Report

TEAPOT

Summarizing the main findings of work package 1 and work package 2

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SUMMARY
This project report is a collection of the work produced in work package 1 and work package 2 in the TEAPOT-project. The main objective of the TEAPOT project is to "Secure positioning for the future transport system under Nordic conditions", while work package 1 specifically is on "Cross-sectoral collaboration and demands for positioning in the transport sector" and work package 2 on " Positioning and introduction of sensor fusion systems for driving in the Nordic region".

The partners of the TEAPOT-project are SINTEF (leader of work package 1), the Norwegian Mapping Authority (leader of work package 2), The Norwegian Public Roads Administration, Aventi, Applied Autonomy and NTNU. All partners have contributed to the content of this report.

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Innholdsfortegnelse

1 Introduction

Petter Arnesen

This report from the TEAPOT (Technology for advanced positioning within the transport system) project is a collection of the notes and summarize the work done in work package 1: " Cross-sectoral collaboration and demands for positioning in the transport sector" lead by SINTEF, and work package 2: "Positioning and introduction of sensor fusion systems for driving in the Nordic region" lead by the Norwegian mapping authority. The TEAPOT project address three main challenges:

1. Clarify the transport sector's needs for positioning technology, with special attention to Nordic conditions.
2. Develop an approach on how different technologies and methods for positioning can be combined using sensor fusion.
3. Describe how to organize cross-sectoral collaboration between the road authority and the positioning community, and how to regulate without hampering the Norwegian private sector.

This report contains state of the art reviews, information gathered through interviews, barrier identifications and recommendations for positioning in the future road transport system, both from the perspective of the positioning community and CCAM (Cooperative, Connected and Automated Mobility) with particular focus on Nordic conditions.

In Chapter 2, current and future needs and requirements for positioning in the road transport sector is discussed using data collected through interviews with all project partners, in addition to workshops and meetings. In Chapter 3, an extensive literature review is conducted to investigate and quantify the future needs for positioning, whereas Chapter 4 specifically discuss the challenges of reference frames and make recommendations for how the ITS sector should cope and collaborate with the developments in this field. Chapter 5 contains a literature review of map matching algorithms as this is, and will be, a crucial part of positioning and navigation of vehicles in the road. Specifically addressing challenges with GNSS positioning in the North, we present in Chapter 6 some perspectives and illustrated using previously collected data. The last two chapters of this report, presents currents trends within the GNSS market (Chapter 7) and technological approaches and challenges for positioning and navigation of vehicles on the road. Work has also been done partly in the TEAPOT project on integrity, included as input in the report Ouassou (2021).

1.1 References

Ouassou, M. (2021) GNSS data analysis – Quality assessments and integrity design. NMA report no. 19-04811-14.

2 Needs and requirements for positioning in the transport sector

Nina Møllerstuen Bjørge, Hanne Seter and Petter Arnesen

2.1 Introduction

In WP1 in TEAPOT (Technology for advanced positioning within the transport system), specifications of needs and requirements for position services need to be settled. The purpose of the positioning services in this project is to locate vehicles in speed through local and global positioning using different technologies. This chapter maps out the requirements and needs for positioning services, identified through interviews with actors that take part in the project.

2.2 The ARKTRANS model

The ARKTRANS reference model (illustrated in Figure 1) is a model for the whole transport sector. As a theoretical framework the ARKTRANS model is applied to help establish the roles of each actor. ARKTRANS is the Norwegian framework for Intelligent Transport Systems (ITS) but might also be applied to positioning services. The model is a top-down approach to define the roles, requirements and needs for each actor in the chosen application. Each sub-domain represents a group of roles where the roles are logically linked together and related to common responsibilities and focus and business areas. A *role* is an abstract entity that is defined by a set of responsibilities. An *actor* is a concrete person, company, organisation or authority that fulfils parts or the whole of the responsibilities of a role. An actor may also cover the responsibilities of more than one role (Natvig, M. et al, 2009).

The role *Demand for positioning service* subdomain covers all transport actors that request a positioning service. The role *Provision of positioning service* includes all actors that provide different positioning services. The role *Management of positioning service* covers all actors that are related to the management, operation and maintenance of the infrastructure in a transport system. The *Regulation and enforcement* subdomain includes all actors related to the regulation and monitoring of positioning services for the transport sector. The role *Support services for positioning service* covers all actors that provide any type of support service for positioning services.

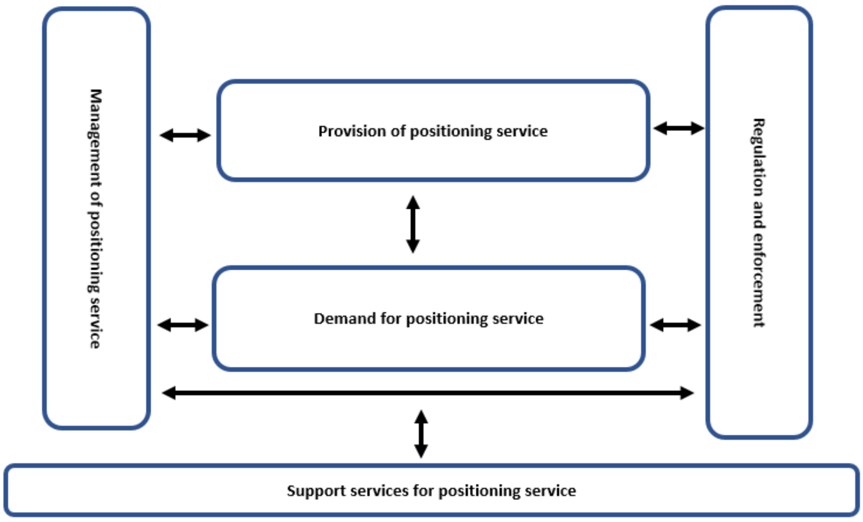

Figure 1: The ARKTRANS model

2.2.1 Demand for positioning service

This sub area contains users of the positioning services. Typical users of positioning services are firms that deliver ITS-services. The responsibilities of this role include for instance defining the need for the positioning service. In the future this role will include actors that need positioning data for autonomous vehicles. Hence, this role is responsible for defining the need for the positioning service, which will vary considerably, particularly based on which level of automation the position service will be used for.

Levels of automation

The requirements for positioning within the transport sector depend heavily on the service in question, and the Society of Automotive Engineers (SAE International) have described levels of driving automation (SAE International, 2021). The five levels range from no automation (the driver performs all tasks) to full automation (the vehicle is capable of performing all driving functions under all conditions). The different levels of automation have different requirements for positioning. Below a description of the different SAE levels are described, but it is important to note that many of the applications on the higher levels are yet to be implemented, and there is no overall agreement on what the positioning accuracy for ITS services should be. A short description of the different SAE-levels can be found in Figure 2.

Figure 2: SAE levels (SAE International, 2021)

However, it is not just the vehicle manufacturers which will be demanding positioning services-Figure 3 exemplifies several different actors which might fill this role, including public transport (AtB), providers of ITS and C-ITS services (Aventi), and providers of new automated transport services and systems (Applied autonomy). These are likely to have different requirements depending on what the purpose of their service is.

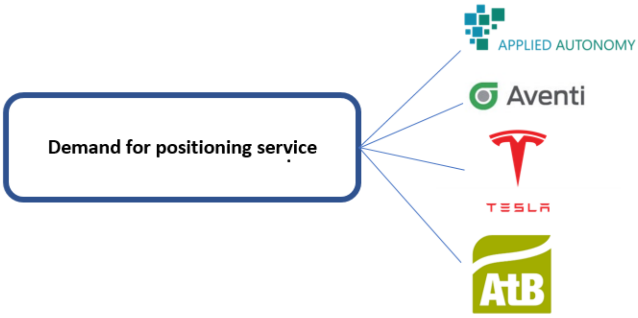

Figure 3: Examples of actors which might fill the role "Demand for positioning services"

2.2.2 Provision of positioning service

The provision of positioning service role covers all actors that provide a positioning service. The most common services are using GNSS for positioning, but other technologies are also available. The provision of the positioning service includes the following sub-domains:

i) *Managing the service*, including defining and marketing the service, making agreements with the users, planning the service according to the users need, surveillance of the service.
ii) *Executing the service*, including plan and prepare, execute service, manage the execution.

Figure 4 shows examples of actors which might fill the role as "Provider of positioning services". Some examples of providers of positioning services are the Norwegian mapping authority (NMA, Kartverket), Sapcorda and Hexagon SmartNet. The latter of these has more users than the NMA's CPOS service in Norway, however both Sapcorda and Hexagon SmartNet base their services partly on data from the CPOS infrastructure. With the development of new services and new technology, new actors may also be providers of positioning services for the transport sector in the future. Another possible service in the future is positioning within the 5G network, which is why Telenor can be found as a relevant actor in Figure 4.

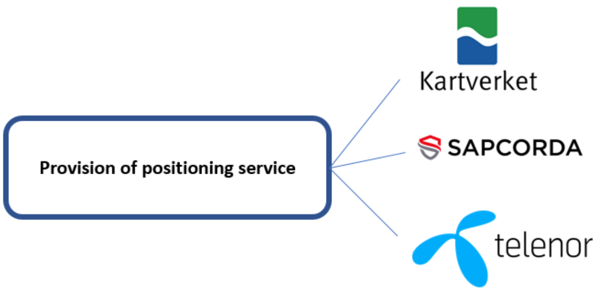

Figure 4 Examples of actors which might fill the role "Provision of positioning services"

2.2.3 Management of positioning service

This role includes all roles related to the management, operation and maintenance of the infrastructure for positioning services. In short, three sub-domains can be identified:

i) *Management of infrastructure*, including planning infrastructure, establishing infrastructure, maintaining infrastructure and distributing information about the infrastructure.

ii) *Management of capacity,* including utilization.

iii) *Handling emergency management.*

With regards to positioning in the transport sector, infrastructure is particularly important. The infrastructure provider is responsible for planning, building, managing, operating and maintaining the *physical* and *digital* infrastructure. Another important aspect with regards to positioning, is the responsibility for the utilization of the position, which includes ensuring that all users have good enough positioning.

Figure 5 shows examples of actors which might fill the role as managers of positioning services. This will depend on the positioning service in question, but if using the CPOS service as an example the NMA has responsibility for infrastructure in Norway and capacity in the current service. The Norwegian Space Agency also has responsibility in terms of managing Norwegian interests in space, for instance ensuring that Norway is playing an active role in developing and operating Europe's new Galileo system. International organisations like The European Space Agency (ESA) also are important actors in these regards.

Figure 5 Examples of actors which might fill the role "Management of positioning services".

2.2.4 Regulation and enforcement

This role includes regulation and enforcement of the positioning services. This domain typically includes roles as transport departments and authorities, which are preparing and issuing laws, regulations, prescriptions and recommendations on how the positioning in the transport system should be used and provided. Communicating laws and regulations to all relevant actors is also a responsibility. Standardization is particularly important in this regard. Specifically, this role includes:

- *Providing laws and rules*, for instance through laws and regulations.
- *Informing all users and actors* about the laws and rules.
- *Collecting data on the transport system* on a national level, such as traffic counts which can say something about for instance the need for the positioning services in certain areas.

Figure 6 shows examples of actors which might fill the role regulation and enforcement. The Norwegian Public Roads Administration (NPRA, Statens vegvesen) is listed, as well as the Department of Transport, which both have important responsibilities in the transport sector. The Norwegian Communications Authority (NKOM) is also an example as they have a responsibility for uncovering spoofing and jamming of GNSS signals. This role could also include international actors such as the European Committee for Standardization (CEN), which are working on standards.

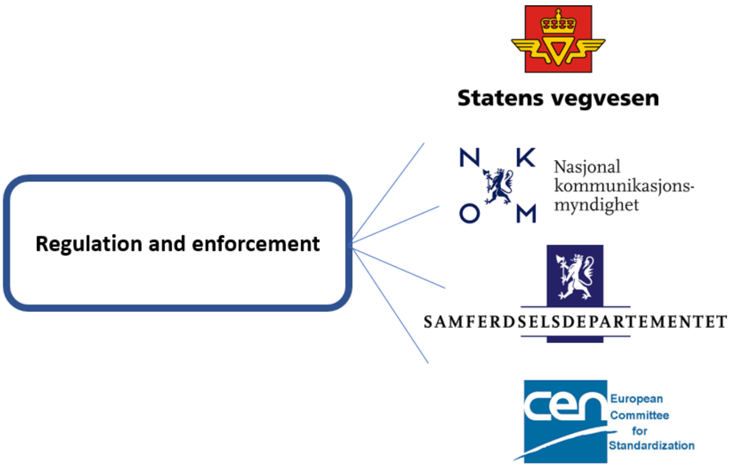

Figure 6: Examples of actors which might fill the role "Regulation and enforcement".

2.2.5 Support services

The last role includes support services to the positioning services which provide input data to the positioning service, such as the telecom network.

2.3 Methodology

To investigate the requirements and needs for establishing functioning positioning services, the actors included in the project were interviewed. For this task we used in-depth semi structured interviews.

In the first phase we started in the research group to discuss different actors that might answer important questions, requirements and needs about positioning services. We decided to arrange the first interview with NMA, due to their role as a provider of the CPOS service, and since they are an important contributor to the project. The intention was that NMA would provide us with helpful information for the next steps in the process.

Before the interviews, we developed a semi-structured in-depth interview guide, with some main themes and questions to cover in the interviews. The interviews were tailored to each informant since their area of expertise varies largely. The conversation should circulate around the questions, but the respondent should feel comfortable enough to add information he or she thinks of as relevant for the study. Information from the informant additional to the questions we asked may be particularly valuable (Tjora, 2012, 113-114).

In this kind of interview, subjective meanings, attitudes, and experiences become present. It is therefore crucial to make the informant feel comfortable so that the conversation is relaxed and flows freely. The quality of the interview relies heavily on the relationship between the informant and the researcher. The importance of making the informant relaxed is therefore crucial for the results and findings (Tjora, 2012:113-116).

In these interviews interested in getting to know the experience, knowledge, and attitudes towards requirements and needs around positioning services. The in-depth interviews will help us to locate other sources and informants that might be essential for the rest of the research project (Tjora, 2012:129).

In addition to interviews, we have also used information collected in workshops and meetings. When exploring an interdisciplinary topic such as the positioning of the transport sector, an important part of the project is having a joint process where a common understanding is generated (Neeley, 2019). Therefore, workshops and meetings are particularly well suited for tracing this exploration of the needs for positioning within the transport sector.

2.4 Roles

In this chapter, we will introduce the actors and their role according to the framework ARKTRANS. Throughout the interview rounds we might have discovered important actors that were not included in the interview round, that might be included in this part.

Positioning is among the most important technologies required for safe and efficient navigation in various environments, particularly so in Norway where the topography and climate make it difficult for self-driving vehicles to navigate based purely on their own cameras and sensors. This report is giving a foundation for knowledge on how positioning for the transport system should be developed under Nordic conditions to ensure the desired effects on society from implementation of ITS-services, including automation.

The discussion evolves primarily around how GNSS is used, and how one can provide correctional data to this service. GNSS is a general term used for all satellite systems that are used for global navigation. GPS is the most frequently used system, although other systems are also increasingly used such as GLONASS, Galileo and Beidou (Halle, 2019). One of the most frequently used correctional data in Norway are data provided by the NMA. NMA provides several different correctional data services, but it is primarily the CPOS service which will be discussed here. Other types of positioning technologies are also mentioned in the discussion, but the main focus will remain GNSS.

2.4.1 Positioning service provider

NMA is a positioning service provider. The NMAs main task is to provide geographical information related to for instance maps. The NMA gathers this data, systemizes it, manages it, and conveys geographical data from other public entities. The NMA provides services that give a highly accurate satellite-based position. Regarding the TEAPOT project, the NMA provides the CPOS service, which provides correctional data to satellite based GNSS that allows for cm accuracy. As of today, the most common users of this service are entrepreneurs, municipalities, and large governmental agencies such as the NPRA. The CPOS service is developed for being a highly accurate positioning service for instance for building of roads and houses. The corrections are received in real time using a cellular connection (GSM/4G) between the receiver and the NMA's servers (NMA, 2021a).

In addition, there are starting to emerge new services based on new technologies, or new services which are built on top of existing services, such as CPOS. As an example of the last, SAPCORDA is a firm that uses tha raw data from NMA's base stations, creating their own correction data (as well as similar data from other countries) to generate a broadcast of correction data instead of using a two-way communication and calculation link. New services for positioning include also using the telecom network as a positioning service, greatly enhanced by the introduction of 5G technology, or local infrastructure, for instance using Bluetooth (as Waze beacons) other RTK (real time kinematics) base stations systems or PPP (Precise Point Positioning) services.

2.4.2 Management of positioning service

In terms of management of infrastructure, the positioning service CPOS is dependent on several infrastructures, including both international satellites and national base stations.

Physical infrastructure: International satellites: In terms of management, the GNSS system is based on access to international satellites through various international collaborations such as European Space Agency (ESA) and the European Space Programs Galileo, EGNOS and Copernicus. The Norwegian Space Agency is the manager of Norway's interests in space, including access to satellites.

For Norway, the available satellites are GPS, GLONASS, Galileo, and Beidou, operated by the US, Russia, Europe and China. The satellites move in a circular orbit, approximately 20 000 km above the earth, a height that provides the best possible coverage of the earth. The infrastructure on earth consists of one central control station, and multiple measuring stations (500+) around the globe in an international collaboration overseen by the International Association of Geodesy (IAG). The measuring stations monitor the performance of navigation and the condition of the satellites and send data back to the control station for processing, which again sends the corrected information back to the satellites (Norwegian Space Agency, 2021).

Physical infrastructure: Base stations in Norway: The NMA is responsible for the physical infrastructure of permanent geodetic base stations in Norway. NMA maintains and owns the base stations used for providing the CPOS-service, see Figure 7 for an overview. When a user of the CPOS service requests correctional data, his uncorrected position is sent to the central system of the NMA in order to generate a virtual reference station (VRS) close to the user location. The VRS principle works the same way as differential GNSS with a physical base- or reference station.

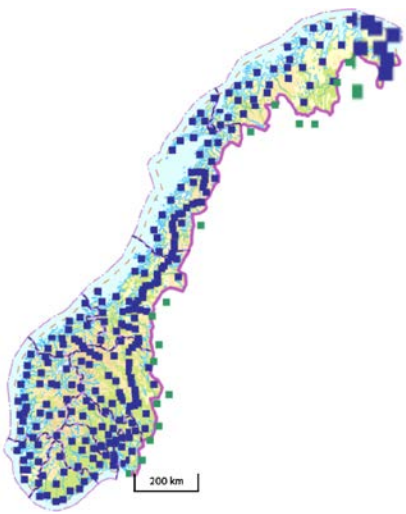

Figure 7 NMA base stations.

The position of the reference station *A* is known. Satellite distances ρ_A can be calculated from the known position in *A*, and broadcast ephemerides (satellite orbits). "*The corrections"* are: 1) the differences between "measured"- and calculated satellite distances ρ in A, and 2) their time derivatives. This method assumes that the error of the satellite signal found in the users physical moving GNSS (rover) B, is equal to the error found in the base station (i.e., close to where the user is located). Combining measured "satellite distances" in the rover (B) with the corrections, a position with cm accuracy is calculated in the rover and available to the user in "near real-time". In the VRS-case, the corrections are calculated with data from the closest physical base stations in the network, and sent to the user from NMA. This principle is illustrated in Figure 8.

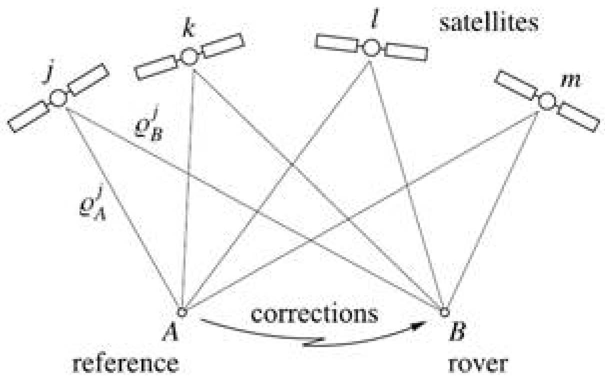

Figure 8 CPOS service illustrated (source: Hoffmann-Wellenhoff et al., 2008).

Management of capacity: With regards to capacity of the positioning service CPOS, this is NMA's responsibility. However, the question is whether this service can be used in its current version if all vehicles were dependent on using it. Today the service has 5000 users in Norway. Providing the service to all vehicles in Norway would challenge the capacity of the system. This question of scalability has led to new ideas concerning how the service should be provided to users, including broadcast services such as SAPCORDA, development of 5G positioning technology and PPP services.

Digital maps: The NMA produces and manages national digital maps, this responsibility will be critical in the future when vehicles start to navigate using for instance HD-maps. Maps is not the main focus here, but this is likely to be an important responsibility in the future for the NMA which is highly important for the transport sector. The project Nordic Dynamic Road Cloud where the NMA was exploring how lidar data can be made available for the public, and is an example ofinitatives to investigate the need and requirements for the application of HD map related data for transport related user cases.

2.4.3 Positioning service users

The role of the positioning service user may involve several different actors that use positioning services. In the case of the TEAPOT project, Aventi and Applied Autonomy are positioning service users.

Applied Autonomy[1] is a company offering services for piloting and testing of self-driving shuttle buses, and they also develop control centre systems for implementation and operation of self-driving vehicles. They operate several routes for self-driving shuttle buses used for public transport purposes around in Norway and abroad.One of these routes in Trondheim has an on-demand solution, and one pilot at Herøya was done without an operator on-board the shuttle. The shuttle buses are delivered by Easy Mile. For global positioning purposes the shuttle buses use high quality GNSS with correctional data from CPOS, the correctional data was a demand from Easy Mile. The bus has other technologies to determine local positioning.

[1] See https://www.appliedautonomy.no/services for more information on the various services provided.

For the on-demand solution the control centre system also must know where the shuttle bus is going to, which is another area of use for positioning services for Applied Autonomy. This implies that when an order for the shuttle bus is placed, the system must identify which bus stop it is going to. In addition, the shuttle bus uses positioning services while driving, because the bus operates by driving after a predefined position on the road, like virtual tram rails. As of today, the shuttle buses are not driving at high speed, and Applied Autonomy's requirements for positioning is likely to change as the speed increases.). Higher speed would for them indicate a higher need for accurate positioning services, and having a stable GNSS equipment is important for the service. Hence, for autonomous driving, stable GNSS connections with high accuracy and low latency of positioning services is key, as vehicles typically drive at speeds up to 110 km/h (with current speed limits in Norway).

Applied Autonomy has also run a demonstration of the shuttle bus in Svalbard and experienced no major disturbances to the GNSS. It is highlighted that they had limited opening hours, and that it is possible that they could have experienced other disturbances during night-time for instance. The interviewee brings forward shadow and longer tunnels as key issues to resolve concerning positioning. Applied Autonomy uses a garage for the shuttle bus where it is charged overnight, and since it is not possible to receive GNSS in the garage, they must drive the car manually out of the garage to initialise the GNSS localisation. Shadow in cities with tall buildings is also an element for concern.

Aventi[2] is a company providing automation solutions and services, primarily for the transport sector. Since Aventi provides C-ITS equipment and services they are also a positioning service user, because the on-board units send out messages to roadside units. Almost all the messages that are sent contain information on position. Including Cooperative Awareness Messages (CAM), Decentralised Environmental Notification Messages (DENM), Signal Phase And Time (SPAT) and Map Data (MAP). Vehicles can then use information from these messages, and due to the information on the position they know the location of the other vehicle, the road side unit, or the incident.

Aventi provides infrastructure for the NPRA, and focuses particularly on equipment for tunnels, such as SOS stations, signs and emergency phones. In the roof of the tunnels automatic incident detection (AID) cameras are installed. The AID cameras can detect cars and people walking in the tunnel and communicate with the traffic control centre. Based on their experience with such solutions, Aventi envisions providing C-ITS equipment, for instance in tunnels. A major challenge for C-ITS in tunnels is providing positioning.

Several alternative technologies when GNSS is not available through line of sights are emerging, including navigation sensors such as LiDAR and radar, algorithms for dead-reckoning including sensors such as IMU and odometer, or local positions infrastructure such as RTK stations, GNSS repeaters or ITS-G5. Operative positioning services in tunnels represents a strong need in Norway.

2.4.4 Regulator

The NRPA are regulating the roads and road systems in Norway and will have a prominent role in the future for regulating the use of automated vehicles. Their main responsibility is to provide an efficient and accessible road system, that will avoid human or environmental damage (NRPA, 2021).

In the future, it is likely that NPRA will be responsible for developing laws and rules related to automated vehicles at different SAE-levels with different requirements for positioning. As of today, there is not much knowledge within the NPRA considering what the requirements for positioning in the transport sector should

[2] See for more information: http://aventi.no/english-summary/

be. As a preparation for this future, the NPRA has started to investigate what the GNSS system for positioning can provide for the transport sector, because the requirements are not known.

As a part of this process, the ITS experts within the NPRA have started to collaborate with the land surveying environment within the NPRA. The land surveying environment is a well-established environment within the NPRA with long traditions for determining accurate positions when building roads for instance. However, accurate positioning in speed is not something which has been a focus previously. Starting with some experiments and analyses provided by master students, the NPRA started to explore the accuracy of GNSS equipment when driving. Based on these initial experiments a discussion with the NMA was initiated to explore the responsibilities and requirements for positioning in the transport sector.

Standards: The NPRA needs to be in close cooperation with the EU and other international actors concerning what the demands for positioning should be, because joint solutions and standardization are needed for transport to work across borders. In this case, the NPRA closely cooperates in international discussions and standardization fora's and promotes Norwegian interest. The European Committee for Standardization (CEN) is leading the standardization work, and the Technical Committee 278, Work Group 7 called ITS Spatial Data works specifically on the issue. WG7 developed in July 2018 a standardization which is called CEN/TS 17268:2018. The validity of the standard is three years, and during 2021 the group will most likely present improvements of the standard. The standardization contains specifications for exchange of road related spatial data. It also defines the physical exchange format for exchange of positioning data, as well as it defines the web services which where needed to make the code data on updates available.

Reference frame: In addition to NPRAs role, the NMA is responsible for providing national standards for maps and geographic information. One particular interest important for positioning within the transport sector is the use of reference frames. NMA is responsible for the national foundation for geodetics, implying that the NMA is responsible for the reference frames that all maps and measurement of the earth surface in Norway is built on. This is important for the transport sector because vehicles are driving in real-time, while the map that the vehicle uses is not real-time. The map, tied to a specific reference frame, is generated with a particular timestamp (realized). Hence, a need from the transport sector is to agree on a joint global reference frame, or set of local reference frames, which all actors should use to relate their positions given a common realization timestamp or continuous common timestamp (4D reference frame) (Poutanen, 2017). This would mean that the position of a vehicle should be provided in 4D as a standard, including information on horizontal, vertical *and temporal* position, in addition to clearly stating where the position is measured on the vehicle, and providing information of the spatial range of the vehicle.

2.4.5 Support services

An important support service for the CPOS service is the telecom network since the data is primarily transferred through the telecom network. With the current technology, 4G, the latency of this process is believed to be somewhere around 0.5 second. In GNSS-CPOS receivers, missing CPOS correction data or data latency are tackled by extrapolating the GNSS correction data, a strategy providing sufficient accuracy within a reasonable time frame. The extent of how long extrapolating would give sufficient accuracy should be investigated and tested. In addition, future developments within the telecom network, such as the implementation of 5G would lower the data transfer latency.

2.5 Requirements and needs for positioning and self-driving

In the field of positioning for the transport sector, there is no overall agreement on what the requirements are. Scholars and professionals disagree on how precise the positioning services need to be, and the requirements will vary according to what SAE-level one is discussing. The most common approach to enhancing position accuracy is fusing GNSS with other technologies, such as road-side equipment or in sensor systems. This is development in rapid paste (e.g., ultra-wide band, a network of RTK stations, road side units, IMU, LiDAR), and fusing of different technologies is perhaps seen as the most likely solution because a single technology is alone not likely to succeed in providing accurate enough position. This development has to be standardized across countries, and perhaps vehicles will have a domain of operation depending on what equipment and services the vehicle has installed.

Some interviewees see it as likely that the self-driving vehicles have to report where they are. Which means that the vehicles must be connected and sharing their position. In the future, the position of vehicles would be important for determining the causes of accidents for instance. For knowing this one is dependent on knowing what the true position is, and without the true position it could in some cases be difficult to prove what the cause is. Hence, accurate position could be a requirement for submission of evidence when vehicles are part of an accident. When vehicles get a black box, as aircrafts does, this could be used for such purposes, and could ultimately be a requirement for driving without a human driver. A question raised in the interview is how could the CPOS-service be organized in the future. Should it be a requirement for vehicles using self-driving functions to use correctional data for determining position?

Based on the discussion above, an important issue to address for the future is to what extent can you trust the accuracy of the given position. Having a measure which can say something about the certainty would be very helpful. Knowing and communicating the exact position of each vehicles navigation system relative to its spatial range would be highly critical, and such information should be standardized.

2.6 Cooperation on positioning

2.6.1 National cooperation

The NMA and the NPRA collaborates when it comes to positioning, and there is a strong collaboration in place for collaborating on land surveying. However, when it comes to collaboration on positioning for moving vehicles the actors have recently started to address this topic. The collaboration is based on a collaborative forum where the two actors meet and discuss relevant topics. The partners meet four times a year and discuss issues and possibilities in the digitalization of the road network.

For the NPRA it is important that positioning for moving vehicles is on the agenda of the NMA. The transport sector is likely to present new challenges which are more specific to the road sector such as the issue of GPS jamming, where drivers of vehicles may attempt to avoid being tracked by the fleet management system or avoid tolling (NLF, 2020). Many of the problems regarding positioning services are highly complicated from a technical point of view and require a high level of skills to discuss and ultimately solve. To some extent, it is unlikely that the NPRA can have all the necessary competence in-house, particularly in the current phase when they are exploring the topic, and therefore the role of the NMA is important as a competent discussion partner. Another very challenging issue is spoofing, where a false GNSS signal is broadcasted.

Due to the different focus and competences of the NPRA and NMA the collaboration is important for breaking down barriers. This should be seen as a process, where different disciplines meet. From an interdisciplinary point of view (Neeley, 2019), the process where these two actors meet and learn from each other is important for improving collaboration and eventually solving some of the challenges which the transport sector is facing when it comes to positioning. This will require a comprehensive understanding of how positioning services can be used for improving safety, environment and efficiency in the transport sector.

