TECHNIQUES ET MÉTHODES

SaPPART White paper

Better use of Global Navigation Satellite Systems for safer and greener transport

Satellite Positioning Performance Assessment for Road Transport
COST Action TU1302

TMI 1

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September 2015

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This white paper is the first deliverable of SaPPART COST Action.
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Executive summary

Effective transportation of people and goods requires an efficient positioning service. This service currently relies mainly on Global Navigation Satellite System (GNSS).

The apparent satisfactory positioning service as perceived when we use car navigation systems or navigation applications often masks the actual weaknesses of GNSSs in challenging environments such as urban areas. As a consequence, the problems associated with obtaining an accurate and reliable position fix in challenging conditions are often underestimated and need to be addressed in greater detail.

Due to the physical principle of satellite based position determination, the level of performance delivered by any terminal using GNSS highly depends on the conditions it is used in. These influencing conditions are primarily due to the physical features in the built and natural environments around the antenna, which have a strong impact on the propagation of radio-waves. Furthermore, the problem of intentional and unintentional signal interference is a major concern.

As the major regions of the world have understood the strategic importance and potential of GNSS, the current two fully operational GNSSs are undergoing modernization, while those in development include features that will improve positioning performance. While each system will have its distinguishing features (e.g. Europe's Galileo offering significant benefits in terms of accuracy and authentication compared to the others), systems compatibility and interoperability should ensure that the end user benefits, continuously and for free, from improved performance due to the increased number of available satellites and other innovative features. The increased performance will partially address some of the current problems.

Depending on the nature or type of application and positioning requirements, the current GNSS deficiencies can be overcome by hybridization with other positioning sensors and digital spatial data (maps). These techniques are of particular interest when opportunistic sensors on-board vehicles are used and they can also provide seamless position fixing capability whilst moving between outdoor and indoor environments.

In the case of critical applications, the actual performance of the positioning terminal should be determined in terms of the commonly used features availability and accuracy, but also in terms of positioning integrity. Integrity measures the level of trust that the user can place in the positioning information provided. Integrity often takes the form of a new output, not always provided by mainstream terminals, which is the protection level bounding the positioning errors with a given probability.

To underpin agreements between partners and to support legislation, ITS stakeholders need clear and standardized performance metrics for positioning terminals and the associated performance assessment framework. Position information exchanged between cooperative entities should be characterized by quantified performance metrics, through references to the applicable standards.

Introduction

Transport and mobility services are crucial to the society that faces important challenges. Up to date, transport facilities and services have been fundamental to economic growth. However, there have significant and unacceptable negative impacts on the environment including pollution, noise and climate change. Therefore, it is paramount that the efficiency of the transport system is improved significantly including lower consumption of energy. A way of achieving this is through the concept of smart transport that exploits Intelligent Transport Systems (ITS) technology. ITS are built on three technology pillars: information, communication and positioning technologies.

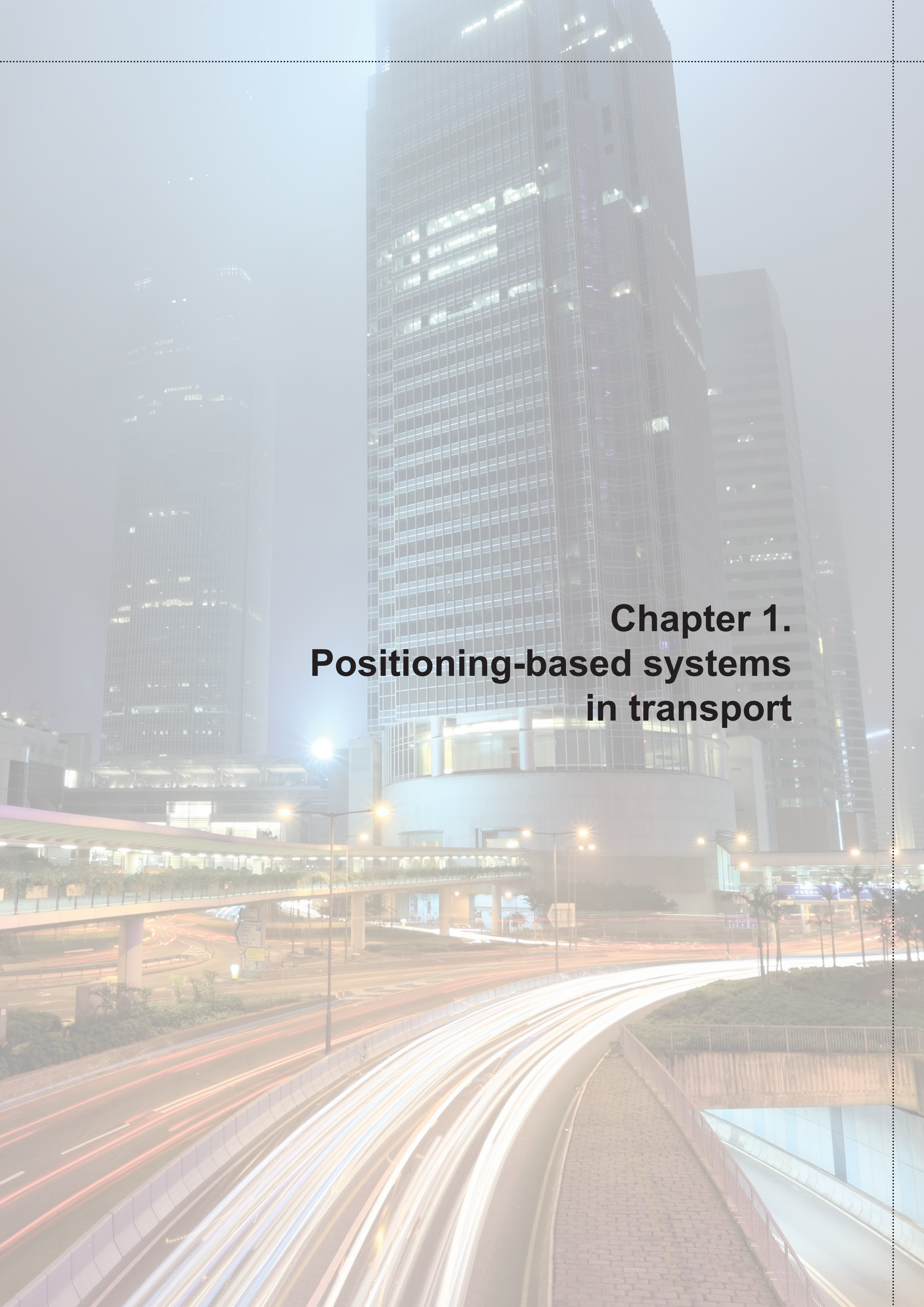
Of the three technologies, positioning could be argued to be the least familiar amongst transport stakeholders. However, a quick investigation reveals that there are a wide variety of transport and related services often associated with communication technologies that are supported by positioning. Currently, the positioning is provided in the majority of the cases by Global Navigation Satellite System (GNSS), among which the Global Positioning System (GPS) is the pioneer and still the most widely used system. The other current fully operational stand-alone system is Russia's GLONASS. As these operational systems were not originally and specifically designed for transport applications, the actual capabilities and limitations of the current GNSS are not fully understood by many stakeholders. Therefore, better knowledge of these limitations and their resolution should enable a much more rapid deployment of ITS.

This white paper is produced by the members of the COST Action SaPPART with two principal aims. The first is to explain the principles, state-of-the-art performance of GNSS technology and added value in the field of transport. The second aim is to deliver key messages to the stakeholders to facilitate the deployment of GNSS technology and thus contribute to the development of smarter and greener transport systems.

The first chapter highlights the important role of positioning in today transport systems and the added value of accurate and reliable positioning for critical systems.

The second chapter is about positioning technologies for transport: GNSS and their different aiding and augmentation methods are described, but the other complementary technologies are also introduced.

The third and last chapter is about the management of performances inside a positioning-based intelligent transport system, between the positioning system itself and the application-specific part of the system which processes the raw position for delivering its service.



Chapter 1. Positioning-based systems in transport

This chapter shows that positioning is used in a majority of transport and mobility systems. Firstly, some of these systems are listed without targeting exhaustiveness. Then, the importance of the quality of positioning service is introduced with examples of dependency of some systems upon the accuracy and reliability of the position data they can have access to. Finally, an outlook is given of the future of Global Navigation Satellite System (GNSS) based Intelligent Transport Systems (ITS).

1.1 Positioning in transport

Transport is the movement of people and goods from one location to another. The transport modes include road, air, and rail, maritime and soft modes such as cycling or walking. One of the key elements in the definition is the location or position of people or vehicles. This describes the origin, destination and even the path of any movement. The awareness of location enables the effectiveness of transport and services including quicker, cheaper, safer, and more optimal operations, and a reduction in the emission of CO_2. Furthermore, it can also facilitate the emergence of new applications and services such as car-sharing or car-pooling applications on smartphones.

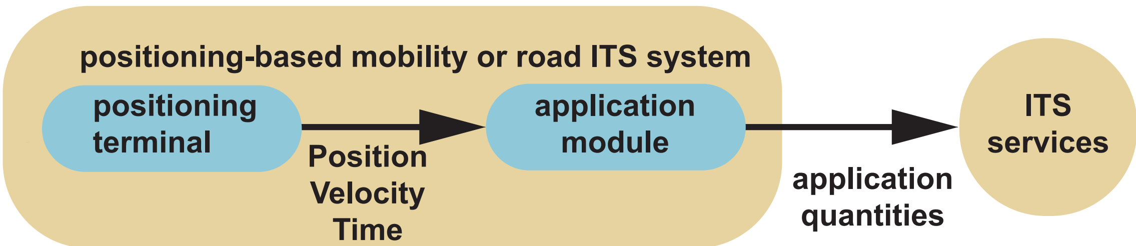
This section, and more generally this document, addresses road and city transport and mobility related issues, including multimodal transport.

1.2 Key definitions

In this document, the term “system” refers to the complete architecture including the positioning terminal. The term application (or application module) refers to the software part of the system that processes the position data and provides the service(s) to the end user.

Figure 1 is a schematic of the basic architecture considered in this document. This architecture is detailed in Section 3.3.

Figure 1
Simplified architecture of a positioning-based road ITS system



For instance, the system Personal Navigation Device (PND) comprises a positioning terminal (the GNSS receiver chipset with its antenna) and an application which performs map-matching, attributes retrieval and user information generation through the human-machine interface. The service is the guidance to the driver.

It should be noted that the output of the positioning terminal consists of Position, Velocity and Time (PVT) plus other related variables. The application quantities represent the parameters computed by the application from the PVT, for instance the map-matched location of the vehicle on the embedded digital map.

1.3 Examples of location-based transport services

Listed below are examples of transport or mobility services that could not be delivered without positioning information. The list is not exhaustive, the number of such services being unlimited.

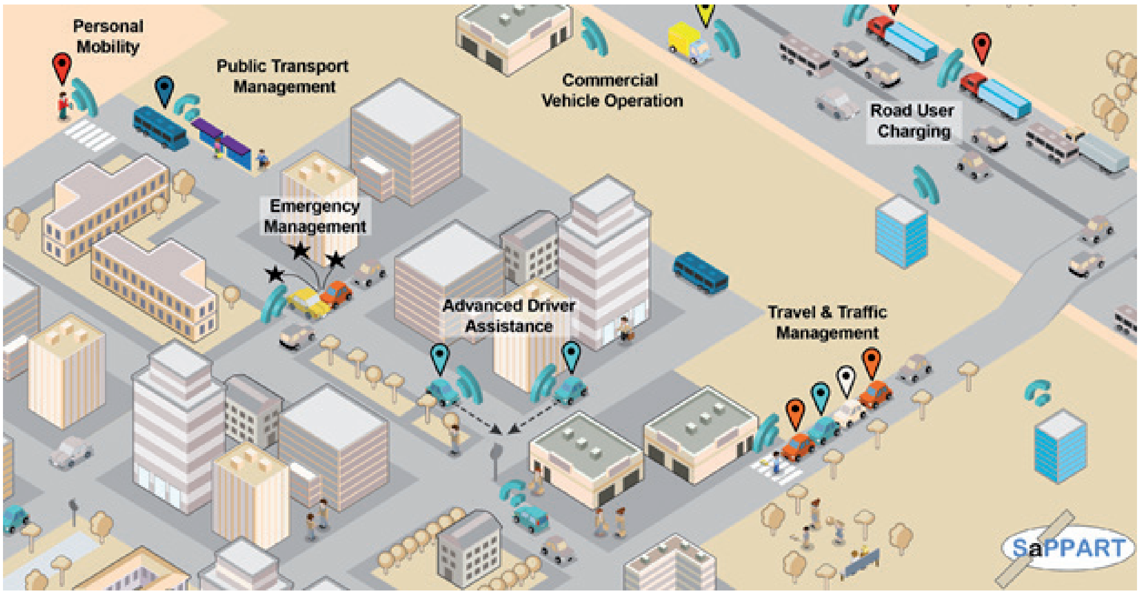
- **travel and traffic management services**
  - pre-trip travel information
  - navigation (route-guidance, re-routing, en-route traveller information, etc.)
  - parking guidance
  - location based services information
  - incident management
  - traffic control
  - travel and traffic data collection
- **public transport management services**
  - en-route transit information
  - public travel security
  - operations automation and optimization
- **personal mobility services**
  - household travel survey
  - mobility services for persons with walking disabilities
  - health surveys: tracking of the health-related impacts of travel behaviour
- **road user charging services**
  - regulated road user charging services (zone-based, distance-based, time-based or place-based charging)
  - commercial services (insurance, car rental, parking, etc.)
- **commercial vehicle operation services**
  - automated roadside safety inspection
  - on-board safety monitoring
  - fleet management
- **emergency management services**
  - emergency notification/personal security
  - emergency vehicle management
  - emergency call

Why do autonomous vehicles need absolute positioning?

Positioning can be “relative” meaning that the position of the mobile object (vehicle) is determined relatively to another object, for instance a road marking or another vehicle, or it can be “absolute”, meaning that the coordinates of the object is known in an absolute (or global) reference frame. For instance, the GPS provides the position in the global geodetic system WGS 84. In case of autonomous vehicles, the two types of positioning are necessary: relative for obstacle avoidance or precise guidance with respect to the road markings for instance and absolute for retrieving from the digital map the information needed for the navigation. Absolute positioning can also be used for relative positioning when the objects of interest are georeferenced.

