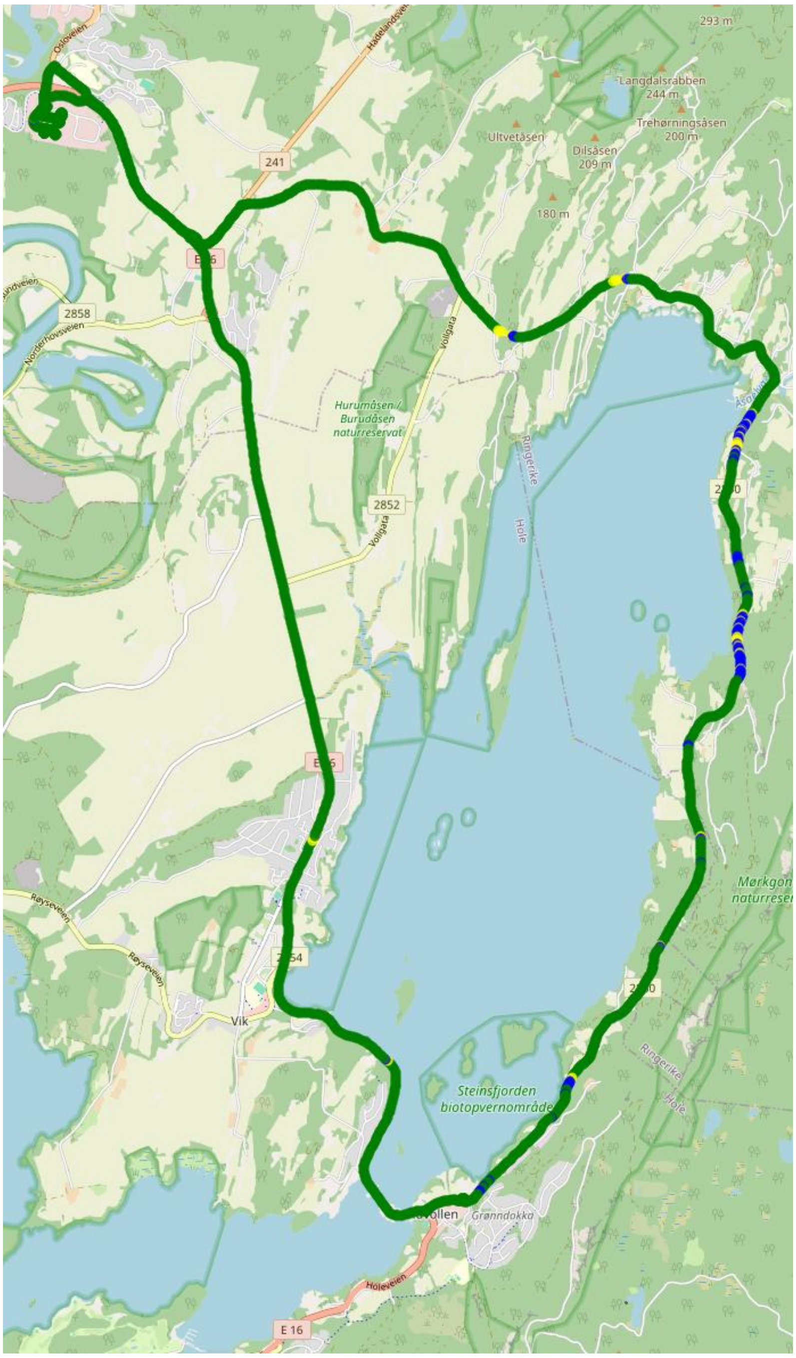

Figure 4: Route of the kinematic campaign on June 12, where position is plotted for each epoch, colored according to position solution type. (Green is RTK-fix, blue is RTK-float, yellow is Differential and red is autonomous solution.)

3 Key Performance Indicators

Key Performance Indicators (KPIs) are defined in order to assess the performance of the service-receiver combinations. These KPIs are commonly used for positioning analysis.

3.1 Position based KPIs

One of the main objectives of this campaign is to compare the positioning accuracy of different correction services, which is why we define multiple KPIs based on position errors. Position error or position deviation is defined as the coordinate difference between the navigation receiver and the reference position, and is given in Easting, Northing and Up coordinates in the UTM32 projection. (The coordinates are projected to UTM32 from the ETRS89 reference frame)

$$\Delta Easting = Easting_{nav} - Easting_{ref}$$
$$\Delta Northing = Northing_{nav} - Northing_{ref}$$
$$\Delta Up = Up_{nav} - Up_{ref}$$

Position errors are calculated according to these formulas, for each epoch where both navigation receiver and GNSS/IMU reference reports a position. The three coordinates are often referred to simply as E, N and U. In the context of driverless driving, the horizontal coordinates are of more interest than the height coordinate, and several KPIs are based on:

$$\Delta Horizontal = \sqrt{\Delta Easting^2 + \Delta Northing^2}$$

HPE95 is defined as the 95th percentile of $\Delta Horizontal$, and VPE95 is defined as the 95th percentile of $abs(\Delta Up)$.

The average position errors are important metrics that can reveal systematic errors, that is, systematic differences between navigation receiver positions and reference positions. These are calculated and reported for each coordinate, like $\overline{\Delta Easting} = (\sum \Delta Easting_i)/n$, where $i = 1,2, \ldots, n$.

Standard deviation is calculated for each coordinate. Standard deviation is a good indication of the precision of the reported positions, that is, the variability of position errors ignoring if they have systematic errors or not.

$$\sigma_{Easting} = \sqrt{\frac{\sum\left(\Delta Easting_i - \overline{\Delta Easting}\right)^2}{n-1}}$$

3.2 Horizontal KPIs

How do different metrics capture different aspects of horizontal positioning performance? The HPE95 is a commonly used metric for positioning accuracy. The average and standard deviation of Easting and Northing are other metrics that can inform accuracy and precision, although only in individual coordinates. The discretized density estimate, which is plotted for each receiver in Section 4.2 and 5.2, can also be useful. The mode of the horizontal position error aligns with the density peak and represents the most common position error. The standard deviation of the horizontal position error is a measure of the width of the density peak and indicates the consistency of the horizontal position estimate.

Another metric that could indicate precision is the horizontal combination of the coordinate standard deviations, namely: $\sigma_{2D} = \sqrt{\sigma^2_{Easting} + \sigma^2_{Northing}}$. This gives a single metric for the 2D precision, unbiased by systematic offsets. Let's call this metric "2D precision" and denote it by σ_{2D}. This metric assumes East/North errors are uncorrelated with similar variance. It's also possible to calculate a full uncertainty ellipse, using covariance.

Based on the discussion above, three main metrics are used for defining horizontal positioning performance: HPE95, the mode of the horizontal density distribution and the 2D precision. The mode, which indicates the most common position error, can be an indication of accuracy, answering the question "How accurate will the position typically be?".

3.3 Service availability

Service availability is an important metric and is defined as the percentage of time where the navigation receiver reports a converged solution. The position solution type is reported by the NMEA GNS messages, and the solution type depends on the service type and the specific receiver implementation. Some services, like NRTK and PPP-RTK, can achieve integer resolution of the wave number ambiguity, and hence they achieve a fix solution type. The receivers using these services have reported RTK-fix solution types.

The service availability represents the ratio of converged epochs to total epochs. The total number of epochs are all epochs where the GNSS/IMU reference reports a valid position, and the navigation receiver is ON. The requirement of the navigation receiver being ON, means that epochs where the receiver is not able to report a position is included in the count of the total number of epochs.

4 Results of static campaign

4.1 Main results

This section reports the main KPIs of position accuracy and service availability, for the kinematic campaign. The results are summarized in Figure 5 and Figure 6, which compares the empirical distribution functions for the different services. The results are also reported in two tables: Table 1 shows the main KPIs to indicate performance levels, while Table 2 shows more detailed statistics for the individual coordinates.

The CPOS results shows NRTK performance in pristine conditions, with a static rover only meters away from the closest reference station. 95% of epochs are within 0.8cm of true horizontal position and 3cm of true vertical position.

HyPos-SSRZ also performs very well, with 95% of epochs within 3.5cm of true horizontal position and 6cm of true vertical position. The closest reference station that is contributing to the SSR corrections is VIKE, which is approximately 23km away. The service availability for HyPos-SSRZ is 98.9%, and it is not known why 2h of data are non-fix solutions.

HyPos-SPARTN performs worse than HyPos-SSRZ. 95% of epoch are within 14cm of true horizontal position and 26cm of true vertical position. There are two possible contributors to the performance gap. HyPos-SSRZ is tested on Alberding A10-RTK, which is more of a high-end receiver, while HyPos-SPARTN is tested on uBlox F9P which is a low-cost receiver. In addition, SSRZ is a more complex format than SPARTN, containing more information for many of the correction types.

HyPos-SPARTN reports a service availability of only 53%. It is not known to us how RTK-fix is defined in the receiver algorithms, but Table 1 shows that the KPIs with RTK-float solutions included are very similar to the RTK-fix KPIs.

HyPos-SPARTN was also tested in a static campaign in September 2023, as described in the previous report, Ref. [1]. The results are quite similar, with HPE95 of 16cm in 2023 (including RTK-fix solutions only), and HPE95 of 15cm in 2025 (when including both RTK-fix and RTK-float solutions). However, the reference station network was different in 2023, with the Hønefoss station included. For the 2023 campaign, the service availability of RTK-fix is reported to be 98%, compared to 53% in 2025. The reason could be the proximity to the Hønefoss reference station in 2023, or some firmware update of the uBlox F9P.

The average coordinate errors can say something about systematic offsets, especially if the average coordinate error is larger than the standard deviation for a certain coordinate. Mostly, the average coordinate errors are very small, but for CPOS and HyPos-SPARTN, the average coordinate errors are larger than the standard deviation in Height/Up-coordinate. Figure 9 and Figure 15 illustrate these systematic offsets. Possible causes of the systematic offsets include erroneous reference coordinates and the use of wrong antenna phase center offset values in the analysis. The receivers, for CPOS and HyPos-SPARTN, used the same antenna, although the average coordinate errors are quite different, 2cm for CPOS and 15cm for HyPos-SPARTN.

