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RESEARCH ARTICLE

GNSS Technology for Precise Positioning in CCAM: A Comparative Evaluation of Services

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ABSTRACT Cooperative, connected, and automated mobility (CCAM) can lead to a significantly improved transport system by increasing safety and efficiency, and reducing emissions. To achieve the goal of fully automated mobility and self-driving vehicles, accurate and reliable positioning is essential. Positioning methods in CCAM often use sensor fusion combining data from multiple sensors with Global navigation satellite system (GNSS) positioning data. In this paper, we focus on the status of GNSS technology by investigating position accuracies and integrities of different state-of-the-art GNSS technologies. We conduct field tests using a self-driving vehicle in Drammen, Norway. Three different types of GNSS positioning services are explored, and a reference trajectory delivered by the vehicle's navigation system is used to determine the performance of each service. We show that the performance of the GNSS methods alone does not fulfill the requirements needed to obtain fully automated mobility. Moreover, we observe a general decreasing trend in GNSS accuracy for more challenging surroundings.

INDEX TERMS CCAM, navigation, GNSS, PPP-RTK, network RTK, sensor fusion.

I. INTRODUCTION

CCAM is expected to have a significant impact worldwide [1]. Fully automated vehicles could lead to smoother traffic flow, increased efficiency, reduced emissions, and better safety. In addition, it would provide accessible mobility to people whom today cannot drive, and challenges related to energy consumption can be addressed.

One of the key enabling technologies for CCAM is precise vehicle positioning. Positioning with decimeter to sub-meter accuracy is a fundamental capability for automated driving and a technology applicable in various use cases. Navigation systems used for CCAM typically specify their performance in terms of availability, accuracy, and integrity [2]. However, the requirements for positioning within the transport sector depend heavily on the service in question and the level of automation. The Society of Automotive Engineers (SAE) defines six levels of automation for automated driving systems [3]. The levels range from no automation (Level 0 – the driver performs all tasks) to full automation (Level 5 – a driverless car able to operate on any road under all conditions). A self-driving vehicle, defined as level 4, requires the driving system to precisely and safely execute driving maneuvers such as lane changes or turns at intersections. Due to complex and dynamically changing driving environments, achieving a sufficiently accurate and reliable position over time or distance is considered one of the main challenges in CCAM [4].

GNSS is an attractive positioning approach due to its low cost, flexibility, and availability. Numerous use cases utilize GNSS in CCAM. Examples are route planning, navigation systems, lane centering, map matching, speed limitation system, and collision avoidance with fixed and known infrastructure [5]. Even though GNSS is a widely used and reliable service for many applications, it is vulnerable to several conditions, especially those caused by challenging urban environments, where CCAM technology is most likely needed [6]. Factors that can reduce the GNSS signal strength include tunnels, urban canyons, topography, satellite availability, and solar storms. When positioning is used in

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route planning to navigate to a specific destination, the consequences of a lost or inaccurate signal will probably not cause any more profound effects but a loss of time. However, in the future, when GNSS positioning is used in the navigation systems of automated vehicles, it is crucial to receive accurate and reliable data over time. As the consequences and complexities of the applications increase, so will the requirements set on the positioning system [7]. For instance, reliable and safe use of GNSS corrections is essential for CCAM, e.g., to guarantee that the corrections and the GNSS signal itself can be trusted, as these are typically safe critical services. However, data security and encryption are not topics covered in this paper.

Most positioning techniques use information from a wide range of sensors to obtain the best possible position estimate. GNSS is often combined with inertial measurements from an IMU (Inertial measurement unit), velocity information from odometers, and optical sensors such as LiDAR (Light detection and ranging), RADAR (Radio detection and ranging), and camera. How information from these sensors is combined within the navigation systems varies from method to method and is currently one of the core innovation fields for developing automated vehicles. Sensor fusion methods use the main advantages of each sensor and combine all information to a best possible final position estimate [8]. The influence of one single sensor is hard to assess due to complex weighting matrices for each sensor which differs from method to method. Sensor fusion algorithms are often black boxes to a scientist due to economic interests of the manufacturers. However, for the sake of reliability and redundancy, it is crucial to assess the individual performance of each sensor. It needs to be understood to some degree by the stakeholders in CCAM to understand the limitations of the technology and what measures must be taken, for instance, in terms of infrastructure, to make CCAM as reliable and safe as possible.

While it can be difficult to evaluate the performance of individual sensors, comparing different models and setups of the same sensor can be equally challenging. When focusing on GNSS, the market has developed complex value chains for their products, where different components depend on each other. For example, many GNSS correction services are limited to use with hardware from the same manufacturer and are far from open source. As a result, it is impossible to separate the performance of the service or hardware from the overall assessment, which will always be biased by the specific test setup. Proprietary formats and economically driven standardization have dominated the GNSS industry since the beginning. A change toward open standards is slow, and especially newer technologies and developments are held secret due to economic interests [9]. Related to this issue, commonly used parameters - such as the prevalent positioning performance indicator ''GNSS fix'' - are not standardized, further complicating the evaluation process. Technically, this term describes the correct integer estimation of the phases in the GNSS signal – which depends on a probability requirement. In many different receivers, the requirements for a fix-position are implemented with varying parameters regarding the success rate and the probability of the estimate [10]. Often, these implementations are dedicated to a specific use case, which segments the hardware market into many different receiver types. In the case of the fix flag, this leads to more conservative or optimistic implementations and, therefore, somewhat different performances.