- **advanced driver assistance & vehicle safety services**
  - intelligent speed adaptation
  - lane guidance
  - active suspension
  - skip, skid prevention
  - warning (e.g. speed limit, wrong direction on one way road)
  - longitudinal/lateral/intersection collision avoidance
  - pre-crash restraint deployment
  - special road condition warning (e.g. low bridge warning for London double decker)
  - autonomous vehicles, automated highway

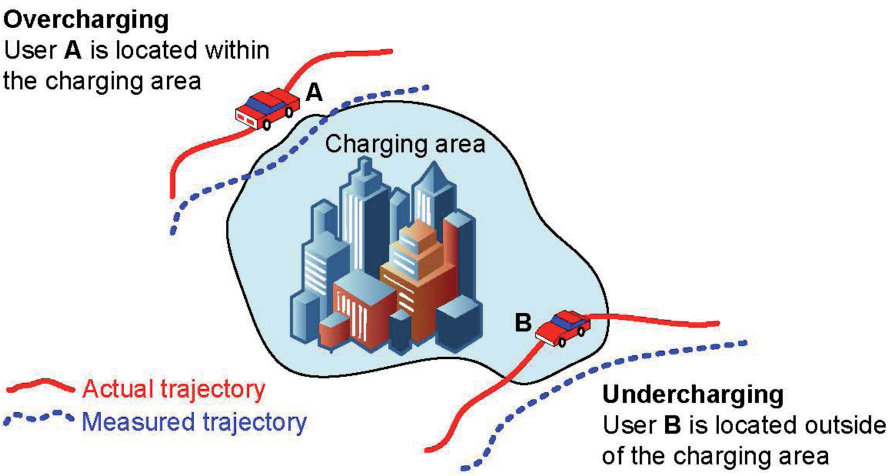
Figure 2
Positioning and mobility in cities



1.4 Added value of accurate and reliable positioning for critical systems

Some of the above systems are mission-critical, including safety, security and liability-critical systems. For instance, any fee collection related systems are liability-critical because road users should be charged fairly, accurately and securely. The operators have the liability for any wrong doing such as overcharge or undercharge. In addition, some of the existing non-critical systems may become critical in the future, for example the transport of vulnerable people. Figure 3 illustrates an example of incorrect charging for an area-based Road User Charging (RUC) system in a city centre.

Figure 3
Impact of positioning accuracy in Road User Charging



The level of services the positioning information[1] can support heavily depends on its accuracy and reliability. Table 1 and figure 4 below show some examples of services and the corresponding required positioning accuracy.

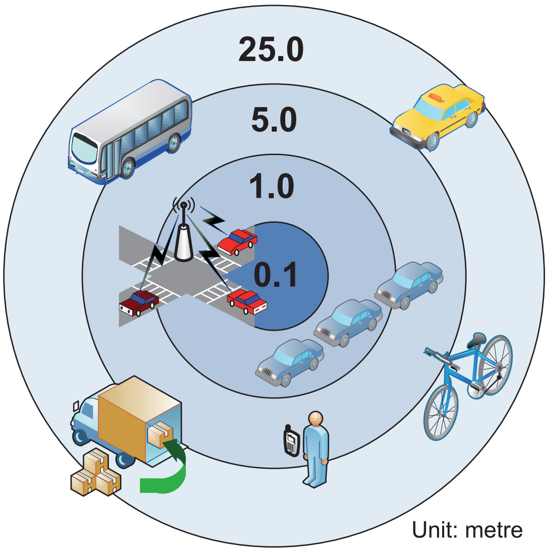
Table 1
Level of accuracy and transport services

Acceptable values	Service name
25 metres (95%)	trip travel information fleet management stolen vehicle recovery dynamic route guidance
5 metres (95%)	in-car navigation urban traffic control emergency call road user charging
1 metre (95%)	collision avoidance restraint deployment intelligent speed adaptation
0.1 metre (95%)	automated highway lane control

In this table, values represent typical errors that are acceptable to the system (e.g. 95% of the time errors should be below that reference), accuracy is the relevant feature[2].

1. Positioning information represents in this document the position and its associated information such as velocity, acceleration or direction.
2. If the reference values were representing maximum allowed errors that have to be bounded with a very high probability (e.g. 99.999%) in order for the application to be reliable, then integrity would have been the relevant feature.

Figure 4
Level of required accuracy in road transport



From these examples, the availability of services depends to a great extent on the accuracy and reliability[3] a positioning system can provide. The more accurate and reliable the positioning information is the more stringent service it can support.

What is integrity for positioning?

Integrity can have different meanings in the information and communication domains. In the positioning context, it refers to the trust the user can have in the positioning quantity delivered. This trust can be expressed by: "How sure can I be that the true error of the quantity I am using will not exceed the estimated error given by the terminal?" This concept is inherited (under a simplified form) from the civil aviation domain in which this trust is of the upmost importance, in particular during the landing phase.

For critical applications, reliability is even more important than accuracy because critical applications also need to take into account the special needs of the people and goods to be transported and the difficult environments such as severe weather, unusual roads or malicious interferences. There are a number of benefits of the use of accurate and reliable positioning information for critical applications. Some of the benefits are highlighted below.

- **Safety-critical systems**

Safety critical systems are those related to someone's life or death. This criticality is absolutely obvious in the case of services such as automated highway, collision avoidance or lane control, for which any unforeseen failure of the positioning system can create immediately a severe accident.

Emergency Call (eCall) systems, even if it is not the system itself which can be hazardous to the driver in case of failure, can be considered as safety-critical systems in a certain way. For example, in case the reported location of the accident scene is on the wrong side of a motorway, the rescue could be delayed by tens of minutes. For seriously injured persons, the delay may cost their lives. Therefore, accurate and reliable positioning information for safety-critical applications has the impact of potentially saving more lives.

- **Liability-critical systems**

One example of liability critical systems is payment or charging, such as mileage based toll charging or vehicle insurance. There is a liability to charge the correct fare. The charging scheme could be very simple to mitigate the liability due to the lack

3. In this document, reliability refers to a general feature which can be expressed by other more specific features such as availability and integrity (see section 3.4 for further details).

of confidence of positioning related information. Accurate and reliable positioning information enables the charging scheme to reflect the links between charge and actual vehicle movement or risk. A fair charging scheme with a high correct charging rate can be supported, subsequently mitigating the liability of incorrect charging.

It should be noted that to guarantee accurate and reliable positioning information at the level of accuracy needed may not always be possible at a reasonable cost. It is important to have quality indicators[4] and integrity monitoring in place to avoid being misled by the information provided. With the progress in positioning technology, especially the integration of GNSS and other positioning technologies, a lot of seemingly impossible mission tasks today will be possible in the future.

- **Security-critical systems**

For the secure transportation of high-risk people (e.g. prisoners) or goods (e.g. cash), it is important to monitor the location and motion pattern of the vehicle. In addition, it is important to control access to the cabin or carriage. Accurate and reliable positioning information is required for access to location-based control, for example, only opening the carriage doors at specified locations.

- **Environment and health-critical systems**

For the transportation of dangerous goods, it is important for the owner and regulator to know the location and motion pattern of vehicle. Accurate and reliable positioning information should increase the period during which the dangerous goods are monitored including driver behaviour (e.g. dangerous driving). Furthermore, such systems will enable a quick response to any incident.

- **Non-critical systems**

Some of the most commonly used positioning systems in road transport today are non-critical systems such as car navigation. Everyday use of these rather reliable systems combined with aiding technologies such as Dead Reckoning (DR)[5] or map-matching has reduced user awareness of the actual position accuracy and integrity. This misleads the users to trust the system unaware of the impending risks that could emerge in potentially critical situations for which these systems were not designed. Therefore, it is vital to establish user and system designer awareness of accuracy and reliability of positioning in road transport.

1.5 Outlook: more connected and more sustainable transport

To fulfil the expectations of transport for the 21st century, ITS should enable people to travel seamlessly across various transport modes and across borders with a wider choice of services and reduced environmental impact on the planet Earth.

This ambitious objective can be reached only if the 3 major technologies that support the ITS, i.e. information, communication and positioning technologies, progress in parallel and are tightly integrated in the various intelligent systems.

The availability of reliable and high quality traffic and mobility data will improve the efficiency of transport operation and increase the resilience of transport networks leading

4. All along this document, indicator and metric are considered as synonym.
5. Dead-Reckoning is s the process of calculating one’s current position by using a previously determined position.

to more environmentally friendly transport. Transport planners and network designers will gain unprecedented insight into transport processes in real time or near real time. This will lead to the development of new adaptive control solutions. Furthermore, predictive algorithms based on the known itineraries of individual vehicles could be used to forecast the traffic situation in advance and predict potential bottlenecks that could then be prevented by instant re-routing or traffic control adjustments.

The advances in cloud computing and big data processing will help solve problems in mobility by unlocking the potential of huge amount of transport data. The big transport data will also enable better informed and more efficient policies, more accurate planning and decision making for the future transport infrastructure investment.

The maturity of wireless communication technologies (vehicular communication ITS-G5 - 802.11p, cellular 4G or 5G, etc.) at affordable costs and with the right level of security will enable the wide deployment of the so-called connected vehicles. All the ITS based upon cooperation and communication between vehicles or between vehicles and infrastructures are called cooperative systems.

It is usual to separate the various communication technologies supporting the cooperative systems into 2 groups:

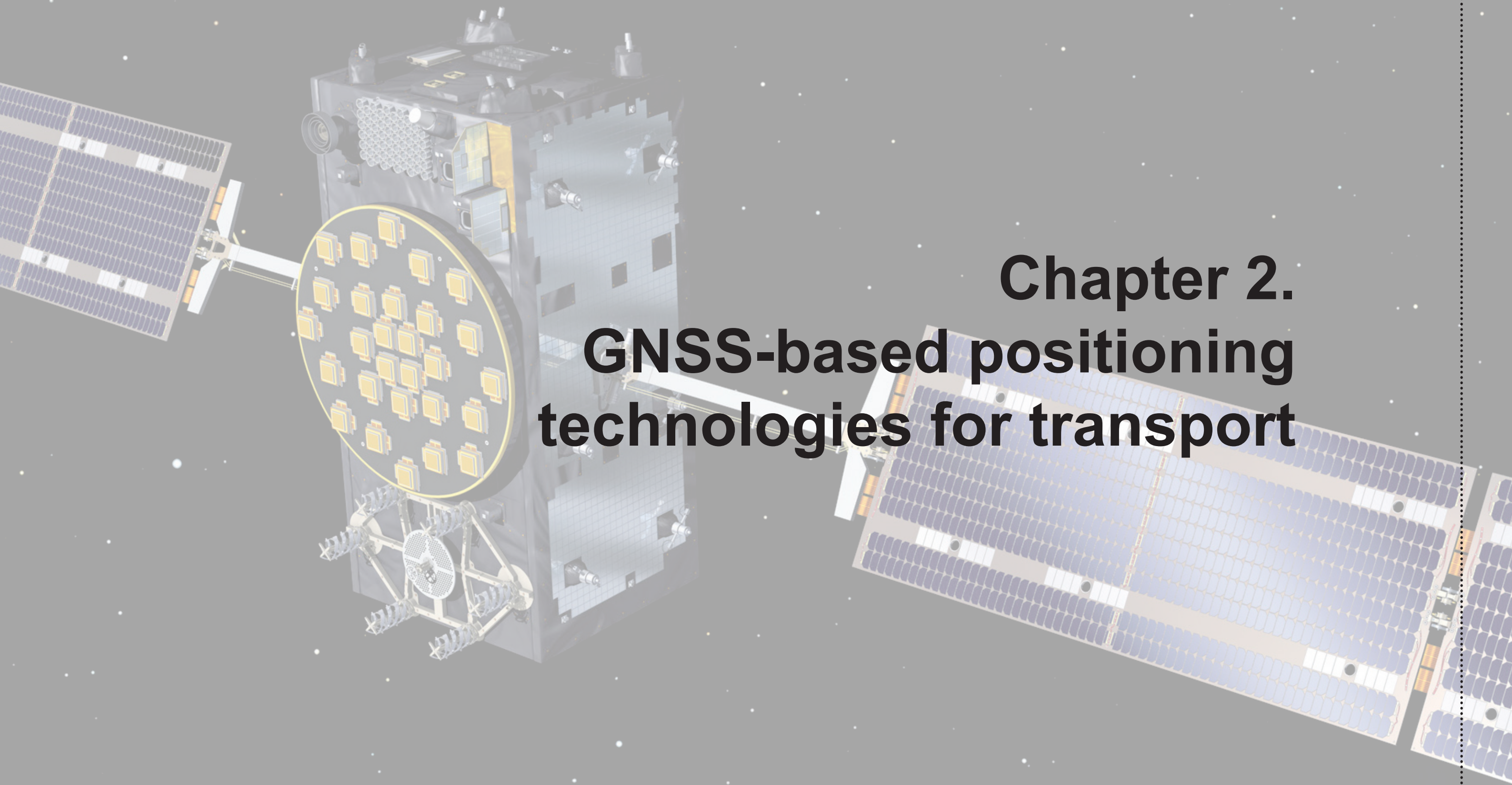
- The Vehicle to Vehicle (V2V) communication, which will enable a safer transport, for example safe distance keeping, collision avoidance, early warning of unsafe conditions.
- The Vehicle to Infrastructure (V2I) communication and vice versa, which will enable better use of the existing infrastructure and provide valuable and consolidated information to the intelligent vehicles: for example improved information regarding travel times, roadwork presence, weather and traffic conditions, up-to-date information about parking availability or other means of transport.

In all cases, together, the information, communication and positioning technologies will play a key role to facilitate the perspectives of the future transport systems and services. For instance, floating car data are mainly composed of position and/or speed information and the Cooperative Awareness Messages (CAM) exchanged by the ITS stations in V2V or V2V communications all contain the reference position of the station emitting the message.

The success of positioning will depend on the capability for better performance (including improvement and control), tight integration with other ITS technologies in smart multi-services and multi-standards platforms, and affordability of the relevant services.

Summary

In transport, positioning is everywhere and the number of road transport systems using positioning, generally based upon Global Navigation Satellite System (GNSS), is almost infinite. The requirements of these systems with respect to the positioning information provided by the positioning terminal can vary from decimetres to hundreds of metres, depending on the application. Some of these systems are critical in terms of safety, liability or security, in that they rely on accurate and reliable positioning information. In the future, positioning will play an even more important role, in combination with the other enabling technologies supporting Intelligent Transport Systems (ITS): wireless communication and information technologies.