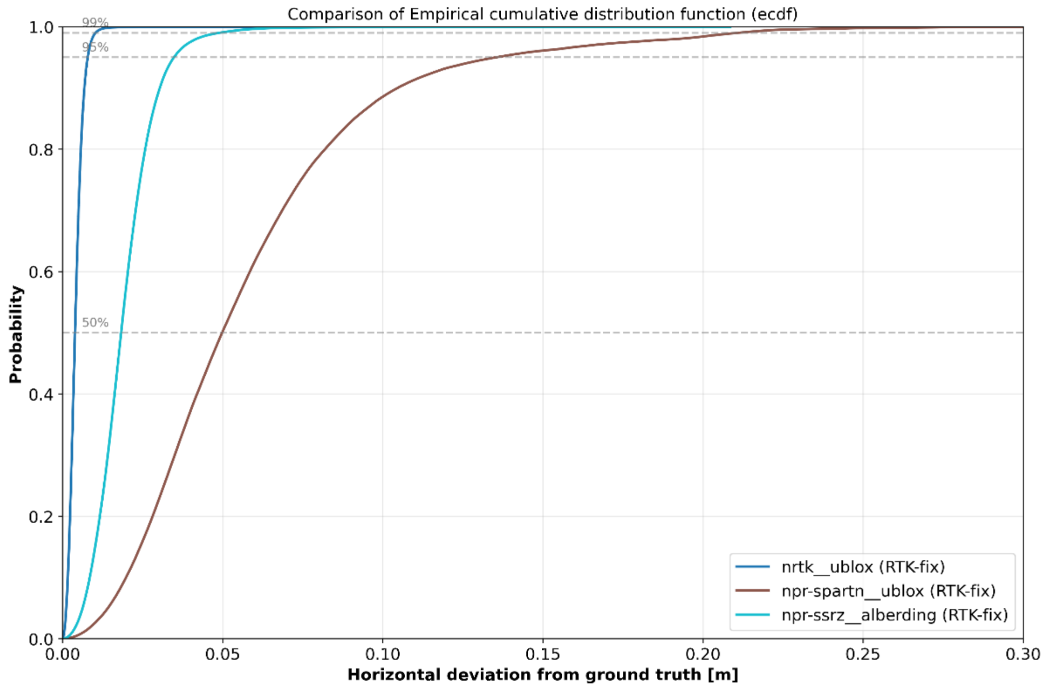

Figure 5: Comparison of empirical cumulative distribution functions of $\Delta Horizontal$, for the static campaign. CPOS on uBlox F9P is denoted as "nrtk__ublox". HyPos-SSRZ on Alberding A10-RTK is denoted as "npr-ssrz__alberding". HyPos-SPARTN on uBlox F9P is denoted as "npr-spartn__ublox".

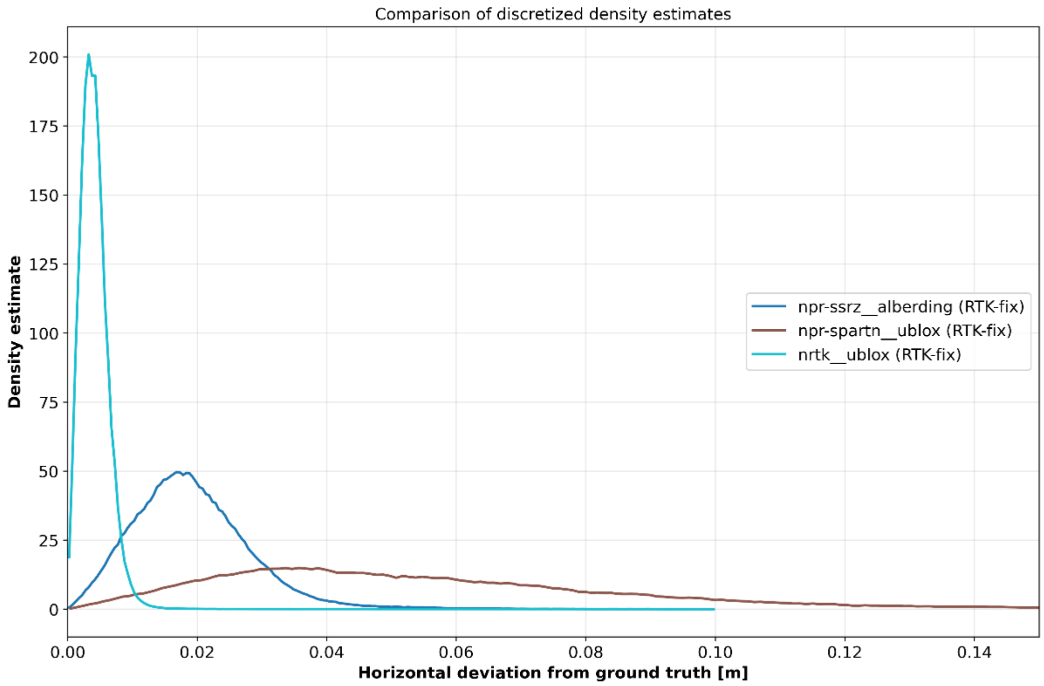

Figure 6: Comparison of discretized density estimates of $\Delta Horizontal$, for the static campaign. CPOS on uBlox F9P is denoted as "nrtk__ublox". HyPos-SSRZ on Alberding A10-RTK is denoted as "npr-ssrz__alberding". HyPos-SPARTN on uBlox F9P is denoted as "npr-spartn__ublox".

Service and receiver type	**Service availability (Solution type) [%]**	**HPE95 [m] VPE95 [m]**	**Mode of Horizontal pos.error [m] 2D precision [m]**
CPOS u-blox F9P	99.997% (RTK-fix) 363.4h/363.5h	HPE: 0.008m VPE: 0.03m Max: 0.18m	0.003m 0.003m
HyPos-SSRZ Alberding A10-RTK	98.9% (RTK-fix) 229.7h/232.3h	HPE: 0.035m VPE: 0.060m Max: 0.21m	0.017m 0.015m
HyPos-SPARTN u-blox F9P	52.9% (RTK-fix) 122.9h/232.4h	HPE: 0.136m VPE: 0.258m Max: 0.32m	0.04m 0.071m
HyPos-SPARTN u-blox F9P (RTK-float and RTK-fix)	99.98% (RTK-fix and RTK-float) 232.4h/232.4h	HPE: 0.145m VPE: 0.287m Max: 1.24m	- 0.087m

Table 1: Results for the static campaign, of April 2025. The second column gives the service availability, the convergence type used for the analysis and how many hours of data is available for each receiver, of converged solutions and all solutions. The third column gives the 95th percentile horizontal and vertical position errors, as well as the maximum horizontal position error. The fourth column gives the mode of horizontal position error, which indicates "what to expect most of the time", as well as the 2D precision, which indicates "how consistent the positioning is".

Service and receiver type	**Service availability (Solution type) [%]**	**Average coordinate errors [m]**	**Standard deviations [m]**
CPOS u-blox F9P	99.997% (RTK-fix) 363.4h/363.5h	0.001m E -0.003m N -0.023m U	0.002m E 0.003m N 0.005m U
HyPos-SSRZ Alberding A10-RTK	98.9% (RTK-fix) 229.7h/232.3h	0.012m E -0.009m N 0.020m U	0.009m E 0.012m N 0.028m U
HyPos-SPARTN u-blox F9P	52.9% (RTK-fix) 122.9h/232.4h	-0.003m E -0.002m N -0.133m U	0.052m E 0.048m N 0.079m U
HyPos-SPARTN u-blox F9P (RTK-float and RTK-fix)	99.98% (RTK-fix and RTK-float) 232.4h/232.4h	0.017m E -0.003m N -0.148m U	0.055m E 0.067m N 0.096m U

Table 2: Results for the static campaign, of April 2025. The second column gives the service availability, the convergence type used for the analysis and how many hours of data is available for each receiver, of converged solutions and all solutions. The third column gives average coordinate errors in Easting, Northing and Up coordinates, while the fourth column gives standard deviations of the position errors of the Easting, Northing and Up coordinates.

4.2 Plots for each service

In this section, plots are shown for each service. The plots are based on the converged solution type.

- **Empirical cumulative distribution function** of $\Delta Horizontal$, showing the portion of positions having a horizontal error less than or equal to a given x-value.
- **Discretized density estimate**, which is an empirical approximation of the distribution of horizontal position errors. Vertical lines are added to indicate the mode, average and 95^{th} percentile. The mode aligns with the density peak and represents the most common position error. The average position error is typically larger than the mode, because the position error distribution is right-skewed heavy-tailed, with a few large position errors pulling up the average.
- **Timeseries** for the Easting, Northing and Up coordinates for a single day of the campaign.

4.2.1 CPOS on uBlox F9P

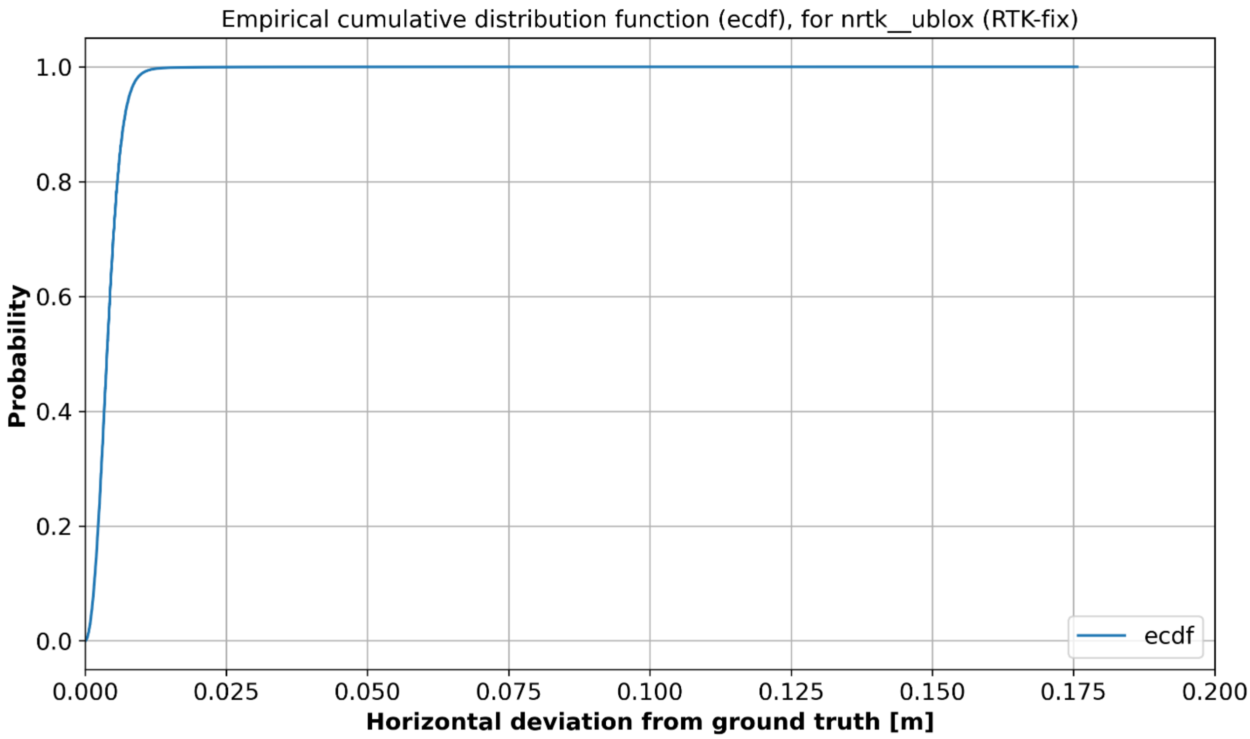

Figure 7: Empirical cumulative distribution function for CPOS on uBlox F9P, denoted as “nrtk__ublox”.