2.6.2 International cooperation

As well as national collaboration, international collaboration is important. In Europe, the processes in the EU system are important. The NPRA are participating in international forums, in which they contribute with their knowledge and experiences. The topics in these forums vary, and in some cases, they participate in expert forums formed by the EU, discussing themes such as international standardizations.

Further on, the NPRA emphasizes the importance of international cooperation when it comes to positioning services, and particularly in standardization-matters. The standardization of positioning services needs to be done at an international level, so that different countries use the same solutions so that vehicles can cross the borders unproblematically. It is therefore important for Norway to cooperate closely with other actors such as the EU and so on.

2.7 Potential barriers and opportunities

2.7.1 Barriers

Technological barriers: One important barrier for the development of positioning services for the transport sector is scalability. The CPOS service will not be able to handle that all vehicles request correctional data. This means that to meet the requirements of the future transport system, new solutions have to be developed that are scalable to the needs of the transport sector, such as developing a broadcast service for CPOS data. Another technical barrier is ensuring as much availability and relevance of correction data as possible, including CPOS and other RTK and PPP service providers. Also, ensuring protection against malicious equipment and attacks such as jamming and spoofing would be of great importance for the ITS sector. Sensor fusion could also be considered a barrier. Most actors agree that supplements to GNSS will be necessary in the future, and setting up such hybrid, and possible cooperative, system is highly complicated.

Competence and knowledge in NPRA and NMA: The issue of positioning for moving vehicles represents a new topic for both NPRA and the NMA. For the NPRA it requires understanding more about how positioning is provided, and what the requirements will be for vehicles at different SAE-levels. For the NMA this requires a shift in focus from positioning standing still, to positing in movement.

Collaboration between the transport sector and the positioning community: Although the NPRA and NMA have an extensive collaboration concerning land surveying, the issue of positioning for moving vehicles represents a new topic, which requires new types of collaborations. This collaboration needs to be interdisciplinary, where transport engineers and geodetics meet.

Standardisation and international collaboration: There is a strong need for more international effort on positioning in the transport sector, for instance to agree on standards. Vehicles across countries and from different OEMs need to operate according to the same procedures. Another important aspect is the lack of a joint frame of reference for the transport sector.

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3 Positioning requirements for the transport sector

Carl Johan Södersten

3.1 Introduction

Connected and Automated Driving is expected to have a significant impact worldwide. Estimates point towards an impact of 71€ billion in 2030 in the UK alone, while other studies estimate a global market for car connectivity of 180€ billion already in 2020 [1]. Furthermore, the societal benefits are expected to be tremendous, both in terms of safety, efficiency, emission-reduction potential, etc. Since most applications related to automated driving rely on the position of the vehicles, a key component of this upcoming revolution of the transport system is the availability of a reliable positioning system.

Vehicle positioning is often associated with technologies based on Global Navigation Satellite Systems (GNSS), which are nowadays taken for granted when navigating on the road network. However, GNSS-based positioning systems still face challenges. Tunnels, urban canyons, topography, satellite availability and solar storms are just some of the factors that may hamper the accuracy GNSS positioning. When positioning is used as a tool to navigate to a certain destination, the consequences of a lost or inaccurate signal will probably not be more dire than loss of time. However, in a future where positioning is used to navigate autonomous vehicles, it is crucial that the positioning system provides accurate data. As the consequences and complexities of the applications increase, so will the requirements set on the positioning system.

In this document, we perform a literature study on the positioning requirements for the transport sector. We begin with an overview of the various parameters that are relevant for positioning technologies and then focus on the accuracy of positioning. We review the different approaches taken when discussing positioning requirements in general and in the transport sector and subsequently summarise the quantified requirements found in the literature.

3.2 Key positioning performance parameters

The challenge of implementing connected and automated / vehicles on roads entails not only requirements on positioning accuracy but on a set of other parameters. While no global standard exists regarding which parameters to include, some parameters are recurrent in the literature. The European GSA (Global Navigation Satellite Systems Agency) has compiled a list of parameters in the 2019 Report on Road Users Needs and Requirements [2] which encompasses multiple studies and reports done on the subject, including [3-5]. While these parameters are explicitly defined as "key GNSS performance parameters", they are used to define the needs of positioning technologies as well. This is typically the norm when discussing positioning requirements in the transport sector [6].

Table 1: List of key GNSS performance parameters with additional details relevant for the road community. Adapted from the European GSA Report on Road Users Needs and Requirements [2]

Parameter	Description	Unit
Availability	The percentage of the time the position, navigation or timing solution can be computed by the user	%
Accuracy	The difference between true and computed position (absolute positioning). This can be categorised as: -Horizontal accuracy: the statistical measure of the horizontal position error (e.g. 95th percentile of cumulative error distribution) -Vertical accuracy: the statistical measure of the vertical position error (e.g. 95th percentile of cumulative error distribution)	m

	-GNSS time accuracy: the statistical measure of the GNSS time error (e.g. 95th percentile of cumulative error distribution)	
Continuity	The ability to provide the required performance during an operation without interruption once the operation has started. Usually expressed as the risk of discontinuity and therefore depends on the timeframe of the application	Scale (low, medium, high), or risk (e.g. 0.001)
Integrity	The measure of trust that can be placed in the correctness of the position or time estimated by the receiver. Usually expressed as probability of a user being exposed to an error larger than alert limits without warning	Scale (low, medium, high) or protection level (m) at certain integrity risk
Robustness	The ability of the solution to mitigate interference or spoofing. Can be subcategorised as: -Position authenticity: the level of assurance that the data provided by a positioning system has been derived from real signals -Robustness to interference: the ability of the positioning system to operate under interference conditions and to maintain the applicable positioning service level required	Scale (low, medium, high)
Time to first fix (TTFF)	A measure of a receiver's performance covering the time between activation and output of a position within the accuracy bounds. Subdivided into "cold start" (the receiver has no knowledge of the current situation), "warm start" (the receiver has estimates of the current situation, and "hot start" (the receiver knows what the current situation is	s
Indoor penetration	The ability of a signal to penetrate inside buildings. This is mostly relevant for positioning technologies that rely on external (to the vehicle) infrastructure (e.g. road-side infrastructure or satellites), and many factors can determine this performance (e.g. the sensitivity of the receiver for GNSS, the availability of Wi-Fi base stations for Wi-Fi-based positioning, etc.)	No agreed or typical unit
Latency	The difference between the time the receiver estimates the position and the presentation of the position solution to the end user. Latency is usually not considered in positioning as many applications operate in real time	s
Power consumption	The amount of power a device uses to provide a position. This will vary depending on the available signals and data	
GNSS sensitivity	The minimum GNSS signal strength at the antenna, detectable by the receiver	dBW or dBm
Position fix rate	The rate at which the positioning terminal outputs the PVT data	Hz

While most of the parameters listed in Table 1 are relevant for positioning technologies in the transport sector, this report will focus on positioning accuracy. For details on requirements regarding other parameters, literature abounds, e.g. [2, 7-14]. Furthermore, this document focusses on positioning systems that combine several technologies (GNSS, Lidar, cameras, etc.) and does therefore not differentiate between the requirements and performance of the individual technologies (which can be found in e.g. [9, 15-17]).

3.3 Positioning in the transport sector

Positioning requirements in the transport sector depend largely on the intended purposes and applications of the positioning systems. Simple applications like toll road billing based on vehicle positioning do not require the same safety boundaries and positioning accuracy as e.g. autonomous vehicles (AVs). Kuuti et al. [15] break down the needs of AVs through three questions that are fundamental for the operation of AVs and which need to be answered by the various systems in place to position the vehicles relative to other vehicles as well as surrounding obstacles, be it infrastructure, humans or other obstacles. Those questions are "Where is the vehicle?", "What is around the vehicle?" and "What does the vehicles need to do next?". Other studies (e.g. [6, 12, 18]) categorise the requirements based on the needed resolution vis-à-vis the road, by subgrouping the needs in terms of "which road" (the positioning system needs only successfully identify the road used), "which lane" (the positioning system must be able to correctly identify the actual lane) and "where in lane" (the relative position in a certain lane is needed). Related to this are studies [16, 19] that divide the requirements based on road type (e.g. urban / rural / highway, or local street / freeway). For instance, Reid et al. define their requirements model based on vehicle size and its effect on error margins in curved streets, and conclude that AVs driving on local streets require more stringent error bounds due to the road geometries [19]. Finally, many studies formulate requirements based on applications. These may be broadly defined, for instance on the Society of Automotive Engineers (SAE) levels of road vehicle autonomy (see Figure 9), which classify the applications based on levels of autonomy, ranging from no automation (the driver performs all tasks) to full automation (the vehicle is capable of performing all driving functions under all conditions) [20, 21]. Other studies provide positioning requirements on a more detailed level, specifying needs for specific tasks / use cases, such as *oversize vehicle warning* or *automated overtake* [2, 6, 11].

3.3.1 Different types of road applications

The range of road applications that rely on positioning is wide, and the positioning requirements for these applications vary. For instance, if the purpose is to provide an optimal route between origin and destination, a positioning error of 5 m will probably not have more serious consequences than leading to a smaller detour. However, if the purpose is to navigate a fleet of independent autonomous cars on a busy highway, a small error in positioning may lead to fatal crashes. As such, most studies differentiate between multiple applications (or use cases), and define positioning needs for each individual case. The range of these applications is not uniquely defined, and no list is likely to be exhaustive.

One scale often used in the literature (e.g. [1, 11, 19, 22-27]) is the SAE levels of road vehicle autonomy, which is shown in Figure 9. This classification is based on different levels, or stages, of vehicle autonomy, and the different categories are subdivided into lists of use cases (e.g. parking assistance, automatic braking, fully automated overtaking, etc.).

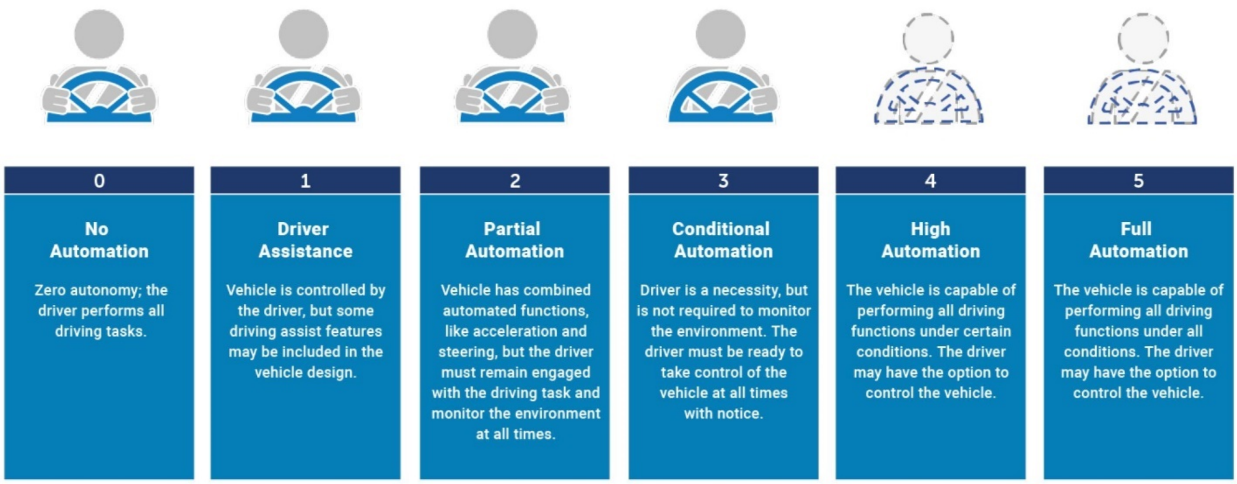

Figure 9: The SAE levels of road vehicle autonomy [20]

The European GSA employs a different scale, which focusses on the type of applications rather than the degree of autonomy. This classification is based on applications provided partly, or fully, by GNSS technologies, but several reports discuss these technologies in connection with applications related to road transport (such as the introduction of partly or fully automated vehicles). In the 2019 Report on User Needs and Requirements, four main road applications group are used: safety critical applications (SCA), payment critical applications (PCA), regulatory critical applications (RCA) and smart mobility (SM) [2]. These have been adapted from a 2015 classification [3] in which most of the elements of SM were included in the SCA category. An overview of the four application categories is given in Table 2, and a comprehensive description is given in the appendix.

Table 2: Different types of road applications as defined by the European GSA [2]

Category	Example of applications
Safety critical applications (SCA)	Forward collision warning (V2X), cyclists and motorcyclists protection (V2X), speed limitation, lane departure warning, autonomous driving
Payment critical applications (PCA)	Road user charging, pay-as-you-drive and pay-per-use insurance schemes, on street parking billing
Regulatory critical applications (RCA)	E-call, digital tachograph, tracking of hazardous materials and livestock transports
Smart mobility (SM)	Freight and fleet management, origin-destination survey, dynamic speed harmonisation

3.3.1.1 Safety critical applications

SCA are defined as applications in which humans (drivers, passengers, and other roads users) can be injured as a result of errors in positioning. Current requirements for SCA are not particularly stringent, but in a future where they will be supported by V2X communications, it is likely that the requirements will be substantially more stringent [2]. SCA rely on positioning accuracy, but also on several of the other key performance indicators (KPI) listed in Table 1, including availability, integrity as well as GNSS sensitivity and robustness.

SCA cover many applications which rely on positioning requirements relative to both maps and/or other vehicles and infrastructure. For instance, applications such as "curve speed warning" and "wrong way driving" require the vehicle to know its position relative to a map. Other applications like "cooperative intersection" and "collision avoidance" require communication between vehicles. The requirements on positioning for the different applications vary vastly; this is discussed further in chapter 3.3.3.

3.3.1.2 Payment critical applications

PCA relate to applications where the positioning and timing of a vehicle is used as basis for billing. As such, the positioning requirements vary depending on the nature of the application. For instance, when the position of the vehicle is used to determine whether the user is driving through a toll, the accuracy needs to be relatively high to avoid wrongly charging users. An example of this could be when a toll-free road runs parallel to a toll road – a positioning error in the tens of meters might misplace the vehicle on the toll road. Other applications entail less stringent requirements, such as pay-per-use insurance schemes. Aside from accuracy, the most relevant KPIs are availability and authenticity; the latter due to the cybersecurity threats that will affect the reliability of payment applications.

3.3.1.3 Regulatory critical applications

Currently, RCA based on onboard positioning and timing devices are few, but these are expected to become more numerous as the technology becomes more widespread. Applications include digital tachographs, eCall (functions that automatically send data to public safety answering points, for instance following a crash), tracing livestock transports, and several applications that will rely on geofencing technologies. The latter includes tracking of hazardous materials (to prevent that such transports unnecessarily enter populated areas) and other types of vehicle regulations (e.g. preventing polluting cars to enter city centres, avoiding heavy goods transport during certain hours, etc.).

3.3.1.4 Smart mobility

The last category defined by the European GSA includes a variety of applications that do not entail any safety, payment, or regulatory requirements but that still rely on vehicle positioning to function. The SM category is subdivided into "SM for traffic managers and transport companies" and "SM for safety and comfort of drivers". The first group includes applications such as cargo fleet management, estimations of origin-destination matrices and emergency vehicle priority systems. The second group relates mostly to applications that assist drivers, such as lane departure warnings, speed limitation information, tailgating advisory, etc. As such, the positioning requirements for the applications in the SM category also vary substantially.

3.3.2 Positioning accuracy

Positioning accuracy is defined as the error in the estimated position of a receiver related to the true position. In the GNSS community, this is sometimes also referred to as the *user accuracy* and is expressed as a radius. The user accuracy depends on a range of factors, including the user range error (URE), which is a measure of ranging accuracy of the satellites used to estimate the position (see Figure 10) as well as other components, such as atmospheric conditions, receiver design, signal blockage, etc. [28]. When estimating the position with multiple technologies, the positioning accuracy depends on the performance of the positioning system as a whole. Because the errors in the estimates vary, positioning accuracy is typically given at a certain confidence interval (a statistical measure of the positioning error, usually expressed as percentile of the cumulative error distribution, or CEF).

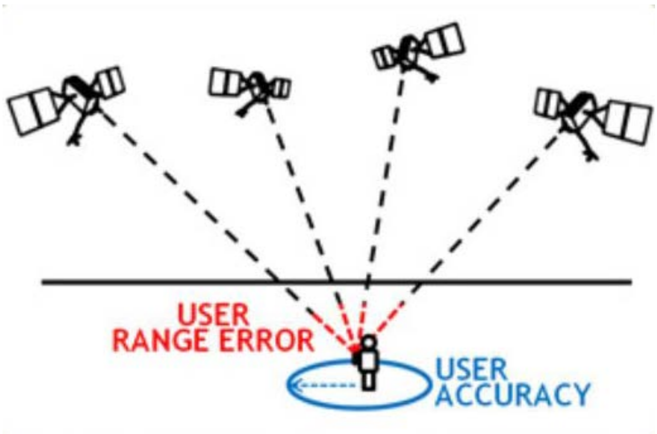

Figure 10: User range error (URE) vs. user accuracy for GNSS positioning systems (source: [28])

Positioning accuracy requirements in the transport sector are therefore often quantified as an error margin (distance) that the positioning system needs to take into account to remain within certain safety limits, (i.e. to establish a protection level for the positioning system due to the uncertainty of the accuracy), ensuring that the risk of accidents remains below a certain level [14, 19]. This entails that positioning requirements are implicitly associated with a measure of integrity of the positioning system. The European Space Agency uses this statistical measure to distinguish between accuracy and integrity, stating that accuracy is measured at the 95% percentile of the CEF, whereas integrity requirements refer to percentiles between 99,999% and 99,999999% [29].

Positioning accuracy requirements in the transport sector distinguish between horizontal and vertical accuracy. Horizontal accuracy is relevant for all the tasks associated with automated driving, with regards to all surrounding environment. This includes V2V (vehicle-to-vehicle), V2I (vehicle-to-infrastructure), V2P (vehicle-to-pedestrian) and V2N (vehicle-to-network). These cases are jointly referred to as V2X (vehicle-to-everything). The range of applications is vast, including toll road billing, collision prevention, stolen vehicle recovery, etc. Vertical accuracy is particularly important for handling cases where traffic occurs on multiple levels, such as highway overpasses.

Because many of the technologies and applications discussed in this document are still in their childhood phase (or are yet to be implemented), there are no international agreements for positioning accuracy standards for ITS technology or required navigation performance for road vehicles [6], nor is there a single standard definition of minimum operational requirements for absolute positioning performance in autonomous driving [12]. Where requirements exist, they are often determined by national or trans-national ITS organisations such as ITS America, ITS Australia and ERTICO-ITS Europe. The highest standard set by ISO 26262 for automotive functional safety is the Automotive Safety Integrity Level (ASIL) D [30], which allows for 10 failures in time (FIT). This translates to 10 failures per billion hours of operation, or 10^{-8} failures per hour. Assuming a Gaussian distribution, this corresponds to 99,999999% [19]. As displayed in Figure 11, achieving such standards considerably increases the error bound that needs to be considered. The values shown in the graph refer to the lateral error bounds needed for personal vehicles driving on US freeways in the study by Reid et al. [19]. A 95% confidence interval requires 0.20 m error bounds, while achieving 10 FIT requires error bounds of 0.57 m. This means that for the latter requirements, a car with a width of 1.8 m needs to be modelled with a width of almost 3 m to avoid collisions. It is worth mentioning that these requirements are defined with respect to a map, which entails that additional error bounds may be needed to consider the inherent uncertainties of the map with respect to the global reference [19] (with additional reference to [31] within).

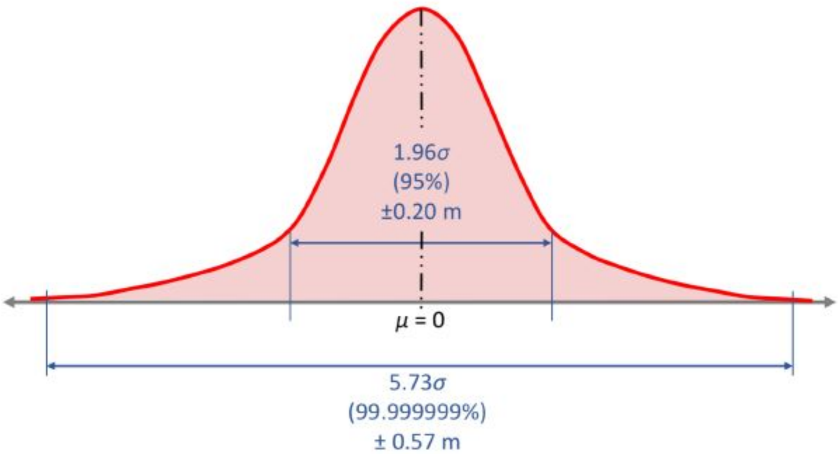

Figure 11: Error distribution for lateral positioning on US freeways (source: [19])

The European Committee for Electrotechnical Standardization (CENELEC) [32] defines horizontal position accuracy as a set of three statistical values given by the 50th, 75th and 95th percentiles of the cumulative distribution function (CDF) of horizontal position errors. While the 95th percentile constitutes the most stringent requirements, the median error (50th percentile) is often used in the literature and is known as the Circular Error Probable (CEP) at 50%, or CEP50 [14]. The French Institute of Science and Technology for Transport (IFSSTAR) uses these thresholds to define three accuracy classes in the Handbook of Satellite Positioning Performance Assessment for Road Transport, summarised in Table 3 and illustrated in Figure 12. For instance, Class 1 requires that 50% of positioning errors be less than 0.2 m, 75% of errors less than 0.3 m, and 95% of errors less than 0.5 m.

Table 3: Accuracy performance classification for horizontal positioning [14]

	50th percentile	**75th percentile**	**95th percentile**
Class 1	P < 0.2 m	P < 0.3 m	P < 0.5 m
Class 2	0.2 m < P < 2.0 m	0.3 m < P < 3.0 m	0.5 m < P < 5.0 m
Class 3	P > 2.0 m	P > 3.0 m	P > 5.0 m

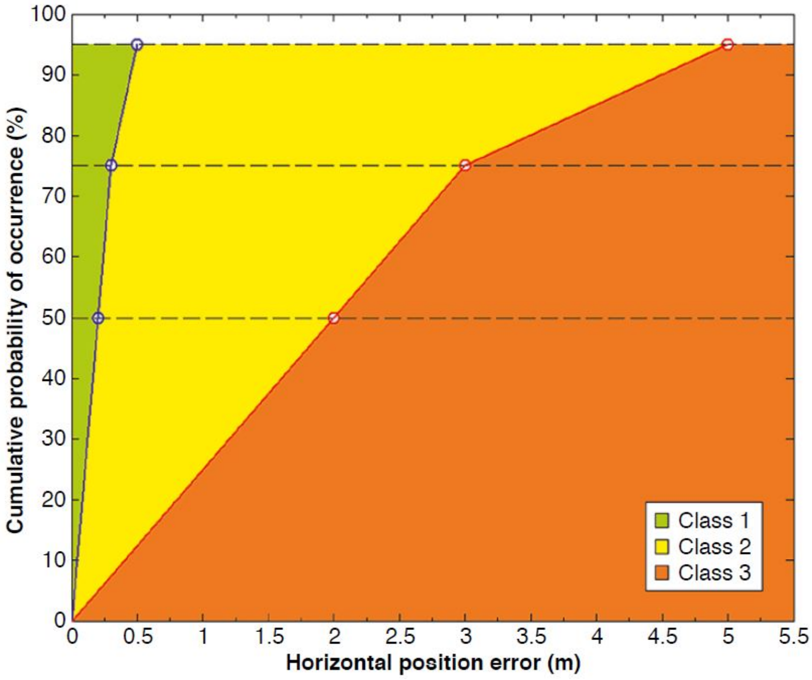

Figure 12: Accuracy performance classification for horizontal positioning as defined by the CENELEC [14]

While most studies discuss horizontal accuracy as one parameter, Reid et al. [19] distinguish between lateral and longitudinal components. Figure 12 shows how these components are defined, along with vertical accuracy. The principle used by Reid et al. is to model a car as a rectangular box, whose size is increased in all directions to generate a position protection level (bounding box), as discussed in section 3.3.2. The protection level boundaries are determined based on the positioning system's desired safety level, and the larger the safety level (i.e. percentile of the error CDF), the larger the bounding box. Figure 13 shows how the combined protection level is then established from the position protection level and the heading protection level, demonstrating the relevance of directional positioning requirements, particularly in urban areas where roads are narrower and curves sharper.

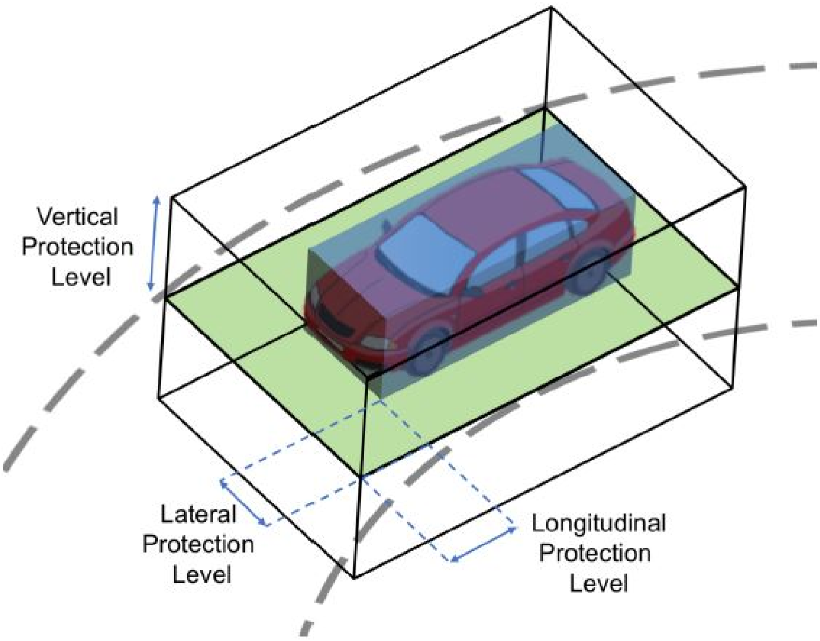

Figure 13: Illustration of different measures of relational positioning (source: [19])

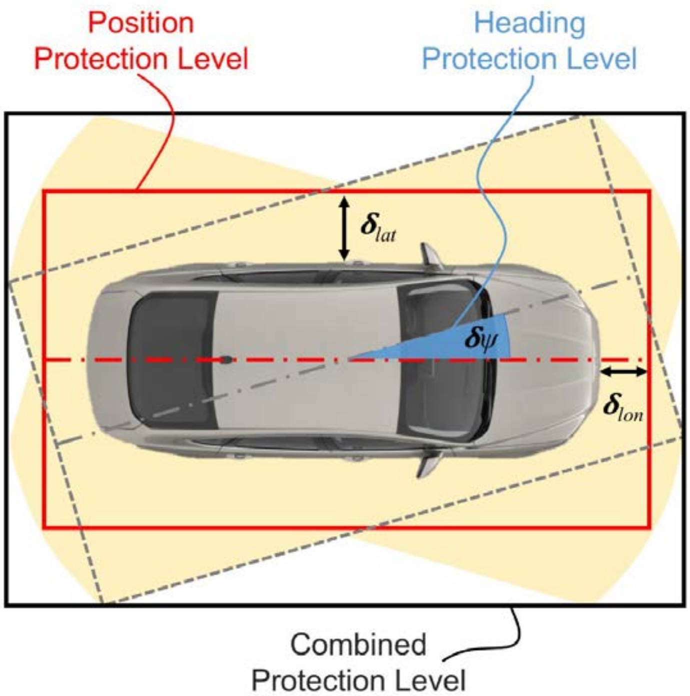

Figure 14: Illustration of directional positioning requirements (source: [19])

The combined protection level can then be used to determine two other important performance parameters listed in Table 1, availability and integrity, as illustrated in Figure 14. The alert limit (AL) can be interpreted as the physical limits of operation, e.g. the lane limits of a road or the distance to nearby obstacles (for instance other vehicles). When the protection level (PL) remains within the AL, an autonomous car will be able to operate safely without interruption. However, if the protection level exceeds the AL, the positioning system can no longer ensure that the car is positioned within the safety boundaries (e.g. lane limits), leading to the system being referred to as unavailable. Under optimal operation (green dot), the actual positioning error (AE) lies within the PL, which in turn lies within the AL. This implies that the error is smaller than the error boundaries defined by the PL, i.e. that such a positioning error has been taken into account by the system. Since the PL is within the AL, it can also be assumed that the autonomous car can operate safely. If the error is larger than the PL but still within the AL (orange dot), the system's integrity is breached, but because the AE is still within the AL, the misleading information is not hazardous, as the car will still be within the lane (or out of reach from nearby obstacles). If the AE is outside of the AL boundaries, the misleading information is considered hazardous (red dot), implying that the car may be located outside of the lane or in direct contact with nearby obstacles.

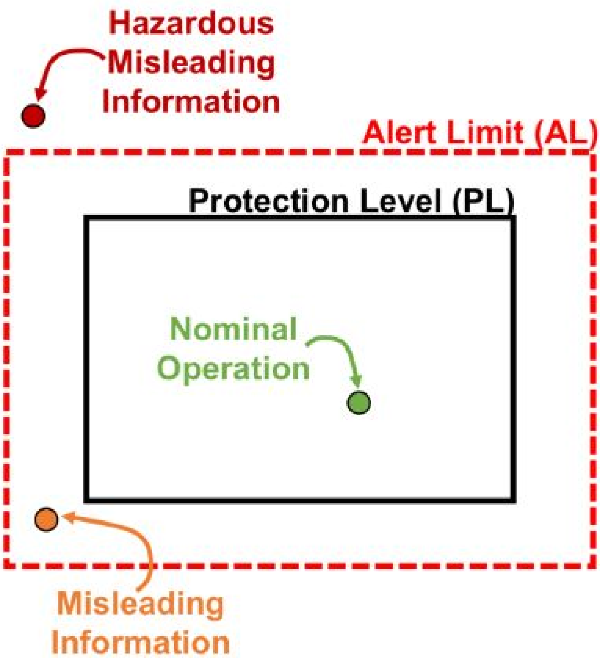

Figure 15: Illustration of protection and alert limits (source: [19])

This modelling principle is used by the European Space Agency [33] to define the availability (and integrity) of a positioning system, as illustrated in a schematic representation of the Stanford Diagram in Figure 16.