Chapter 2.
GNSS-based positioning technologies for transport

This chapter introduces the different technologies used for positioning with a particular focus on satellites-based systems. The first part puts Global Navigation Satellite Systems (GNSSs) in their historical context and describes their main components. Then it explains the working principles and the different techniques for computing a position from GNSS measurements and gives an outlook on the market. The second part describes how GNSS measurements can be hybridized with standard vehicle sensor data, or map data, and the resulting enhancements. The third part is devoted to other positioning technologies which can be used as alternative or complementary technologies to GNSS. The last part is about the trends in GNSS positioning for transport.

2.1 Basic principles of GNSS

2.1.1 Introduction

Global Navigation Satellite System (GNSS) is the standard generic term used for satellite systems providing autonomous, geo-referenced positioning and timing information with global coverage of stationary or moving objects using radio-wave signals emitted by a satellites constellation. At present, modern society is highly reliant on GNSS. In addition to the key role in the transport and Location-Based Services (LBS) domains, fundamental infrastructures also, like service provision of electricity and telecommunications, are becoming more and more dependent on GNSS time service. Being an innovative industry, GNSS accelerates the economic activities worldwide, e.g. in farming, construction and transportation. Also, it has contributed and will further contribute to the improvement of safety and environmental quality.

8 false ideas about GPS

Below common false ideas about GPS that will be set straight in this white paper:

1. A GPS ~~is a car navigation device~~.
2. GPS ~~provides only position~~.
3. GPS ~~makes use of satellite images~~.
4. GPS is ~~a "Big Brother" allowing you to trace anything~~ or anybody.
5. GPS ~~satellites are geostationary satellites, like telecom~~ satellites.
6. Military ~~GPS receivers are more accurate than civil~~ ones.
7. GPS ~~usage is subject to a usage or license~~ fee.
8. GPS ~~is operational~~ everywhere.

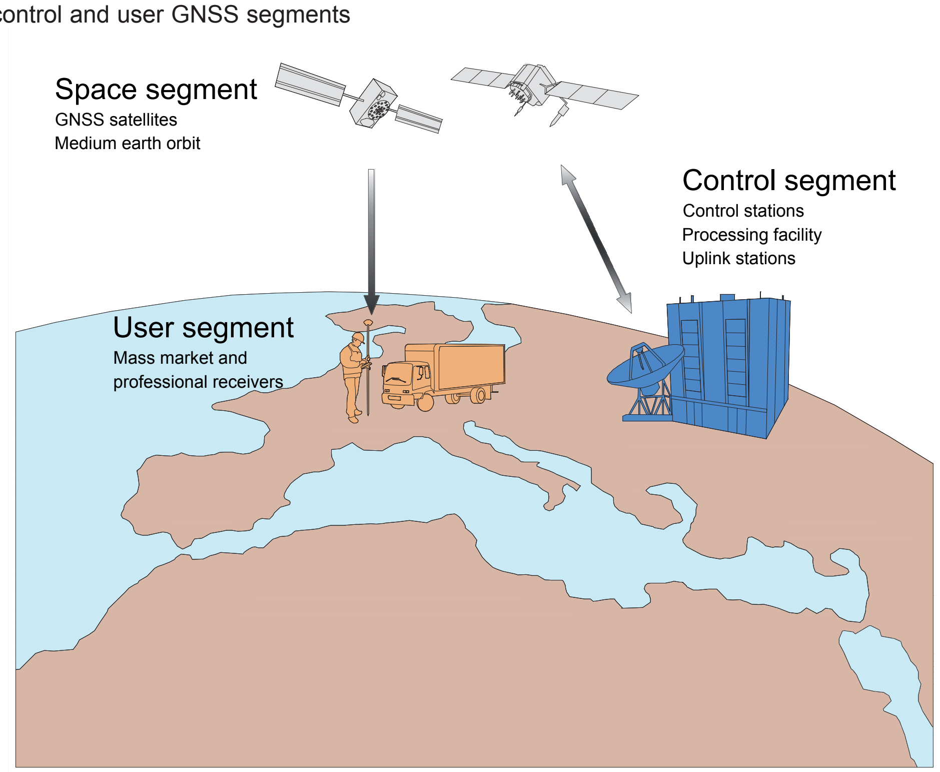
The acronym GPS is broadly used and refers to different navigation concepts. It is worth remembering that GPS is the US programme for Global Positioning System, designed in the 70's (called NAVSTAR GPS), which was the first satellite navigation system that enabled users to determine precisely their PVT in a well-defined coordinate system.

The easy access to global coordinates anywhere on the Earth had a strong impact on the promotion of the American positioning system, which made the acronym GPS very popular. The abbreviation was broadly used for any types of portable devices, applications and car navigation systems. Nowadays, it is sometimes unclear what is behind these three letters GPS and for a large number of users it is more than the satellite positioning system itself.

For many years, GPS was the only fully operational GNSS. Originally, GPS was constructed to be a military navigation system, but since 2000 its civil signals have been available with no intentional degradation any more for public use. Since the end of 2011, the Russian GLONASS also provides again a continuous service after having experienced some problems of maintenance in the mid-90s. Currently, Europe and China are developing their own systems named Galileo and BeiDou (formerly called COMPASS), respectively. BeiDou already proposes an initial operating service with a reduced number of satellites (14 at the end of 2014), whereas Galileo is scheduled to do so by 2018. Both systems are expected to have full operational capability in 2020. The simultaneous usage of satellites from several GNSSs by a single receiver is called multi-constellation GNSS. Still many of today's GNSS receivers are not fully capable of using GNSSs other than GPS, although the number of GPS-GLONASS capable receivers is growing rapidly. The next generation of receivers will benefit from enhanced performance based on the multi-constellation and multi-frequency techniques.

Every GNSS consists of three segments: space, control and user segments. The space segment consists of 24 to 35 satellites distributed in orbits inclined at different angles to the equator (e.g. 55° for GPS and 64° for GLONASS). The satellites are mainly situated at the Medium Earth Orbit (MEO), 20,000 kilometres above the surface of the Earth and have an orbital period of approximately 12 hours, i.e. the view of the satellite constellation from the Earth is repeated approximately every 24 hours. These satellites continuously broadcast signals to the control and user segments. The control segment is a network of monitor, control and uplink stations placed at pre-surveyed, very precisely known locations used to predict satellite orbital information, clock parameters and atmospheric data as well as to monitor GNSS integrity in terms of satellite health condition. Lastly, the user segment is realized by equipment of variable capabilities and cost able to receive and process the GNSS signals to compute their PVT.

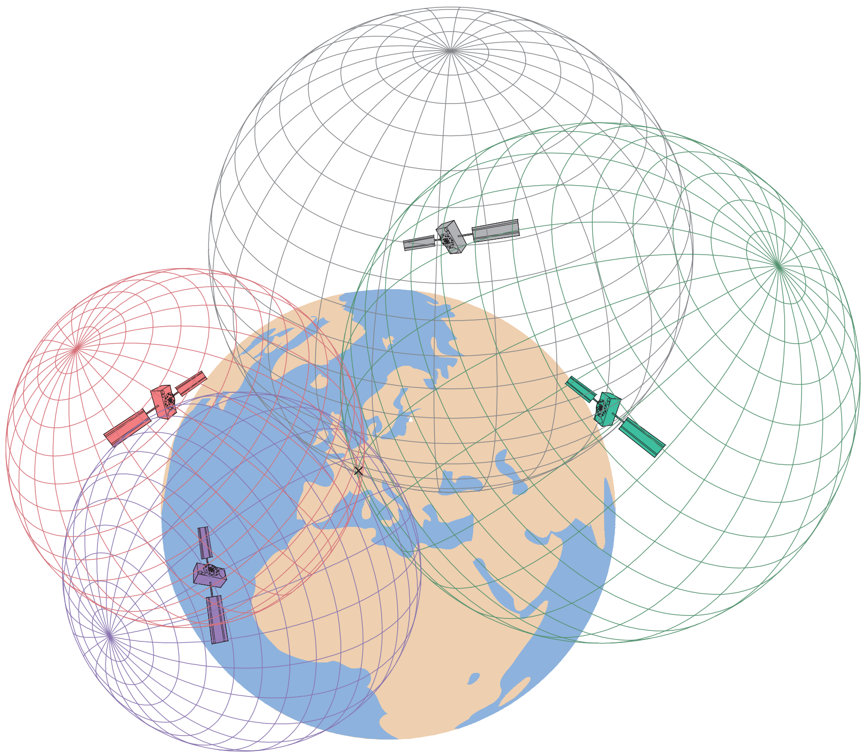
Figure 5
Space, control and user GNSS segments



2.1.2 Positioning principles

The GNSS positioning principle resides on the trilateration concept by which an unknown point location (receiver) is estimated using distance measurements observed from known point locations (satellites). The basic observable of the system is the travel time required for a signal to propagate from the satellite to the receiver multiplied by the speed of light to compute a distance. The receiver can then be anywhere on the surface of a sphere centred on the satellite with radius that equals this distance. In geometric terms, ranges from three satellites are required to estimate the user's position through intersection of three spheres. However, as the clocks of the satellites and the receiver are not precisely synchronized, the distance contains an unknown clock offset and is, thus, referred to as "pseudorange". As the highly accurate atomic clocks of the satellites are synchronized among each other at the first order, this offset can be considered as identical for any satellite. Thus, a fourth satellite is sufficient to solve this time ambiguity and also, by conception, to transform each GNSS receiver into a worldwide synchronized time source. An increased number of satellites usually further enhance the position quality. Furthermore, GNSS provides the user's velocity via measuring the Doppler frequency of the received GNSS signals as a result of the relative satellite-receiver motion.

Figure 6
Position computation by trilateration



The quality of raw GNSS observables is affected by several factors originating from the satellites, signal propagation and receiver (see figure 7).

- Satellites' clock offsets and inaccurate orbits directly induce biases on the pseudorange measurements which are, to a certain extent, mitigated via corrections broadcast to the satellites by the control segment.

- The signal transmitted by a satellite propagates through the atmosphere, where it is subject to delays caused by ionosphere and troposphere media. The effects of these delays are only partially compensated thanks to global models in single frequency receivers.
- At the ground level, multipath, namely the reception of signals reflected from e.g. buildings surrounding the receiver, can occur, inducing one of the largest errors that are difficult to model as it is strongly dependent on the receiver environment. The worst situations are experienced when only reflected signals are received (Non-Line-of-Sight signals, or NLOS signals), resulting is pseudorange errors of several tens of metres or larger in extreme cases.
- Finally, random errors are encountered at the receiver level due to receiver thermal noise.

The receiver clock offset (much bigger that the satellites' one) does not create any error since it is considered as an unknown and calculated together with the position.

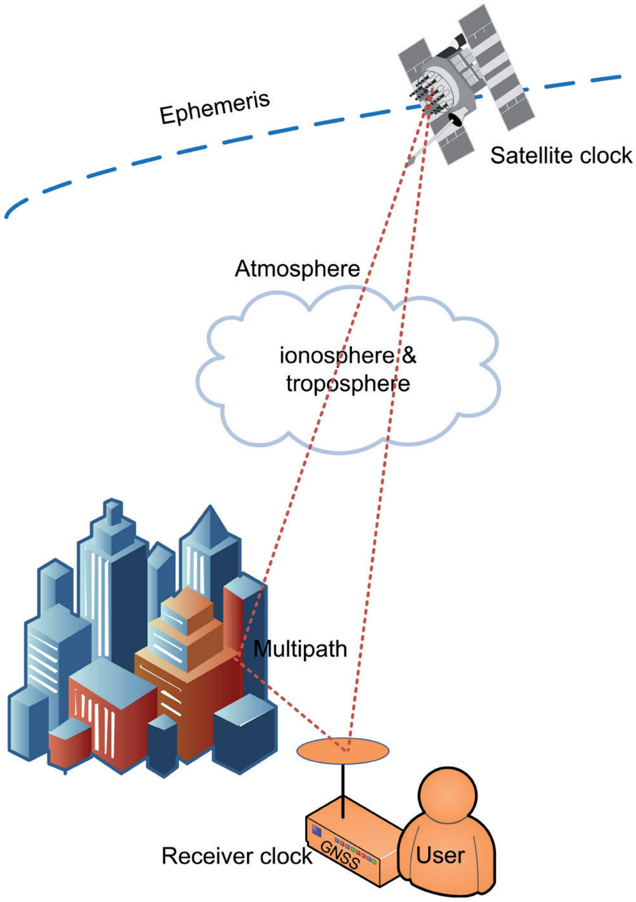
The position error that results from the measurement errors above depends also on the relative geometry between the receiver and the satellites, referred to as Dilution of Precision (DOP). Accuracy is maximized when directions to tracked satellites are more uniformly spread around the receiver.

The following table indicates the order of magnitude of the errors on the position resulting from the main error sources listed above. These indications are valid only for standard stand-alone single frequency GNSS receivers.

Table 2
Order of magnitude of the errors on the position from the main error sources

Source of error	Resulting position error
Satellites' clock and orbits	0.5 m – 1 m
Atmospheric delays	1 m – 3 m
Multipath and NLOS signals	0.1 m – 100 m
Receiver thermal noise	0.1 m

Figure 7
Error sources



The frequency band allocated to Radio Navigation Satellite Service (RNSS) is the L-band, in particular its upper (1559-1610 MHz) and lower (1151-1214 MHz) parts. Each satellite transmits signals at two or three frequencies in the L-band that have three main components: ranging code, carrier phase and navigation message.

- The ranging code consists of a stream of pseudo-random binary digits which modulates the carrier wave and allows computing the signal travel time through correlating the received code with a replica code generated by the receiver. The search of the maximum correlation peak indicates when the replica and the code received are synchronized resulting in time of flight measurement. The resulting distance measurement is called the pseudorange.

Demand for centimetre accuracy

Using ranging codes and techniques such as Differential GNSS (DGNSS), sub-meter accuracy may be obtained in favourable conditions. However, many applications require accuracy of sub-decimetre or beneath, which can be brought only with carrier phase measurements. This measurement is 1,000 times more precise than the code measurement, due to its high resolution, but ambiguous and therefore more complicated to be processed.

Accuracies, surpassing even the ones obtained with protected military signals, can be obtained in real-time and in kinematic mode through Real-Time Kinematic GNSS (RTK-GNSS) provided that high-end equipment and a radio link to receive differential corrections are available.

However, utilization of RTK requires the reference receiver with known location to be within a few tens of kilometres range from the user receiver. RTK services are in most cases provided by commercial entities and consequently subject to a fee.

The equivalent of RTK in post-processed mode is called Post-Processed Kinematic (PPK) and always provides solutions even more accurate.

