Challenges in Characterization of GNSS Precise Positioning Systems for Automotive

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Abstract

Autonomous driving is currently one of the main focuses of attention in the automotive industry. A requirement for efficient and safe driving of autonomous vehicles is the ability to precisely pinpoint the location of the vehicle, in the decimeter- to centimeter-level on a global scale. GNSS is expected to play a major role in providing accurate absolute and global positioning, yet many challenges arise in dense urban environments due to lack of line-of-sight to satellites and multi-path, decreasing availability and accuracy. Also, the position accuracy announced by GNSS receiver manufacturers is rather optimistic, typically obtained in best-case scenarios. However, this is rarely encountered in real-world driving conditions, especially in urban areas, leading to a mismatch between receiver specification and real world performance. This paper provides a systematic study regarding the requirements, methods, and solutions available for the characterization/evaluation of a GNSS positioning system in real world driving conditions. An architecture for a precise Automotive Global Reference System (centimeter-level), able to characterize a decimeter-level accuracy GNSS positioning system in dynamic conditions, is proposed. To the best of authors' knowledge, such a study is not available in the literature.

Keywords

Autonomous Driving, Precise Positioning, GNSS Receiver Characterization, Reference System

1. Introduction

GNSS positioning systems have been providing a wide range of services to the population, industry and governmental organizations for many years. The improvements in GNSS technology have been significant in the past decade, with a faster time-to-first-fix accurate position acquisition, improved receiver sensitivity, more constellations and functional satellites, as well as improved signals [1, 2, 3]. These improvements create the opportunity for the development of new receivers with support for multiple constellations and multiple signal bands, making the GNSS one of the most scalable and reliable technologies for global high accuracy positioning.

In Autonomous Driving (AD), GNSS is expected to play a major role in providing accurate absolute positioning, with other technologies (e.g. LiDAR, Cameras) providing relative positioning [4, 5]. In a report released by the European GNSS Agency, the requirements for AD are defined as better than 20 cm of horizontal accuracy with 95% confidence [4]. The performance

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of autonomous vehicle systems will benefit greatly from high accuracy GNSS systems, for example for safety critical applications, such as forward collision warning (V2X) [4]. However, there are many challenges to solve in order to achieve reliable decimeter or better accuracy to support AD. A GNSS receiver collects and processes signals subjected to several impairments (e.g. troposphere and ionosphere interference), as well as multi-path effects, where the signals are reflected from nearby objects and reach the receiver through multiple and indirect trajectories. When the receiver's line-of-sight is blocked, the positioning accuracy is severely degraded. This problem has significant impact in AD applications, since vehicles are frequently moving through tunnels and in large urban areas, where the GNSS signals are blocked by tall buildings (urban canyons) [4]. Therefore, the receiver architecture, positioning algorithms and correction systems play a major role in mitigating these effects in order to obtain high accuracy.

GNSS manufacturers typically announce accuracies obtained in controlled conditions, with direct line-of-sight to a clear sky which is the best-case scenario and not realistic for applications with demanding requirements. Real-world driving conditions are far more challenging for GNSS signals than the best-case scenario. AD is expected to outperform a human-controlled vehicle in terms of reliability and security. Since GNSS positioning is of utmost importance in this context, a full characterization of the system accuracy in real-world is mandatory to guarantee that the system is capable of providing centimeter- or decimeter-level accuracy 24/7.

To evaluate a GNSS receiver with decimetre positioning accuracy (e.g. 20 cm, as previously defined) a reference system should fulfill the following requirements: (1) provide reliable absolute ground truth with one order of magnitude better accuracy (e.g. 2 cm, 95% confidence); (2) maintain high performance (e.g. 99.9% availability [4]) in real-world driving conditions (e.g. highway speeds, tunnels, urban canyons); (3) globally available.

The main contribution of this paper is a systematic study on the challenges and possible solutions for a suitable reference system able to meet the requirements for accurate characterization and evaluation of precise positioning GNSS systems in real world driving conditions, which the authors could not find in the current literature. Section 2 describes the main parameters for a GNSS receiver characterization. Section 3 and 4, discuss approaches to improve the performance of GNSS positioning, in order to obtain suitable ground-truth to evaluate high accuracy systems in dynamic conditions. Section 5 presents the architecture for the proposed Global Reference System.

2. GNSS Receiver Characterization Parameters

To characterize a GNSS receiver it is necessary to obtain a set of parameters that provide information on the performance of the device when capturing and processing GNSS signals. There are three dimensions (Fig. 1) where the performance of the receiver is tested: time, signal power and accuracy [6].

