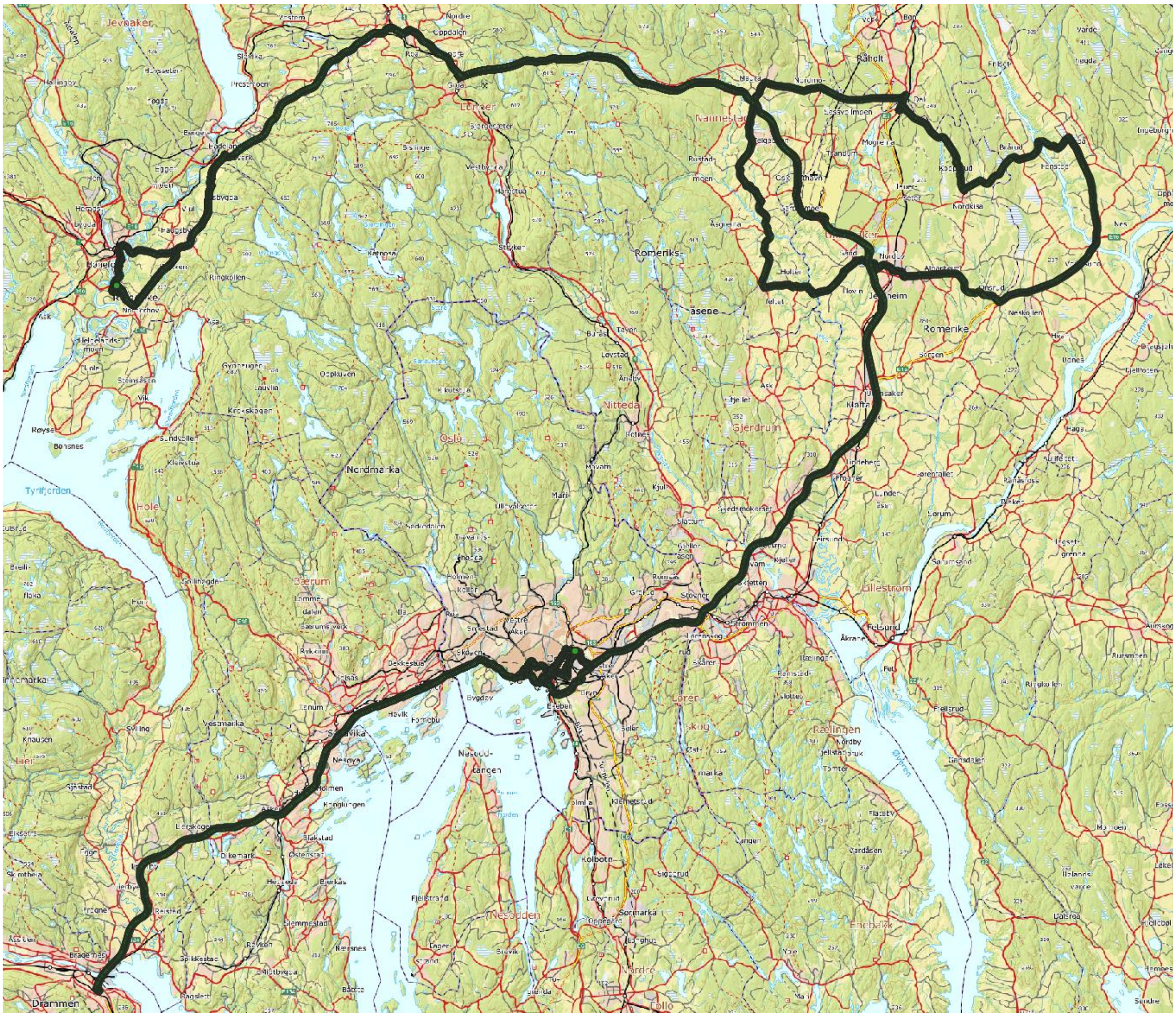
Kartverket

REPORT:

HyPos – Work Package 2: GNSS SSR



REPORT:

HyPos – Work Package 2: GNSS SSR

Project	HyPos - Nasjonal Hybrid Posisjonstjeneste for Fremtidens Digitale og Autonome Samfunn
Client	Research Council of Norway
Client project reference number	331984
Version	1.0
Date	14.12.2023
Editor	Anders M. Solberg (NMA)
Authors	Anders M. Solberg (NMA), Gunhild Berget (SINTEF), Fredrik Gunnarsson (Ericsson), Morten T. Brunes (NMA)

Contents

1 About this document

This report contains results and technical literature review for Work Package 2, Positioning with distributed GNSS corrections, in the HyPos project. Overall goals in the project are to explore how positioning with distributed GNSS corrections and positioning with 5G can be combined to a new hybrid correction service where the best qualities from each technology will be combined into a new hybrid correction service, HyPos. Work packages related to user demands and business models are important to ensure benefit of the project.

Intended readers for the report are people working with CCAM and ITS since precise positioning technology is a key technology for automated vehicles. There are existing GNSS correction services today, one group of services are highly accurate but not scalable to an unlimited number of simultaneous users and another group is less accurate but scalable to an unlimited number of simultaneous users. In HyPos work package 2 the project group explores and analyzes whether it is possible to scale up number of users and remain highly accurate position and performance.

The project has established a GNSS SSR correction service, performed data capture with various GNSS correction services and analyzed positioning performance. Results from this work is presented in this report.

Current challenges or status of the technology for GNSS SSR related to software to create GNSS SSR correction service, GNSS receivers, distribution methods and GNSS SSR formats are discussed.

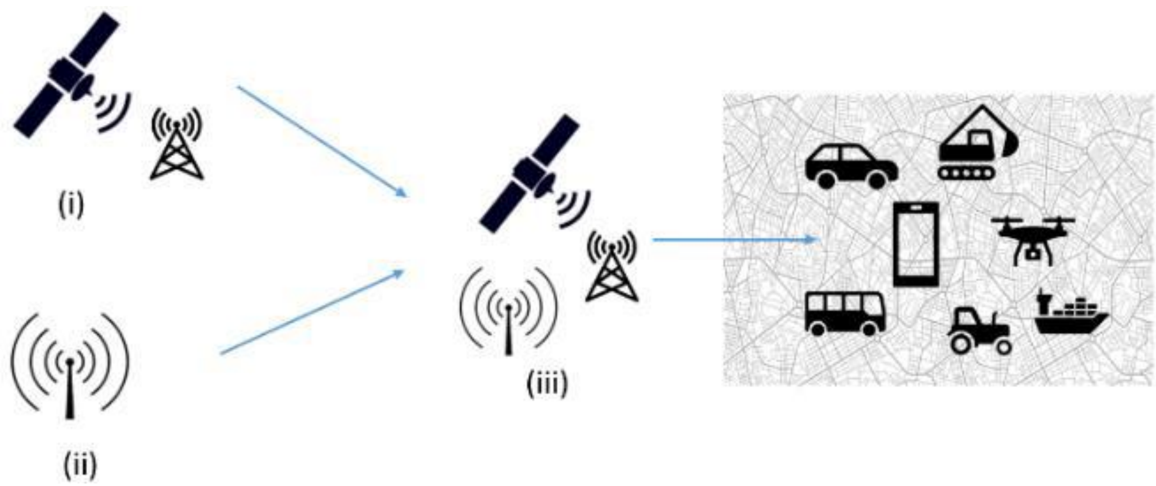


Figure 1-1: Basic principle of HyPos. (i) GNSS SSR correction service with NMA's infrastructure. (ii) Positioning with 5G (iii) Hybrid positioning service and user groups

2 Introduction

Global satellite navigation systems, commonly referred to as GNSS, are today providing absolute positioning 24/7 worldwide at an accuracy level of a few meters. This is sufficient for a lot of tasks, but an increasing number of applications require accuracy at a few decimeters or even centimeters. To achieve this, GNSS correction services have been developed. They are essentially services that correct GNSS measurement errors so that the users obtain a higher positioning accuracy (typically sub-meter, decimeters, or centimeters). There are several existing GNSS correction services today. One group of services are highly accurate but not scalable to an unlimited number of simultaneous users and another group is less accurate but scalable to an unlimited number of users.

In Work Package (WP) 2 of the HyPos project, the project group explores and analyses whether it is possible to scale up the number of simultaneous users while still obtaining highly accurate positioning performance. The main task of WP 2 is to establish and test performance of a prototype GNSS SSR correction service and validate the prototype against existing GNSS correction services based on either OSR or SSR.

Correction services based on OSR have been around for years and have proven high accuracy positioning to 1-2 cm accuracy (with a professional user receiver) and a stable performance. An example of such a service in Norway is CPOS, which is provided by the Norwegian Mapping Authority (NMA / Kartverket). With CPOS, the user device (user's GNSS receiver) sends its coarse uncorrected position to a server where a software calculates corrections for the GNSS signals and sends the relevant data back to the user device. This communication uses cellular network to transfer data between the server and the user device. Then the user's GNSS receiver calculates a high accuracy position. This implies that there is a two-way data transfer between GNSS receivr and server, and that the software calculates GNSS corrections for each user. Hence, the OSR technology is not directly scalable to an unlimited number of simultaneous users. The SSR technology mitigates the scalability challenges of OSR by calculating corrections for the individual GNSS error sources and distributing these corrections. With SSR corrections are sent one-way from server to users, and calculations on server are valid for all users. Basic principles for OSR and SSR are illustrated in Figure 2-1.

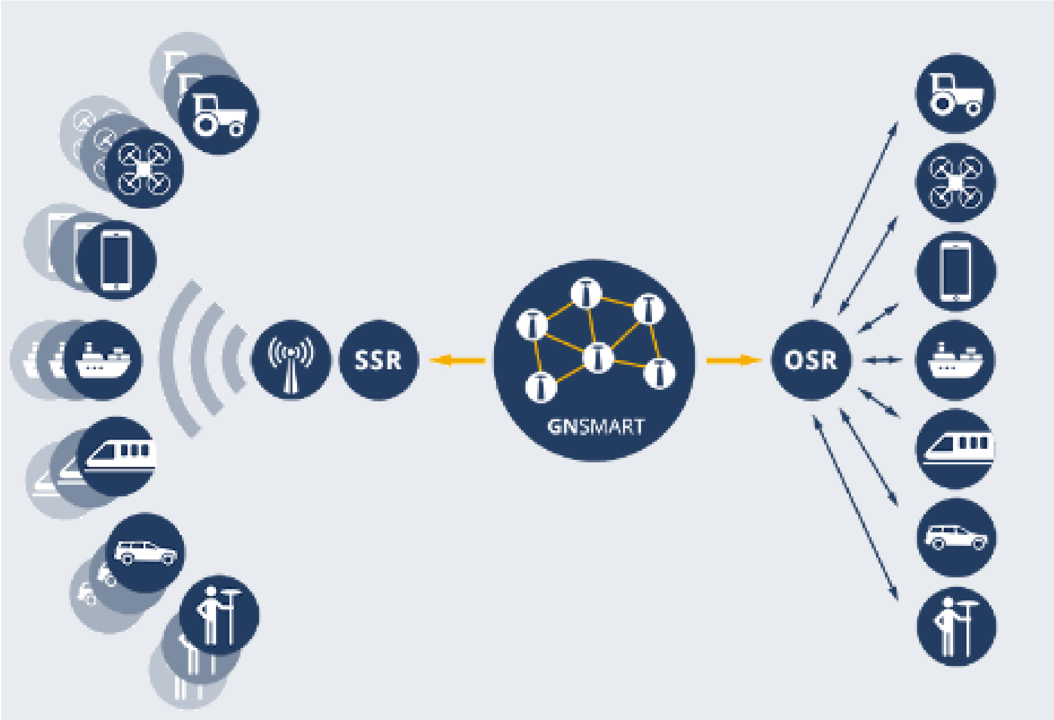


Figure 2-1: Illustration of SSR vs. OSR. GNSMART is a software that calculates GNSS corrections on server. Yellow arrows indicate GNSS correction method output from software, while OSR shows two-way data traffic and SSR shows one-way distribution [16]

In this report the prototype SSR service, which is set up in the HyPos project, will be referred to as HyPos SSR. Performance analysis in the user domain is done based on data capture campaigns. This means that GNSS user receivers have computed their positions and related quality measures, using correction data from HyPos_SSR and existing OSR and SSR correction services. From these positioning data we have calculated several key performance indicators (KPIs) in the user domain, e.g., service availability, position accuracy, systematic position errors, etc. Both static and kinematic performance tests have been conducted.

This document contains:

- Information about HyPos GNSS SSR correction service (chapter 3).
- Information about the GNSS data collection campaigns performed in the work package (chapter 4).
- A theory chapter to establish the technical terms used and to ease the understanding of the results of the data collection campaigns (chapter 5).
- The most important results of the campaigns (chapters 6,7, and 8).
- Brief descriptions of relevant data formats and protocols for GNSS correction data, in particular for SSR (chapters 9, 10, and 11).
- Brief analysis of pros and cons of different data formats and protocols (chapter 12).

3 HyPos_SSR GNSS correction service

HyPos_SSR is a prototype correction service built from the following constituents:

- Permanent reference stations. A permanent reference station consists of a high-end geodetic GNSS receiver connected to a high-end GNSS antenna (which receives the GNSS signals from the satellites) mounted either on top of a building or on top of a small mast (ref. Figure 3-1). In addition, a reference station typically includes communication equipment (internet modems) and various power supply systems. NMA's reference station network consists of more than 300 GNSS reference stations spread all over Norway, ref. Figure 3-2. Most of these stations are used for producing NMA's CPOS service.

Figure 3-1: Example of antenna and receiver for a permanent reference station. Credits: NMA, Leica Geosystems.

A small subset of the reference station network of NMA is used for producing HyPos_SSR. This subset is located around Oslo in the southern part of Norway. Figure 3-2 and Figure 3-3 show approximately where these reference stations are located. For GNSS correction service users it is a general rule of thumb that you should be located inside the network of reference stations to obtain good performance, because the reference stations are the measurement points that "sense" the spatially correlated GNSS errors. See chapter 5.2 for a very brief overview of the most important GNSS error sources.

Figure 3-2: NMA's permanent reference stations. HyPos_SSR subset is inside the red rectangle.

- Communication lines from the reference stations to NMA control center. Satellite measurements taken at the GNSS antennas by the GNSS receivers are forwarded in real-time to the NMA control center in Hønefoss via fiber or cellular connectivity.
- NMA control center. This is located at NMA's main office in Hønefoss. This includes a framework for reception of real-time GNSS data from the permanent reference stations, for dissemination of real-time GNSS data, and a data processing software for calculating SSR corrections (GNSMART from Geo++ GmbH). Dissemination of real-time GNSS data, including SSR corrections calculated by GNSMART, is done by use of an NTRIP caster software from Trimble Inc., and the SSR corrections are transferred to user devices via a cellular network.
- Lastly, a user of HyPos_SSR needs a GNSS receiver (user device) that is able to
    - do high-precision GNSS measurements (code and phase observations), and
    - receive and apply SSR corrections from HyPos_SSR on given formats, and
    - perform phase ambiguity resolution and compute positions accordingly.

  Still, there are not too many available receivers that are compliant with all these requirements. Here in WP 2, we have used two different receivers for testing HyPos_SSR in the user domain: One high-end receiver, and one low-cost receiver.

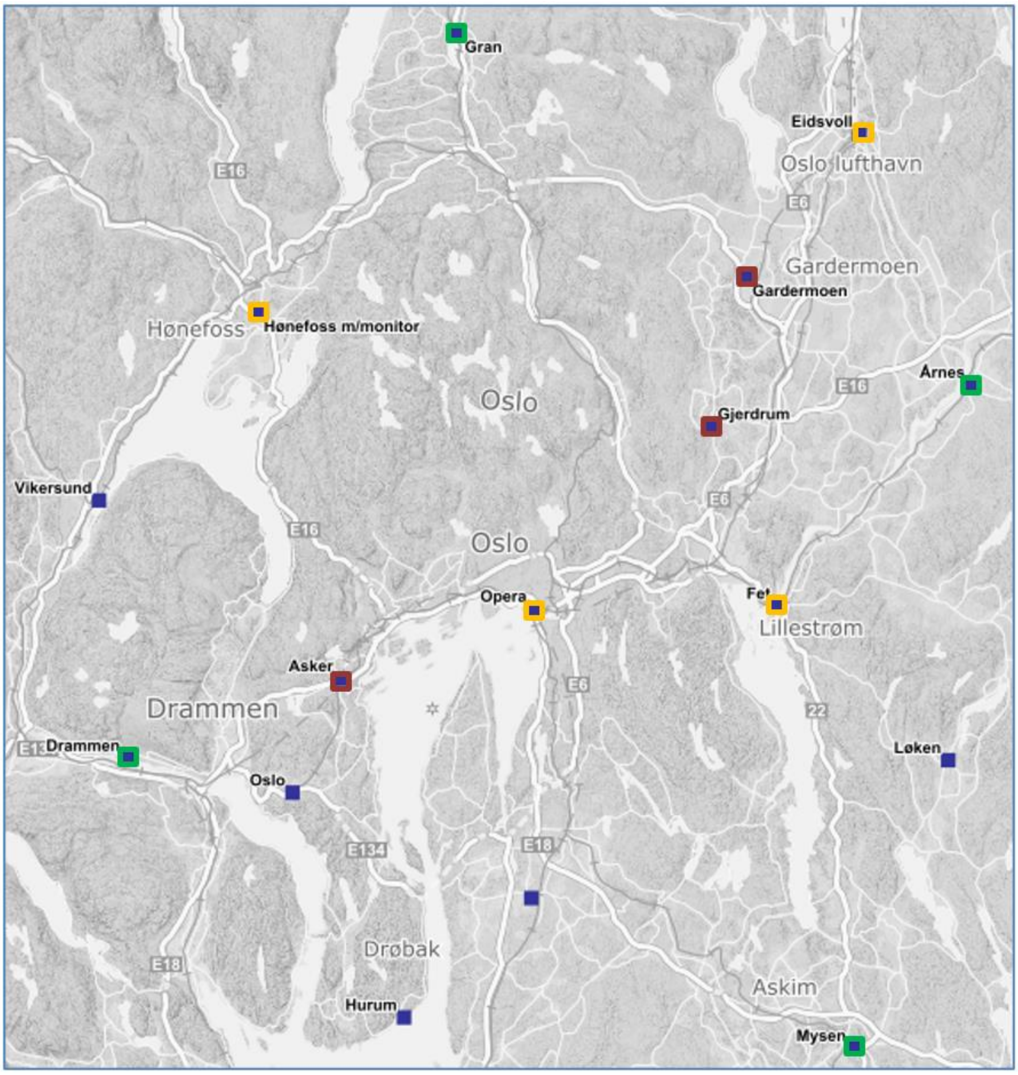


Figure 3-3: HyPos_SSR reference stations

The HyPos_SSR reference station network, ref. Figure 3-3 and explanations below, covers the areas around Oslo. Both kinematic and static data collection campaigns are conducted in the area covered by these stations.

- The 5 stations marked with clean dark blue squares are not used in HyPos_SSR, but they are used in the CPOS service. (Several stations outside this map are also used in CPOS.)
- The 3 stations marked with dark blue squares enclosed by dark red squares are used in the Full reference station configuration of HyPos_SSR, ref. chapter 6.3.
- The 4 stations marked with dark blue squares enclosed by yellow squares are used in the Full and Medium reference station configurations of HyPos_SSR, ref. chapter 6.3.
- The 4 stations marked with dark blue squares enclosed by green squares are used in the Full, Medium, and Minimum reference station configurations of HyPos_SSR, ref. chapter 6.3.

4 Outline of data collection campaigns

Both kinematic and static data collection campaigns have been performed. The purpose of this is to measure and analyze the performance of HyPos_SSR and some other comparable GNSS correction services with both high-end and low-cost user devices. The kinematic campaigns try to document user-realistic navigation performance under dynamic movement, where satellite visibility and other GNSS measurement conditions are varying quite rapidly. The static campaigns are performed under excellent satellite visibility, so we expect that the analysis of the static campaigns is able to identify how the performance is under nearly optimal conditions. The kinematic campaigns are further described in chapters 6, and the static campaigns are described in chapter 7.

For the kinematic campaigns, NMA's measurement vehicle (the car in Figure 4-1) was used. The car was equipped with several different GNSS receivers, each of them performing positioning using HyPos_SSR or one of the other GNSS correction services. Positions computed by these receivers must be compared to a well-known trajectory (a so-called ground truth trajectory, ref. chapter 6.2, list section 1). To be able to determine a ground truth trajectory, the car is equipped with a high-precision reference positioning system consisting of different sensors: A high-end GNSS receiver AsteRx4 from Septentrio, GNSS antenna Zephyr Geodetic 2 from Trimble and an inertial measurement unit (IMU) Apogee-D from SBG Systems. Raw data from this navigation system are post-processed in the Qinertia software from SBG Systems, using sophisticated data-processing algorithms combining the different sensors to obtain the highest possible position accuracy.

Figure 4-1: Measurement vehicle. More antennas have been added since this photo was taken.

For the static campaigns, the same KPIs with the same GNSS correction services and using the same user devices are calculated and analyzed as for the kinematic campaigns. The GNSS antennas are mounted on pillars with known coordinates. The location for the static campaigns was the rooftop of the NMA main office building just outside Hønefoss. The instrument setup and data collection periods are described in chapter 7.1.

5 Basic geographic positioning theory

To ease the understanding of the campaign results and the discussion of those, some basic technical terms are briefly described here. The terms that are used are not necessarily officially standardized, but they shall at least be used consistently within this document.

5.1 Coordinates and GNSS positioning

A set of coordinates (a coordinate set) describes the position of an object in a given coordinate system. In geographic applications, coordinates are usually defined in one of the three following categories of coordinate systems:

- Geocentric cartesian coordinates [X, Y, Z], illustrated by Figure 5-1.
- Ellipsoidal coordinates [latitude (φ), longitude (λ), height (h)], illustrated by right panel of Figure 5-1 and left panel of Figure 5-2.
- Projected coordinates [Easting, Northing, height], illustrated by right panel of Figure 5-2.

These three are only different ways of expressing the same information.

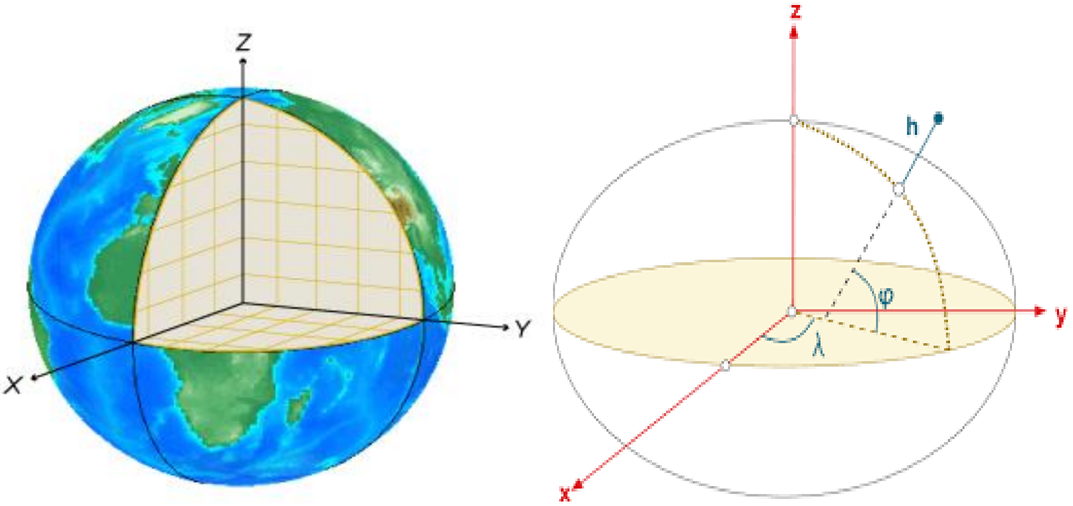


Figure 5-1: Geocentric and Ellipsoidal coordinate system (Credits: MathWorks (left), ESA (right))

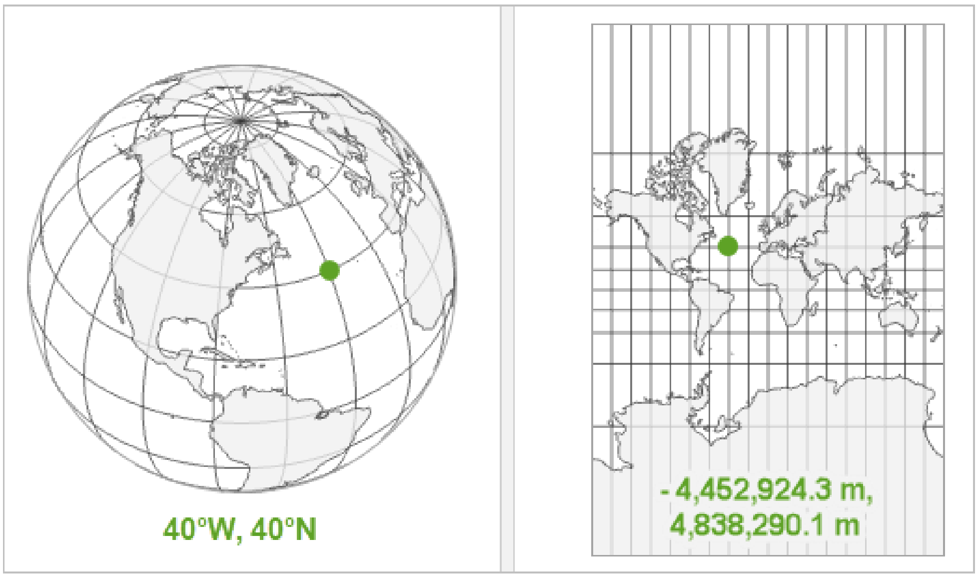


Figure 5-2: Ellipsoidal and Projected coordinate system (Credit: ESRI)

In this document, the term **positioning** means “performing measurements and using these measurements to compute (estimate) the coordinates of an object”. In the context of GNSS, this means that the device that performs positioning measures distances (ranges) to satellites and uses these measurements together with the known coordinates of the satellites to compute (estimate) its own coordinates, ref. Figure 5-3.

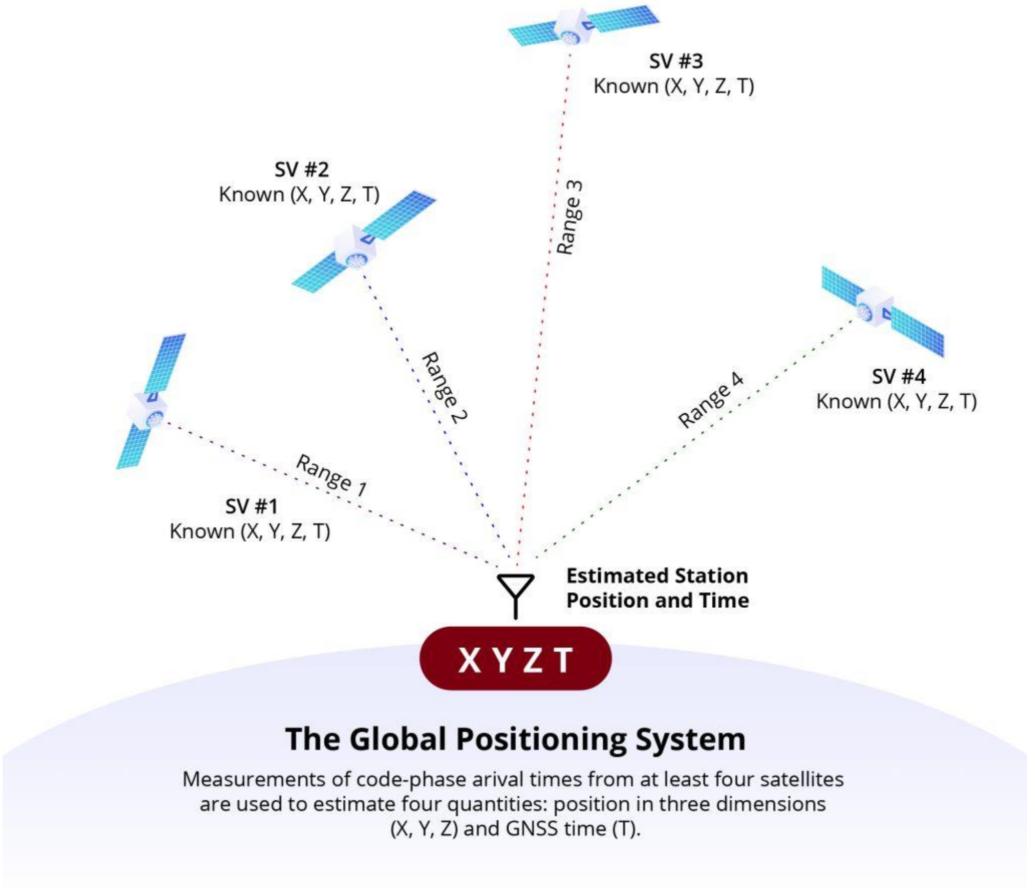


Figure 5-3: GNSS positioning. Credit: https://www.tallysman.com/

The computed set of coordinates [X, Y, Z] can automatically be converted to ellipsoidal coordinates ([latitude, longitude, height]) and then to projected coordinates ([Easting, Northing, height]), which is often convenient to work with when analyzing the accuracy of a series of coordinate sets or when visualizing those in a map. In this report, projected coordinates are used when calculating position errors and statistics.

In this document, “**a position”** simply means **a set of coordinates (a coordinate set)**.

To be able to compute a position with GNSS, it is necessary to simultaneously observe (measure ranges to) minimum 4 satellites (in several applications, the minimum requirement can be a larger number, though). Simply put, the computed positions are more reliable the more satellites that are observed. Another important factor is the geometrical distribution of the satellites on the local sky. The more outspread the observed satellites are, the better, ref. Figure 5-4. The professional term for describing geometrical distribution of satellites relative to the receiver is **satellite geometry**.

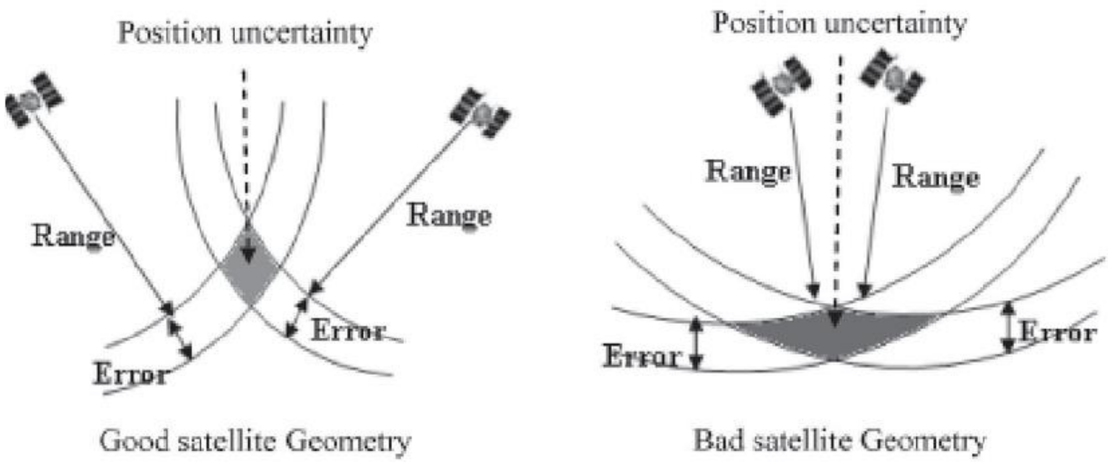


Figure 5-4: Satellite geometry. Credit: Swarna Ravindra Babu, https://researchgate.net

5.2 GNSS error sources and correction services

GNSS position errors originate from a combination av several sources. The most important ones are illustrated in Figure 5-5. The numbers in the figure refer to the effect each error source can typically have on the range measurement between the receiver and each satellite. Satellite related errors and atmospheric (ionospheric + tropospheric) errors are corrected by the GNSS correction services. Multipath (interference by reflected signals) and receiver noise have a very local nature and must be handled by the user receiver as far as possible.

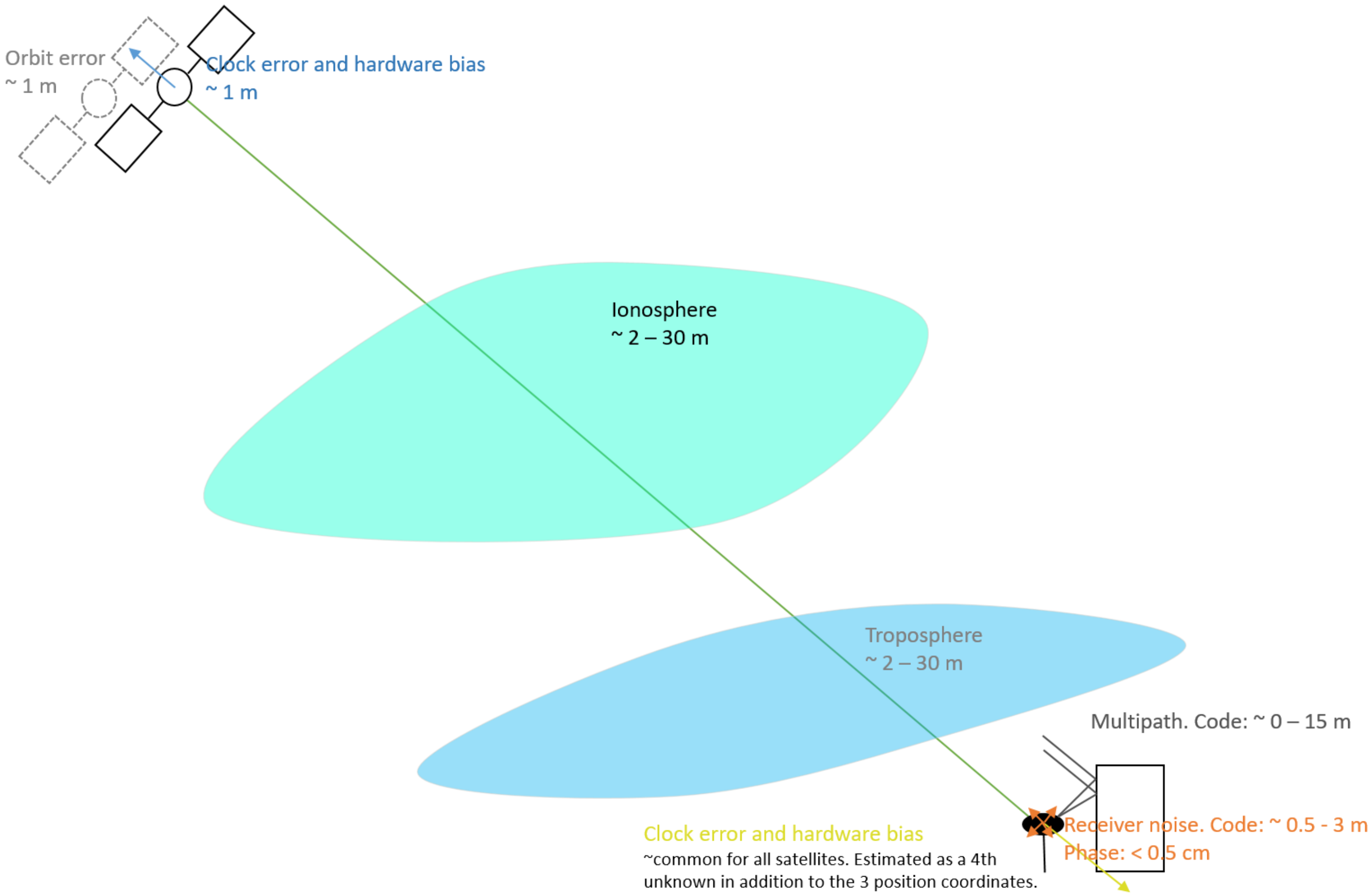


Figure 5-5: GNSS error sources

Correction services using the OSR principle provides the users with data that corrects the sum of the mentioned relevant errors (satellite related errors, ionosphere, troposphere) at the user's location. There are several groups of services using OSR. In the high-accuracy segment, Network RTK is perhaps the dominating OSR concept, and it uses a network of permanent reference stations. There are several different varieties of Network RTK, but the probably most widely used approach is called the "Non-physical Reference Station" approach, ref. illustration in Figure 5-6. The concept can roughly be described as follows: All the reference stations continuously (every second) send their range measurements for each observed satellite to the control center ("Central Server" in Figure 5-6). The OSR data processing software at the control center estimate range errors at the reference stations (which all have well-known precise coordinates). The software then makes a spatial mathematical model of the range errors between the reference stations. The user GNSS receiver sends its uncorrected position to the control center. The OSR data processing software can then interpolate in the model so that it can calculate differences between the range corrections in the station network and obtain a correction difference valid at the user's (uncorrected) position. This position is called a non-physical or virtual reference station. These range correction differences are then applied to observation data based on the nearest physical reference station. The result is a set of synthetic range observations containing very much the same errors as the range observations of the user receiver do.