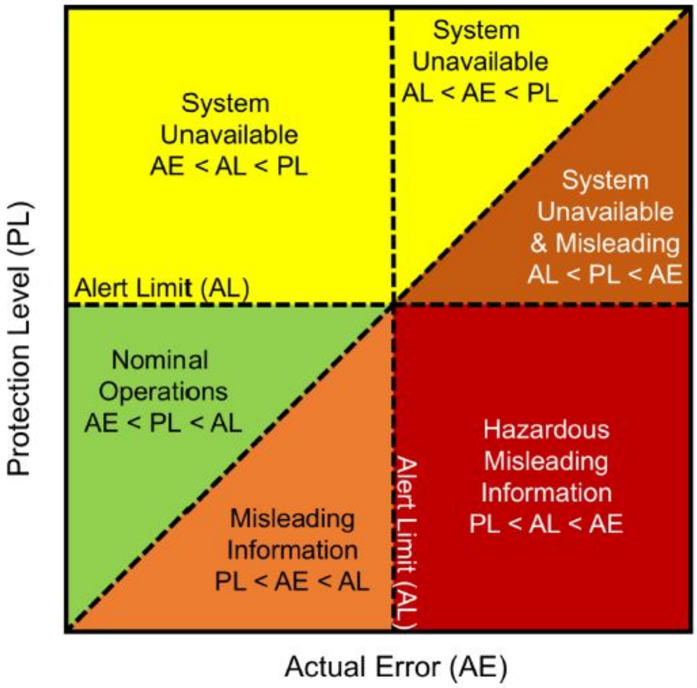

Figure 16: Stanford Diagram that shows the availability of a positioning system based on protection level (PL), alert level (AL) and actual error (AE) (source: [19], based on [33])

The upper level of Figure 16 shows the cases where the PL exceeds the AL, rendering the system unavailable. The lower part illustrates the three cases pictured in Figure 15, with nominal operation (green dot), misleading information (orange dot) and hazardous misleading information (red dot).

3.3.3 Positioning accuracy requirements in the transport sector

The quantified requirements found in the literature varies on the choice of classification. As mentioned previously, some studies classify requirements based on the intended application (or use-case), such as "obstacle on road", "autonomous driving", etc. (see Table 4 to Table 8). Other studies group requirements depending on the road characteristics, either based on resolution ("which road", "which lane", "where in lane" – see Table 12) or road type ("freeway", "local street" – see Table 13).

Furthermore, the level of detail of positioning requirements varies as well. While most studies specify horizontal requirements to a certain precision, vertical requirements and refined horizontal requirements are less common. The most precise requirements were found in Reid et al. [19], who specify vertical, horizontal (both lateral and longitudinal), as well as directional requirements (heading protection level). The reason for distinguishing between lateral and longitudinal requirements as well as including directional requirements is illustrated in Figure 13 respectively Figure 14.

Most of the positioning requirements found in the literature are scale-based; that is, requirements are defined as e.g. high (H), medium (M) or low (L), or using a numbered scale (1, 2, 3) where each number entails a minimum positioning of e.g. "<1 m" or "between 1 m and 10 m". This section summarises the positioning requirements found throughout the performed literature study.

3.3.3.1 Application-based requirements

The first type of requirement is based on specific applications (or use cases). Table 4 to Table 8 summarise the findings of the European GSA's Report on Road User Needs and Requirements concerning horizontal and vertical accuracy positioning requirements for various applications relying, to a certain degree, on GNSS positioning. Each table corresponds to the subcategories described in section 3.3.1.

Table 4: Safety critical positioning requirements set by the European GSA [2]

Application	Horizontal accuracy	Vertical accuracy
Red light violation	10 m	10 m
Queue warning	Between 1 m and 10 m	10 m
Obstacles on the road	Between 1 m and 10 m	10 m
Work zone warning	Between 1 m and 10 m	10 m
Obstacles on the road	Between 1 m and 10 m	10 m
Weather-based hazards	Between 1 m and 10 m	10 m
Curve speed warning	Between 1 m and 10 m	10 m
Emergency electronic brake light	Between 1 m and 10 m	10 m
Oversize vehicle warning	10 m	10 m
360° all around view	≤ 1 m	10 m
Blind spot lane change warning	10 m	10 m
Pedestrians in crossroads	Between 1 m and 10 m	10 m
Wrongway driving	≤ 1 m	Between 2 m and 10 m
Cooperative intersection collision avoidance	≤ 1 m	Between 2 m and 10 m
Automatic speed limitation	Between 1 m and 10 m	10 m
Emergency brake assist system, forward collision avoidance	≤ 1 m	10 m
Automatic driving	≤ 1 m	≤ 2 m
Autonomous car [34]	≤ 20 cm	≤ 2 m

Table 5: Payment critical positioning requirements set by the European GSA [2]

Application	Horizontal accuracy	Vertical accuracy
Road user charging	Between 1 m and 10 m	10 m
Pay as you drive insurance	Between 1 m and 10 m	10 m
Pay per use insurance	Between 1 m and 10 m	10 m
Taxi meter	Between 1 m and 10 m	10 m
Parking fee calculation	Between 1 m and 10 m	10 m

Table 6: Regulatory critical positioning requirements set by the European GSA [2]

Application	Horizontal accuracy	Vertical accuracy
Digital tachograph	10 m	10 m
Hazardous material tracking	Between 1 m and 10 m	10 m
eCall	10 m	10 m
Geo-fencing (low emission zone area, forbidden area, alert)	Between 1 m and 10 m	10 m

Table 7: Smart mobility for traffic management and transport companies set by the European GSA [2]

Application	Horizontal accuracy	Vertical accuracy
Freight and fleet management	Between 1 m and 10 m	10 m
Cargo / asset management	Between 1 m and 10 m	Between 2 m and 10 m
Vehicle access / clearance control	Between 1 m and 10 m	10 m
Floating car data	10 m	Between 2 m and 10 m
Origin-destination survey	Between 1 m and 10 m	Between 2 m and 10 m

Dynamic speed harmonisation	Between 1 m and 10 m	10 m
Emergency vehicle priority	Between 1 m and 10 m	10 m
Bus and tram priority at traffic lights	≤ 1 m	10 m

Table 8: Smart mobility for user's safety and comfort set by the European GSA [2]

Application	Horizontal accuracy	Vertical accuracy
Road navigation with lane level positioning	10 m	10 m
Speed limitation information	Between 1 m and 10 m	10 m
In vehicle signage	Between 1 m and 10 m	10 m
Electronic horizon	Between 1 m and 10 m	10 m
Reduce speed warning	Between 1 m and 10 m	10 m
Do not pass warning	Between 1 m and 10 m	10 m
Green light optimal speed advisory	10 m	10 m
Automated parking	10 m	10 m
Tailgate advisory	Between 1 m and 10 m	10 m
Lane departure warning system	10 m	10 m
Slow or stationary vehicle	Between 1 m and 10 m	10 m
Traffic jam ahead	Between 1 m and 10 m	10 m
Connected eco driving	Between 1 m and 10 m	10 m
Snowplough in operation	Between 1 m and 10 m	10 m
Dynamic ride sharing	Between 1 m and 10 m	10 m
Stolen vehicle recovery	Between 1 m and 10 m	Between 2 m and 10 m

A 2015 white paper published by the European Commission discussed the introduction of new technologies that will demand increased positioning requirements. The paper is the outcome of series of discussions and workshops between representatives from both the automotive and telecom industries and various research institutes, and treats not only positioning accuracy but also several of the other KPIs listed in Table 1. Six applications were analysed in detail in the paper and horizontal accuracy requirements were suggested for four of these (listed in Table 9). The quantified requirements in the table refer to the maximum positioning error allowed for the positioning system. No horizontal accuracy was listed for the two remaining ones (see-through and bird's eye view).

Table 9: Key performance indicators set by the European Commission [11]

Use case	Horizontal accuracy
Automated overtake	30 cm
Cooperative collision avoidance	30 cm
High density platooning	30 cm
Vulnerable road user discovery	10 cm

Table 10 summarises key findings from a 2016 PhD thesis by Stevenson [6], which also takes basis in applications to define horizontal accuracy requirements for positioning in the transport sector. The applications are subdivided into those that already existed at the time of writing (current – c) and those that were still only in the development phase (future – f). The quantified horizontal accuracy refers to the required navigation performance (RNP), which is based on the positioning requirements used in aviation, where the RNP is used to define the radius with which an aircraft can determine its own position within 95% total system error. The RNP typically includes accuracy, integrity, continuity and availability. Stevenson also discusses the introduction of a required autonomous driving performance (RADP), which adapts the RNP to the cases of autonomous driving, for instance assuming a certain maximum speed and inherent requirements of availability, continuity and integrity. The values shown in Table 10 assume a maximum speed of 155 mph.

Table 10: Required navigation performance of current (c) and future (f) ITS applications [6]

Application	Horizontal accuracy
Black spot warning (c)	5 m
Blind spot warning (c)	70 cm
Overtaking vehicle warning (c)	1 m
Inter-vehicle hazard warning (c)	5 m
Active braking (c)	1.4 m
Lane departure warning (c)	20 cm
Vehicle platooning (f)	20 cm
Motorcycle lane position (f)	20 cm
Intelligent speed control (f)	2 m
Intersection collision avoidance (f)	2 m
Driver monitoring (f)	5 cm
Autonomous vehicles (f)	5 cm

Table 11 presents horizontal accuracy requirements based on the ADAS levels / categories described in section 3.3.1, stemming from an article in Telematics Wire discussing the requirements of GNSS technologies for V2X applications and automated driving.

Table 11: Requirements by ADAS level (as described in Figure 9) [21]

Application / ADAS level	Horizontal accuracy
V2X	< 1 m (CEP50)
ADAS levels 1-3	< 20 cm (CEP50)
ADAS levels 3-5	< 20 cm (CEP50) + protection level

3.3.3.2 Road-based requirements

The second class of requirements identified does not relate to explicit applications, but to the level of accuracy that one wishes to obtain. Table 12 summarises an approach taken in several studies, where the requirements are based on the lane-level resolution, often categorised as "which road" (the positioning system needs only successfully identify the road used), "which lane" (the positioning system must be able to correctly identify the actual lane) and "where in lane" (the relative position in a certain lane is needed). While these categories are not explicitly associated with specific applications, one could link these requirements to the various applications listed in 3.3.3.1. For instance, origin-destination estimation would only require knowledge of road taken, while relative lane positioning is needed for collision avoidance. Furthermore, a fourth category is added to this classification, titled "active control", requiring decimetre-level accuracy [6]. This category would apply to e.g. autonomous driving.

Table 12: Required navigation performance by position accuracy categories [6, 12, 18]

Position accuracy category	Horizontal accuracy	Source
Which road	5 m	Stephenson 2016
	Between 5 m and 10 m	Thombre 2019, Feng 2018
Which lane	1.5 m	Stephenson 2016
	Between 0.5 m and 1 m	Thombre 2019, Feng 2018
Where in lane	0.5 m (possibly to the nearest dm)	Stephenson 2016
	Between 10 cm and 30 cm	Thombre 2019, Feng 2018
Active control	10 cm	Stephenson 2016

Lastly, the paper by Reid et al. studies the positioning requirements and the horizontal accuracy needed for the integration of autonomous vehicles and differentiates between the requirements for vehicles driving on US freeways (highways) and local streets. Hence, this corresponds to ADAS levels above 3 and to the active control category described in the previous section.

The requirements are summarised in Table 13. As opposed to the requirements listed in previous tables, this study distinguishes between lateral and longitudinal horizontal accuracy (as illustrated in Figure 13) as well as directional requirements, which define the required accuracy of the vehicle heading relative to the road.

Table 13: Required error bounds for autonomous vehicles by road type [19]

Road type	Lateral accuracy	Longitudinal accuracy	Vertical accuracy	Orientation accuracy
Freeway	57 cm (20 cm, 95%)	1.4 m (0.48 m, 95%)	1.3 m (43 cm, 95%)	1.5 deg (0.51 deg, 95%)
Local street	29 cm (10 cm, 95%)	29 cm (10 cm, 95%)		0.5 deg (0.17 deg, 95%)

3.4 Summary and outlook

As we have seen throughout this document, positioning requirements in the transport sector depend on the intended applications. The level of application detail varies across the literature, with some studies differentiating between detailed use cases while others bundle together applications in groups. Hence, the requirements vary substantially, ranging from tens of meters down to centimetre accuracy (with one study arguing that 5 cm accuracy is needed for autonomous vehicles, and several others indicating a required accuracy of 10 cm). Because of the variations in error estimates, positioning accuracy is closely linked to integrity of the positioning system. While integrity requirements have not been the focus of this report, they are implicitly linked to the quantified accuracy requirements listed in the previous section. Quantified accuracy requirements are often given as a maximum allowed error in positioning at a certain confidence interval; this level of confidence needed is also linked to the type of application, with applications such as autonomous driving requiring much higher confidence than e.g. the navigation applications discussed in the introduction.

The purpose of this report was to shed light on the positioning *requirements* of the transport sector and has therefore not described the current state-of-the-art of GNSS positioning technologies and positioning systems that combine multiple technologies (e.g. advanced GNSS receivers, cameras, radar, lidar, wi-fi, etc.), of which studies abound. However, such state-of-the-art systems are expensive and are therefore unlikely to become widely adopted as standard equipment on personal vehicles. Hence, the challenge that car manufacturers will face is to develop affordable positioning systems that meet the requirements listed in this report.

3.5 Appendix

3.5.1 Different types of road applications

The following tables provide more comprehensive lists of the different types of road applications described in section 3.3.1 as defined by the European GSA.

Table 14: Examples of safety critical applications (source: [2])

Applications	Application description
Red light violation warning	An in-vehicle device determines according to its position and speed if the vehicle is in danger of violating a red light or a stop and sends a message to others
Curve speed warning	An in-vehicle device determines according to its position on the map and speed if the vehicle is in danger of losing its trajectory
360° all around view, blind spot lane change warning, oversize vehicle warning	The vehicles exchange in real time their position with other road users to mitigate blind spot effect
Obstacles on the road, work zone warning, weather based hazards, Queue warning, pedestrians in crossroads, cooperative intersection, collision avoidance including railways	An in-vehicle device displays the position of the danger to the driver with a certain accuracy and in real time
Emergency brake assist, collision avoidance	The vehicles exchange in real time the position, speed and direction to set up an emergency braking
Wrong way driving	The in-vehicle device must be able to determine according to its position on the digital map that the vehicle is driving on the wrong way of the motorway
Emergency electronic break light	In case of severe braking or blockage of the road the vehicle sends an alert message with its location to coming vehicles
Automatic speed limitation,	An in-vehicle device limits automatically the speed of the vehicle matching the position with a speed limit data base
Automated driving	Accurate positioning linked to other sensors will assist the driver to secure the automatic driving
Autonomous car	Only a deep integration of sensors will be able to secure the movements of autonomous car in various environments.
Synchronisation	Precise time synchronization will always be a strong requirement in all safety related applications

Table 15: Examples of payment critical applications (source: [2])

Applications	Application description
Road user charging	Position and timing provided by GNSS is recognized in the EU directive on interoperability of tolling systems and already commonly used in Europe
Pay as you drive insurance	Positioning, speed and timing can be linked to how, where and when a vehicle is driven, and provide valuable information for the insurance company
Pay per use insurance	Coverage of the assurance can be based on mileage aggregated from GNSS data
Taxi meter	A taxi meter is a device installed in car that calculates passenger fares based on combination of distance travelled and waiting time. Use of GNSS will simplify the device.
Parking fee calculation	Where satellite signal is available, positioning and timing provided by satellite can be used to calculate the parking fee. In addition, the vehicle can inform the parking manager that the place is free when it starts.

Table 16: Examples of regulatory critical applications (source: [2])

Applications	Application description
Digital tachograph	In order to facilitate the verification of compliance with the regulation the position of the vehicle shall be recorded at specific points where the satellite signal is available
eCall	In case of crash or after manual activation, the vehicle must send a minimum set of data to public safety answering points, in which time stamp and location are provided by satellite positioning.
Hazmat tracking	A fleet management concept adapted to hazardous material tracking is under review in the UNECE group.
Livestock tracing	See Commission implementing decision on the protection of animals during transport
Geo fencing (low emission area, forbidden area, alert, …)	The in board GNSS based device triggers an alert when the vehicle enters or exit boundaries defined by geographical coordinates. It can be used as an access control to specific zones where only authorized vehicles are accepted. No regulations so far have been adopted but the geo fencing can play a major role in many applications like access control protected areas or tolling in urban centres

Table 17: Examples of smart mobility for traffic managers and transport companies (source: [2])

Applications	Application description
Freight, Fleet, cargo asset management	Timely position of trucks, trailers, wagons, drivers, cargo, forklift and load units, remote vehicle diagnostics are key data for the optimum management of the supply chain.
Vehicle access/ clearance control	An authenticated position can facilitate the clearance control of vehicles travelling in and out an area
Floating car data	Localization, speed and time information produced by on board devices are intensively used by service providers an road network operator to produce traffic information
Origin destination survey	Precise geo coded of origin and end of trips provides a detailed picture of patterns and travels choice that help urban planners
Dynamic speed harmonisations	At specific location and timing vehicles are invited to slow down to adapt an appropriate speed to increase the capacity. This measure is also developed as an A-CCS
Emergency vehicle priority	An appropriate GNSS on board device can locate the priority vehicle relative to the traffic lights, send a message to adapt the signal phase timing and get a green light
Bus and tram priority at traffic lights	Same as above but I that case the tram or the heavy bus can't stop if it has no green light

Table 18: Examples of smart mobility for safety and comfort of users (source: [2])

Applications	Application description
Road navigation with lane level positioning	The accuracy of the GNSS based device and map shall be able to provide a lane level positioning.
Speed limitation information	The speed limitation is displayed to the driver according to a speed data base and the location of the vehicle.
In vehicle signage	A static or dynamic sign information is displayed to the driver without roadside units just taken into account the localization and direction of the vehicle on the road
Electronic horizon	Thanks to an accurate digital map the driver can be informed of potential dangers located ahead of his current vision like sharp curve, pedestrian crossings or round about
Reduce speed warning	A warning is automatically issued to the driver if his speed doesn't match the lay out of the road taken into account the characteristics of the vehicle
Do not pass warning	During an overtaking knowing the exact position of vehicles coming in the opposite direction is strong request
Green light optimal speed advisory	Taken account the relative position of the vehicle and the traffic lights an optimum speed advice is given to the driver to pass the next traffic lights during a green phase
Automated parking	A very accurate positioning is needed to guide the vehicle during the parking process
Tailgating advisory	Exchange of relative positions between heavy vehicles to warn the driver that he is too close to another vehicle in front of it, creating an unsafe driving condition
Lane departure warning	An accurate position and a precise map can warn the driver that he is drifting off the lane
Traffic jam ahead and snowplough in operation	Knowing how far away is the next traffic jam helps the driver to adapt his speed, same for a plough in operation
Connected eco driving	Eco driving uses a map and the location of the vehicle to advice timely the driver so he can adjust his driving to save fuel and reduce emission. The service can be connected for real time data
Dynamic ride sharing	In dynamic ride sharing GNSS helps to precise the location of meeting points and facilitate the fee calculation
Stolen vehicle recovery	This application provides the position of the stolen vehicle
Electro mobility	Applications allowing the optimising usage of EV (Electric Vehicle) while providing the best route, including charging spots as necessary
Mobility services	Application where the user is not the drivers but use vehicle from a service provider (taxi, public transport …) needing the position of the clients and the vehicles

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4 Reference frames for ITS

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4.1 Introduction

This document is describing basic principles for measuring a coordinate with Global Navigation Satellite System (GNSS) on the earth's surface, which is constantly moving. In the following chapters we try to answer the questions:

- What is the concept of a reference frame and why is it important?
- What is important for the ITS community to think about with regards to reference frame?

4.1.1 Abbreviatons

Galileo		European global navigation satellite system
GNSS	Global Navigation Satellite System	Standard generic term for satellite navigation systems
GPS	Global Positioning System	American global navigation satellite system
EUREF89	European Terrestrial Reference Frame 1989	Reference frame fixed to the Eurasian plate
EGM2008	Earth Gravitational Model 2008	World wide gravitational model
ITRF2014	International Terrestrial Reference Frame 2014	Global reference frame
ITS	Intelligent Transportation Systems	
NRTK	Network Real Time Kinematic	Regional GNSS correction method, achievable accuracy 1-2cm
PPP-RTK	Precise Point Positioning – Real Time Kinematic	Global GNSS correction method, achievable accuracy 5cm
PPP	Precise Point Positioning	Global GNSS correction method, achievable accuracy 20cm
UTM	Universal Transversal Mercator	A common map projection
WGS84	World Geodetic System 1984	Global reference system
WGS84G1762	Newest WGS 1984 realization, reference epoch GPS-week1762 from 1980 Jan. 1st. (October 2013) Reference Frames in GNSS - Navipedia (esa.int)	Global reference frame

4.2 Background: Surface of the earth is moving

The surface of the earth is continuously moving. In daily life no one notices this, but earthquakes are well known to everybody and a proof to it. This is known as continental drift, and there are roughly seven large areas on the earth that are moving towards or from each other. Norway is located on the Eurasian plate covering Europe and most of Asia [2].

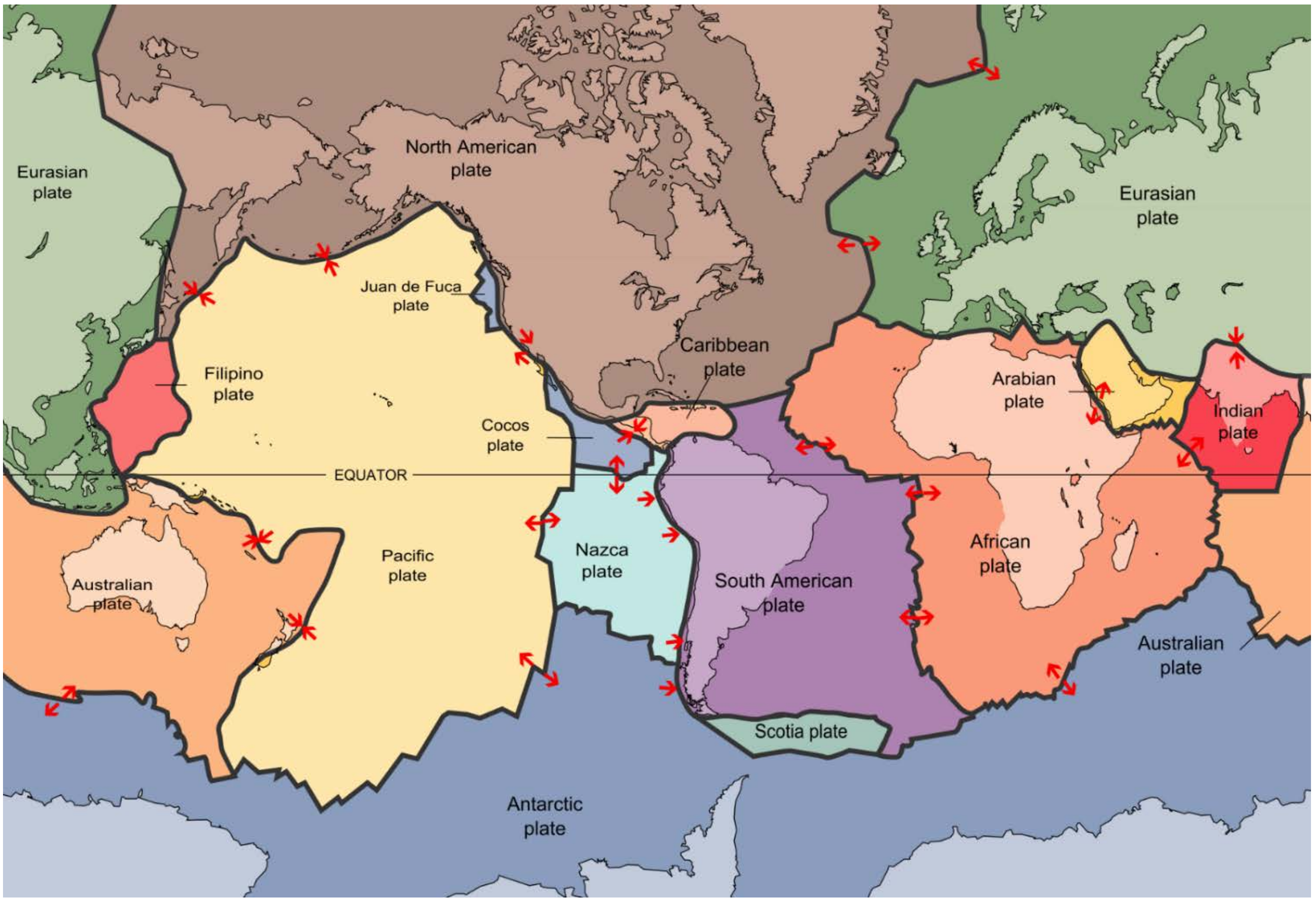

Figure 17: Simplified map of Earth's tectonic plates [2]

Some questions arise. How do you measure a coordinate on a moving surface, and how can you find the same coordinate you measured five years earlier?

The science of geodesy is knowledge about the earth's shape, movements, field of gravity and how these change over time. With geodetic measurements, continental drift is measured with respect to fixed points in space [1]. Knowledge of earth surface movements is fundamental for global satellite positioning systems like GPS or Galileo, commonly known as GNSS systems. For all systems and technological fields (such as ITS) which are depending on accuracy in the positioning, these earth movements must be accounted for.

4.3 Positioning on a moving surface

4.3.1 Reference frame

To measure a coordinate with GNSS on earth's moving surface, we need a reference. This is in geodesy called a reference frame and is a specific definition of how you can associate a coordinate to a point on the surface of the earth. These reference frames are valid on a global or regional scale. A specific point or physical object will have different values for coordinates depending on which reference frame being used. It is therefore important to have a conscious mindset with regards to which reference frame to apply, as your moving objects position might be correlated towards other objects position.

In Figure 18, measured plate velocities in Scandinavia are shown.

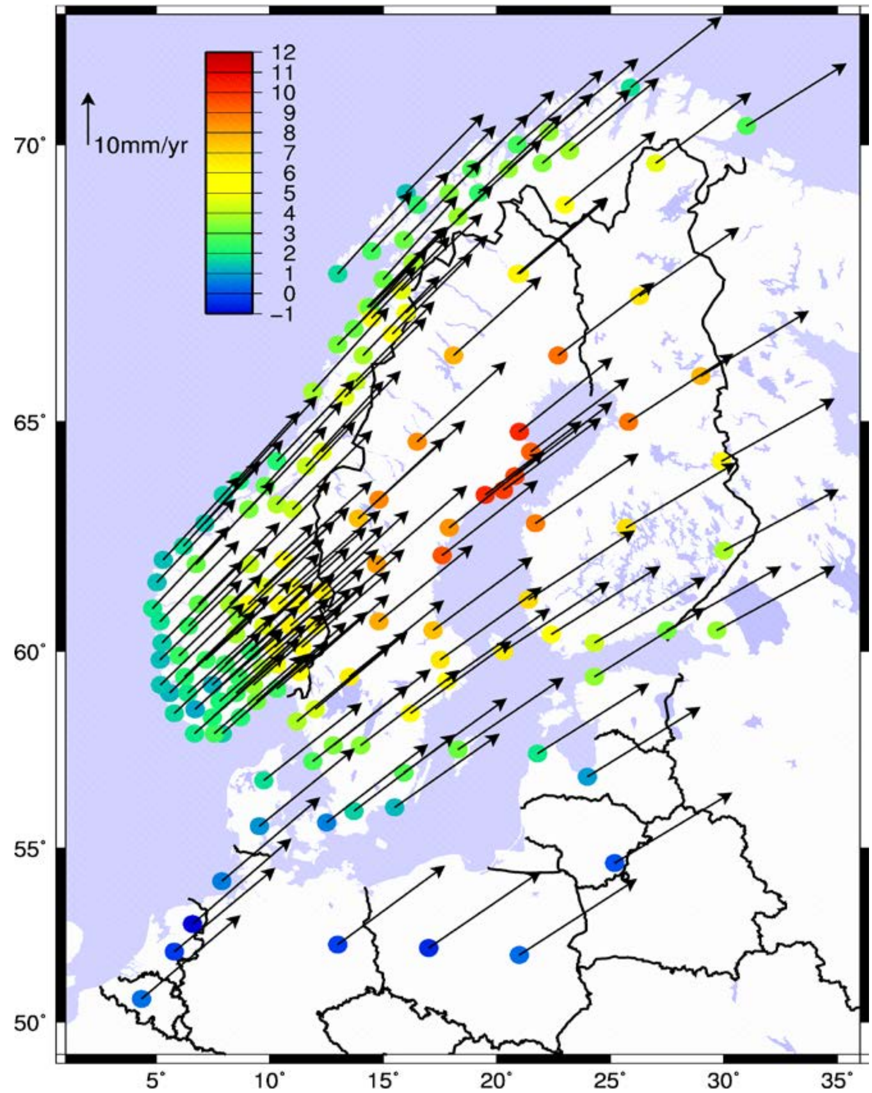

Figure 18: Velocity field in Scandinavia. The arrow shows movement in plane while point colours show land uplift [6]

4.3.2 Global reference frames

Global reference frames are fixed to the globe, and do not take into account continental drift. Therefore, global reference frames also include a velocity model, describing how fast points or areas on earth's surface move. Points measured in a global reference frame must also have information about when they were measured in order to implement the velocity model correctly.

There are two common global reference frames being used:

- ITRF2014 – created by International Earth Rotation Service. It is planned to replace this within few years with ITRF2020.
- WGS84 – created by National Geospatial-Intelligence Agency and GPS is using this frame. When this frame is updated it does not change its name, but has a suffix rarely noted. For example WGS84 (G1674) is created at GPS week 1674.

With time, these two reference frames have converged and are now nearly identical and in most use cases there are no practical differences. A physical object measured twice at a different time, can be compared directly when the timestamp is known.

Uncorrected GNSS positions from for example smartphones, and correction services like Precise Point Positioning (PPP) and PPP-RTK aiming for the automotive industry are using a global reference frame. Typical accuracy of these GNSS correction services are about 20cm and better, and uncorrected GNSS has an accuracy of 2-10 meters.