The time dimension includes the Time-To-First-Fix (TTFF) under different conditions (cold start: no information about the satellite position and time; warm start: valid almanac information, no ephemeris information, position is within 100 km of last fix and time is known; hot start: all information is known and position is within 100 km of last fix) [6]. Reacquisition time is also an important parameter for automotive applications. This measures the time necessary for a position fix to be obtained after a momentary signal outage, such as when a vehicle enters a tunnel. Faster reacquisition times enable the navigation system to provide driving directions immediately after the end of a tunnel.

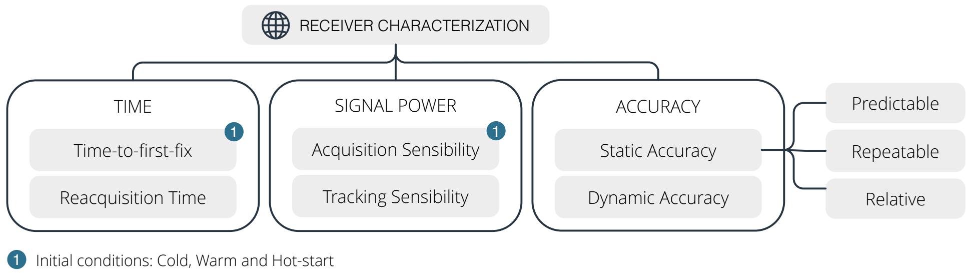

Figure 1: Fundamental GNSS Receiver Characterization Parameters

In the power domain, the minimum power level of the signals is typically evaluated at different stages of the signal processing. The acquisition sensitivity parameter is the minimum power level such that the correlators are able to search and identify a signal, which is typically below noise level, until a first fix is obtained. This parameter is also dependent on the initial conditions (cold, warm and hot-start) of the receiver, since knowledge of which satellites to search will speed-up the process. Tracking sensitivity is the minimum power level that allows the receiver to maintain lock of the signal.

The accuracy is divided in two components: static and dynamic. The static parameter can be subdivided into three categories: predictable, repeatable and relative. Static predictable is the accuracy of a receiver's position solution with respect to a known fixed point of a map. Static repeatable is the accuracy with which a user can return to a position whose coordinates have been measured previously with the same receiver under the same conditions (precision of the receiver). Static relative is the accuracy with which a user can measure position relative to another user with the same receiver in the same conditions. Dynamic accuracy measures the receiver ability to pinpoint the true position of the vehicle in a map, when the vehicle is undergoing motion in any of the axes.

Many of the characterization parameters described above are obtained in laboratorial environment using two types of devices: GNSS simulators (e.g. from Spirent and Rohde & Schwarz) and Record & Replay (R&R) systems (e.g. from Spirent and RaceLogic). The former simulates one or more constellations of satellites, by generating the signals that would be observed by a GNSS receiver in a specific location on earth. The latter records real GNSS data, which can then be reproduced for each receiver under test.

Simulation typically does not address highly complex scenarios. When multi-path simulation is offered, it is often a simplistic test for a very specific use case. The influence of moving objects (e.g. cars, trucks) and the properties of the materials surrounding the receiver (e.g. trees, buildings) are also absent. Despite allowing testing GNSS receivers under very limited conditions, this type of devices are expensive (100-300K€). With R&R systems, data must first be collected in different conditions (e.g. in open area, intermediate/light urban area and urban area [4]). Compared to the GNSS simulation, the R&R system has lower flexibility since new data must be collected in order to test different scenarios. However, this type of device replicates real signals, which allows benchmarking different receivers with real conditions and the cost is typically significantly lower (10K-30K€).

While timing and power characterization are well covered by these devices, the same cannot be said for the accuracy parameters. On one hand, the GNSS simulation generates a given coordinate precisely, allowing for direct accuracy characterization, yet presents a simplistic scenario when implementing interference and multi-path. On the other hand, a R&R system captures interferences and replays them, although the exact position of recording may not be well accounted for, especially in dynamic scenarios. In addition, another GNSS receiver is needed, one with higher accuracy than the device under test, in order to characterize accuracy using the R&R system.

However, there is a fundamental issue regarding receiver characterization using only GNSS signals. As mentioned before, the position being estimated is affected by multiple external factors, and ultimately it may contain significant errors, even for the high accuracy GNSS receiver used as reference. Therefore, comparing against another higher quality GNSS receiver, cannot guarantee that the real accuracy is being characterized. Ideally, the system being used to characterize accuracy should be immune to the error sources that affect the device under test. However, considering the requirements defined (e.g., 2 cm 95%, 99% availability and global coverage) for this type of reference system, this is extremely difficult to achieve.