The rest of the process is done by the user receiver. It forms differences between its own range observations and the synthetic ones. Then, all common errors are cancelled out and the user receiver may compute a precise position.

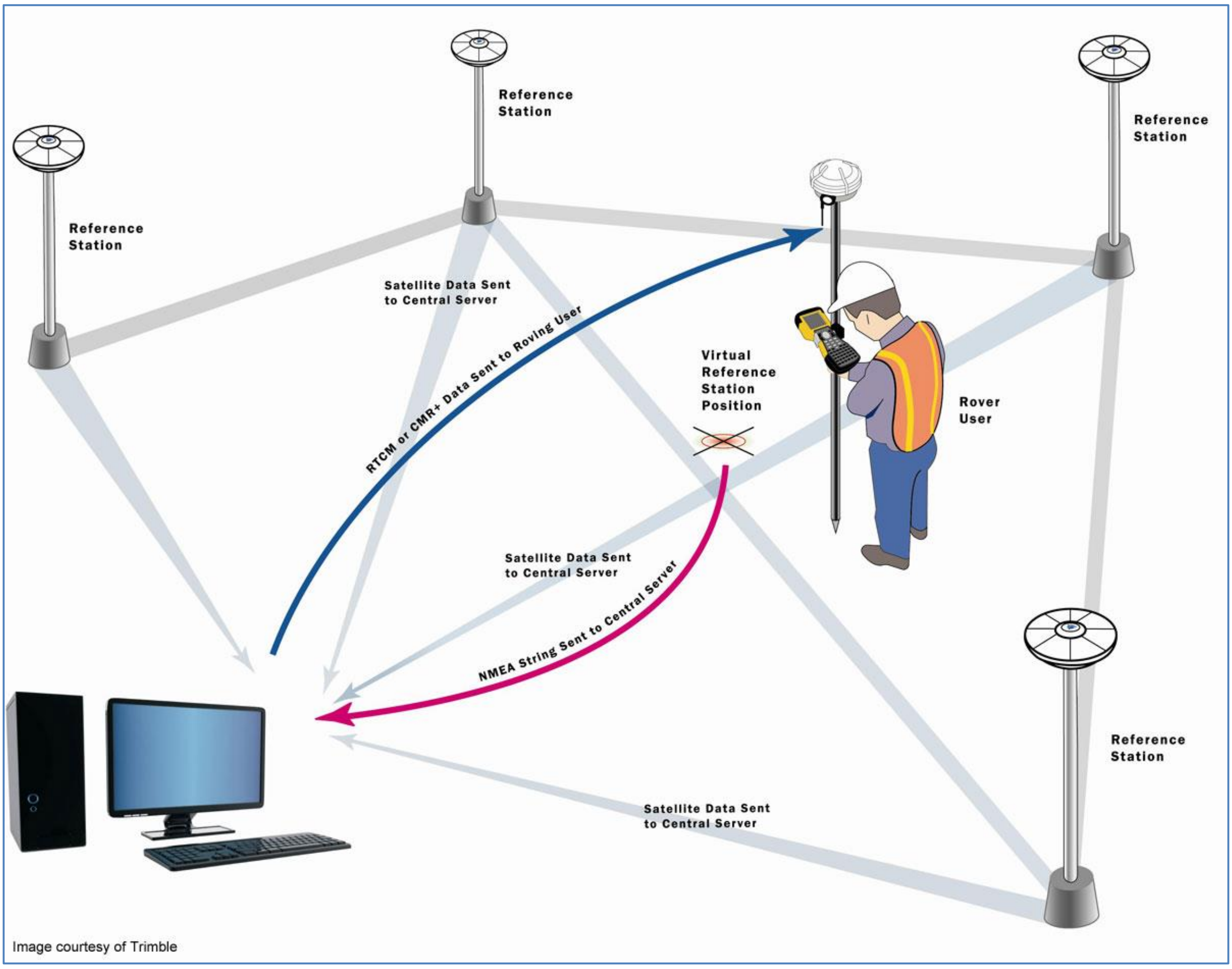


Figure 5-6: OSR: Non-physical (Virtual) Reference Station concept. Credits: Trimble / U.S. Geological Survey

An SSR service, on the other hand, computes corrections for each of the mentioned individual error sources and disseminate these corrections to the users, in principle so that the users can apply these corrections directly and compute a precise position, instead of the more indirect way of error correction that is performed in the OSR - "Non-physical Reference Station" method. Traditionally, SSR services are based on regional (covering continents or subcontinents) or global reference station networks. The reason is that this is geometrically favorable for computing precise satellite orbits due to a solid observational geometry and continuity when using wide area station networks. There is heavy mathematical correlation between some of the error sources (e.g., satellite clock error and tropospheric delay ([19])), so that they can be difficult to separate from each other in the estimation process of the service. The HyPos network, however, has a very limited geographical coverage. But as long as the different error estimates are treated consistently in the service so that the sum of errors is effectively mitigated, this should not be a problem even for services using small local reference station networks, like HyPos. An underlying prerequisite is that the user is geographically located inside the network of reference stations, like for OSR Network RTK.

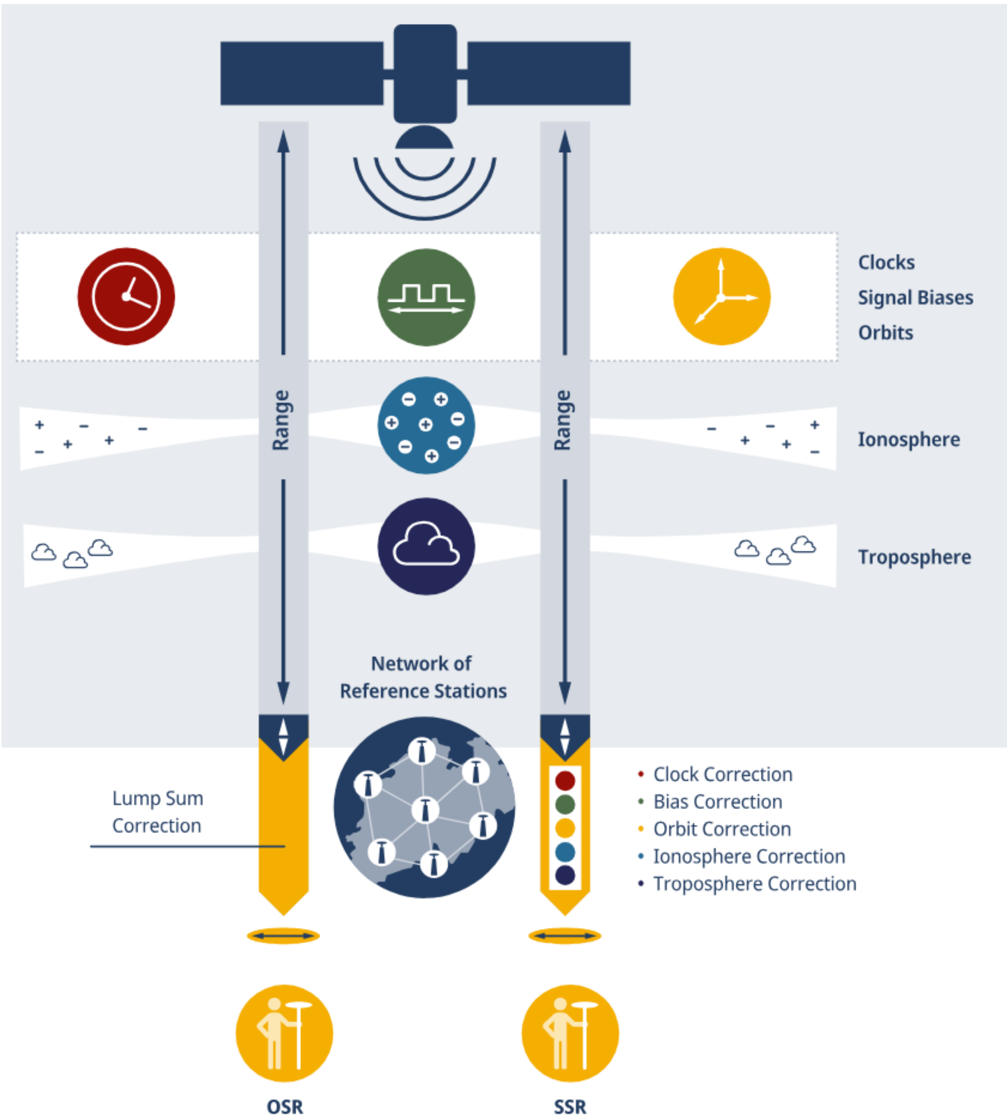


Figure 5-7: OSR vs. SSR. Credit: Geo++ GmbH

5.3 Phase ambiguity integer resolution

Basic GNSS positioning uses the ranging codes that are modulated on the radio waves that are broadcast by the GNSS satellites to obtain the range measurements shown in Figure 5-3. Code measurements, as these range measurements are called, have a noise at the meter level. A GNSS receiver can use its code measurements together with corrections from a correction service and obtain a somewhat improved position accuracy. This is called a **code-based differential solution**. However, due to the noisy nature of code measurements, GNSS operations aiming at a positioning accuracy better than ~0.5 m requires the receiver to use phase measurements on the carrier waves of the GNSS signals in addition to the code measurement technique. Phase measurements have a precision down to the millimeter level. The drawback of the phase measurements is that they are ambiguous to the number of wavelengths between the satellite and the receiver antenna, ref. Figure 5-8. For information, the typical wavelength of a carrier GNSS signal is between 19.0 and 25.5 cm.

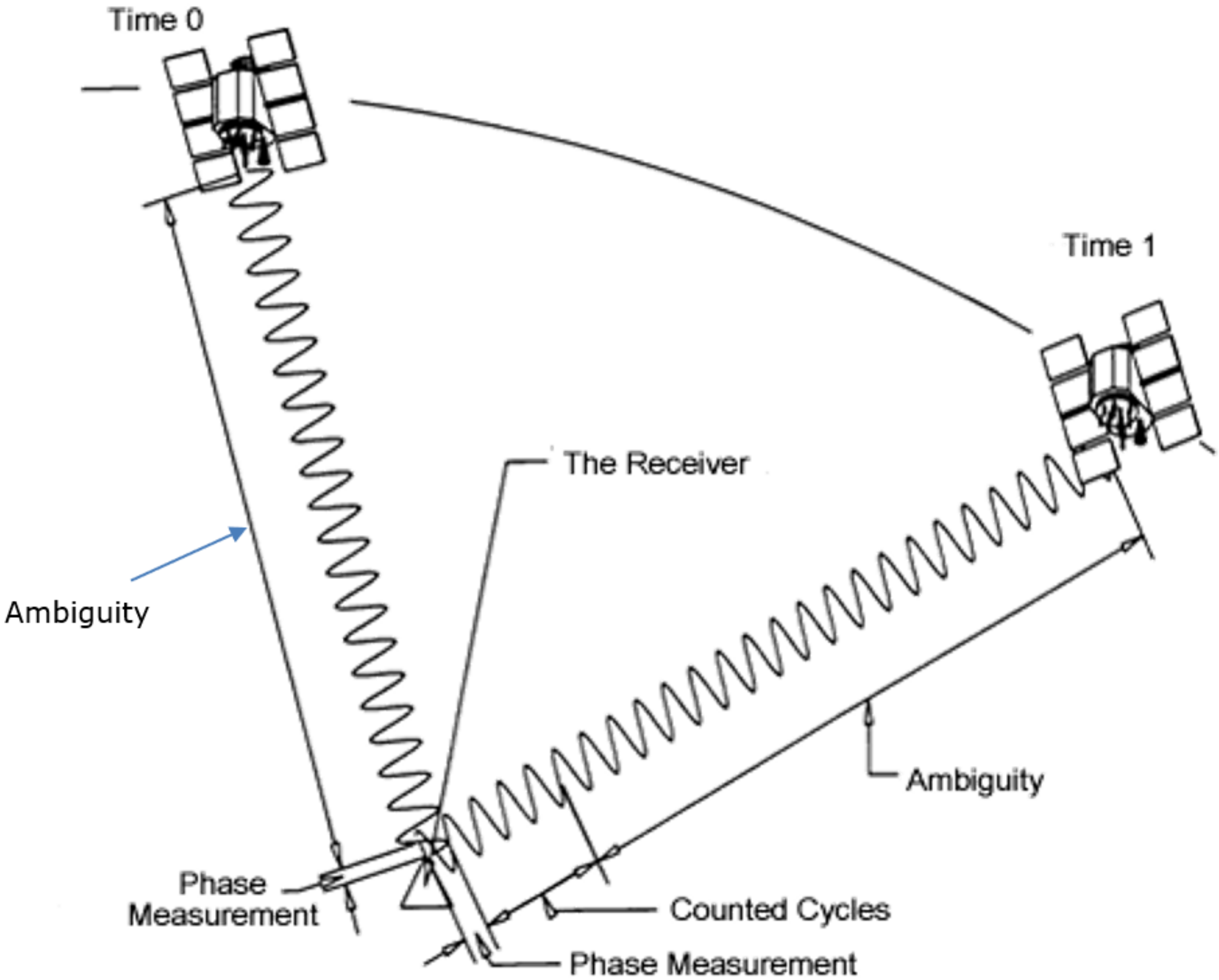


Figure 5-8: Phase measurements (Credit: Aaron Boda at wordpress.com. Figure slightly revised.)

During phase measurement, the receiver keeps track of number of wavelengths that is passed between each time instance of measurement (ref. "Counted Cycles" in Figure 5-8), but the initial number of wavelengths, which is called the phase ambiguity, remains unknown. By using code range measurements for finding a first guess on the ambiguity value and some estimation calculations it is fairly simple to estimate a floating-point number that is an approximation of the true integer value for the ambiguity. When doing so for all the satellites used, the solution to the positioning problem is called a **float solution**. However, the precision of float ambiguity estimates is not stable, so phase measurements and estimation must be done continuously for at least ~20 minutes to achieve good positioning accuracy, and still the accuracy will not necessarily reach the centimeter level. In order to obtain centimeter level accuracy within a few seconds, the phase ambiguities must be estimated as integers, and this requires a process called ambiguity resolution. Ambiguity resolution involves both estimation of the integers (for the different satellites) and validation of those estimates (see e.g., [17]). After ambiguity resolution is done, positions can be computed where the phase ambiguities are now considered to be known integer values. A position computed this way is called a **fixed solution.** Fixed solutions realize the high-precision potential of using phase measurements and correction data, and they normally have the high accuracy that is desired.

After a fixed solution is obtained, the receiver can continue to use the estimated ambiguity for each satellite[1] as a known fixed value until it loses track (=continuous measurement) of the signal from that satellite. If it loses track of sufficiently many satellites so that there are too few satellites left to compute a position, and then regains track of the satellites, the receiver will either produce a code-based differential solution or a float solution, because the number of counted cycles has now been reset, and consequently the ambiguities are unknown and must be estimates again. This is typical behavior if, e.g., the receiver antenna passes under a bridge. The time consumed before a fixed solution is re-obtained depends on several factors: Number of visible satellites, satellite geometry, multipath (interference from indirect signals reflected by object surfaces near the receiver antenna), atmospheric conditions, and the quality of the correction data.

Unfortunately, the ambiguity resolution process can be somewhat vulnerable, even though validation is part of the process, especially under difficult GNSS measurement conditions. As an example, bad satellite geometry combined with extensive multipath can be unfortunate. If the integer estimate is wrong for the phase ambiguities of some satellite(s), it can result in position errors that sometimes may have a size of several decimeters or even a few meters.

[1] In reality, ambiguities are often estimated for pairs of satellites instead of single satellites, but that is beyond the scope of this text.

6 Results of kinematic data collection campaigns

6.1 Driving routes and area type definitions

A kinematic data collection campaign in the framework of this project, involves collecting GNSS positions and related data on the measurement vehicle presented in chapter 4.

The kinematic data collection campaigns were conducted in the HyPos_SSR coverage area (ref. Figure 3-3) on the following days in June and July 2023:

- On June 5^{th}, a short trip in the Hønefoss area was made.

  Route: NMA office → Norderhov → Klekken → Hønefoss → NMA office

- On June 6^{th}, 7^{th}, 8^{th}, a country road trip through a large part of the southern coverage area was made.

  Route: NMA office → Norderhov → Klekken → Roa → Maura → Dal → Vormsund → Jessheim → Holter → Maura → Roa → Klekken → Norderhov → NMA office

- On June 20^{th}, 21^{st}, 22^{nd}, a trip on a motorway passing through a large part of the southern coverage area was made.

  Route: Gardermoen → Drammen → Gardermoen

- On June 27^{th}, 28^{th}, and July 3^{rd}, a trip around in some central parts of Oslo was made.

The driving routes are depicted on the front page of this document and in Figure 6-1.

Positioning performance of GNSS is somewhat dependent on the local conditions on the ground. Buildings, trees, and terrain may block satellite signals so that the positioning accuracy is degraded or even positioning is lost. Buildings and trees typically also generate so-called multipath, which can be explained by GNSS signals reflected from a surface nearby the receiver and interfering with the direct signal in the receiver, causing position biases and degraded accuracy. Therefore, we have split each driving route into different area types to try to distinguish between areas with different ground conditions. The area types are:

1. Country road, little vegetation along the road. Ref. yellow areas in Figure 6-1. We generally expected relatively good positioning performance in these areas.
2. Country road, forest along the road. Ref. green areas in Figure 6-1. We generally expected a slightly degraded performance in these areas compared to area type 1.
3. Motorway. Ref. violet areas in Figure 6-1. Here we expected quite good performance except for numerous passages under bridges and potentially some degradation effects if heavy traffic of large vehicles is experienced.
4. Urban areas. Ref. orange areas in Figure 6-1. Here we expect degraded performance in a lot of cases, due to GNSS signal shadowing by buildings.
5. (Data exclusion area type) Tunnels. Ref. black areas in Figure 6-1. When the car is entering a tunnel, the navigation receivers will typically continue to compute positions for a few seconds before positioning is lost. These positions typically have a poor quality, and we do not want them to pollute the results of the other area types. Therefore, we have made this area type to exclude such positions from statistics computations.

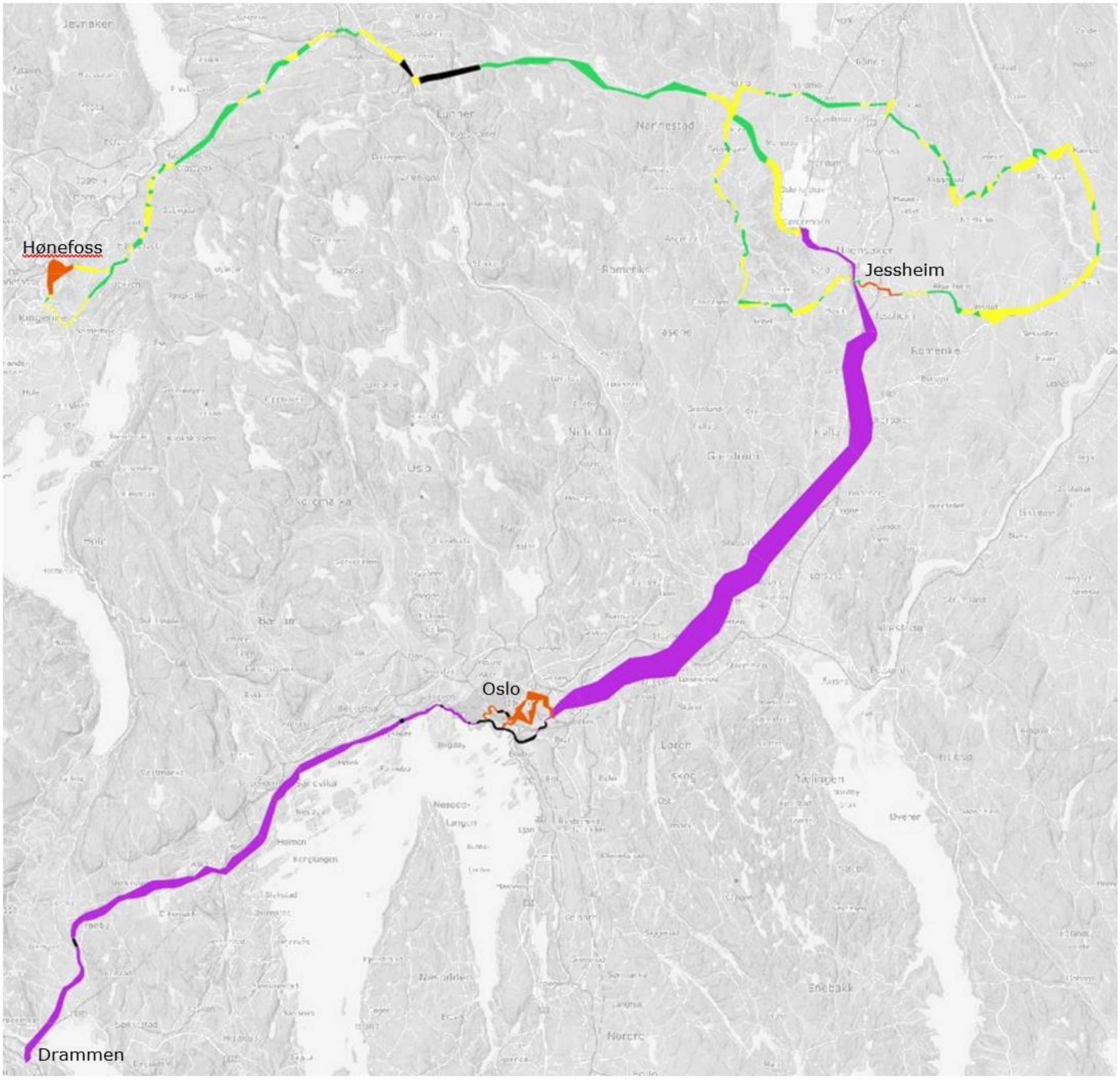


Figure 6-1: Driving routes and area types.

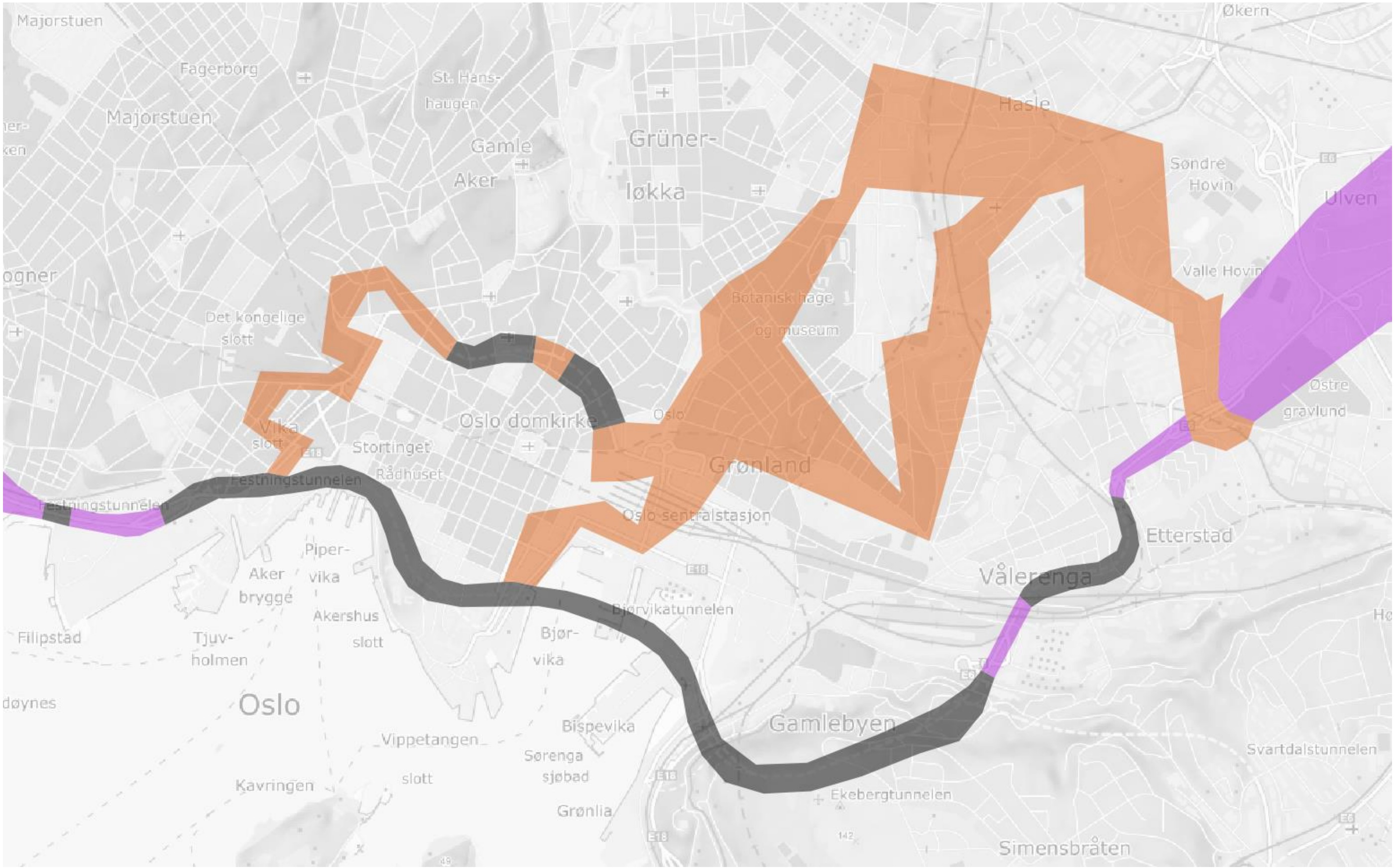


Figure 6-2: A zoom-in over the driving routes through central Oslo.

6.2 Data sets

To achieve the goal mentioned above, several GNSS receivers were mounted in the car. Two basic types of positioning are going on during a data collection campaign with the car:

1. Ground truth measurements

   As outlined in chapter 4, the car is equipped with a high-precision reference positioning system, which includes a high-end GNSS receiver and an inertial measurement unit (IMU). After the data collection trip, the data collected by this reference positioning system is post-processed using sophisticated algorithms (including a combination of forwards and backwards processing), which results in a highly accurate and reliable track of computed coordinates along the driving route of the car. These positions serve as “ground truth” for evaluating the accuracy of HyPos_SSR and the other services.

2. Navigation positioning

   For testing the user domain positioning performance of HyPos_SSR and some other correction services, the following six GNSS receivers were mounted in the car:

   a. Teria PYX, used with HyPos_SSR, corrections distributed in the SSRZ format. This is a high-end user receiver made for high-precision positioning tasks.

      The resulting data set is called **HyPos-SSRZ__TeriaPYX**.

   b. Trimble R10, used with CPOS, OSR corrections distributed in the RTCM format. This is also a high-end user receiver made for high-precision positioning tasks.

      The resulting data set is called **CPOS__TrimbleR10**.

   c. u-blox F9P, used with HyPos_SSR, corrections distributed in the SPARTN format. This is a mass-market receiver which costs a fraction of the price of the Teria PYX.

      The resulting data set is called **HyPos-SPARTN__ublox**.

   d. u-blox F9P, used with CPOS, OSR corrections distributed in the RTCM format.

      The resulting data set is called **CPOS__ublox**.

   e. u-blox F9P, used with PointPerfect (SSR service of u-blox AG ([13])), corrections distributed in the SPARTN format. PointPerfect is based on a global sparse reference station network with regional densifications. The network is densified in Norway, but it is still much sparser than the CPOS network.

      The resulting data set is called **PointPerfect__ublox**.

   f. u-blox F9P, used with HyPos-Ericsson, which is an OSR implementation processed and distributed in the 3GPP LPP format by Ericsson, using the same reference station network as HyPos_SSR.

      The resulting data set is called **HyPos-Ericsson__ublox**.

Brief presentations of the different correction formats can be found in chapter 9.

6.3 Reference station network configurations for HyPos_SSR

Operation and maintenance of GNSS reference stations imply costs for the operator. One of the goals of WP 2 is to find out more about the necessary density of reference stations for a future SSR service. One way to put this question is whether SSR services can use a sparser station network than the existing OSR service, but still obtain the same positioning performance for the users. To investigate this question, HyPos_SSR has used different station network configurations (setups) in the southern reference station network on different campaign days. The different configurations are:

- Full configuration: 11 stations
- Medium configuration: 8 stations
- Minimum configuration: 4 stations

The colored squares correspond to the station indicators in the Figure 3-3 map. The original plan was to have more stations in all the configurations, but this had to be reduced because problems with the real-time processing with GNSMART arose. This is the reason why not all the stations shown in Figure 3-3 were used in HyPos_SSR. The final configurations were chosen so that they should fit the kinematic data collection road trip routes that had been decided beforehand.

Table 1 shows which configuration that was used for HyPos_SSR (and for HyPos-Ericsson, which is an OSR service) and which road trip that was made on each of the campaign days.

Table 1: Overview over different reference station configurations and data collection road trips

Date	Full configuration	Medium configuration	Minimum configuration
05.06.2023	Hønefoss trip		
06.06.2023	Country road trip		
07.06.2023			Country road trip
08.06.2023		Country road trip	
20.06.2023	Motorway trip		
21.06.2023		Motorway trip	
22.06.2023			Motorway trip
27.06.2023	Central Oslo trip		
28.06.2023		Central Oslo trip	
03.07.2023			Central Oslo trip

The existing services CPOS and PointPerfect were used with their normal setup on all campaign days. This implies that, with the exception of receiver failure or service failure, approximately 3 times as much data was collected for the existing services as for each of the different configurations of HyPos_SSR and HyPos-Ericsson.

6.4 Position error calculation and KPIs

A position error is defined as the coordinate difference (in one or more geometric dimensions) between the position computed by the navigation receiver and the ground truth position:

$$\Delta East = Easting_{nav} - Easting_{truth}$$

$$\Delta North = Northing_{nav} - Northing_{truth}$$

$$\Delta Height = Height_{nav} - Height_{truth}$$

When analyzing the results of the kinematic data collection campaigns, we focus more on the horizontal coordinates than on the height component. Using the Pythagorean theorem, we have:

$$\Delta Horizontal = \sqrt{\Delta East^2 + \Delta North^2}$$

In the data collected by our kinematic campaigns, $\Delta East$, $\Delta North$, $\Delta Height$, and $\Delta Horizontal$ is calculated for each point in time where both a ground truth position and a navigation position have been computed. The output data rate is 1 Hz (1 computed position per second) for both the ground truth computation system and for all the navigation receivers, but sometimes one or several of the systems fail to compute a position, e.g., due to GNSS signal shadowing caused by the car passing under a bridge. Positioning may also be lost due to technical problems in receivers or in receiver related software. If both a ground truth position and a navigation position has been computed at a point in time, and this navigation position is classified as valid for statistics computation contribution (one requirement may be that it is a fixed solution), we call this pair of coordinate sets a **data point**.

Based on the position errors, several KPIs can be calculated.

- HPE95 is defined as the 95th percentile of $\Delta Horizontal$ over a given period.
- VPE95 is defined as the 95th percentile of $abs(\Delta Height)$ over a given period.
- HPE99 and VPE99 are defined in the same way, with 99th percentile.

These KPIs describe the accuracy of the positioning, relative to the truth values.

Another common way of describing positioning accuracy is RMS:

- $RMS\_WestEast = \sqrt{\frac{\sum(\Delta East_i)^2}{n}}$ for $i = 1 \dots n$, where n is the number of data points.
- $RMS\_SouthNorth = \sqrt{\frac{\sum(\Delta North_i)^2}{n}}$ for $i = 1 \dots n$, where n is the number of data points.
- $RMS\_Height = \sqrt{\frac{\sum(\Delta Height_i)^2}{n}}$ for $i = 1 \dots n$, where n is the number of data points.

The average error for each coordinate component reveals systematic errors, that is, systematic differences between the navigation positions and the truth values:

- $\overline{\Delta East} = \frac{\sum \Delta East_i}{n}$ for $i = 1 \dots n$, where n is the number of data points.
- $\overline{\Delta North} = \frac{\sum \Delta North_i}{n}$ for $i = 1 \dots n$, where n is the number of data points.
- $\overline{\Delta Height} = \frac{\sum \Delta Height_i}{n}$ for $i = 1 \dots n$, where n is the number of data points.

We also compute the standard deviation for each coordinate over each campaign period. These KPIs describe the precision of the computed positions, that is, their variability ignoring if they have systematic errors or not:

- $StDev\_WestEast = \sqrt{\frac{\sum (\Delta East_i - \overline{\Delta East})^2}{n-1}}$ for $i = 1 \dots n$, where n is the number of data points.
- $StDev\_SouthNorth = \sqrt{\frac{\sum (\Delta North_i - \overline{\Delta North})^2}{n-1}}$ for $i = 1 \dots n$, where n is the number of data points.
- $StDev\_Height = \sqrt{\frac{\sum (\Delta Height_i - \overline{\Delta Height})^2}{n-1}}$ for $i = 1 \dots n$, where n is the number of data points.