In this study, a particular focus is put on Nordic areas and primarily on higher latitudes. There are several challenges in the north related to localization of automated vehicles and CCAM. The winter can be harsh and dark, with snow, fog, and low temperatures affecting the sensor performance. For instance, both LiDARs and cameras are highly influenced by such circumstances. From a GNSS perspective, satellite visibility is more limited in areas with extreme latitudes. Also, a more active ionosphere hampers high-accuracy GNSS positioning. This paper studies some GNSS solutions and focuses on factors that may reduce the accuracy of GNSS positioning. Since CCAM services prompt high integrity requirements, it is necessary to carefully analyze potential faults and failures of GNSS technologies.

We conduct a field test using a self-driving vehicle in Drammen, Norway. Three different GNSS positioning services are explored, and a reference trajectory delivered by the vehicle's navigation system is used to determine the accuracy of each service. The performance is studied for different surroundings, ranging from open to more urban areas.

The paper is organized as follows. Background on the use of GNSS in CCAM is presented in Section II. The data collection strategy and method are described in Section III, followed by the results of the analysis and conclusions in Sections IV and V, respectively.

II. BACKGROUND: GNSS FOR CCAM

This paper emphasizes the role of GNSS in a vehicle's sensor fusion system. Although the manufacturer of a positioning device typically possesses in-depth knowledge of the established parameters and the interdependencies within the employed algorithms, it can be challenging for users or researchers to discern the impact of each sensor in the fusion process. As a result, understanding the individual contributions and limitations of each sensor can be difficult. Consequently, acquiring the expertise to ensure optimal conditions for the sensor fusion system to function effectively, such as maintaining infrastructure, can be a demanding undertaking.

GNSS, as a global positioning technology, is a critical component for most applications of CCAM. GNSS technology is based on the availability of visible satellites from the used constellations, where as a rule of thumb, a higher number of visible satellites translate into a more accurate position. The first system developed was the Navstar Global positioning system (GPS) which is still operated by the United States Space Force. Contemporaneously with GPS, Russia developed its system, Glonass, which took some years longer to become fully operable. In recent years, both the European Galileo and the Chinese Beidou navigation satellite system have been implemented to a usable state which results in four navigation systems with global coverage. All systems allow for simpler code navigation and more precise and advanced carrier phase positioning.

Most receivers are designed to use the two oldest constellations: GPS and Glonass. Newer receivers that came to the market in the previous few years often include Galileo and Beidou. The four independent satellite systems provide a comprehensive offer of satellites in the sky.

A. PRECISE POSITIONING

The simplest applications of GNSS only use unprocessed satellite signals for positioning and some additional data provided via an internet connection for faster initialization.

This forms the most common type of application, as it is found in, e.g., mobile phones, sports watches, fleet management systems, etc. For route planning purposes, this type of positioning delivers an accuracy of a few meters which is sufficient for these applications. On the other hand, professional GNSS users (e.g., land surveyors) have in many years based their measurements on corrected GNSS positions, where correction data is used to enhance the quality of the unprocessed GNSS signals. This correction data is generated from fixed geodetic stations, commonly referred to as reference stations, and is essential for eliminating inherent GNSS measurement errors to achieve precise positioning.

Various methods for precise positioning exist, with the primary distinction arising from the type of error representation [11]. Observation Space Representation (OSR) involves the user receiver transmitting its position to the server, which then calculates position-specific corrections for the user, removes errors through correlation, and returns the corrections to the user. In contrast, State Space Representation (SSR) identifies error sources independently and broadcasts correction parameters, allowing the receiver to compute the corrected position for its specific location. The data flow from reference stations to end users for both OSR and SSR is illustrated in Figure 1. Table 1 presents the key characteristics of these two methods.

The infrastructure requirements differ between various types of OSR and SSR. Network RTK (Real Time Kinematics) typically features baselines between reference stations of approximately 30 to 50 km. In contrast, the PPP-RTK (Precise Point Positioning – RTK) services employed have reference stations spaced between 80 km and 120 km. Network RTK necessitates a comprehensive GNSS infrastructure, with Norway boasting over 300 reference stations for the Network RTK method tested in this paper. Conversely, PPP-RTK methods are significantly less demanding regarding infrastructure, with the approaches examined in this paper incorporating only 18 to 21 stations in Norway. Note that this

TABLE 1. The two most used methods for correcting GNSS signals and some of their characteristics. [12], [13], [14], [15], [16], [17].