Dynamic accuracy is definitely the most challenging evaluation parameter, but at the same time one of the most important in the automotive context. This problem can be addressed by using GNSS Augmentation and merging GNSS with information from other sensors (e.g., Inertial Measurement Units (IMUs), Odometers, etc), in order to obtain higher accuracy ground truth in dynamic conditions. The following sections introduce the approaches of GNSS Augmentation and GNSS fusion with other sensors.

3. GNSS Augmentation

The typical accuracy of a GNSS system (2-3 m in open sky conditions [7, 5]) can be drastically improved using correction data obtained with GNSS Augmentation.

The augmentation can be based on a single reference station or on a network of reference stations, providing corrections with different coverage and accuracy (up to centimetre-level). With these approaches, satellite position, clock and atmospheric errors can be greatly minimized, leading to higher navigation performance (improved accuracy, integrity, continuity, availability). However, not all GNSS errors can be eliminated (e.g. multi-path errors caused by skyscrapers). Depending on the source of external information used, the augmentation can be classified as Satellite-Based Augmentation Systems (SBAS) or Ground-Based Augmentation Systems (GBAS). In SBAS [8, 9] GNSS measurements are collected by reference stations (e.g. located across an entire continent), and computed in a central system to extract differential corrections and integrity messages. The correction parameters are broadcast using geostationary satellites, usually providing wide-area or regional augmentation. Many regions have their own SBAS system (e.g. European Union (EGNOS)), with many others in development. GBASs [10] are used to improve the GNSS service in a limited area (e.g. to support landing and take off at airports [11]). The main objective of a GBAS is to provide integrity assurance, but it is also able to provide accuracy better than 1 m. Four or more GNSS receivers are used to collect pseudo-ranges for the primary satellites, computing and broadcasting integrity information.

More recently [12], another classification used for GNSS augmentation systems is Observation State Representation (OSR) and State Space Representation (SSR) (Fig. 2). In OSR, the corrections provided are in the form of differential observations that are used by the rover (vehicle's GNSS receiver) to correct local errors, where the error is a lump sum of all sources affecting the distance measurement. In SSR, the corrections are provided as parameters that model the various errors affecting the distance measurement.

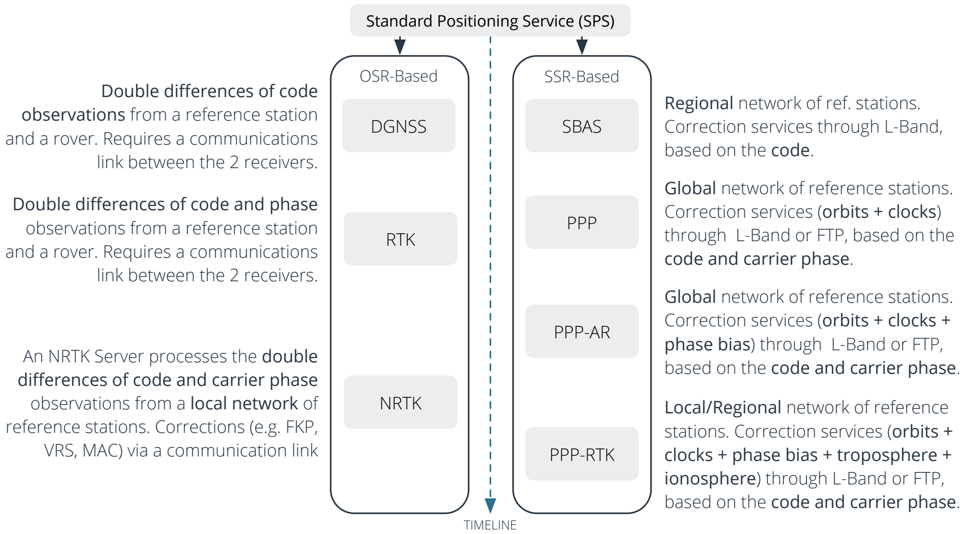

Figure 2: Correction Services Overview

3.1. OSR-Based

Differential GNSS (DGNSS) [2] is an augmentation system based on a network of ground reference stations, that broadcast differential information to the rover. This type of system only provides position accuracy improvements, not assuring integrity. The correction parameters are also typically broadcasted using short-range ground transmitters. The classic DGNSS technique (Fig. 3) finds the deviation between the accurately known reference station and the currently estimated positions. Based on this deviation, corrections to the measured pseudo-ranges are computed and used to correct the rover's position. The achieved accuracy is up to 1 m for distances in the range of tens of km.