6.5 Results

6.5.1 Service availability

Service availability is in this document defined as the percentage of fixed solutions with respect to the total number of navigation positions.

Table 2: Service availability [%]

Area type / Service & Receiver type	1) Country road, little vegetation	2) Country road, forest	3) Motorway	4) Urban
HyPos-SSRZ Full configuration Teria PYX	88	87	68	14
HyPos-SSRZ Medium configuration Teria PYX	30	32	53	17
HyPos-SSRZ Minimum configuration Teria PYX	22	30	36	3
CPOS Trimble R10	87	85	73	73
HyPos-SPARTN Full configuration u-blox F9P	64	75	65	52
HyPos-SPARTN Medium configuration u-blox F9P	57	68	68	46
HyPos-SPARTN Minimum configuration u-blox F9P	37	32	8	3
CPOS u-blox F9P	96	96	92	80
PointPerfect u-blox F9P	87	93	77	96 [2]
HyPos-Ericsson Full configuration u-blox F9P	17	29		
HyPos-Ericsson Medium configuration u-blox F9P	19	43		
HyPos-Ericsson Minimum configuration u-blox F9P				48

[2] This data set only includes the small urban areas of Hønefoss and Jessheim, not Oslo, where the buildings are higher on average. Therefore, the result may be overly optimistic.

We observe that the service that gives the best availability overall seems to be CPOS. As expected, the availability is in most cases lower inside urban areas than outside.

6.5.2 HPE95

The upper number of each cell in Table 3 is the number of data points that is used to calculate the KPI value. Only fixed solutions are used in the calculation. The lower number is the KPI value itself. Values significantly higher than 20 cm are written in **red bold**.

Table 3: HPE95 [meters]

Area type / Service & Receiver type	1) Country road, little vegetation	2) Country road, forest	3) Motorway	4) Urban
HyPos-SSRZ Full configuration Teria PYX	8481 0.14 m	7107 0.14 m	6398 0.14 m	1079 0.17 m
HyPos-SSRZ Medium configuration Teria PYX	2635 0.27 m	2752 0.27 m	3813 0.12 m	1578 0.10 m
HyPos-SSRZ Minimum configuration Teria PYX	1965 0.21 m	2392 0.12 m	2467 **1.07 m**	204 0.26 m
CPOS Trimble R10	20657 0.07 m	18583 0.06 m	15170 0.06 m	13658 0.13 m
HyPos-SPARTN Full configuration u-blox F9P	6203 **0.83 m**	6181 **0.87 m**	4358 0.08 m	3944 0.19 m
HyPos-SPARTN Medium configuration u-blox F9P	4953 0.18 m	5774 0.15 m	4904 0.15 m	4270 **0.73 m**
HyPos-SPARTN Minimum configuration u-blox F9P	3202 **0.67 m**	2626 **0.76 m**	579 0.93 m	176 0.09 m
CPOS u-blox F9P	26056 0.06 m	23754 0.05 m	19407 0.08 m	18986 0.07 m
PointPerfect u-blox F9P	18050 0.13 m	16967 0.11 m	13048 0.19 m	1276 0.19 m
HyPos-Ericsson Full configuration u-blox F9P	594 0.13 m	696 0.13 m		
HyPos-Ericsson Medium configuration u-blox F9P	425 0.23 m	1200 0.19 m		
HyPos-Ericsson Minimum configuration u-blox F9P				1835 0.14 m

6.5.3 Average coordinate errors (coordinate biases)

The upper number of each cell in Table 4 is the number of data points that is used to calculate the KPI value. Only fixed solutions are used in the calculation. The lower numbers are the values for the KPIs $\overline{\Delta North}$ and $\overline{\Delta East}$, respectively. N = North direction (negative value means that the coordinates are biased to the south). E = East direction (negative values means that the coordinates are biased to the west).

Table 4: Average horizontal coordinate errors [meters]

Area type / Service & Receiver type	1) Country road, little vegetation	2) Country road, forest	3) Motorway	4) Urban
HyPos-SSRZ Full configuration Teria PYX	8481 0.018 m N -0.063 m E	7107 0.016 m N -0.060 m E	6398 0.021 m N 0.007 m E	1079 0.015 m N -0.087 m E
HyPos-SSRZ Medium configuration Teria PYX	2635 0.059 m N -0.086 m E	2752 0.039 m N -0.082 m E	3813 0.016 m N -0.055 m E	1578 0.000 m N -0.064 m E
HyPos-SSRZ Minimum configuration Teria PYX	1965 0.022 m N -0.062 m E	2392 0.031 m N -0.054 m E	2467 0.112 m N -0.006 m E	204 0.119 m N -0.064 m E
CPOS Trimble R10	20657 -0.005 m N 0.004 m E	18583 -0.002 m N 0.003 m E	15170 -0.003 m N 0.003 m E	13658 0.003 m N 0.003 m E
HyPos-SPARTN Full configuration u-blox F9P	6203 0.024 m N 0.044 m E	6181 -0.024 m N -0.053 m E	4358 0.016 m N 0.007 m E	3944 0.005 m N -0.009 m E
HyPos-SPARTN Medium configuration u-blox F9P	4953 0.051 m N -0.023 m E	5774 0.049 m N -0.029 m E	4904 0.045 m N -0.047 m E	4270 0.014 m N -0.020 m E
HyPos-SPARTN Minimum configuration u-blox F9P	3202 0.105 m N 0.078 m E	2626 0.095 m N -0.014 m E	579 0.214 m N 0.066 m E	176 0.007 m N 0.066 m E
CPOS u-blox F9P	26056 -0.023 m N -0.006 m E	23754 -0.011 m N 0.000 m E	19407 -0.005 m N 0.003 m E	18986 0.001 m N 0.004 m E
PointPerfect u-blox F9P	18050 -0.008 m N 0.009 m E	16967 -0.001 m N 0.007 m E	13048 -0.016 m N 0.003 m E	1276 0.058 m N -0.018 m E
HyPos-Ericsson Full configuration u-blox F9P	594 0.028 m N -0.000 m E	696 0.039 m N -0.002 m E		
HyPos-Ericsson Medium configuration u-blox F9P	425 0.015 m N -0.025 m E	1200 0.074 m N 0.083 m E		
HyPos-Ericsson Minimum configuration u-blox F9P				1835 -0.013 m N 0.009 m E

Under ideal circumstances, we would expect these biases to be a couple of centimeters or smaller. However, missing antenna calibration corrections, multipath and incorrect ambiguity resolution may lead to higher numbers than that. The CPOS__TrimbleR10 option, which uses a high-end geodetic GNSS antenna, and for which the number of data points is large for all four area types, have small (sub-centimeter) coordinate biases. For HyPos-SSPZ__TeriaPYX, the biases are larger (almost consistently to the west by several centimeters). We have no experience with the Teria PYX receiver and antenna before the HyPos project. Therefore, there may horizontal antenna offsets that we have not managed to account for. However, since the driving direction is changing almost constantly (uncorrected horizontal antenna offsets are then likely mitigated), the problem seems to be related to the service or the receiver processing. An example of a potentially relevant topic is the handling of coordinate reference systems in the service or in the receiver. The biases can also be caused by unknown errors on our own side which we are as of now unable to identify.

The u-blox antennas are very different from the high-end ones (Trimble, Teria). We must assume that the phase center in such an antenna is much less well-defined and less stable. Therefore, we both expect higher biases (ref. this chapter) and higher noise (ref. chapter 6.5.4) for the navigation options using u-blox receivers and antennas. On the other hand, the biases for CPOS__ublox are mostly quite small, and the amount of data is high in that option. So it might be that the biases for the HyPos-SPARTN options using u-blox receivers could have been smaller if the numbers of data points were higher.

6.5.4 Standard deviations

The upper number of each cell in Table 4 is the number of data points that is used to calculate the KPI value. Only fixed solutions are used in the calculation. The lower numbers are the values for the KPIs $StDev\_SouthNorth$ and $StDev\_WestEast$, respectively. SN = South/North direction. WE = West/East direction.

Table 5: Coordinate standard deviations [m]

Area type / Service & Receiver type	1) Country road, little vegetation	2) Country road, forest	3) Motorway	4) Urban
HyPos-SSRZ Full configuration Teria PYX	8481 0.117 m SN 0.095 m WE	7107 0.338 m SN 0.238 m WE	6398 0.351 m SN 0.109 m WE	1079 0.162 m SN 0.050 m WE
HyPos-SSRZ Medium configuration Teria PYX	2635 0.062 m SN 0.064 m WE	2752 0.054 m SN 0.049 m WE	3813 0.121 m SN 0.285 m WE	1578 0.022 m SN 0.027 m WE
HyPos-SSRZ Minimum configuration Teria PYX	1965 0.381 m SN 0.136 m WE	2392 0.041 m SN 0.044 m WE	2467 0.213 m SN 0.167 m WE	204 0.049 m SN 0.026 m WE
CPOS Trimble R10	20657 0.045 m SN 0.029 m WE	18583 0.046 m SN 0.049 WE	15170 0.048 m SN 0.061 m WE	13658 0.084 m SN 0.060 m WE
HyPos-SPARTN Full configuration u-blox F9P	6203 0.137 m SN 0.232 m WE	6181 0.180 m SN 0.261 m WE	4358 0.108 m SN 0.082 m WE	3944 0.164 m SN 0.063 m WE
HyPos-SPARTN Medium configuration u-blox F9P	4953 0.065 m SN 0.071 m WE	5774 0.050 m SN 0.049 m WE	4904 0.041 m SN 0.069 m WE	4270 0.247 m SN 0.204 m WE
HyPos-SPARTN Minimum configuration u-blox F9P	3202 0.162 m SN 0.263 m WE	2626 0.106 m SN 0.154 m WE	579 0.255 m SN 0.259 m WE	176 0.025 m SN 0.017 m WE
CPOS u-blox F9P	26056 0.262 m SN 0.172 m WE	23754 0.164 m SN 0.110 m WE	19407 0.031 m SN 0.031 m WE	18986 0.049 m SN 0.056 m WE
PointPerfect u-blox F9P	18050 0.058 m SN 0.051 m WE	16967 0.049 m SN 0.036 m WE	13048 0.061 m SN 0.057 m WE	1276 0.058 m SN 0.062 m WE
HyPos-Ericsson Full configuration u-blox F9P	594 0.063 m SN 0.029 m WE	696 0.050 m SN 0.037 m WE		
HyPos-Ericsson Medium configuration u-blox F9P	425 0.106 m SN 0.044 m WE	1200 0.066 m SN 0.085 m WE		
HyPos-Ericsson Minimum configuration u-blox F9P				1835 0.066 m SN 0.041 m WE

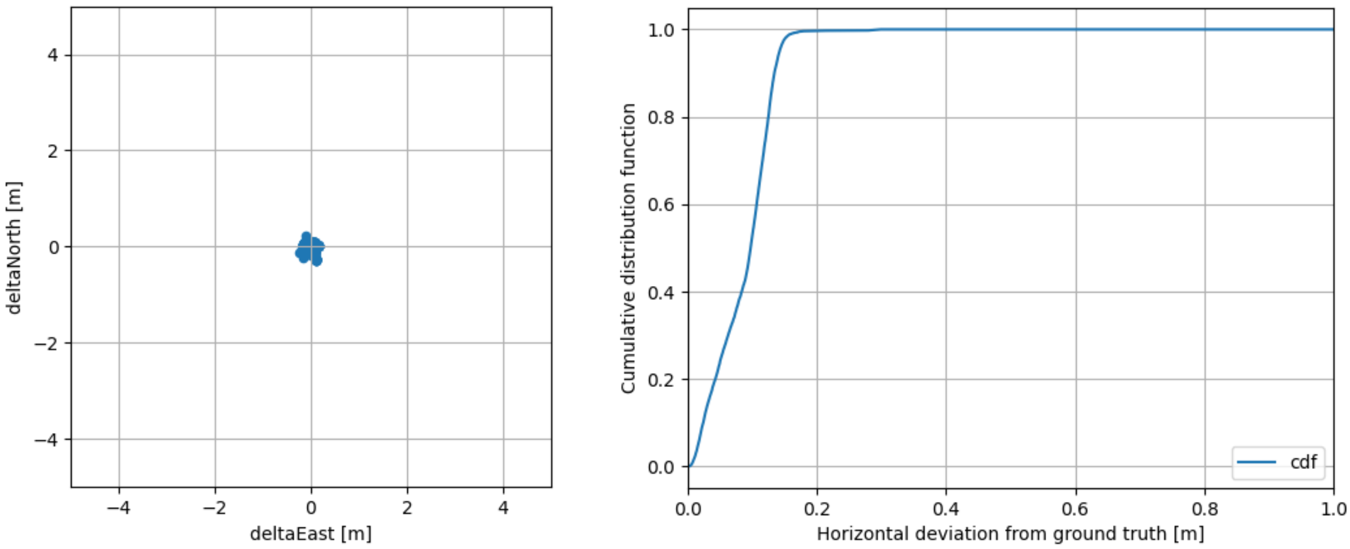
6.5.5 Plots for each service

In this chapter, we present two plots for each service / reference station configuration / receiver variant / area type. The plot to the left is a scatter plot that plots the horizontal position error components ΔNorth and ΔEast vs. each other. The plot to the right shows the cumulative distribution function for the horizontal position errors ΔHorizontal, that is, how large portion (between 0 and 1) of positions have a horizontal error less than or equal to the function value. Where the graph crosses the value 0.95 on the y-axis, the HPE95 (ref. chapter 6.5.2) can be found on the x-axis. The x-axis is cut off at ΔHorizontal = 1 m, even though there are values higher than 1 m in several cases.

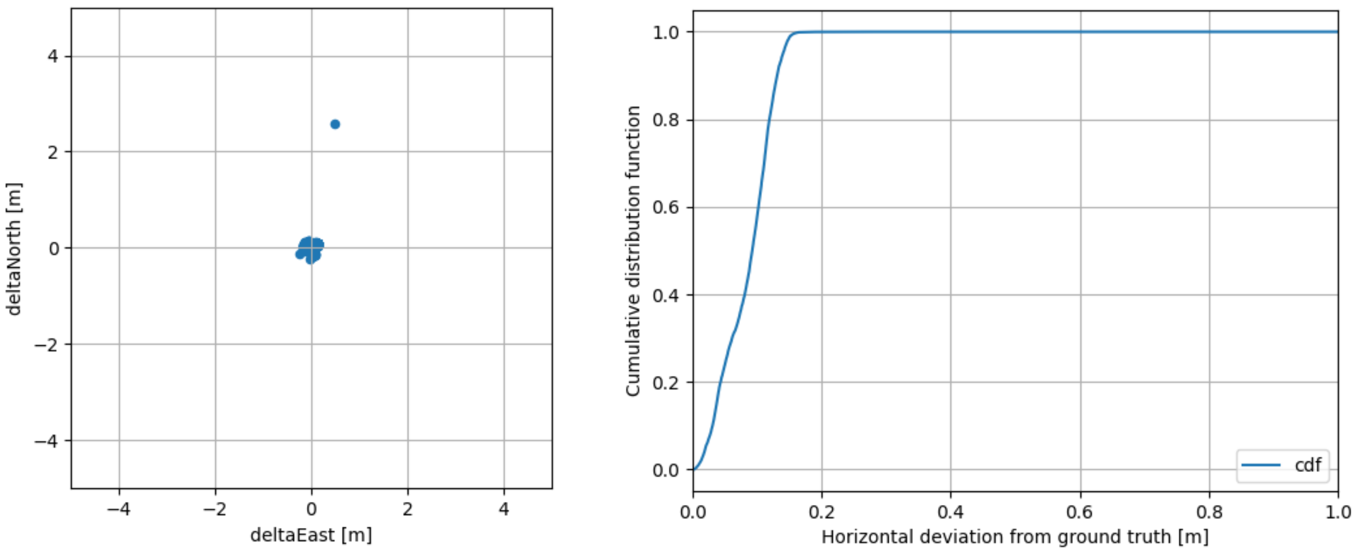
Both plots only contain fixed solutions. The number of fixed solutions, followed by a fractional line "/", then the total number of computed positions and the resulting service availability percentage are shown in each case. So are also the HPE95 value and the maximum HPE value, both in the unit meters.

6.5.5.1 HyPos-SSRZ__TeriaPYX, full reference station configuration

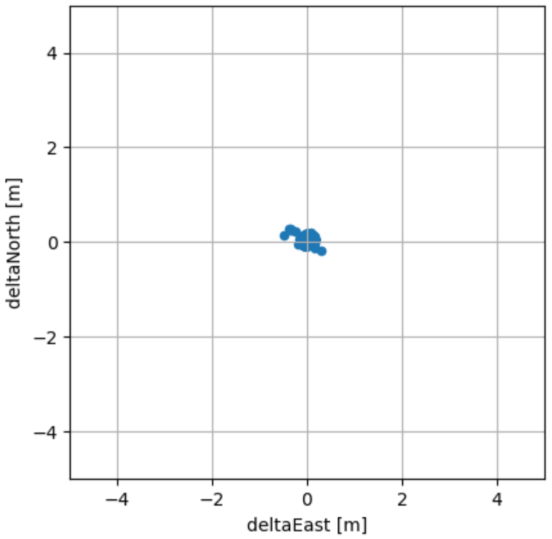
6.5.5.1.1 Country road, little vegetation. 8481 / 9606 = 88 % availability. HPE95 = 0.14, HPE_max = 12.22

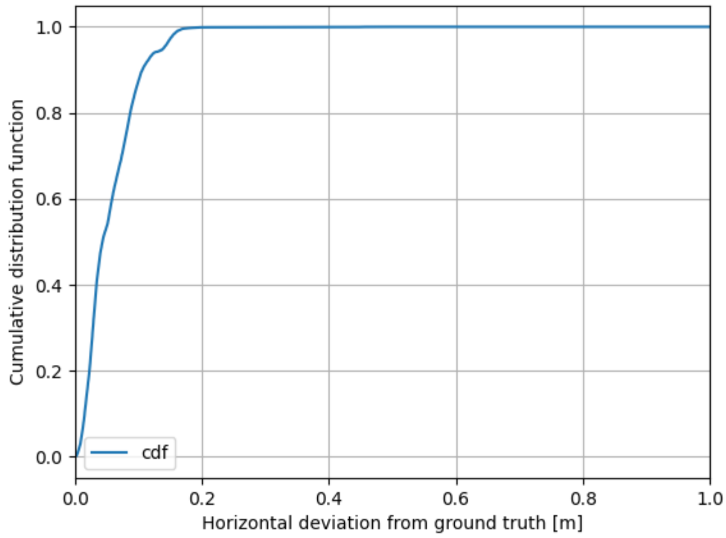


6.5.5.1.2 Country road, forest. 7107 / 8201 = 87 % availability. HPE95 = 0.14, HPE_max = 24.47

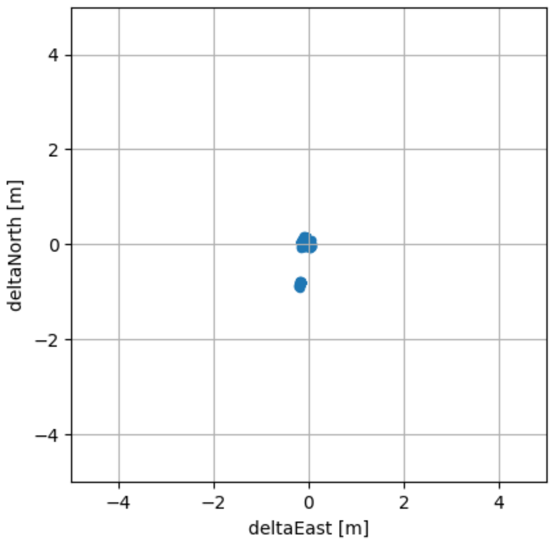


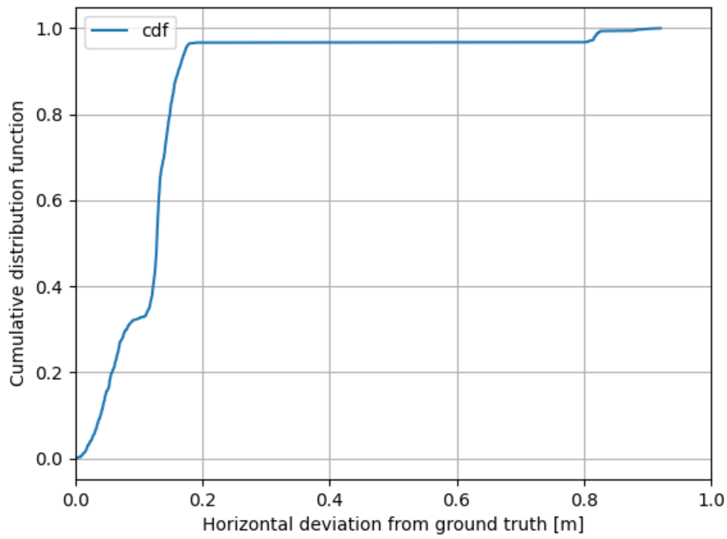
6.5.5.1.3 Motorway. 6398 / 9363 = 68 % availability. HPE95 = 0.14, HPE_max = 28.94





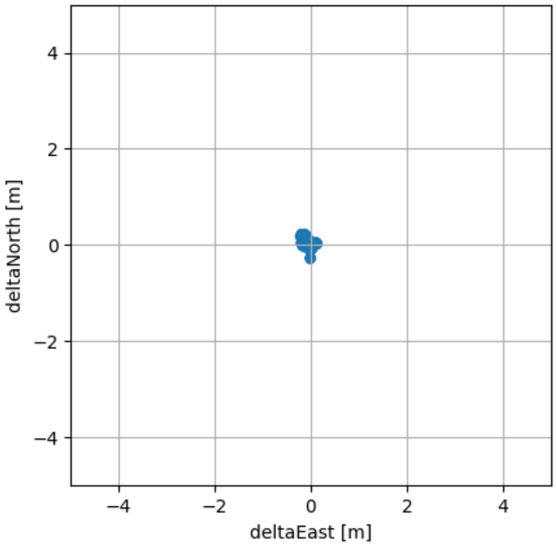
6.5.5.1.4 Urban. 1079 / 7522 = 14 % availability. HPE95 = 0.17, HPE_max = 0.92

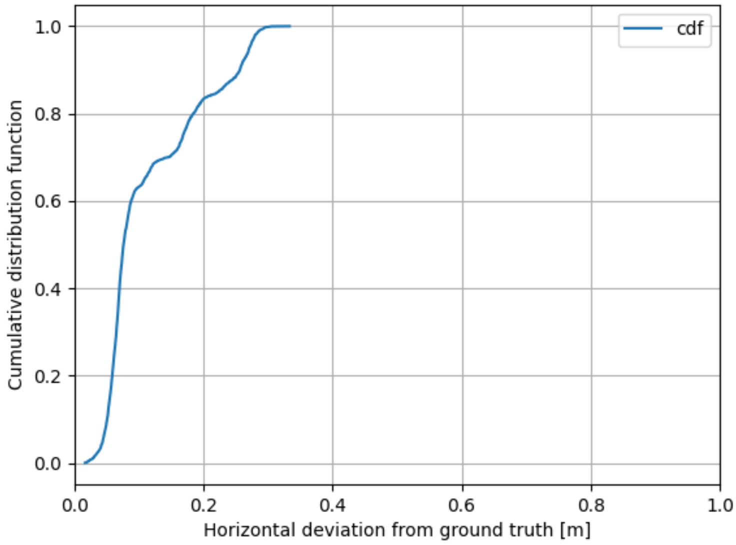




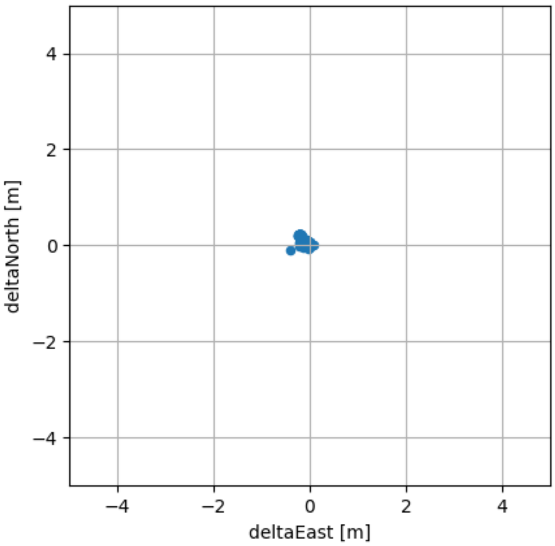
6.5.5.2 HyPos-SSRZ__TeriaPYX, medium reference station configuration

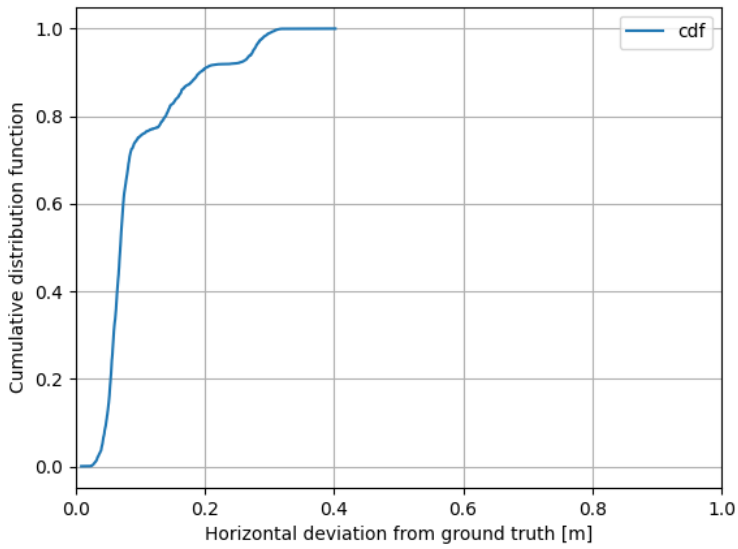
6.5.5.2.1 Country road, little vegetation. 2635 / 8713 = 30 % availability. HPE95 = 0.27, HPE_max = 0.33



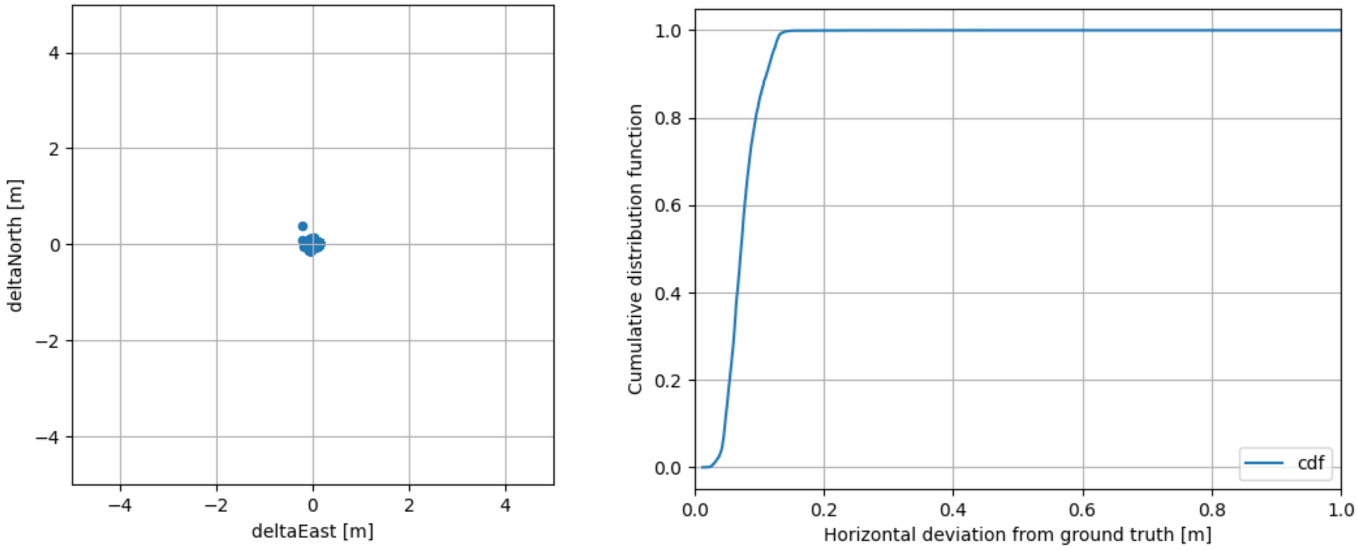


6.5.5.2.2 Country road, forest. 2752 / 8634 = 32 % availability. HPE95 = 0.27, HPE_max = 0.40

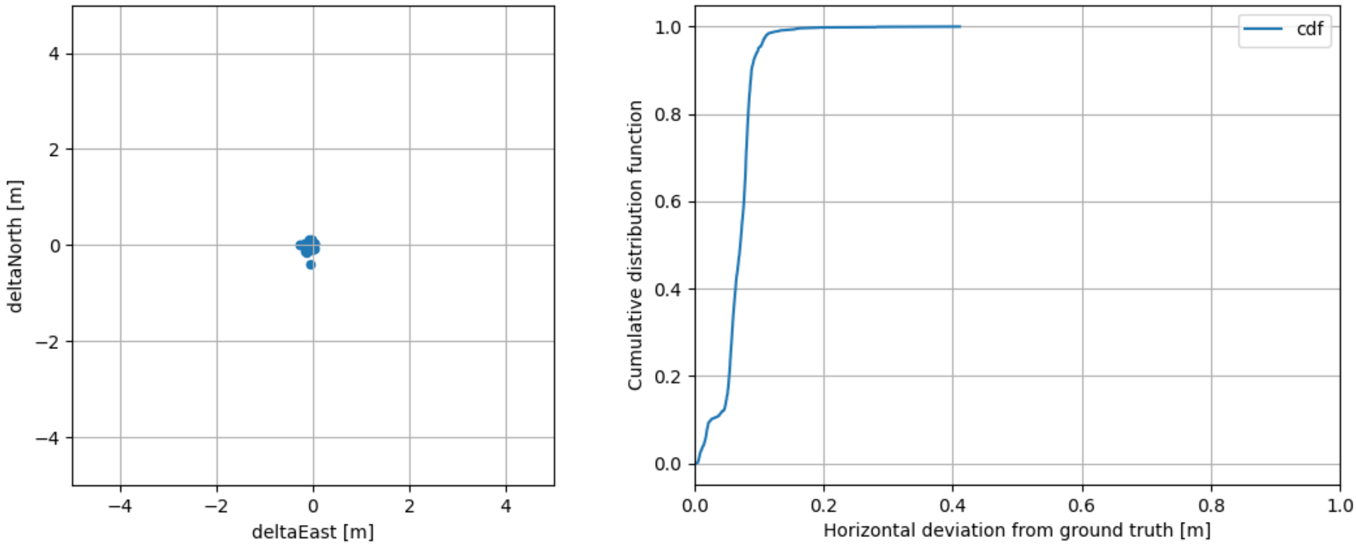




6.5.5.2.3 Motorway. 3813 / 7188 = 53 % availability. HPE95 = 0.12, HPE_max = 18.85

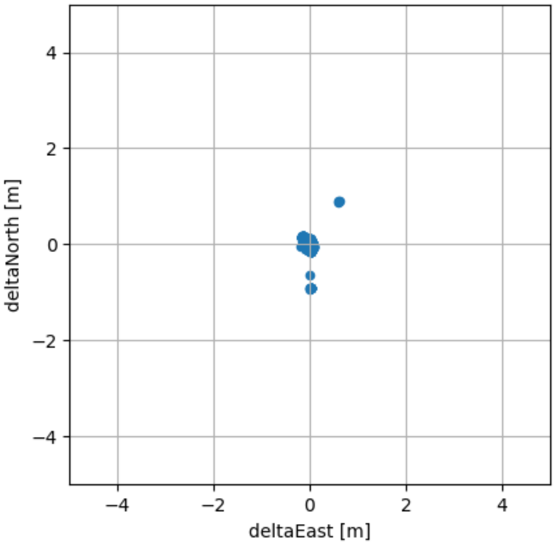


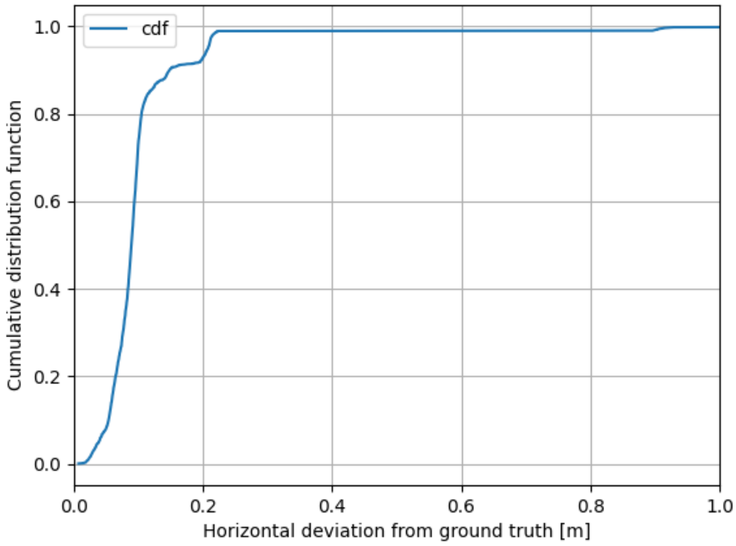
6.5.5.2.4 Urban. 1578 / 9224 = 17 % availability. HPE95 = 0.10, HPE_max = 0.41



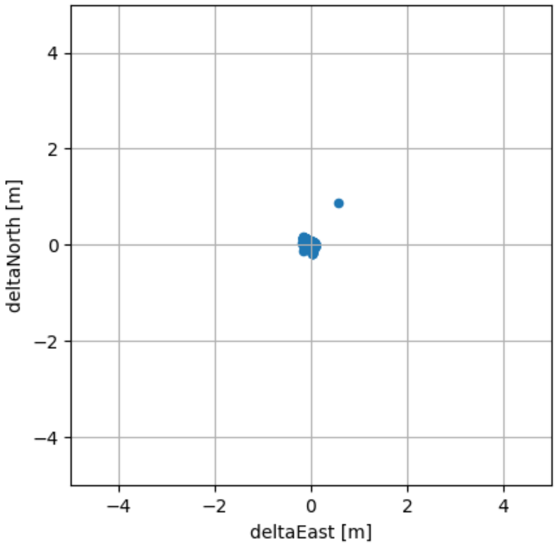
6.5.5.3 HyPos-SSRZ__TeriaPYX, minimum reference station configuration

