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# Certification of automotive GNSS receivers using aerial image data

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**Abstract:**
A new method for calibration, validation aiming at certification of GNSS receivers used in the automotive industry addressing the levels 3 and 4 of automation under real world conditions is presented. The method uses simultaneously acquired high-resolution aerial image data, from a helicopter, which is precisely georeferenced with Ground Control Points. The method provides a reference trajectory for vehicles in GNSS critical areas, e.g., GNSS-denied type environments. The images obtained contain the vehicle's roof with the signalized GNSS receiver antenna. Together with a precise height model of the road surface, the absolute position of the GNSS receiver in world coordinates can be derived from the position in the image. The main results of a test campaign, performed in July 2021, using the method are presented. It was investigated how the quality of the GNSS sensors is influenced by the environment (Rural, Highway and Urban) and what added value the method provides. The method proved to be resilient and robust to situations where the GNSS position accuracy degrades, even when RTK is used, as local effects do not impact the new method. The method provides high-precision reference trajectories facilitating calibration, validation, and conformity testing. In this contribution the focus will be set on the validation and testing process leading to certification.

**Key words: Certification, GNSS, Aerial imagery, Validation**.

## Introduction

Determining the absolute position of a vehicle with a high degree of accuracy is a relatively new and considerable challenge in the automotive industry. This is due to the high complexity of the hardware and software systems involved, their complex interaction and dependence on, e.g., environmental conditions, physical properties of the terrain and landscape, the use of different data types, GNSS correction data services, e.g., Real-Time Kinematic (RTK) data, and other factors. To date, the main need for positioning in the automotive sector has mainly been in applications where the requirements for positioning accuracy are not so high. The vehicle position determination has only been used as a commodity of convenience for basic functions such as navigation or for the provision of points of interest (PoI's). However, these requirements change for vehicles with automated driving functions.

Vehicles with automated driving functions specifically designed for SAE-L3 (L3) or SAE-L4 (L4) definitions [1] are bound by the highest reliability and data quality of positioning systems due to their safety requirements. Since automated driving functions require accurate absolute position information derived from GNSS data with optional support from auxiliary sensors such as INS and odometers, it is necessary to ensure that GNSS receivers meet and maintain the position requirements. This means that GNSS sensors must be tested regarding the position accuracy during development and integration before they are deployed on the road. This assessment process requires a method that provides a ground-based reference trajectory (GTRT). This trajectory is compared with the trajectory of the vehicle measured by a GNSS sensor. To date, GNSS-INS, or high-quality devices for dynamically determining a ground reference trajectory have been widely used on the road, but there are few alternative methods for independently validating these devices under realistic conditions. It is assumed that by using a high-quality GNSS system, an accurate and error-free GTRT can be determined. This

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approach has the disadvantage that the same system-intrinsic GNSS errors cannot be identified and most likely both the reference system (RS) and the system under test (SUT) are affected simultaneously. The extent of the system-intrinsic errors affecting both the GNSS RS and the GNSS SUT generally remains unknown without calibration, validation, or a test process.

Currently there is an urgent need for a reliable and independent method for verifying accuracy guidance when using GNSS data in the context of autonomous driving. Especially as OEMs and Tier 1 companies are looking for exactly such methods for the validation process of required key performance indicators (KPI), such as the absolute position accuracy of the vehicle. Independent reference trajectories of known quality can finally be used to characterise GNSS-based solutions and support their development and validation.

Two viable approaches to determine a GTRT (position, velocity, orientation and time) are relative positioning using robotic total stations, and absolute positioning using aerial imagery in combination with ground control points (GCP) derived from the TerraSAR-X satellite based on radargrammetric measurements or from static GNSS equipment.

## The Objective

The main objective was to develop a conformity scheme based on test principles that can be used to support the calibration, validation and in particular a certification process of GNSS sensors used in the field of automated driving. A conformity assessment process comprises a set of procedures to demonstrate that a product, service, or system meets the requirements of a standard, regulation, law, etc. Conformity assessment brings several benefits, including additional consumer and stakeholder confidence, competitive advantage, or assurance to regulators that all specified requirements and conditions have been met.