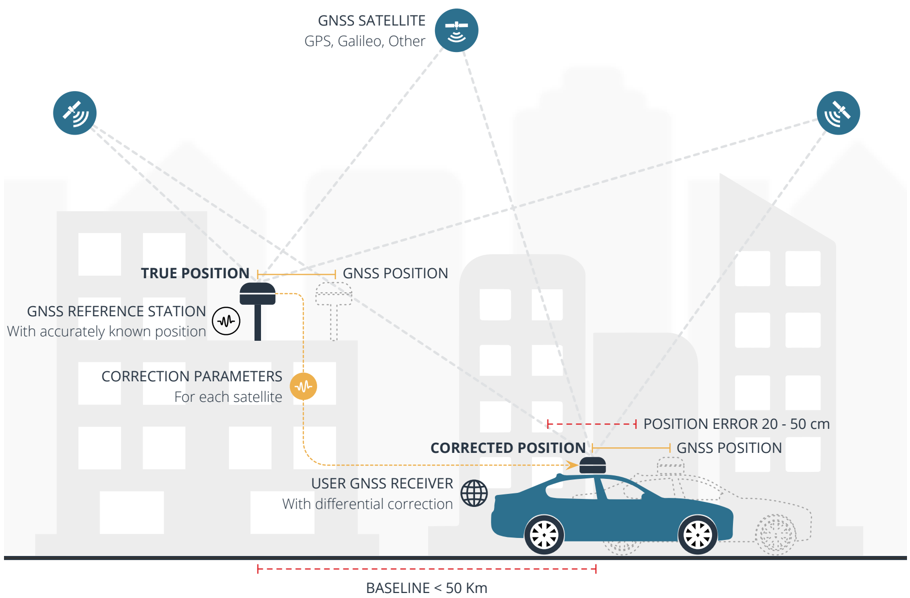

Figure 3: Classic Differential GNSS (DGNSS)

With Real-Time Kinematic (RTK) [13] a reference station provides information about the pseudo-range and carrier phase measurements. RTK can provide real-time corrections to the rover (for distances between 10-20 km), being possible to achieve centimetre-level accuracy (<5 cm), being frequently used for example for land surveying and Unmanned Aerial Vehicle navigation. Using a network of base stations (Network RTK (NRTK)) the working distance increases to 50-70 km, by mitigating atmospheric dependent effects over distance. With NRTK using OSR, the rover must be within (or at least near) the reference network. The Wide-Area RTK (WARTK) technique allows the extension of local services to wide-area scale (400 - 1000 km), using a permanent reference station network, with accuracies between 5 and 10 cm.

3.2. SSR-Based

A Precise Point Positioning (PPP) system [14, 15, 16] models GNSS errors using a network of ground reference stations, and transmits the corrections for the different signals broadcasted by each satellite (Fig. 4). The PPP system architecture is similar to a SBAS system, however the correction data can be broadcasted to the rover via satellite or Internet. PPP can be used worldwide, while an SBAS system coverage is regional or continental.

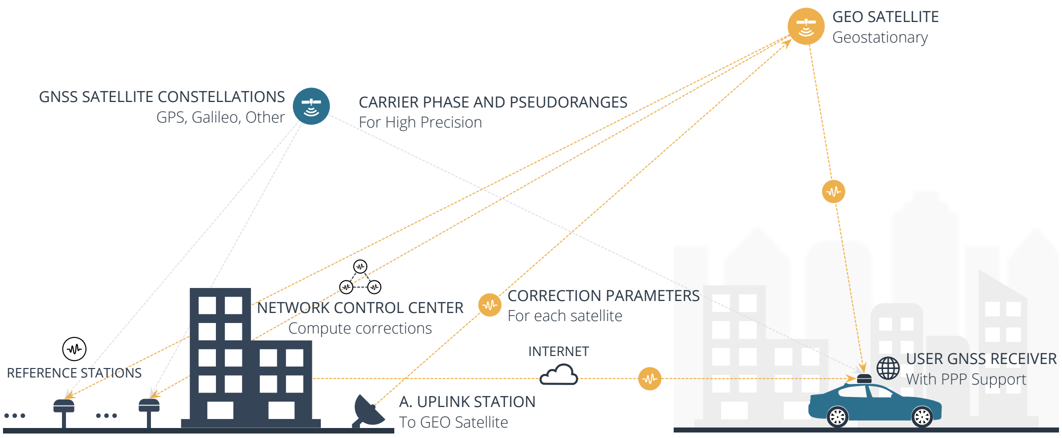

Figure 4: Precise Point Positioning (PPP)

In order to deal with local biases, such as atmospheric conditions, multi-path and satellite geometry, a convergence time is required to achieve decimetre level or better accuracy (typically up to 3 cm). To obtain a 10 cm horizontal error, a convergence time between 20 and 40 minutes is usually necessary. Convergence time depends on the number of satellites available, satellite geometry, quality of the correction products, receiver multi-path environment and atmospheric conditions.