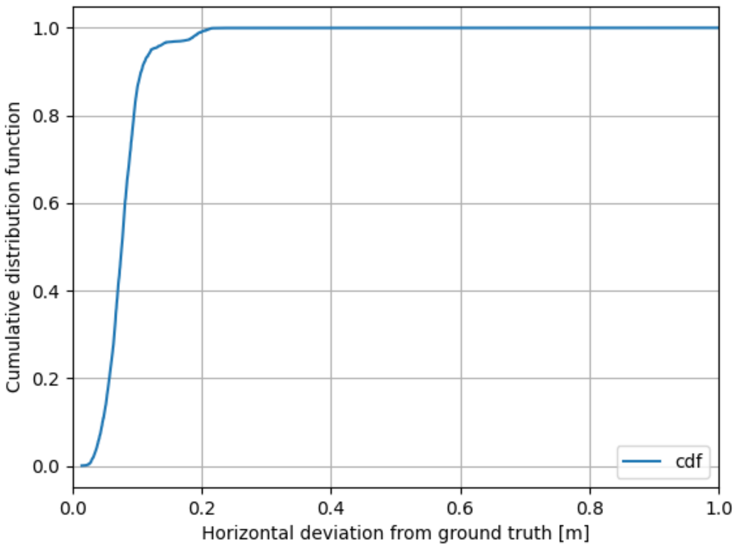
6.5.5.3.1 Country road, little vegetation. 1965 / 8773 = 22 % availability. HPE95 = 0.21, HPE_max = 17.12



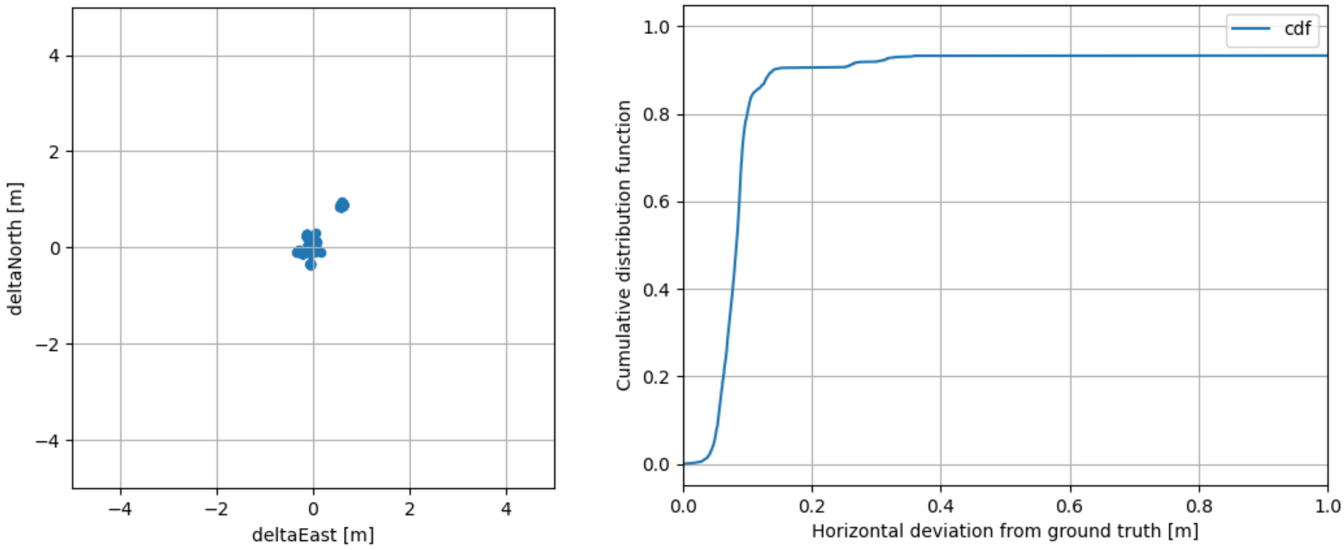


6.5.5.3.2 Country road, forest. 2392 / 8092 = 30 % availability. HPE95 = 0.12, HPE_max = 1.03

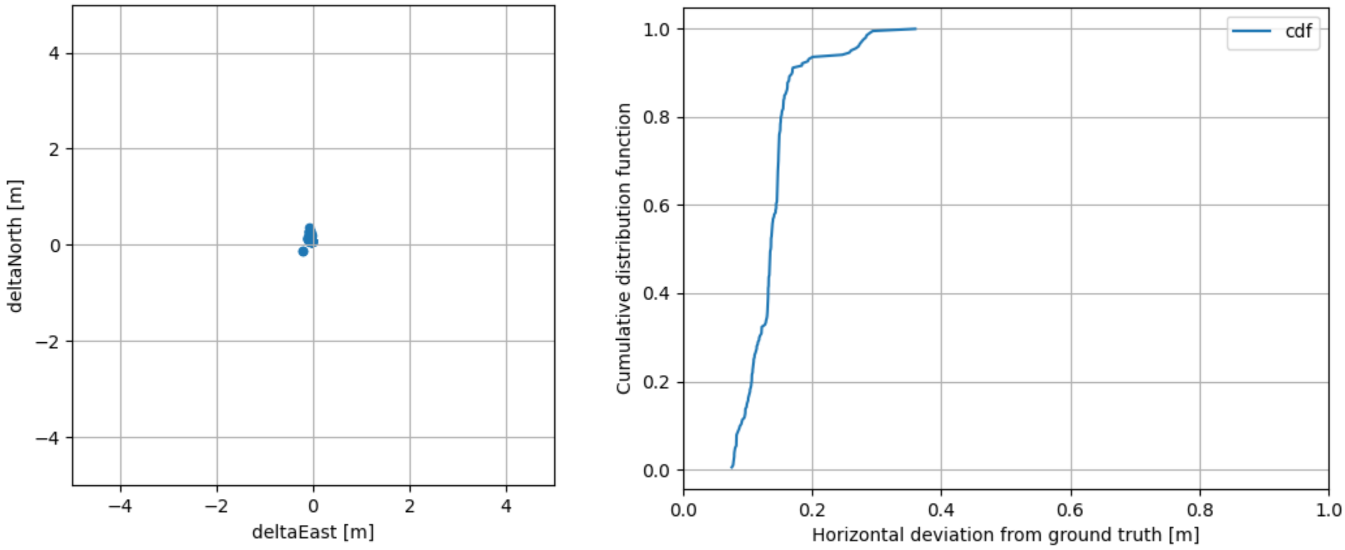




6.5.5.3.3 Motorway. 2467 / 6905 = 36 % availability. HPE95 = 1.07, HPE_max = 1.12

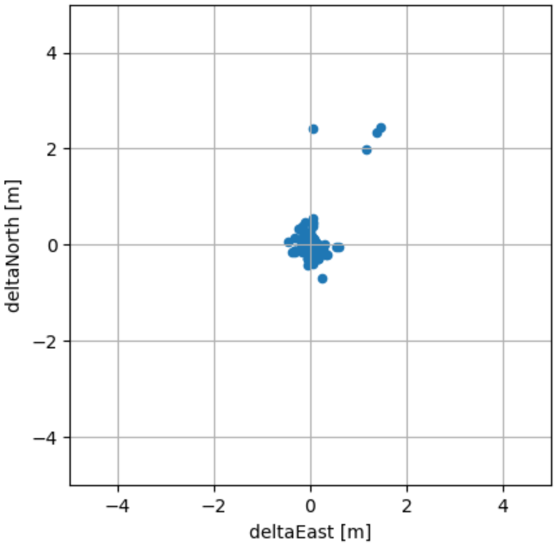


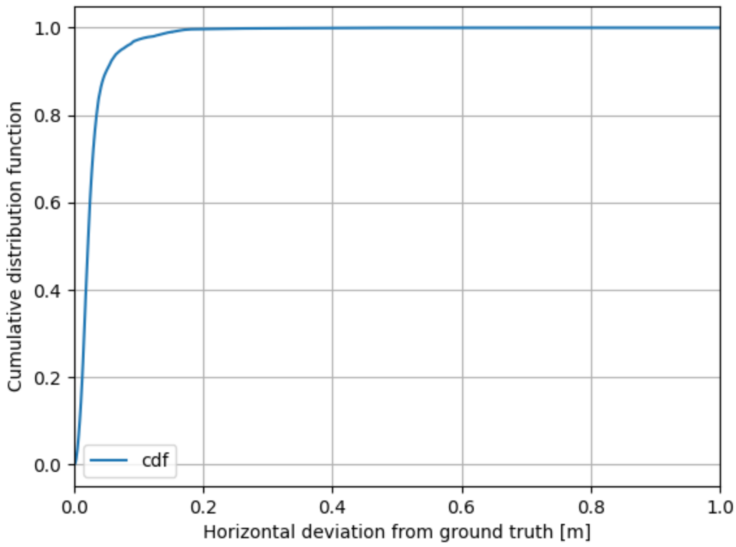
6.5.5.3.4 Urban (very little data). 204 / 6611 = 3 % availability. HPE95 = 0.26, HPE_max = 0.36



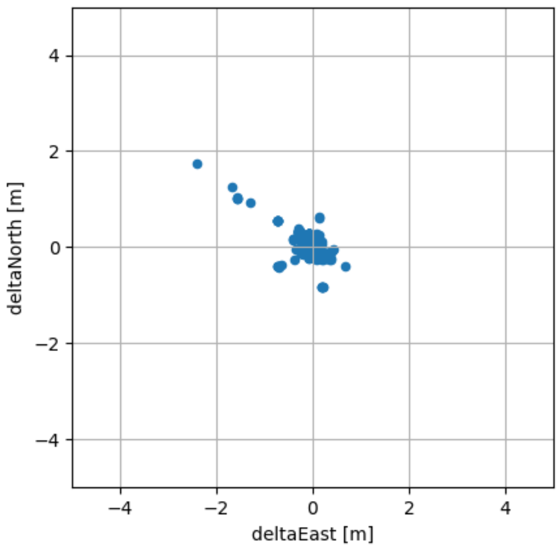
6.5.5.4 CPOS__TrimbleR10

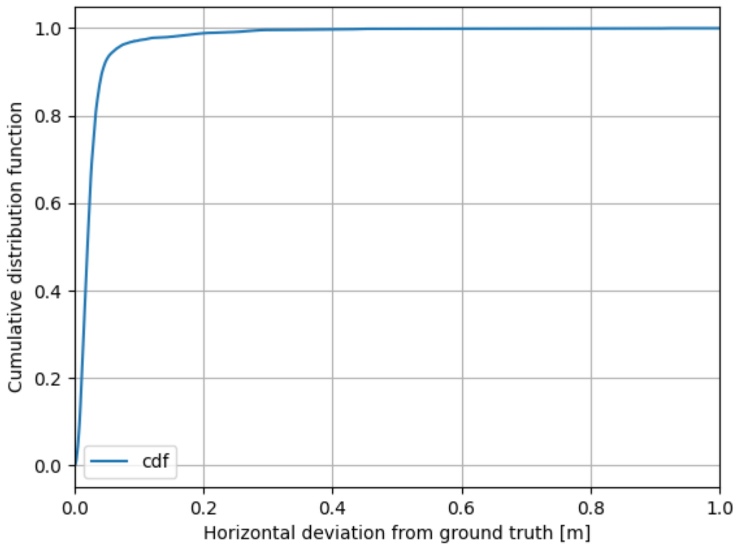
6.5.5.4.1 Country road, little vegetation. 20657 / 23768 = 87 % availability. HPE95 = 0.07, HPE_max = 2.86



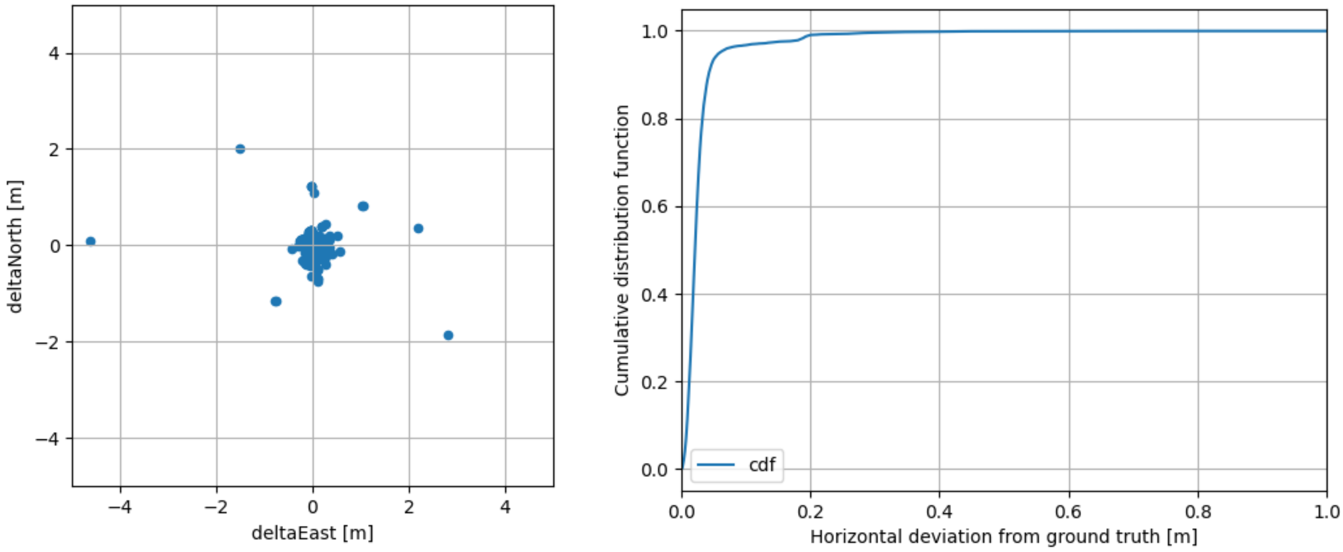


6.5.5.4.2 Country road, forest. 18583 / 21933 = 85 % availability. HPE95 = 0.06, HPE_max = 2.96

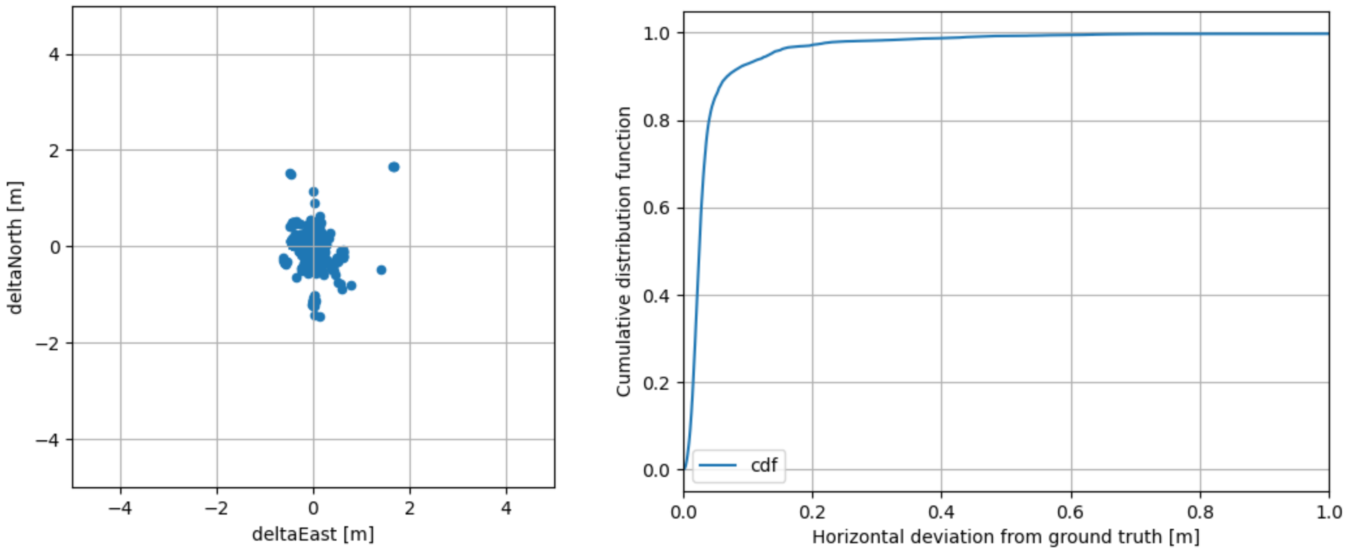




6.5.5.4.3 Motorway. 15170 / 20653 = 73 % availability. HPE95 = 0.06, HPE_max = 4.64

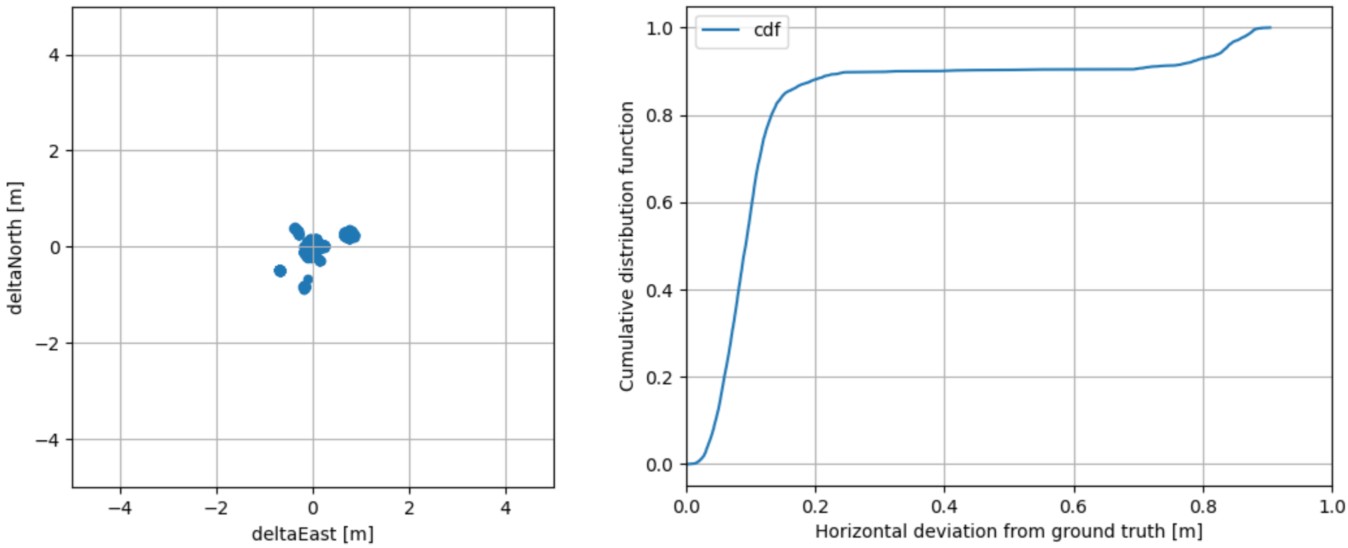


6.5.5.4.4 Urban. 13658 / 18599 = 73 % availability. HPE95 = 0.13, HPE_max = 2.36

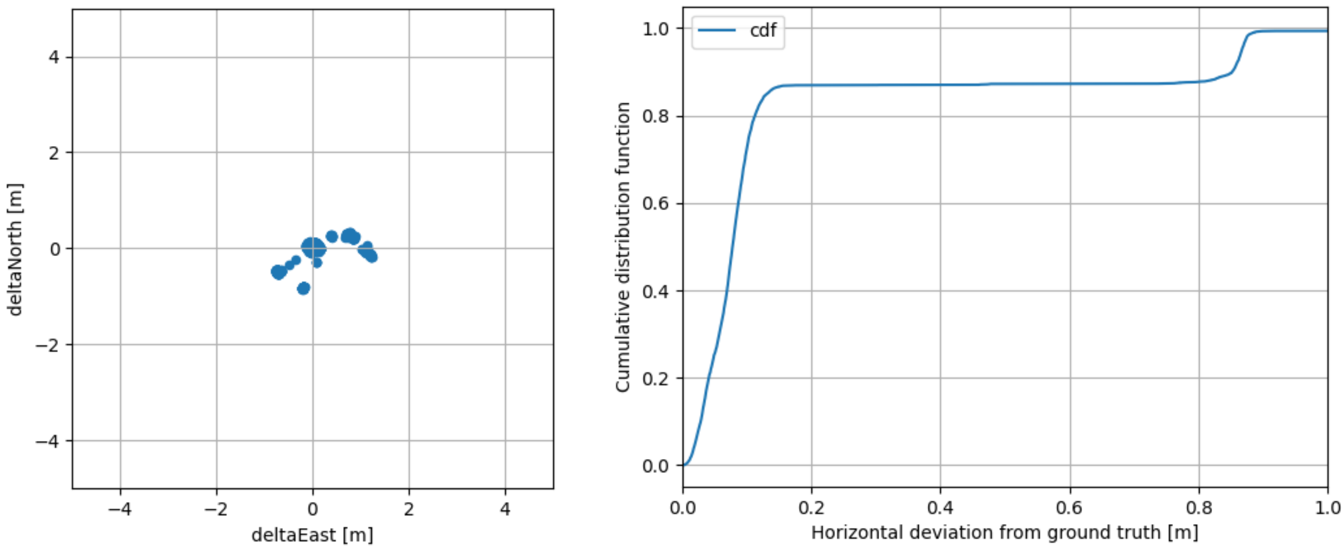


6.5.5.5 HyPos-SPARTN__ublox, full reference station configuration

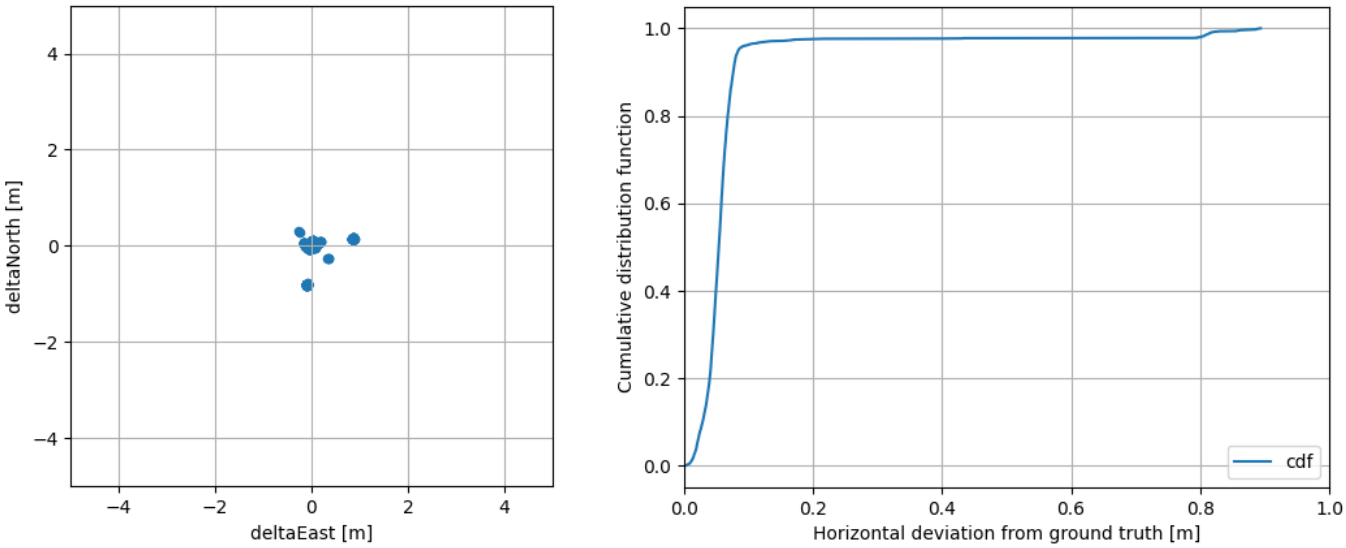
6.5.5.5.1 Country road, little vegetation. 6203 / 9602 = 64 % availability. HPE95 = 0.83, HPE_max = 0.90



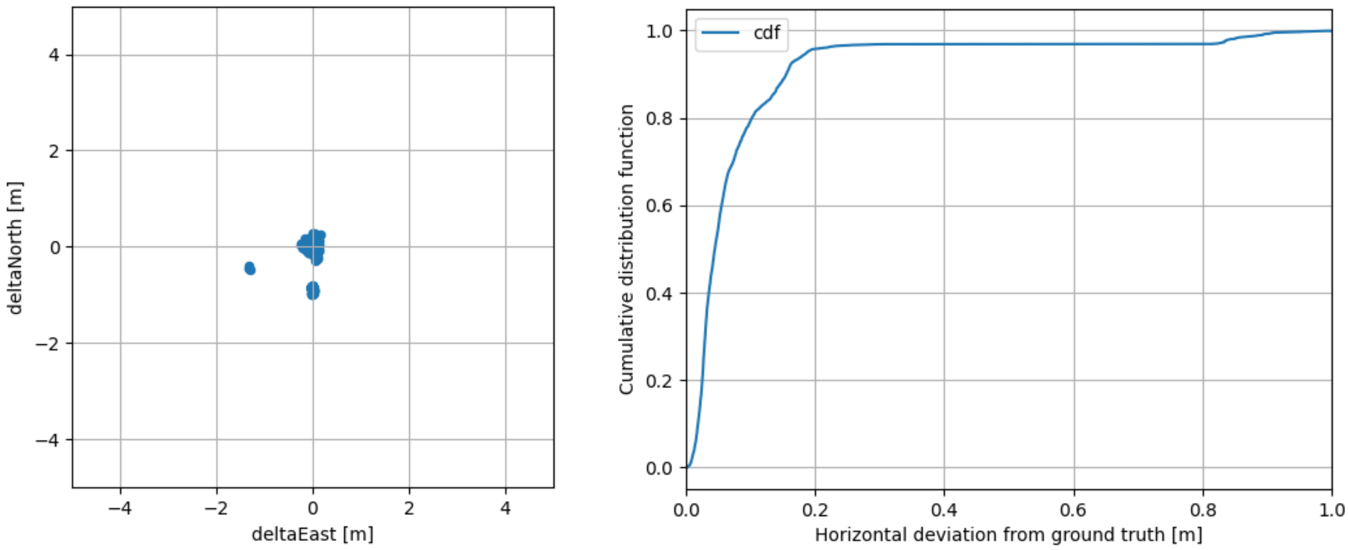
6.5.5.5.2 Country road, forest. 6181 / 8205 = 75 % availability. HPE95 = 0.87, HPE_max = 1.25



6.5.5.5.3 Motorway. 4358 / 6695 = 65 % availability. HPE95 = 0.08, HPE_max = 0.89

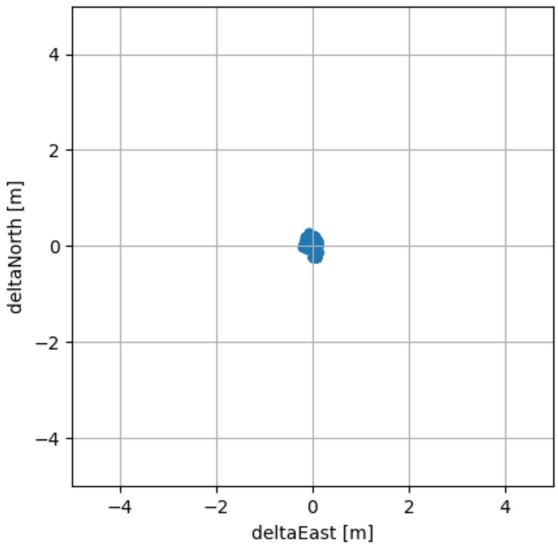


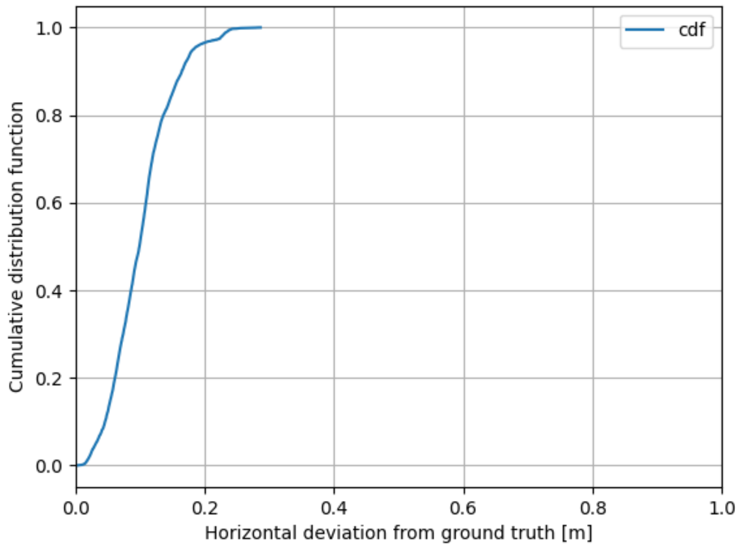
6.5.5.5.4 Urban. 3944 / 7613 = 52 % availability. HPE95 = 0.19, HPE_max = 1.40



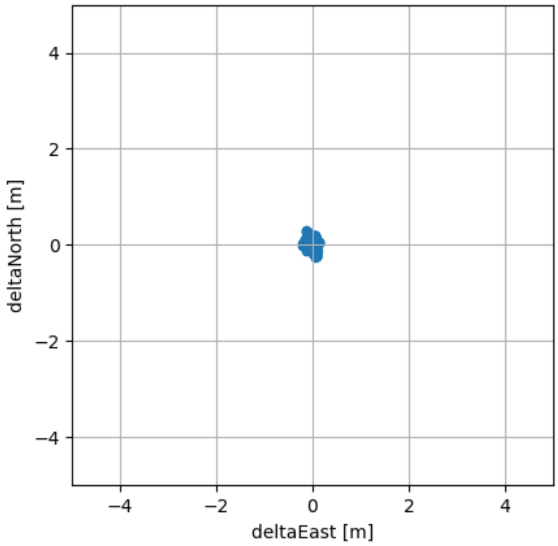
6.5.5.6 HyPos-SPARTN__ublox, medium reference station configuration

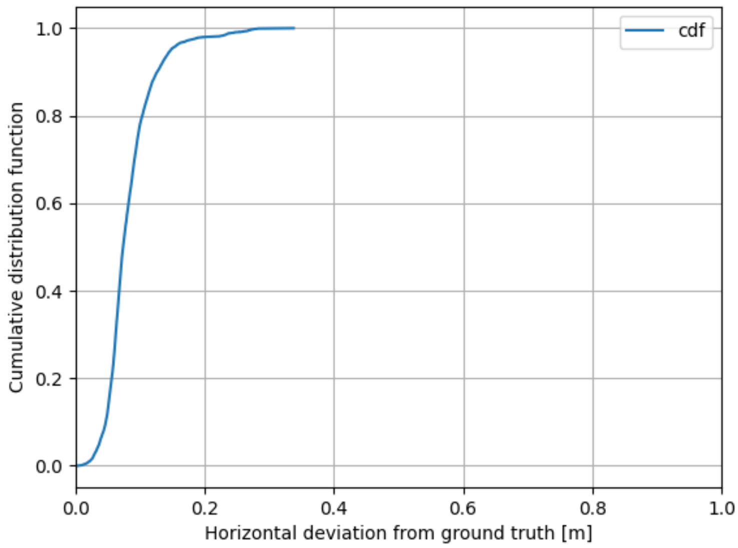
6.5.5.6.1 Country road, little vegetation. 4953 / 8694 = 57 % availability. HPE95 = 0.18, HPE_max = 0.29



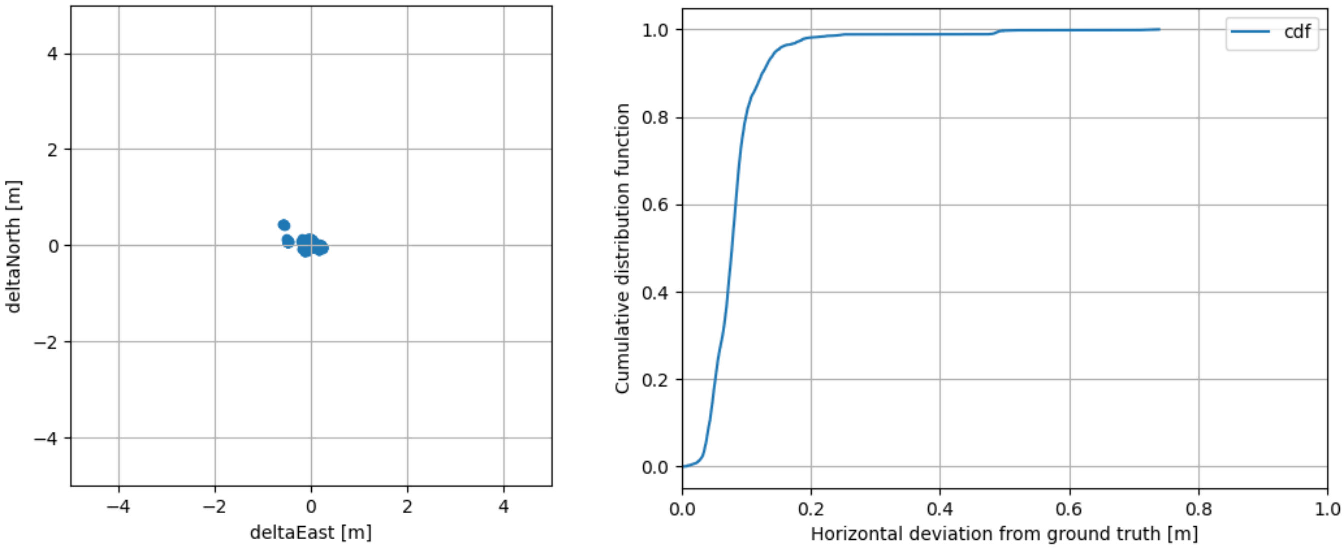


6.5.5.6.2 Country road, forest. 5774 / 8489 = 68 % availability. HPE95 = 0.15, HPE_max = 0.34

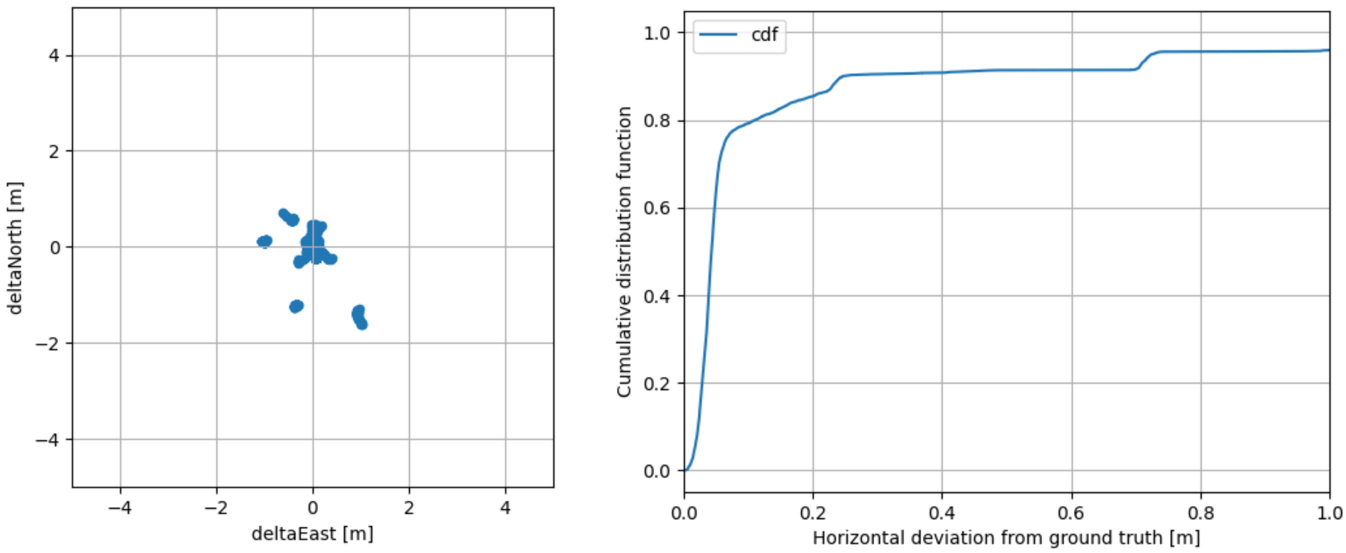




6.5.5.6.3 Motorway. 4904 / 7187 = 68 % availability. HPE95 = 0.15, HPE_max = 0.74

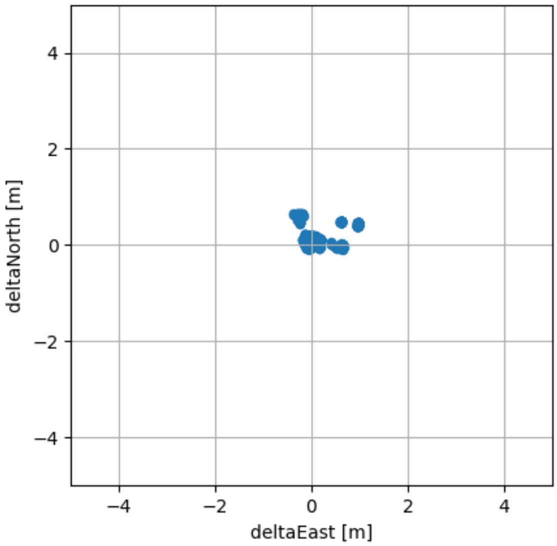


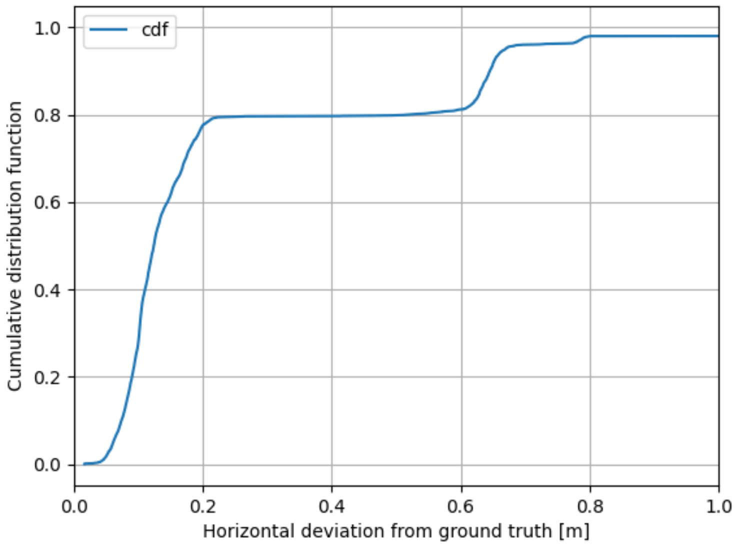
6.5.5.6.4 Urban. 4270 / 9273 = 46 % availability. HPE95 = 0.73, HPE_max = 1.91