4.3.3 Regional reference frames

In Europe a regional frame fixed to the Eurasian plate is used. This means that the coordinates are fixed and moves with the continent. This eliminates the need for a velocity model. The reference frame is named EUREF89 and was aligned with ITRF in 1989, but the difference between these frames increases over time due to the continental drift. The continental Eurasian plate moves approximately 21 mm in northeast direction per year (Rates for Trondheim, North: 16mm/yr, East: 14.2mm/yr). In 2021, the difference between ITRF2014 and EUREF89 is approximately 70cm.
The benefit with the regional reference frame is that a physical object measured twice at different time, can be compared directly without knowing the timestamp [8][9].

GNSS correction services like Network Real Time Kinematic (NRTK) operating in one country are usually using a regional reference frame typical accuracy of NRTK is 1-2cm.

4.3.4 Height systems

There are two different principles for describing a height:

- Ellipsoidal height is with respect to a mathematical model of the earth (which is an ellipsoid). All GNSS systems are using this method.
- Orthometric height – for many practical cases it is needed to measure height with respect to sea level. By measuring earth's gravity field a model describing the difference between ellipsoidal and orthometric height is created. Norway has a local model, and there exist global models as well, like for example EGM2008.

The difference between ellipsoidal and orthometric heights in Oslo area is approximately 40m.

Heights also change over time due to post glacial land uplift after the last ice age, where the land was deformed due to weight of ice masses. In Scandinavia this impact is several mm per year, see Figure 19, but other countries have nearly no land uplift [7].

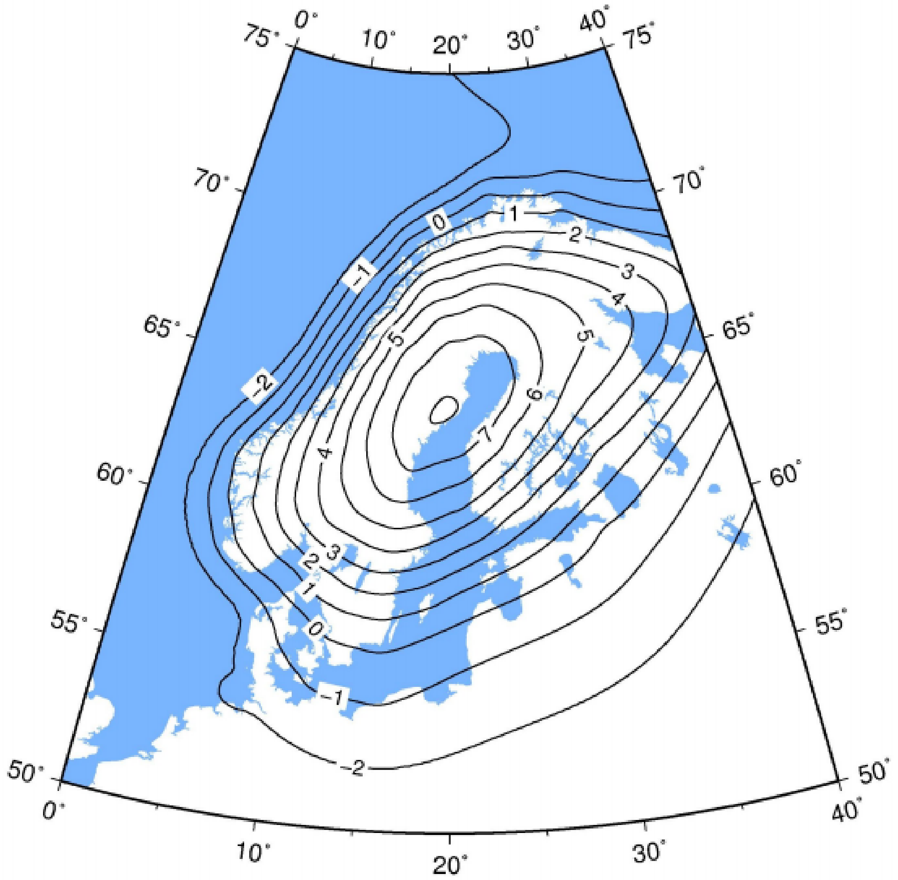

Figure 19: Land uplift model for Scandinavia, NKG2005LU. Each line describe 1mm/year uplift [7]

Similar issue as for reference frames can be seen in heights, if a road intersection is complicated with a culvert, road and on top of a bridge there are roads at three different heights. If heights from navigation systems and maps are used together, type of height in data sources must be taken care of to achieve the needed accuracy.

4.3.5 Map projections

Map projections are used to go from coordinates on an ellipsoid shaped earth to a plane two-dimensional map. This introduces distortions to some extent, depending on chosen projection, which relates to properties like area, shape, direction, bearing or distance. Coordinates are expressed as east and north in meters.

For large scale maps Universal Transverse Mercator (UTM) projection is widely used, but other can be in use. UTM preserves angles and shapes, but distance and area are distorted. The earth is divided into 60 zones covering 6° each, and each zone is projected to a theoretical cylinder. Within a zone, a measured distance on map can be up to 4cm wrong per 100m, but for general mapping applications this is of no concern. Norway has a local variant of this projection, Norwegian Transverse Mercator, with zone width of only 1°. This gives negligible distortions, distance errors can only be up to 1mm wrong per 100m. NTM is common in construction industry where prefabricated elements are used.

Figure 20: UTM zones in Scandinavia [3]

UTM zones in Norway are 32 – 35 for regional maps, UTM zone covering national maps (as NVDB) is 33.

4.3.6 Transformations between reference frames and projections

Since coordinates can be expressed in different reference frames, height systems and projections, transformations are quite often needed to go from one set of coordinates to another. There are formulas, software and web-services available for doing this. PROJ is an open source software for projection and geodetic transformations; it is available through a command line program or as an API [4]. Standard GIS tools do use the PROJ library for transformations and programming languages have adapted it - it is for example implemented in Python as the pyproj package.

Figure 21 shows the impact of continental drift for coordinates in different reference frames.

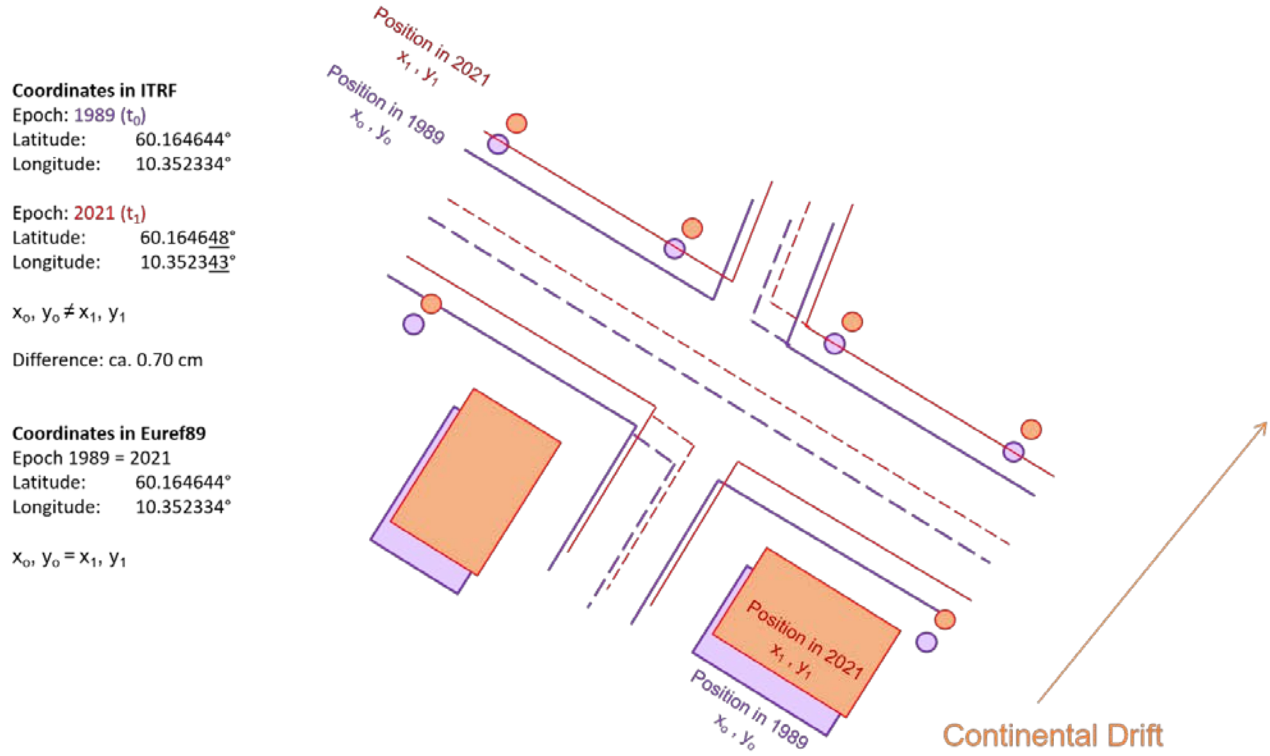

Figure 21: Map sketch with different timestamp and reference frames

4.3.7 Summary

In the above chapter we have described the concept of a reference frame and height systems.. In summary, it is important to be aware that there are different reference frames, projections and height systems and that all these have different properties and purposes, and coordinates can be transformed from one system to another.

4.4 Reference frames for the ITS community.

The choice of reference system- and frame is of importance for the ITS sector as many of its applications rely on technologies utilising reference frames (GNSS positioning, maps, etc). In the last few decades, major technological advancements have increased the need for positioning and map accuracy as vehicles are becoming increasingly automated.

Depending on the intended application, the degrading accuracy of position estimates may not necessarily constitute a problem. For instance, the European GNSS Agency identifies a range of applications requiring positioning technologies in their Report on Road Users Needs and Requirements [10], in which it specifies the minimum horizontal accuracy needed for each application. For most applications, the required accuracy lays in the range "between 1m and 10m". Hence, a 70cm discrepancy (as described in Section 3.2.1) may be critical for applications approaching the lower bound of 1m, but it is likely that many applications do not require such accuracy (for instance *Work Zone Warning*, *Road User Charging*, *Hazardous Material Tracking*, etc). Furthermore, a range of applications are characterised as necessitating only a 10m accuracy and would therefore not be affected by below metre discrepancies in positioning. Hence, the problems associated with reference frames may only constitute a challenge for specific applications, most of which comprised in the upper levels of the SAE levels of road vehicle autonomy [11], such as *Vehicle Platooning*, *Cooperative Intersection Collision Avoidance*, *Autonomous Vehicles*, etc.

4.4.1 Challenges related to ITS applications

The ITS community faces two challenges with respect to reference frames. **The first challenge** is the very existence of different reference frames, a problem that until now has received little focus in the ITS community. Different GNSS positioning methods give results in different reference frames (for instance, CPOS is based on EUREF89 while SPP (Single Point Positioning) is based on ITRF14). This entails that any set of coordinates must be accompanied by the reference frame used. If the same reference frame is used (both in space and time), coordinates can be compared without the need for additional transformations. For instance, the distance between two nearby vehicles (V2V) using the same reference frame can be computed with simple geometrical formulas. If different reference frames are used, additional transformations are required (to convert to a common reference frame, both in space and time). Moreover, as a second example, if positioning systems used within the future ITS and autonomous vehicle market follows the ITS standards of today, the coordinates will be provided in a global reference frame, geographic coordinates (latitude and longitude) and ellipsoidal heights. If this position should be used with high-definition maps, which in Norway probably will have coordinates in a regional reference frame (EUREF89), UTM map projection and orthometric heights (NN2000), then data has to be transformed to be consistent with each other. **The second challenge** is related to the Earth dynamics (tectonic activity, earthquakes, etc.), causing both continental drift and intra-plate deformations. This entails additional difficulties regarding for instance V2I operations using maps, since the coordinates of physical objects in a regional reference frame will become less accurate over time.

4.5 Advice to the ITS sector

The future of ITS is still being shaped, and the requirements in terms of reference frames and map accuracy of the next generation of vehicles remain to be seen. Describing the way forward for the ITS sector is therefore a tentative endeavour. All avenues come with pros and cons, and weighing the trade-off is likely to raise debate. Furthermore, the needs may differ across geographical locations depending on the type and magnitude of the deformations, applications, existing geodetic infrastructure, etc [12].

Regardless of the choice of reference frame system, the time dimension needs to be better integrated in future systems. While time is implicitly featured in the definition of reference frames, it is often being disregarded or ignored in many applications. For instance, coordinates of physical locations are currently typically given statically, despite that they are inherently associated with the timestamp when they were defined. Furthermore, coordinates of moving objects (e.g. vehicles in traffic) are provided in real-time, while map coordinates are fixed in time (i.e. are associated with a timestamp). Today, WGS84 is used for ITS standards [13], but the datum epoch (that is, the date when the realisation was established) is rarely specified. If the aim is to reach cm- or dm-level accuracy, time needs to be somehow integrated so that the required transformations can be performed.

Furthermore, there is a need for establishing a common language that can be understood by all actors and practitioners across the various fields that contribute to the technologies used in the ITS sector. Developing the tools of the future of mobility relies on foundations and inputs from multiple fields, including geodesy, cartography, topography, geography, navigation, space research, ITS, to name a few. One of the main goals of the TEAPOT project is to strengthen the collaboration between stakeholders in or related to the positioning field, and this has shed light on a recurrent problem with cross-sectoral collaboration and communication. Each of the fields listed above utilises its own vocabulary to define and describe core concepts, and while the semantics may not be an issue within a specific field, it can easily lead to misinterpretations or misunderstandings if applied elsewhere. This highlights the need for establishing a common framework, perhaps in the form of a standard (new or pre-existing), where the discrepancies in terminology are harmonised or at the very least revealed and clarified.

As mentioned earlier, the challenges associated with reference frames are only of concern when the aim is to achieve fine accuracy. Since many future ITS applications will require well below metre accuracy, it is likely that the ITS sector needs to move beyond reliance on regional reference frames, as they lead to degrading accuracy over time when real-time geospatial data (ITRF coordinates) are given in a static regional reference frame, and where existing maps are made by surveys based on a static datum (past ITRF coordinates at the epoch of static datum definition) [14]. The solution may lay in the adoption of dynamic (or semi-dynamic) reference frames, see next Section.

4.6 Next step: Dynamic reference frames

With the knowledge that coordinates from regional and global reference frames can't be directly compared without a time dependent transformation, this leads to challenges when high accuracy global positioning services shall inter-operate across borders with regional maps or other geodata. Global and regional reference frames are also deformed over time due to changing velocity of plates and deformations within a plate. These deformations are described in Figure 22.

There is an ongoing discussion among geodesists if a dynamic reference frame should be implemented. With this approach, it is one global reference frame with a continuously updated velocity and deformation model for the earth's surface. When an earthquake occurs, the reference frame will be updated accordingly. This would also mean that coordinates will change with time, but the benefit is that all coordinates measured with GNSS are in correct reference frame and valid across borders. The implementation of a dynamic reference frame may therefore be more demanding. In a study of dynamic reference frames in Iceland, Evers et al. [15] list the following main preconditions for a successful implementation of a dynamic reference frame:

1- A sufficiently dense active geodetic infrastructure (CORS) with known coordinates in a global reference frame (ITRF)
2- A way to distribute the reference frame to the users, e.g. positioning devices
3- Transformations and/or deformation models with sufficient accuracy to meet the future demands for comparison and compiling coordinates from different epochs
4- GIS systems that are able to handle dynamic coordinates in general and in particular the time dimension of a dynamic reference frame and the various transformations needed

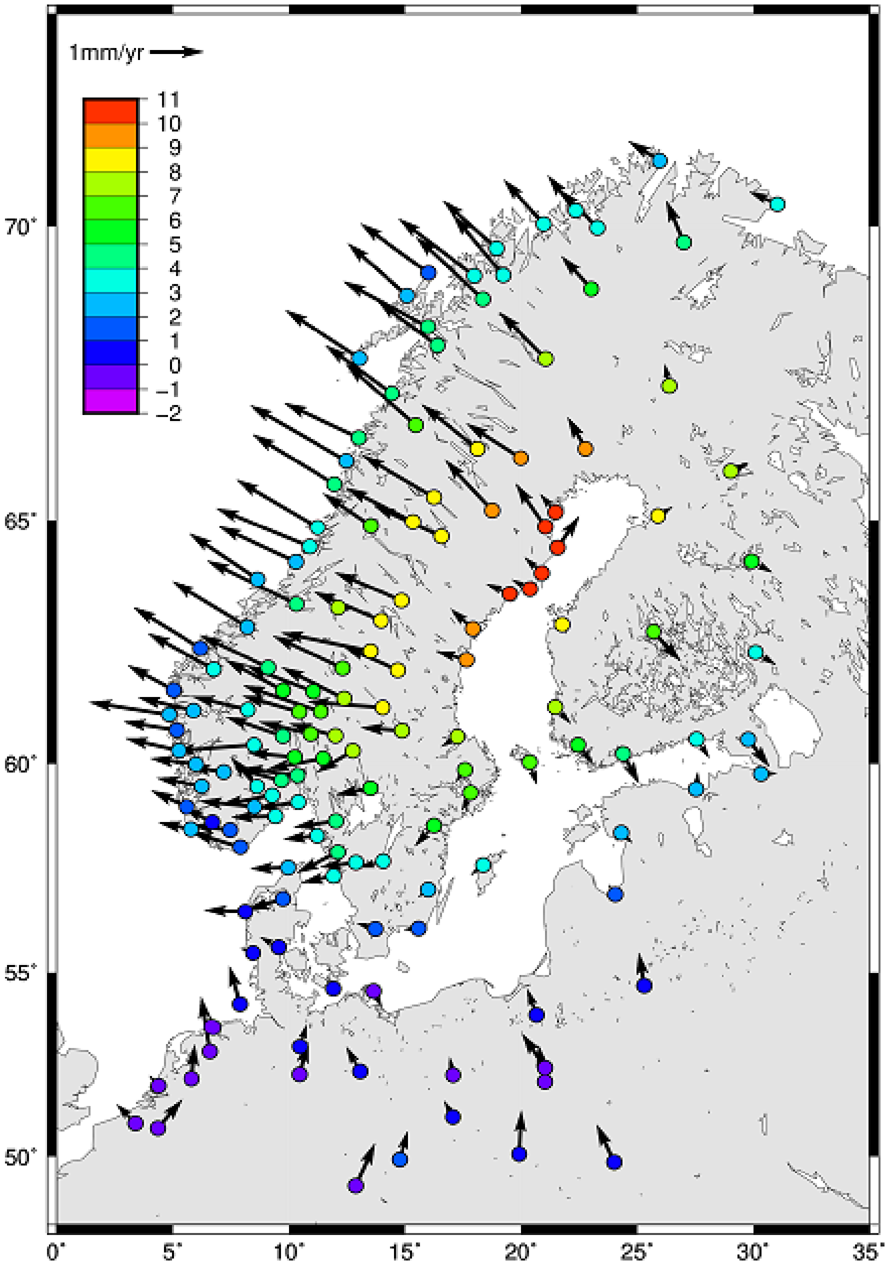

Figure 22: Deformations and velocities within a plate. The arrow shows movement in plane while point colours show land uplift [6]

Most geodetic tools and theory exist, but there are other practicalities to overcome. For example GIS and other software are not able to handle dynamic coordinates Meanwhile, PROJ already has the framework to handle dynamic reference frames. There are also legal issues within cadastre, and users need training and willingness to change their way of working [5].

Dynamic reference frames with continuously updated velocity and deformation model might be the solution in the future, but it is impossible to tell when this might happen due to all the practical challenges to overcome.

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5 Introduction to map-matching and overview of past and current research

Carl Johan Södersten

5.1 Introduction

Map-matching (MM) is the process of matching recorded geographic coordinates to a logical (and digital) model of the real world, often using some sort of geographical information system (GIS). The task of MM algorithms involves reconciling inaccurate locational data with an inaccurate map / network data, often in applications such as tracing the itinerary of a moving vehicle. This can, in essence, be done in three different ways [1]. The first method is to use some sort of dead reckoning based on vehicle speed, direction, etc. The second method entails using a ground-based beacon that broadcasts its location to nearby users. The third method, by far the most common, is to use radio or satellite positioning systems that transmits information that the vehicle can use to determine its location. In practice, this entails using recorded, serial location points (e.g. obtained using GNSS) and compare them to edges of an existing street map, usually in a sorted list so that the direction of travel of the user can be identified.

MM gained attention in the end of the 1980s / early 1990s as GNSS technology was being considered as potential use in road vehicles. In a 1990 paper outlying a method for determining vehicle position via map-matched dead reckoning, Collier argues that "In-vehicles Route Guidance Systems have reached a point of practical usefulness within reasonable cost criteria" [2]. Subsequently, various MM methods and algorithms were developed in the 1990s ([2-10]), and the MM problem was formally defined in 1996 by Bernstein and Kornhauser [1]. In the last two decades, the arrival of smartphones, mobile internet, detailed digital maps and cheaper GNSS receivers has propelled the development further, and MM algorithms are now both ubiquitous and plenty. Therefore, this document does not aim to cover all state-of-the-art MM algorithms but rather to introduce the concept of MM along with its fundamental principles and challenges, and then to briefly cover the different types and classes of algorithm found in the literature as well as summarise their main application areas. More comprehensive reviews can be found in e.g. [11-15].

5.2 Classification of MM algorithms

MM algorithms can be differentiated and classified according to different criteria. This section describes the classification systems often encountered in the literature.

5.2.1 Online / offline MM algorithms

Map matching algorithms can be divided into online (real-time) and offline algorithms, which differ mainly in two aspects. Firstly, online algorithms estimate the current road segment immediately after a data point is recorded, whereas offline algorithms perform the procedure a posteriori and can therefore also integrate location points occurring after a given point, as they batch process the entire input trajectory before generating the solution. Secondly, online algorithms are inherently required to generate the solution within a relatively short time frame (since their function is to produce an output in "real-time"), while offline algorithms are typically less constrained with regards to time performance. This entails that offline algorithms are generally more accurate than real-time algorithms, and as they can tolerate slower performance in favour of accuracy.

In terms of applications, online algorithms are typically used to guide a user through a road network, such as in route planning apps, where the user's recent GNSS history is used to locate his/her location on an existing map to e.g. give suggestions for the future optimal itinerary to reach an intended destination. Offline algorithms are often used for more complex and analytical tasks, such as generating detailed inputs for traffic analysis models, assessing road network expansion needs, etc.

5.2.2 Classification based on levels of information

MM algorithms can be divided into methods that use some known information about the expected route of the user and methods that have no a priori knowledge. Greenfeld [16] distinguishes between three classes of complexity depending on the target circumstances.

The first, most straightforward algorithm entails a user travelling on a fixed network, for instance a bus travelling along a predefined route. As the bus is expected to travel only on a set of know street segments, the MM procedure can be broken down to locating the bus on one of the known street segments, which considerably narrows the search domain for a street segment as match candidate.

A second level of MM algorithms is used in e.g. mobile route planning applications, where the user has entered the intended destination and the application has suggested an optimal itinerary (based on certain conditions, such as whether or not to travel on toll roads, use ferries, etc). In such a case, the user is expected to follow a predefined route which enables the algorithm to primarily focus the MM procedure on the relevant street segments. If the user deviates from the suggested route, the route planner typically computes a new optimal itinerary and changes the MM search accordingly. A drawback of such algorithms is that the algorithm may be biased towards the expected route, entailing that if the user chooses a slight deviation from the expected route (e.g. a parallel road) the algorithm will assume that the expected route is being taken.

Thirdly, the most general MM algorithm does not assume any prior knowledge or any other information regarding the expected location of the user, and uses only the coordinates and the street network to perform the MM procedure.

5.2.3 Other classifications

5.2.3.1 Low / high sampling methods

Low sampling methods are used when position data are sampled less frequently, typically for time intervals longer than 30 seconds [14]. High sampling methods are required for navigation assistants, while low-sampling methods suffice for tracking and mapping applications. While most of the research on MM algorithms focus on high sampling methods, there are methods specifically designed for low-sampling-rate applications [17-24].

5.2.3.2 Classification based on applications

Alternatively, MM algorithms can be classified depending on the intended applications. Kubicka et al. [14] distinguish between three types of applications. MM for navigation, MM for tracking, and MM for mapping. The former application is perhaps the most complex but also the most common, as it includes navigation assistants used in e.g. portable devices and car navigation systems. The latter two usually make use of low sampling and offline algorithms.

5.2.3.3 Indoors / outdoors methods

These differ mainly in the technologies used; outdoor methods typically make use of satellite navigation, while indoors methods rely on other technologies, such as inertial navigation, radio beacons, etc. [25]

5.2.3.4 Classification based on transport mode

MM algorithms can be classified depending on transport mode / user, e.g. pedestrian, vehicle or multimodal. The main difference between these is that pedestrian MM can be both indoors and outdoors while vehicle

MM is assumed to be only outdoors [26]. Multimodal MM entails that the user combines different transport modes (e.g. bicycle and bus) [27].

5.3 Examples of MM algorithms

5.3.1 A formal description of the MM problem

This section describes the principle of MM using the same notation as Bernstein and Kornhauser [1], which have also been used in other papers (e.g. [16]). The problem at hand is to identify the road taken by a vehicle moving along a finite set of streets, $\bar{N}$. The vehicle location is provided with GNSS at a finite number of points in time, denoted by $(0,1,2,\ldots,t)$. We denote the vehicle location at time t with $\bar{P}^t$ and the estimate of the position with P^t. Hence, the goal is to find the street in $\bar{N}$ that contains $\bar{P}^t$. Furthermore, we also wish to determine the location of the vehicle with respect to the endpoints on the street.

The set of streets $\bar{N}$ is represented through a network representation N, constructed using various mapping techniques, as illustrated in Figure 23. The street network N consists of a set of curves (called *arcs*) in $\mathbb{R}^2$, all of which assumed to be piecewise linear. Hence, each arc $A \in N$ can be characterised by a finite set of points $(A_0, A_1, \ldots, A_n)$. The endpoints A_0 and A_n are referred to as the *nodes* while the points $A_1, \ldots, A_{n-1}$ are called *vertices* or *shape points*. A node is therefore a point where an arc begins or terminates while the vertices show the geometry of the arc. A node can be a transition between arcs (a street intersection) or a terminal (e.g. a dead-end street). The MM problem then entails matching the estimated location (P^t) with an arc (A) in the network representation of the map (N) and then to determine the street ($\bar{A}$) on the real map ($\bar{N}$) that corresponds to the vehicle's actual location ($\bar{P}^t$). A second goal is to determine the position on A that best corresponds to $\bar{P}^t$. It is worth mentioning that this procedure assumes a one-to-one correspondence between the actual street network $\bar{N}$ and the network representation of the street network N.

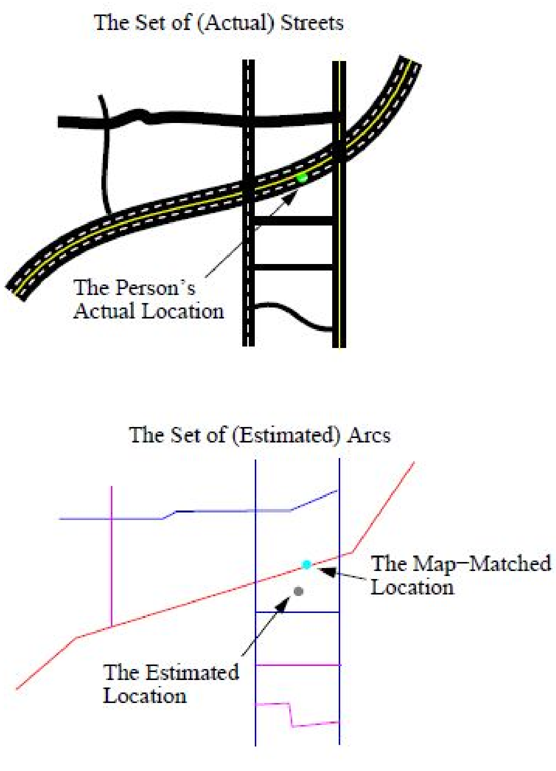

Figure 23: Illustration of the MM problem [1]

5.3.2 Geometric MM algorithms

Geometrically, finding the nearest segment to a point poses no problem, and the MM problem may at first sight appear intuitive. However, because the point corresponds to the location of a moving object, the MM problem comes with an additional set of constraints relating both to limitations in the real world (e.g. it is assumed that a road vehicle can only travel between streets that are connected with a node, i.e. not "jump" between parallel streets) and to expected vehicle behaviour (e.g. the vehicle is assumed to follow a logical itinerary to some degree, i.e. not bounce back-and-forth between neighbouring streets). The complexities of the MM problem are best illustrated with a few examples.

5.3.2.1 Geometric point-to-point matching

One intuitive way to solve the problem would be to match P^t to the nearest node or vertex by calculating the shortest Euclidean distance. This method is relatively simple but can easily result in undesirable results, as illustrated in Figure 24. The user's GNSS position is shown by P^i and the network snapshot contains the arcs A, B and C. While it appears that the user in this case is travelling on the arc B and then turns left to continue on arc C, the algorithm results in the route $B^0 - A^1 - A^2 - B^1$, which is clearly not realistic for a road vehicle.

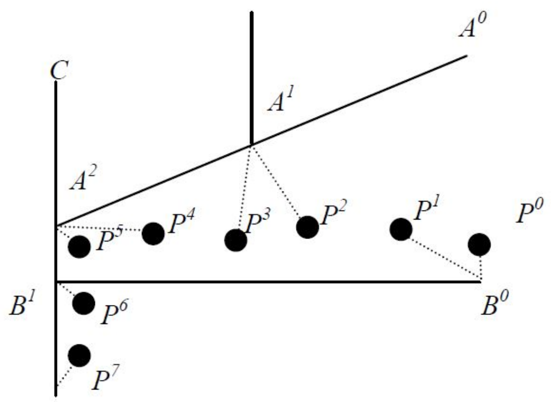

Figure 24: Matching to the nearest shape point (point-to-point matching) [16]

5.3.2.2 Geometric point-to-curve matching

Another intuitive method would be to find the nearest arc to the user's position rather than the nearest node, which can be done by finding the shortest perpendicular distance of the estimated position P^t to the set of arcs, as illustrated in Figure 25.