In the context of automated driving, there is no defined GNSS-based standard or regulation that addresses the absolute accuracy of positioning KPIs. The standardisation organisations CEN/CENELEC and ETSI have worked extensively on the development of standards for the use of GNSS sensors in automotive applications. This work focused on the more traditional automotive users, i.e., it did not consider the high positioning accuracy requirements needed for automated driving. This situation will certainly change in the near future. The CEN/CENELEC standard series EN 16803 [2] - Use of GNSS-based positioning for intelligent transport systems (ITS) in road transport - and the ETSI standard series TS 103 246 [3] - GNSS-based positioning systems (GBLS) - are examples of this important work in road transport. These standard series were used as a starting point and inspiration for the defined accuracy KPI metrics, the associated performance classes and the use cases developed in this work. For position accuracy, the horizontal and vertical position errors (HPE, VPE) were defined as the main KPIs, with the 68.3rd, 95.4th and 99.7th percentiles as associated metrics. The proposed HPE and VPE KPIs and associated metrics are used to establish pass/fail criteria in this particular case in the context of conformity assessment, i.e., in the context of a certification scheme based on testing activities.

## The Method

The newly proposed calibration and validation method allows absolute positioning using simultaneously acquired aerial imagery from a flying platform [4] (see Fig. 1) in combination with ground control points (GCPs) derived from the TerraSAR-X satellite based on radargrammetric measurements [5] (see Fig. 2) or acquired from stationary GNSS equipment. The latter require medium- to long-term measurement series of defined GCPs along the test track(s).

*Fig. 1. Artistic depiction of the concept. A flying platform equipped with a DLR 4k camera system mounted on the fuselage of a helicopter follows a test vehicle obtaining imagery along the test track.*

This method is based on the idea of comparing the measurements of a GNSS receiver on board a test vehicle with those of a validated and GNSS-independent RS, which provides higher accuracy and coverage even in GNSS-denied areas by using aerial imagery.

The method enables for the first time the calibration and validation of automotive GNSS receivers under real-world conditions through the use of aerial imagery and GCPs and, unlike previous calibration and validation test methods, is independent of GNSS-related sources of error.

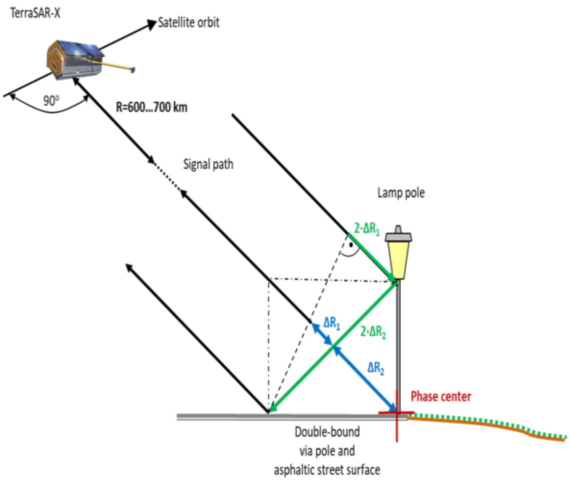


*Fig. 2. Radargrammetric measurement principle using the TerraSAR-X satellite for the extraction of a GCP position data from a streetlamp pole. The method can use other GCP types, e.g., derived from mid or long-term stationary GNSS measurement series.*

This method enables the absolute positioning of moving objects with the help of aerial images by forward intersection of image objects. For forward intersection, an image beam is defined from the precisely defined position and orientation of the aerial camera and the position of the vehicle in the image. To determine the position of the vehicle along this image beam, the beam must be intersected with a digital terrain model (DTM). By applying the collinearity equations for all image beams in the high frame rate image sequences, the reference position, velocity, orientation, and time of the mobile GNSS receiver antenna on the vehicle roof can be determined.

The derivation of 3D positions of objects from a 2D image requires additional information from the DTM. Therefore, the method requires GNSS-independent height information at the position of the GNSS antenna on the vehicle roof, which can be used to derive the horizontal position of the GNSS antenna (X and Y). The absolute height of the vehicle GNSS antenna is a central parameter that is simply the sum of the absolute road surface height from the DTM at that position and the height of the GNSS receiver relative to the ground. The aerial imagery is georeferenced by a bundle adjustment using GCPs, on-board GNSS/inertial measurements and automatically high-density tuned link points. The method is independent of the type of GCPs provided. The GCPs are measured as standard with a stationary GNSS device with an accuracy of one centimetre. The base points of lampposts or road signs are usually used as reference points, which can often be clearly identified radar satellite data as well as in the aerial images. After georeferencing the images, the reference trajectory of the vehicle is derived. This is then used to evaluate the trajectory of the SUT derived from the GNSS sensors by calculating the various KPI metrics using the vehicle position obtained from the imagery and GCPs as the reference trajectory.