Correction Method	Observation Space Representation (OSR)	State Space Representation (SSR)
Possible Accuracy	1-2 cm	3-20 cm
Mode of correction	Correlation with additional observations	Identification of the error sources
Coverage	Regional	Global
Initialization	< 5 s	< 30 s – 5 min
Communicatio n	Two-way	One-way
Examples	RTK, Network RTK	PPP, PPP-RTK

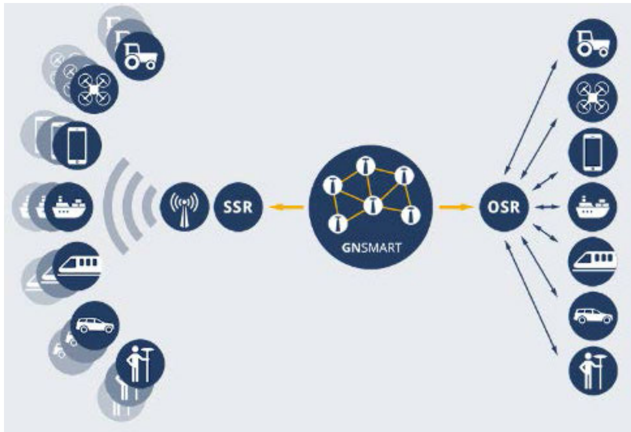

FIGURE 1. The illustration demonstrates the key differences between OSR and SSR. GNSS reference stations and correction computation by the server software (GNSMART) are depicted, as well as two-way communication for OSR and broadcasting for SSR to an unlimited number of users [41]. Communication between reference stations, server, and GNSS receivers is facilitated through LTE.

leads to an exponential increase of stations between the two services when the coverage expands.

SSR services are typically designed for large areas and limited accuracy, while OSR aims for high accuracy within smaller regions. Given that OSR requires extensive infrastructure and users must be in close proximity to a reference station to achieve the intended accuracy level, it is more susceptible to reference station outages than SSR, which can maintain the designed accuracy even in the event of an outage. Consequently, OSR is heavily dependent on the uptime and functionality of GNSS reference stations, while SSR services can preserve their designed accuracy level and demonstrate greater robustness, even during reference station outages.

In this study, one Network RTK (OSR) service is examined as the state-of-the-art method for corrected GNSS positioning services, while two PPP-RTK (SSR) services are evaluated as emerging positioning service technologies, see Tabel 2. OSR requires two-way communication and is not scalable. Still, it is a well-established technology offering high positioning accuracy and rapid convergence time due to the short distance to reference stations. The primary motivation for utilizing SSR is its scalability, achieved by broadcasting corrections to an unlimited number of users, making it essential for CCAM applications (see Figure 1). However, this comes at the cost of reduced accuracy and longer initialization time.

With the relatively dense network in Norway, the Network RTK service has around 15 times more reference stations than the PPP-RTK services. Network RTK technology has some drawbacks, including coverage often limited to a single country or region. Moreover, many remote areas are not economically viable for a Network RTK service due to the high costs associated with infrastructure maintenance. PPP-RTK, on the other hand, boasts the advantage of global coverage and requires only a fraction of the infrastructure needed for Network RTK. However, PPP-RTK is a relatively new technology and is currently limited to the use of dedicated hardware, while the standardization of open formats is a benefit for Network RTK technology, allowing it to be used with various, more affordable hardware options.

B. SATELLITE GEOMETRY AND LINE-OF-SIGHT

Previous studies have demonstrated that the local geometry of satellites significantly influences the performance of GNSS positioning (refer to [5] and [18], and the citations therein). The geometry is dependent on the receiver's geographical location, as well as line-of-sight (LOS) in the local environment and the placement of the receiver [19], [20]. For instance, in urban canyons, which are common in city areas, tall buildings may obstruct GNSS signals, resulting in a limited LOS (see Figure 2). Practical experiences of GNSS users indicate that local disturbances leading to non-line-of-sight (NLOS) situations are among the most significant weaknesses of satellite positioning. Consequently, numerous receivers have incorporated algorithms designed to detect and mitigate the adverse effects of these phenomena.

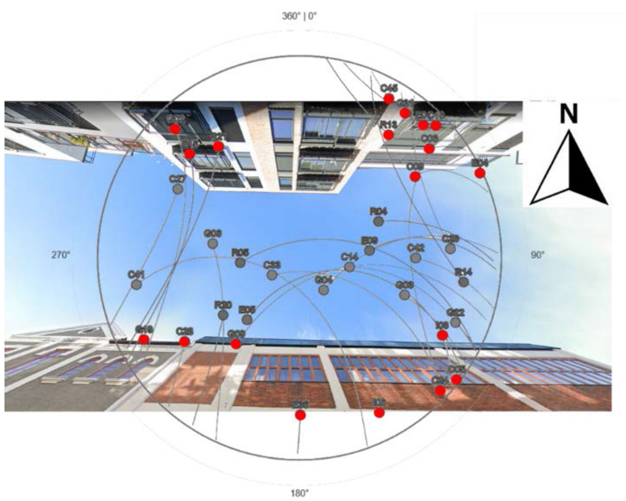

FIGURE 2. Visible satellites at a selected timestamp in the study area in a sky plot. The red marked satellites do not have a direct line-of-sight to the user due to the buildings in the urban canyon.