- The carrier phase measurement consists in the phase of the sine radio wave carrying the code, expressed in cycles of carrier wave.
- Finally, the navigation message contains all the required data for the position computation, namely: ephemeris (i.e. parameters to calculate the satellite position at a given time), time parameters and clock corrections, satellite health information, ionospheric model parameters and satellites almanacs necessary for signal acquisition.

2.1.3 Positioning techniques

Positioning with GNSS can be performed in two ways known as Single Point Positioning (SPP) and relative positioning, also called Differential GNSS (DGNSS). SPP refers to the estimation of antenna receiver coordinates using pseudoranges leading to a typical accuracy from 5 m (95%)[6] in open sky conditions to 15 m (95%) in constrained environments. To overcome the accuracy limitations inherent to the SPP approach, differential techniques have been developed to mitigate common error sources in pseudorange and/or carrier phase measurements by employing two or more receivers simultaneously tracking the same satellites. The performance of DGNSS techniques varies depending upon the type of GNSS observable, user equipment, processing algorithm (in particular real-time or not), operating environment and mission mode (static or kinematic). Standard DGNSS techniques based on single-frequency pseudorange measurements can typically deliver positioning accuracies ranging from a few metres to sub-metre.

Precise Point Positioning (PPP)

PPP refers to high quality positioning for a single receiver using accurate orbit and satellite clock corrections and ionospheric-free functions.

However, while post-processed PPP has proved a suitable option for many static applications, its use for surveying and real-time kinematic applications still has limitations, in particular its high initialization time. The major advantage of this technique is the possibility to reach centimetre accuracy without dedicated reference stations.

Notwithstanding DGNSS techniques offer an increased accuracy level, their use presupposes a network of Continuously Operating Reference Stations (CORS) to provide the user with differential corrections. Such positioning infrastructure is currently available in most countries worldwide. However, as it is costly to establish and maintain at an appropriate level of station density, as well as signal availability and integrity, other approaches gradually gain increased interest in the GNSS market.

To increase the accuracy and integrity of stand-alone GNSS, Satellite-Based Augmentation Systems (SBAS) can improve the GNSS navigation solution. Such systems rely on a number of accurately-located monitoring stations deployed across continental regions that are used to produce differential error corrections and integrity messages which are then broadcast to the users using geostationary earth orbiting satellites as an overlay to the generic GNSS navigation message. Such systems are the Wide Area Aviation System (WAAS) developed by the Federal Aviation Federation in the US for use by the aviation industry and the European Geostationary Navigation Overlay Service (EGNOS) developed and funded by the European Commission and by the European Space Agency for critical air navigation services. A similar regional

6. Ninety-five% accuracy means that 95% of the positions calculated have an error lower or equal to the given value.

system exists in Japan, MSAS, and others are under development. Although the SBAS have been primarily developed for civil aviation needs, they can also benefit to terrestrial transport.

Figure 8
Differential GNSS

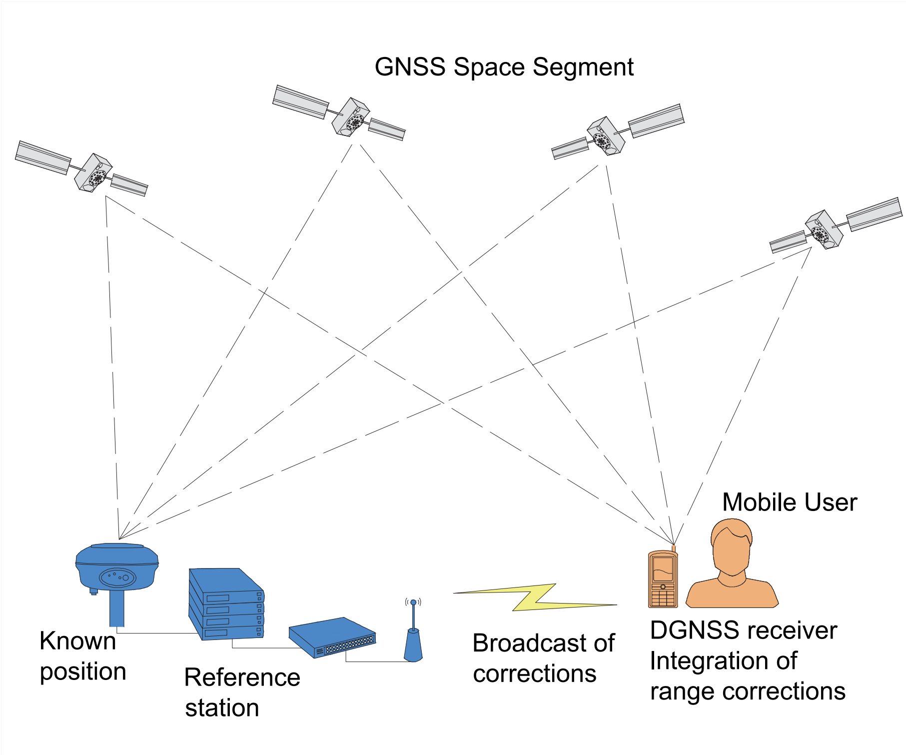
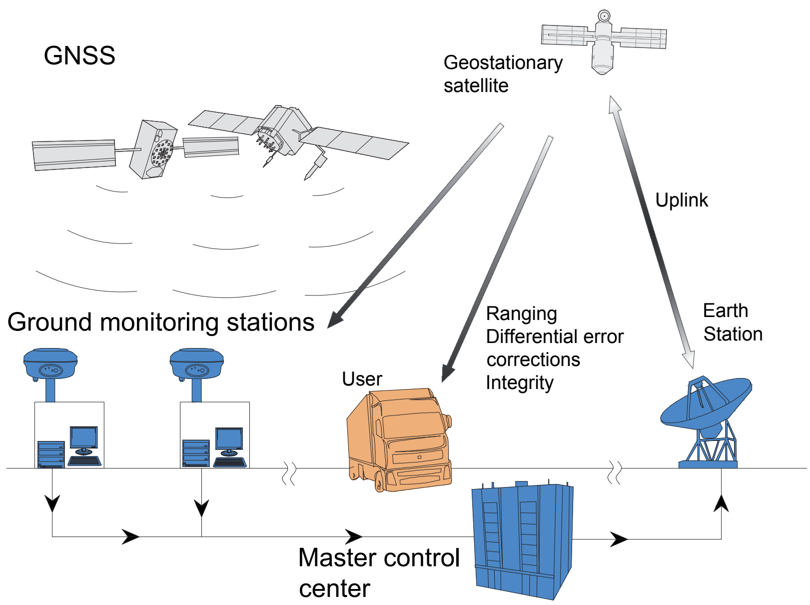


Figure 9
Satellite-based augmentation systems architecture



Assisted-GNSS (A-GNSS) is a method used mainly in smartphones to improve positioning performance and especially the time needed to compute the receiver position when positioning is activated: i.e. Time To First Fix (TTFF). A-GNSS is based on providing data with the help of mobile network services, e.g. a rough estimate of location or satellite orbital data, to the receiver via cellular network.

2.1.4 GNSS for timing

Apart from, or more exactly concomitantly with, computing a position, GNSSs are used to provide at a very low cost a very accurate time scale, synchronised with the Universal Time Coordinated (UTC). Today, the GPS time, accessible with a simple receiver with an accuracy of few nanoseconds, is widely used for the synchronization of many industrial, telecommunication or even trading processes.

Summary

Global Navigation Satellite Systems (GNSSs) are systems providing Position, Velocity and Time (PVT) information for the user. In addition to the widely known US GPS, there are other GNSSs existing or under development, such as European Galileo, Russian GLONASS and Chinese BeiDou. GNSS consists of three segments: space, control and user. Measurements from at least four satellites are needed to compute the user's (three dimensional) position due to the unknown receiver clock bias. Position accuracy obtained using a stand-alone GNSS receiver is typically between 5 to 10 meters (95%) in favorable conditions. Additional methods may be used when improved accuracy, integrity, and time to initialize the positioning process, are required. These include Differential GNSS (DGNSS), Satellite-Based Augmentation Systems (SBAS) and Assisted-GNSS (A-GNSS). GNSS is also a critical technology for synchronization of important industrial systems thanks to the provision of a very accurate and affordable time scale.

2.2 GNSS solutions from the industry, costs and performances

Depending on the targeted market, GNSS receivers can exist under different forms, configurations and costs. The most sophisticated, high performance and expensive devices are indeed the multi-constellation multi-frequency phase-differential receivers capable of centimetre accuracy in real time (see above the framed text on centimetre accuracy) and mainly used for precise surveying or machine guidance. They are sometimes also used as a means to establish the true position (referred to as the "ground truth") when assessing the accuracy of a positioning system in field tests.

Today, for the ITS and LBS market, there is a large industrial offer of positioning terminals, e.g. smartphones and hand-held GNSS receivers, achieving a reasonable combination of low cost and good performances, even in urban environments. At present, most of these terminals process GPS and GLONASS signals and are supported by A-GNSS capability. The prices of GNSS receivers are reasonable thanks to the large amount of terminals being sold.

Integration with other technologies (discussed below in more detail) is implemented in some terminals, e.g. WiFi in LBS devices, and Inertial Measurement Units (IMUs) or Controller Area Network bus (CAN bus) connection for some automotive devices.

In addition to GPS and GLONASS, other satellite navigation systems such as EGNOS, and Galileo and Beidou in the future, are available in some products from different chipset manufacturers. EGNOS brings qualified GNSS Signal In Space (SIS) from the civil aviation sector to the road and LBS domains in open scenarios. However, as discussed above, in urban environments the local conditions (multipath) are the main source of GNSS signal errors and EGNOS is therefore of limited value in such environments. An additional service from EGNOS is provided by the EGNOS Data Access Service (EDAS), which offers a ground-based access to EGNOS data. This improves the continuity of EGNOS under bad reception of signals broadcasted by geo-satellites. However, this service will not replace the necessary line-of-sight to receive correct signals from GNSS satellites.

Multi-constellations increase not only the number of tracked satellites, which is a key factor for positioning availability in urban environments, but also the number of directly visible satellites (i.e. those whose lines of sight are free of obstacles), which allows devices to use only good quality signals, thus boosting positioning accuracy as well. Continuous availability of at least 4 or 5 directly visible satellites will be much more ensured with integration of a third constellation. The performance improvement derived from the use of more than one GNSS is fully available with only the L1 navigation band common for all navigation systems. The only modification needed in the receivers is addition of digital channels, so their increase in cost and complexity will be relatively small. This increased availability of measurements will result in improved accuracy as well as integrity, brought by the redundancy.

GNSS is particularly prone to unintended and malicious interference due to the extremely low power level of the signal at the user's receiver after travelling from the satellite transmitter to the user receiver on the Earth. Jamming means deliberately transmitting high-power radio waves at GNSS frequencies using cheap devices called jammers and therefore disturbing or denying position computation. Spoofing is a more sophisticated form of intentional interference, namely deluding the receiver by GNSS-like fake signals, synthesised to provide a false position after being processed by the receiver.

Major technology advances that have allowed a substantial performance improvement in the abovementioned urban environments are, along with aforementioned techniques (A-GNSS, multi-constellation, integration with other technologies, etc.), associated with the high sensitivity of receivers and anti-jamming capacities. Unlike anti-jamming, anti-spoofing techniques are not yet mature.

High sensitivity with the support of A-GNSS information, allows satellites to be acquired at lower signal powers, for instance inside a parking garage where only the attenuated multipath signals are available. Another relevant feature is the capability of reacquiring satellite measurements very quickly after the frequent occultation intervals among the buildings. In any case, multi-constellations could reduce the need for high sensitivity, whereas multipath mitigation will probably emerge as a key feature in the quest for high-quality navigation based on directly visible satellites.

Another trend under discussion is whether multi-frequency brings benefits to low-end receivers in urban scenarios. Multi-frequency corrects the ionospheric effects and this is an advantage in open scenarios but less relevant in urban ones. Some low-end GNSS chipsets manufacturers are not considering multi-frequency due to its limited benefit, at the cost of an increased receiver complexity.

High-accuracy positioning supported by external services such as RTK or PPP is also starting to be envisaged in ITS and LBS.

In relation to positioning performances, the key problems in urban environments are signal blockage, reflections and attenuation by obstacles although, as previously mentioned, existing technologies substantially mitigate these limitations. The key feature has been, as argued above, the high sensitivity in acquisition and tracking.

State-of-the-art GPS-GLONASS chipsets achieve positioning accuracy of about 5 meters (95%) in open-sky scenarios whilst in urban scenarios this accuracy is typically above 15 meters. TTFF of a few seconds is achieved thanks to the use of A-GNSS. High availability of GNSS signals is achieved even in deep urban canyons but is very much constrained in tunnels. Even integration with other low-cost positioning techniques (as generally required for ITS applications), or with CAN bus, does not provide reasonable solutions in long tunnels.

“Map-aiding” means the action of projecting the absolute position obtained using GNSS to a map reference for improving the position accuracy by correcting e.g. a deviating vehicle position to the road on the map. Map-aiding is discussed in more detail in the next section.

The level of performances discussed in the previous section, combined with the global availability of detailed maps, have boosted the development of a huge market of consumer applications, from Automatic Vehicle Location (AVL), automotive navigation and eCall solutions to a host of LBS applications supported by handheld PNDs and smartphones. In addition, there are many initiatives to develop industry-specifications and standards for regulated applications in the coming years in the road and LBS domains. These pose a particular challenge to continuing improvement of GNSS performance in the future, mainly in terms of accuracy, availability and robustness from several perspectives: from position error bounding or integrity to anti-spoofing capability in the receivers or authentication of the navigation data.

Summary

There is a very large offer of different types of GNSS receivers today, with highly variable performances and costs. For ITS and LBS, the standard in 2015 is the single-frequency GPS L1 receiver, with increasing SBAS and dual-constellation (with GLONASS) capabilities. LBS receivers (smartphones) are also often assisted (A-GNSS) and even hybridized with positioning based on communication networks. The possibility to use multiple GNSS improves the accuracy, integrity and availability of positioning, especially in urban areas. The modifications needed in the receivers for multi-GNSS capability are minor and will not increase the costs of the receivers significantly. Multi-GNSS will mitigate the effects of intentional interference, namely jamming. The good performance of GNSS has induced emergence of various consumer applications, which for its part oblige continuing improvement of GNSS performance in terms of accuracy, availability and robustness.

2.3 Hybridization and aiding systems

As discussed above, satellite positioning can benefit from the assistance of other technologies that can be exploited for vehicle or even pedestrian positioning. Below the fundamentals of GNSS-aided positioning are presented, by providing an overview of technologies and techniques necessary to apply them.