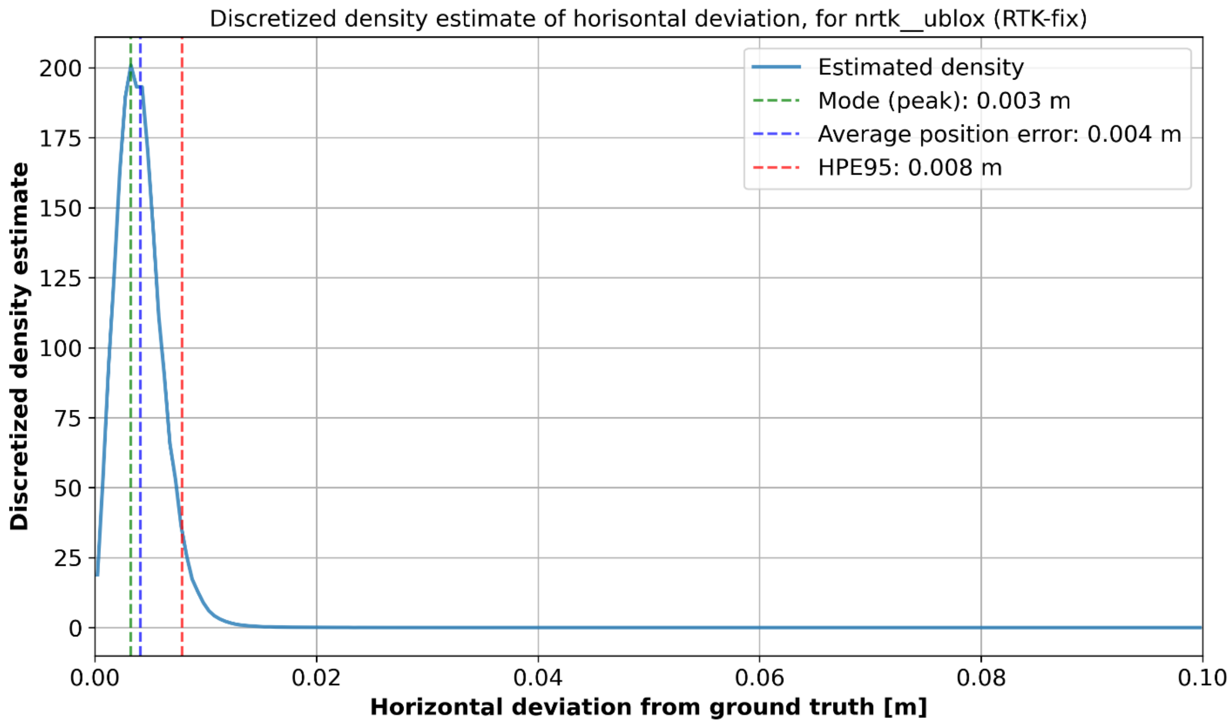

Figure 8: Discretized density estimate for CPOS on uBlox F9P, denoted as “nrtk__ublox”.

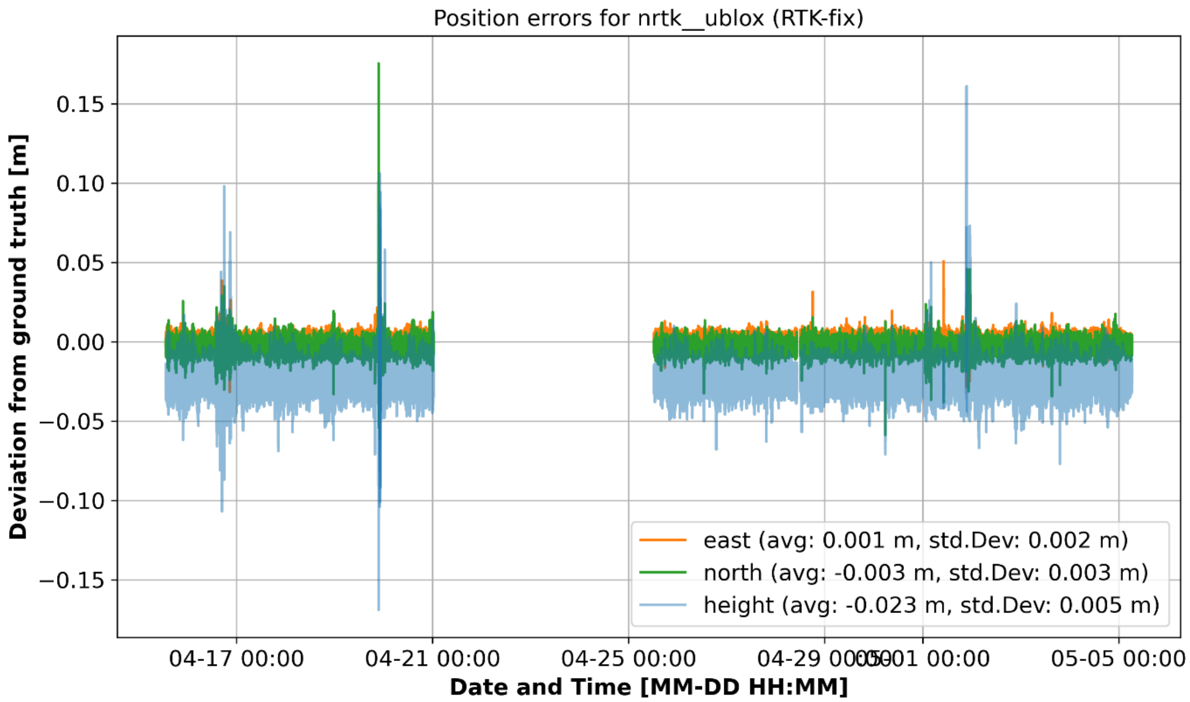

Figure 9: Time series for CPOS on uBlox F9P, denoted as “nrtk__ublox”.

4.2.2 HyPos SSRZ on Alberding A10-RTK

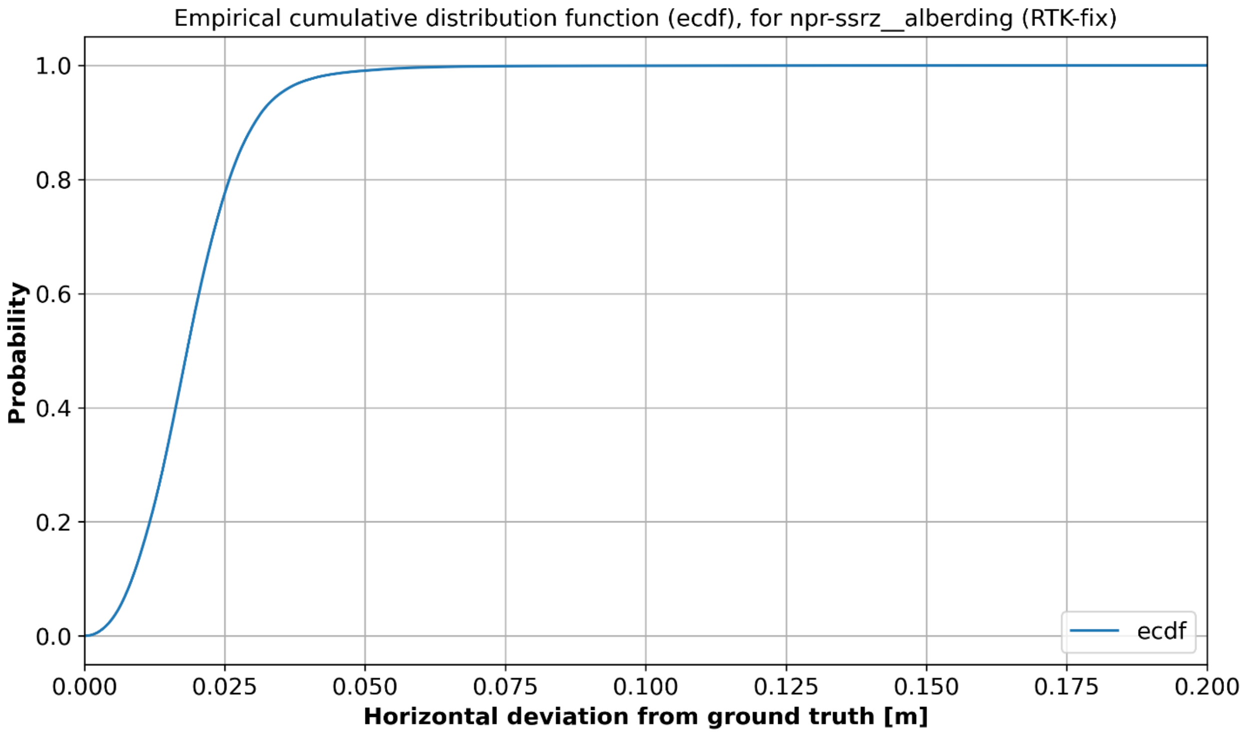

Figure 10: Empirical cumulative distribution function for SSR service on Alberding A10-RTK, denoted as "npr-ssrz__alberding".