When comparing PPP with differential processing, the main disadvantage of PPP is that usually it takes longer to converge [15], due to the lack of ionosphere and troposphere information. On the other hand, the differential RTK solution performance degrades with the increase of distance between the rover and the reference station.

PPP-RTK can be seen as an extension of NRTK with SSR, or also as PPP with fast ambiguity resolution [15]. In addition to the orbits and clocks, information about the satellite phase biases is also sent to users [17], reducing the convergence times when compared to PPP-AR [18]. PPP-RTK provides all state parameters that are relevant for centimetre accuracy, including for ionosphere and troposphere using SSR messages, that can be directly used by the rover to correct his own observations [17]. SSR has good scalability compared with OSR, and in terms of performance, SSR local reference station effects are greatly reduced or eliminated. Regional services in Korea and Japan provide SSR data for free, based on the GNSMART software from Geo++ [17].

3.3. Global Correction Services

Figure 5 places the main GNSS augmentation techniques in terms of accuracy versus coverage. Although some augmentation techniques provide a good accuracy, the technical requirements (required base stations, coverage) may not be suitable to evaluate a positioning system for AD on a global scale.

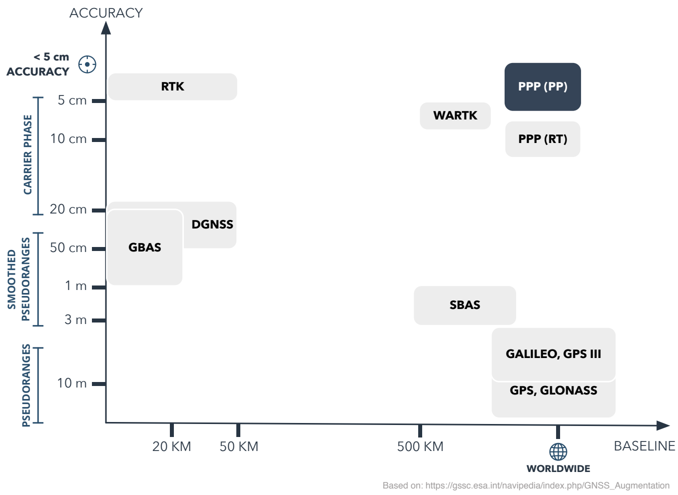

Figure 5: GNSS Augmentation

There are several providers of global PPP correction services, with products where the error and the convergence time vary (see Table 1) [19, 20]. Almost all of them charge a fee to access the corrections. The announced performance is usually measured in static conditions over long periods of time [19].

Table 1
Correction Services Comparison

SERVICE	HORIZ. RMS ERROR (cm)	CONDITIONS	CONV. TIME	SUPPORT	SOURCE
TerraStar-C	3.3 - 5.3	Static	30 min	GPS/GLO	[20] , novatel.com
TerraStar-C PRO	2.5	Static	< 18 min	GPS/GLO/GAL/BDS	novatel.com
TerraStar-D	4.1 - 5.9	Static	*	GPS/GLO	[19]
TerraStar-X[2]	2	*	< 1 min	GPS/GLO	novatel.com
OmniSTAR G2	4.4	Static	< 45 min	GPS/GLO	[19] , omnistar.com
IGS (Final)[1]	2.9 - 5.6	Static	12 - 18 days	GPS/GLO	[19] , igs.org
VERIPOS Apex	< 5	Static	*	GPS/GLO/GAL/BDS	veripos.com
StarFire	< 5	*	*	GPS/*	navcomtech.com

* - No information or unclear. 1 - Free. Remaining are commercial. 2 - Regional coverage. Remaining are global.

Post-Processing techniques can also be used to obtain the maximum accuracy for applications that do not require real-time positioning. In post-processing, data can be processed offline using forwards and backwards smoothing, allowing to minimize errors that would be obtained in real time [21].

4. Fusion of GNSS with Motion Sensors

A reference system can fuse GNSS signals with information from other sensors [22], such as Inertial Navigation Systems (INS) and Distance Measuring Instruments (DMI). While an INS, due to integration drift (very significant in lower grade INS), provides an accurate relative measure of position only in the short term, GNSS provides an absolute position in the long term. The integration of INS and DMI technologies allow to complement irregularities in the GNSS with continuous inertial, speed and distance measurements, improving the quality of the ground truth data, even in GNSS signal outages or when the line of sight to satellites is blocked.