2.3.1 Aiding navigation technologies

GNSS positioning can be aided by the integration of other sources of information like the measurements of speed and orientation (e.g. inertial sensors), the relative localization based on beacons detection (e.g. digital images, radar) and the geometrical road elements (e.g. maps). In this section, we focus on today's most commonly used alternative technologies to determine the position, velocity and attitude; dead reckoning and inertial sensors. They are very common because measurements can be easily retrieved from the CAN bus of vehicles and from the inertial sensors installed on board modern cars, as well as from the Micro Electro Mechanical System (MEMS) sensors equipping most of the modern smartphones (sensor fusion for pedestrian navigation will not be further developed in this document).

The mathematical tools for combining measurements from different information sources are referred to as data fusion. The purpose of data fusion is the combination of all the navigation information into a single hybridized output that benefits from the complementary nature of the different sources, such as GNSS and DR, but also such as GNSS and map information.

When the data are measurement data coming from sensors, it is often referred to as sensor fusion. Data can also be a priori data, stored in a database prior to travel, in this case, the more general term data fusion is preferred.

2.3.2 Hybridization between GNSS and DR sensors

Principle

Dead Reckoning (DR) is the process of calculating current pose (position and heading) based on previous ones, by integrating travelled distance, velocity and acceleration. Usual DR sensors used in vehicles are odometers (wheel sensors), accelerometers and gyroscopes, providing travelled distance, acceleration and turn rate, respectively. The fact that these sensors provide measurements of the first or second order derivative of the pose implies that the position and heading estimates are subject to cumulative errors. The magnitude of these errors depends on the sensor accuracy (affected by noise and bias), but also on the techniques employed for the PVT calculation, including the modelling of the sensor errors and the vehicle models. In the case of positioning systems hybridizing GNSS and DR, the fusion architecture and the fusion algorithm have a marked impact, as well.

The use of a GNSS-based multi-sensor positioning brings different benefits. For a conventional configuration with encoders and inertial sensors, the most relevant features may be enumerated as follows:

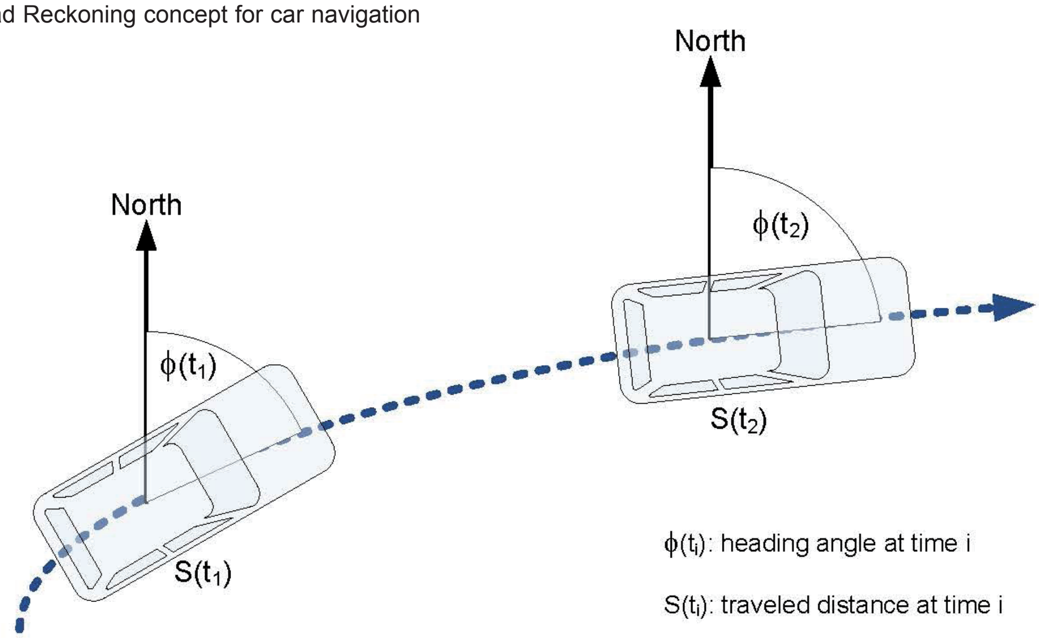
1. immunity to usual GNSS problems, such as signal blockage, jamming, weather conditions, etc., thanks to the nature of inertial navigation, unaffected by such problems
2. provision of PVT at a higher rate, as inertial sensors usually work 1 or 2 orders or magnitude faster than GNSS receivers (typically 1-5 Hz)
3. complementary information, such as acceleration and attitude (roll, pitch, yaw)
4. redundant positioning estimates coming from different sources

Feature 1 supports the availability and continuity of the position, particularly when GNSS satellite visibility is reduced. The combination of features 2 and 3 allows the navigation systems to track the vehicle dynamics. Feature number 4 brings redundancy, and the possibility to improve both accuracy and integrity.

Vehicle models

Vehicle models help to provide the means to integrate the DR estimation of the position with noisy sensors. A common assumption when slippage can be neglected is that the vehicle motion is considered as "non-holonomic", meaning that the forward velocity vector is tangential to the movement described by the position of the wheels. The literature shows many examples of how a good choice of the vehicle model for a DR system leads to important reduction of the positioning error. Vehicle models become of special interest in the case of a system with low-cost sensors, as the worse the sensor performance is, the more convenient it is to constrain the positioning problem to avoid the rapid accumulation of the positioning error.

Figure 10
Dead Reckoning concept for car navigation



Sensor data fusion architectures

Depending on the measurements used in the fusion algorithm, the fusion architecture can be either loosely coupled or tightly coupled.

In loosely coupled fusion architectures, the GNSS position is merged with the position estimate of the system, e.g. the vehicle position and heading.

In tightly coupled architectures, the fusion is not carried out with positioning variables, but with the GNSS pseudorange and Doppler measurements data. At the expense of a higher complexity of the architecture, this approach allows three significant benefits:

1. The GNSS pseudorange measurements errors are, a priori, less correlated than the errors of the calculated positioning variables, what matches better the principles of data fusion.
2. It avoids the need of switching to pure DR navigation when the number of locked satellites is less than four.

3. It makes it possible to exploit DR measurements for detecting faulty satellite measurements, enhancing the integrity of the position.

Sensor data fusion algorithms

Most common algorithms for data fusion are the optimal filters, among which the most famous one is the Kalman filter. The objective of such filters is to estimate the optimal value of a state (in our case, the state can be the position of a specific point of the vehicle, or the position and the heading angle, etc.) given some direct or indirect measurements of this state as well as some assumptions on its evolution (movement) and on the errors attached to the measurements. “Optimal” means that it can be demonstrated that these filters minimize the variance of the error between the true state and the estimated state, when the system is linear and the errors respect certain characteristics.

In the reality, these conditions to be optimal being rarely met, the filters that are commonly used are variants of the Kalman filter. To cope with the non-linearity of the system, engineers often use the extended Kalman filter or the unscented Kalman filter and, to cope with biased and correlated measurement errors (often the case for GNSS in urban environments), the particle filter is a more and more popular tool despite its computational load.

Other fusion techniques coming from the so-called artificial intelligence that do not use an explicit model of the system and demand often a learning phase (e.g. Neural networks, Fuzzy logic) can also be envisaged.

2.3.3 Map-aided GNSS positioning

Digital map data bases are key components to the majority of transport and mobility systems. The main reason is that the map reference is generally the reference system in which the final position-based service is delivered, from simple navigation to fleet management or RUC more complex systems. This means that, at one moment or another of the application process, the absolute position has to be map-matched, e.g. projected into the map reference, which is the only one of interest for the end-user of the service.

However, map data can also benefit directly the positioning process, at the level of the positioning system. The two main principles of map-aided GNSS positioning are:

1. use of 2D map data as constraints in the data fusion process
2. use of 3D map data to improve the raw measurements data quality

In the first case, the map information, under the form of the analytical description of the road borders, is used by the data fusion algorithm (such as Kalman filter or particle filter) to constraint the solution (the vehicle is assumed to be on the road) and to converge towards a more reliable solution.

In the second case, the knowledge of the 3D environment (mainly the buildings) is used to analyse the propagation conditions of the satellite signals in order to qualify and to correct the pseudorange observables delivered by the receiver.

These techniques are not only compatible with the sensor data fusion presented above but the combination of both methods is highly recommended to optimize the final solution.

Summary

The performance of GNSS may be improved by data fusion, namely by integrating sensor measurements, other positioning means or a priori data such as digital data bases. This data fusion brings enhancement at 3 levels: (1) the standard Position, Velocity and Time (PVT) is improved in terms of availability, accuracy and integrity, (2) additional information such as attitude angles may be provided and (3) the output rate is increased by one or two orders of magnitude. The final performance of the hybridized augmented PVT depends on the quality of the models and of the fusion method, in addition to the quality of the sensors themselves.

2.4 Alternative and complementary technologies to GNSS

In this section, competitive and complementary positioning technologies are described to provide readers with the basic information about positioning possibilities other than GNSS. When positioning technology is about to be implemented, it is important to evaluate the requirements of the service provided. The scope should not only cover accuracy, but also implementation costs as both of these may differ significantly when different technology is used.

The technology described below can be envisaged as alternative to GNSS in environments where GNSS are not feasible or available like indoors but also, and this way is of greater interest, as complementary technology, to be hybridized with GNSS like inertial sensors.

2.4.1 Wireless networks

Positioning based on utilization of wireless networks has become popular in recent years especially in dense urban and indoor environments. Positioning can be performed using different types of measurements, the most common being:

- signal power measurements, e.g. Received Signal Strength (RSS)
- angle to transmitter measurements, e.g. Angle of Arrival (AoA)
- propagation time measurements e.g. Time of Arrival (ToA), Time Difference of Arrival (TDoA), Differential Time Difference of Arrival (DTDoA)

RSS based positioning provides reasonable accuracy especially in WiFi networks, however typically needs some pre-processing (“Fingerprinting” framework) or very accurate signal propagation models (distance-based positioning).

Under certain conditions, positioning system based on AoA measurements can provide high accuracy (sub-meter level); however the line of sight propagation between transmitter and receiver has to be assured. Positioning based on AoA can be implemented for example in parking buildings. Positioning based on ToA measurements needs precise time synchronization between transmitters and receivers in the wireless network to provide position estimates, which are not always possible, and then TDoA measurements can be used instead. TDoA still requires time synchronization between the transmitters, which may further be omitted using DTDoA methods. The accuracy of positioning system based on time measurements highly depends on the time measurement accuracy since error of 1 μs in time represents error of 300 m in distance.

2.4.2 RFID

Radio Frequency Identification (RFID) is a wireless radio technology, such as CEN DSRC (Dedicated Short Range Communication) at 5.8 GHz, which can be used to determine position. The basic idea of RFID positioning is to provide information about RFID tag's proximity, carried by the user, to the RFID reader. The RFID-based positioning requires infrastructure. For this reason, RFID technology is usually implemented on gateways to provide information about the traffic in the area, e.g. for monitoring how many vehicles that pass the RFID reader. It can also be used locally as complementary positioning technology in some specific points like tunnels by GNSS-based tolling systems. Positioning performance in general is dependent on the RFID technology used for the implementation and of the density of the tags network.

2.4.3 Camera

Cameras are increasingly used for positioning for a wide field of applications at all levels of accuracy. The success of optical methods originates from miniaturization and advancement in the technology of detectors (e.g. CCD sensors). In parallel there has been an increase in data transmission rates and computational capabilities of processing equipment as well as profound development of algorithms in image processing. On intelligent vehicles, cameras are of high interest to be used independently or, preferably, hybridized with GNSS, since they are equipping more and more frequently the new vehicles and therefore can provide valuable information at a very low additional cost.

Camera-based positioning systems can be categorized into self-positioning systems, where a vehicle equipped with the camera needs its own position, and surveillance systems, where static cameras locate moving vehicles in images. This section is only about the 1st category.

Several positioning methods can be used. The most popular stores a base of images acquired with the camera, in the same conditions it will operate in real-time, together with the true trajectory of the vehicle. Then, during its operation, the system compares the actual images with the stored ones and determines from this matching the deviation from the recorded trajectory and consequently its position. This method has demonstrated impressive positioning performances in terms of accuracy in many R&D projects. It can also be applied with synthetic images in place of real images.

However, high sensitivity to the weather and light conditions remains an important drawback for all camera-based methods.

2.4.4 LIDAR

LIght Detection And Ranging (LIDAR) can be an attractive technology for positioning due to its high accuracy in ranging, wide area view and low data processing requirements. LIDAR positioning is based on transmitting a laser pulse and calculating distance to surrounding constructions based on the signal return time. The computation methods, like those used with cameras, also need some kind of learned base of images with the difference that the images are composed of range data instead of grey level data.

LIDAR-based positioning often suffers from noise issues and its reliability is highly dependent on the distance and reflectivity of different objects, but is quite robust to light conditions. Although this technology is increasingly being considered by the autonomous vehicles developers, mainly for obstacle detection but sometimes also for positioning, its cost still remains a significant drawback for the automotive industry.

Summary

When GNSS signals are degraded or not available at all, like in indoor environments, other positioning technologies may be used. Good examples are wireless networks, Radio Frequency Identification (RFID), camera-based, or LIDAR-based positioning. The used method should be selected based on the service requirements in the form of accuracy, availability, integrity and implementation costs. Despite their capacities, f or most of outdoor ITS services, none of these technologies are really competitive to GNSS in terms of performances or cost, even if they can be successfully combined of hybridized with GNSS for certain specific use cases.

2.5 Trends in GNSS positioning for transport

Future generations of GNSS receivers will obviously take advantage of the multiple constellations of satellites. These GNSSs are designed to be compatible and interoperable with each other, where Code Division Multiple Access (CDMA) is generally accepted as common channel access method. Interoperability of all GNSSs is important for better positioning accuracy and multipath resistance where signals from numerous satellites can be processed by receiver algorithms and better localization quality can be reached.

The existence of multiple GNSSs will improve the positioning availability by increasing the number of satellites in the sky and therefore the number of line-of-sight signals available even in dense urban areas. The second generation of GNSS will transmit multiple signal frequencies also for civil use, providing improved positioning accuracy by enabling the mitigation of ionospheric errors.

For transportation, and particularly in cities, the number of visible satellites in any point and at any time of observation should increase significantly, also improving the navigation of vehicles, persons and goods. The improvement will be noticeable in terms of positioning availability and continuity: it will be quicker to start a GNSS receiver and to keep it navigating with no interruption even in deep urban canyons.