For any test procedure, be it calibration, validation, or conformity assessment, it is important to evaluate the reference system theoretically and practically. From a theoretical point of view, the expected accuracy of the method is better than 10 cm compared to the accuracies of GNSS receivers of more than 100 cm. The overall accuracy of the method was analysed in the field under good GNSS conditions and using SAPOS GNSS data corrections for post-processing. The average differences between the positions of the aerial vehicles and the post-processed GNSS data were better than 10 cm and thus in line with the theoretical assessment [6].

## Test framework

The architecture of the test frame consists of the elements associated with the new method, i.e., the DLR 4k optical camera system (see Fig 1) and the associated processing algorithms, as well as the test object, i.e., the GNSS receivers of the vehicles. Two nadir-viewing cameras of the DLR 4k system with different focal lengths of 35 mm and 50 mm are used to record the aerial image sequences. In order to enable automated measurement of the position of the GNSS receiver in the aerial images, it is necessary to uniquely recognise the vehicle and to be able to measure the exact position of the receiver on the car roof. For this purpose, a magnetic sticker with eye-catching colours and high contrast was placed on the roof of the target vehicle (see Fig 3).

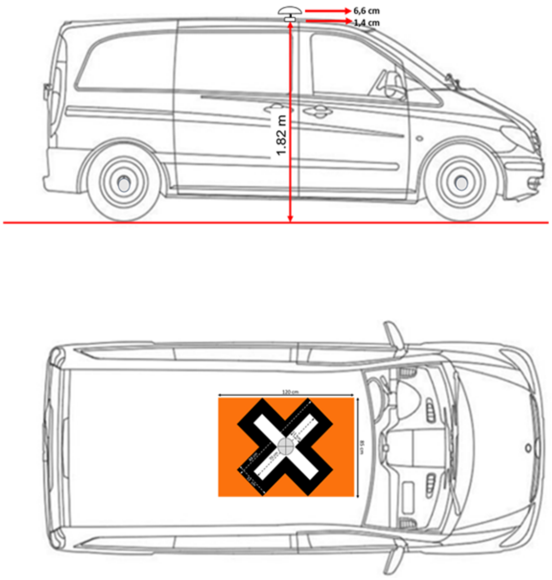


*Fig. 3 Magnetic sticker with cross installed on the vehicle roof to enable the automatic tracking during image data processing. The GNSS antenna was installed in the center of the cross mark. The antenna height is an important parameter.*

Figure 4 provides an example of the image resolution in terms of the Ground Sample Distance (GSD) using the 35 mm and 50 mm optical cameras at a height of 500 meters. The defined image data rate is of 1 Hz. Each aerial image frame is synchronized with GNSS and inertial navigation system capturing the GNSS position and the image attitudes (i.e., the exterior orientation of the camera system) at the time of exposure.

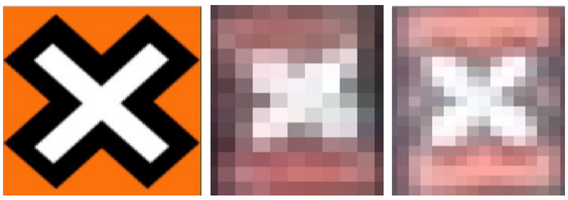

*Fig. 4 Resolution comparison between the original magnetic sticker marker and the imaged magnetic sticker with 10 cm GSD and 7 cm GSD, respectively.*

Determining the exact position of the GNSS antenna in the image sequence is an important part of image processing and is done automatically. It is based on an NCC matching algorithm, see Fig. 5. The aerial images are then georeferenced by a bundle adjustment method using GCPs, onboard GNSS and inertial measurements associated to the images, and automatically highly dense matched tie points. The method is independent of the type of GCPs provided for the method. The most important aspect to consider in relation to the GCPs is accuracy, which should ideally be in the centimetre range.