An INS uses an Inertial Measurement Unit (IMU) to obtain angular velocity and linear acceleration measurements. These are used to compute a relative position and orientation (roll, pitch and heading) of the system over time in relation to a starting point, by applying dead reckoning techniques. There are different IMU grades, usually divided in: marine, aviation (sometimes grouped as navigation grade), tactical and consumer. Each grade has different bias [23], with higher grades translating into lower accumulated errors.

IMUs can use MicroElectroMechanical System (MEMS) accelerometers and gyroscopes, or higher quality sensors such as Servo accelerometers and Fiber-Optic (FOG) or Ring Laser (RLG) gyroscopes. FOG and RLG do not contain moving parts, therefore they generally perform much better over vibration and shock. More information about FOG and MEMS gyroscopes can be found in [24, 25].

The gyroscope's bias is a critical point, since an error in the orientation will translate to an integration of part of the acceleration from gravity (which is usually much greater than the linear accelerations from the vehicle itself) in a different direction, leading to drift that, if not compensated, increases exponentially with time [26].

The integration of a DMI into the reference system provides speed and distance information that can be used to reduce the error accumulation of the double integration process. It can also be used to detect when the vehicle is immobile, allowing some IMUs to self-calibrate, as well as for integrity, complementing GNSS Receiver Autonomous Integrity Monitoring (RAIM) techniques, which are based on a consistency check of satellite measurements [27]. The integrity requirements for AD are very strict, due to the small safety distances that autonomous vehicles are required to handle [5]. Integrity is also an important parameter for a reference system, since the ground truth data must be reliable to characterize accurately the GNSS system being evaluated.

Wheel-mounted rotary shaft encoders and non-contact optical sensors are examples of DMIs that can be installed in a vehicle and used in a reference system. Wheel-mounted devices are affected by measurement errors ($\approx$ 0.12 km/h [28]). Wheel slipping due to loss of traction, wheel lifting above the ground (e.g. during tight curves or inclined pavements) and tire wear also introduce errors. Non-contact optical sensors provide slip-free measurement of distance, speed or angle and some models can be used at high speeds (up to 400 km/h). They are widely used in vehicles to evaluate parameters such as braking systems, tyres and sideslip angles [29, 30] and in demanding fields, (e.g. in Formula 1). The downside is the cost of this type of device (≈ 30K€), when compared with the wheel-mounted option (≈ 5K€).

There are devices that integrate a GNSS receiver and an INS device, some into a single enclosure. In addition, many of these devices allow the input from a DMI. These integrated devices are used in different applications (e.g. mapping and surveying) and the cost of a high-end system is virtually unlimited. Many of them can be configured with the state of the art technologies, including high end IMUs, with Servo accelerometers and FOG or RLG.

Depending on the level of integration (GNSS+INS), the device architecture can use loose, tight or deep coupling (Fig. 6). The typical approach used for sensor fusion is Kalman filtering, with: loosely-coupled, the sensor fusion is performed at the solution level (high grade INS are required); tightly-coupled, the sensor fusion is performed at the measurement level (requires more processing power); deeply-coupled, the sensor fusion is performed at the signal processing level (requires feedback to the GNSS measurement engine).

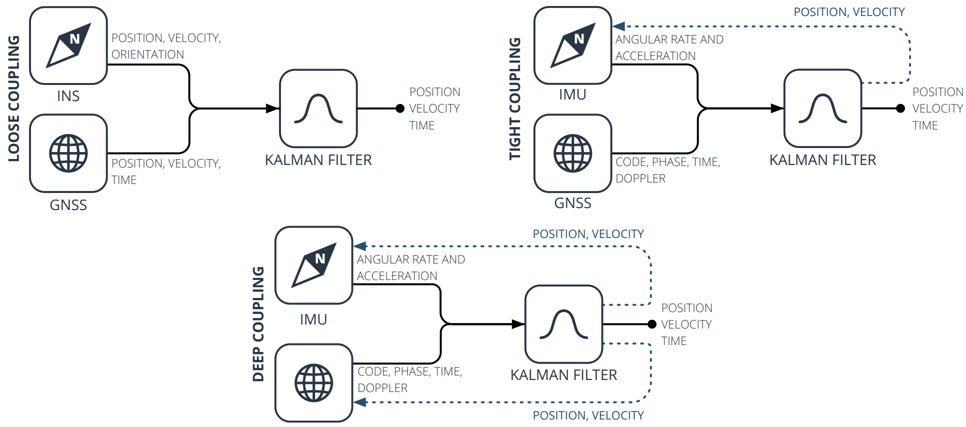

Figure 6: GNSS+INS Integration Architecture

The benefits of tightly coupled systems are presented in [26], using real-world aircraft and land vehicle datasets. The authors show that a tightly coupled system provides a distinct advantage in urban environments, maximizing the amount of GPS measurements available for aiding in real-time and post-processing. The deep coupling approach uses feedback to the IMU and GNSS receiver, which improves the cold start and the reacquisition time, however most GNSS+INS devices on the market are loose or tight coupling.