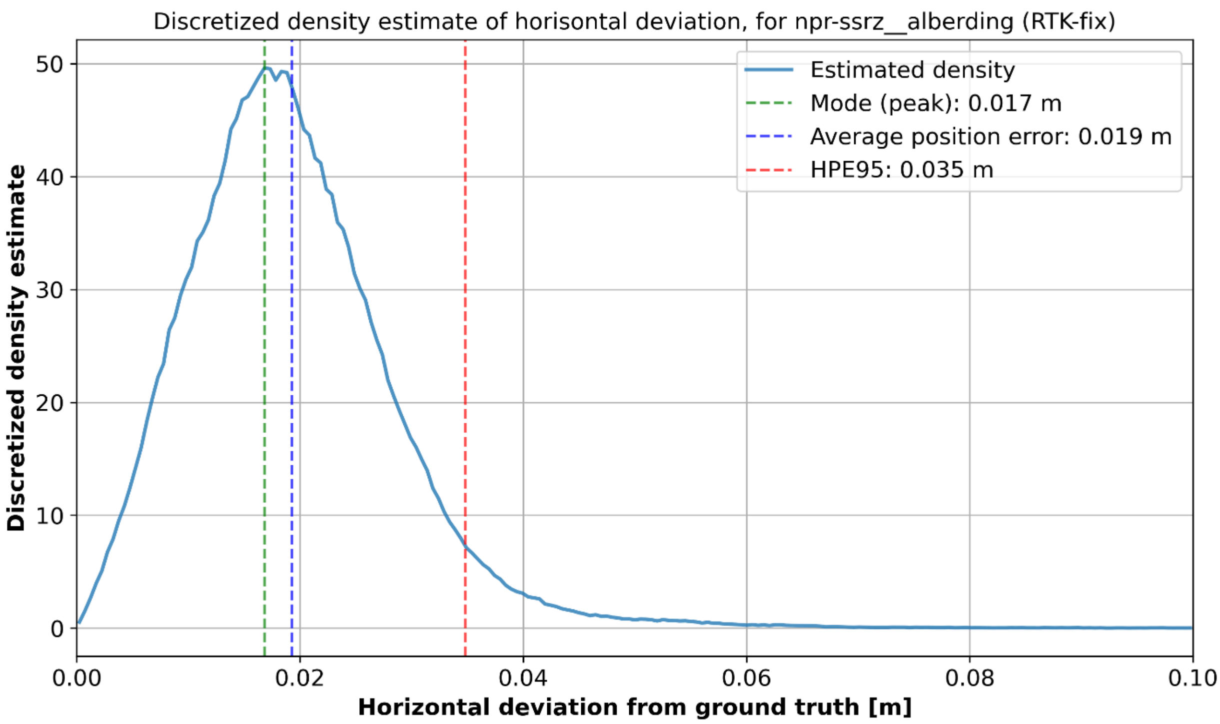

Figure 11: Discretized density estimate for SSR service on Alberding A10-RTK, denoted as "npr-ssrz__alberding".

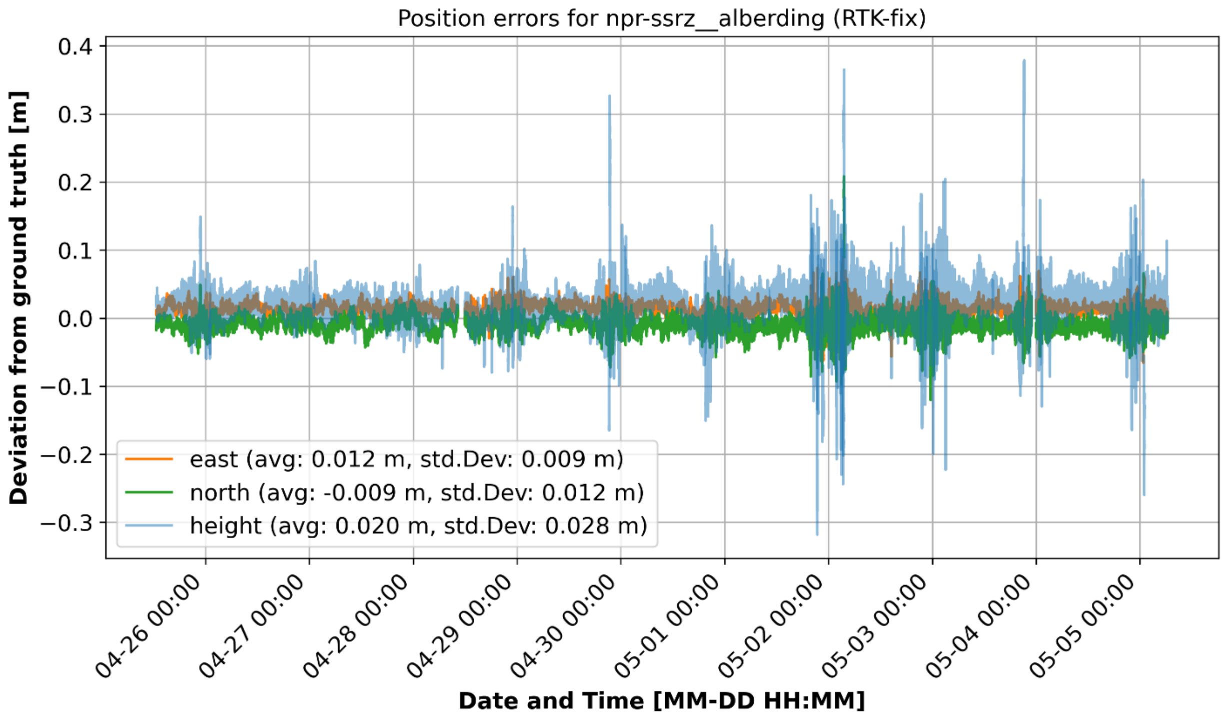

Figure 12: Time series for SSR service on Alberding A10-RTK, denoted as “npr-ssrz__alberding”.

4.2.3 HyPos SPARTN on uBlox F9P

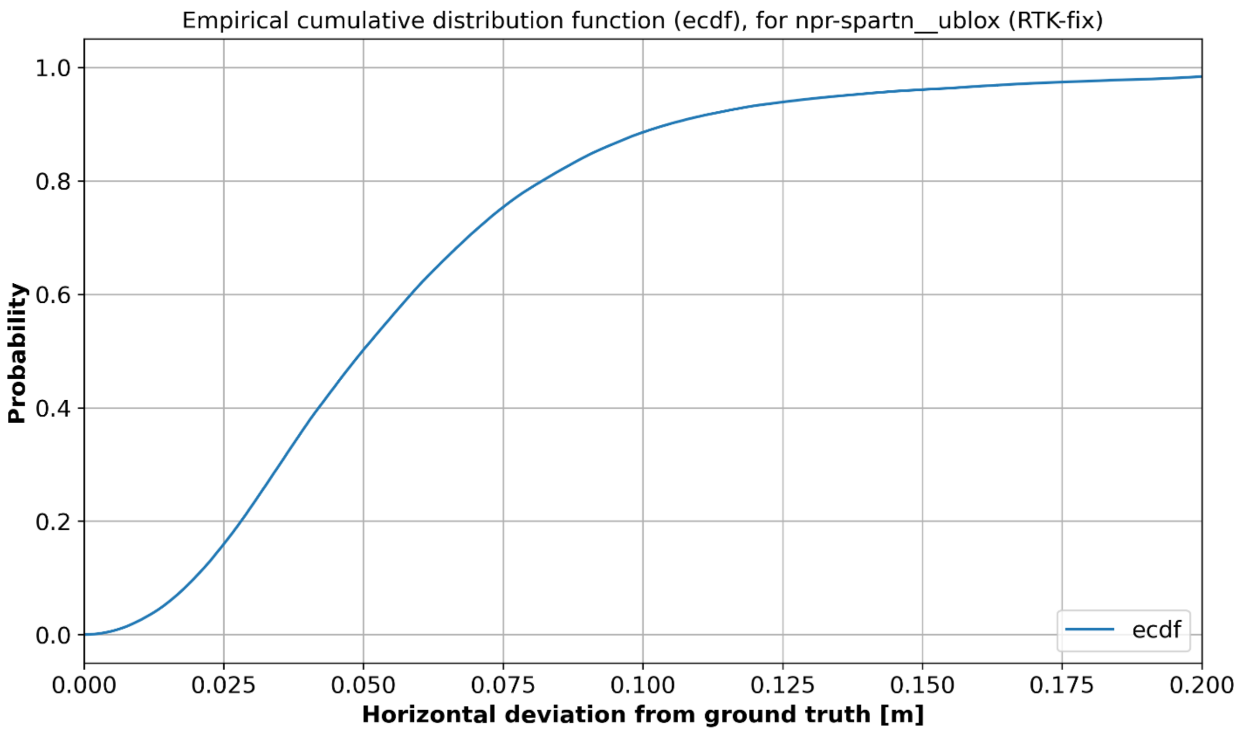

Figure 13: Empirical cumulative distribution function for SSR service on uBlox F9P, denoted as “npr-spartn__ublox”.