The vulnerability of GNSS geometry cannot be directly compared across different locations due to the varying orbits of satellites in both time and space. Measurements taken in extreme latitudes will encounter different geometry than those closer to the equator. As a result, not only do global geometries differ, but the local impact of NLOS also varies between applications worldwide. Using the example of tall buildings in an urban canyon, the window permitting LOS to satellites remains consistent at different latitudes, but the number of visible satellites changes according to the position on the globe.

For this purpose, the following study has been undertaken. By using a GNSS planner, the changes in satellite geometry in relation to the position on the globe are compared. Considering the small city of Drammen (Figure 2), different building heights can be applied to a NLOS scenario. A comparison has been calculated for latitudes between 0 and 80 degrees and building heights exceeding the vehicle's position by 1 to 20 meters. The vehicle's position relative to an urban canyon is given from a real position in the study of Drammen, with the vehicle positioned 4.8 m from the buildings in the south and 8.6 m from the buildings in the north. In the chosen region, the road and the resulting canyon are situated in an east-west direction, which allows for a cut-off of the NLOS-satellites in the south and north planes, defined by the elevation resulting from the buildings. The study was done for two points in time on the same day: 01.12.2021, 8 o'clock and 14 o'clock. The satellites included are from the four main navigation systems: GPS, Glonass, Galileo, and Beidou. The average of the results is shown in Figure 3.

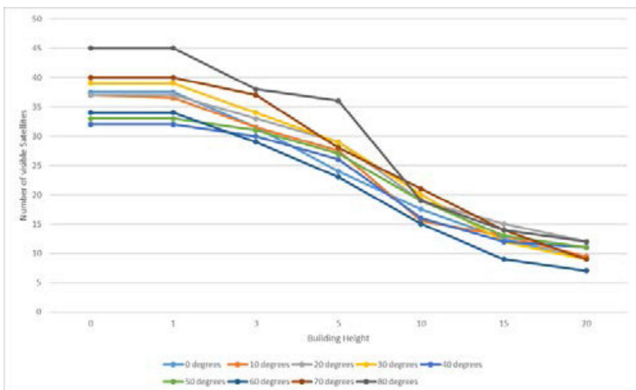

FIGURE 3. The dependence of the number of visible satellites on the geolocation in relation to the building heights around the user.

Based on the results in Figure 3, it can be inferred that the relative position on the globe only marginally affects the number of visible satellites. Additionally, the figure demonstrates that the influence of the cut-off angle according to the building height remains consistent across different areas, despite variations in satellite constellations. As anticipated, the number of satellites not visible to the GNSS sensor increases significantly with taller buildings, as many satellites are positioned at lower elevations (see

Figure 2). However, this trend is quite similar across all locations, and the gradients of the curves are comparable. In the worst-case scenario, the number of visible satellites for the four constellations at the given timestamp is still above six. While this may be sufficient for a valid position in most receivers, sub-meter accuracy cannot be expected.

C. POSITIONING REQUIREMENTS FOR CCAM

Navigation systems used for CCAM typically specify their performance in terms of availability, accuracy, and integrity [2]. For a fully automated system, the availability must be 100%, as a loss of position while driving would be critical. The accuracy of a method is described by the error; typically, the mean error and percentiles are used. Again, future CCAM services will also have a high demand for accuracy. Lastly, the integrity is described by the extremes of the error. That is, how often/or for how long do we experience errors larger than a maximum accepted error?

In [21], it is stated that there currently do not exist any common values for the accuracy, integrity, and availability requirements for automated driving systems. Different requirements have been proposed, like [22] reviewing suggestions for localization accuracies below 0.3 m; see also overview in [5] or [23]. Still, due to the most reasonable scientific grounding and the stringent accuracy requirements, in this work, we rely on the definitions by [2], which use 0.1 m accuracy at 95% confidence. They also define alert limits of 0.29 m with integrity levels of 10^{-8} per hour.

D. EVALUATING THE PERFORMANCE OF GNSS POSITIONING METHODS

Navigation with GNSS has a long history and continues to grow in importance, leading to an abundance of literature on performance assessments and technical reviews. Many studies that examine the performance of corrected GNSS are done in static applications since the traditional application field is mainly found in geodesy and survey. Dynamic applications often utilize low-cost sensors that do not allow for correction. However, with the rapidly decreasing costs of higher-quality receivers, the application of corrected GNSS on a mass market scale for dynamic applications is emerging. To facilitate this, modern broadcast technologies like SSR must be introduced. New technologies like SSR are expected to dominate the professional market of corrected GNSS in the coming years, and assessing the performance in real urban environments is crucial for the transportation sector. To date, no studies have tested SSR and traditional RTK in a real-life urban environment application. In this paper, the issue of obtaining a correct baseline reference dataset was resolved through the commercial navigation system of the automated vehicle, which is estimated to be highly reliable (see the following section for details). In Table 3, a short literature review of performance evaluation methods of GNSS is presented, including a summary and the difference from the approach used in this paper.

TABLE 2. The three investigated positioning services and their characteristics, including distance to the nearest reference station from the city of Drammen and hardware type.