Some GNSS+INS devices support multi-constellation and dual antenna, that can be installed in the vehicle (e.g. two meters apart), providing heading estimations from GNSS signals [22, 31, 32], with an accuracy proportional to the distance between antennas. These estimations are a complementing source of heading information, since the use of magnetometers inside of a moving car is not possible due to the harsh magnetic environment. In addition, they can also be used for integrity and to reduce the drift, when the vehicle is immobile or moving at low speeds.

5. Global Reference System Architecture Proposal

Considering the benefits and limitations of the technologies, services, and approaches discussed above, the architecture presented in Figure 7 was defined in order to meet the requirements presented at the beginning of this paper. The proposed reference system solution is based on a Tightly-Coupled GNSS+INS device, with dual antenna, and an Optical DMI or/and a Wheel DMI to provide velocity information. Another essential element of the reference system is the GNSS correction service. As stated before, reliable centimeter-level accuracy is only obtained with GNSS correction data and post-processing. Although a camera does not provide information that can enhance the performance of the reference system, it is essential, for example, to identify possible sources of perturbation on the data from the other sensors.

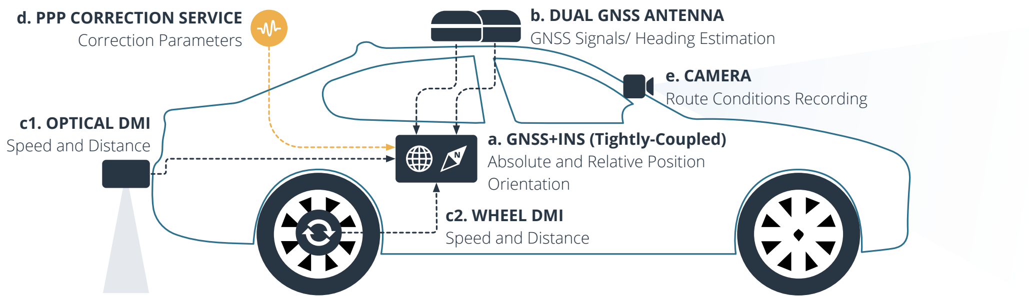

Figure 7: Architecture of the Proposed Global Reference System for Automotive

The performance of the reference system is directly linked to the selected GNSS receiver and IMU. However, there are hundreds of these devices on the market, and selecting the best combination is a challenging task. There are several GNSS+INS as well as DMI devices on the market with different characteristics and cost. The technologies in these devices are usually protected, therefore the information regarding the devices' characteristics and operation is very limited. Gathering information such as the one presented in Table 2 is difficult, because data sheets do not fully specify the conditions under which the tests were performed, making the comparison impossible or unfair. As we can see in Table 2, GNSS+INS devices with very distinct characteristics and price range ($\approx$ 20 - 100+K€) announce similar positioning and orientation performance.

Considering the information available from the manufacturers and presented in Table 2, all these devices report horizontal accuracy of 2 cm after applying DMI information, correction data, and post-processing. However, as mentioned earlier, these performances are usually obtained for best-case scenarios (e.g., open sky conditions), leading to different performance in real-world conditions. Moreover, the high price tag of these devices, limits the access to compare multiples devices in fair experiments with the same conditions.

Without reliable information, we opt to base the selection criteria on the characteristics and limitations of the technologies, and not on announced performances. This is the reason why a systematic study, such as the one presented in this paper, is important. In this context, considering these aspects, a device with Servo accelerometer, RLG or FOG, dual antenna, and DMI support, is one of the best candidates to obtain a stable 2 cm accuracy in real-world conditions.