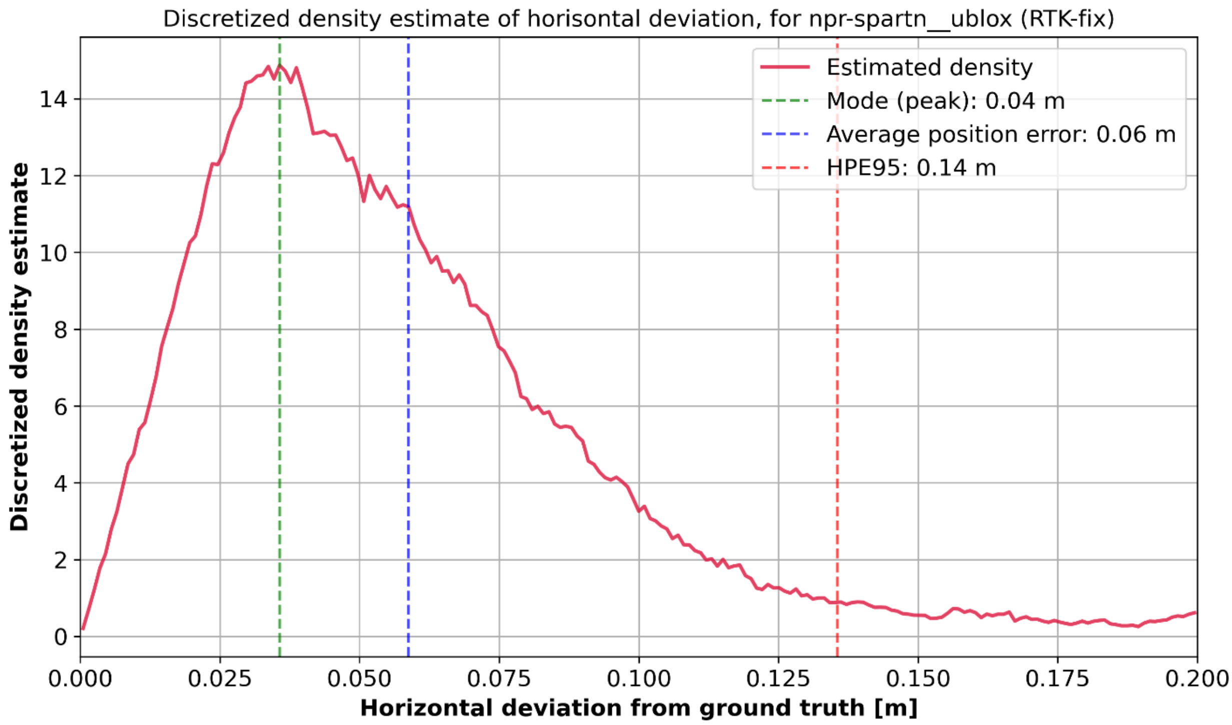

Figure 14: Discretized density estimate for SSR service on uBlox F9P, denoted as "npr-spartn__ublox".

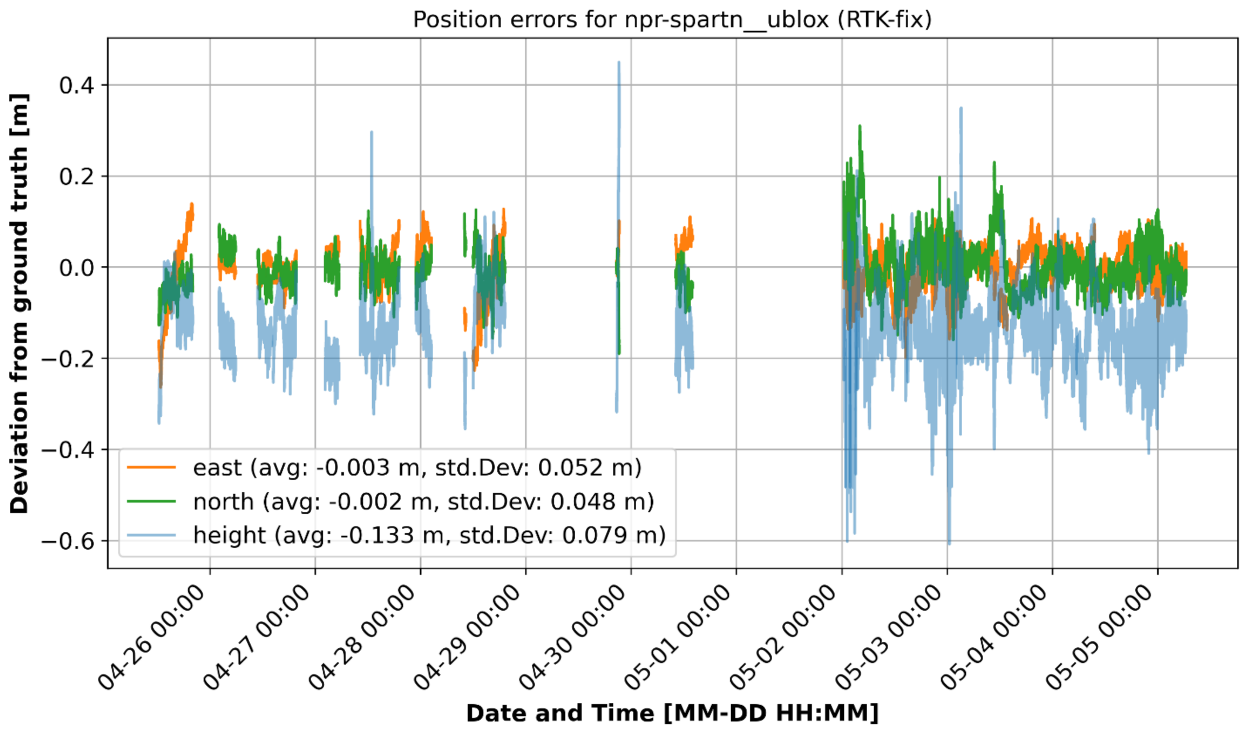

Figure 15: Time series for SSR service on uBlox F9P, denoted as "npr-spartn__ublox".

5 Results of kinematic campaign

5.1 Main results

This section reports the main KPIs of position accuracy and service availability, for the kinematic campaign. The results are summarized in Figure 7 and Figure 8, which compares the empirical distribution functions for the different services. The results are also reported in two tables: Table 3 shows the main KPIs to indicate performance levels, while Table 4 shows more detailed statistics for the individual coordinates.

The CPOS results show that 95% of epochs are within 3cm of true horizontal position and 4cm of true vertical position. The service availability was 95%. Service availability not being 100% can be attributed to eight tunnel passages and some driving in forest and hilly terrain.

HyPos-SSRZ performs very well, almost as good as CPOS. The service availability is 95% for HyPos-SSRZ as well, and 95% of epoch are within 4cm of true horizontal position and 9cm of true vertical position. The poorer performance in the vertical direction can be explained by a systematic offset. The average coordinate error in Height/Up coordinate is 4.7cm, which can be seen in Figure 23. This average offset is large compared to the standard deviation of 2.8cm, which suggests a systematic offset. Possible causes of the systematic offset include receiver implementations, GNSMART processing and the use of wrong antenna phase center offsets values in the analysis.

This HyPos-SSRZ performance is much better than the 2023 kinematic campaign, where the TeriaPYX receiver, on "country road", gave approximately 88% service availability with HPE95 being 14cm rather than 4cm. Both campaigns were of limited duration, so comparisons should be interpreted with caution.

HyPos-SPARTN performs considerably worse than HyPos-SSRZ, with HPE95 being an order of magnitude larger: 43cm for HyPos-SPARTN and 4cm for HyPos-SSRZ. The performance gap is even larger for the kinematic campaign than it was for the static campaign. As discussed earlier, the performance gap can be caused by different receivers and SSRZ containing more information than SPARTN for many correction types.

For reference, the HyPos-SPARTN testing in the 2023 kinematic campaign was also poor and variable. For the "full configuration" of reference stations, HyPos-SPARTN had a service availability of 52-75% and HPE95 of 8-87cm. The drive on "country road" was particularly poor, with HPE95 of more than 80cm.

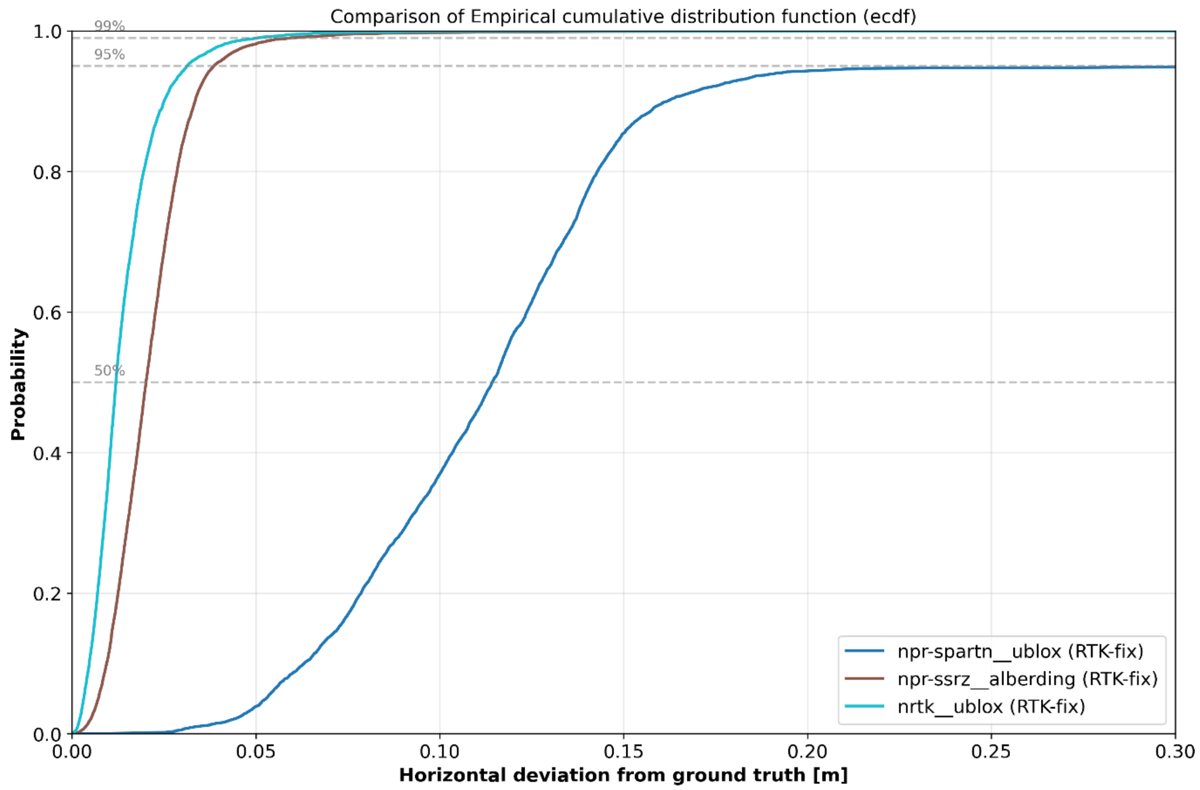

Figure 16: Comparison of empirical cumulative distribution function of $\Delta Horizontal$, for the kinematic campaign. CPOS on uBlox F9P is denoted as "nrtk__ublox". HyPos-SSRZ on Alberding A10-RTK is denoted as "npr-ssrz__alberding". HyPos-SPARTN on uBlox F9P is denoted as "npr-spartn__ublox".