Ser-vice	Type of correctio n	Closest reference station	Receiver	Weight	Constellatio ns
1	Network-RTK (OSR)	Drammen – 7.5 km	Trimble NetR9	1.75 kg	GPS + GLO + Gal + BD
2	PPP-RTK (SSR)	Spikkestad – 8.9 km	Trimble NetR9	1.75 kg	GPS + GLO
3	PPP-RTK (SSR)	Kongsberg – 32.5 km	u-blox F9P	< 100 g	GPS + GLO

TABLE 3. Summary of papers on evaluation of GNSS performance and difference from the work presented.

Paper (year)	Summary	Difference from this work
[19] (2016)	Availability and RTK performance in an urban area for different techniques	Static application, only RTK methods
[24] (2017)	RTK performance in staged urban conditions on moving vehicle	Only RTK services, no real-life application
[25] (2019)	Singular, simultaneous evaluation of different receiver types on vehicle	Not enhanced GNSS
[26] (2019)	RTK performance for low-cost receivers	Static application, only RTK services
[27] (2020)	Availability of GNSS receivers in dynamic applications in urban areas	Not enhanced GNSS, no comparison of different services/receivers
[28] (2020)	Performance comparison of different receivers used in an agricultural context	Limited enhanced GNSS, staged – no real-life application
[29] (2020)	Performance comparison of SSR services and different products	Static application, non-commercial SSR service
[30] (2020)	RTK performance for low-cost receivers in challenging environments	No comparison of different receivers, only. Only RTK services
[30][31] (2020)	Performance assessment for SSR services and multi constellations	Static application, no-real life application
[26][32] (2022)	Evaluation of GNSS performance with the use of multi constellations	Not enhanced GNSS, no comparison of different receivers, no real-life application

Table 3 shows that most studies focus on static applications of GNSS, although applications using positioning on moving objects with dynamic properties are increasing. This can be attributed to the traditional use cases of corrected GNSS in surveying and science. Additionally, reliable reference data from dynamic applications is hard to acquire since the reproducibility of the exact trajectories is hard. Consequently, many studies simulate real-life conditions, such as urban areas, by adding uncertainty factors to data acquired in optimal conditions. Furthermore, newer SSR technologies have not been widely assessed, particularly commercial service providers, as many of these services have only recently achieved full operability.

The present case study aims to use data acquired from an operating, dynamic system. Additionally, various commercial enhancing services are logged from the same antenna, and their performance is compared.

III. MATERIALS AND METHODS

The objective of the practical test is to compare different positioning services on a self-driving vehicle with the reference trajectory delivered by the vehicle's navigation system. In addition, the performance of the GNSS-based positioning system should be assessed in relation to the surroundings in an urban area. To allow for a direct comparison, the receivers with different positioning services were installed on the vehicle and connected to the vehicle's antenna.

The data collection was performed in the period 10.11.2021 – 16.12.2021, resulting in a 32-day campaign. The vehicle used for the collection is part of a self-driving pilot study for public transport in Drammen, Norway. The small bus (see Figure 4) has been deployed and successfully operated in various European cities. The navigation system on the bus relies on traditional sensor fusion between GNSS, IMU, LiDAR, and odometer sensors.

FIGURE 4. The bus from EasyMile (left picture) was used for the practical test in Drammen. The box on the right shows the installation of the receivers and the computer/modem used for remote access and to receive GNSS corrections for all receivers.

The reference data used as ground truth is the final position computed by the bus's sensor fusion system. Hence, the data does not only include input from the GNSS navigation but is also highly influenced by the other sensors such as LiDAR, odometer, and IMU [33]. Therefore, this position is expected to be very precise and reliable for comparing different positioning services. The sensor fusion system of the bus uses input from a corrected GNSS service provided by the Norwegian Mapping Authority [14]. As mentioned earlier, the sensor fusion system has a complex weighting algorithm implemented, which controls the influence of each sensor in relation to the others and finds the best solution for the final position. This part of the sensor fusion system is a black box, but the system developer claims an accuracy of 1 centimeter for the final position.

Three positioning services are tested on the vehicle simultaneously. Not all the positioning services are configurable with the same receiver, and the receivers slightly vary in quality, particularly in the price class. All the receivers are connected to the same Novatel GPS-704-X antenna through an antenna splitter, and they receive corrections via mobile communication (LTE) and not satellite (L-band) since this is more reliable in a city environment with obstructions to the sky. The reference data refers to the center of rotation in the bus, not the GNSS antenna. Therefore, a lever arm correction has been implemented to account for the bus's orientation at every timestamp.

All three GNSS services rely on a network of GNSS reference stations. The configuration of the network varies for each service, depending both on the type of augmentation, but also the preferences and prioritizations of the provider. Two of the services are based on the method of SSR, while the third is based on the traditional OSR method, see Table 1. The main characteristics of the three services are described in Table 2. For both types of correction, the distance to the nearest reference station is expected to be relevant, as local variations in the correction data increase with distance.