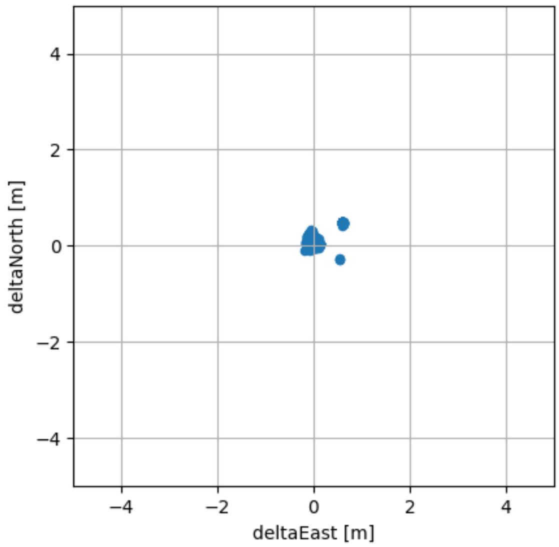
6.5.5.7 HyPos-SPARTN__ublox, minimum reference station configuration

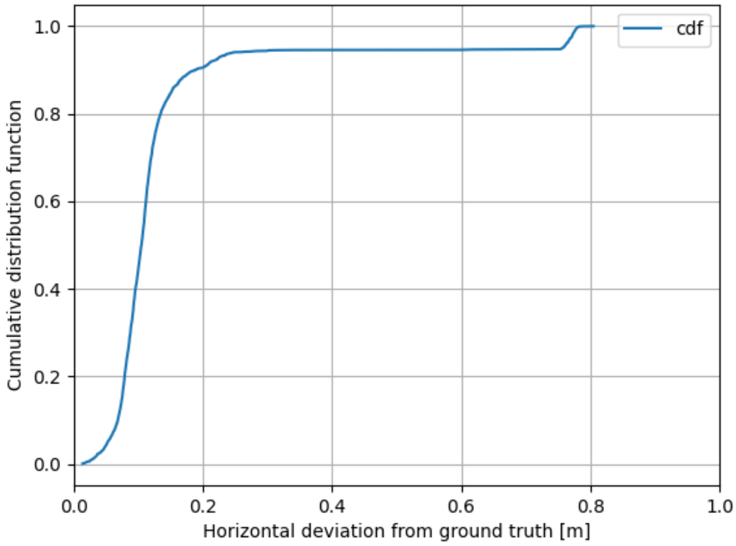
6.5.5.7.1 Country road, little vegetation. 3202 / 8758 = 37 % availability. HPE95 = 0.67, HPE_max = 1.09



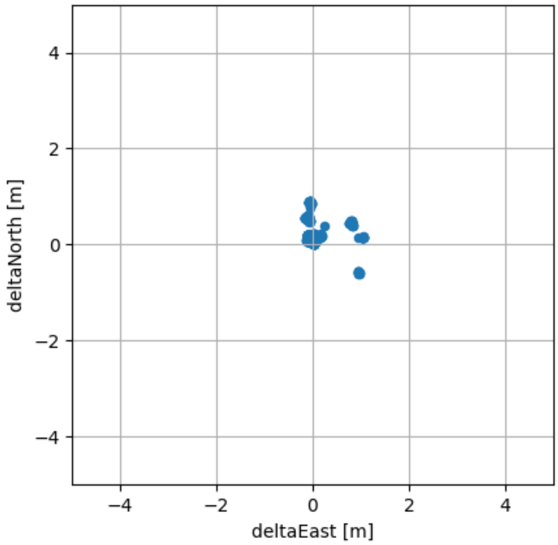


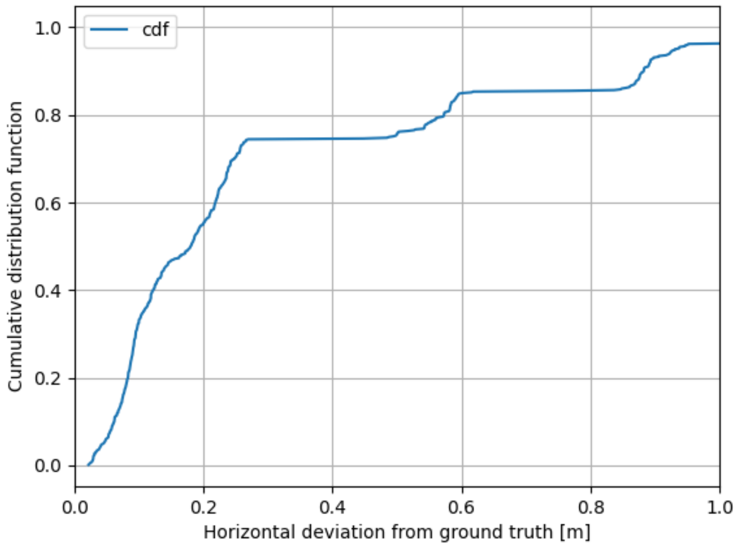
6.5.5.7.2 Country road, forest. 2626 / 8097 = 32 % availability. HPE95 = 0.76, HPE_max = 0.80



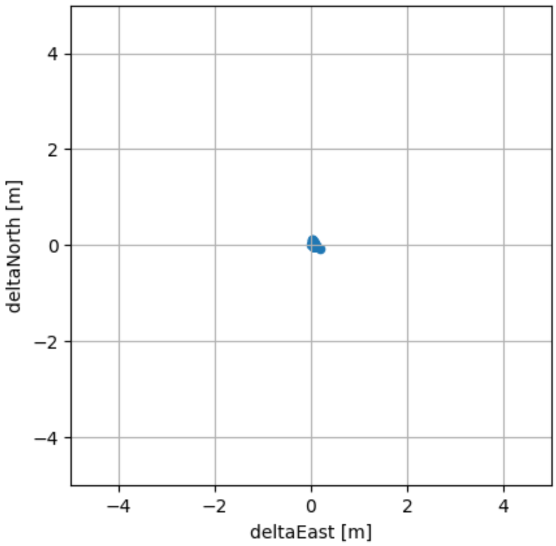


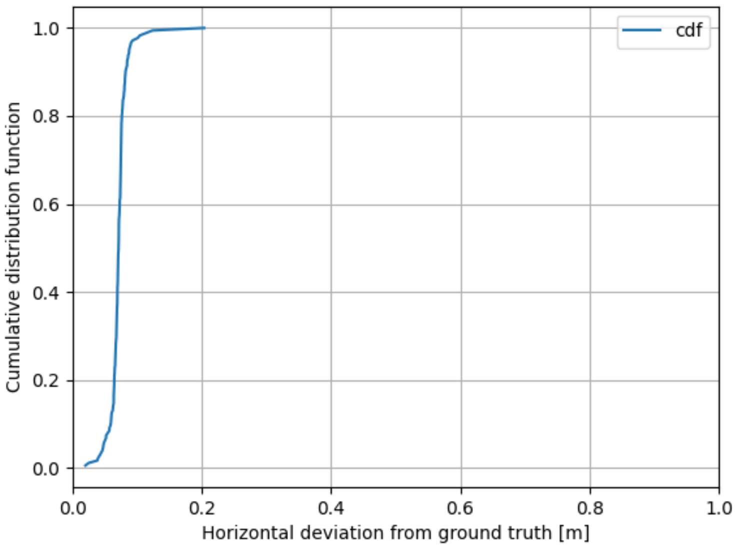
6.5.5.7.3 Motorway (<u>very little data</u>). 579 / 6901 = 8 % availability. HPE95 = 0.93, HPE_max = 1.15





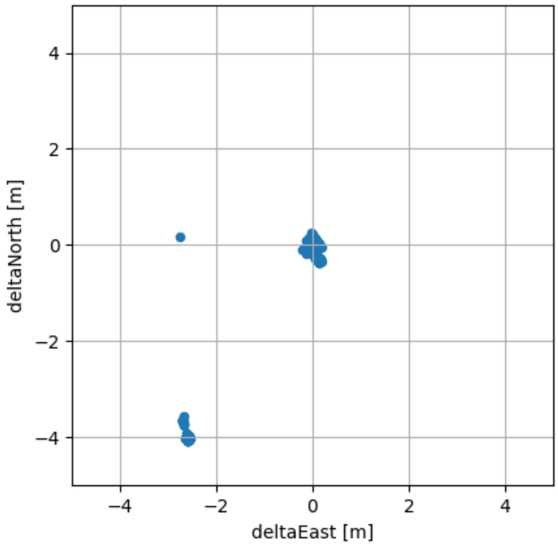
6.5.5.7.4 Urban (<u>very little data</u>). 176 / 6683 = 3 % availability. HPE95 = 0.09, HPE_max = 0.20

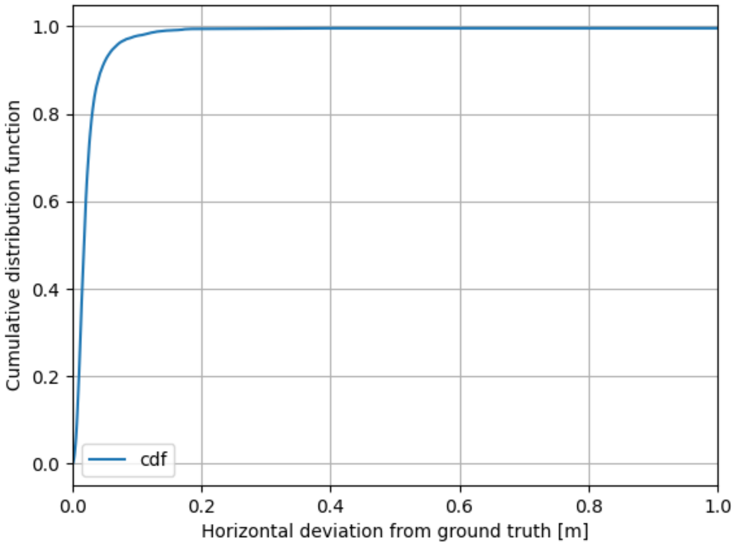




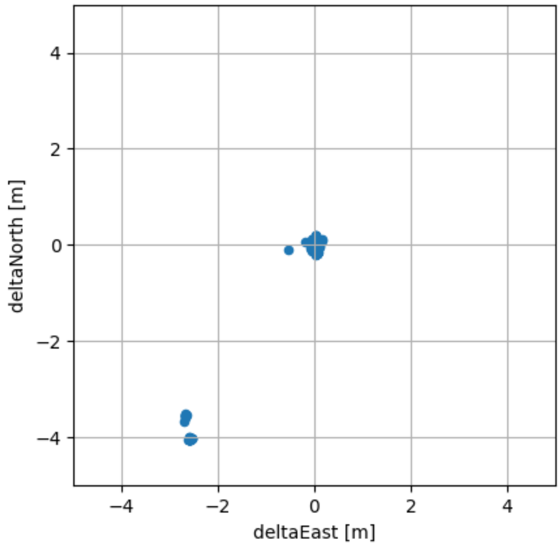
6.5.5.8 CPOS__ublox

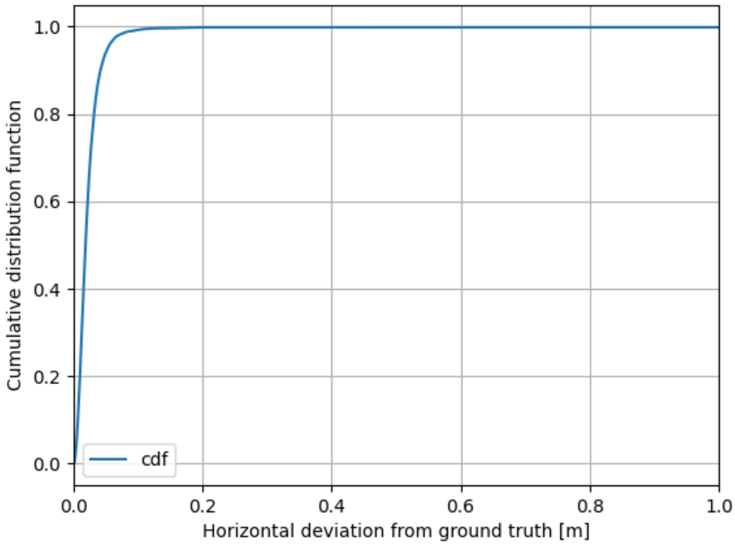
6.5.5.8.1 Country road, little vegetation. 26056 / 27112 = 96 % availability. HPE95 = 0.06, HPE_max = 4.83



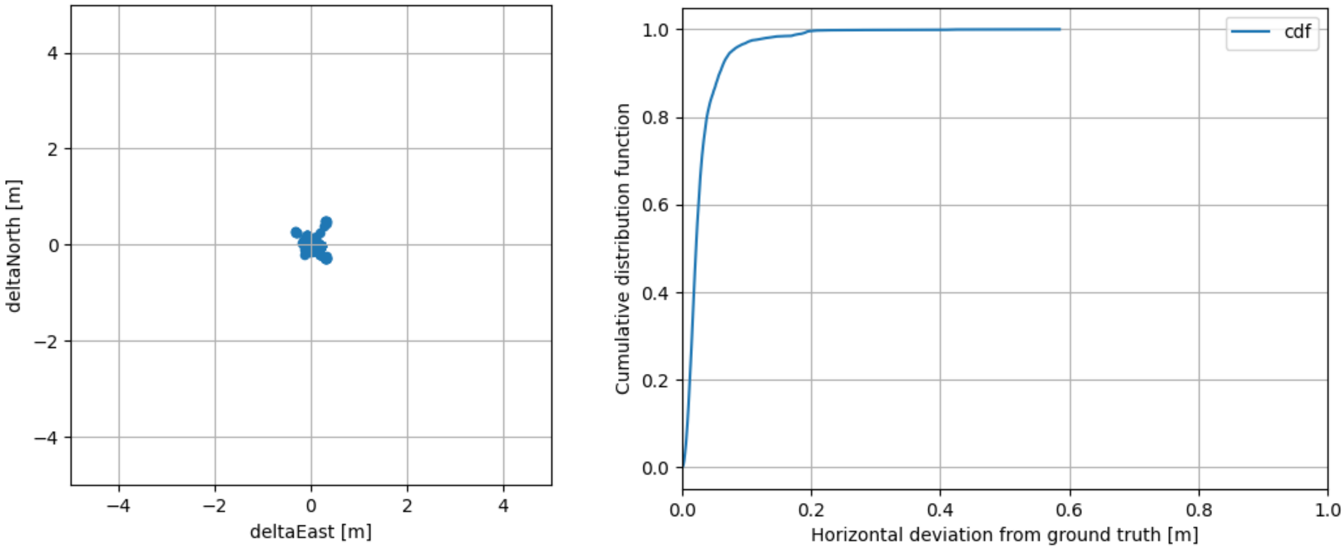


6.5.5.8.2 Country road, forest. 23754 / 24821 = 96 % availability. HPE95 = 0.05, HPE_max = 4.82

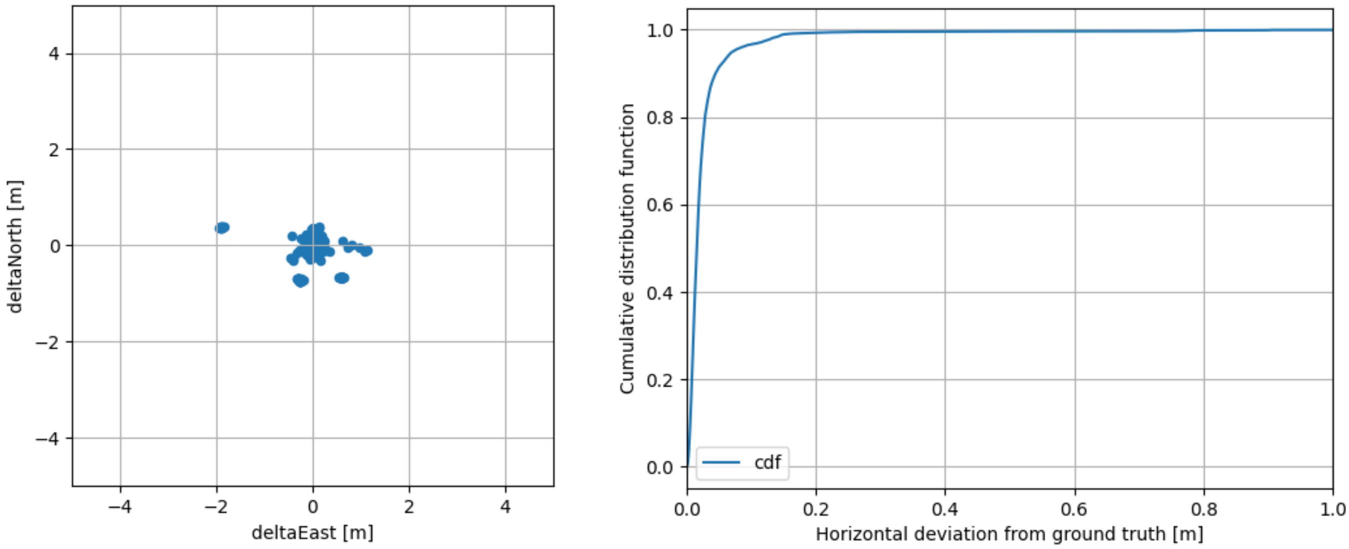




6.5.5.8.3 Motorway. 19407 / 20993 = 92 % availability. HPE95 = 0.08, HPE_max = 0.58

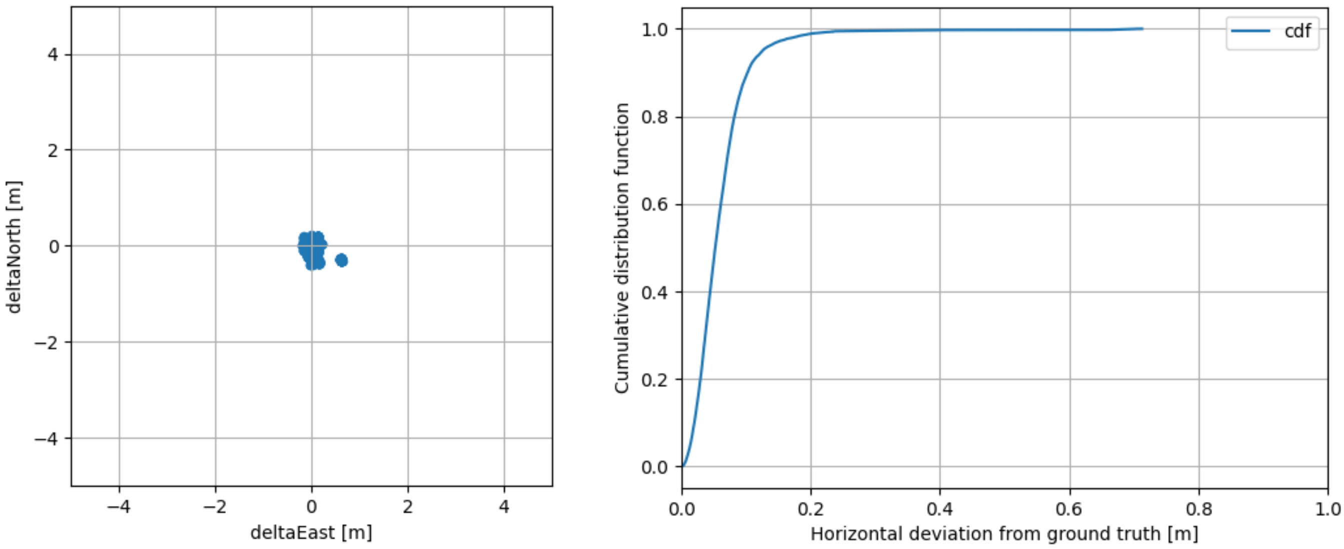


6.5.5.8.4 Urban. 18986 / 23607 = 80 % availability. HPE95 = 0.07, HPE_max = 1.98

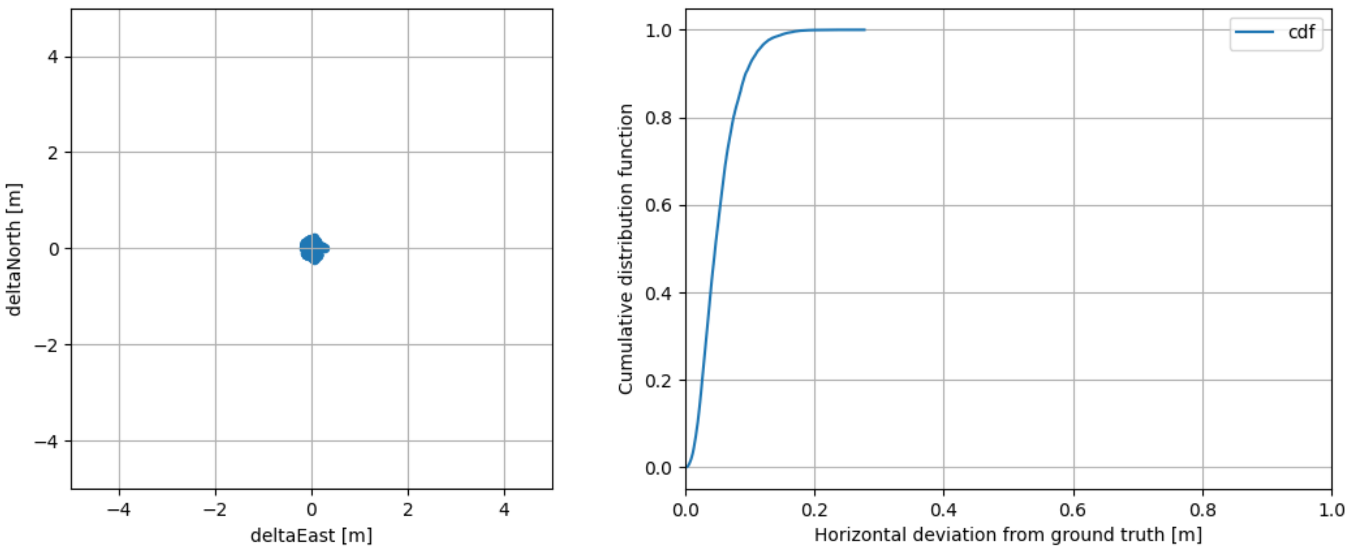


6.5.5.9 PointPerfect__ublox

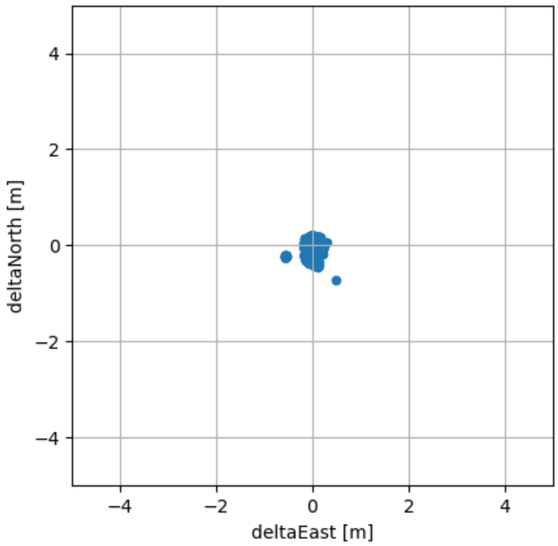
6.5.5.9.1 Country road, little vegetation. 18050 / 20642 = 87 % availability. HPE95 = 0.13, HPE_max = 0.71

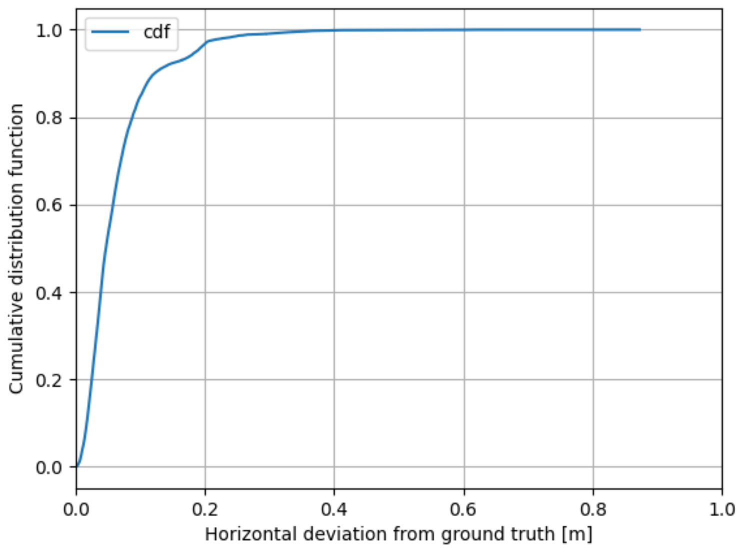


6.5.5.9.2 Country road, forest. 16967 / 18187 = 93 % availability. HPE95 = 0.11, HPE_max = 0.28

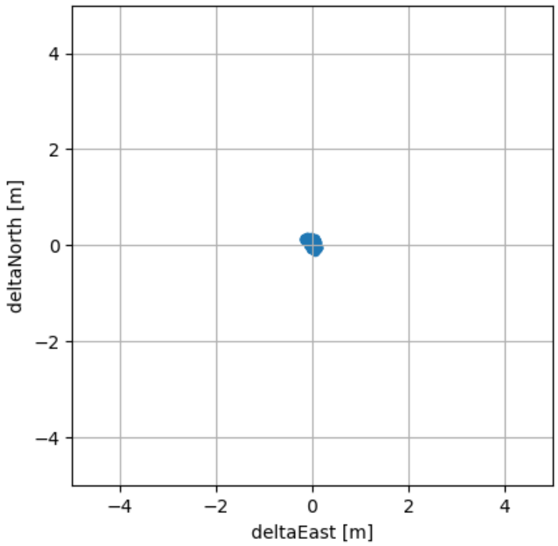


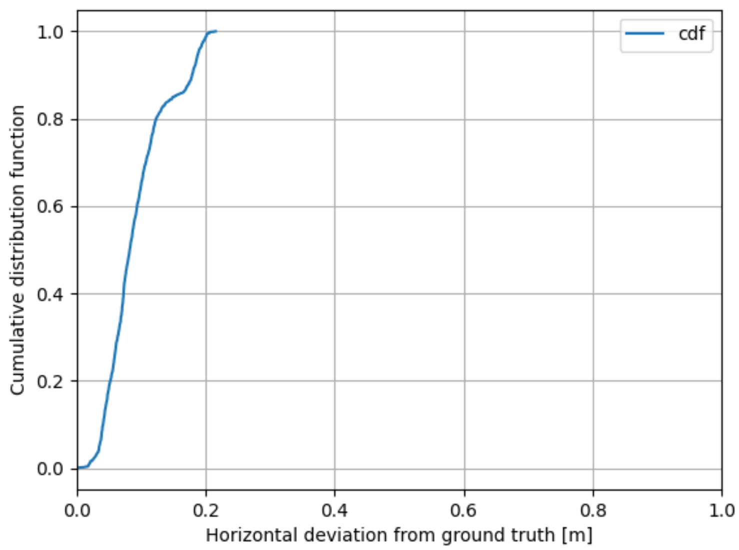
6.5.5.9.3 Motorway. 13048 / 16933 = 77 % availability. HPE95 = 0.19, HPE_max = 0.87





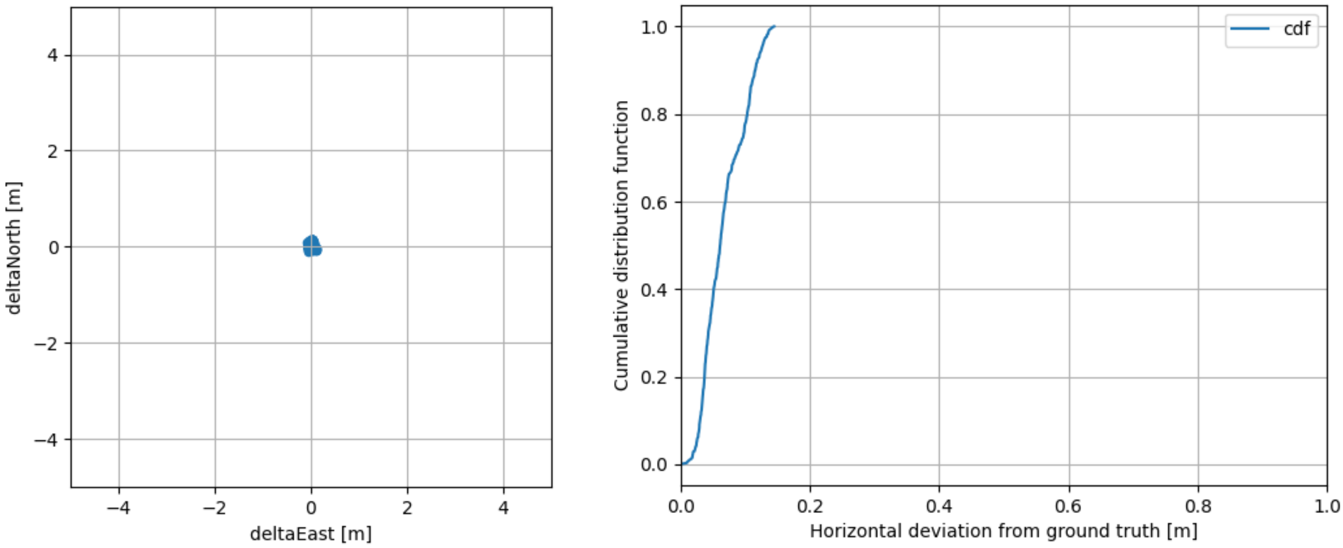
6.5.5.9.4 Urban (no data from Oslo). 1276 / 1336 = 96 % availability. HPE95 = 0.19, HPE_max = 0.22