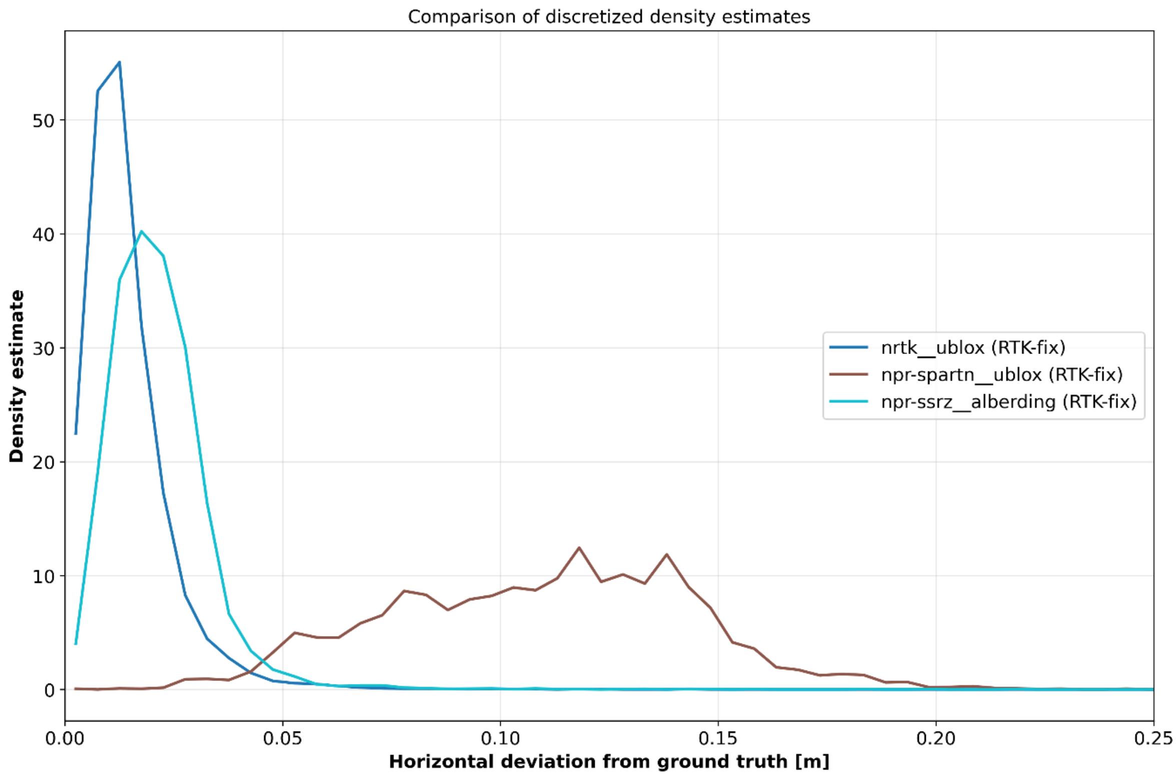

Figure 17: Comparison of discretized density estimates of $\Delta Horizontal$, for the kinematic campaign. CPOS on uBlox F9P is denoted as "nrtk__ublox". HyPos-SSRZ on Alberding A10-RTK is denoted as "npr-ssrz__alberding". HyPos-SPARTN on uBlox F9P is denoted as "npr-spartn__ublox".

Service and receiver type	**Service availability (Solution type) [%]**	**HPE95 [m]** **VPE95 [m]**	**Mode of Horizontal pos.error [m]** **2D precision [m]**
CPOS u-blox F9P	94.5% (RTK-fix) 2.2h/2.3h	HPE: 0.03m VPE: 0.04m Max: 0.8m	0.01m 0.02m
HyPos-SSRZ Alberding A10-RTK	95.3% (RTK-fix) 2.4h/2.6h	HPE: 0.04m VPE: 0.09m Max: 0.8m	0.02m 0.02m
HyPos-SPARTN u-blox F9P	75.1% (RTK-fix) 1.8h/2.4h	HPE: 0.43m VPE: 0.25m Max: 1.0m	0.12m 0.15m
HyPos-SPARTN u-blox F9P (RTK-float and RTK-fix)	97.0% (RTK-fix and RTK-float) 2.3h/2.4h	HPE: 0.56m VPE: 0.75m Max: 6.1m	- 0.30m

Table 3: Results for the kinematic campaign, of June 11th and June 12th, 2025. The second column gives the service availability, the convergence type used for the analysis and how many hours of data is available for each receiver, of converged solutions and all solutions. The third column gives the 95th percentile horizontal and vertical position errors, as well as the maximum horizontal position error. The fourth column gives the mode of horizontal position error, which indicates "what to expect most of the time", as well as the 2D precision, which indicates "how consistent the positioning is".

Service and receiver type	Service availability (Solution type) [%]	Average coordinate errors [m]	Standard deviations [m]
CPOS u-blox F9P	94.5% (RTK-fix) 2.2h/2.3h	0.000m E -0.002m N 0.000m U	0.011m E 0.018m N 0.020m U
HyPos-SSRZ Alberding A10-RTK	95.3% (RTK-fix) 2.4h/2.6h	0.013m E -0.009m N 0.047m U	0.014mE 0.016mN 0.028m U
HyPos-SPARTN u-blox F9P	75.1% (RTK-fix) 1.8h/2.4h	-0.067m E -0.013m N -0.047m U	0.138m E 0.049m N 0.111m U
HyPos-SPARTN u-blox F9P (RTK-float and RTK-fix)	97.0% (RTK-fix and RTK-float) 2.3h/2.4h	-0.033m E 0.037m N -0.082m U	0.170m E 0.250m N 0.362m U

Table 4: Results for the kinematic campaign, of June 11th and June 12th, 2025. The second column gives the service availability, the convergence type used for the analysis and how many hours of data is available for each receiver, of converged solutions and all solutions. The third column gives average coordinate errors in Easting, Northing and Up coordinates, while the fourth column gives standard deviations of the position errors of the Easting, Northing and Up coordinates.

5.2 Plots for each service

In this section, plots are shown for each service. The plots are based on the converged solution type. There are three types of plots, as described in Section 4.2.

5.2.1 CPOS on uBlox F9P

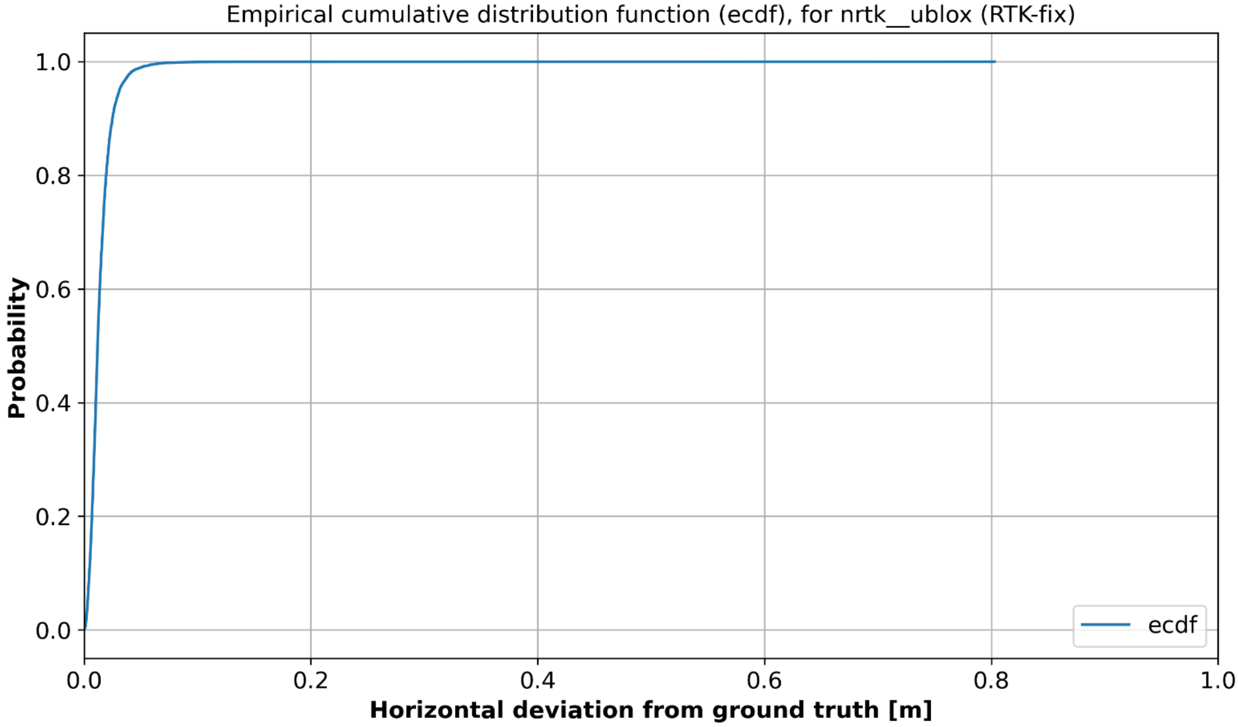

Figure 18: Empirical cumulative distribution function for CPOS on uBlox F9P, denoted as “nrtk__ublox”.

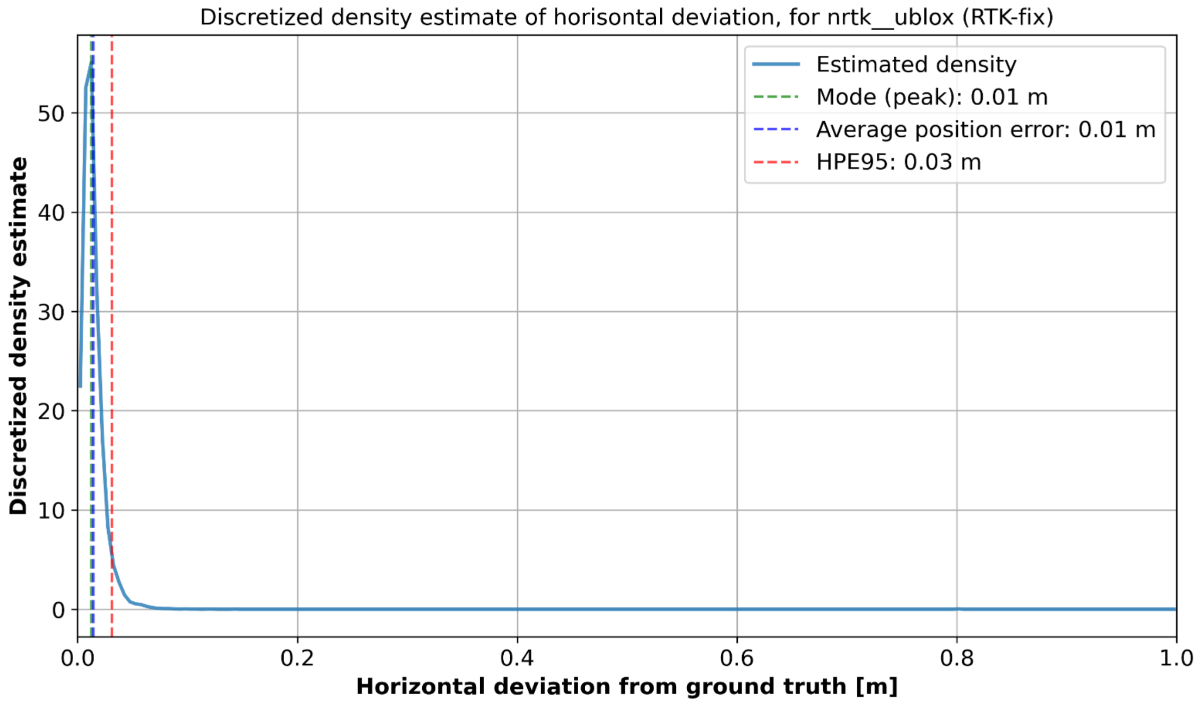

Figure 19: Discretized density estimate for CPOS on uBlox F9P, denoted as “nrtk__ublox”.