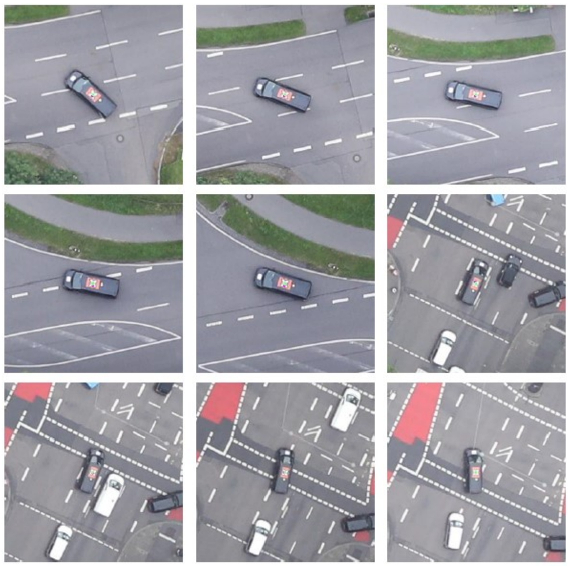

*Fig. 5 A series of aerial image sequences with the cross center in the middle of the image patch obtained during the test campaign.*

The test architecture allows several SUTs, in our case several GNSS receivers, to be tested simultaneously. This is also important for certification purposes. Two different types of GNSS receivers were used as part of a test campaign. A high-quality GNSS receiver (multi-constellation and multi-frequency) that can use RTK corrections and a GNSS receiver for the automotive industry (multi-constellation and single frequency) were used (see Fig. 6).

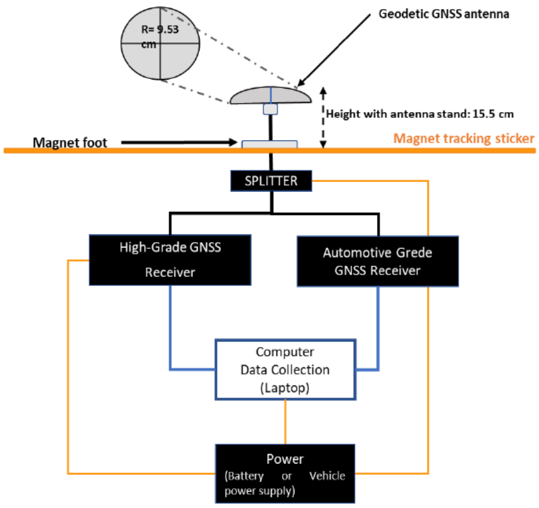


*Fig. 6 Architecture used during a test campaign. During which two different GNSS grade receivers were tested.*

In July 2021, the procedure was put into practice in a test campaign. The test campaign was conducted on two consecutive days. On the first day, the GNSS RTK corrections from the high-quality GNSS receiver could be used.

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On the second day, the same test architecture was used, but this time without GNSS RTK corrections for the high-quality GNSS receiver. This allows the performance and behaviour of the GNSS receivers to be compared.

Two nadir-looking cameras of the DLR 4k camera system on a helicopter were used to record the aerial image sequences. The predefined test routes included various real environmental scenarios in the Munich area and in the city. In this way, it was investigated how the quality of the GNSS sensors is influenced by the environment and what added value the new method can offer. The test tracks include three different test cases: in the countryside, on the motorway and in the city of Munich and its surroundings (see Fig. 7). These cases can be traced back to the scenario types described in the CEN/CENELEC EN 16803 series [2]. This aspect is important when developing or defining a certification scheme, as the certification scheme can be based on standards or elements of existing standards. An example of scenario type is "*standard old big cities with relatively narrow streets, but sometimes large avenues or ring roads, with buildings from medium height to tall, masking angles up to 60° generating frequent multipath and non-line-of -sight phenomena*" which applies to the city of Munich.