Different augmentation methods such as SBAS, A-GNSS and DGNSS discussed above will be used more and more as standard supplements of GNSS helping to overcome the biggest localization errors in the environments where the local multipath and non-line-of-sight phenomena are not too severe. GNSS receiver manufacturers plan to move to a multi-constellation design additionally employing European Galileo and Chinese BeiDou systems in the post-2020 era.

What Galileo will bring

Galileo is the GNSS which will bring positioning and timing autonomy from GPS or GLONASS to Europe.

In addition to its strategic importance, Galileo has been designed to bring also significant differentiators:

- optimised interoperability with GPS, increasing accuracy, availability and integrity
- higher level of robustness to multipath signal
- anti-spoofing capabilities with signal authentication
- higher precision with Commercial Services based on PPP method
- satellites infrastructure placed under civil governance

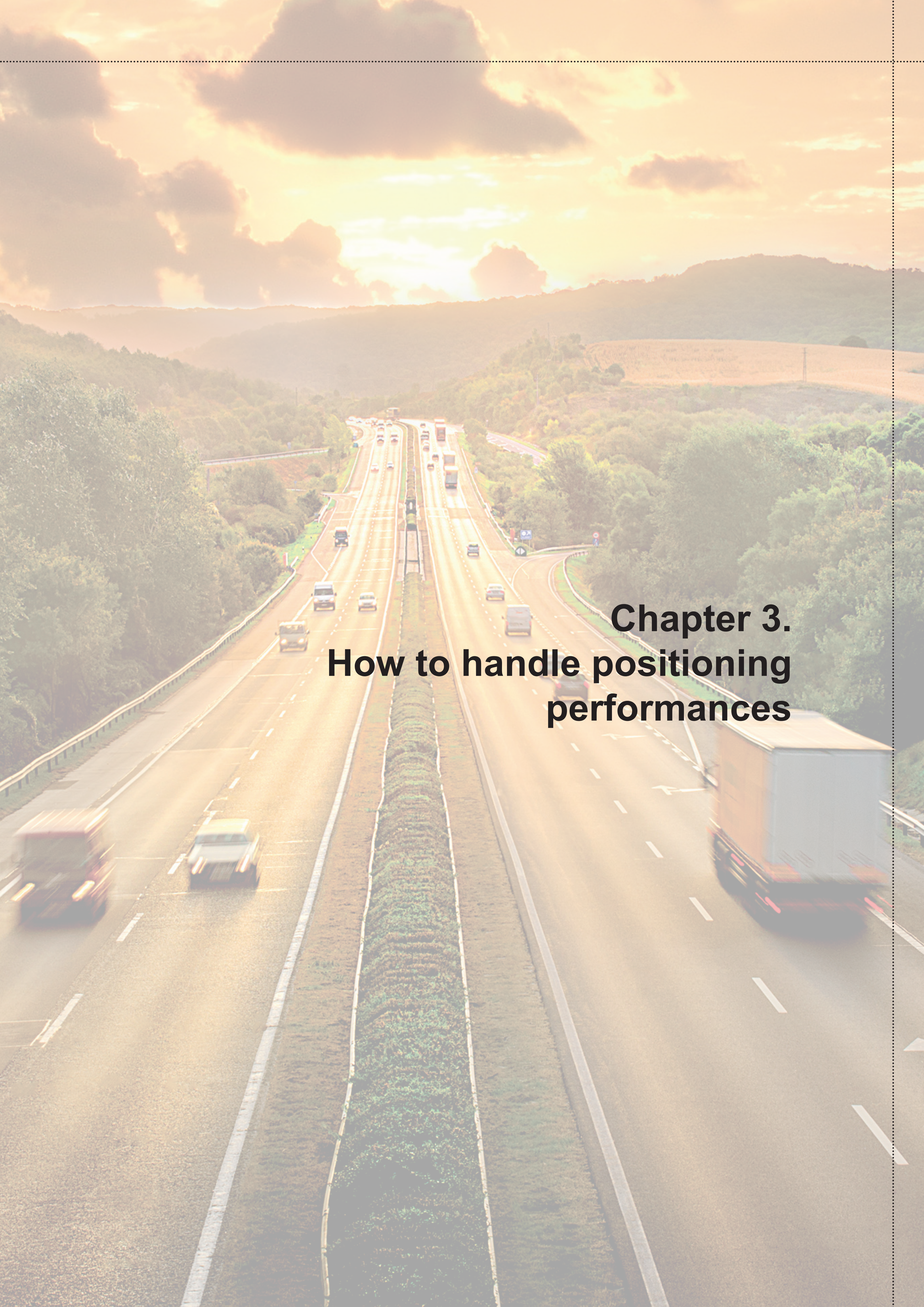
Industrial providers of receivers can already design and develop tracking hardware and navigation software which comply with the specifications of all GNSS and augmentation systems at the same time. GNSS chips should be powerful enough to implement complex localization algorithms in real time, although for some kinds of scenarios post-processing can be used. In the future, compact and robust multi-antennas able to track different signals as well as powerful and energy efficient architectures will be used in mainstream GNSS receiver chipsets.

Another direction of research and development for GNSS in transport concerns what one generally denotes as “seamless positioning”. In future applications of mobility, continuity of the positioning service would be required when moving from outdoor to indoor, and vice versa. This is noticeably expected by people using their smart-device (e.g. smartphone, smartwatch, tablet) to navigate, including scenarios when riding urban tubes, trains, or personal vehicles. The challenges of seamless positioning are those of indoor positioning, i.e. positioning without or with very poor GNSS signals. Other technologies like the ones mentioned in sections 2.3 and 2.4, including accurate indoor maps, have to be used, and none of them can be compared to outdoor GNSS in terms of performance for the moment.

Summary

One of the most influential trends in GNSS is the use of multiple systems to achieve better error mitigation (e.g. multipath), resistance to interference and positioning accuracy. In addition to the new systems under development, existing systems are continuously being improved e.g. by adding new signals. All existing and emerging GNSS are designed to be compatible and interoperable. Ground and satellite based augmentation systems will also be used more in the future for improved position accuracy and integrity. The craving for ubiquitous position information is also driving the development of complementary and compensatory techniques for GNSS for enabling seamless outdoor/indoor positioning.

Thus, trends in positioning for transport and mobility cover several sources of information; multiple satellite-constellations, a variety of embedded sensors, multi-antennas allowing processing of multiple signals, powerful computational units allowing real-time localization and digital maps for indoor and outdoor navigation.



Chapter 3.
How to handle positioning performances

This chapter starts by discussing the place of positioning performance in the frame of a complete intelligent transport system using positioning. This is done through two examples of strategic systems in which the position data are processed by the applicative part of the system and a third one in which the position data are directly used as it is. This is followed by emphasising the high sensitivity of the GNSS performance to the environment and a list of the main outputs of a positioning terminal, also called positioning quantities that may be used by the applications. The concept of performance features and metrics is presented through the specific example of horizontal position accuracy and a detailed explanation of the concept of position integrity. Finally, the chapter provides an overview of the related work to standardize the positioning performance indicators and the associated examination framework.

3.1 Examples of strategic road ITS

As discussed in the previous chapters, a high number of road ITS and personal mobility systems make use of positioning, most of which rely on GNSS technology, sometimes hybridized or assisted by other sensors or data. In a significant majority of cases, the requirements expected from the positioning system are not really stringent and are generally met on average. For these systems, the situations when the positioning fails generally do not cause any serious damage.

However, in section 1.3, it was highlighted that there exist critical ITS that require positioning capability. Therefore, the quality of the positioning output (PVT) must be guaranteed by ensuring that the End-to-End (E2E) performances of the system are within the specified requirements.

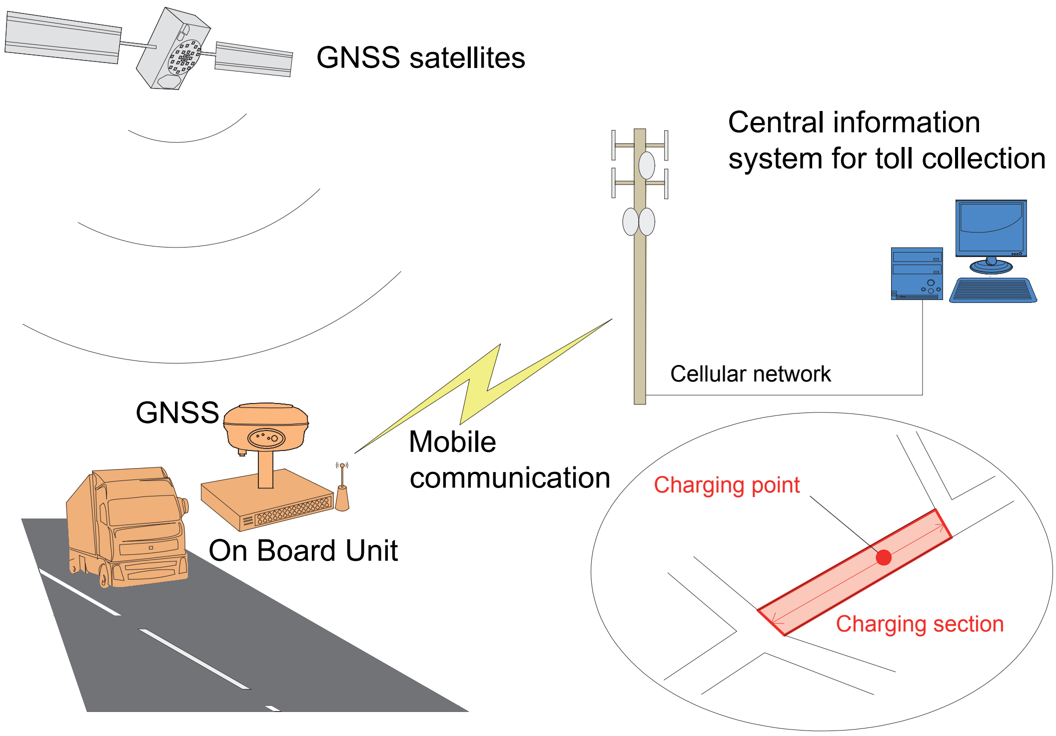
Among these critical systems, some are strategic either because they are pushed by European regulation or/and because they can have a tremendous impact on the transport economy and sociology, as: GNSS-based RUC, eCall or cooperative Advanced Driver Assistance Systems (ADAS).

3.1.1 GNSS-based Road User Charging

Road User Charging (RUC), also called road tolling or electronic fee collection, systems operate automatically to collect charging data and check user compliance of vehicles travelling on a chargeable road or within a chargeable zone. Although such systems are generally deployed on motorways, they are increasingly being deployed on highways and inside cities. The two most common charge collection technologies used in Europe are based on DSRC at 5.8 GHz and GNSS. This chapter focuses on GNSS-based systems.

The principle is illustrated in figure 11, taking as an example a section-based charging system, in which the charging event is established when the truck is detected as having passed the charging point (sometimes called virtual gantry) located on the section.

Figure 11
Example of GNSS-based Road User Charging system[7]



Performances at the system level

The RUC system (i.e. including data and processing beyond the vehicle's positioning terminal) should detect and collect charging data for each liable vehicle that crosses the charging point, and should not detect the vehicles driving on the roads nearby. The detection technique is commonly considered as belonging to the so-called geofencing[8] techniques. Still at this elementary level, the performance figure of the system can be represented as shown in table 3.

Table 3
Performance matrix for elementary events of RUC systems based on discrete schemes

		System detects charging event	
		Yes	**No**
Actual charging event	**Yes**	Correct detection	Missed detection (Undercharging)
	No	False detection (Overcharging)	Correct non-detection

In the matrix there are two successful scenarios (correct detection and correct non-detection), and two unsuccessful (missed detection and false detection) scenarios. The unsuccessful scenarios look similar but have very different consequences.

7. The figure illustrates the charging part of the system, noting that the overall system also encompasses a compliance checking and enforcement system.
8. Geofencing is a method for determining the presence of given objects inside a given area.

A missed detection is a gain for the road user, who is not charged, whilst it is a loss for the toll charger, who fails to get paid. A false detection offers some additional revenue for the toll charger, but this comes at the cost of a significant legal rights' violation of the road user (who is unfairly charged), which ultimately risks eroding trust in the system.

Thus, false detection has a much more negative impact on the system necessitating its probability of occurrence to be very low (typical values of 10^{-5} or 10^{-6}) whilst for misdetections probabilities lower than 10^{-3} are typically acceptable.

At the level of the whole system, the E2E performance is much more complex to define and assess. It is required to consider all the vehicles driving around all the charging points and to define global performance metrics based on the performance matrices of all the pricing points. Generally, the 2 main E2E performance indicators considered are:

- overall rate of missed detections, on a given period (e.g. one month)
- overall rate of false detections, on a given period

Performances at the positioning terminal level

As far as GNSS-based positioning performance is concerned, the important point to note is that the performance of the system depends on the performance of the GNSS position, but also significantly on the performance of the detection algorithm that can compensate for poor positioning performances. In the RUC case, this detection algorithm is applied to all the vehicles that are circulating on a charging section (i.e. several thousand at the same time).The combination of the success of all the individual detection events, cumulated during one month, will determine the E2E performance.

This means that it is not obvious to derive the required performances at the positioning level from the E2E performances required at the system level. This derivation needs a thorough analysis of the:

- typology of the tolling network
- performance of the detection algorithm in the typical tolling environments, with different classes of positioning terminals
- way to compute the E2E performance indicators knowing the application's performance for each typical tolling environment

For some specific detection algorithms, the integrity concept (with the associated quantities protection level and integrity risk) can be fruitfully used to link the overall false detection rate with the positioning terminal performance.

3.1.2 Emergency call

Emergency call, with the example of the European initiative eCall, can be considered as an automatic crash notification system with the purpose to bring rapid assistance to motorists. An eCall-equipped car automatically calls the nearest emergency centre via the emergency number 112 and transmit a Minimum Set of Data (MSD), including the position of the crash to the Public-Safety Answering Point (PSAP). Therefore, immediately after an accident, emergency services know that there has been an accident and its location. The benefit of eCall arises through the reduction in response times for emergency services attending to an accident, thus helping to save lives and to treat injuries more rapidly.

Performances at the system level

The service provided by the overall eCall system is to inform, as fast as possible and as accurately as possible, the emergency services of a car crash and its location on the road network. Thus, the location of the crash should be a map-matched position, at the level of the carriageway in the case of a highway or motorway with separate carriageways. It implies that the PSAP part of the eCall system should have an up-to-date and accurate digital map and a map-matching tool to be able to know where on the network they have to deliver aid.

The E2E performance indicators of the complete system should be expressed in terms of exactness of the carriageway segment indicated after map-matching and the accuracy of the along-track position on the segment.