Services 2 and 3 now include all four constellations. However, during the data collection period, only GPS and Glonass were available for these services. Adding the additional constellations increases the satellite availability, especially in more challenging areas (such as urban canyons).

The bus follows a route in the city center of Drammen, with only slight variations on certain days. Due to the challenging driving environment in the city center, including congested areas and pedestrians, the bus often needs to be driven manually. However, the driving mode does not influence the results from the field tests or the data analysis, as the reference data is collected in real-time.

As discussed in Section II, the geometry of the surroundings can significantly impact the GNSS signal. The route is generally characterized by challenging conditions for GNSS, including high buildings, some vegetation, and narrow urban canyons. To investigate this further, the survey area is categorized into three groups defined by the surroundings: "Rather open", "Mixed" and "Challenging". The characterization of the surroundings is based on local knowledge of the test site, city center imagery, and openly available building height data sets from the Norwegian mapping authority to classify the areas into one of the three categories [34]. Table 4 summarizes the specifications of the three defined area types.

TABLE 4. The descriptions of the three different areas that were analyzed in this study. Only data overlapped with these regions were analyzed and used for the results.

Surrounding type	Building heights	Character	Distance
Rather open	< 5m	Some buildings, Vegetation, some open sky	517 m
Mixed	5 – 10 m	Many buildings, some open sky	772 m
Challenging	> 10m	Many buildings, limited open sky	855 m

An example showing the three surrounding types along the driving route in Drammen is depicted in Figure 5.

FIGURE 5. Example of the three surrounding types used to distinguish between GNSS conditions on the test site.

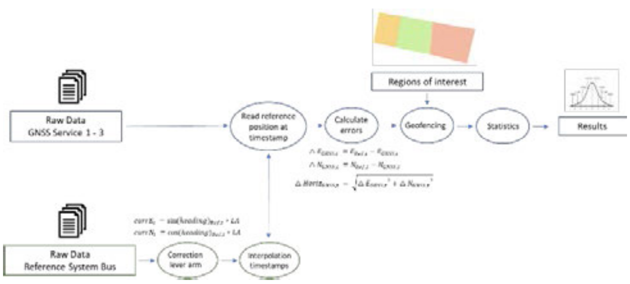

FIGURE 6. Workflow for the data analysis with the different inputs in the square-shaped areas and the methods in the rounded ones.

The workflow of the data processing from the raw data into the results is illustrated in Figure 6. Note that only the horizontal coordinates have been analyzed. The lever arm is provided in a local reference system on the vehicle, which is typical for such navigation systems. For analysis, the offset must be transformed into the global coordinate system (East and North). The vehicle's heading value is used for orientation in the global reference system, and the offset is distributed on the horizontal coordinates accordingly. After interpolation, calculations, and geofencing, statistics are generated. Only positions with a valid fix flag are included in the results, as it is expected that sensor fusion systems will attribute less weight to uncertain GNSS positions, especially in cases with no valid fix flag [35]. Various parameters describing the GNSS quality flags in the receivers are hidden and may therefore vary between different manufacturers. For each service, outliers of more than 5 m are excluded, as it can be expected that the common navigation system will detect outliers at this scale, for example, in combination with precise map data.

IV. RESULTS

The main results for horizontal errors between the measured GNSS positions and reference data are shown in Table 5. The results show a significant difference between the two types of correction methods – OSR and SSR. Service 1, a Network RTK service based on OSR, has smaller horizontal errors in all assessed parameters, in addition to a higher mean number of satellites. Service 2 has slightly better results than Service 3 overall (mean, median, and 95% quantile), but Service 3 seems to perform better with respect to higher quantiles, at least the 99% quantile.

TABLE 5. The main results for the horizontal errors compared to the reference data from the bus for the three services. These are the overall results, without any distinction between different area types.

Service	Type of correction	Mean	Median	95 % Quantile	99 % Quantile	Mean # satellites
1	Network-RTK (OSR)	0.236	0.146	0.656	2.219	14.6
2	PPP-RTK (SSR)	0.419	0.206	1.650	3.774	11.5
3	PPP-RTK (SSR)	0.467	0.235	1.685	2.877	11.9

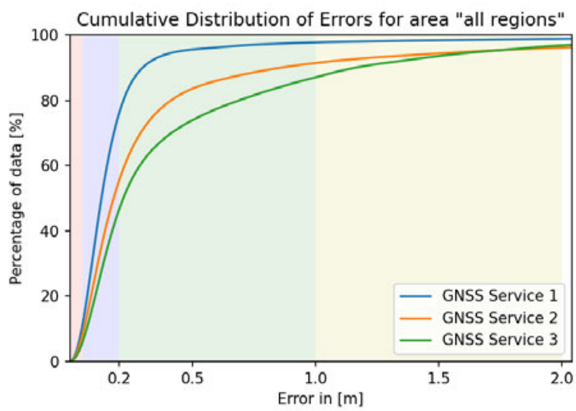

FIGURE 7. Cumulative distribution of the horizontal errors for the complete data set.