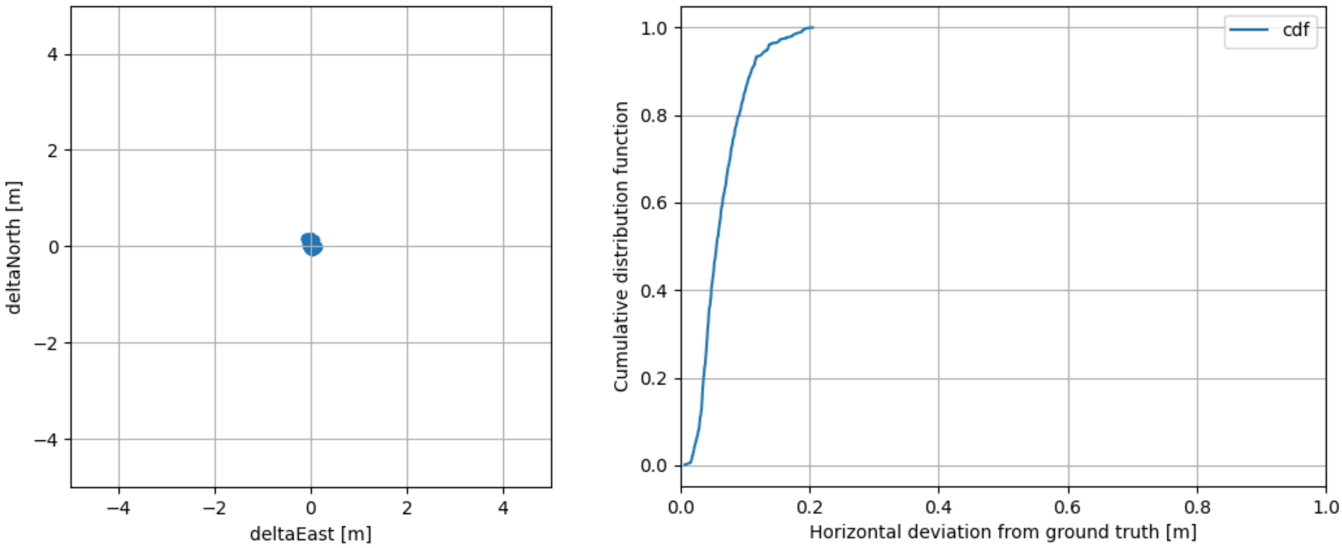


6.5.5.10 HyPos-Ericsson__ublox, full reference station configuration

6.5.5.10.1 Country road, little vegetation. 594 / 3580 = 17 % availability. HPE95 = 0.13, HPE_max = 0.14

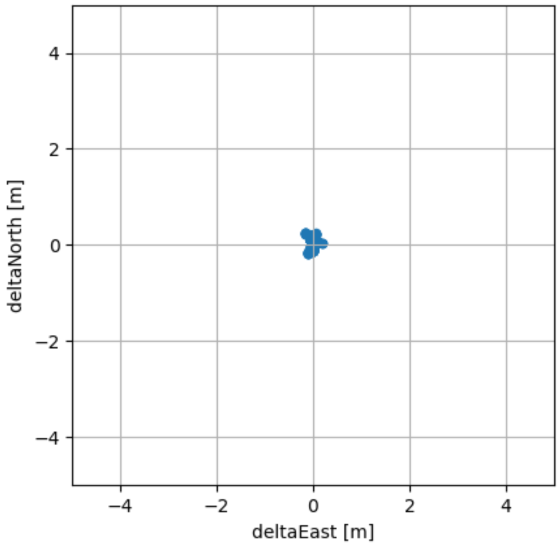


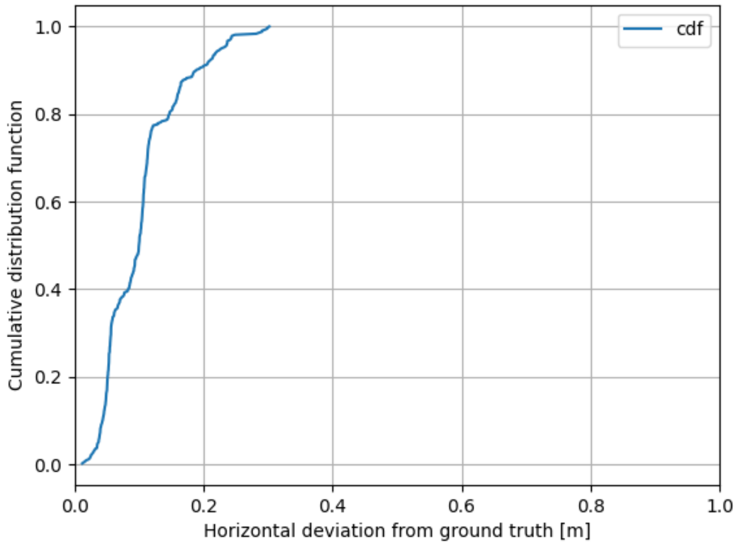
6.5.5.10.2 Country road, forest. 696 / 2420 = 29 % availability. HPE95 = 0.13, HPE_max = 0.20



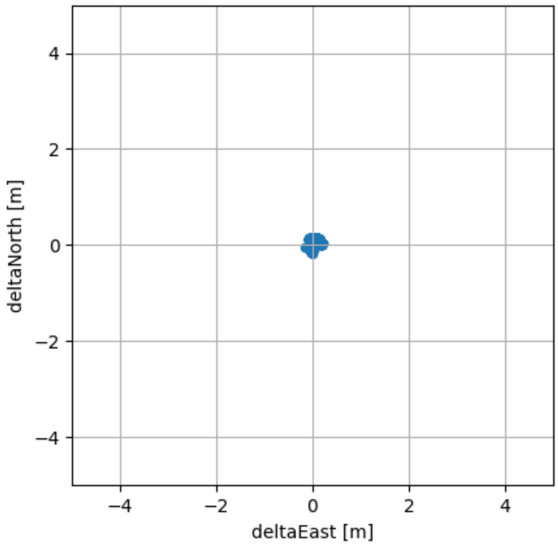
6.5.5.11 HyPos-Ericsson__ublox, medium reference station configuration

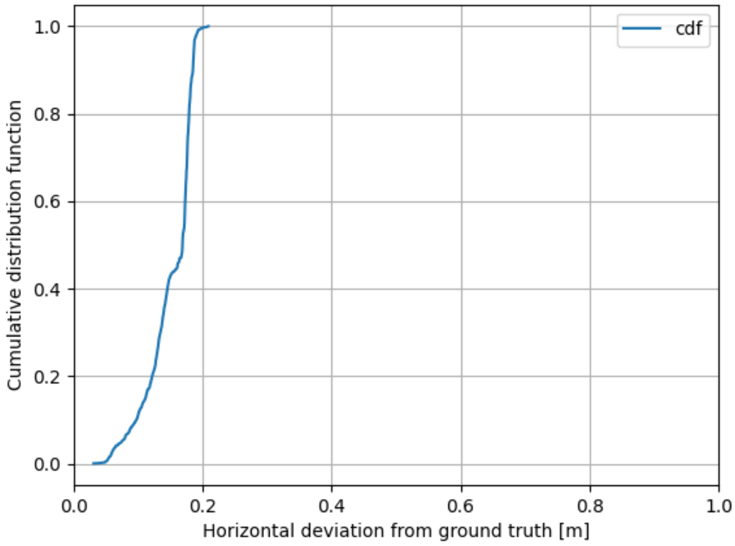
6.5.5.11.1 Country road, little vegetation. 425 / 2234 = 19 % availability. HPE95 = 0.23, HPE_max = 0.30





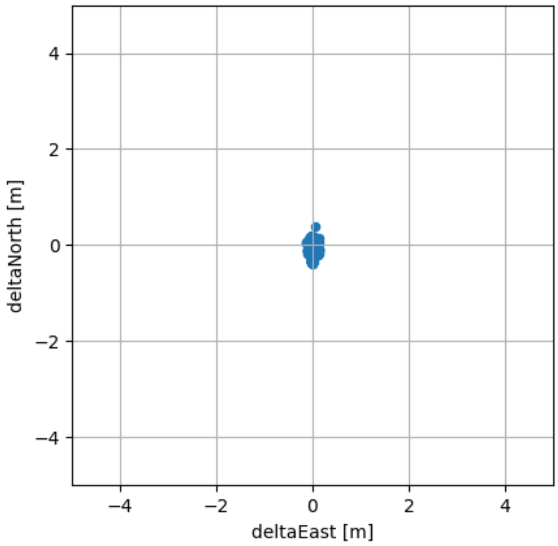
6.5.5.11.2 Country road, forest. 1200 / 2801 = 43 % availability. HPE95 = 0.19, HPE_max = 0.21

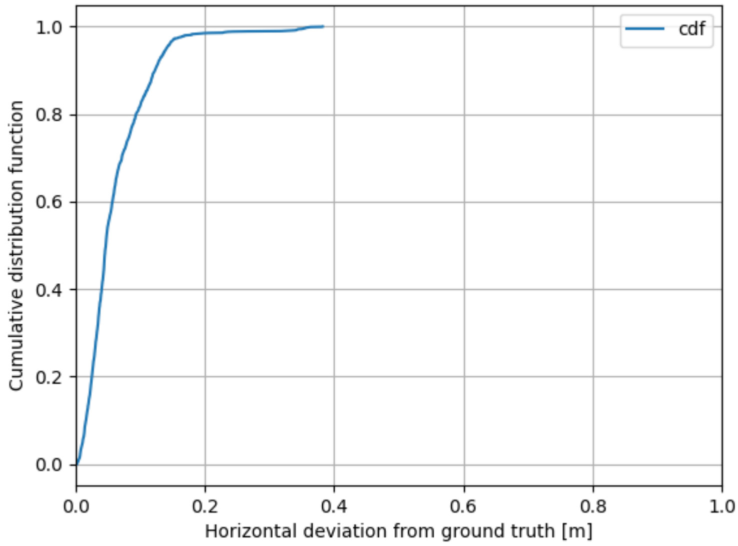




6.5.5.12 HyPos-Ericsson__ublox, minimum reference station configuration

6.5.5.12.1 Urban. 1835 / 3859 = 48 % availability. HPE95 = 0.14, HPE_max = 0.38





6.5.6 Significance of distance to closest reference station

We performed some simple checks to find out whether the distance between the user and the nearest reference station has a significant effect on the horizontal position errors in an SSR service. In northern Norway, where the spatial and temporal variation in ionospheric errors is high, the position accuracy using an OSR service is generally degraded as the distance to the closest reference station increases ([18]). The service's ability to represent the actual ionospheric and tropospheric errors between the reference stations is somewhat limited because the interpolation algorithms are not (and can never be) perfect. Unfortunately, we do not have data for southern Norway corresponding to [18]. An SSR service solves the same basic problem as an OSR service, just in another way, so basically, an SSR service will face the same nature-given problems as an OSR service. But since the technical representation of the different error sources is different, it is for us an open question whether the distance-dependent effect in an SSR service is similar to that of an OSR.

In the analysis of the data from the kinematic campaigns, we calculated the correlation coefficient between horizontal position error (ΔHorizontal, Horizontal deviation from ground truth) and the distance to the closest reference station. We also created scatter plots of the two variables vs. each other. The main conclusion is that we did not find a consistently clear correlation between these two variables in our data sets. We observe that there may be an effect for distances greater than 30 km. This is based on these two data sets:

- HyPos-SPARTN__ublox, Medium reference station configuration: Motorway
- HyPos-SPARTN__ublox, Minimum reference station configuration: Country road, forest

However, more data is needed to draw firm conclusions.

On the other hand, the mentioned correlation analysis was only made on the fixed solutions. We generally observe a worse service availability (portion of fixed solutions) for the HyPos_SSR options with Medium and Minimum reference station configuration than for the Full reference station configuration (even if there are exceptions for some area types). The reference station configuration has of course a great influence on the average distance to the closest station during a campaign driving trip. If we had included float solutions in the analyzed data sets as well, it seems likely that the correlation would be higher. But we do not know if the majority of availability loss (loss of fixed solutions) happens when the car is far away from the nearest station, or if it happens relatively close to a station. An enhanced data analysis, and possibly more data, is needed to draw clearer conclusions in this matter.

6.5.7 Examples of large position errors

6.5.7.1 Example 1: CPOS__ublox

Figure 6-3 shows an example where some positions suffer from what seems to be incorrect ambiguity resolution (ref. chapter 5.3). In the figure, positions computed on June 6th, 7th, 8th, 20th, 21st, and 22nd are shown. The ground truth positions are plotted in green color, whereas the navigation positions are plotted in violet color. For most of the days where the car was passing through the depicted area, the violet navigation position dots are hidden behind the green ground truth dots, because they agree (within centimeters or millimeters). However, on June 22nd, the navigation positions do not agree with the ground truth positions and claim that the car is outside the road (which is not the case). The horizontal position errors were here approximately 4.8 meters, and we have drawn "error vectors" as black arrows to illustrate the magnitude and direction of the position errors.

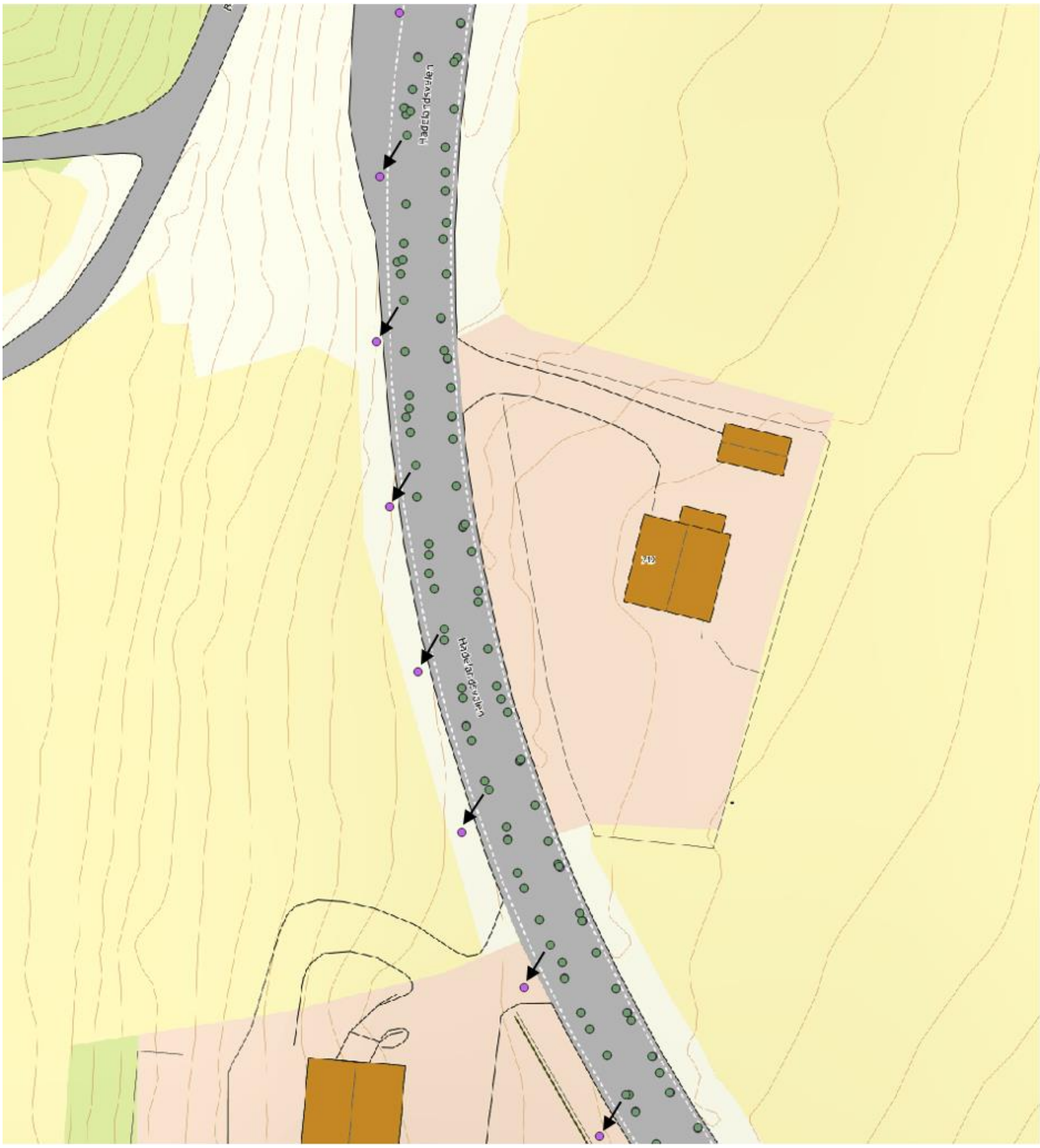


Figure 6-3: Example 1, large position errors, possibly incorrect ambiguity resolution. CPOS with u-blox F9P.

This condition lasted for about 2 minutes before fixed solution was lost and the receiver turned to float solution. For the next 2 minutes, the receiver occasionally reported fixed solution in between the float solution positions, but still the magnitude and direction of the position errors these fixed solutions were almost the same. The problem started at a location where the satellite geometry is good. The observation conditions should be quite good, too. One important note is that along- and cross-track error effect from such a condition will depend on the driving direction. In this particular case, when the position errors are constantly pointing to the south-west, the cross-track error is maximized when the car is driving towards the south-east. However, when the problem started, the road was directed so that the car was driving is towards the south-west, and then the cross-track errors are minimized while the along-track errors are maximized.

6.5.7.2 Example 2: HyPos-SPARTN__ublox, full configuration

Figure 6-4 shows another example of similar behavior as described in the previous subchapter. This example occurred on June 6th, using HyPos_SSR, full reference station configuration, with u-blox F9P receiver (corrections on SPARTN format). Ground truth positions are plotted as green dots, navigation positions as violet dots. The condition lasted for about 15 minutes (17 minutes before a correct fix solution was obtained again). The position errors had a magnitude of 0.7-0.9 m. This is much smaller than for those in Example 1, but still the situation is unwanted. The long duration of the problem highly affects the overall statistics for this navigation variant, ref. chapters 6.5.5.5.1 and 6.5.5.5.2.

Figure 6-4: Example 2, large position errors, possibly incorrect ambiguity resolution. HyPos-SPARTN, full configuration, with u-blox F9P.

6.5.7.3 Example 3: HyPos-SSRZ__TeriaPYX, full configuration

Figure 6-5 shows part of an example in central Oslo. Ground truth positions are plotted as green dots, navigation positions as violet dots. This example is quite similar to examples 1 and 2, but the duration is shorter, and it is split into 4 segments by periods with float or code-based solutions. The 2 last segments of the example is shown in this figure. The car is driving westbound through the street Grønlandsleiret, stops and waits for an opportunity to turn to the left, due to traffic light or the general traffic situation. While the car is standing still, fixed solution is regained after 27 seconds with float or code-based solutions. Then the car starts moving again and turns to the left into the street Tøyenbekken. The navigation positions have approximately the same bias as in the first 2 segments of the situation (about 1 minute before what is shown in the figure): About 80 centimeters to the south and about 15 centimeters to the west. In other words, the same position bias is produced when the fixed solution is regained after half a minute with float or code-based solutions. The fact that the car was at rest for the last 5 seconds before fixed solution was achieved again did not help.

Figure 6-5: Example 3, large position errors, possibly incorrect ambiguity resolution. HyPos-SSRZ, full configuration, with Teria PYX. Only fixed solutions are shown.

6.5.7.4 Example 4: CPOS__TrimbleR10

Figure 6-6 shows an example which is quite expected, and which we do not consider very problematic from a safety point of view. Ground truth positions are plotted as green dots, navigation positions as violet dots. The car is driving northbound on a motorway and passes under a bridge. When the car is under the bridge, a fixed solution position with a horizontal error of about 4.6 m in western direction is computed. However, the situation normalizes quickly afterwards in the sense that the receiver does not produce a fixed solution for the next 7 seconds, so the faulty condition does only last for 1 second. This particular position could also have been eliminated using simple quality checks, because the so-called DOP values, which are standard output parameters from the receivers and describe the number of satellites used and their geometry, are extremely high for this position. High DOP values indicate few satellites or/and bad satellite geometry. Generally, in the HyPos kinematic data collection campaigns, the Trimble R10 receiver used with CPOS rarely produces positions with large errors for longer periods than a few seconds.

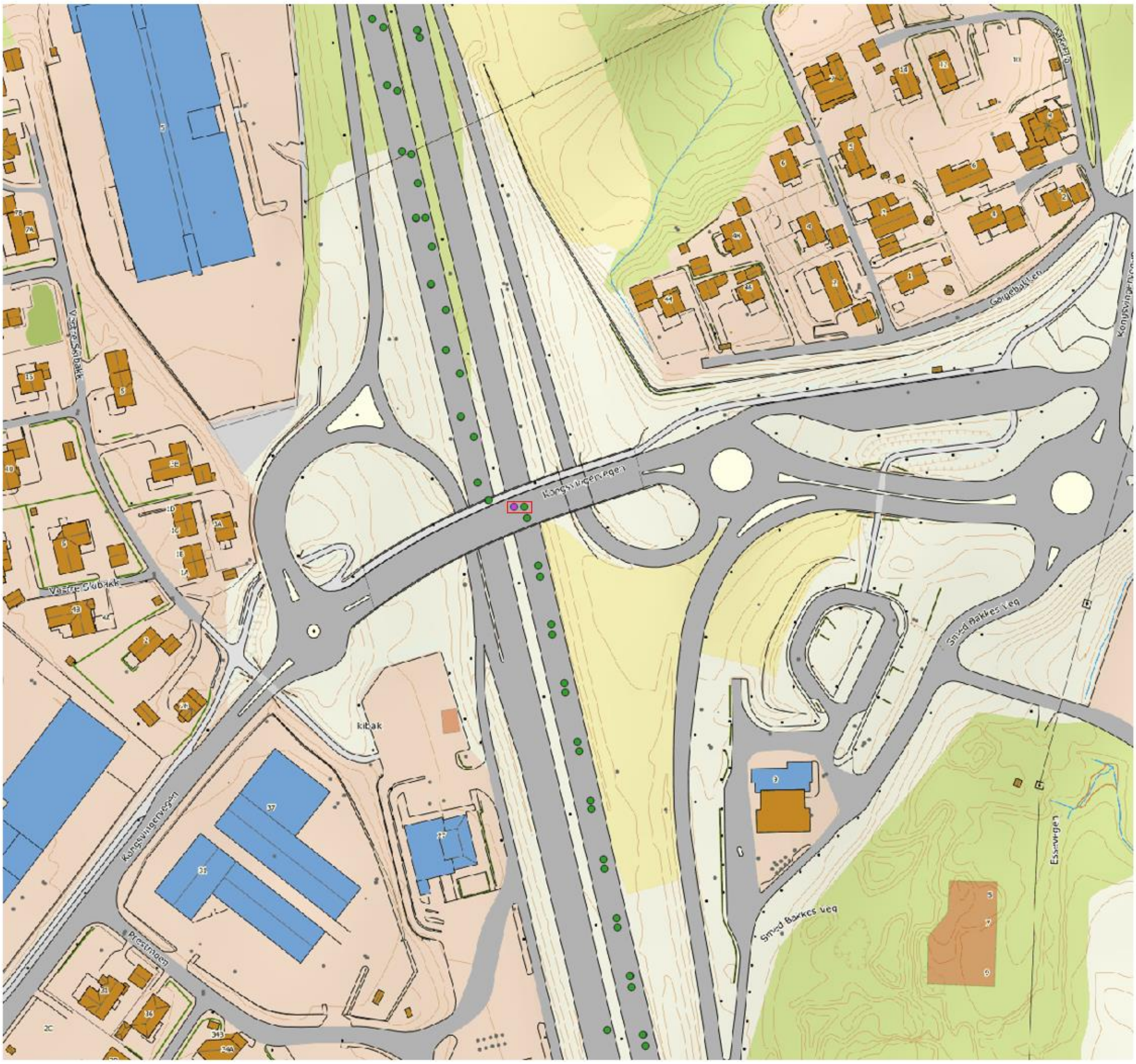


Figure 6-6: Example 4, large position error (shown in red rectangle), possibly incorrect ambiguity resolution. CPOS with Trimble R10. Only fixed solutions are shown.

6.6 Comments to the results

6.6.1 Important notes regarding the positioning accuracy results

There are some important aspects to remember when the positioning accuracy results are interpreted. One of those is uncertainty about the antenna phase centers of the different GNSS antennas mounted on the car. There might be offsets here that are difficult for us to account for, and that may lead to biases (contribution to the numbers chapter 6.5.3) and noise (contribution to the numbers in chapter 6.5.4) in the results.

Another aspect is the obvious fact that the ground truth values are not perfect. They will inevitably also be polluted by some noise and, hopefully small, bias. Noise can be mathematically described by standard deviation, which is the square root of the variance:

$$StDev(z) = \sqrt{Var(z)}$$

Slightly simplified, each coordinate error (ΔNorth, ΔEast (and ΔHeight)) that we calculate for each data point, can be viewed as a difference between two random variables. From fundamental mathematical statistics, we know that the variance of a difference between two random variables x and y equals the sum of the variance of x and the variance of y, minus the covariance between x and y:

$$Var(x-y) = Var(x) + Var(y) - 2 \cdot Cov(x,y)$$

If the navigation position coordinates are described by x, and the ground truth coordinates by y, and if we assume that Cov(x,y) is small compared to Var(x) and Var(y), this means that the coordinate errors contain more noise than the coordinates computed by the navigation receivers themselves. If we had access to a perfect ground truth trajectory, Var(y) would be zero, but this is impossible to fulfill in reality. The expression for the variance of the navigation positions becomes:

$$Var(x) = Var(x-y) - Var(y) + 2 \cdot Cov(x,y)$$

And consequently, the standard deviation of the navigation positions:

$$StDev(x) = \sqrt{StDev(x-y)^2 - StDev(y)^2 + 2 \cdot Cov(x,y)}$$

We do not have access to fully reliable values for the standard deviation of the ground truth (StDev(y)), only estimates that may be somewhat too optimistic. But we assume that the numerical degradation effect caused by the noise of the ground truth values is probably within 2 cm in most cases in our kinematic data series.

6.6.2 Service availability

We do not consider short (< 15 s) unavailability occurrences that typically arise after passes under bridges, problematic. These events will inevitably occur. For automotive applications, simple IMUs should be able to bridge gaps of such short duration. It will also be interesting to see what contribution 5G positioning could give here. That being said, the availability numbers are generally lower than what we think is necessary for a core technology service for automated driving in Nordic conditions, where snow may cause problems for navigation sensors like LIDAR and cameras. The results indicate that, if 20 cm absolute positioning is required for automated vehicles, other navigation sensors than GNSS are needed for this task also in areas with generally good GNSS observation conditions.

We observe that the service availability is reduced in most cases for variants of HyPos_SSR with reduced reference station density (Medium, Minimum).

6.6.3 Gross errors / possibly incorrect ambiguity resolution

We observe several cases with long-lasting biased fixed solutions. We do not know any of the positioning algorithms used in the receivers, so our assessments are based on our *general* knowledge of high-accuracy GNSS positioning. However, we choose to classify these biased fixed solutions as incorrect fixed solutions, in the sense that the ambiguity resolution process has produced incorrect integer values for phase ambiguities of some satellite(s). If such biased positions are produced for more than a few seconds in a row, it might be a problem for navigation safety (depending on what other navigation sensors that are available and how the different sensors are weighted). The problems with wrong fixed solutions are most prominent for the u-blox F9P receiver (both with HyPos_SSR and CPOS), but we also observe this for the Teria PYX receiver. The Trimble R10 (with CPOS) only seem to produce very short-lived instances of wrong fixed solutions. In other words, there may be a correlation between the receiver/antenna cost and the amount of such problems. On the other hand, several features of both signal processing algorithms and positioning algorithms are often optimized for specific use cases. Our experience with u-blox F9P receivers indicate that they tend to use satellite signals even if their signal-to-noise ratio is relatively low. This may be a design choice so that the receiver is able to compute positions under harsh local measurement conditions where other receivers give up. This may sometimes be an advantage and sometimes a disadvantage. Other design choices could perhaps have led to different results without necessarily making the equipment more expensive.

6.6.4 Forest vs. non-forest

We expected more differences in navigation performance (regarding both availability and accuracy) between the area types "Country road, little vegetation" (non-forest) and "Country road, forest" (forest). Trees can both shade satellite signals and create unfortunate multipath. Therefore, we expected most results in forest areas to be worse than in non-forest areas. However, we do not see this in our results. Actually, some of the results are a little bit better in forest areas than in the non-forest ones. The most plausible explanation for this is our method for classification of area types along the roads. This classification is based on map data. A quite big portion of the areas that are marked as forest in the map, are areas where the road (the E16) is modern, with very good clearance between the roadsides and the trees, typically 15-30 meters horizontally. The GNSS conditions here may perhaps be as good as in the non-forest areas.

6.6.5 Number of used GNSS constellations

There are currently 4 major GNSS constellations: GPS, GLONASS, Galileo and BeiDou. As mentioned in chapter 5.1, the number of satellites available for use can be an important factor when it comes to positioning performance, especially the service availability. In our kinematic campaigns, there are some differences between the service-receiver combinations regarding which of these constellations that are used:

a. HyPos-SSRZ__TeriaPYX: GPS, GLONASS (from June 20th), Galileo.
b. CPOS__TrimbleR10: GPS, GLONASS, Galileo.
c. HyPos-SPARTN__ublox: GPS, GLONASS, Galileo, BeiDou.
d. CPOS__ublox: GPS, GLONASS, Galileo, BeiDou.
e. PointPerfect__ublox: GPS, GLONASS, Galileo, BeiDou.
f. HyPos-Ericsson__ublox: GPS, GLONASS, Galileo, BeiDou.

The service availability results for the two Country Road area types (both “Little vegetation” and “Forest”) using the HyPos-SSRZ service with the Teria PYX receiver may have been somewhat degraded because Teria PYX receiver did not use GLONASS satellites on the days where the data for these area types were collected (June 5th – 8th 2023).

6.6.6 HyPos_SSR vs. existing services

Both availability and accuracy values are generally worse for the HyPos navigation options than for the existing services CPOS and PointPerfect. There may be several reasons for this, and we can mostly only speculate. The following aspects are speculative based on our general knowledge about GNSS and GNSS correction services:

- As mentioned in chapter 6.3, we planned to use more reference stations than we were able to use during the campaigns. But under testing with the planned number of reference stations we observed something that seemed to be throughput problems related to the GNSMART software, so we had to reduce the number of stations to obtain a stable output of data.
- Unfortunately, we could not use the same high-end receiver for HyPos_SSR and CPOS in parallel, because SSR is in an early stage and some standardization is yet to be completed. In the high-end segment, we used a Teria PYX for HyPos_SSR and a Trimble R10 for CPOS. We are not sure whether the Teria PYX receiver worked optimally during the campaigns. For example, from time to time, the number of used satellites is relatively low in the fixed solutions produced by the Teria PYX in our campaigns. The main reason is that Teria PYX did not use the GLONASS constellation before June 20th. This may have had a negative effect on the service availability for the HyPos-SSRZ__TeriaPYX variants.

  More generally, it is not unthinkable that some receivers tend to use less satellites than others, due to a conservative ambiguity validation scheme (satellites are thrown away because the validation algorithm does not trust their estimated integer ambiguities). The choice between using or not using a satellite is a trade-off: Assuming random white noise measurement errors, it is mostly good to use as many satellites as possible so that the random errors are averaged as well as possible; on the other hand, non-random or gross measurement errors (such as incorrect integer ambiguities) should be removed before computing a position.
- The practical implementation of SSRZ format in the TeriaPYX seems to involve conversion from SSR to OSR. We have no insight in this process, and we do not know if it can have any negative implications.

6.6.7 HyPos-Ericsson with u-blox F9P (low-cost) receiver

Unfortunately, the HyPos-Ericsson OSR test service did only provide data on some of the campaign days, so the amount of data is very limited. Therefore, some of the cells in the tables of chapters 6.5.1 - 6.5.4 are empty. Due to the small data amounts, we should not draw too firm conclusions. Anyway, we observe that the service availability numbers are relatively low (ref. chapter 6.5.1). The positioning accuracy is approximately at the same level as HyPos_SSR with the Teria PYX (high-end) receiver.

7 Results from static data collection campaigns

7.1 Introduction

The kinematic data collection campaigns give information about navigation performance in realistic and partially challenging conditions. However, in such campaigns, there are many variables beyond our control that can alter the results differently in the different campaigns. For example, on one day, there might hypothetically be a big truck driving in front of the data capture car shadowing some GNSS signals for several minutes, while on the next day there are perhaps no such problems. Therefore, it is valuable to also collect data under more controlled conditions, and a static campaign is perhaps the easiest way to achieve this. In a static campaign, the same GNSS receivers for navigation positioning were used as in a kinematic campaign, and they were configured exactly the same way. The difference is that each receiver is mounted at a stationary point. This makes the complexity of data handling and analysis much simpler in the static case. The antennas are placed on pillars for which very accurate ground truth coordinates are computed beforehand, based on long-term GNSS measurement campaigns and sophisticated data processing.

The location of the pillars for the static campaigns is the rooftop of the main office building of NMA just outside Hønefoss. The GNSS measurement conditions there are excellent. The reference station configurations and the KPI definitions are the same as for the kinematic campaigns (ref. chapters 6.3 and 6.4), and the dates for the static campaigns were the following:

- Full reference station configuration: September 7th – 8th, 2023
- Medium reference station configuration: September 11th – 12th, 2023
- Minimum reference station configuration: September 12th – 13th, 2023

Each campaign started early in the morning and lasted for approximately 24 hours until the next morning. An exception is the PointPerfect__ublox option, which uses a continuous data logging setup. The logged 24 h data from the calendar dates September 7th, 11th, and 12th (2023) are used for that navigation option.

Figure 7-1: Pillar with the u-blox antenna used for the four u-blox F9P receivers.

7.2 Results

7.2.1 Summary table

Table 6 contains the key results of the static campaigns. The KPIs shown are the same as for the kinematic results presented in chapters 6.5.1, 6.5.2, 6.5.3, and 6.5.4, respectively. The result data from the HyPos-SSRZ__TeriaPYX option are omitted due to technical problems with the Teria PYX receiver.

Table 6: Summary table of statistics, static campaigns

KPI / Service & Receiver type	Service availability [%]	HPE95 [m]	Average coordinate errors [m]	Standard deviations [m]
HyPos-SSRZ Full configuration Teria PYX				
HyPos-SSRZ Medium configuration Teria PYX				
HyPos-SSRZ Minimum configuration Teria PYX				
CPOS Trimble R10	99.7	176134 0.01 m	176134 -0.004 m N -0.002 m E	176134 0.004 m SN 0.003 m WE
HyPos-SPARTN Full configuration u-blox F9P	97.5	84113 0.16 m	84113 0.035 m N -0.001 m E	84113 0.042 m SN 0.063 m WE
HyPos-SPARTN Medium configuration u-blox F9P	89.5	77812 0.25 m	77812 0.041 m N -0.087 m E	77812 0.054 m SN 0.071 m WE
HyPos-SPARTN Minimum configuration u-blox F9P	12.1	9771 0.42 m	9771 -0.036 m N -0.109 m E	9771 0.558 m SN 0.162 m WE
CPOS u-blox F9P	98.8	250760 0.01 m	250760 -0.003 m N 0.000 m E	250760 0.004 m SN 0.003 m WE
PointPerfect u-blox F9P	87.3	226328 0.09 m	226328 -0.020 m N -0.016 m E	226328 0.049 m SN 0.041 m WE
HyPos-Ericsson Full configuration u-blox F9P	11.2	4782 0.20 m	4782 0.064 m N -0.043 m E	4782 0.068 m SN 0.086 m WE
HyPos-Ericsson Medium configuration u-blox F9P	11.2	3782 0.21 m	3782 0.086 m N -0.039 m E	3782 0.070 m SN 0.040 m WE
HyPos-Ericsson Minimum configuration u-blox F9P	8.6	2852 0.24 m	2852 0.089 m N -0.055 m E	2852 0.148 m SN 0.099 m WE

7.2.2 Plots for each service

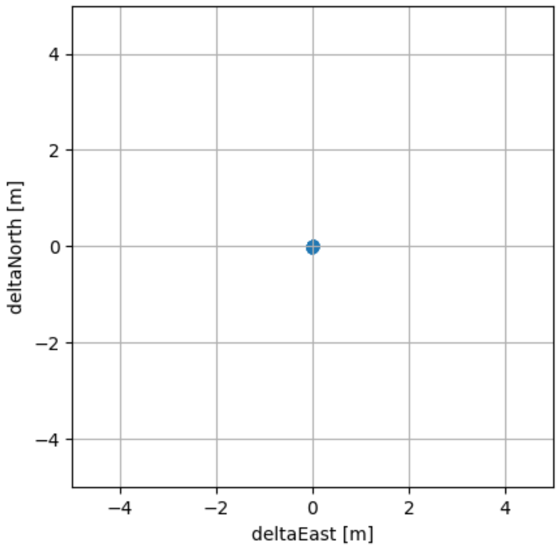
In this chapter, we present two plots for each service / reference station configuration / receiver variant. The plot to the left is a scatter plot that plots the horizontal position error components ΔNorth and ΔEast vs. each other. The plot to the right shows the cumulative distribution function for the horizontal position errors ΔHorizontal, that is, how large portion (between 0 and 1) of positions have a horizontal error less than or equal to the function value. Where the graph crosses the value 0.95 on the y-axis, the HPE95 (ref. chapter 6.5.2) can be found on the x-axis. The x-axis is cut off at ΔHorizontal = 1 m, even though there are values higher than 1 m in several cases.