Performances at the positioning terminal level

The positioning terminal of the eCall system is a module of the In-Vehicle System (IVS) and has to deliver the absolute position of the vehicle just before the crash. Since it would be too complicated to integrate in each IVS an up-to-date map consistent with the one that will be used at the PSAP, the IVS does not perform map-matching and the position is delivered in an absolute reference system, e.g. World Geodetic System 1984 (WGS 84). The question is: what data in terms of position, velocity, heading, etc. are necessary to ensure a correct and trustable map-matched location of the crashed vehicle at the PSAP? This is actually a pure map-matching issue and it is clear that the result depends not only on the accuracy of the position, but also on the effectiveness of the map-matching algorithm which may request more than the crash's position to operate. For instance, the heading information and a series of prior positions would be better that one single position to help determine the link on a carriageway. Information on the integrity of the position (and derivatives such as heading) could also be necessary to run the map-matching algorithm in the ambiguous cases.

Once again, even if the data processing performed by the application on the PVT data is much simpler than in the RUC case, it is not straightforward to specify the performances at the PVT level without considering also the performance requirements of the application (map-matching at the carriageway level in this case).

3.1.3 Cooperative Longitudinal Collision Risk Warning

Longitudinal Collision Risk Warning (LCRW) is one example of cooperative ADAS which are ADAS based upon communication between vehicles (V2V) or between vehicles and infrastructure (V2I). Basically, ADAS rely upon messages exchanged between communication terminals called ITS stations, which have been standardized to support several ITS applications. The most important message which is exchanged periodically between the ITS stations is the CAM. For the vehicle ITS station, the CAM contains time, position of the vehicle, motion state, etc.

Performance at the system level

Among the system minimum performance requirements (according to the standard ETSI TS 101 539-3) appears at the first place: "Longitudinal alignment and vehicle position accuracy". In the standard, the minimum requirement for the (horizontal) position accuracy is: "Less or equal to 1 metre with a confidence level of 95%".[9]

9. It can be noticed that the way how this performance can be assessed is not mentioned, since positioning performance standards were not existing at the time this ETSI standard was written.

The other requirements are expressed in terms of “Communication coverage”, “E2E latency time” and “Message processing performance”.

Performances at the positioning terminal level

For this ITS system, very specific and important as far as safety is concerned, the link between performance at system level and performance (as it is expressed in the standard) is quite straightforward. This illustrates a case where the E2E performance of the service is directly expressed in terms of technical performances of the 3 technologies supporting the system: positioning, communication and data processing.

In this case, the application does not apply any processing to the raw position output by the positioning terminal.

Summary

A road transport or personal mobility application often performs a more or less complex processing chain, using the raw output of the positioning terminal to deliver the expected service. In this case, the End-to-End (E2E) performance of the system has to be apportioned between the performances of the terminal itself and that of the application algorithm.

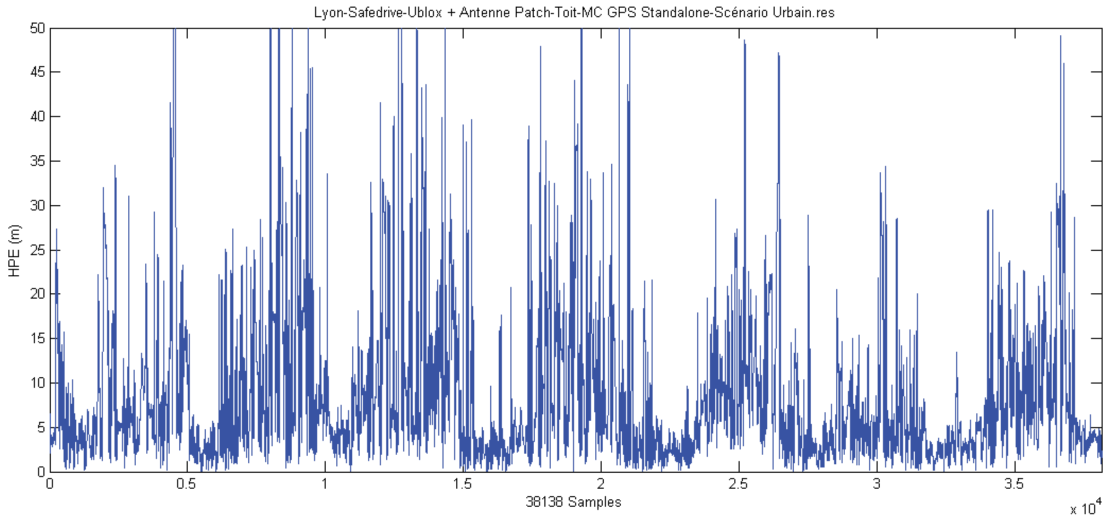
3.2 Specificity of GNSS-based positioning

The previous examples have shown that although good performance of the positioning terminal is not sufficient to ensure the achievement of the E2E performance requirements at the system level, it remains of key importance.

The specificity of GNSS-based systems is that their performance has a strong dependence on their operational conditions and in particular on the physical environment in which the GNSS receiver operates. They depend also on the time, since the satellite systems are continuously moving, meaning that even static receivers will show time-dependent performances. For a moving target such as a vehicle driving in an urban environment, the two effects are combined and the performance is highly dynamic.

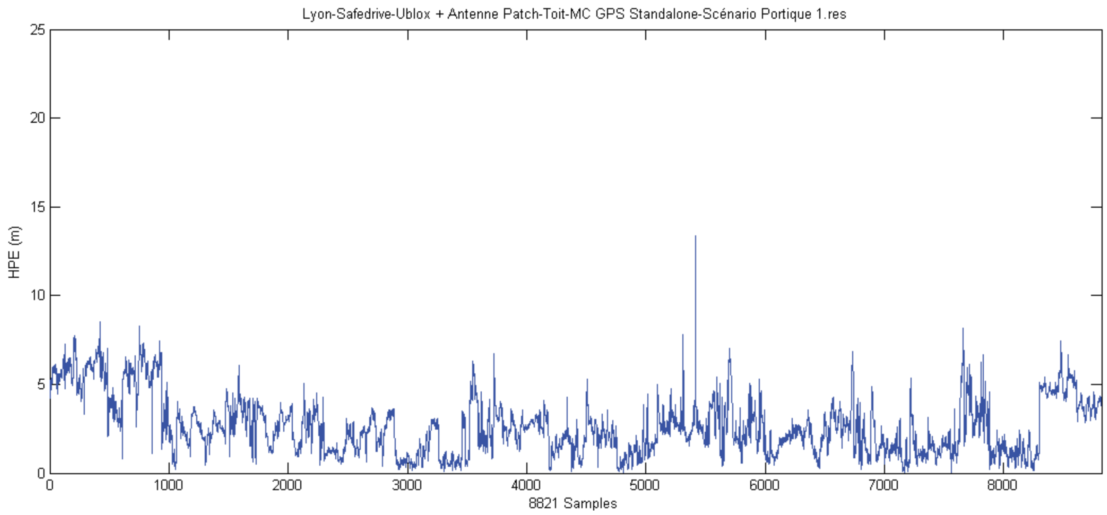
Figures 12 and 13 show the Horizontal Position Error (HPE) of a low-cost stand-alone GPS receiver, whose antenna was installed on the roof of the test vehicle, during a 2.5 hours test in an urban area (7 loops) and a ½ hour test on a relatively clear ring road, respectively.

Figure 12
Example of time-dependent error of a GPS receiver in an urban environment



Source: M3 Systems, EGNOS on the road, 2009

Figure 13
Example of time-dependent error of a GPS receiver in a relatively clear environment



Source: M3 Systems, EGNOS on the road, 2009

These figures show very clearly the dependence of the error on the time and on the type of environment.

Consequently, it is clear that a positioning performance such as accuracy (measured by the error) cannot be determined by a single measurement performed in any place. Since the error behaves as a random process, statistical indicators are mandatory to measure the performance. Moreover, the environment in which the error samples used to measure the performance have been acquired must be clearly defined.

Summary

The performance of any positioning system based upon GNSS is highly dependent upon the time and the environment surrounding the antenna. The consequence is that this performance has to be measured with statistical indicators from a large sample of test data, acquired in conditions representative of the real operational scenarios.

3.3 Main outputs of a positioning terminal

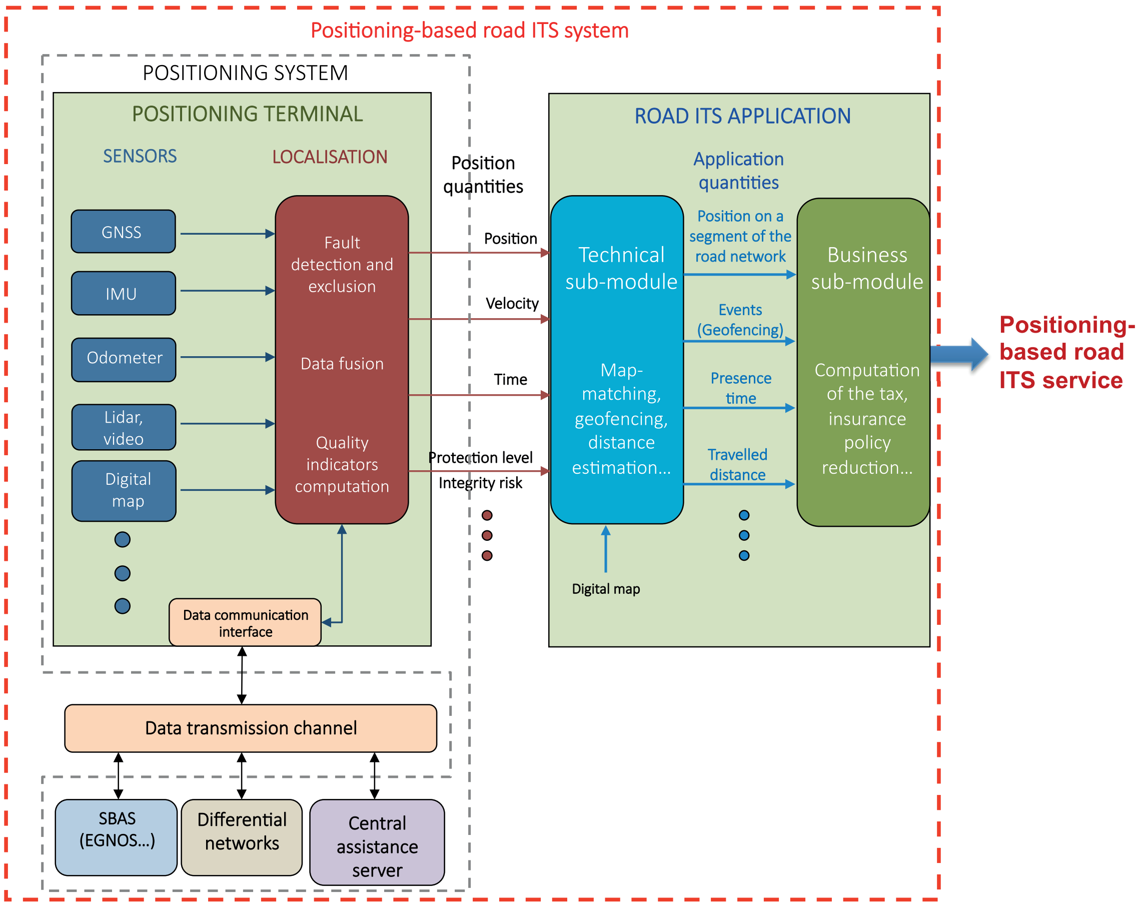
This section presents a more detailed architecture of a positioning-based road ITS system, introduced in a simplified form in section 1.2.

Figure 14 below illustrates the reference architecture used by SaPPART COST Action to represent the main functional components of a positioning-based road ITS system using GNSS. Such a system provides a positioning-based road ITS service, and it comprises a positioning system and an application module, using position quantities to provide an added-value service for the user, like navigation aid, tracking or tolling events detection.

The application is generally composed of a technical module, which processes the position quantities to compute the application quantities, and a business module not be considered in this document.

The difference made here between positioning system and positioning terminal is that the positioning terminal is only the on-board module whereas the positioning system may be composed of other modules located elsewhere and communicating with the terminal thanks to a data transmission channel.

Figure 14
Reference architecture of a positioning-based road ITS system



A GNSS-based positioning terminal, potentially merging other sensors or sources of data, provides a position (3D, 2D or 1D) expressed in an absolute reference system, such as WGS84. However, depending on the processing done in the terminal and the chosen data stream, it can also provide velocity (3D or 2D vector), speed (the magnitude of the velocity) and time (in the GNSS time reference or UTC reference) under the form of a timestamp, i.e. a tag that indicates the time to which all the other outputs correspond and a periodic pulse (Pulse Per Second, PPS).

Additionally, the output stream of the terminal can include some quality-related quantities such as DOP parameters, elements of the variance-covariance matrix of the computation process when it is based upon Bayesian estimation, like standard deviations. Also, in the case when the terminal is providing integrity, outputs can include protection levels and integrity risk.

All these outputs are generally called position quantities or PVT in a simplified way.

Summary

For road transport or mobility systems, the positioning terminal is part of the on-board piece of equipment delivering the positioning quantities to the application. These quantities are of course positions, but can be velocities, speed, time or specific quality indicators or integrity-related quantities such as protection levels.

3.4 Performance features and metrics for a positioning terminal

3.4.1 General definition

The performance of any system can be characterized with respect to different features, or characteristics. For ITS and mobility applications, the most relevant performance features have already been introduced previously and are availability, accuracy and integrity. This section proposes simple definitions and corresponding metrics.

These features can be relevant for different outputs of the terminal, such as horizontal position, altitude, longitudinal speed, etc. So, there exists a large number of combinations of features and outputs that can be assessed during performance characterization of a positioning terminal.

Each characterization process needs a performance metric (or indicator) to be carried out. The performance metric is a precise definition of the means of measuring a given performance feature of a given system output. Performance metrics are necessarily associated with a standardized test protocol defining the test procedures and means (test vehicle, simulator, record and replay equipment, etc.), the test scenario and the way the test results will be transformed into indicators.

A new availability metric adapted to the application?

Depending on the application, it could be of interest to define as availability interval the period of operating time T during which at least one output is expected from the positioning terminal, for instance 10 s for a navigation system. So, a more relevant metric than the standard one would be to measure the percentage of availability intervals during which the positioning terminal provides at least one position output.

The test scenario should define precisely the set-up conditions of the terminal (in particular of the GNSS receiver antenna), the trajectory, the sample size, the environmental conditions, the interference conditions, etc. It should reflect as faithfully as possible the real operational conditions in which the ITS system using this positioning terminal will operate.