Figure 7 shows the cumulative distribution of the horizontal errors for the complete dataset. For GNSS Service 1, more than 80 % of the errors are lower than 20 cm. For Services 2 and 3, these percentages are slightly above 50 %, meaning that only half of the data points have a precision of 20 cm or lower. Again, it is clear that OSR performs better than SSR.

The complete dataset has also been split into diurnal variations, presented in Figure 8. Note that Service 3 does not have a marker point for all days, as the service was unavailable on some days. This result echoes the conclusions from Table 5. Service 1 performs better than Service 2, while Service 2 might be assessed as slightly better performing than Service 3.

By separating the data points into the three types of surroundings, "Rather open", "Mixed" and "Challenging"

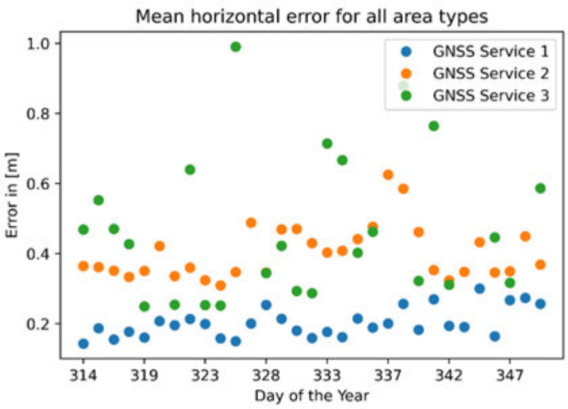

FIGURE 8. Daily means for the horizontal error and the three services over the complete data set.

(as described in Section III), the influence of the different surroundings can be assessed.

TABLE 6. The results for the horizontal errors for the three different surrounding types. Only the mean value and the 99 % quantile are shown here.

	Rather open		Mixed		Challenging	
Service	Mean	99 % Quantile	Mean	99 % Quantile	Mean	99 % Quantile
1	0.188	0.960	0.231	1.454	0.274	3.253
2	0.265	1.498	0.314	2.468	0.635	4.399
3	0.457	2.682	0.504	3.018	0.441	2.863

Table 6 summarizes the accuracy of the horizontal positions for the different surrounding types. Comparing OSR and SSR methods, the same behavior as the overall results can be observed, with OSR delivering better accuracy than SSR (lower mean and quantile value). As expected, the errors for Services 1 and 2 are slightly higher for the "Mixed" and "Challenging" areas [36]. For Service 2, there is a rather significant difference between "Mixed" and "Challenging", with both mean and quantile values approximately doubling. Service 3 is more inconclusive; Only the difference between "Rather open" and "Mixed" is as expected. Surprisingly, the "Challenging" areas show slightly better results than "Mixed" and "Rather open" in terms of mean value and better than "Mixed" also in terms of the 99 % quantile. A cumulative distribution diagram for the surrounding type "Challenging" is shown in Figure 9.

The results above demonstrate that the traditional OSR based Network RTK (Service 1) performs better than the newer SSR based correction methods (Services 2 and 3). This is expected for several reasons: As discussed in Section II.A, the number of reference stations for the tested Network RTK (Service 1) is much higher than for the other two services. In addition, the two PPP-RTK services (Service 2 and 3) only use two main navigation systems (GPS and Glonass), while Service 1 also uses Galileo and Beidou.

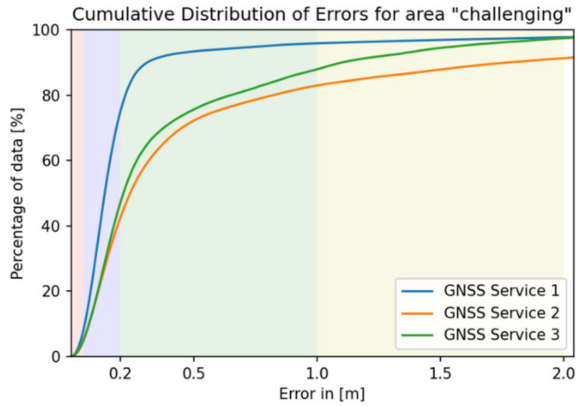

FIGURE 9. Cumulative distribution of the horizontal errors for the area type "Challenging".

The difference in receivers used for the various GNSS services may also explain the difference in performance between the methods. Service 1 and 2 use a receiver designed for traditional RTK correction, while Service 3 uses a less expensive receiver that might negatively influence the results. Therefore, slightly higher errors for Service 3 can be attributed to the quality of the receiver.

Overall, the typical perception that local conditions significantly influence GNSS performance is supported by the results. A clear trend from the "Rather open" region to the "Challenging" region is observed. In particular, the performance of Service 1 follows the same trend as for the complete data set (Figure 7). However, it should be noted that the order of performance for Services 2 and 3 is swapped for the "Challenging" areas, compared to the overall results, as Service 3 performs slightly better, especially considering the errors larger than 1 meter. The cause of this unexpected improvement in Service 3 for "Challenging" areas is difficult to determine and may be interpreted more as a lack of degeneration due to "Challenging" areas, suggesting that the observed slight improvement constitutes a more random observation.