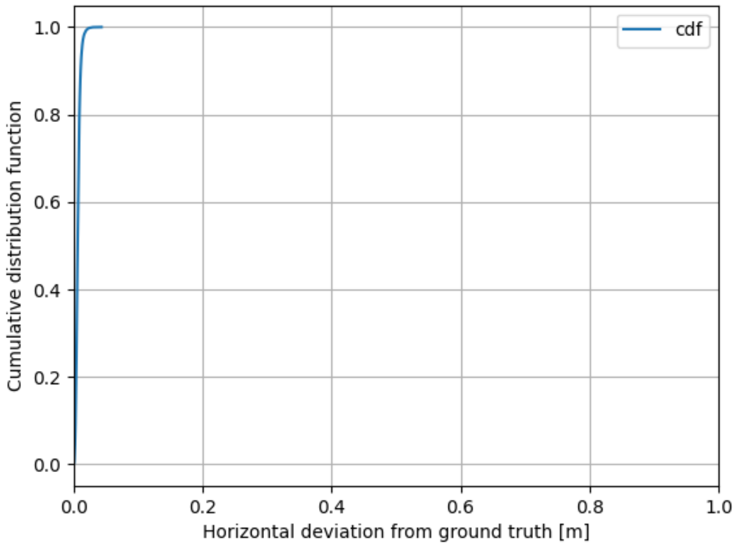
Both plots only contain fixed solutions. The number of fixed solutions, followed by a fractional line "/", then the total number of computed positions and the resulting service availability percentage are shown in each case. So are also the HPE95 value and the maximum HPE value, both in the unit meters.

The result data from the HyPos-SSRZ__TeriaPYX option are omitted due to technical problems with the Teria PYX receiver.

7.2.2.1 CPOS__TrimbleR10 (GPS satellites only)

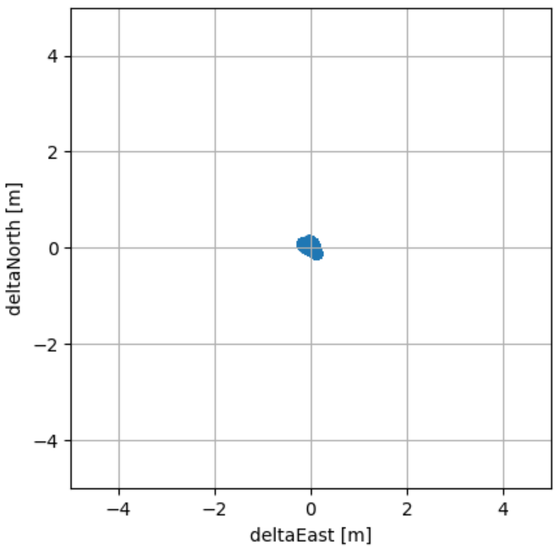
176134 / 176717 = 99.7 % availability. HPE95 = 0.01, HPE_max = 0.04

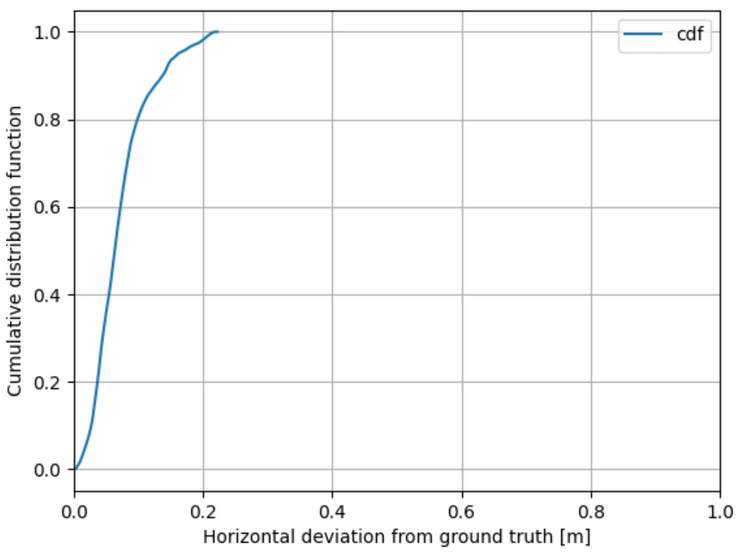




7.2.2.2 HyPos-SPARTN__ublox, full reference station configuration

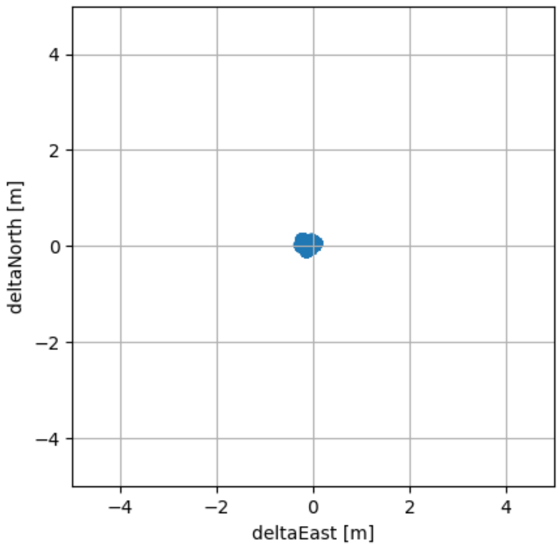
84113 / 86293 = 97.5 % availability. HPE95 = 0.16, HPE_max = 0.22

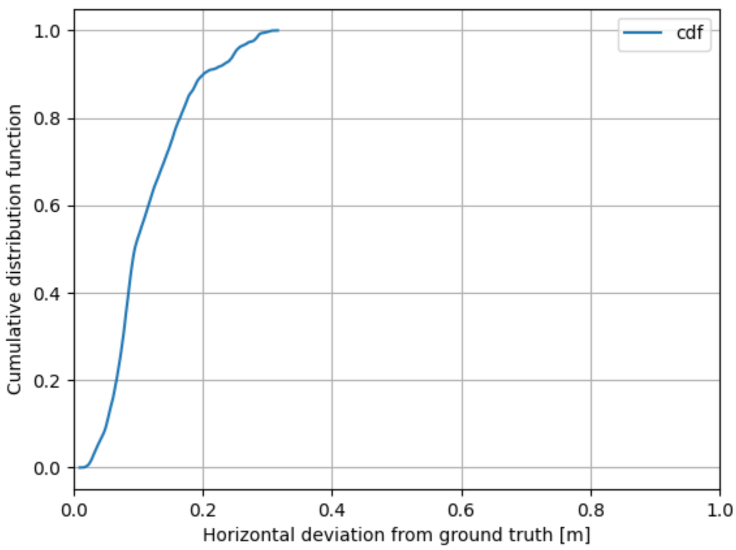




7.2.2.3 HyPos-SPARTN__ublox, medium reference station configuration

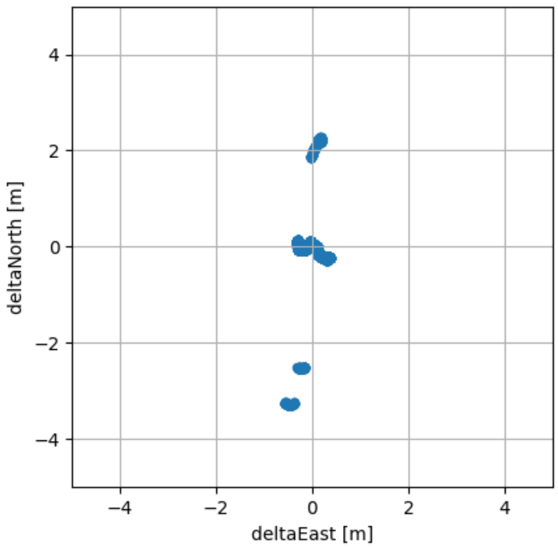
77812 / 86970 = 89.5 % availability. HPE95 = 0.25, HPE_max = 0.32

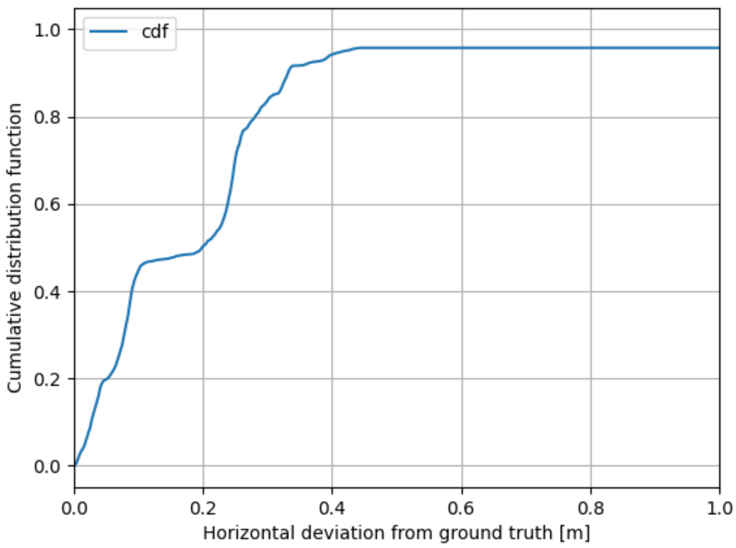




7.2.2.4 HyPos-SPARTN__ublox, minimum reference station configuration

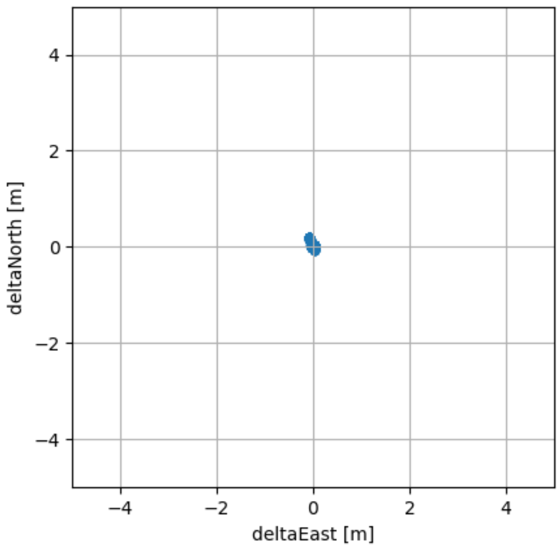
9771 / 80805 = 12.1 % availability. HPE95 = 0.42, HPE_max = 3.33

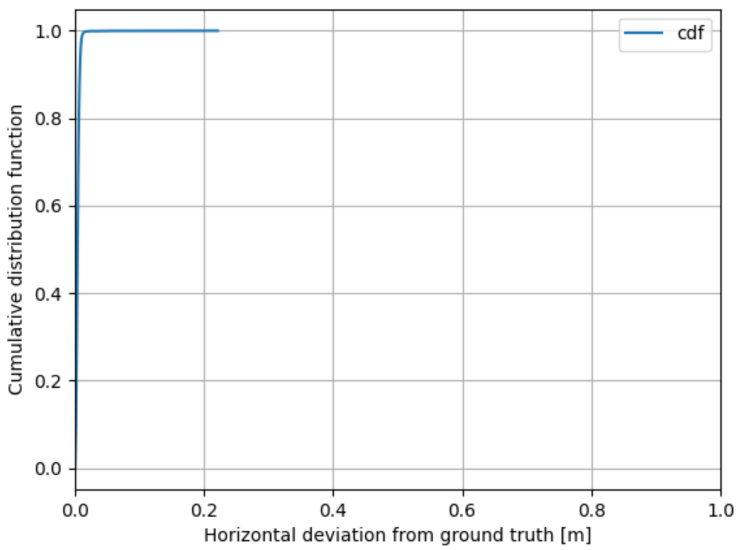




7.2.2.5 CPOS__ublox

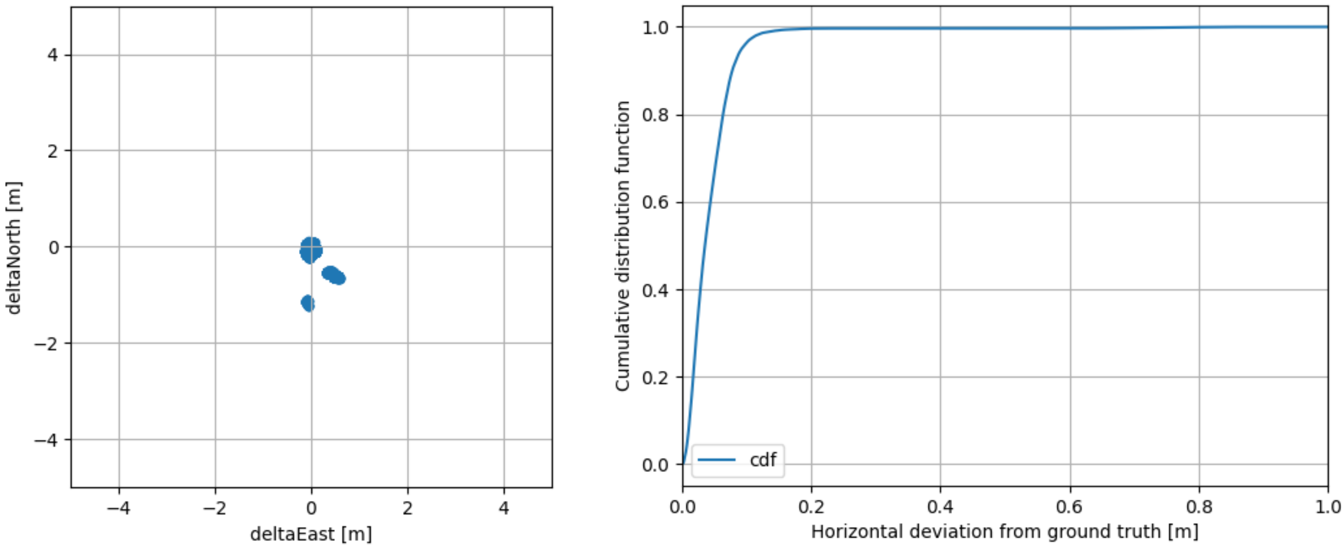
250760 / 253700 = 98.8 % availability. HPE95 = 0.01, HPE_max = 0.22





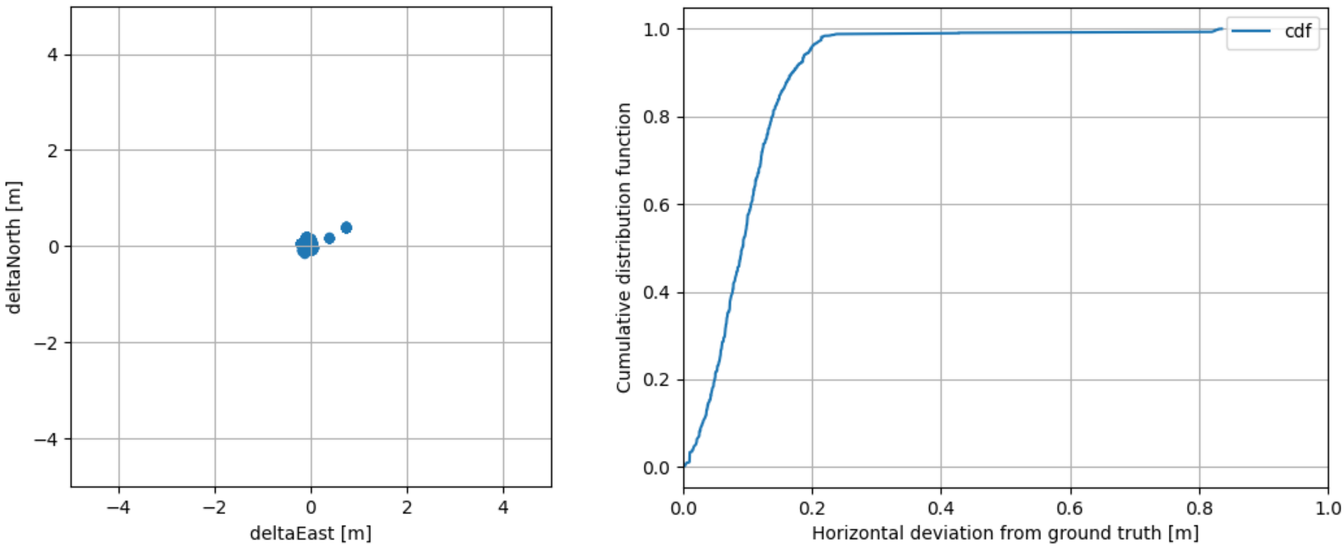
7.2.2.6 PointPerfect__ublox

226328 / 259200 = 87.3 % availability. HPE95 = 0.09, HPE_max = 1.25



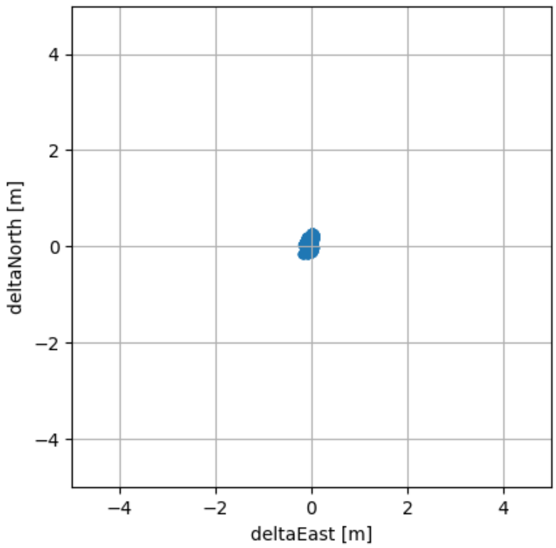
7.2.2.7 HyPos-Ericsson__ublox, full reference station configuration

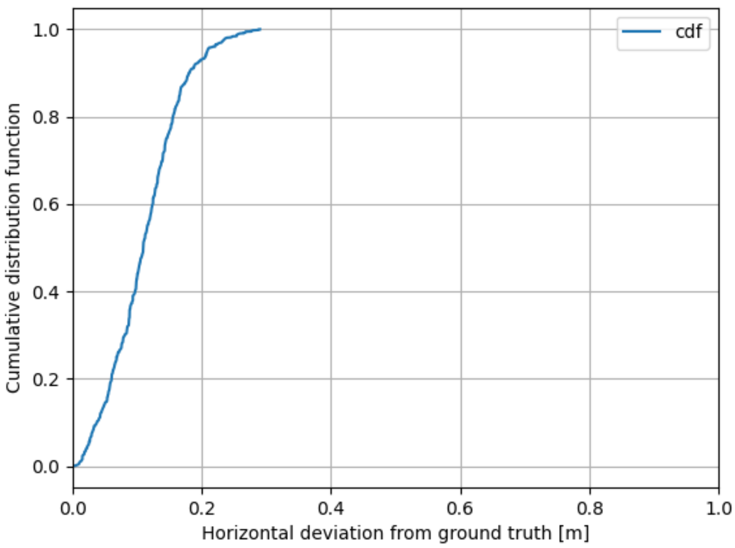
4782 / 42818 = 11.2 % availability. HPE95 = 0.20, HPE_max = 0.84



7.2.2.8 HyPos-Ericsson__ublox, medium reference station configuration

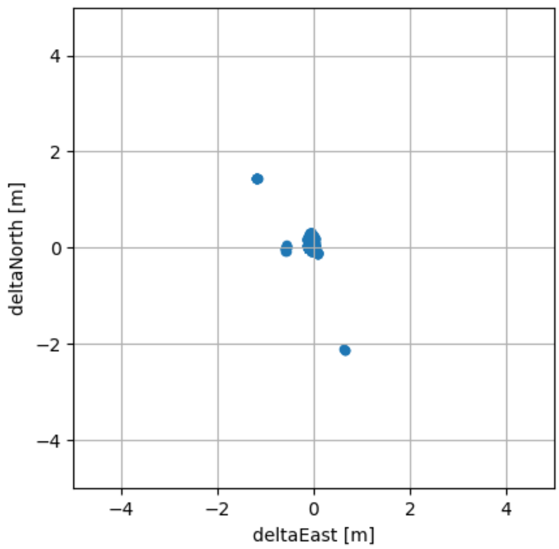
3782 / 33904 = 11.2 % availability. HPE95 = 0.21, HPE_max = 0.29

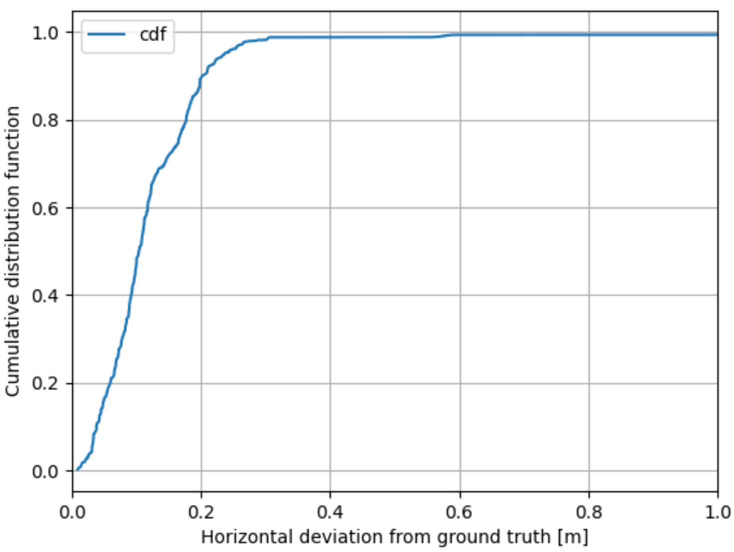




7.2.2.9 HyPos-Ericsson__ublox, minimum reference station configuration

2852 / 33198 = 8.6 % availability. HPE95 = 0.24, HPE_max = 2.21





7.3 Comments to the results

The CPOS__TrimbleR10 option showed, as expected, both a very good availability and an excellent accuracy, even though only GPS satellites were used (instead of GPS + GLONASS + Galileo), possibly due to a configuration error. It should be noted that the antenna pillar is located only a few meters away from the closest reference station, so we expected a very good performance in this case.

The CPOS__ublox option also showed a very good availability and accuracy (the maximum error is much higher than for the Trimble R10 receiver, though). This shows that under good GNSS conditions, a low-cost receiver has the potential to perform almost as well as a high-end receiver.

HyPos-SPARTN__ublox, full configuration, showed a quite good availability, but the accuracy was not at the CPOS level, even if the nearest reference station is only a few meters away. The same service and receiver with medium configuration had a somewhat worse availability and a bit worse accuracy, too.

HyPos-SPARTN__ublox, minimum configuration variety had a very poor availability and a poor accuracy which also suffered from what seems to be incorrect fixed solutions. Here the distances to the reference stations are large, though.

The PointPerfect__ublox option showed a not too impressing availability, but the accuracy was at the expected level for a service with a sparser reference station network.

HyPos-Ericsson__ublox with all 3 reference station configurations showed a very poor service availability. We suspect that the receiver or related telecommunication equipment did not work properly. The accuracy is best in the full configuration case, a little bit worse in the medium configuration case and even a little bit worse in the minimum configuration case, and this is not very far from what we expected, even though we perhaps expected larger accuracy differences between the three cases (like for HyPos-SPARTN__ublox). The accuracy numbers themselves are more or less at the same level as those of HyPos-SPARTN__ublox.

8 Main conclusions

In WP 2, we have demonstrated that a GNSS correction service using the SSR principle (HyPos_SSR) can provide horizontal positioning accuracy of 20 cm (95th percentile) or better, both in several kinematic use cases and in static use cases with kinematic processing. However, the accuracy cannot be guaranteed in any way: We have observed systematic error conditions, probably caused by incorrect phase ambiguity resolution, lasting for several minutes, both when using low-cost receiver and when using a high-end receiver. On the other hand, such problems also occur when using CPOS with a low-cost receiver, so the problem may be independent of the service itself. Phase ambiguity resolution is briefly described in chapter 5.3.

The service availability (portion of fixed phase ambiguity solutions) of HyPos_SSR is not as good as what we perhaps should require from a core technology for absolute positioning in Nordic conditions, where snow may cause problems for some other navigation sensors. But some of the availability results may have been degraded by the lack of use of GLONASS satellites. The availability is of course also dependent on the mobile communication connectivity. Regarding the use of HyPos_SSR with the Teria PYX receiver, the data is

Based on our restricted amount of collected data, it does not seem that the density of the reference station network can be reduced with SSR (compared to OSR) without performance degradation.

The CPOS service (OSR), which traditionally has been mostly used in static or semi-static applications with kinematic processing, seems to work very well also in several of the kinematic use cases that were tested.

There are some uncertainties regarding how the SSR corrections are used in the Teria PYX receivers. We also ask ourselves whether the systematic position errors that are observed can originate from the handling of coordinate reference systems within the service, either in the GNSMART software, in the Teria PYX receiver, or both. In addition, the implementation of SSRZ support in the Teria PYX receiver currently involves an extra step where the SSRZ data from HyPos_SSR are sent to a server at Teria in France, where some data handling is performed (it is unknown to us what kind of data handling this is) and the output data of that process is sent to the Teria PYX receiver. This extra step appears to us as a workaround, and we do not know if it has been ideal for the results or not.

The standardization of SSR within the RTCM Special Committee 104 is an ongoing work that is expected to lead to a standard release during 2024 or early 2025. We expect that this standardization will boost the implementation of SSR support in several GNSS receiver types and correction service software packages. We recommend that new data collection campaigns are performed with equipment supporting this standard once it is available. We also recommend that future data collection campaigns in urban areas have a longer duration in order to obtain more reliable results.

9 GNSS SSR formats used in WP 2

In the SSR concept, information about the states of different GNSS error sources are disseminated from the service provider to the users so that the users can correct for these errors. The errors sources that are typically covered by an SSR service in order to provide fast convergence of the user's position calculation, are:

1. Satellite orbit errors
2. Satellite clock errors
3. Satellite hardware code biases
4. Satellite hardware phase biases
5. Ionospheric signal delay/advance
6. Tropospheric signal delay

Several streaming data formats are defined for disseminating SSR data from service providers to users. Focusing on the developing entities of the different formats, we can roughly categorize the formats into 3 groups:

A. Formats which are defined by organizations that are not service/software/receiver providers (members of the organizations may be such providers, though). In this group we have the following formats:

   RTCM SSR[3], IGS SSR[4], 3GPP LPP

B. Formats which have their descriptions openly available, even if they are still proprietary in the sense that they are defined and controlled by the service/software/receiver provider. In this group we have the following formats: SPARTN, SSRZ, Compact SSR, Galileo HAS, BeiDou PPP

C. Formats which are defined by the different service/software/receiver providers, and which are strictly proprietary, that is, they are defined and controlled by service/software/receiver providers and the format descriptions are not disclosed to the public. These formats are not mentioned further here, even though they are widely used in commercial services.

The article [1] provides an overview and analysis of most of the formats in group B and C. Unfortunately, it does not analyze SSRZ, because the article was written before the SSRZ format was made publicly available.

The streaming data formats that are used in HyPos_SSR:

- SPARTN
- SSRZ
- 3GPP LPP

These three formats, together with the unfinished SSR part of RTCM, are briefly described in the following subchapters.

For completeness we mention that the OSR part of RTCM is used in the CPOS variants in this WP. Similarly, the OSR part of 3GPP LPP is used by the HyPos-Ericsson variant.

---

[3] Under development.
[4] It could be claimed that IGS is a service provider, but IGS SSR services are rather prototype/scientific services than fully operational services.

9.1 SPARTN (Secure Position Augmentation for Real-Time Navigation)

Sapcorda Services GmbH was a joint venture formed by u-blox, Bosch, Geo++ and Mitsubishi Electric in 2017. The versions up to 1.8 (January 2020) of the SPARTN format were developed by Sapcorda. In March 2021, u-blox AG acquired full ownership in Sapcorda, and consequently Sapcorda ceased to exist. The current version of SPARTN is called 2.0.1 and was released by u-blox in September 2021. Even though SPARTN is under full control by u-blox, the format description is openly available for free download via the webpage[2] . Official information about SPARTN can be found in [2].

Following [3], SPARTN 2.0.1 can carry the following elements:

- Satellite orbit correction (radial, along-track, cross-track): $\delta\boldsymbol{O} = \begin{bmatrix} \delta O_{radial} \\ \delta O_{along} \\ \delta O_{cross} \end{bmatrix}$
- Satellite clock correction: δC
- Satellite code bias correction (for certain selected signal types)
- Satellite phase bias correction (for certain selected signal types)
- High-precision atmospheric correction:
    1. Ionospheric correction (STEC per satellite): Polynomial coefficients for a defined area plus grid points with residuals).
    2. Tropospheric correction (TZD): Polynomial coefficients for a defined area plus grid points with residuals.
- Basic precision ionospheric correction (probably not used in HyPos): VTEC grid model.

9.2 SSRZ

SSRZ is a format developed by Geo++ GmbH. Like SPARTN, the format description is openly available for download. It can be downloaded from the webpage [3]. The current version is called 1.1.2 and was released in November 2022. Compared to SPARTN, SSRZ is a more complex format, and the information elements are broken down into more constituents.

SSRZ 1.1.2 can carry the following elements:

- Satellite orbit correction (radial, along-track, cross-track):
  $$\delta\boldsymbol{O} = \begin{bmatrix} \delta O_{radial} \\ \delta O_{along} \\ \delta O_{cross} \end{bmatrix}_{lowrate}, \delta\dot{\boldsymbol{O}} = \begin{bmatrix} \delta\dot{O}_{radial} \\ \delta\dot{O}_{along} \\ \delta\dot{O}_{cross} \end{bmatrix}_{lowrate}, \delta O_{radial_{highrate}}$$
- Satellite clock correction polynomial coefficients: $C_0, C_1, and\ C_{highrate}$,

  such that the total clock correction is:
  $\delta C = C_0 + C_1(t - t_0) + C_{highrate}$
- Satellite code bias correction
- Satellite phase bias correction
- Ionospheric correction (sum of up to 4 constituents):
  1. Global VTEC (coefficients for spherical harmonic expansion)
  2. Satellite dependent Global VTEC (coefficients for Chebyshev polynomial expansion)
  3. Satellite dependent Regional VTEC (coefficients for Chebyshev polynomial expansion)
  4. Satellite dependent Gridded VTEC
- Tropospheric correction:

  A multi-stage approach is used:
  1. Predefined model: For the fundamental tropospheric delay correction part, empirical weather model data (pressure, temperature, water vapor pressure, temperature lapse rate, water vapor “lapse rate”) taken from RTCA DO-229 ([4]), valid for orthometric height = 0.
     - These zero-height meteorological parameters are used as input to Saastamoinen’s model for tropospheric delay.
  2. Disseminated correction parameters:
     - Polynomial coefficients for a regional tropospheric correction derived from the network processing of reference station GNSS data. Chebyshev polynomial expansion is used in the horizontal plane, whereas algebraic polynomial expansion is used in the vertical component.
     - Gridded corrections derived from the network processing of reference station GNSS data.

9.3 3GPP LPP (LTE Positioning Protocol)

The 3GPP LPP (3rd Generation Partnership Project - LTE Positioning Protocol) [5] standard defines a protocol for mobile network positioning based on 4G/LTE and 5G/NR networks. It defines:

- Generic session and transaction management to establish an LPP session, and to support one or several transactions in parallel. One transaction can handle exchange of capabilities, one to provide assistance data, either once or periodic, one to manage device reporting, etc, see **Feil! Fant ikke referansekilden.** for an example of an LPP s ession for periodic GNSS assistance data.
- Common parts such as reporting a device-based position using whichever of the available positioning methods.
- RAT-dependent positioning including 4G/LTE positioning and 5G/NR positioning with a plethora of positioning methods ranging from more crude IoT positioning to very precise positioning using cellular network procedures
- RAT-independent positioning including GNSS, WiFi, Bluetooth, Barometric altimeter, IMU, beacon systems, etc

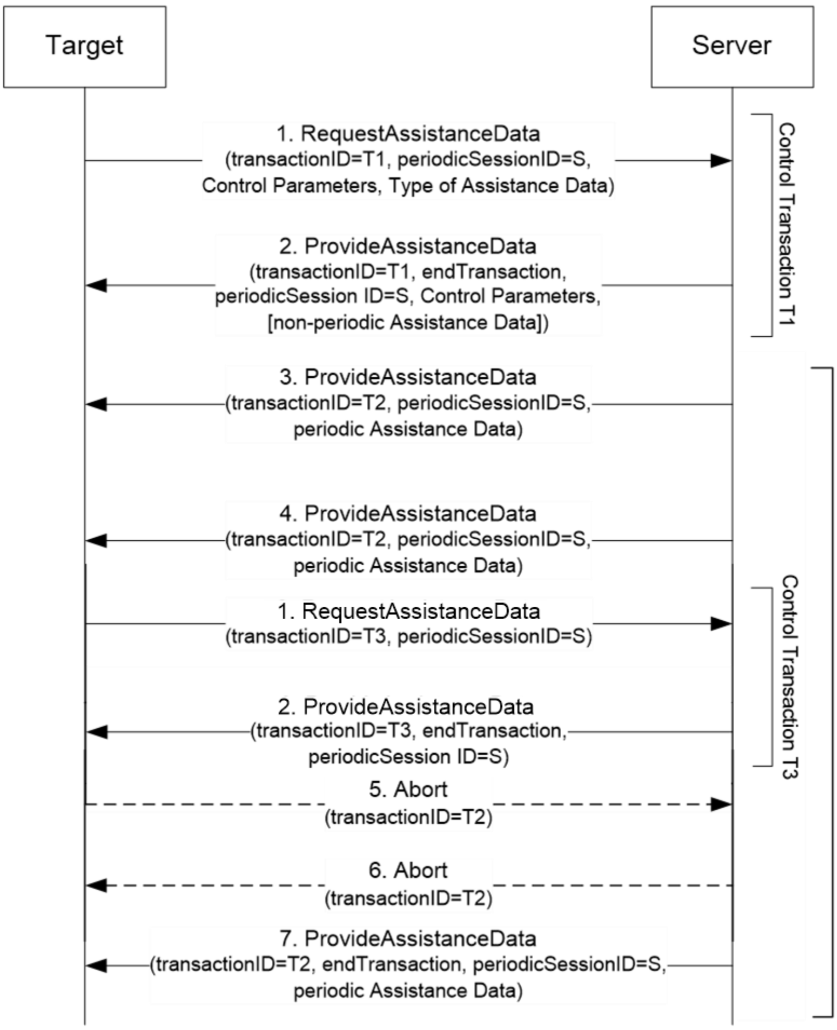


Figure 9-1: LPP session example with multiple LPP transactions.