Figure 20: Time series excerpt for CPOS on uBlox F9P, denoted as "nrtk__ublox".

5.2.2 HyPos SSRZ on Alberding A10-RTK

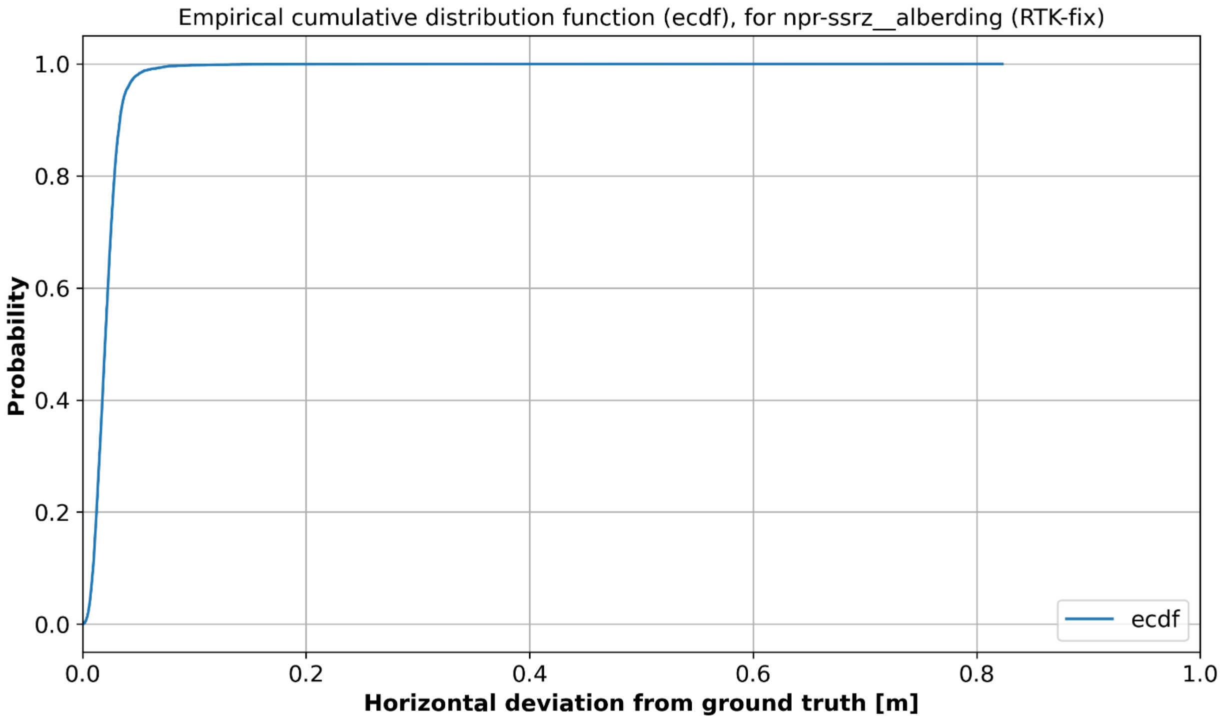

Figure 21: Empirical cumulative distribution function for SSR service on Alberding A10-RTK, denoted as "npr-ssrz__alberding".

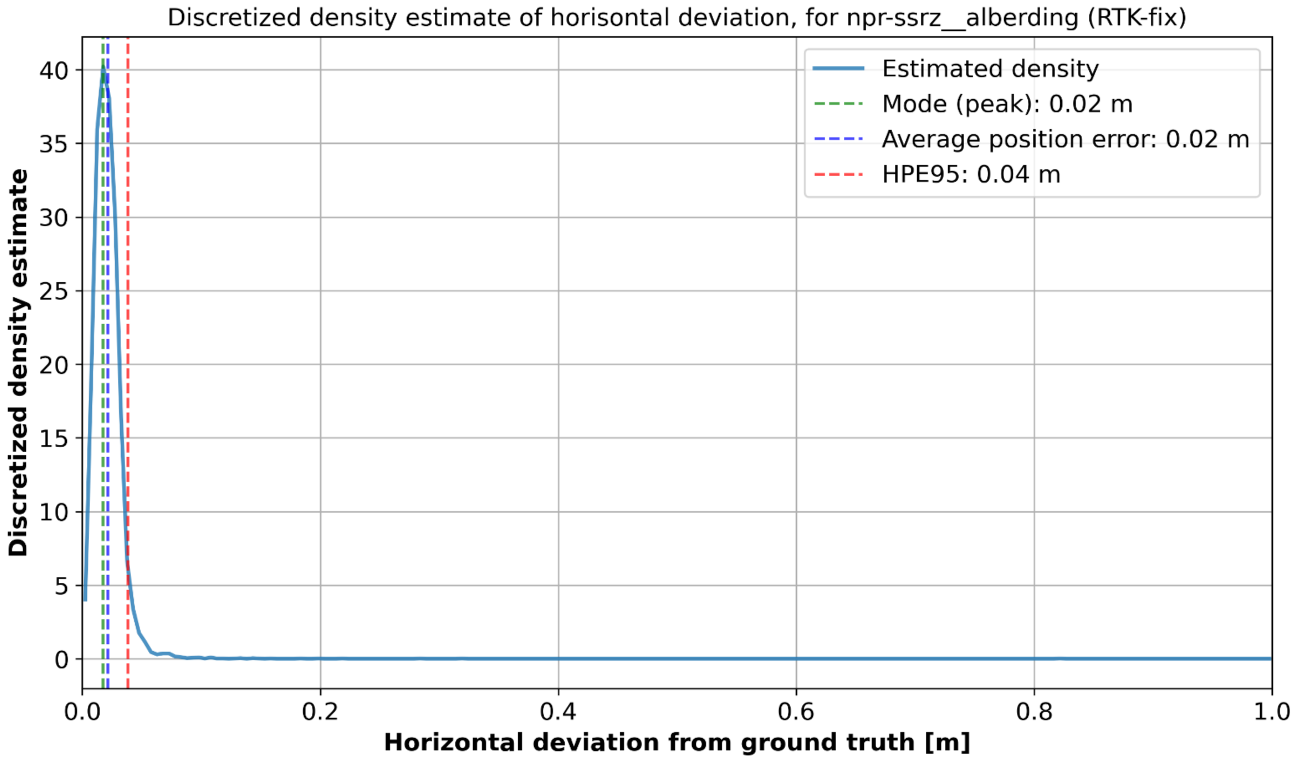

Figure 22: Discretized density estimate for SSR service on Alberding A10-RTK, denoted as "npr-ssrz__alberding".

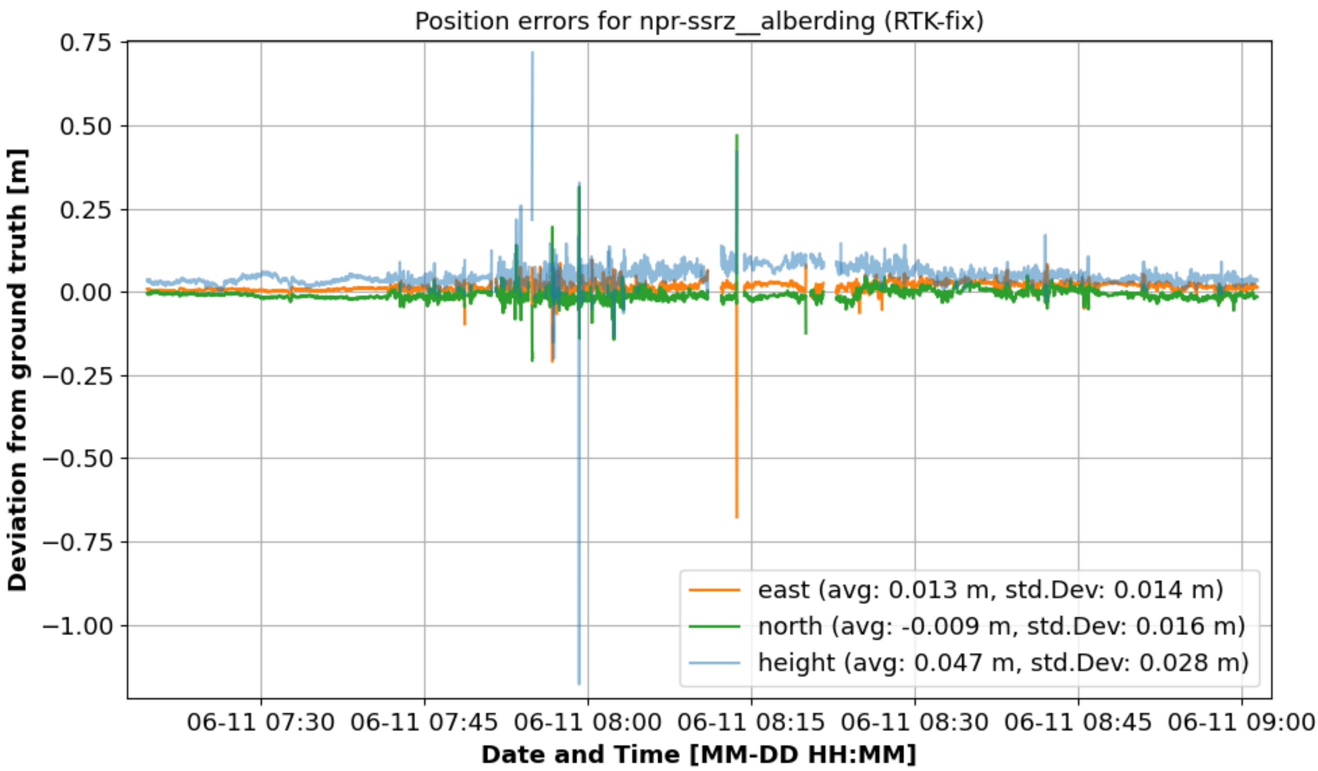

Figure 23: Time series excerpt for SSR service on Alberding A10-RTK, denoted as "npr-ssrz__alberding".