The decreasing trend in performance from the "Rather open" region to "Challenging" region is consistent for all cases, except for Service 3, which has slightly smaller errors for the "Challenging" environment compared to the "Mixed" environment. A possible explanation for this is the different implementation of the fix-flag. As previously mentioned, different hardware producers report a GNSS-fix with different criteria. Service 3 is possibly tested on a receiver that is rather conservative when reporting fix. This can also be supported by the fact that the receiver is designed for use in the automotive industry. Therefore, it may be more conservative in reporting fix for positions, where Services 1 and 2 still report a fix solution.

In general, it could be expected that the trends between the different area types are more pronounced. A possible explanation for the deviations from this in our results is that the conditions overall are relatively demanding. Therefore, the errors for all three services are higher than could be assumed from earlier experience [12], [14], [37].

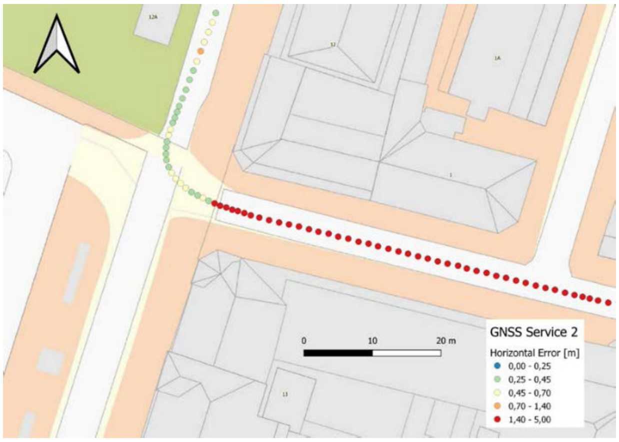

FIGURE 10. Example of one trajectory on 14.12.2021 for the GNSS Service 2 with the corresponding horizontal errors.

In conclusion, Figure 10 provides an example of reduced GNSS performance due to the phenomenon of NLOS signals. As the vehicle enters the urban canyon, the number of visible satellites decreases compared to the region to the west in the figure, leading to a noticeable increase in horizontal error.

V. DISCUSSION AND CONCLUSION

The advancement seen in the development of vehicle sensors and the sophisticated algorithms being developed within the vehicle industry can accelerate the development of automation in the transport sector [38]. To achieve this, it is crucial to understand and evaluate vehicle sensors under various conditions, as these are critical components for the perception of the vehicle. The main purpose of this study has been to address GNSS as a core technology for vehicle sensor fusion systems.

Although experience shows that position errors remain stable in dynamic conditions, only a few studies focus on this subject [5], [39]. Documenting this stability would be important for the CCAM community, as every potential source of error is critical for safety. More open research and documentation of the quality of individual sensors under different scenarios (e.g., in high speed) and conditions are needed in the development of SAE level 4 and 5 driving.

Considering the requirements suggested for fully automated driving in Section II.C (0.1 m at 95% confidence), the performance of the tested GNSS technologies alone is not sufficient. Figures 7 and 9 show the cumulative distribution of the errors, demonstrating that integrity levels for CCAM are not met from these services alone. This emphasizes the need to integrate GNSS corrected positions with other sensor inputs in larger sensor fusion systems, which is the direction we see in the navigation systems of piloted automated vehicles.

Still, a precise GNSS position is a preferable option. This is particularly true for vehicles that can be expected to have less advanced sensor fusion systems than cars. For instance, for various automatic service vehicles, such as automatic lawnmowers and pavements sweepers, the accuracy of GNSS might be more critical for their operations because they are likely to have less sophisticated sensor fusion systems.

Some limitations of the test setup must be mentioned. Obtaining a ground truth to compare the GNSS measurements with is a challenging task, and in this study, the positioning system onboard the bus is used as a reference trajectory. However, this reference has its uncertainties. Still, the reference is expected to outperform the GNSS methods alone, as the LiDAR and IMU supported navigation systems in these vehicles can replicate a predefined and pre-measured route with high accuracy. This can, for instance, be seen by comparing two or several of the position traces from the navigation system from the same route. Therefore, we rely on the data from the bus itself as a reference, and since all the compared GNSS services are evaluated against this same reference, it provides a reasonable estimate of the performance of the services.

Traditional Network RTK services demonstrate good performance, but a major drawback is the two-way communication which makes it hard to increase the number of users. In contrast, SSR based services use one-way communication and are scalable. For CCAM services, with potentially billions of users, this is essential. SSR based services are under development, and standardization and non-proprietary solutions would be preferable, as opposed to the main developments we see today. Also, as SSR correction data are developed with the mass market in mind, the distribution method becomes important. Should one continue to transmit data by IP protocol like most OSR solutions today or rely on some more efficient method, e.g., through the broadcast protocol currently being under development and testing under the 3GPP standardization of the mobile network [40]?

In the case of GNSS technology, authorities are involved in building necessary infrastructure, there are supply chains of different companies building different components of the technology, and researchers and scientists need to know the current status to improve the technology further and make sound recommendations. Establishing an open dialog between all stakeholders is preferable, as it would lead to more efficient technology development and a safer, more efficient, and environmentally sound transport system.

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