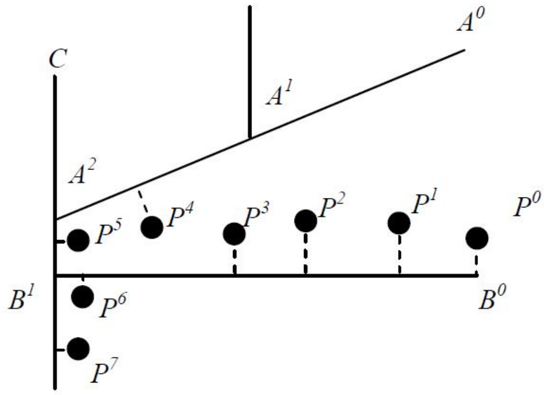

Figure 25: Matching to the nearest arc by calculating the shortest perpendicular distance (point-to-curve matching) [16]

Again, this method yields undesirable results, as both points P^4 and P^6 are mapped to the "wrong" arcs.

5.3.2.3 Geometric curve-to-curve matching

A logical improvement to the point-to-curve matching method would be to match a curve to a curve; that is, to consider m positions simultaneously by matching to the arc that is closest to the linear curve P defined by the points $P^0, P^1, \ldots, P^m$. However, measuring the distance between two curves is not as straight-forward as with single points. For instance, if the minimum distance is defined as the minimum distance between any of the vertices in the curves, e.g.

$$\left|\left|A - B\right|\right|_{min} = \min_{a \in A, b \in B} \left|\left|a - b\right|\right|$$

the results may not be satisfactory, as illustrated in Figure 26, where P is matched to arc A although the route taken intuitively correlates better with arc B.

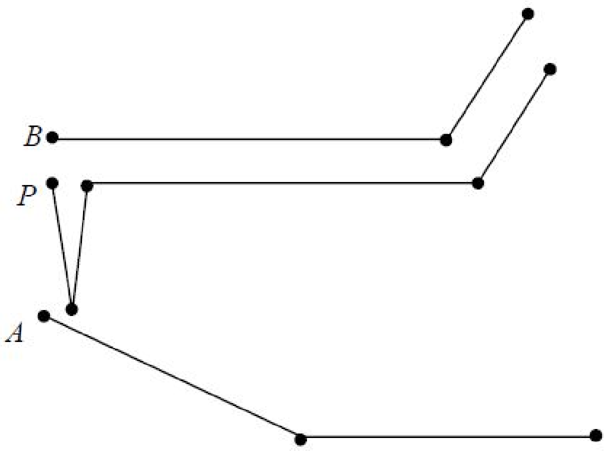

Figure 26: Matching curves by taking the minimum distance of individual vertices (curve-to-curve matching) [1]

An alternative to the method above would be to take some sort of average distance between the curve, for instance by parametrising the curves as such:

$$a: [0,1] \rightarrow A$$

Then the distance could be computed as

$$||A - B||_2 = \int_o^1 ||a(t) - b(t)||dt$$

However, this may not be optimal when the lengths of the curves differ a lot, and a more sensible way would be to measure the distance between P and equal length portions of the arcs under consideration, as illustrated in Figure 27.

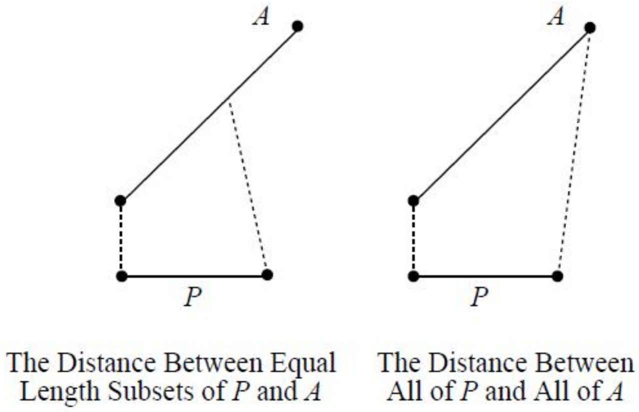

Figure 27: Measuring the distance between curves of different lengths [1]

While this solves some problems encountered in the previous approaches, it can still yield erroneous results, as illustrated in Figure 28, where the curves can be parametrised as

$$\begin{cases} a(\alpha) = \begin{pmatrix} 6t \\ 6 \end{pmatrix}, \alpha \in [0,1] \\ b(\alpha) = \begin{pmatrix} 3 \\ 3t \end{pmatrix}, \alpha \in [0,1] \\ p(\alpha) = \begin{pmatrix} 6 \\ 3 \end{pmatrix}, \alpha \in [0,1] \end{cases}$$

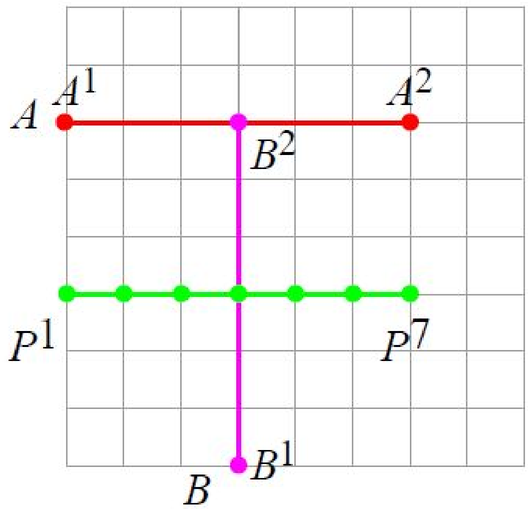

Figure 28: Curve-to-curve matching [1]

The distance between P and A is then calculated as

$$\int_0^1 ||P(\alpha) - A(\alpha)||d\alpha = \int_0^1 \sqrt{\big(p_1(\alpha) - a_1(\alpha)\big)^2 + \big(p_2(\alpha) - a_2(\alpha)\big)^2}\, d\alpha$$

This yields a distance of $\int_0^1 ||P(\alpha) - A(\alpha)||d\alpha = 3$ and $\int_0^1 ||P(\alpha) - B(\alpha)||d\alpha = \sqrt{4.5}$, hence matching P to the perpendicular curve B rather than the parallel curve A.

The algorithms described in section 5.3.2.1 to 5.3.2.3 are the simplest versions of the geometric approaches, and it is obvious that more advanced algorithms can be constructed using combinations of these. For instance, Phuyal et al. [28] proposed a compound curve-to-curve algorithm consisting of an initial identification of nodes using point-to-point matching followed by a curve-to-curve algorithm akin to those described in 5.3.2.3. Other methods have been suggested for calculating the distance, including variants of the Fréchet distance and Hausdorff distance, but the complexities involved with matching the movement of a vehicle on a set of streets limit the usefulness of purely geometric algorithms.

5.3.3 Topologically based MM algorithms

The examples in section 5.3.2 show that MM using only geometric information can easily lead to undesirable (inaccurate) results. Therefore, state-of-the-art MM algorithms leverage the road network topology to produce better results. MM algorithms that utilise the geometry of the road and the connectivity of the road segments are known as topological MM algorithms.

Algorithms that consider the connectivity of the road network typically model the constraints with speed, travel time, shortest path distance, vehicle heading, etc., to filter out outliers and achieve more accurate MM results. Early examples such as Bernstein and Kornhauser's improved curve-to-curve matching [1], Greenfeld's weighted topological algorithm [16] and Quddus et al.'s enhanced topological algorithm [29] make use of the closeness and shape of the road segments as well as the connectivity of the road network to derive navigation data. Since then, a "tremendous number of MM algorithms" have been proposed [11], and it is beyond the scope of this document to list them all, let alone to describe their principles. To illustrate how the topology of the road network can be used to enhance the performance of a MM algorithm, a few uses cases are described in this section.

5.3.3.1 Handling intersections

Greenfeld's algorithm combines an initial point-to-curve algorithm with a pre-selected distance tolerance entailing that if the distance between the point and the matched curve exceeds a certain value, the algorithm assumes that the coordinates are implausible. In that case, the data point is ignored, and the procedure is performed anew with the next data point. Once a plausible initial location has been established on the network representation and a segment A^i has been selected, a subsequent algorithm is applied, consisting in the following steps:

1. Obtain the next data point P^t
2. Construct the segment between P^{t-1} and P^t
3. Calculate the distance and orientation of the segment to the currently matched street segment A^i using an evaluation scheme
4. If the new point P^t does not map onto the current segment A^i following the evaluation scheme in step 3, find another segment A^{i+1} that is either connected to or nearby A^i using the same evaluation scheme

The evaluation scheme performed in step 3 (and potentially 4) can be designed in various ways. If the segment between two points (e.g. points P^1 and P^2 in Figure 29) intersects the current matched segment

(A^1) at a low entry angle (e.g. intersection a), it is an indication that the match is correct. On the other hand, if the interception angle is close to perpendicular (such as interception c), it is less likely that the segment matches the arc (for instance, the path $P^1 - P^4$ in Figure 29 clearly follows the arc A^1 at the intersection between A^1 and A^2 rather than turn left onto A^2). When the segment does not intercept with the street segment (i.e. if the intersection occurs at the extension of the street segment, such as intersection d), additional evaluation steps are needed.

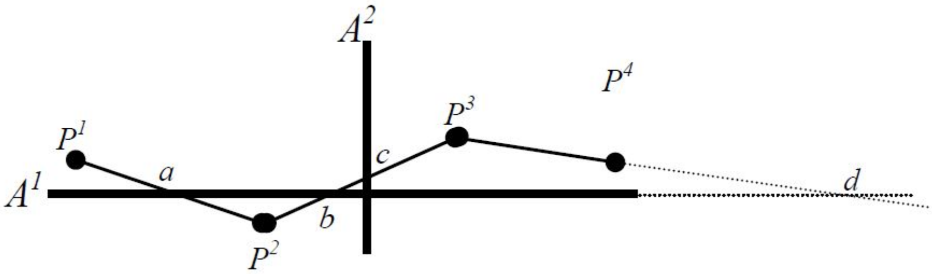

Figure 29: Intersection of GNSS lines and street segments

Greenfeld suggests a similarity evaluation scheme where the different criteria are weighted according to a weighting formula (weight-based algorithm):

$$W = W_A + W_D + W_I$$

Where W is the total score, W_A is the weight for the similarity in angle (orientation), W_D is the similarity in distance and W_I is the weight for intersection (if applicable). While Greenfeld also proposes alternatives for how these weights are calculated, they are not unique, and the exact formulations are less relevant in this general algorithm presentation.

Following Greenfeld's weight-based MM algorithm, Ochieng et al. [30] formulated a similar algorithm, where the steps involve identifying:

1. An ascending or descending trend in heading for about 2-5 s
2. An absolute difference between the headings of current and last GNSS position fixes of more than 30°
3. An absolute difference between the headings of current and second to the last GNSS position fixes of more than 35°

While Ochieng et al.'s algorithm resulted in good estimations, it neglected that GNSS heading information during low-speed turnings is often erroneous. Furthermore, the difference in headings of consecutive GNSS points at low speed are often small due to high polling frequency. Velaga et al. [31] added additional criteria to detect an intersection, including that the previously matched location need to be less than 20 m from the intersection and that the vehicle's heading must be deviated from the segment by 5°, but the efficacy of such additional thresholds varies with the quality and scale of the digital map, positioning quality and location update rate.

5.3.3.2 Filtering outliers

As the accuracy of GNSS signals may decline due to e.g. the effect of multipath, physical obstructions, challenging environments such as urban canyons, etc., it is common to observe outliers in the obtained itinerary. This is illustrated in Figure 30, where point P^4 deviates substantially from the assumed itinerary.

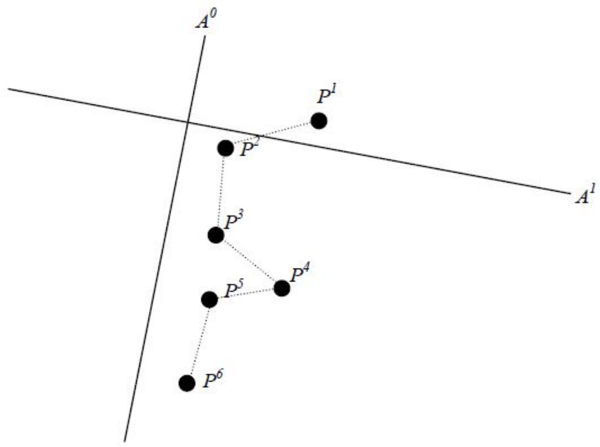

Figure 30: Outlier caused by erroneous GNSS signal

Therefore, MM algorithms need to include safeguards that account for potential errors in GNSS signals. This can be done in many ways; for instance, one avenue could be that a short time delay is applied to the MM procedure to allow for the generation of additional points. If a significant deviation from the assumed path is taken (e.g. $P^4 - P^5$), the algorithms awaits point P^6 (and perhaps P^7) before finalising the MM results. In the example shown in Figure 30, this would allow the algorithm to classify point P^4 as an outlier since the segments $P^3 - P^4$ and $P^4 - P^5$ do not concur with the segments $P^2 - P^3$, $P^5 - P^6$ and the matched arc A^0.

5.3.3.3 Skipping arcs

Another common problem with topological MM algorithms is that they often assume continuity between travelled arcs. That is, a vehicle can only travel from arc A^i to arc A^{i+1} if the two arcs are connected with a node. However, when arcs (streets) are short, when the vehicle travels fast or when there is a temporary loss of GNSS signal, a situation can arise where none of the points obtained from the GNSS signal is mapped onto an arc even though the vehicle is in fact travelling on the corresponding street, as illustrated in Figure 31.

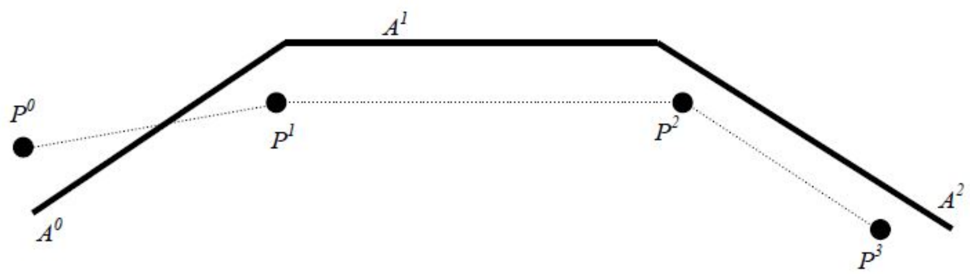

Figure 31: Skipping of an arc

Greenfeld suggests two ways to solve the arc-skipping problem. The first option would be to reinitiate the algorithm when the situation arises, so that P^2 becomes P^0. An obvious drawback of this method is that all the already known information about the location of the user is lost in the process. The other option entails refining the algorithm, for instance by allowing not only arcs that are connected to the endpoints of the current arc to be matched, but also arcs connected to the endpoints of the arcs connected to the endpoints of the current arc (i.e. finding all possible arcs A^{i+1} *and* A^{i+2}). This increases the topological complexity of the algorithm but improves its performance and accuracy.

5.3.3.4 *Integrity monitoring*

Correct MM is often difficult when there is large incongruence between the map and the observed trajectory. In such cases, it is sensible to put additional emphasis on assessing the reliability of the results by estimating a confidence level, which is referred to as integrity monitoring, introduced by Quddus [32] and further developed by [31, 33-36]. In essence, integrity monitoring yields integrity indicators based on the trajectory, map, and MM outputs. These indicators are then compared to pre-selected alarm levels. This procedure is not straight-forward and requires thorough tuning and sensitivity analysis, as too many false alarms and / or too many missed detections decrease the performance of the MM algorithm.

Karimi et al. [36] differentiate between three areas of uncertainty: uncertainty in identified segment, uncertainty in projected location on that segment and total uncertainty in identified segment and projected location. Many approaches combine various error sources associated with positioning data and digital road maps and discuss them jointly in terms of confidence levels [15]. Confidence levels need to take into account the density and complexity of the roads in the vicinity of the GNSS point. For instance, the popular approach introduced by Karimi et al., which entails creating an error ellipse around the point, does not perform well in dense roads even when the error ellipse is small. Conversely, a large error ellipse may still yield correct matching in sparse roads [15].

5.3.4 Advanced MM algorithms

The interest in the field of topological MM algorithms has followed the exponential increase in MM use (particularly driven by navigation assistants). This has resulted in classes of more complex algorithms as well as more advanced systems involving complementary sensors aside from GNSS data, such as inertial measurement units [37, 38], accelerometer [39], cameras [26], LiDAR, etc. As described in 5.3.2.3, curve-to-curve matching is particularly challenging as the range of cases complicates the development of a universal algorithm. A lot of research had been devoted to such MM, using various techniques for calculating the distance between curves, such as the Fréchet distance [40-44] and Hausdorff distance [45].

One class of algorithms often classified as a MM category on its own are probabilistic algorithms. These entail the definition of an elliptical or rectangular confidence region around the position estimate. This was pioneered by Honey et al. [46] and further developed by e.g. [27, 30, 47, 48]. Another milestone in the development of MM algorithms was the introduction of hidden Markov models (HMM). The first published algorithm using a HMM appeared in a paper by Hummel [49] in 2006 and has led to at least ten other methods applying an HMM [11, 14], including [22, 49-54]. While HMM are usually used for offline MM, they can also be applied to online models using a sliding window technique [52]. Other types of advanced MM algorithms include weight-based algorithms [18, 51, 52, 55-57], algorithms based on particle filter and Bayesian filtering [58-61], multiple hypothesis technique [34, 62-66], Dempster-Shafer's mathematical theory of evidence (belief theory) [67-70], inertial sensors [30, 37], dead reckoning [71-73], conditional random fields [74, 75], machine learning [52, 74, 76, 77], fuzzy logic [5, 53, 78-82], multi-layer road index system [83], Viterbi algorithm [53, 84], nearest-neighbour [85-87], SLAM [88, 89], etc.

While none of the existing algorithms yields perfect results, a review of MM algorithms by Hashemi [15] showed that advanced algorithms typically result in better MM accuracy, as illustrated in Figure 32.

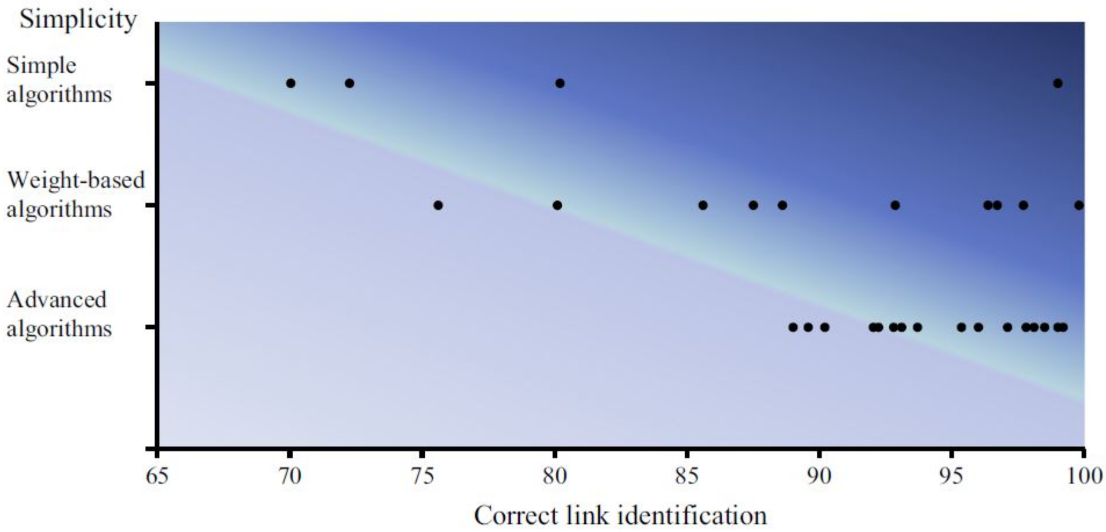

Figure 32: Accuracy of MM algorithms versus level of complexity [15]

Hashemi also concluded that many algorithms do not put enough consideration to the topology of the road network and that there typically is an unbalanced trade-off between performance and accuracy. In particular, the most complex algorithms, while providing high accuracy, suffer from low performance, a feature that limits their uses in applications such as real-time navigation assistants.

5.3.5 HD maps

By using a range of sensors and applying one or several of the algorithms described in the previous sections, a new class of maps can be produced, called HD maps. HD maps differ from traditional maps in the sense that they contain more detailed and complete information. They are typically shown at the centimetre scale and often feature elements such as lane placement, road boundaries, curve severities, road surface gradient, locations of signs, etc. They are compiled using a variety of instruments and sensors, including lasers, radars, LiDARs, cameras and GNSS receivers, and can be updated through crowdsourced inputs from commercial fleet partners. HD maps are specifically designed to be read by machines, and are typically constructed in layers, as illustrated in Figure 33.

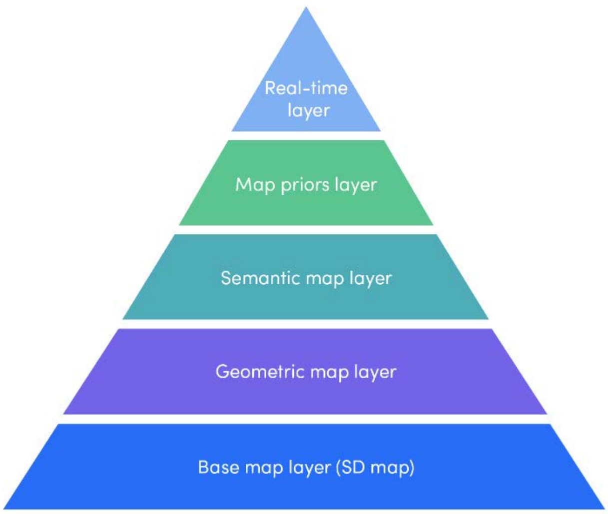

Figure 33: Layer structure of a HD map (from [90])

The geometric map layer contains 3D information about the world, compiled using LiDAR, cameras, GNSS and IMU sensors, processed through one or more of the algorithms mentioned in the previous chapters. The semantic layer builds on the geometric map layer by adding semantic objects, such as lane boundaries, intersections, crosswalks, parking spots, traffic signs and traffic lights, etc. The map priors layer contains derived information about dynamic elements as well as human driving behaviour. This could be, for example, the order in which traffic lights cycle through their various states. Another example is the parking prior, which are represented as polygonal regions on the lanes with metadata that capture the probability of encountering a parked vehicle at the location on the lane. When an AV encounters a stationary vehicle in a map region with a high parking prior, it will more aggressively explore plans that route the AV around the vehicle and demote plans that queue up the AV behind the (assumed) parked vehicle. Also, the parking prior could allow perception systems to be more cautious to car door openings and emerging pedestrians. Finally, the real-time layer is the layer designed to be updated while the map is in use by the AV, containing information such as observed speeds, congestion, newly discovered construction zones, etc. The real-time layer is designed to support gathering and sharing of real-time global information between a whole fleet of AVs.

While some companies specialise in compiling HD maps (Tomtom, HERE, Carmera, DeepMap), HD maps are also produced by companies providing advanced driver assist systems (ADAS) (such as Mobileye) and actors in the self-driving cars industry (Waymo).

5.4 Current practices

This section summarises the practices among the main actors in the mapping and self-localisation industry.

5.4.1 Tomtom

Tomtom provides HD maps and automated driving (AD) map technology, and report that 3 million cars use their HD maps for AD (including vehicles by Fiat, Renault, Lexus, Mazda amongst others). Their AutoStream delivery service communicates with onboard client software to provide the most recent and relevant HD map data [91]. The HD maps developed by Tomtom contain information about lane models, traffic signs, road furniture and lane geometry, with accuracy down to "a few centimetres" [92]. They have been compiled using a set of localisation layers in the Tomtom HD map called RoadDNA, that consists of multiple sets of data tailored to the different types of sensor used by today's automated vehicles (radars, cameras, LiDARs).

5.4.2 HERE

HERE is Nokia's former mapping business now owned by Audi, Mercedes and BMW. HERE's answer to Tomtom's HD map is the HERE HD Live Map, a cloud-based service comprising highly detailed mapping layers that are continuously updated to support connected ADAS and highly automated driving solutions. The layers are structured into a Road Model (containing road topology, road centreline geometry and road-level attributes), a HD Lane Model (containing topology data and lane-level attributes) and a HD Localisation Model (containing other features supporting localisation strategies) [93].

5.4.3 Mobileye

Mobileye [94] (owned by Intel since 2017) is reportedly the largest supplier of ADAS for new cars [95], providing ADAS for e.g. Volkswagen, BMW and Nissan. Mobileye's Road Experience Management is an end-to-end mapping and localisation engine for full autonomy that constructs HD maps using a variety of sensors and consolidated and updated using information provided from its active users who are driving 8 million kilometres each day in cities all over the world. The solution is comprised of three layers: harvesting agents (any vehicle equipped with camera) that transmit data about the driving path's geometry and stationary landmarks around it; map aggregating server, a cloud server reconciling the continuous stream of data into a map (the "Roadbook"); map-consuming agents (autonomous vehicles), that automatically localise the vehicles in the Roadbook by real-time detection of all landmarks stored in it.

5.4.4 Other actors

Waymo [96, 97], Google's self-driving car division, also uses HD maps constructed by manually driving around the world continuously updated with a perception system that detects e.g. temporary road closures and construction zones. Other notable actors producing HD maps include Carmera, DeepMap, Civil Maps and lvl5.

5.4.5 LiDAR versus cameras

A recurrent topic in the mapping industry is the use of LiDAR versus cameras in the construction of maps. While most actors in the self-driving industry are relying on LiDARs to construct HD maps in the pursuit of developing self-driving cars [92], Tesla stands out as a an exception advocating against the use of LiDAR and HD maps [98-100]. Instead, Tesla's Autopilot relies primarily on visual perception using multiple cameras combined with radar and ultrasonic units around the vehicle [101]. The approach is that onboard cameras in vehicles collect information about the road onto "micro maps" that are then shared with the Tesla fleet [102].

While LiDARs can provide high accuracy and precision (Waymo's LiDAR system is reportedly able to tell which direction pedestrians are facing and predict their movements [103]), there are some disadvantages associated with them. First, LiDARs remain expensive and relatively bulky. Second, it is thought that a full-scale implementation of LiDARs could lead to problems related to interference and jamming (when all vehicles generate laser pulses). Third, LiDAR systems still struggle through fog, snow and rain. Cameras, although cheaper and more compact than LiDARs, only provide raw image data back to the system, and therefore rely on powerful machine learning algorithms to identify objects and determine the vehicle position. Hence, some actors, such as Mobileye and TuSimple, rely primarily on visual perception but use inputs from a LiDAR system as a backup (redundant) system [103].

5.5 Conclusion

As described in this report, the field of MM is extensive, well-researched and still very much a popular and relevant field of research. A range of MM algorithms have been developed, and ultimately which method to choose boils down to the intended application, as no universal method exists that fits all possible applications [14]. When choosing MM algorithm, one needs to consider several aspects, including the intended application, MM performance, required computational effort, sensitivity to tuning, whether pre-processing is needed, etc. In particular, accuracy and performance are two equally important factors that cannot be immoderately traded with one another.

Applications such as navigation assistants require online, high sampling rate algorithms with relatively low computational efforts. For such applications, Kubacki suggests the multiple-sensor system by Toledo-Moreo et al. [35], fuzzy logic methods such as [78], methods using belief theory [69, 70] or multiple hypothesis techniques [63, 66], while the HMM-derived methods are less useful as they often require large computational efforts. Tracking applications are usually less constrained with regards to time performance and computational power needed which makes them suitable for HMM-based algorithms. Other methods suggested by Kubacki include path inference filtering [74], the fast Fréchet distance algorithm by Driemel et al. [41], Wei et al.'s geometric method [43], low sampling rate methods [17, 18, 20, 22], and others [50, 65]. Mapping applications are similar to tracking applications in the sense that they are performed offline and with less constraints on time performance, but the trajectories need to be more densely sampled. Matching accuracy is crucial while computational effort is not, which makes geometric methods suitable for this endeavour [40, 104], as well as Pink and Hummel's Kalman filter / HMM algorithm [105].

Nevertheless, increasing the complexity of an algorithm is not necessarily beneficial. Hashemi [15] argues that some of the most advanced algorithms are indeed so complex and computationally intensive that they improve neither accuracy nor performance. Conversely, simpler weight-based algorithms balance simplicity and accuracy well, and while they do not always produce optimal results in their more general forms, they can be fine-tuned by taking in account the circumstances of each GNSS point to yield high accuracy.

The range and variety of existing MM algorithms is directly linked to range in the classification types listed in section 5.2, but also to the challenges that MM algorithms face. In their 2018 review of MM algorithms, Kubicka et al. identify four main challenges. The first is the original challenge that led to the field of MM, namely reconciling positioning data with map data. This entails both handling the errors in positioning data (due to e.g. incongruent GNSS data) and errors in map data (including both random, systematic, and modelling errors). The second challenge relates to integrity monitoring, as unbounded errors entail that there can never be any guarantee of correct matching and that undetectable missed integrity alarms are possible. A third challenge concerns the evaluation of MM performance, as there is currently a lack of consensus on how MM algorithms should be evaluated. Fourthly, trajectory pre-processing is listed as a procedure where literature remains scarce despite that the techniques are commonly used in mapping and tracking applications. Hashemi concludes on a similar note, and adds that further research is needed on the constraints set by the algorithms, including the arc-skipping problem described in 5.3.3.3 as well as handling the case where a vehicle turns (advertently or inadvertently) onto an illegal road segment (as most algorithms assume that vehicles follow traffic rules).

5.6 References

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6 Challenges of GNSS in the North

Samuel Schiess, Arnlaug Høgås Skjæveland and Morten Taraldsten Brunes

6.1 Introduction

Positioning techniques and GNSS are highly dependent on regional conditions. High latitudes challenge the safe application of satellite navigation and performances in these regions have to be assessed carefully. In addition, local variations like topography, weather or infrastructure can require a separate analysis. Some of the most important factors and challenges for GNSS in the north are listed in this report.