5.2.3 HyPos SPARTN on uBlox F9P

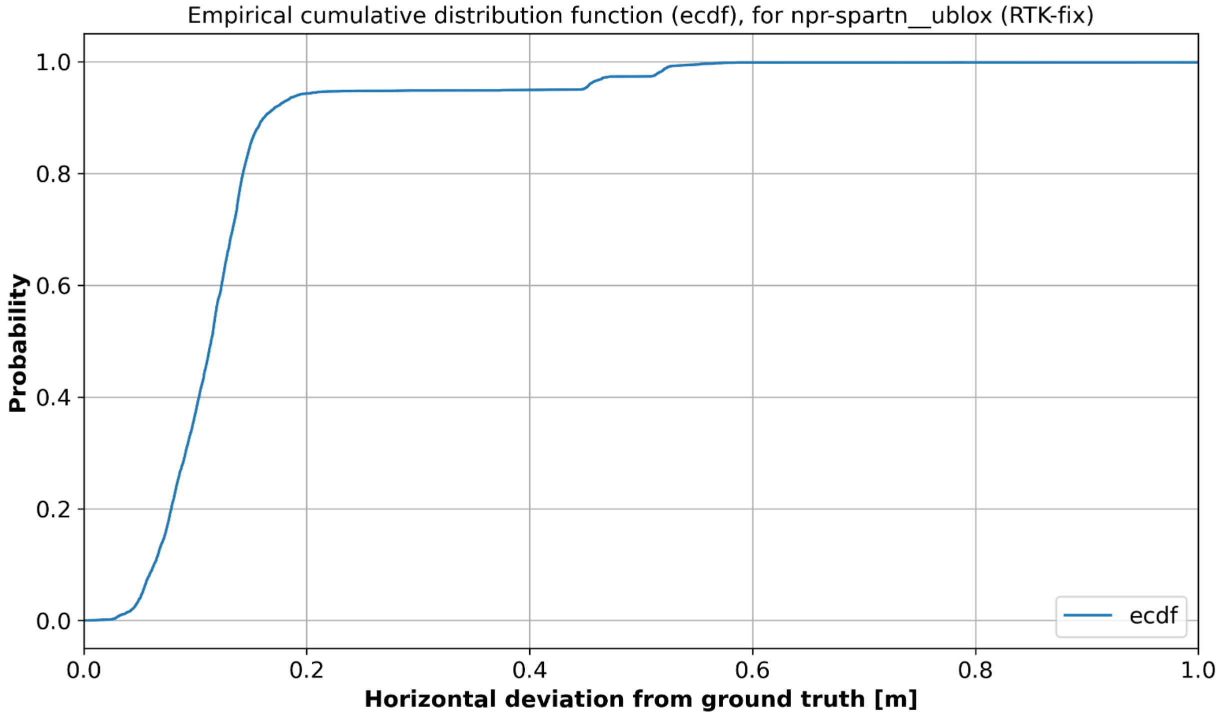

Figure 24: Empirical cumulative distribution function for SSR service on uBlox F9P, denoted as "npr-spartn__ublox".

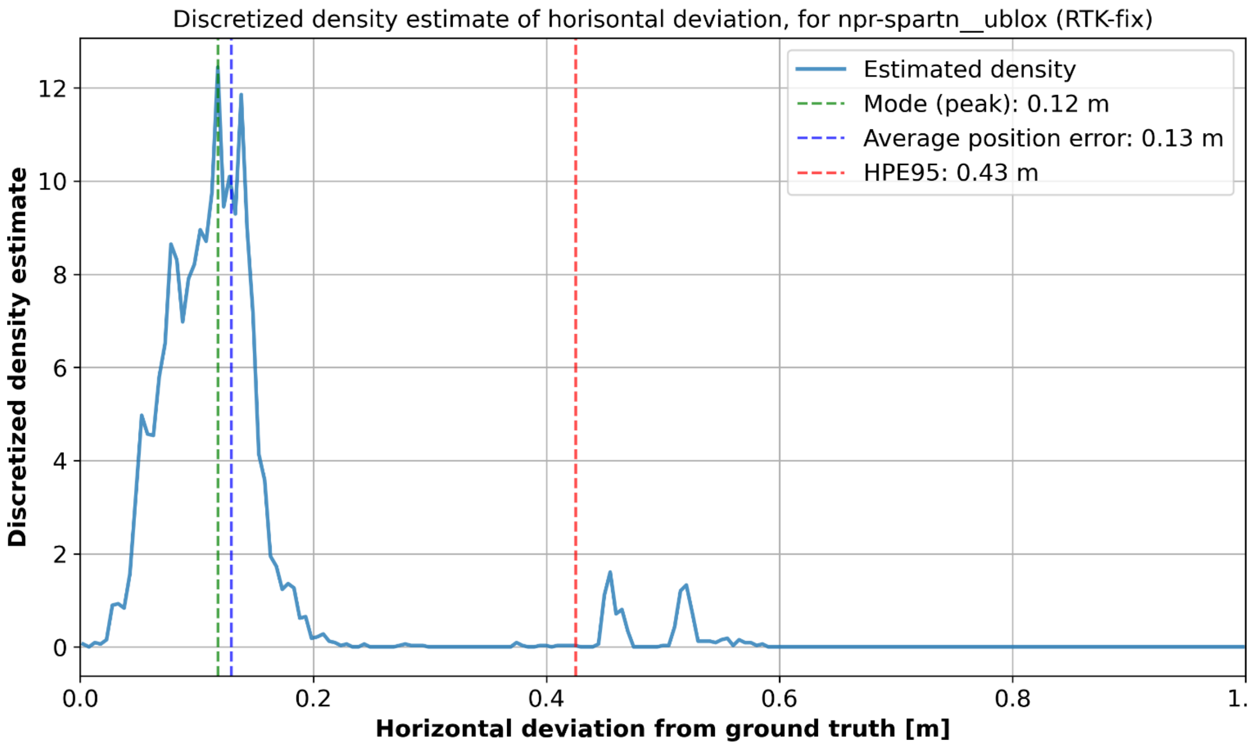

Figure 25: Discretized density estimate for SSR service on uBlox F9P, denoted as "npr-spartn__ublox".

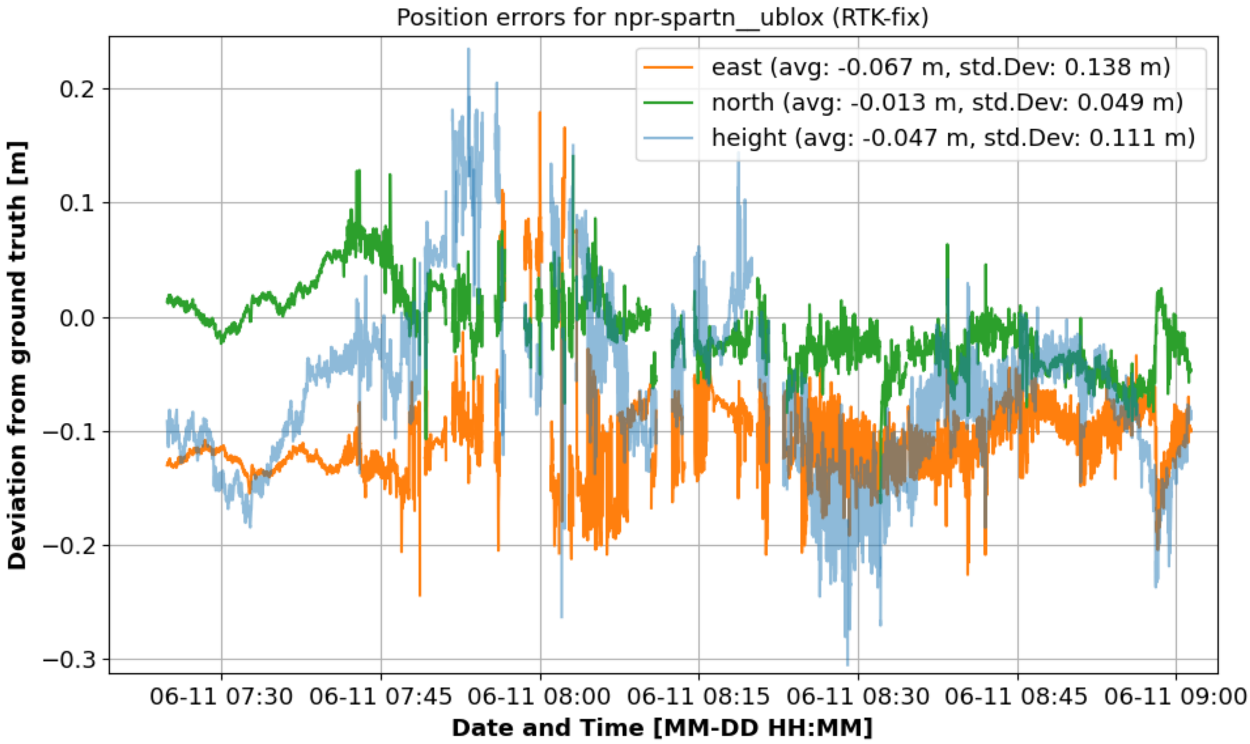

Figure 26: Time series excerpt for SSR service on uBlox F9P, denoted as “npr-spartn__ublox”.

6 References

[1] A. Solberg, et.al.: “HyPos – Work Package 2: GNSS SSR”. Kartverket, 2024. URL: https://www.kartverket.no/globalassets/forskning-og-utvikling/rapporter/hypos-wp2-report-2024-12-1.pdf