Table 2
GNSS+INS Devices Specifications Comparison

DEVICE	ACC	GYRO	BIAS STABILITY ACC (mg) / GYRO (°/hr)	DUAL ANTEN.	COUPLING	DMI IN.	HEADING (deg) GNSS / GNSS OUTAGE	ROLL&PITCH (deg) GNSS / GNSS OUTAGE	HORIZ. POS. INS+RTK (GNSS / GNSS OUTAGE) m	HORIZ. POS. (POST-PROC.) m
NovAtel SPAN CPT7	MEMS	MEMS	1.7 - 3 / 0.25 - 0.45 (1σ)	Yes	Tight	*	0.03 / 0.04 (10s)	0.01 / 0.02 (10s)	0.02 / 0.12 (10s)	0.01
Honeywell Hguide n580	MEMS	MEMS	1.7 - 3 / 0.25 - 0.45 (1σ)	Yes	*	*	0.05 (1σ) / 0.07 (10s)	0.015 (1σ) / *	0.01 (1σ) / 0.2 (10s)	*
Trimble BX940[4]	MEMS	MEMS	*	No	Tight	*	0.50 / 0.50 (10s)	0.10 / 0.10 (10s)	0.05 / 0.3 (10s)	<0.04
Trimble BX992[4]	MEMS	MEMS	*	Yes	Tight	*	0.09 / 0.50 (10s)	0.10 / 0.10 (10s)	0.05 / 0.3 (10s)	<0.04
Applanix POS LV 620[4]	*	*	*	Yes	*	Yes	0.02 / 0.02 (60s)	0.005[1] / 0.005[1] (60s)	0.035[1] / 0.035[1] (60s)	0.020
Applanix POS LVX	MEMS	MEMS	*	Yes	*	Yes	0.09 / 0.30 (60s)	0.03[1] / 0.09[1] (60s)	0.02[1] / 1[1] (60s)	*
OxTS RT3003G	Servo	MEMS	0.002 / 2	Yes	Tight	Yes	0.1 (1σ) / *	0.03 (1σ) / *	0.01 / *	*
SBG Ekinox-D	MEMS	MEMS	0.002 - 0.005 / < 0.5	Yes	*	Yes	0.05 - 0.08 / *	0.02 - 0.03 / *	0.01 / 3[1] (60s)	0.02
SBG Apogee Land/Air	MEMS	MEMS	< 0.015 / < 0.08	Yes	*	Yes	0.04 / 0.06 (60s)	0.008 / 0.012 (60s)	0.01[1] / 0.5[1] (60s)	< 0.01[1]
iXblue Atlans	*	FOG	* / 0.1	No	SIGIL[3]	Yes	0.02 / 0.025 (60s)	0.008 / 0.008 (60s)	0.006 / 0.35 (60s)	0.006
iMAR iTraceRT-MVT-510	*	FOG	0.015 / 0.01	Yes	Tight	Yes	< 0.01 / 0.02 (60s); 0.28 sec(lat)[2]	< 0.01 / < 0.01° (60s)	0.02 / 0.1 (10s); 0.3[1] (60s)	0.02
iMAR iTraceRT-MVT-600	Servo	RLG	< 0.012 / < 0.0015	Yes	Tight or Loose	Yes	< 0.01 / 0.086 sec(lat)[2]	<0.01 / < 0.025°	0.01 / 0.05 (10s)	0.02

Note: These specifications must be used only as a reference. The official data sheets must be consulted before acquisition.
* - No information or unclear.
1 - With DMI.
2 - Gyro-compassing, no GNSS.
3 - SIGIL: Septentrio iXblue GNSS Inertial link.
4 - Unclear ITAR restrictions. The remaining are ITAR free.

As mentioned before, the correction service is also one of most important parts to achieve high accuracy on a global scale, and from the announced performances (usually also for optimistic scenarios) (see Tab. 1), TerraStar is one of the services with higher performance. However, it is also important to consider that some of the GNSS+INS devices only work with a limited set of correction services or even with only a single proprietary one. Therefore, the correction service must be selected considering the GNSS+INS device.

Other practical aspects must also be considered when choosing a GNSS+INS device, such as the fact that some of these devices may not be ITAR free (US International Traffic in Arms Regulations), and these restrictions can lead to shipment delays or even in limitations of use in some locations.

6. Conclusion and Future Work

In this paper, the challenges related to the characterization and evaluation of GNSS systems for precise automotive positioning, in real-world driving scenarios, were discussed, resulting in an architecture that is proposed as adequate for an Automotive Global Reference System. Several technologies must be combined to create a reference system able to obtain precise ground-truth. High-grade dual antenna, multi-constellation GNSS+INS devices (with Servo accelerometer and RLG), as well as an optical DMI device, ensure the best available technology for this type of reference system. However, the high cost is a limitation, when considering worldwide tests with multiple vehicles. Correction services were discussed since they play a major role in achieving centimetre-level accuracy on a global scale. The specifications of most of these services show that in post-processing, it is possible to obtain consistent and accurate positioning. Therefore, since real-time evaluation is not usually required in the discussed context, and RTK is not practical in urban environments and for worldwide testing, the use of post-processing techniques is the ideal approach.

One of the main challenges in designing a reference system solution is that the performance promoted by the manufacturers of GNSS+INS systems is very similar, despite very distinct technologies and cost. The lack of real-world experiments conducted by independent researchers makes it difficult to find the ideal cost/performance balance. Therefore, a future work goal is to test different GNSS+INS systems in the same real world driving conditions and compare the obtained results.

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