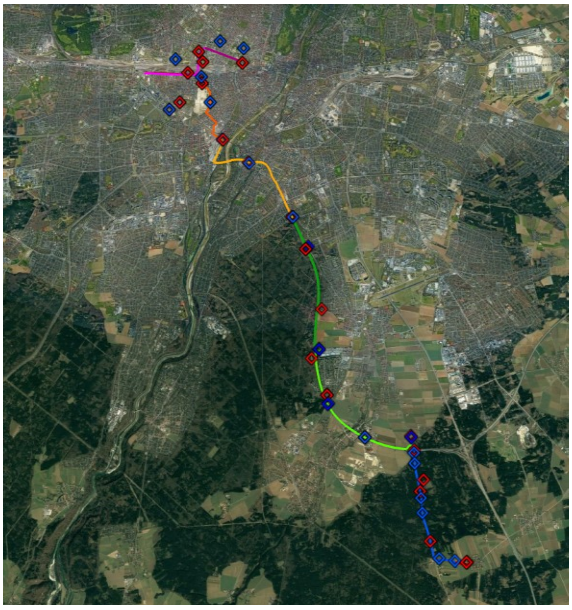

*Fig. 7 Test cases: rural (in **dark blue**), highway (in **green**) and urban (in **light and dark orange**, and **purple**). The diamond symbols depict check points (in **blue**) and ground control points (in **red**), respectively.*

As can be seen in Fig. 8, deviations of different degrees are seen for both high-end and automotive receivers. This is particularly surprising for the high-quality receiver, as this receiver used RTK corrections on the first day of the campaign.

*Fig. 8 Examples showing deviations regarding the derived vehicle positions by the high (in **red**) and automotive (in **blue**) grade receivers as compared with the new method (in **yellow**). During this test GNSS RTK corrections were used.*

On the second day of the test campaign, the same settings were used, except that the high-grade GNSS receiver did not use RTK corrections.

Figure 9 shows situations where the position solution of the high-quality GNSS receiver deteriorates significantly when using multiple constellations and multiple frequencies. In these situations, the position solution is even much worse than that of a typical automotive GNSS receiver.

The new method proved to be resilient and robust to situations where GNSS position accuracy degrades, even when RTK is used, as local effects do not affect the method.

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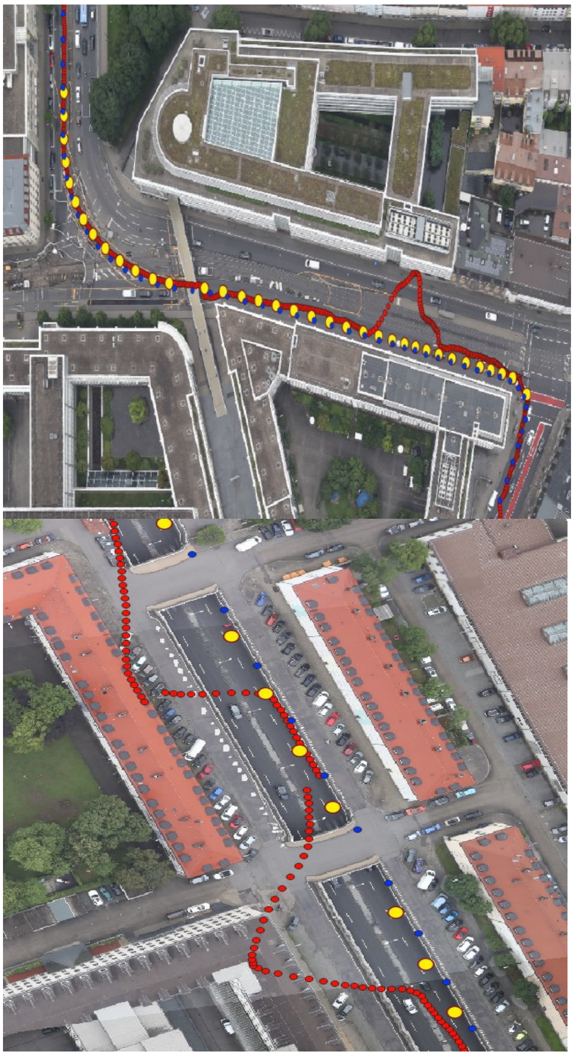

*Fig. 9 Examples showing deviations regarding the derived vehicle positions by the high (in **red**) and automotive (in **blue**) grade receivers as compared with the new method (in **yellow**). During this test **no** GNSS RTK corrections were used.*

These situations show that using a high quality GNSS receiver as an RS to build a GTRT can be problematic, as it operates on the same principles and is therefore subject to the same errors and problems as the GNSS receiver under test. It is therefore important to use test methods that are as independent as possible from the operating principles of the SUT. The new proposed method goes exactly in this direction by avoiding the use of GNSS measurements at the level of the vehicle, where problems often occur, as is the case with multipath effects.