6.1.1 Abbreviations and Definitions

DOP	Dilution of Precisions	Factor for geometry
HPE	Horizontal Position Error	KPI for position
VPE	Vertical Position Error	KPI for position
RTK	Real Time Kinematics	Correction method
PPP	Precise Point Positioning	Correction method
SBAS	Satellite Based Augmentation System	Distribution method for correction signals
GBAS	Ground Based Augmentation System	Distribution method for correction signals
EGNOS	European Geostationary Navigation Overlay Service	European GPS augmentation system
Galileo		European global satellite navigation system
GLONASS	Globalnaja Navigatsionnaja Sputnikovaja Sistema	Russian global satellite navigation system
GNSS	Global Navigation Satellite System	Common name for all navigation systems
GPS	Global Positioning System	American global satellite navigation system
NMA	Norwegian Mapping Authority	National mapping agency Norway
ESA	European Space Agency	

6.2 Basics of GNSS

Some basics of global navigation satellite systems (GNSS) will be recapulated here and some useful resources given for more background information on the topic. Note that this chapter does not aim to give a complete summary of the GNSS standards, but a quick-start.

6.2.1 General Function

In its basic application, a navigation satellite sends a message containing the current timestamp, which registered by the receiver is compared to the timestamp of reception. Thanks to the known velocity of the signal, the resulting distance can be calculated. This requires knowledge of the satellites position when sending the signal and a precise clock on both the satellite and as far as possible on the receiver. For an absolute position of the receiver, at least four satellites are needed. This is three for the three unknown coordinates and a fourth for the clock error of the receiver. This is due to the fact that satellites have relatively precise atomic clocks installed, which the clock of the receiver cannot match in precision. Some smaller errors from the satellites' clocks persist. The position of the satellites is known, but contains an unprecision and thus another error source. In addition to these two error sources, ionospheric and tropospheric activities and biases in the signal are always present and have to be considered. These errors add up to a some meters accuracy in good conditions, when measuring with a low-cost receiver as for example installed in a mobile phone.

A first improvement is the measuring of phases, additionally to the codes (which contain the before mentioned information). The so-called carrier phase is the measure of the range between the satellite and the receiver given in cycles of the carrier frequency. Simply put, the last cycle will not be finished completely and its phase can be measured very precisely with professional receivers. The number of whole cycles (denoted N) on the other hand is not measureable, and has to be calculated through a short initialization phase. This method offers better results in itself and offers some enhancement opportunities, which are discussed in more detail in work package 2.2 Trends.

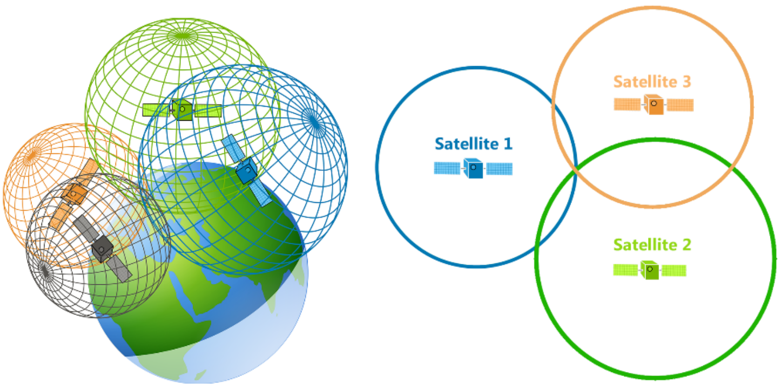


Figure 34: Illustration of principle satellite positioning. Showing the spheres of distances from each single satellite and the resulting intersection as actual position. From (GISGeography, 2021).

6.2.2 Correction Technologies

As mentioned, precise positioning technologies are looked at in more detail in work package 2.2 Trends.

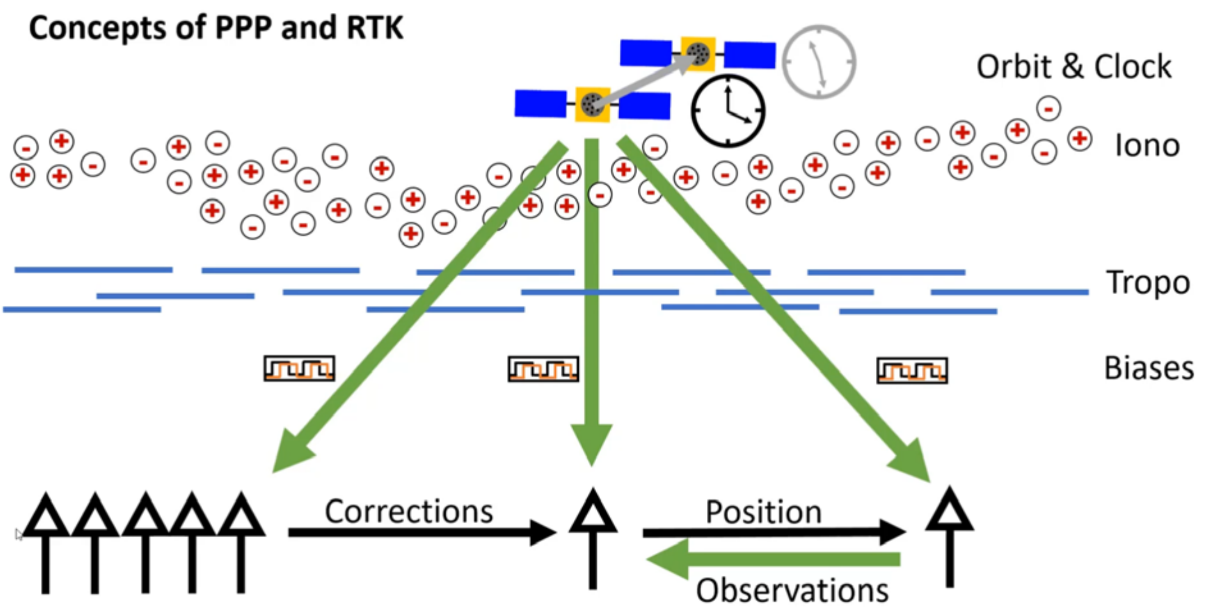


Figure 35 Visualization of the GNSS error sources and concepts of PPP and RTK (with single base station installed onsite). Taken from (Novatel, 2021).

Due to the error sources, as described in 2.1, GNSS measurements require correction for higher precision applications. Generally spoken, there exist two main possibilities for this.

Real time kinematics (RTK) uses additional information from high-end receivers installed on the ground, called base stations. This can either be a network of stations or one single base station installed close to the receiver. The receiver sends its information to the base station and receives the observations of the base station back. Together with its own observations, the errors can effectively be eliminated for precise positioning. The use of a local base station is cost and time intensive, while network base stations usually have a subscription price.

Precise Point Positioning (PPP) and related techniques do also need measurements on the ground, but a few global stations are enough for a functioning correction service. The concept here is based on adding precise positions of the satellites, errors of the satellite clocks and correction of signal biases to the receiver's observation. For this, an initialization time is needed, which has significantly been reduced through the last years. Still, the required time until first fix is the biggest handicap of PPP technologies. Precision of RTK solutions is on a centimeter level. The newest, local services of PPP can nearly match these precisions, being around 10 – 20 cm.

Table 19: Characteristics of RTK and PPP technologies summarized (after (Novatel, 2021))

	RTK	**PPP**
Principle	Cancellation through correlation	Correction parameters and modeling
Communication	Bi-directional	One way
Coverage	Local or regional	Wide range or global
Status	Established technique	Rather new

6.3 General

6.3.1 Space Weather

The ionosphere is the upper most layer of the atmosphere and has an altitude of approximately 60-1000 km. It consist of free electrons, positive ions and neutrals, this type of gas is also known as plasma. The number of electrons per m^3 defines the plasma density. Solar radiation and particle precipitation are the main sources of ionisation in the ionosphere, thus there are large daily and seasonal variations in the plasma density. (Baumjohann & Treumann, 1996) The density of the ionosphere effects the delay of a GNSS-signal. Knowledge of the density of the ionosphere is therefore useful to accurately determine the position. The ionosphere is a dispersive medium meaning the refractive index is frequency dependent. Using two frequencies the electron content can be calculated, but this requires a GNSS-receiver capable to receive multiple frequencies (Hofmann-Wellenhof , et al., 2007). Single-frequency receivers can use models like Nequick-G or Klobuchar to approximate the ionospheric delay.

Many space weather phenomena can create irregularities in the ionosphere. Irregularities can cause scintillation on the GNSS-signal, leading to cycle slips and loss of lock (Kintner, et al., 2007). Scintillations are most prevalent in polar and equatorial regions, and are an important hazard to GNSS-signals.

The solar wind is the main driving force for space weather. The earth's magnetic field is protecting us from the solar wind, but when the magnetic field in the solar wind is pointing southwards, magnetic reconnection between the solar wind's and the earth's magnetic field occurs, and a magnetic field line opens up. The open field line convects over the polar cap towards the night side and is temporary stored in the magnetotail. After some time, there is magnetic reconnection on the night side, and charged particles are accelerated along the magnetic field lines into the ionosphere. When colliding with the ionosphere particle precipitation creates aurora and thus the area with magnetic reconnection is called the aurora oval. During the day the aurora oval is located above Svalbard, and is one of the few habituated places with daytime aurora. Northern parts of Scandinavia is underneath the aurora oval during the night. Depending on the amount of reconnection the location of the aurora oval can expand further south.

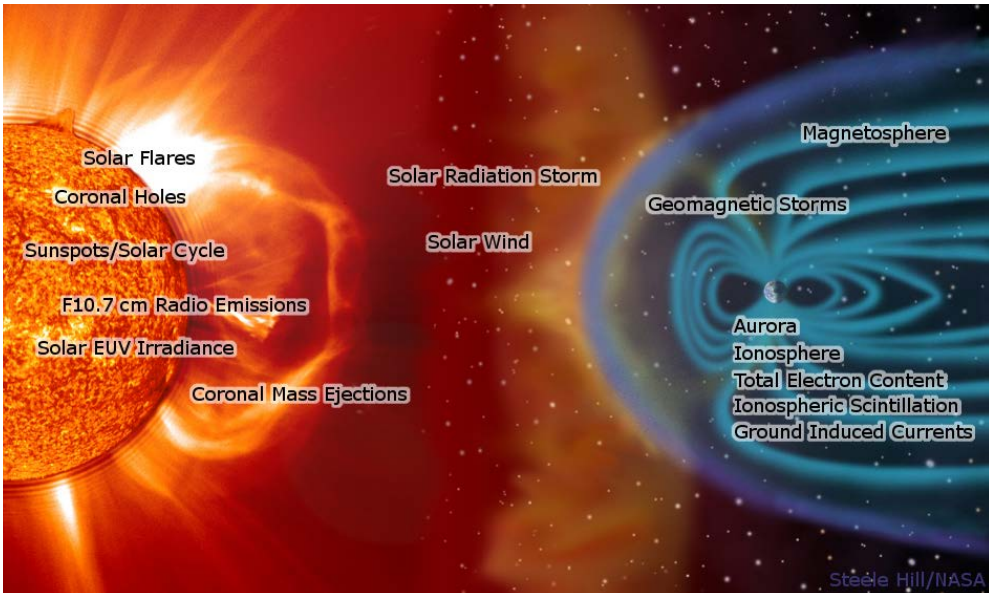


Figure 36: Model of the Earth's magnetic field and the solar wind. (SWPC, 2021)

Interaction between the solar wind and the earth's magnetic field induces two convection cells in the ionosphere from the day side towards the night side over the polar cap, and with return on the outside of the polar cap. Patches of high density plasma is transported from the day side, over the polar cap, to the night side. Both particle precipitation and polar cap patches are highly associated with scintillations, and are problems for GNSS in the North (Jin, et al., 2015). At times with high geomagnetic activity scintillations can occur south of the aurora oval, this is mainly a post-midnight phenomena (Spogli, et al., 2009).

Forecasting the space weather is nontrivial. Measurements from the solar wind can give an indication, but accurately determine when, where and how strong the effects on the GNSS-signals is difficult.

The impact of ionospheric disturbances is generally impacting the signals of the navigations satellites and thereby problematic. Single frequency measurements, as for example done in mobile phones, does only use the mentioned models implemented in the GNSS signals for an approximation of the errors. Some correction technologies do include better approaches – where for example the EGNOS system sends corrections for the current state of the ionosphere to the receivers. RTK, as mentioned in the next section, does eliminate error sources through correlation, which also eliminates the effects of ionospheric disturbances – the remaining errors are mostly because of local variations between the basestations and the receiver. Pure PPP services do most often not correct for the ionospheric effects.

6.3.2 Troposphere

When the GNSS-signal propagates the stratosphere and troposphere it will be slowed down, this is referred to as tropospheric delay. The tropospheric delay can be divided into a wet and a dry component and of the two the dry component is the largest one. Gases like nitrogen, oxygen, argon and more cause the dry component delay. The delay is dependent on temperature and atmospheric pressure, but these parameters are predictable and the delay can be modelled quite well. Water vapour and clouds cause the wet component delay, changes in this component are more unpredictable and harder to model than the dry component. (Sanz Subirana, et al., 2011)

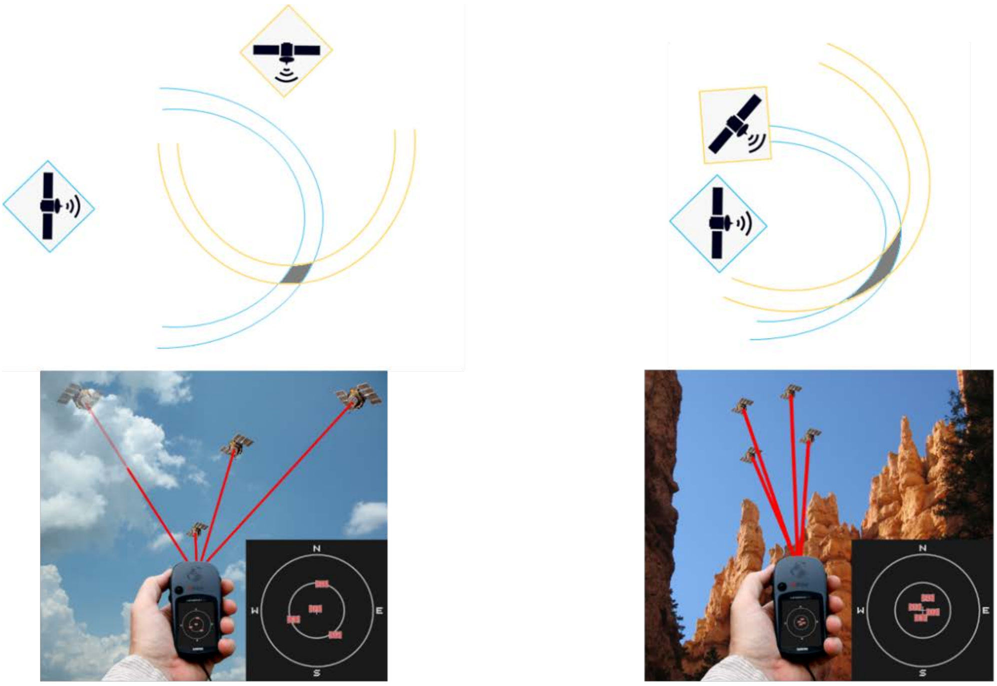
At higher latitude is the signal path longer due to lower elevation of the satellites, this can lead to larger tropospheric effects. The topography effects the weather, parts of Scandinavia are dominated of high mountains and deep valleys and fjords, one valley can have a different weather than its neighbour. If using a reference station, topography might cause a difference in the tropospheric delay between the reference station and the user (Yu, et al., 2020), e.g. if the user is in a valley and the reference station is on a mountain, under certain weather conditions the troposphere can be different.

Tropospheric delays can be corrected with models in post processing missions. A most simple application of GNSS does only use the a priori models for the atmospheric and ionospheric corrections, which does eliminate parts of the effective disturbances. Sometimes the tropospheric and ionospheric errors are referred to together. It is important to note that the errors with source in the troposphere are only on a centimetre level, while the ionosphere errors are on a decimetre level.

6.3.3 Satellite Geometry

Satellite geometry is one of the most important factors for positioning with GNSS and underlies a local and temporal variation. As a quantification of the satellite geometry, different characteristic values can be investigated. The geometry is mainly influenced by the orbits of the satellites in the different satellite constellations, which do not always result in optimal numbers of visible satellites.

Geometric Dilution of Precision (GDOP) or just DOP is an indicator for the current geometry of the visible satellites in the sky. When these satellites are widespread and have sufficient distances to each other, the positional DOP (PDOP) is small. A low DOP value is highly correlated with better precision in the final position and should in the best case be around 1. Therefore, DOP is usually used as a qualitative indicator for the precision of the position. For a more precise estimate of the position's quality, PDOP can be split into horizontal HDOP and vertical VDOP. Usually, satellites close to the horizon are ignored (often 10 or 15 degrees), when they are under the so-called cut-off angle. Therefore, HDOP is often smaller than VDOP, which results in more precise measurements in horizontal plane than vertical (Santerre, 2017).



Low DOP value
Favourable Geometry

High DOP value
Unfavourable Geometry

Figure 37: Visualization of the DOP problematic, related to a cut off horizon. (Lower illustrations from (DOP, 2021))

The DOP values vary throughout the day, but underlie a systematic loop between the days. This is due to the fixed return periods for the satellite constellations. This return period differs between the constellations but is for example in the case of GPS around four minutes shorter than the usual sundial day – this is the common duration of a day according to the sun. This results in us observing the same satellite constellations four minutes earlier on each subsequent day. The reason for this is, that the satellite orbits are synchronized with the sidereal time, which is used in general when working with celestial objects. It is the time scale that takes into account the relative rotation of the earth to the fixed stars (Anon., 2006).

Table 20 shows the explanation for the practical use of DOP values in measuring campaigns. (Anon., 2011)

DOP Value	Rating	Description
1	Ideal	Highest possible value
1-2	Excellent	Allows very accurate measurements
2-5	Good	Minimum appropriate for professional applications
5-10	Moderate	Usable, but quality is decreased
10-20	Fair	Bad measurements at a low confidence level
>20	Poor	Very inaccurate, up to several hundred meters

The most part of the satellites orbits are centred on the equator as seen in Figure 38: GNSS availability from gnssplanning of Trimble for Sotuh and North positions. The turning orbits can be observed in both directions and it is to be seen, that GLONASS (red) reaches slightly higher latitudes.. The availability of the signals is therefore degraded the higher north or south a user is measuring. This is due to the before mentioned cut-off angle and the sheer visibility of the satellites, as they are more often hidden behind the earth. This property is called line of sight in satellite navigation. It is a special challenge in the north of Europe, because globally, there are only few regions in extreme latitudes that are inhabitable. One of the objectives of the introduction of Galileo was to improve the satellite coverage in the northern parts of Europe. The definition of the orbits is a political trade off, since as many users as possible should benefit, but border regions be included as well.

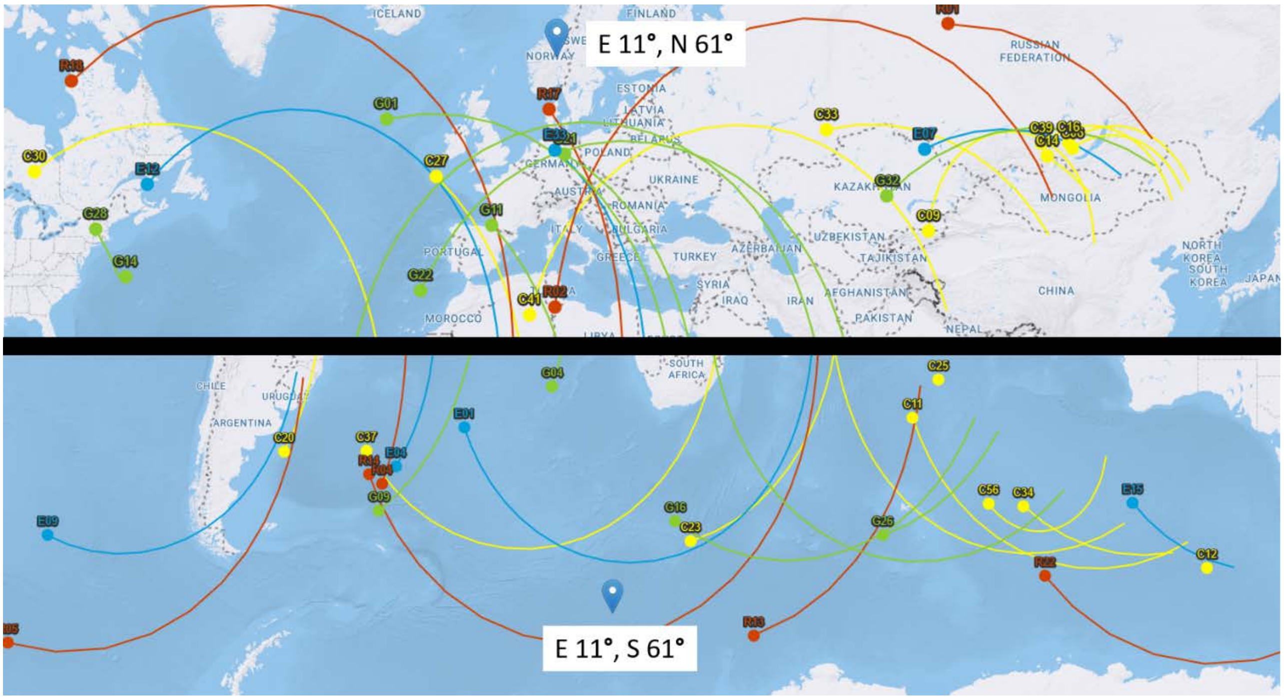


Figure 38: GNSS availability from gnssplanning of Trimble for Sotuh and North positions. The turning orbits can be observed in both directions and it is to be seen, that GLONASS (red) reaches slightly higher latitudes.

Table 21 shows the maximal latitudes of the four different GNSS.

GNSS	**Orbiting between**
GPS	55° S, 55° N
GLONASS	64.8° S, 64.8° N
Galileo	56° S, 56° N
Beidou	More complex

Compared to the other three GNSS, Beidou does also used geostationary satellites in its system and is organised in three different orbits, which are different from the other GNSS. Some of the Beidou satellites do have good availability in the higher latitudes as well.

One of the effects of the orbits is that the DOP values generally are higher when measuring longer south or north on the earth. The bad distribution and especially the missing satellites in near-Zenith positions are attributed for in the DOP calculation.
Another possibility to get an idea of the geometry of the used satellites is to check for the elevations and optionally for the azimuth values of each satellite. This demands a little more effort but can be helpful to identify weaknesses in the current geometry and can often explain varying performance. An approach to this can be seen in the next chapter.

Absence of near-Zenith satellites does not automatically result in a smaller number of satellites. This is thanks to the huge distance of the satellite's orbits and the recursive architecture of the constellations. Many of the satellites are not only visible southwards, but can at some point of the day be seen in the North as well – when they pass the "other" side of the globe. This effect can be compared to the phenomena of midnight sun above 66 degrees of latitude.

It should also be noted, that the different geometries all over the world have different characteristics. When looking at Figure 37 , the unfavourable geometry in the right image is especially bad for horizontal positioning. On the other hand, the vertical positioning is rather precise, due to the redundancy in measurements from directly above. For this reason, a separation in HDOP and VDOP can be important, especially in regions with reduced sky view and unfavourable latitudes (ca. above 55° North and South). (Jiexian, 2006)

The effect of the geometry and these phenomena are described in more detail in Section 6.3.5.

6.3.4 Topography

Topography does have an impact on the visibility of the satellites. This is directly connected to the described characteristics in Section 6.4.3. Most of the typical measures around GNSS take the topography into account, as for example the DOP value can be greatly increased due to it.

As DOP values and other geometric characteristics are predictable in time, it is possible to plan the perfect timeframe for a GNSS measuring campaign with respect to accuracy. This has especially been important before the release of Galileo and Beidou constellations, as the number of visible satellites varied more and fewer signals were available. Still, these predictors are very useful for applications that depend on GNSS signals, especially in challenging areas. A problem is, that there is no commercial GNSS performance predictor that enables topography obstructions in the simulation. Different publications and attempts on the subject exist in the literature (f.e. (Stefano, 2011)), but no application is freely available.

When implementing an integrity function for individual GNSS users, topographical aspects have to be included in some way, as their effect is severe. Luckily, the elevation data does not have to be very precise and such data is freely available in most of the industrial countries. This can for example be a nationwide digital elevation model (DEM) or more optimally a digital surface model (DSM). The latter also includes vegetation, buildings and other obstacles (roughly).

Take for example the random place in the **Jostedalen** (61.5595 °/ 7.2984 °), with relatively high mountains along the valley. The actual screenshot from Google Streetview is taken at a height of 121 above mean sea level. Additionally, a screenshot from the same place is added, which is taken from the application Peak Finder. This application allows for 3D positioning in a DEM – originally with the purpose of detecting peaks surrounding the observer. It uses national DEM and data from OpenStreetMaps.

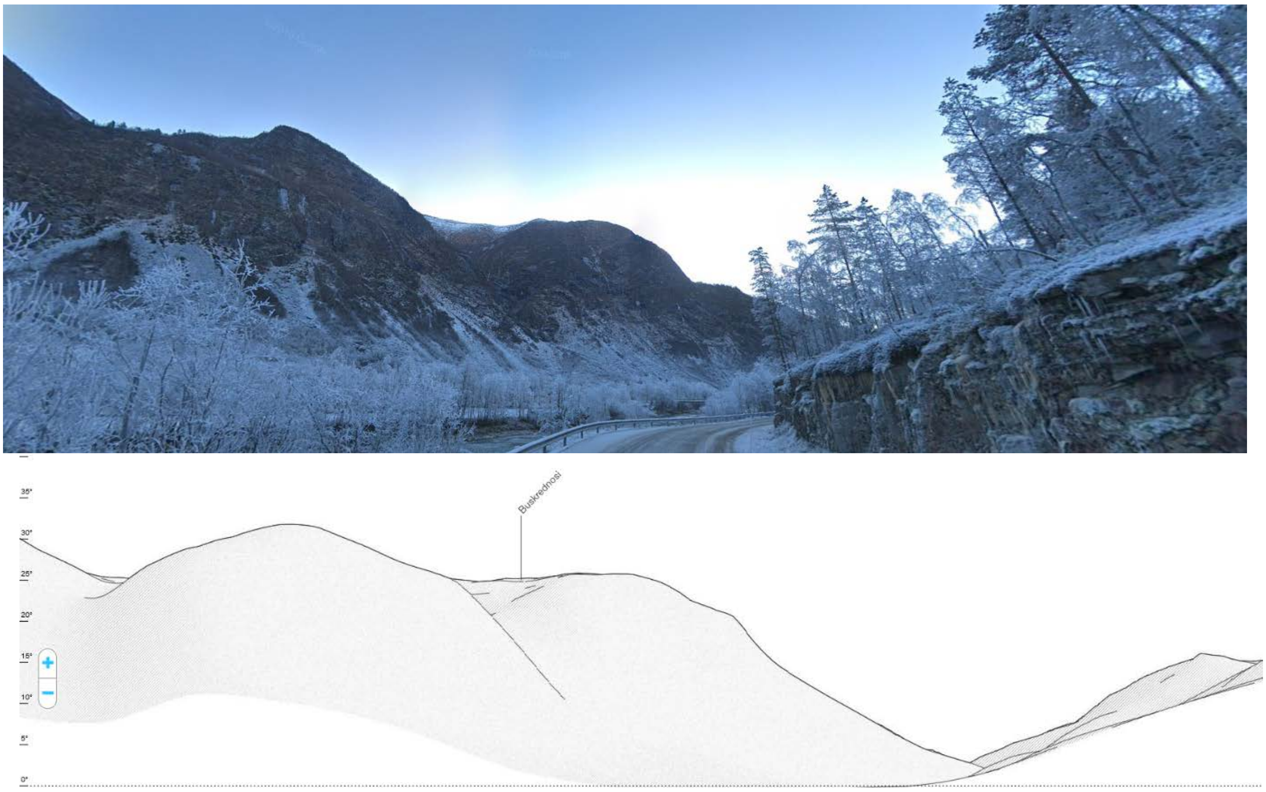


Figure 39: Screenshot from Google Streetview above from the Jostedal Valley. Below, a screenshot of the same site in the application Peak Finder.

In the screenshot, we see two major peaks: the Gravdalsbandet (with 1398 amsl) and the Buskrednosi (with 1505 amsl). The field of view is facing South. Together with the distance, the elevation can directly be calculated by the following formula:

$$\alpha = \arctan\left(\frac{Height\ Difference}{Distance}\right)$$

Table 22 Distances and height difference from the viewer's position to the two mountain peaks, with the calculated cut off angle.

Peak	Height Difference	Distance	Elevation
Gravdalsbandet	1277 m	2661 m	25.64 °
Buskrednosi	1384 m	3124 m	23.89 °

When looking at the Figure 39 in the Peak Finder part, we can see the elevation on the left edge. It is slightly higher than what is calculated from the values above – this can be due to the fact, that the two mountain peaks are not seen directly, but behind relatively higher obstacles in the Peak Finder model.

In any case, this experiment does not aim to be very precise, but it can be developed a little further to give an idea of the effect of this elevation cut offs. As mentioned before, a constant cut off angle is always applied to GNSS calculations, it usually is about 10 or 15 degrees. This means that the roughly calculated elevation cut off values from above will result in around 10 additional degrees of cut off in this direction.

Most of the satellite observations in these latitudes are coming from the South. To give an idea of the impact on the satellite observations, we can use a planning tool (https://www.gnssplanning.com/) and apply a cut off angle of 23 degrees for the complete horizon. This value is rather low regarding the calculated elevations. We can compare this to a scenario with no surrounding mountains, applying a cut off angle of 10 degrees. The number of visible satellites for the scenario ignoring the mountains is around 40 for an average day and we achieve a GDOP of nearly 1. When applying the cut off of 23 degrees, the number of visible satellites is decreased to around 27 and the GDOP to ~1.4. In both cases, the number of satellites is more than sufficient, but note the big difference anyway.

Another, more detailed approach to the cut-off problematic is given in the **Section 6.3.6** about Obstacles and Multipath effects. Compared to obstacles, topography has the obvious advantage of being available in many data sources and therefore its effect easier to model. 6.3.6

6.3.5 Geometry versus Latitude

In line with bigger challenges in the satellite geometry, the precision is expected to be lower with increasing latitudes. Only limited literature is available on this topic, but it can be theoretically analyzed.
In this chapter, an approach to investigating the correlation between precision and latitude is given.

From theory, DOP values and other parameters of satellite navigation are expected to be more unfavourable in higher latitudes (south and north). An oversight of these relation can be seen from pure theory, as the constellations' orbits are well known and calculations are mainly based in geometry. Additionally, the effect of the ionosphere, as described in Section 6.3.1, is increased in extreme latitudes, which does impact the precision additionally. Thanks to a large and dense permanent geodetic network of GNSS receivers, empirical values can be analysed to draw a conclusion from actual measured values.