For instance, in the example of test data illustrated in figure 13, the test scenario can be summarized as follows: GPS receiver with antenna installed on the roof of the test vehicle, driving 7 times a loop of 9 km, at normal speed (average speed = 23 km/h), during 2.5 hours, in the city centre of Lyon, with no particular interference, the output rate being 5 Hz.

3.4.2 Availability

Generally speaking, availability refers to the percentage of time during which the output of the positioning terminal is available. This feature can be defined in many different ways according to the application needs.

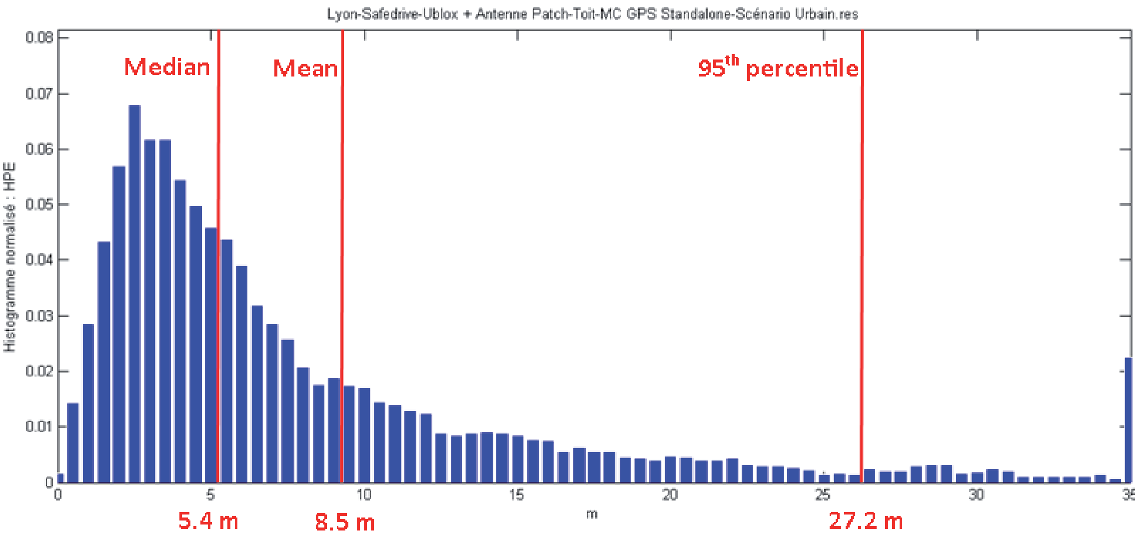
Generally, availability refers to the percentage of the measurement epochs (time periods) where the considered output is delivered with the required performance. A more straightforward metric can be simply the percentage of the measurement epochs where the considered output is delivered by the terminal, whatever its quality.

3.4.3 Accuracy

This feature refers to statistical figures of merit of position error, velocity error or speed error. Accuracy metrics have to be built from the statistical distribution of the errors.

As example, the normalized histogram of the HPE resulting from the test corresponding to figure 12 is presented in figure 15. As the number of samples is large and covering most of the random variations, this histogram is as a good estimator of the Probability Density Function (PDF) of the error, considered here as a random variable.

Figure 15
Example of histogram of Horizontal Position Error (HPE) and accuracy indicators



Source: M3 Systems, EGNOS on the road, 2009

In this example, the following metrics were chosen for the accuracy of the horizontal position: mean value, median value (or 50th percentile[10]) and 95th percentile of the histogram.

10. The Nth percentile of a distribution is the value X such as N% of the values of the sample are below this value.

In this specific case, the values of the metrics were:

- mean value = 8.5 m
- median value = 5.4 m
- 95^{th} percentile = 27.2 m

3.4.4 Integrity

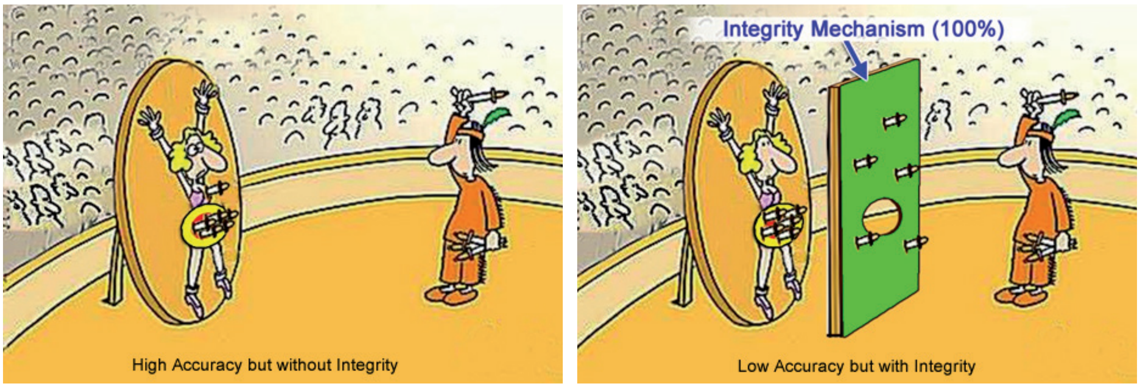
The integrity concept was introduced by civil aviation to measure performance affecting safety e.g. for a safe landing; it is not enough that errors are small in average (accuracy), they must remain small all along every landing (integrity). In the scope of this document, dedicated to road transport and mobility, the definitions related to integrity are inspired by, but significantly simpler than, the definition of the same concept for the civil aviation community.

High accuracy does not mean high integrity. The drawing in figure 16 illustrates the interest of an integrity mechanism in which the error is monitored to avoid any risk of dramatic accident.

The definition adopted inside SaPPART is the following:

Integrity is a general performance feature referring to the trust a user can have in the delivered value of a given position or velocity quantity (e.g. horizontal position). This feature applies to 2 additional quantities associated to the value delivered at each epoch of measurement: the protection level and the associated integrity risk.

Figure 16
Illustration of the interest of integrity monitoring



Source: Dias, Ronaldo - GMV

The protection level is a positive scalar value that statistically bounds the errors on the quantity estimated by the positioning terminal with respect to a given Target Integrity Risk (TIR). Symmetrically, the integrity risk is the probability that the error on the quantity exceeds the associated protection level. This risk should generally be kept at a very low level, from 10^{-3} to 10^{-7}, depending on how much the application is critical. This risk can be estimated for each independent measurement for a given period containing a certain number of independent measurements.

The most common approach is that receivers compute a protection level for a given TIR but as an alternative, the output of the receiver could be the estimated integrity risk for a given error bound.

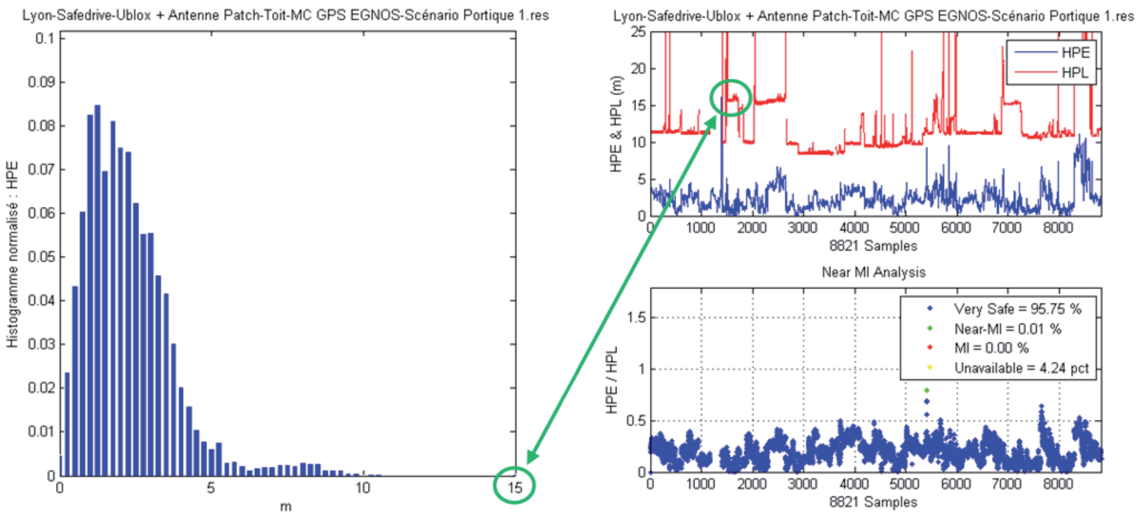
Different methods of computing protection levels and integrity risks can be used. They are generally based upon data redundancy and refer as to Fault Detection and Exclusion (FDE) or Receiver Autonomous Integrity Monitoring (RAIM) in the civil aviation world.

From a probabilistic point of view, integrity deals with quite rare events that can cause very large errors, i.e. with the tail of the histogram estimating the PDF.

Another example of HPE histogram is given in the left diagram of figure 17, for an EGNOS capable receiver. This histogram shows a quite short tail with only one peak of error of about 15 m and no large errors like on figure 16. In this case, a protection level was computed using EGNOS data and the MOPS[11] standard, corresponding to a TIR of 10^{-7} per hour. The upper right diagram shows the actual error (HPE) in blue and the protection level (Horizontal Protection Level, HPL) in red. The lower right diagram shows the ratio HPE/HPL, ideally smaller than 1. When this ratio is greater than 1, the system experiences misleading information.

A metric for protection levels can be its size, using similar indicators (percentiles of the distribution) than the ones used for quantifying the error.

Figure 17
Example of integrity analysis using EGNOS protection levels



Source: M3 Systems, EGNOS on the road, 2009

Does EGNOS bring integrity to the terrestrial transport also?

EGNOS is the European GNSS augmentation system which has been developed for the European civil aviation mainly to complement GNSS with increased accuracy and integrity features. The standardized method describing how to use the EGNOS messages to build the EGNOS Protection levels (PL) is assuming given error models corresponding to an aircraft environment. Whereas the EGNOS PL is relevant in the case the vehicle drives in a clear sky environment, it often leads to underestimated PL in typical road and city environments. In the example shown in figure 17, it can be seen that the rate of misleading information is equal to zero, meaning that the PL computed with the EGNOS data is actually relevant in this case.

11. MOPS : Minimum Operational Performance Standard for Global Positioning System/Wide Area Augmentation System airborne equipment», RTCA standards, DO229C, 28 November 2001.

Summary

Depending on the application, several features characterizing the performance of the positioning terminal have to be considered, the most important ones being availability, accuracy and integrity. Each feature can be applied to any output component of the terminal and needs a performance metric to be quantified. Availability metrics are generally percentages of epochs or periods when the output is present, accuracy metrics are based upon statistical indicators built on the Cumulative Distribution Function (CDF) of the error and integrity metrics are based on the size of the protection level.

3.5 Overview of the standardization work undergoing

The previous sections have shown that it is quite complex to measure GNSS-based positioning terminal performances. However, the ITS stakeholders need clear information on how such a positioning terminal would perform in such environments and many of them expect some standardized and quantified classes of performances, with respect to the various features of terminal outputs, in order to guide their choice. This is the job of the standardization bodies.

Since 2012, mainly 2 standardization organizations have been directly addressing these performance issues: CEN-CENELEC (TC-5, WG-1) and ETSI (TC-SES, WG-SCN). Their approaches are coordinated and complementary.

CEN-CENELEC addresses position quantities performances and the relation between position quantities performances and E2E service performances, only for ITS applications. ETSI addresses position quantities performances, positioning system architecture issues and also data exchange protocols issues for any terrestrial application.

As far as the test methods and facilities are concerned, CEN-CENELEC prepares standards based on field tests using test vehicles and reference positioning equipment whilst ETSI develops lab tests using GNSS constellation simulators. Both approaches have their advantages and drawbacks and can also be complementing each other, depending on the context.

Definitions of the main concepts used in this standardization activity have been agreed between the 2 groups, ensuring that way the consistency between the final standards.

Summary

Two standardization groups, respectively at CEN and at ETSI, are currently writing standards on performance metrics for GNSS-based positioning terminals, supported by test specifications.

List of acronyms

ADAS	Advanced Driving Assistance Systems
A-GNSS	Assisted-GNSS
AoA	Angle of Arrival
AVL	Automatic Vehicle Location
CAM	Cooperative Awareness Message
CAN bus	Controller Area Network bus
CCD	Charge-Coupled Device
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CEN	Comité Européen de Normalisation/European Committee for Standardization
CENELEC	Comité Européen de Normalisation en Electronique et Electrotechnique/ European Committee for Electrotechnical Standardization
CORS	Continuously Operating Reference Stations
COST	European COperation in Science and Technology
DGNSS	Differential GNSS
DOP	Dilution Of Precision
DR	Dead Reckoning
DSRC	Dedicated Short Range Communication
DTDoA	Differential Time Difference of Arrival
E2E	End-to-End
eCall	Emergency Call
EGNOS	European Geostationary Navigation Overlay Service
EDAS	EGNOS Data Access Service
ETSI	European Telecommunications Standards Institute
FDE	Fault Detection and Exclusion
GLONASS	Global’naya Navigatsionnaya Sputnikovaya Sistema
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HPE	Horizontal Position Error
HPL	Horizontal Protection Level
IMU	Inertial Measurement Unit

ITS	Intelligent Transport Systems
IVS	In-Vehicle System (eCall)
LBS	Location-Based Services
LCRW	Longitudinal Collision Risk Warning
LIDAR	LIght Detection And Ranging
MEMS	Micro Electro-Mechanical Systems
MEO	Medium Earth Orbit
MOPS	Minimum Operational Performance Standard
MSAS	Multifunctional transport Satellite Augmentation System
MSD	Minimum Set of Data (eCall)
NLOS	Non-Line-Of-Sight
PDF	Probability Density Function
PND	Personal Navigation Device
PPK	Post-Processed Kinematic
PPS	Pulse Per Second
PPP	Precise Point Positioning
PSAP	Public-Safety Answering Point (eCall)
PVT	Position, Velocity and Time
RAIM	Receiver Autonomous Integrity Monitoring
RFID	Radio Frequency Identification
RNSS	Radio Navigation Satellite Service
RTK	Real-Time Kinematic
RUC	Road User Charging
SBAS	Satellite-Based Augmentation Systems
SIS	Signal In Space
SPP	Single Point Positioning
TDoA	Time Difference of Arrival
TIR	Target Integrity Risk
ToA	Time of Arrival
TTFF	Time To First Fix
UTC	Universal Time Coordinated
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
WAAS	Wide Area Augmentation System
WGS 84	World Geodetic System 198

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