**Certification results**

As described in the previous sections, the proposed method has been shown to be resilient and robust to situations where the derived position accuracy of a purely GNSS-based reference system degrades. This has also been observed when using RTK-GNSS corrections, as local effects affecting GNSS signals have no impact on the airborne method used. Since the proposed method provides more accurate data than the SUT and performs very well in all use cases, it can also be used for conformity assessment. One form of conformity assessment is certification. The certification aspect is very important for OEMs and Tier 1 companies as it increases confidence in a product by ensuring that the specified requirements are met and thus certified GNSS equipment has a distinct market advantage over equipment without certification. We have developed a test scheme for certification purposes. The certification scheme and certification content include three categories of accuracy levels associated with horizontal and vertical position errors. These accuracy levels or classes are linked to the use case, i.e., highway, urban or rural. This certification system allows the selection of one or more accuracy classes. We have followed the principles proposed in standards [2] and [3] in defining the classes and criteria, except that we have defined our values based on the value of 20 cm at 68.3rd percentile proposed in [7]. This scheme was defined for the case where an OEM, Tier 1 or manufacturer is interested in certifying its GNSS sensor(s) for only one class. In the context of testing and certification activities, in addition to defining the classes, it is important to define the metrics to be applied, the pass/fail criteria and the sample size. The proposed pass/fail criteria are based on the mean values of HPE/VPE and in particular on the 95.4 percentiles of HPE/VPE as defined in Table 1.

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*Tab. 1: Proposed accuracy classes definitions and associated pass/fail criteria for the proposed certification scheme.*

| Accuracy Metrics | Position Error | | |
|---|---|---|---|
| | Class I - Urban | Class II – Rural | Class III - Highway |
| | **Maximum Horizontal Position Error [m]** | | |
| HPE \| $68.3^{th}$ percentile | $\leq 0.20$ | $\leq 0.25$ | $\leq 0.33$ |
| HPE \| $\mathbf{95.4^{th}}$ percentile | $\leq \mathbf{0.40}$ | $\leq \mathbf{0.50}$ | $\leq \mathbf{0.66}$ |
| HPE \| $99.7^{th}$ percentile | $\leq 0.60$ | $\leq 0.75$ | $\leq 1.00$ |
| | **Maximum Vertical Position Error [m]** | | |
| VPE \| $68.3^{th}$ percentile | $\leq 1.00$ | $\leq 1.20$ | $\leq 1.50$ |
| VPE \| $\mathbf{95.4^{th}}$ percentile | $\leq \mathbf{2.00}$ | $\leq \mathbf{2.40}$ | $\leq \mathbf{3.00}$ |
| VPE \| $99.7^{th}$ percentile | $\leq 3.00$ | $\leq 3.60$ | $\leq 4.50$ |

The minimum sample size required for each class is based on the statistical consideration that the measurement error must be ten times better than the confidence level of 95.4 defined for the selected accuracy class. With these considerations in mind, 625, 400 and 230 measurement samples were defined for classes I, II and III, respectively. This is also a requirement for the proposed method, as this minimum number of samples must always be achieved during the test campaign for both the proposed method and the SUT. After the test campaign, the data were processed. The aerial photo data were used to define the GTRT. The high-grade and automotive grade type GNSS receiver’s trajectory position data were then compared to the GTRT. The analysis and position error results show that only one GNSS receiver would be eligible to receive certification, and only for one class type. The main certification results are summarised in Table 2.