As mentioned in the Section 6.3.3, some of the satellites can be observed in the North when passing the other side of the globe. This can easily be shown on a skyplot as seen in Figure 40. In the left plot from Honningsvåg, the satellites observed in the North do rise up to 25 degrees elevation, while they only reach around 13 in Kristiansand.

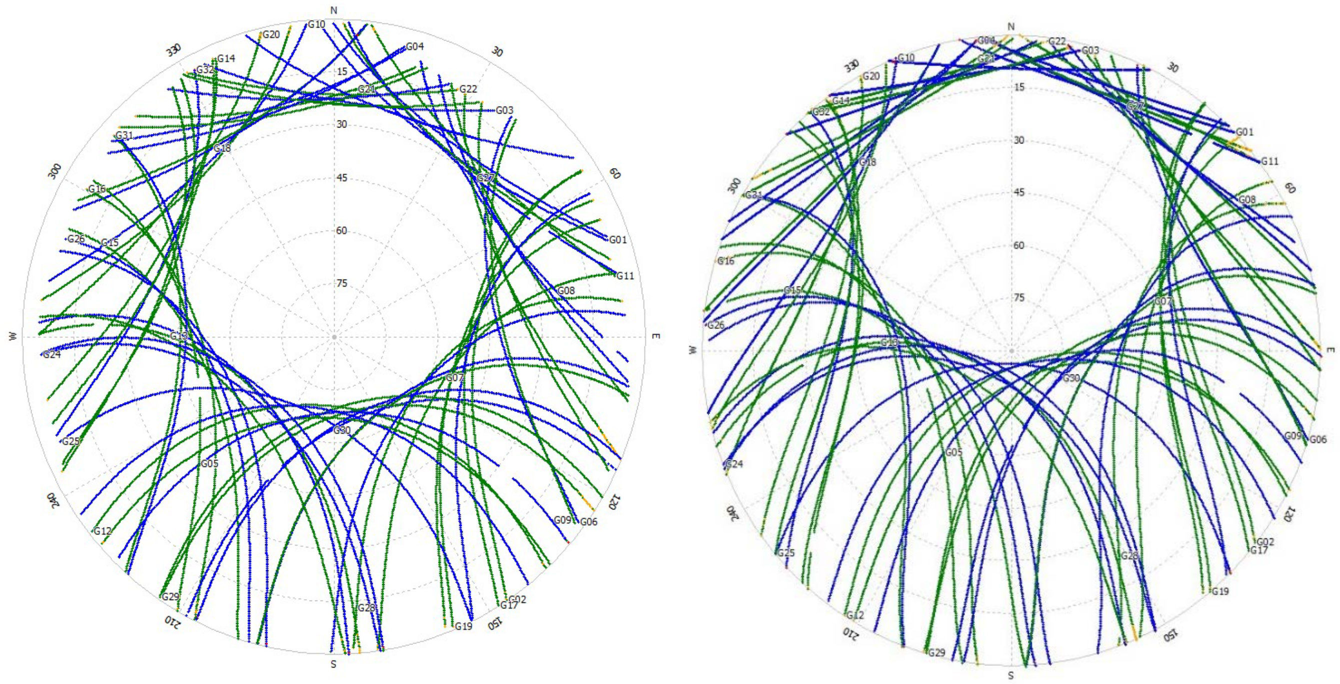


Figure 40 Daily skyplots of the permanent GNSS stations at Honningsvåg (left) and Kristiansand (right) for the GPS satellites (Blue = F1 only, Green = F1 and F2).

Leaves the question of which effect is stronger – the missing satellites with high elevations or the fewer satellites observed in the south. There is no easy answer on this matter, without investigating more. In any case, a difference between horizontal position error (HPE) and vertical position error (VPE) has to be made. We have seen in Section 6.4.3 that this differentiation also is made for the DOP values.

GNSS theory concludes that many satellites with low elevations “stabilize” the rover’s position horizontally, but cannot eliminate each other’s error budget in the vertical axis. This results in a theoretically higher uncertainty and error in VPE in higher latitudes. The inverse situation applies for exclusively observations from high elevations – this results in a higher HPE, due to missing satellite observations from the side. This can for example happen in a steep valley or a canyon, as seen in Figure 37.

This theoretical aspect can be supported by analysing reference station data from the International GNSS Service (IGS) and the Norwegian Mapping Authority (NMA). The results are the average HPE and VPE over three months in 2020. The GNSS data is processed as Single Point Positioning (SPP), which is the simplest positional algorithm to dedicate a position, as for example used in GPS watches or many mobile phones. From the same analysis, the HDOP and VDOP values can be read and analysed in their relation to the latitudes. Note that the results do only include Galileo E1 frequency, as these are results produced in NMAs deliveries to the European Space Agency (ESA). This is done in a project connected to the monitoring of the Galileo system in Norway. The same analysis can be scaled up to more navigation systems, frequencies and stations, for more detailed background.

The Galileo constellation still lacks a few navigation satellites, but can be looked at as completely functioning. The characteristics of Galileo are similar to the ones of GPS and GLONASS. Still, the analysis of multi constellation data would be more accurate and comprehensive for this purpose.

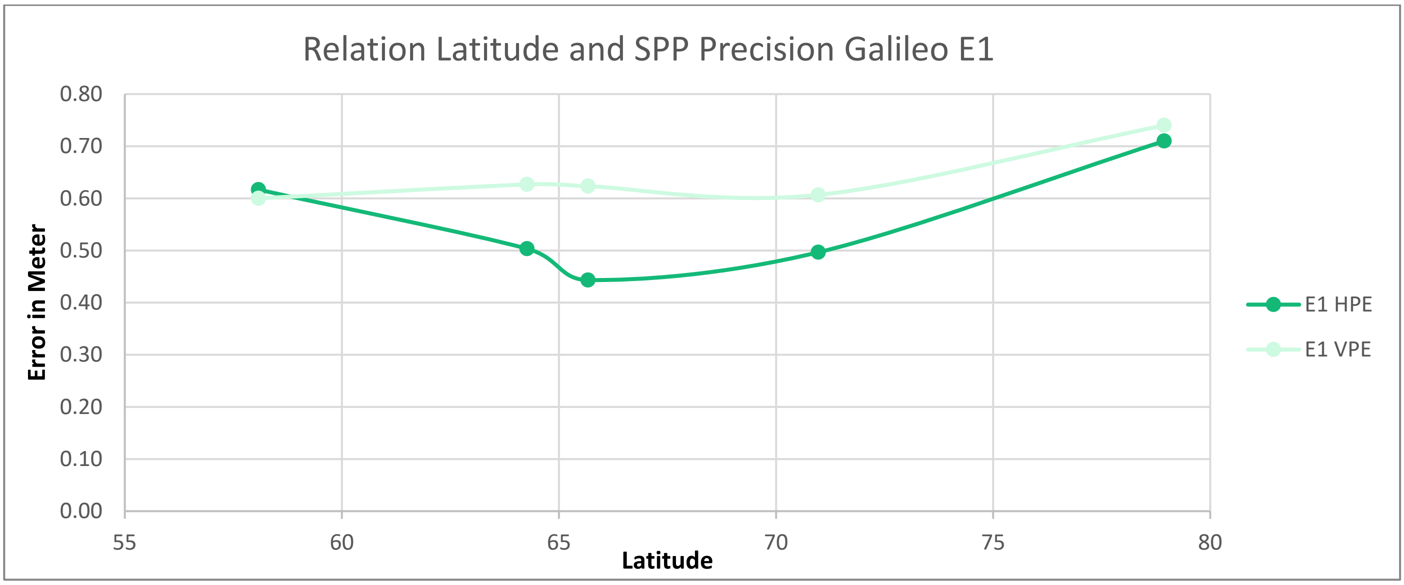
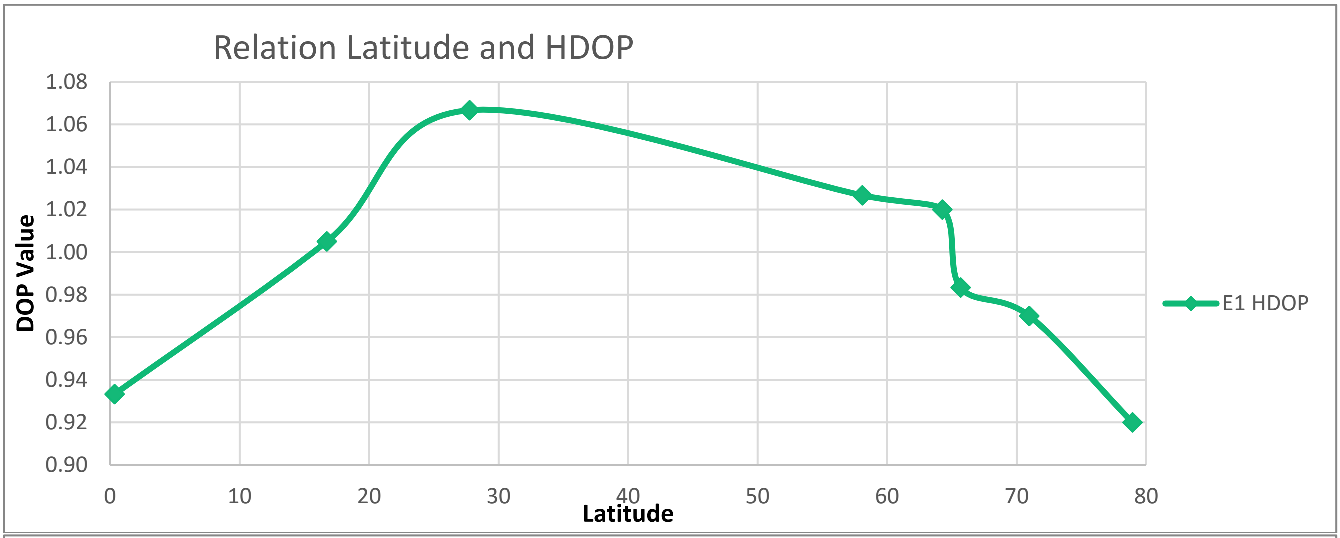


Figure 41: Shows the plot for horizontal and vertical position errors plotted in relation to the latitudes of the stations. The values are averages over three months for the Galileo E1 frequency. Results are from the stations in Kristiansand, Høfn, Vega, Honningsvåg and Ny Ålesund.

We can see from the plot in Figure 41 that VPE generally is worse above 60 degrees. This does directly underline the theoretical statement of unstable positioning in the vertical axis, when no or only few satellites are situated directly above the receiver. Generally, both the HPE and VPE increase slightly, when analysing data from stations higher North. Nevertheless, the relation is not very clear, as the difference between the mean values of the station longest south (Kristiansand) and longest north (Ny Ålesund) only are 9 cm and 14 cm for HPE and VPE, respectively for SPP.

The positional errors are tightly coupled to the DOP values, as has been mentioned before. Still, there are many other factors that also have an influence in the effective position errors. This is for example the ionosphere model underlying the signals, which does not have the same precision in all parts of the world. For this reason, we will also have a look on the pure relation between the HDOP and VDOP to the latitudes. As this are as well mean values over three months, they do represent a pure geometrical state from the satellites constellation. This is due to the elimination of temporal differences when looking at means of long time observations.



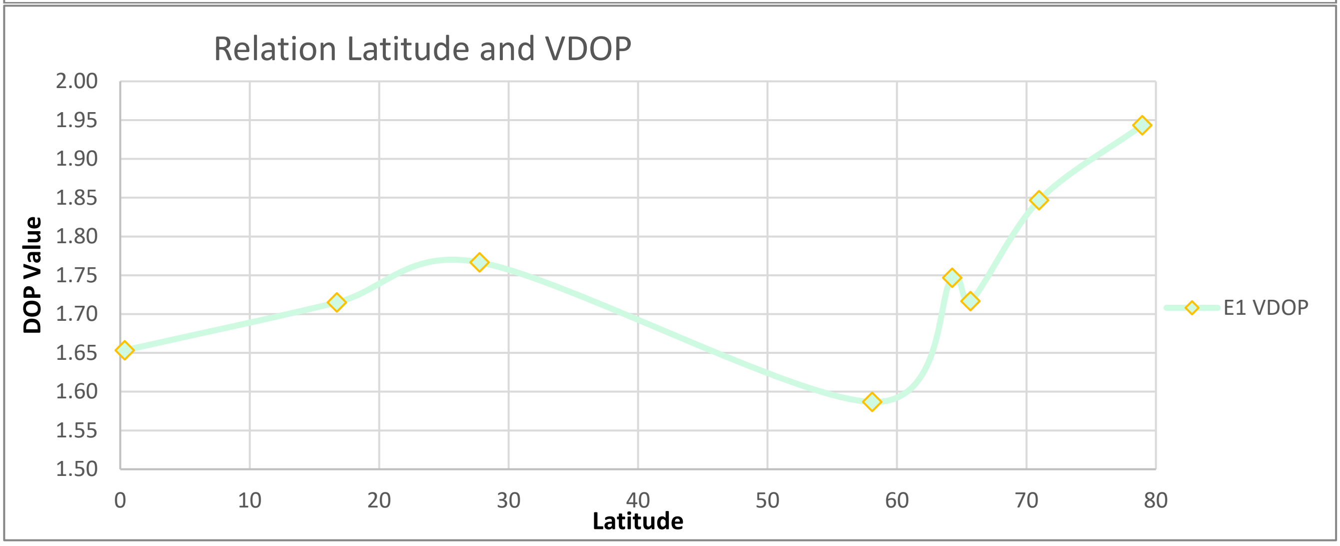


Figure 42: Shows the plots for horizontal and vertical DOP values related to the latitude of the reference station. The DOP values do represent the distribution of the Galilleo satellites at the observation station over three months. The stations are at Libreville (Gabon), Espargos (Cabo Verde), Maspalomas (Spain), Kristiansand, Høfn, Vega, Honningsvåg and Ny Ålesund.

We can see from the plots in Figure 42 that the HDOP values are low in equatorial latitudes and slightly higher between 20 to 60 degrees. The trend is pointing downwards longer North, due to the same reason described before. More satellite signals coming in from the sides and additional satellites from the north stabilize the horizontal geometry. On the other hand, the lack of satellites in high elevations results in more uncertainty in the vertical plane and therefore a higher VDOP. Recalling Table 20 in Section 6.3.2, this higher VDOP at higher latitudes has an unfavourable effect on the positioning solution. Still, the differences between equatorial and northern stations are not huge, but significant. Note also, that VDOP generally is much higher than HDOP, regardless of the station.

As mentioned before, more analysis and investigation can be done, to support the statements of this chapter. A remarkable thing is for example the behaviour of HDOP and HPE in higher latitudes, where they do not correspond, which they should. In Figure 41, the positioning error is increasing in the higher latitudes, while the HDOP is lower. A reason for this unexpected behaviour can lie in the used positioning method, which uses a predefined model for the ionospheric disturbances. The accuracy of these models is often varying for different locations, where higher latitudes usually are less prone to these type of errors.

This small study of the relation between satellite geometry and Latitude is done with long term, static data. It has to be assumed that many effects of the extreme latitudes are eliminated through the inclusion of a very long time line. Additionally, the effect of the ionospheric and tropospheric disturbances is not separately looked at in this data.
The scope of kinematic (moving) positioning has many difficulties that are even harder to simulate and investigate. For example can a vehicle be unlucky and drive at a time of the day, where high DOP values occur. This situation is in any case more likely to happen in extreme latitudes, than in near equatorial places.

Other typical measures for estimating the performance of navigation systems are the **availability**, **continuity** and **integrity**. All these three are also assessed by NMA in the context of EGNOS and Galileo monitoring to the ESA, but are not documented in here. Integrity does on the other hand include all of these three measures and is the topic of work package 2.4.

An interesting paper does analyse the availability of Galileo and GPS in a theoretical approach. In Figure 43 a plot from the paper is depicted here, which shows the availability of satellites in relation to the latitude. It is obvious, that both constellations have a reduction in number of available satellites as a function of higher latitudes up to about 65 degrees, where a small increase in number of satellites is observed going towards higher latitudes. It is also nicely illustrated, that the visibility is again increased in the highest latitudes (around 80 degrees).

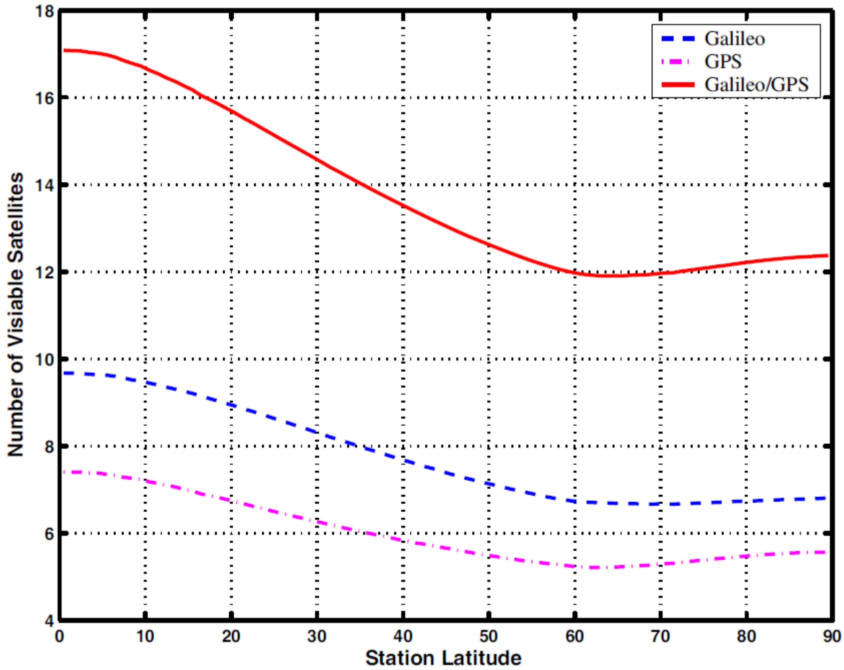


Figure 43 Relation between the visibility of Galileo and GPS satellites and the latitudes of a station. From (Jiexian, 2006).

6.3.6 Obstacles and Multipath Effect

6.3.6.1 Obstacles

A problem of satellite based navigation that is often not sufficiently addressed are the surrounding obstacles that have a very relevant influence on the measurements. These objects consist mostly of vegetation, stones, cliffs and buildings. Thus, this influence is exclusively place dependent. Regions can be known to have a

degraded line of sight around for example roads. This can seem as a very obvious problem, but should nevertheless not be neglected.

Compared to topography in for example a valley, the distributed and non-continuous hinders along a road do usually rise up in relatively higher elevations, since so close to the receivers position. Thereby, a higher cut-off potential for signals is given through these close obstacles. It leads especially also to lost or incorrect fix, due to some missing epochs in the GNSS measurements. This adds a risk to continuous measurements and uncertainty into the integrity of the determined position. (Eloise, 2018)

This problem is not only applicable for Northern regions, but also to many countries with higher vegetation density along roadsides and urban areas. On the other hand, some parts of the world are characterized by exceptionally good signal conditions, due to completely free sight around the road. Norway's roads are mostly recognized for longer forest crossings with variable topography, as depicted in Figure 44.

Klokkeslett:07:08:42 Dato: 2020–07–07

	dE	dN	dP	dH	#Sat	PDOP	StdPlan	StdHoyde	Postype
Referanse–GRE					7	N/A	0.028	0.032	Float+DR+Odometer
F9K–CPOS–GREC–samlet	+0.234	−0.044	+0.238	+1.070	18	1.7	0.099	0.156	Float+DR
F9P–CPOS–GREC–samlet	+0.074	+0.142	+0.160	+0.413	20	1.4	0.206	0.580	Float
Forerunner220–SP–G	+2.199	−2.452	+3.294	+2.100	N/A	N/A	N/A	N/A	SPP
TrimbleNetR9–CPOS–GR	+0.502	+0.582	+0.769	+1.661	12	1.9	0.404	0.594	DGNSS
TrimbleNetR9–CPOS–GRE	+0.765	+0.208	+0.793	+0.606	18	1.5	0.207	0.373	DGNSS
TrimbleNetR9–CPOS–GREC	+0.231	−0.136	+0.268	+0.403	21	1.5	0.422	0.806	DGNSS
TrimbleNetR9–RTX–GREC	−0.302	−0.972	+1.018	−1.595	21	1.5	0.381	0.751	CP PPP
XiaomiMi8–SP–GREC	+1.272	−0.950	+1.588	+0.215	N/A	N/A	4.000	N/A	SPP

Figure 44: Illustration of forest closure avoiding free line of sight. Video snapshot from GNSS analysis work in the Norwegian Mapping Authority, Image from Røyse in Hole Municipality. - (Kartverket, 2020).

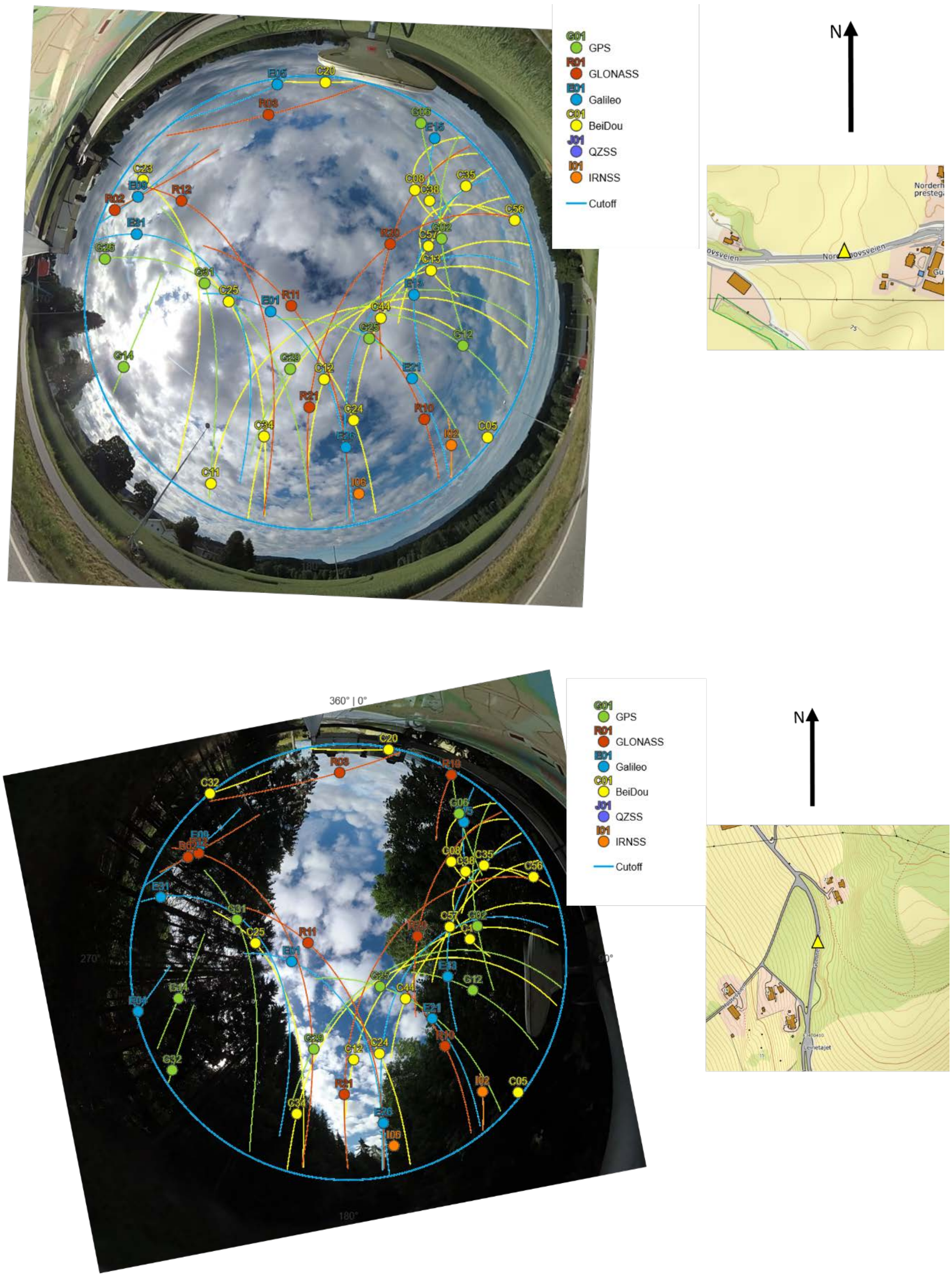


Figure 45: Skyplot with current satellite observations from the navigation file and the 360° video screenshot. Representation from a test route from Røyse in Hole municipality. Created for illustration purposes and only relatively precise.

Figure 45 shows two skyplots from the same area in Hole Municipality. A 360 ° image is focused on the sky and overlaid with the skyplot of the satellite navigation systems at the exactly same timestamp (exported from the GNSS planner mentioned before). It can easily be seen, that many satellites are not visible in the second skyplot, where the vehicle passes a steep forest area. The skyplots are from nearly the same place in Eastern Norway and only separated by around ten minutes. A publication on obstructions in urban canyons has been written by (Tongleamnak, 2016). The amount of multipath effect in different areas is not investigated properly here, but will be an important question for future applications.

Recalling the skyplots from Figure 40 in Section 6.3.5, the satellite hole moves towards the center of the plot, when latitude is increased. In the plots of Figure 45, some few GLONASS satellites do still nearly pass in a perpendicular elevation to the vehicles position. In more extreme latitudes, the forest area would lead to nearly no visible satellites, as none of the constellations are passing directly above these regions.
This problem is luckily decreased through less vegetation in the northern areas, but still present due to other obstructions.

6.3.6.2 Multipath

Multipath is the phenomena of signals being reflected on nearby obstacles and arriving at the receiver from incorrect directions as depicted in Figure 46 below. This error is more pronounced in code measurements (timestamp on the original message), due to the dilatation of the signal and the related wrong distance calculation to the satellite's position. For code measurements, the error can theoretically be up to 450 m, but is usually around 3 – 5 meters. Phase measurements are more prone to multipath than code, as the maximum error is a quarter of the frequency's wavelength – resulting in some centimetres. This is due to the characteristics of phase measurements, where only the phase of the last cycle is measured and the number of full cycles N is calculated. (Sanz Subirana, 2020)

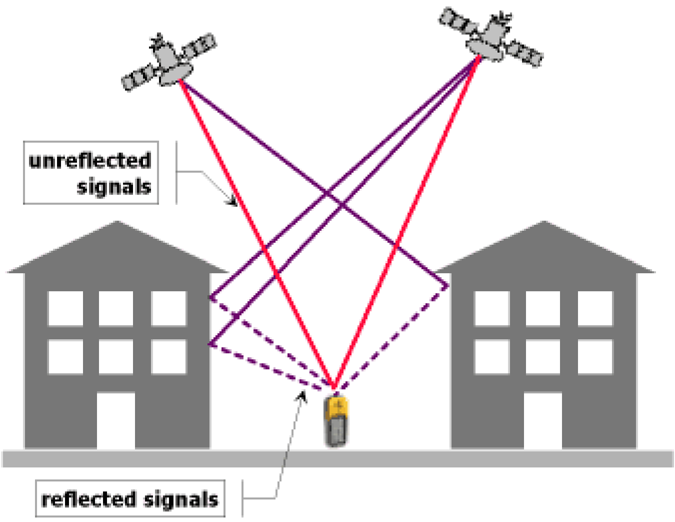


Figure 46: Illustration for the multipath effect in an urban area. From (Kumar, 2020).

Multipath does apply to the situations depicted in Figure 44 and Figure 45, as trees are characterized by a clear multipath effect on GNSS signals. Nevertheless, the most classic case of multipath for vehicles is in urban canyons and close to infrastructures along the roads. Still, it has to be remembered that multipath can happen due to nearly all objects, such as rock cliffs, wet rocks, vegetation, buildings or other vehicles.

6.3.7 Receive and distribute correction services

6.3.7.1 Satellite based distribution

Similar to the distribution of navigation data from the GNS systems, satellite based communication for GNSS correction data is used. This happens usually with the help of so called geostationary satellites, satellites that are always visible at the same place of the earth. This is achieved through simultaneous movement with the earth's rotation, which requires the correct orbit height (around 36 000 km) and velocity. Most satellite based augmentation systems (SBAS) use this method for distribution of improving positioning data as shown in . This is usually information about more precise ephemeris of the satellites and the clocks, correction for biases and in some cases ionospheric disturbances. Also, integrity information can be implemented, which in case of safety of life applications is of great importance. The European SBAS (EGNOS) does for example send a real-time integrity information for the GPS constellation. More on this in the report part 2.3. Note that SBAS does only refer to the method of communication, the calculations of the correction are always based in back office calculation centers on the ground. Most often, satellite distribution is pure broadcasting and does not include a two-way communication between the receiver and the satellite.

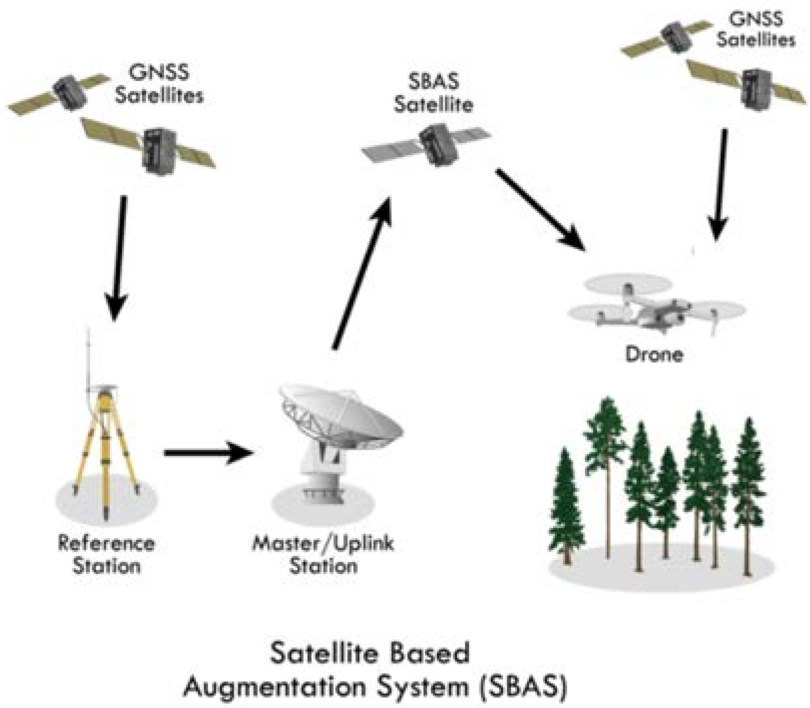


Figure 47: Illustration of SBAS, where the correction signal is processed from a reference station as input in a Master and sent back to a satellite, which then sends the corrections to a rover (from (Robert, 2021)).