The specification procedure is fully open with a wide range of companies engaged representing mobile network operators, service providers, governmental and regulatory organizations, academic and commercial institutes, network vendors, device vendors, chipset vendors, different engineering firms, etc. All meeting protocols and specifications are fully open, not only to members, see [20].

3GPP LPP can be combined with other protocols such as RRC (control radio resources between base station and mobile), LPPa/NRPPa (exchange of device-specific location information between base station and server), HSS/UDM (subscription management), GMLC/NEF (network exposure including location information to network applications). Such interactions enable for example:

- Hybrid positioning between 4G/5G and GNSS, but also between device and network
- Network verification of a device position, where safety critical operations demand the use of at least two independent positioning methods, where device based GNSS assisted from the network can be one, and cellular positioning the other.
- Convenient service provisioning of for example GNSS assistance for high accuracy, meaning that only flip of one or several bits in the subscription information for users is needed to enable the service – no username/password handling etc. is needed, and user differentiation is possible. Some users can get access to OSR, some to SSR PPP only, some to complete SSR, some to integrity, etc. Convenient provisioning is crucial for mass-market services.
- Standardized network exposure to coordinating use cases such as UAV coordination with automated controlled airspaces, logistics, asset tracking, digital twin integration.
- Provisioning of precise time references to ensure that a set of devices has the same understanding of a common precise time reference.

Specifically for GNSS, Rel 9 (2010) supports A-GNSS, Rel 15 (2019) supports OSR and SSR phase one, Rel 16 (2020) supports complete SSR, Rel 17 supports GNSS integrity.

LPP can be distributed via

- cellular network control plane unicast using protocols such as LPPa/NRPPa and RRC to carry the messages in containers.
- cellular network system information broadcast extending the broadcast information with positioning enabling essentially infinite scalability, see Section 11.1
- userplane unicast based on SUPL, see Section 10.2
- technically, LPP can be distributed with any other protocol as well, as long as there is device and server support, but the above the distribution forms are the ones standardized by 3GPP.

3GPP LPP SSR Rel 16 can carry the following elements:

- Satellite orbit correction (radial, along-track, cross-track):

$$\delta\boldsymbol{O} = \begin{bmatrix} \delta O_{radial} \\ \delta O_{along} \\ \delta O_{cross} \end{bmatrix} \;, \delta\dot{\boldsymbol{O}} = \begin{bmatrix} \delta \dot{O}_{radial} \\ \delta \dot{O}_{along} \\ \delta \dot{O}_{cross} \end{bmatrix}$$

- Satellite clock correction polynomial coefficients: $C_0, C_1, and\ C_2$

  such that the total clock correction is:

$$\delta C = C_0 + C_1(t - t_0) + C_2(t - t_0)^2$$

- Satellite code bias correction
- SSR User Range Error (URA)
- Satellite phase bias correction
- Ionospheric correction:

1. Satellite dependent Regional STEC
   $\delta Iai = C_{00} + C_{01}(\phi - \phi_0) + C_{10}(\lambda - \lambda_0) + C_{11}(\phi - \phi_0)(\lambda - \lambda_0).$
2. Satellite dependent gridded STEC residuals

- Tropospheric gridded corrections for vertical delays with two components
  1. Tropospheric hydrostatic delay
  2. Tropospheric wet delay

3GPP LPP is here reusing the mathematical representation concepts from RTCM SSR and Compact SSR.

9.4 RTCM SC-104

RTCM SC-104 v3.3 includes support for OSR with some different variants and is the most widely adopted representation for high accuracy GNSS today. It also includes some components for SSR, which are mentioned here for completeness, but these are not used in WP 2:

- Satellite orbit correction (radial, along-track, cross-track):
  $$\delta\boldsymbol{O} = \begin{bmatrix} \delta O_{radial} \\ \delta O_{along} \\ \delta O_{cross} \end{bmatrix}, \delta\dot{\boldsymbol{O}} = \begin{bmatrix} \delta \dot{O}_{radial} \\ \delta \dot{O}_{along} \\ \delta \dot{O}_{cross} \end{bmatrix}$$
- Satellite clock correction polynomial coefficients: $C_0, C_1, and\ C_2$

  such that the total clock correction is:
  $$\delta C = C_0 + C_1(t - t_0) + C_2(t - t_0)^2$$
- Satellite code bias correction
- User Range Accuracy (URA)

Phase bias is also represented in draft messages that are also in practical use by several institutions. However, it is important to notice that the draft messages are not part of the official RTCM standard. Also, the elements that are defined in the official standard are only defined for GPS and GLONASS. Currently, there is an ongoing task force within RTCM to complete the SSR work and publish a baseline that can be extended over time.

10 Internet Communication Protocols

Internet communication protocols specify the structure of digital messages and the guidelines for transmitting data over the Internet. To ensure successful transmission, communication devices must establish agreement on various aspects of the data. Communication protocols can define several transmission properties, including packet size, transmission speed, error correction methods, handshaking and synchronization techniques, address mapping, acknowledgement processes, flow control, routing, and address formatting.

10.1 HTTP, TCP and UDP

Application protocol:

HTTP is a web application protocol mainly designed to ease communication between a client and a web application hosted by a server. Although HTTP would be the simplest way for a client to communicate with the server, HTTP may introduce unnecessary latency due to its interfacing process with the underlying and reliable transport protocol called **TCP**. HTTP can also use unreliable transport protocols such as **UDP**.

Transport protocols:

TCP offers reliable, ordered, and error-checked delivery of a stream of data between a server and clients. Unlike HTTP, TCP is a low-level communication protocol that provides raw socket connection between a server and a client. Each of the TCP packets consists of a TCP header of length 20 Bytes, as well as a TCP payload. The TCP header contains information necessary to guarantee data packet can be transmitted to the destination, while the TCP payload contains the information to be delivered to the destination. TCP requires connection to be established via a three-way handshake before sending and receiving streams of data. Furthermore, TCP has flow control capability, which manages the rate of streaming data, and it also ensures the arrival of all sent data by retransmitting lost packets. TCP is also used as a communications protocol in a private computer network (an intranet or extranet).

Another widely used low-level communication protocol is **UDP**. Like TCP, UDP offers raw socket connection between a server and a client. But unlike TCP, UDP does not require a proper connection to be established before a packet can be sent from a server to a client. Furthermore, UDP header doesn’t have a sequence number, acknowledgement number, or flags in comparison with TCP. Apart from a smaller 8 Bytes packet size compared to TCP’s 20 Bytes packet, UDP only uses the length to indicate the size of the entire datagram and the checksum to verify the header data. UDP’s main concern is the speed of sending the packet rather than securing the packet or retransmitting any lost packet.

10.1.1 NTRIP (Networked Transport of RTCM via Internet Protocol)

Ntrip ([6], [7]) stands for an application-level protocol for streaming Global Navigation Satellite System (GNSS) data over the Internet. It is a generic, stateless protocol based on the Hypertext Transfer Protocol HTTP/1.1. The HTTP objects are enhanced to GNSS data streams. Ntrip is an RTCM standard designed for disseminating differential correction data (e.g., in the RTCM-104 format) or other kinds of GNSS streaming data to stationary or mobile users over the Internet, allowing simultaneous PC, Laptop, PDA, or receiver connections to a broadcasting host. It supports wireless Internet access through Mobile IP Networks like GSM, GPRS, EDGE, or UMTS.

Ntrip is implemented in three system software components: NtripClients, NtripServers and NtripCasters. The NtripCaster is the actual HTTP server program whereas NtripClient and NtripServer are acting as HTTP clients.

Ntrip is meant to be an open none-proprietary protocol. Major characteristics of Ntrip dissemination technique are:

- Based on the popular HTTP streaming standard; comparatively easy to implement when having limited client and server platform resources available.
- Application not limited to one particular stream content; ability to distribute any kind of GNSS data.
- Potential to support mass usage; disseminating hundreds of streams simultaneously for up to thousand users possible when applying modified Internet Radio broadcasting software.
- Considering security needs; stream providers and users do not necessarily get into contact, streams often not blocked by firewalls or proxy servers protecting Local Area Networks.
- Enables streaming over any mobile IP network because of using TCP/IP.

10.2 Secure UserPlane Location (SUPL)

SUPL [8], defined by Open Mobile Alliance, is an IP-based end to end session oriented signaling protocol for positioning defined by Open Mobile Alliance. It is widely supported by mobile devices to retrieve A-GNSS data from a network server. Version 1.0 supports 2G/GSM and 3G/WCDMA, and version 2.0 adds 4G/LTE and 5G/NR. It supports different types of security options such as TLS/SSL, GBA, etc.

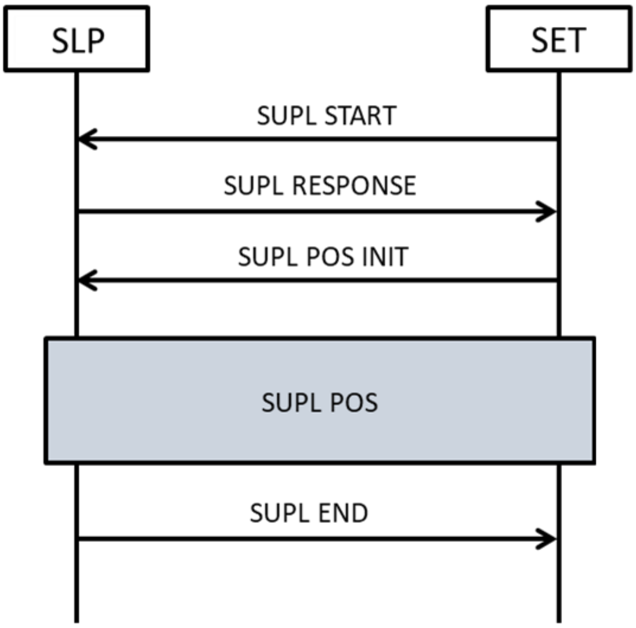


Figure 10-1: SUPL session signaling.

Feil! Fant ikke referansekilden. illustrates the how a SUPL session is established between a SUPL Enabled Terminal (SET) and a SUPL Location Platform (SLP). The session is initiated by the device (SET) with a SUPL START message to the server (SLP), which is confirmed by the server with a SUPL RESPONSE message. The session is initiated with a SUPL POS INIT message to establish the container message SUPL POS, which from that point and onwards carries the messages between server and device. One example of messages is 3GPP LPP, see Section 9.3.

Prior to initiation, the SET determines which SLP to connect to, either by using a pre-configured IP address, or by a DNS lookup based on a standardized fully qualified domain name compiled using the mobile network operator identity information from the SIM card. This means that a SET will find the correct SLP automatically and the SET is generic without any operator-specific configurations.

The SUPL session is able to support mass-market distribution of assistance data for example for GNSS positioning but also 5G positioning enabling hybrid positioning. It also supports extensive feedback of reports from devices, thereby playing a role in use cases where location data is provided to coordinating network applications.

There are a few SUPL 2.0 open source client stacks for Java [9] and C++ [10].

10.3 Machine to Machine (M2M)

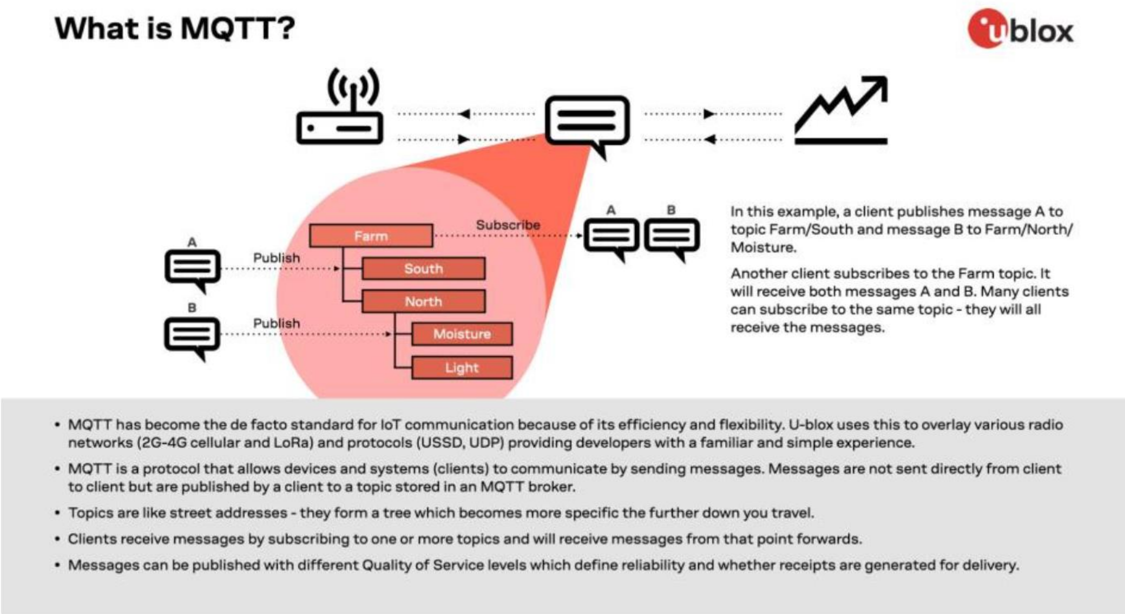
M2M refers to the communication technology that allows two devices to exchange information asynchronously within a wired or wireless communication channel. M2M technology is a whole concept that involves communication among machines, allowing process automation between mobile devices and machines (mobile to machine), and between men and machines (Man to Machine).

The main motivation in pursuing a direct communication between electronic devices using a common technology is to provide smart and intelligent services which require access of information and control of remote devices. The networking of multiple electronic devices such as smart phones, tracking unit, sensors and actuators forms a connectivity which is commonly known as IoT.

Due to the rapid movement of data between devices in an IoT network, M2M communication requires a protocol that supports asynchronous calls, which can minimize computing resources. Message queues provide an asynchronous communication protocol, meaning that the sender and receiver of the message do not need to interact with the message queue at the same time. Messages placed in the queue are stored until the recipient retrieves them. Message queues have implicit and explicit limits on the size of data that may be transmitted in a single message and the number of messages that may remain outstanding on the queue.

10.3.1 MQTT

MQTT is a messaging protocol designed to create a reliable standard for machine-to-machine communication by IBM’s Andy Stanford Clark and Eurotech’s Arlen Nipper in 1999. MQTT has a client/server model architecture, where every sensor is a client and connects to a server, known as a message broker. Message transmission in MQTT utilizes two key methods known as Publish and Subscribe. Every message is published to an address, known as Topic. MQTT clients may subscribe to multiple topics. Every client subscribed to a topic receives every message published to the topic. MQTT typically uses IP (Internet Protocol) as its transport but can also use other bi-directional transports.



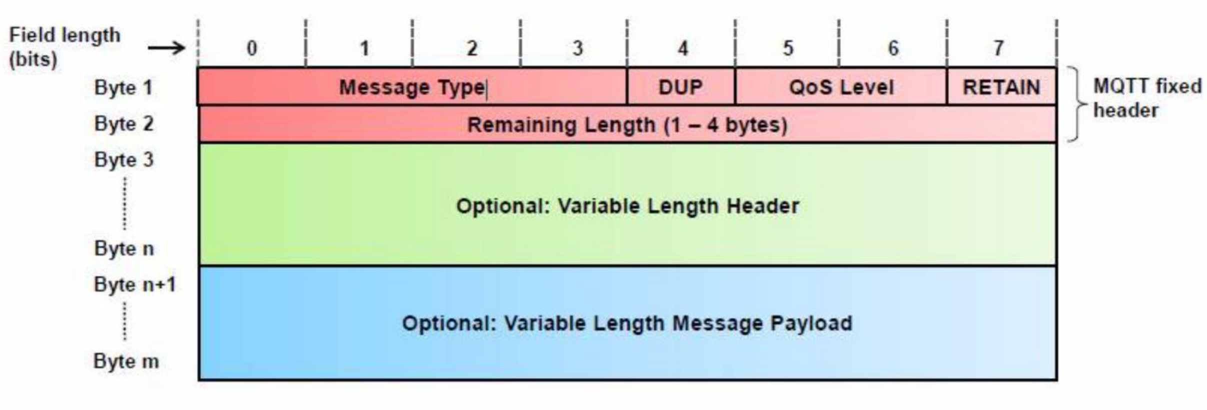


Figure 10-2: MQTT message format

As shown in Figure 10-2, MQTT messages contain a mandatory fixed length of 2 bytes header and an optional message-specific variable length header and message payload.

10.3.2 CoAP

CoAP is a document transfer protocol that is specifically designed for use in constrained environments, such as low-power, low-bandwidth networks or resource-limited IoT devices. Packets in CoAP are much smaller than HTTP/TCP flows and the packets are simple to generate and can be parsed in place without consuming extra memory. CoAP runs over UDP instead of TCP. Similar to MQTT, CoAP follows client/server model. Clients communicate with servers using GET, PUT, POST and DELETE messages commands (RESTful principles). It is designed to be lightweight and efficient, using minimal network resources and providing low-latency communication for real-time applications. CoAP also supports multicast communication, allowing a single message to be sent to multiple recipients.

10.3.3 AMQP

AMQP stands for Advanced Message Queuing Protocol. It is an open standard protocol used for message-oriented middleware, allowing different applications to communicate with each other through a messaging system. AMQP provides a framework for the transfer of messages between applications, using a message broker as an intermediary to route messages between senders and receivers. It defines a set of rules for how messages are formatted, addressed, and delivered, and provides mechanisms for message queuing, routing, reliability, and security.

AMQP is designed to be transport agnostic, which means it can be used with different transport protocols such as TCP, SSL, or WebSocket. This makes it a flexible and scalable solution for building distributed systems and applications that require reliable and efficient message delivery. AMQP is widely used in enterprise messaging systems and cloud-based applications, providing a standardized and interoperable way for applications to exchange messages across different platforms and technologies.

11 Broadcast distribution

GNSS corrections can be broadcasted to devices to address scalability, where two types of broadcast is considered – cellular network system information broadcast and satellite broadcast. This chapter is for information only as no broadcast distribution will be evaluated in HyPos.

11.1 Cellular Network System Information Broadcast

LPP assistance data can be split up in blocks – positioning system information blocks (posSIB). The posSIBs can be configured for distribution in system information messages in parallel to other system information such as information about network identifiers, how to initially connect to the network, public warnings etc.

There are posSIBs for A-GNSS, GNSS OSR, GNSS SSR, GNSS integrity, 4G and 5G positioning. Table 7 lists the posSIBs related to GNSS OSR, SSR and integrity as of Rel 17, where the ones related to SSR are presented with a shaded background.

Table 7: GNSS-related posSIBs in 3GPP LPP Rel 17

	posSibType	***assistanceDataElement***
GNSS Common Assistance Data (clause 6.5.2.2)	*posSibType1-5*	*GNSS-RTK-ReferenceStationInfo*
	posSibType1-6	*GNSS-RTK-CommonObservationInfo*
	posSibType1-7	*GNSS-RTK-AuxiliaryStationData*
	posSibType1-8	*GNSS-SSR-CorrectionPoints*
	posSibType1-9	*GNSS-Integrity-ServiceParameters*
	posSibType1-10	*GNSS-Integrity-ServiceAlert*
GNSS Generic Assistance Data (clause 6.5.2.2)	*posSibType2-9*	*GNSS-AuxiliaryInformation*
	posSibType2-12	*GNSS-RTK-Observations*
	posSibType2-13	*GLO-RTK-BiasInformation*
	posSibType2-14	*GNSS-RTK-MAC-CorrectionDifferences*
	posSibType2-15	*GNSS-RTK-Residuals*
	posSibType2-16	*GNSS-RTK-FKP-Gradients*
	posSibType2-17	*GNSS-SSR-OrbitCorrections*
	posSibType2-18	*GNSS-SSR-ClockCorrections*
	posSibType2-19	*GNSS-SSR-CodeBias*
	posSibType2-20	*GNSS-SSR-URA*
	posSibType2-21	*GNSS-SSR-PhaseBias*
	posSibType2-22	*GNSS-SSR-STEC-Correction*
	posSibType2-23	*GNSS-SSR-GriddedCorrection*

The system information messages containing posSIBs are defined both for 4G/LTE/EPC and 5G/NR/5GC.

11.2 Satellite Broadcast

There are different systems for broadcast distribution of GNSS SSR, including Galileo HAS, BeiDou PPP-B2b, u-blox PointPerfect and different proprietary representations.

Galileo HAS (High Accuracy Service) became available in January 2023 and provides initially corrections for satellite orbit errors, satellite clock errors and satellite signal biases, and the full service will later also include atmospheric corrections valid for Europe. The corrections are broadcast via the Galileo satellites themselves, through the E6-B signal component in the E6 frequency band with a center frequency of 1278.75 MHz ([21]).

The BeiDou PPP-B2b service of BDS-3 satellites provides corrections for satellite orbit errors, satellite clock errors and satellite signal biases, the corrections being valid for China and some surrounding regions. The corrections are broadcast via the geostationary satellites in the BDS-3 constellation (3 out of 30 satellites in this constellation are geostationary), through the B2b_I signal component in the B2b frequency band with a center frequency of 1207.14 MHz ([22]).

Several commercial SSR services exist, typically with global, continental, or sub-continental coverage. Many of these services broadcast their SSR corrections via satellites. As an example, SSR corrections in the SPARTN format (ref. chapter 9.1) are distributed via satellites as one option of the commercial PointPerfect service, provided by u-blox ([13]). Here in WP 2 of the HyPos project, however, the cellular communication option is used when testing PointPerfect.

12 Analyzing requirements and distribution abilities

There is a plethora of requirements on high accuracy GNSS correction distribution mechanisms, and some of them are discussed in this chapter.

1. Compatibility and interoperability. RTCM, LPP, published and proprietary
   - Compatibility and interoperability is a combination of correction representation and distribution form. A correction representation can be widely adopted, but still needs a supported distribution form. RTCM via NTRIP is widely supported, while RTCM via MQTT is not, etc.
   - The more open representations RTCM and 3GPP are fully interoperable, while the published SPARTN and SSRZ can be interoperable by implementation and proprietary are not interoperable.
2. Scalability and efficiency
   - Scalability and efficiency concerns the
     i. data volumes generated by the SSR representation due to encoding and information rate
     ii. distribution protocol overhead
   - Broadcast means provides full scalability, and combinations with unicast distribution is attractive to reach efficiency for low and/or uneven spatial user density
   - There does not seem to be large differences between the different SSR representations and distributions – the possibility to migrate to broadcast seems most important.
3. User provisioning
   - Convenience when onboarding new users, both individually and in large groups, becomes very important in mass-market deployments.
   - Most options need to provision username, password, and server IP address, where it is common to rely on pre-configuration or transfer via email, SMS etc. and manual configuration of the device.
   - 3GPP-LPP either via SUPL or cellular broadcast is different in this regard, since provisioning by the mobile network operator is similar as for any additional service – via a subscription database or interface, which makes provisioning of large number of users convenient. In addition, the unicast server IP address is automatically configured meaning that no device side provisioning is needed, and the same general device can be deployed in any mobile network.
4. Security
   - Key aspects include authentication, authorization, differentiation and user privacy
   - Authentication confirms that a user is who it claims to be
   - Authorization gives those users access to the service
   - Differentiation enables the service provider to offer different service level/quality/scope to different users
   - User privacy ensures that position information associated to a user is not exposed to someone unauthorized. None of the protocols for SSR corrections require the device to report its precise position to the service.
   - All considered protocols seems to support authorization and authentication. User privacy can be ensured by implementation.

5. Hybridization with 5G
   - Combination with high accuracy GNSS based on SSR corrections and 5G positioning can be of two kinds:
     i. Integrated combination where the same protocol is used both for SSR correction assistance data distribution and 5G positioning. It also can include mechanisms for periodic position reporting, either the combined position or two individually determined positions. It is only 3GPP LPP that supports this.
     ii. Implemented combination, where different protocols are used for SSR correction assistance data distribution and 5G positioning. This option is possible for all considered protocols.
6. Latency
   - Latency end to end can have many contributions, including:
     i. Processing delays in the service backend to process data from a network of reference stations
     ii. Signaling delays due to communication link quality and bandwidth
     iii. Protocol delays
   - The latency is dominated by the first part, so variations in the third part does not have a large impact in relative terms.
7. Reliability
   - Part of the reliability concerns the ability to ensure that the correction data is correct, but also the allow the device to bound its error sources. The latter is commonly referred to as integrity, which is outside the scope of HyPos. Several of the considered representations also support integrity. The integrity scope also needs to be verified as well as the different nodes and functions.
8. Representativity and performance
   - There are some variations in the representations ability to represent the SSR values. These include differences in parameter value ranges and resolution, in number of parameters in models to represent a component, quality values and scope etc.
   - The resulting performance is due to a combination of the quality and density of the reference station network, the processing entity algorithms, the representation, the local device environment, the device antenna and the device positioning engine. Therefore, it is difficult to make a comparison between the impact on performance from different representations.
9. Exposure
   - Some network applications rely on precise position information from devices, and in such cases it is endorsed to configure reporting of position information from the device to the server and expose the information to network applications. Only 3GPP LPP can be combined with such features as part of the standardized interfaces in 3GPP.

A research project by FrontierSI with primary project partners Geoscience Australia and Queensland University of Technology have analyzed a subset of the protocols [11] with respect to requirements categories 2, 4, 6 and 7.

12.1 Improving access to precise positioning information by utilizing modern data transmission protocols

This subchapter refers to a research project by FrontierSI [11] together with the primary project partners Geoscience Australia and Queensland University of Technology.

They define the **challenge**:

"*Real-time streaming of GNSS data and corrections via the Internet is one of the key enablers for precise positioning solutions. For more than a decade, NTRIP or Network Transport of RTCM (a standard) via Internet Protocol, has been the standard to disseminate GNSS data and corrections streams in real-time for accurate and precise positioning applications, as well as scientific and research communities. With technology advances in the hardware, software, and wireless communications, NTRIP faces several challenges that may limit the uptake and reduce the efficiency of precise positioning by modern mass-market applications. These include system hierarchy and scalability; operation efficiency and optimization; and protocol and software support. The objective of this scoping study is to review and evaluate modern data transmission protocols for improving access to real-time precise positioning information for modern mass-market applications.*"

This study examined and assessed seven modern data protocols for transmitting GNSS data in IoT applications, including HTTP, CoAP, MQTT, AMQP, WebSocket, Kafka, and LPP. The study relied on standards, academic literature, and industry whitepapers over the past decade. The protocols were evaluated based on their adherence to open standards, compatibility with modern applications, scalability, reliability, security, and additional features such as data buffering and bandwidth optimization.

Figure 12-1 shows a summary of the performance of the different protocols for selected key indicators.

Key Performance Indicator	Most promising protocol				Least promising protocol
Latency					
Over LAN	CoAP	MQTT QoS0	AMQP	Websocket	HTTP/REST
Mobile network	MQTT QoS0	CoAP	Websocket	MQTT QoS1	
Required bandwidth	CoAP	MQTT	AMQP		HTTP/REST
Throughput	MQTT		CoAP	AMQP	
Reliability	MQTT	AMQP	CoAP	Websocket	HTTP/REST
Security	AMQP / MQTT 5	HTTP	CoAP		MQTT 3.x
Developer's preference	MQTT	HTTP/REST	Websocket	CoAP	AMQP

Figure 12-1: Performance of the different protocols.

MQTT was found to perform well in most areas, while HTTP and WebSocket were found to be less suitable due to their request-response model designed for web applications. NTRIP, which is based on HTTP, has similar characteristics and performance to HTTP. The study recommends MQTT as the most flexible and versatile data communication protocol for future GNSS precise positioning applications.

In conclusion, the precise position landscape is fast evolving, modern applications are expected to have different requirements to existing applications, as such a hybrid solution that aggregates the strengths of multiple protocols may further improve the overall GNSS data transmission landscape, as shown in Figure 12-2. The backbone services can be managed with MQTT, NTRIP and AMQP - where AMQP handles inter-system data transmission with high message throughput (between service providers). Several supportive protocols may be used for GNSS data processing (Kafka), web application (WebSocket) and mass market data delivery (3GPP / MQTT-SN / CoAP).

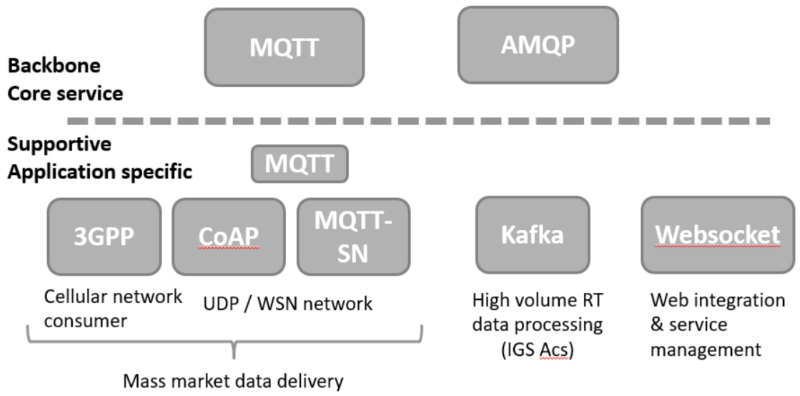


Figure 12-2: Hybrid solution.

13 List of abbreviations

3GPP	**3**rd **G**eneration **P**artnership **P**roject
AG	(Ger.) **A**ktien**g**esellschaft
BeiDou	GNSS of China. Also commonly referred to as BDS.
CPOS	**C**entimeter **Pos**ition (NMA's high-precision OSR service)
DOP	**D**ilution **O**f **P**recision
Galileo	GNSS of European Union
GLONASS	**Glo**balnaya **Na**vigatsionnaya **S**putnikovaya **S**istema (GNSS of Russia)
GmbH	(Ger.) **G**esellschaft **m**it **b**eschränkter **H**aftung
GMLC	**G**ateway **M**obile **L**ocation **C**enter
GNSS	**G**lobal **N**avigation **S**atellite **S**ystem
GPS	**G**lobal **P**ositioning **S**ystem (GNSS of USA)
HAS	**H**igh **A**ccuracy **S**ervice (A service by Galileo)
HPE	**H**orizontal **P**osition **E**rror
HyPos	**Hy**brid **Pos**itioning Service
IGS	**I**nternational **G**NSS **S**ervice
IMU	**I**nertial **M**easurement **U**nit
KPI	**K**ey **P**erformance **I**ndicator
LPP	**L**TE **P**ositioning **P**rotocol
LTE	**L**ong-**T**erm **E**volution
NEF	**N**etwork **E**xposure **F**unction
NMA	**N**orwegian **M**apping **A**uthority
NR	**N**ew **R**adio
NTRIP	**N**etworked **T**ransport of **R**TCM via **I**nternet **P**rotocol
OSR	**O**bservation **S**pace **R**epresentation
PPP	**P**recise **P**oint **P**ositioning
RAT	**R**adio **A**ccess **T**echnology
RTCA	**R**adio **T**echnical **C**ommission for **A**viation
RTCM	**R**adio **T**echnical **C**ommission for **M**aritime Services
RTK	**R**eal **T**ime **K**inematic (concept for high-accuracy GNSS positioning)
SPARTN	**S**ecure **P**osition **A**ugmentation for **R**eal-**T**ime **N**avigation
SSR	**S**tate **S**pace **R**epresentation
STEC	**S**lant **T**EC (TEC along the path of GNSS signal between satellite and receiver)
SUPL	**S**ecure **U**ser**P**lane **L**ocation
TEC	**T**otal **E**lectron **C**ontent (standardized unit closely related to the delay/advance of GNSS signals in the ionosphere)
TZD	**T**roposphere **Z**enith **D**elay. Also commonly referred to as ZTD.
VPE	**V**ertical **P**osition **E**rror
VTEC	**V**ertical **TEC**
WP	**W**ork **P**ackage

14 References

[1] R. Hirokawa, I. Fernández-Hernández, S. Reynolds: "PPP/PPP-RTK open formats: Overview, comparison, and proposal for an interoperable message". Wiley / ION, 2021.

[2] SPARTN format description. https://www.spartnformat.org/

[3] SSRZ format description. https://www.geopp.de/ssrz/

[4] Minimum Operational Performance Standards for Global Positioning System / Wide Area Augmentation System Airborne Equipment. RTCA, 2001.

[5] 3GPP LTE Positioning Protocol (4G and 5G), TS 37.355. https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3710

[6] NTRIP, RTCM 10410, Standard for Networked Transport of RTCM via Internet Protocol (Ntrip) - An application-level protocol that supports streaming Global Navigation Satellite System (GNSS) data over the Internet.

[7] E. Lenz: Networked Transport of RTCM via Internet Protocol (NTRIP) – Application and Benefit in Modern Surveying Systems, FIG Working Week, Athens 2004.

[8] Open Mobile Alliance, "Secure User Plane Location (SUPL) 2.0", available at http://www.openmobilealliance.org/release/supl/

[9] Google SUPL Client, https://github.com/google/supl-client

[10] Ericsson SUPL 3GPP LPP client, https://github.com/Ericsson/SUPL-3GPP-LPP-client

[11] FrontierSI, Modern Data Transmission Protocols for Precise Positioning. https://frontiersi.com.au/project/mdtp/

[12] Workshop IGS. https://s3-ap-southeast-2.amazonaws.com/igs-acc-web/igs-acc-website/workshop2018/presentations/IGSWS-2018-PY04-04.pdf

[13] u-blox: PointPerfect. https://developer.thingstream.io/guides/location-services/pointperfect-service-description

[14] u-blox: MQTT beginner's guide. https://www.u-blox.com/en/blogs/insights/mqtt-beginners-guide

[15] I. Idris (2017). Real-time vehicle monitoring and positioning using MQTT for reliable wireless connectivity. Master thesis (Queensland University of Technology). https://eprints.qut.edu.au/106921/1/Izwan_Idris_Thesis.pdf

[16] GNSS SSR and OSR, https://www.geopp.de/gnsmart-for-ssr-broadcast/#

[17] A. Boda: "What is Ambiguity Resolution?". https://aaronboda.wordpress.com/, 31.01. 2019.

[18] K. S. Jacobsen, N. Sokolova, M. Ouassou, A. M. Solberg: "Study of time- and distance-dependent degradations of network RTK performance at high latitudes in Norway". Springer Nature Applied Sciences, 2023.

[19] J. Böhm: GNSS Processing based on IGS Products - Troposphere Modelling. Technical University of Vienna / International GNSS Service. Presentation 17.02.2022.

[20] 3GPP website. https://www.3gpp.org

[21] Galileo HAS Service Definition Document, Issue 1.0. European Commission, January 2023.

[22] BeiDou Navigation Satellite System Signal In Space Interface Control Document - Precise Point Positioning Service Signal PPP-B2b, Version 1.0. China Satellite Navigation Office, July 2020.