*Tab. 2: Main results of the of accuracy analysis according to classes definitions for the proposed certification scheme. The results show that only one GNSS receive, the high-grade GNSS receiver, could be certified for the highway class type and, solely, when using RTK corrections.*

| Track Case/ Device | $p_{HPE}^{68.3th}$ [m] | $p_{HPE}^{95.4th}$ [m] | $p_{HPE}^{99.7th}$ [m] | $p_{VPE}^{68.3th}$ [m] | $p_{VPE}^{95.4th}$ [m] | $p_{VPE}^{99.7th}$ [m] |
|---|---|---|---|---|---|---|
| **Rural** | | | | | | |
| High-Grade (RTK)[1] | 0.33 | 1.24 | 1.81 | 0.25 | 2.76 | 4.60 |
| High-Grade [2] | 0.30 | 1.20 | 3.71 | 0.68 | 1.06 | 1.45 |
| Automotive-Grade [1] | 1.56 | 2.75 | 3.07 | 2.22 | 5.65 | 6.90 |
| Automotive-Grade [2] | 2.12 | 2.90 | 5.73 | 2.08 | 4.71 | 7.79 |
| **Highway** | | | | | | |
| High-Grade (RTK) [1] | 0.21 | **0.34** | 0.62 | 0.07 | **0.11** | 0.37 |
| High-Grade [2] | 0.41 | 0.60 | 1.05 | 0.24 | 0.47 | 0.83 |
| Automotive-Grade [1] | 0.60 | 0.90 | 1.09 | 1.27 | 2.97 | 3.32 |
| Automotive-Grade [2] | 1.25 | 1.79 | 3.96 | 2.63 | 3.94 | 4.45 |
| **Urban** | | | | | | |
| High-Grade (RTK) [1] | 0.29 | 0.86 | 4.74 | 0.06 | 1.26 | 16.8 |
| High-Grade [2] | 1.51 | 4.33 | 26.46 | 1.90 | 5.90 | 20.1 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Automotive-Grade [1] | 1.18 | 2.23 | 3.48 | 2.30 | 4.01 | 6.39 |
| Automotive-Grade [2] | 1.21 | 2.48 | 5.82 | 3.90 | 5.75 | 6.41 |

[1] First day of the testing campaign. [2] Second day of the testing campaign.

Generally, certification is based on standards or regulations. However, the certification of GNSS devices for autonomous road vehicles supporting automated driving functions is currently neither standardised nor regulated. As there are currently no bidding GNSS-based standards or regulations for automated driving, certification would be based on a voluntary scheme .For the proposed voluntary certification system with the defined pass/fail criteria, only high-quality receivers and only when using RTK corrections could be certified as Class III - highway. As shown in the main results in Table 2, neither the high-quality receiver itself using RTK corrections, nor the GNSS receiver for vehicles could meet the proposed criteria. However, with the advancement of technology and the use of more GNSS constellations and frequencies by the receivers, it is expected that better performance will be achieved, so it is likely that the proposed pass/fail criteria will be met and thus certification based on a voluntary scheme can be obtained.

## Conclusions

A conformity process based on testing principles is introduced. The conformity process is based on a certification scheme aiming at certifying and validating GNSS receivers, in the automotive domain, addressing the L3 and L4 levels of automation under real world conditions. The certification system uses a new method that provides a GTRT based on high-resolution aerial imagery from a test vehicle equipped with a GNSS receiver. The imagery is precisely geo-referenced with high accuracy GCPs, allowing accurate positions of the vehicle of ~10 cm to be derived. This new method has proven to be resilient and robust to situations where the GNSS position accuracy of the receivers used has degraded due to local effects, even using RTK-GNSS corrections. The presented method provides a reference trajectory for motor vehicles in GNSS critical areas, e.g., in environments where GNSS is denied, subject to multipath effects, etc., which are not only a problem when evaluating the intrinsic GNSS performance of the equipment during testing, but also when the reference system is GNSS-based. This method can be used by OEM and Tier 1 companies during development and test activities to facilitate calibration, validation and performance evaluation of their positioning and navigation systems. As an independent method that provides highly accurate position data, it can also be used as a certification tool that GNSS receiver manufacturers can apply for to certify their products. From now on, the new method can be used for calibration and validation, supporting the developed conformance scheme required for certification activities, which will be used commercially by NavCert. As a certifier, NavCert can offer a voluntary certification service for GNSS receivers by issuing a certificate and providing the TÜV SÜD certification mark as proof of the achieved performance. The results show that this method can be used successfully for the process of certifying automotive type grade GNSS receivers aiming to reach L3 and L4 levels of automation

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