SBAS does have the disadvantage, that the geostationary satellites often are positioned around the equator. This leads to often bad reception higher north/south than ca 60 degrees of latitude. For this reason, SBAS correction is not always a good solution, especially in the Northern parts of Scandinavia. Due to the very low elevation of the geostationary satellites, small obstacles south of the receiver can lead to a loss of correction signal. This problem is less acute when distributing through the navigation satellites, as their orbits vary much more and also reach more extreme latitudes.

Similar to SBAS, but not a part of, is the distribution of correction signals through the navigation satellites directly. This application is more recent and only possible on the newer generations of navigation satellites, as the newer block of GPS or the Galileo satellites. The future high accuracy service of Galileo will be distributed on a frequency distributed from the navigation satellites.

6.3.7.2 Ground based distribution

The distribution of correction signals does often happen with ground based communication systems. This happens most often through simple internet communication, as for example the broadband cellular networks or WiFi. These systems can also use other frequencies of communication, as for example Bluetooth, or ITS G5. In these cases, the reception of the signals can also be used for calculation of a reference position.

Local systems can be found around ports or airports and important and frequented spots of individual transport, these are usually called ground based augmentation systems (GBAS). On more regional or national levels, DGNSS or CGNSS systems are found, which in comparison to the local systems most often are distributed through broadband networks. An example for such a service are network RTK, which use a dense system of reference stations, or PPP. Note that in some cases, a two-way communication is needed to be able to connect to the service. This means, that the signal are not distributed by broadcast but on demand. This is never the case with satellite based correction.

Advantage from distributing information from the ground is generally better reception in any urban part of the world – as the telecom network is sufficiently equipped. In more remote areas, network coverage is often worse and this can then lead to signal loss. Therefore, ground based correction should be preferred over satellite based in regions with good network connections. Nevertheless, remote areas as landroads can often benefit from use of satellite supported distribution, where no cellular network is available.

6.3.7.3 Term clarification

Note: The abbreviations GBAS and SBAS are often used as the general distribution methods, which is not entirely correct. Historically, SBAS and GBAS do only correct code measurements and do therefore only include some of the correction systems available. For example the service Fugro Seastar is distributed over satellites, but not an SBAS, since it includes both code and phase measurements. The same applies for example for NRTK services on the ground, which are strictly spoken no GBAS.

6.3.8 Forced Signal Interference

GNSS communication is based on low power radio frequency. Most navigation systems send messages in at least two frequency bands and the messages contain ranging codes and navigation data. The frequencies for the different systems and bands can for example be found on this website. (ESA, 2021)
Spoofing does willingly falsify the information communicated through the frequency band, while jamming does simply overlay the frequency with random information and hides the relevant information for the receiver.

6.3.8.1 Jamming

Radio Jamming includes techniques that block, interfere or jam authorized wireless communication systems. In the case of GNSS positioning, this is a relevant problem due to military or criminal motivations. It should be noted, that interference can occur naturally, due to device malfunctions or oscillating signals from other communication channels. Nowadays, the term “interference” is used for unwillingly disturbed signals, while jamming is done on purpose.
The methods used for jamming are usually a relatively energy intensive overlay of the targeted frequency, so the receiver does no longer “see” the correct signal. A distinction into subtle and obvious jamming is usually made. Obvious jamming emits and jams using a noise signal, while subtle jamming blocks the receiver from receiving information. The latter makes things look as normal and some time is needed to detect the attack.

Jamming in the Northern countries affects mostly the Northern parts of Norway, especially Finnmark. Since 2017, jamming incidents on the GNSS network can be observed regularly. The jamming is suspected to have its origin in Russian activities, connected to hidden conflicts in the Northern area. The incidents are reported to the Norwegian Intelligence Services (PST) and the Norwegian Communications Authority (NKOM). In most cases, the jamming activities are correlated with exercise activities on the Norwegian side, as for example during NATO's "Trident Juncture" exercise in 2018 in Figure 48 (Danilov, 2018).

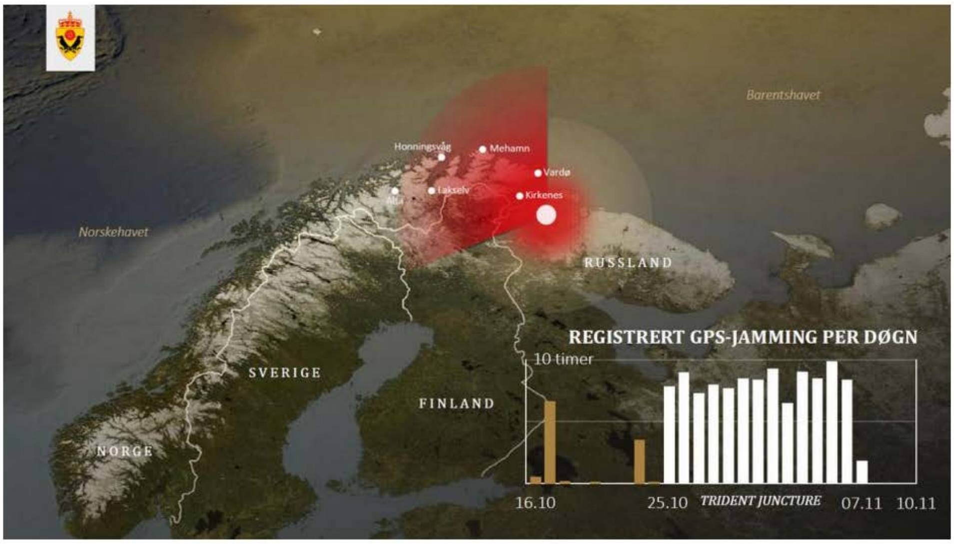


Figure 48: Registered GPS Jamming per day in the period of the 16.10.2018 – 10.11.2018 in the Finnmark region, according to Norwegian Intelligence Services data. In this period, the NATO exercise Trident Juncture was deployed. (Danilov, 2018)

Jamming of GNSS does not always have its reason in military motivations. Private customers can equip their mobiles or cars with "Personal Privacy Devices" (PPD), which disguise their position. This method is for example used in car theft criminality or smuggling operations. (Bazec Matej, 2020)

For a monitoring of jamming activities, the easiest analysis method is the Carrier-to-Noise ratio (often denoted to C/N0). The ratio can usually be observed to drop in times of jamming activities on the affected frequencies, as the noise level increases. An example of jamming behaviour on GPS L1 is seen in Figure 49.

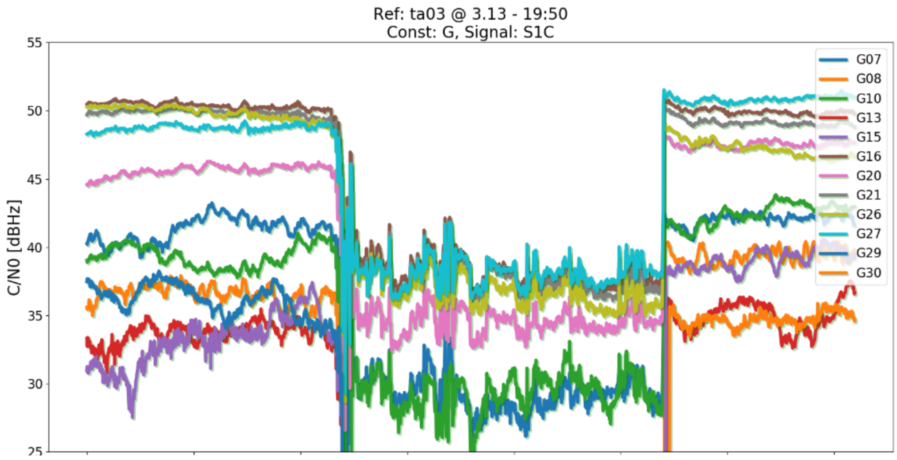


Figure 49: Depiction of Jamming effect on L1 GPS signals, seen in the Carrier-to-Noise ratio. (From (Olesen Daniel, 2020)).

A study of the Technical University of Denmark (DTU Space) investigated the effect of Jamming over a year in their GNSS testbed. The Testbed in Aarhus for Precision Positioning and Autonomous Systems (TAPAS) consists of 11 densely aligned GNSS reference stations. Results showed clearly that mainly L1 frequencies are effected by Jamming activities. In cases where more frequencies were attacked, all the frequency bands showed some differences. Additionally, urban areas such as the port or downtown are more often affected by such activities. In total, 148918 seconds registered jamming through the Carrier-to-Noise analysis, which results in around 4.7‰ of the run time. (Olesen Daniel, 2020)

6.3.8.2 Spoofing

Spoofing does not only include a blocking noise or inhibiting of information, but does falsify it. In a positional context, this is most often a willingly wrong position distributed to the receiver. A simple, widely known tool are the Virtual Private Networks (VPN), where a user can simulate its position to another country. (Wikipedia, 2021)

The most relevant problem with spoofing in GNSS positioning comes from spoofers broadcasting false data in a targeted region. This method is more complicated than jamming and less investigated. A possible defense technique, which has been implemented in some receivers, is the use of control points from historical data in the receiver. With this method, a jump of the positional context can be detected and ignored. On the other hand, more sophisticated methods of spoofing overcome this problem by dragging a victim smoothly away from the original position. In this case, position and time fix are not lost at any point, which makes the attack harder to detect. In any case, a combination of different positioning techniques can fastly detect a spoofing attack on one of the sensors. (Psiaki Mark, 2015)

More widely, the term can also stand for successfully falsifying data of any kind.

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7 Trends

Morten Taraldsten Brunes

7.1 Abbreviations

Beidou		Chinese global navigation satellite system
C-ITS	Cooperative ITS	ITS stations exchanging information
DGNSS	Differential GNSS	Differential GNSS like RTK, but use code signal
EGNOS	European Geostationary Navigation Overlay Service	European regional augmentation system
Galileo		European global navigation satellite system
Galileo HAS	Galileo High Accuracy Service	Galileo PPP service
GLONASS	Globalnaja Navigatsionnaja Sputnikovaja Sistema	Russian global navigation satellite system
GNSS	Global Navigation Satellite System	Standard generic term for satellite navigation systems
GPS	Global Positioning System	American global navigation satellite system
GREC	GPS, GLONASS, Galileo, Beidou	
IMU	Intertial Measurement Unit	Measures acceleration and orientation
ITS	Intelligent Transport Systems	
ITS-S	Intelligent Transport Systems - Station	road user, i.e. a car, bus, pedestrian
NMEA	The National Marine Electronics Association	Organization that defines standard formats
NRTK	Network RTK	Use multiple base stations to generate RTK
OSR	Observation State Representation	GNSS correction method
OEM	Original Equipment Manufacturer	Company that provides parts or equipment that another manufacturer use
PNT	Position, Navigation and Timing	
PPP	Precise Point Positioning	GNSS correction method where satellite orbit and clocks are corrected
PPP-AR	PPP Ambiguity Resolution	PPP with resolved phase ambiguities
PPP-RTK		Hybrid solution of PPP and RTK
QZSS	Quasi-Zenith Satellite System	RNSS for Japan
QZSS CLAS	Centimetre Level Augmentation Service	Correction service for QZSS

RNSS	Regional Navigation Satellite System	
RTCM	Radio Technical Commission for Maritime Services	Organization that defines standard formats
RF	Radio Frequency	
RTK	Real Time Kinematic	GNSS correction method where positioning is relative to a GNSS receiver
RTX	Trimbles positioning services	Family of real-time GNSS positioning services
RTLS	Real Time Locating System	Relative radio based location systems
RAIM	Receiver Autonomous Integrity Monitoring	Algorithm for integrity within a receiver
R-ITS-S	Roadside - ITS-S	Sign etc.
SNR	Signal to Noise Ratio	Signal power to noise power
SAR	Search And Rescue	
SPP	Single Point Positioning	Standalone GNSS positioning without corrections
SSR	State Space Representation	GNSS correction method
TTFF	Time-To-First-Fix	Time from GNSS device is on and fix solution is achieved
TTRD	Time To Retreive Data	Time to retreive full Galileo HAS message
UWB	Ultra Wide Band	Short range radio frequency positioning system
VHF	Very High Frequency	
WiFi RTT	WiFi Round Trip Time	Short range radio frequency positioning system

7.2 General overview

All GNSS (Global Navigation Satellite Systems) providers are continuously developing their system, and they will provide navigation for the foreseeable future. Interactional cooperation gives more modern and cross platform design to benefit end users. In recent years multi-constellation (multiple satellite systems, see section 7.2.1 and 7.2.2) support in receivers have been in focus, now the trend is to support multi-frequency (see section 7.2.2) as well [6].

7.2.1 Latest status for GNSS systems

GPS are modernizing their satellites and launched generation 3 satellites in 2020, GLONASS are updating their signal design to support better multi-constellation implementation and latest satellites also carry an SAR transponder, BeiDou reached full constellation in 2020 with their newest satellites that also support better multi-constellation implementation. Galileo will finish their constellation in 2021, have features for spoofing protection, is the first GNSS to support SAR and will serve a high accuracy service (7.4.7 - Galileo High Accuracy Service). Total available GNSS satellites are now above 100 [6].

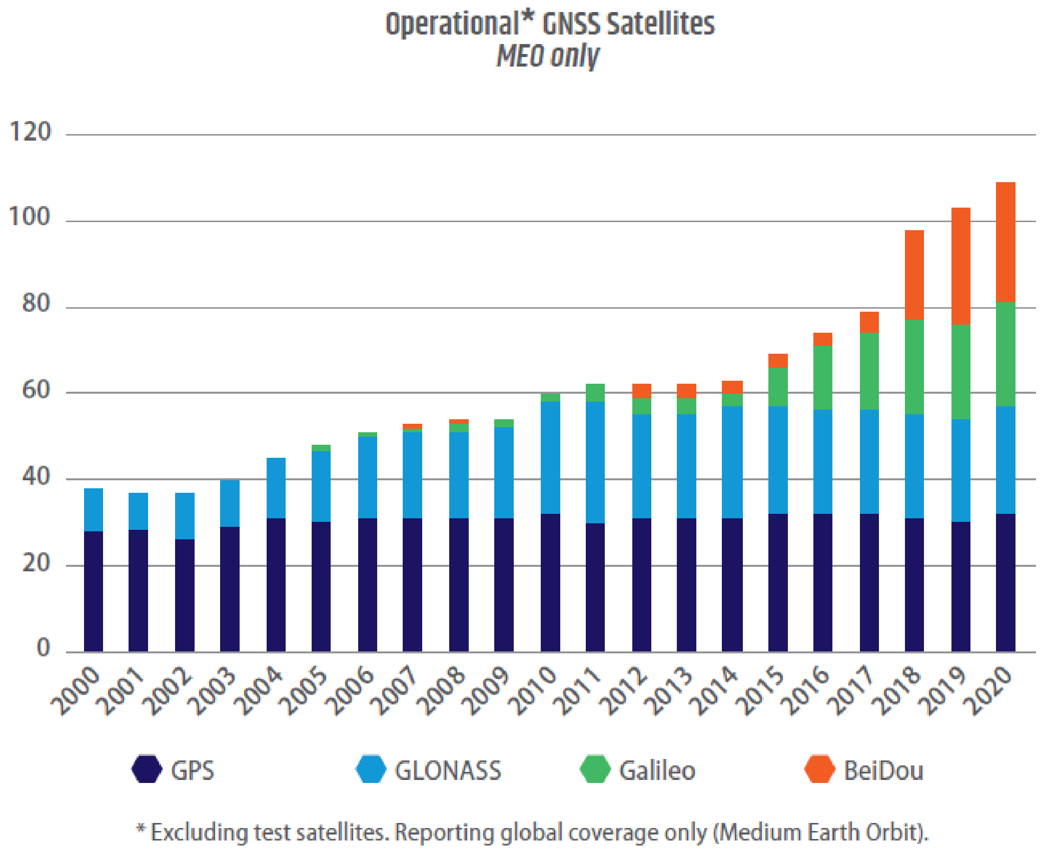

Figure 50: Overview of total available satellites from GNSS systems. [6]

With online tools, for example www.gnssplanning.com, it possible to estimate how many satellites can be seen at a given coordinate and time. Note that this gives a best estimate with no obstructions to the sky, and for instance the total number of satellites are from 36 at Hønefoss (latitude 60° North) and 40 at Nordkapp (latitude 71° North) at 12:00 2020-12-16.

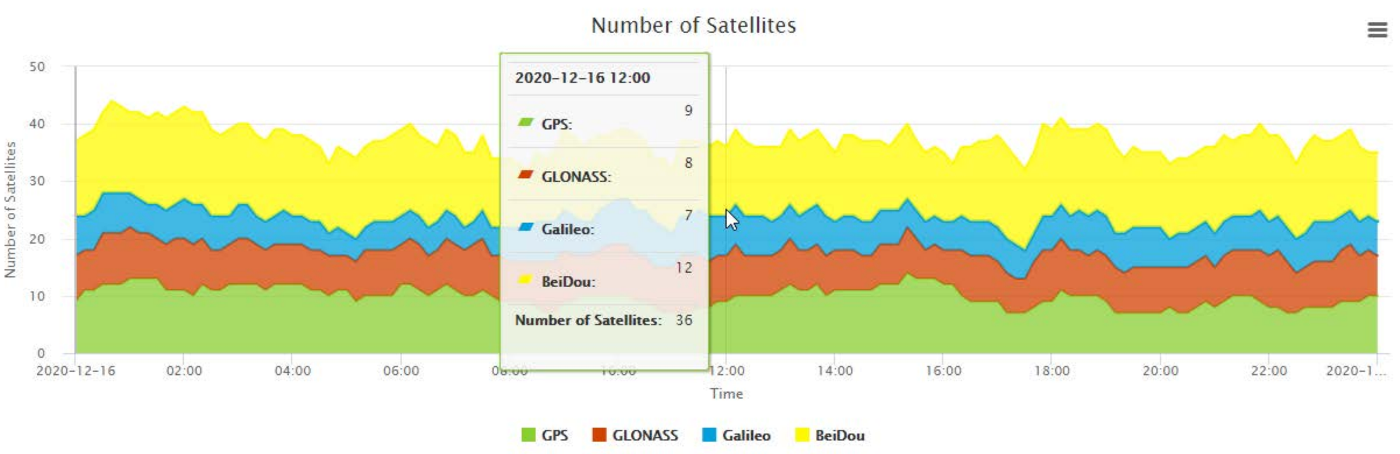

Figure 51: Satellites in view at Hønefoss, 16.12.2020.

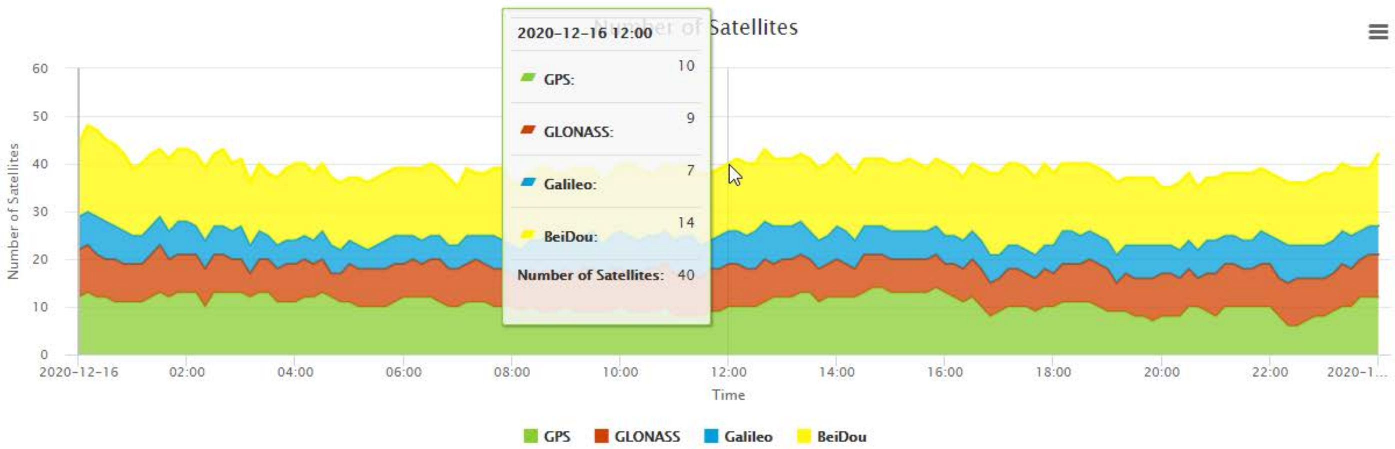

Figure 52: Satellites in view at Nordkapp, 16.12.2020

7.2.2 Multi-constellations and multi-frequency

Multi-frequency gives better resistance to interference due to wider frequency range and two “groups” of frequency ranges. Receivers capable of receiving dual-frequencies have until recently been for high-end expensive instruments, but are now available for mass marked receivers.

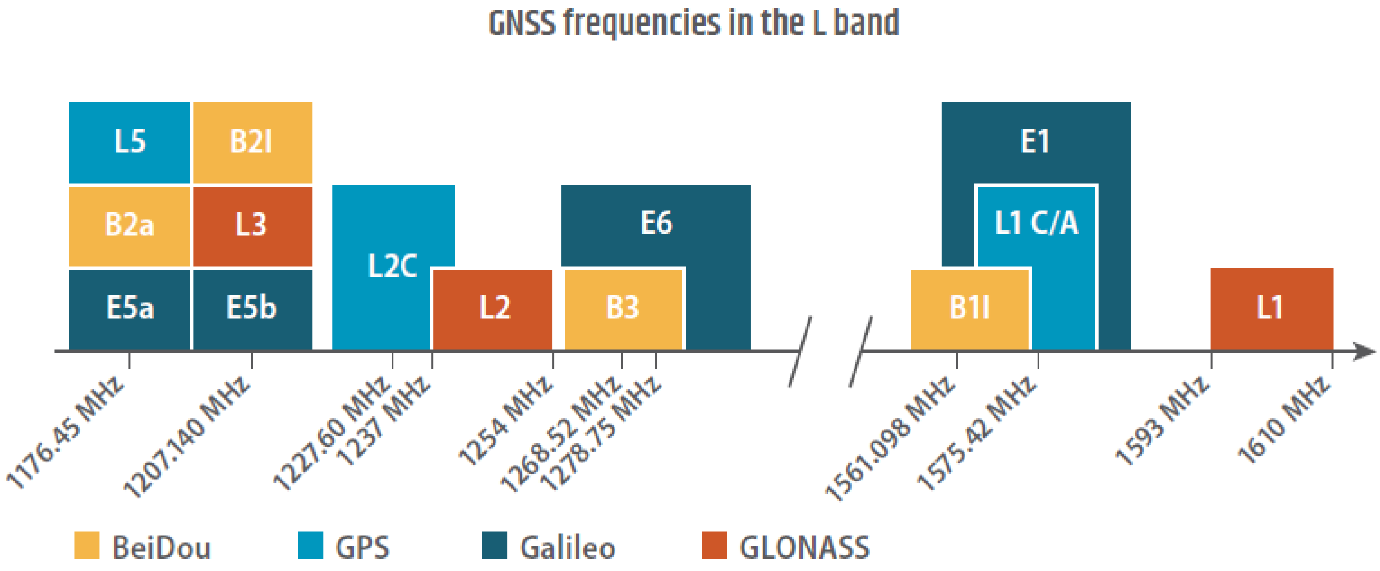

Figure 53: GNSS frequencies

Frequencies for E5 are used by all GNSS, adopted widely from mass marked to professional receivers, protected band suitable for safety of life applications and better SNR (Signal to Noise Ratio) values than other bands. Dual frequency processing is state of the art and common procedure for high precision techniques, e.g. RTK, PPP-RTK and PPP (Real Time Kinematic, Precise Point Positioning). Although it is possible with triple frequencies which would improve reliability, time to compute position and longer baseline, this is currently only adopted by high end receivers [6].

As mass market receivers are adopting multi-frequency, multi-constellations seem to become the norm. Only special low energy applications use one constellation only. Multi-constellation results in more satellites, and gives a position where previously was not possible, better accuracy in difficult environments and better robustness to spoofing [6].

7.2.3 EGNOS development

EGNOS (European Geostationary Navigation Overlay Service) is a Satellite Based Augmentation System (SBAS) covering Europe; there are similar systems for other regions. EGNOS is currently supporting GPS with one frequency (L1) only, but plans to upgrade EGNOS to support two frequencies and capable of sending correction data for GPS and Galileo on two frequencies from 2025 [6].

EGNOS provides integrity and has been used mostly in aviation, but after upgrading EGNOS it can run as a competitive correction service and give better accuracy for a broader market. This can also be in the transport sector at land or sea, and especially in remote areas. This service aims at accuracy better than 1m horizontal and 1.5m vertical [6].

7.2.4 Receiver development

Receiver design is also receiving attention when developing satellite positioning.

There are an increasing number of smaller and cheaper GNSS receivers that perform quite well even when compared to more expensive high-end equipment [4]. Due to low cost and size, many GNSS receivers are embedded with a simple IMU in a sensor fusion.

Most improvements are seen in interference, jamming and spoofing mitigation. Algorithms like RAIM (Receiver Autonomous Integrity Monitoring), are now implemented in many receivers. Most receivers compute a position in real time with an estimated position uncertainty, and as mentioned more receivers use a sensor fusion or newer processing methods as PPP or PPP-RTK.

7.2.5 Antenna development

GNSS antennas are an important factor for accuracy, and especially challenging for mass marked applications where size, shape, power consumption and location of antenna is a limiting factor.

Trends and focus within antenna development are [14]:

- Multi-frequency - new antennas have to support frequency bandwidth for modern GNSS signals.
- Multipurpose - antennas now are made for easy integration and embedded into third party designs.
- Miniaturisation – all classes of antennas are developing antenna design to reduce size and weight.

7.2.6 Mass market focus on low power consumption

Mass market receivers running on battery are focusing on consuming as little energy as possible to keep good positioning while keeping sensors small, user friendly and running longer on battery. Short summary of used techniques are [6].

- Receiver duty cycling – power off GNSS except location request.
- Ephemeris prediction – Receivers do not do acquisition from GNSS signal, but instead receiver compute it or download from internet.
- Assisted-GNSS – assistance to timing, Doppler and provide clock and ephemeris.
- Snapshot acquisition – Computes a position only with a small portion of GNSS signal, but sacrifices reduced sensitivity and accuracy.
- Cloud processing – Position computation is done in the cloud, but this requires a good internet connection.

7.2.7 GNSS and ITS support sensors

Both in the professional and mass market there is a trend for utilizing sensor fusion. Applications like agriculture or mobile mapping use IMUs to reduce position errors, but also to give a better orientation. Even mass market exploits this in mobile phones, only with smaller and cheaper sensors. Traditionally this has been used in dynamic environments like trajectory computation, but now also a land surveyor uses this when measuring points with NRTK (Network RTK). Before they had to manually hold the GNSS sensor vertically, but now a GNSS/IMU integration gives more accurate vertical position and there is no need to hold GNSS sensor vertical for correct measurements [6].

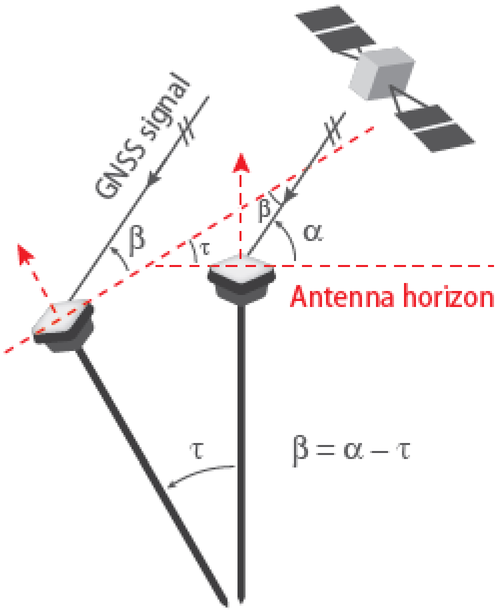

Figure 54: IMU measure antennas tilt for a land survey application [6].

All positioning sensors can be used in a sensor fusion where the goal is to exploit each sensors advantages and bridge the gap in accurate and reliable positioning in case one sensor would come to short. In an ITS perspective 5G and ITS (Intelligent Transportation Systems) roadside equipment can be used for supporting or compute positioning. The future probably gives more hybrid technology and sensor fusion in all market segments.

7.2.7.1 5G as a contributor to transport and positioning

5G has received a lot of attention due to significant improvements in latency, data speed and capacity for mobile connectivity compared to technology used today, and the Internet of Things (IOT) where all kinds of devices are connected online is mentioned as the next digital revolution. Even safety applications that need reliability and security are applicable, autonomous vehicles and vehicle-to-everything (V2X) are one of these. The ITS sector will require real time, and large scale data exchange with infrastructure and vehicles [6].

5G also introduce better derived direction and time of signals, especially for direct line-of-sight conditions, this leads to positioning capability within meter or sub-metre. It is believed that a hybrid GNSS/5G solution will be used especially in cities where 5G is not as constrained as GNSS by urban canyons, tunnels and other indoor areas [6].

Today GNSS corrections are distributed by satellite or internet, reception of signals from satellite can be limited in cities, deep valleys, forest or other areas with obstructions. Due to low latency, large data speed and capacity 5G is well suited for massive distribution GNSS corrections when more and more devices and instruments will use this type of positioning.

Achievable position accuracy with 5G is unknown and no reports of real-life accuracy test has been found. Telenor are participating in a large European 5G project, 5G-VINNI, and are aiming to do accuracy tests together with TEAPOT project to use 5G as a positioning source and answer these questions.

7.2.7.2 ITS roadside equipment

ITS Station is typically equipped to road users, such as cars, busses, pedestrians etc, or to road infrastructure. Every ITS-S requires knowledge about timing and their absolute coordinates to be able to operate together and exchange information. This exchange is called C-ITS (cooperative ITS).

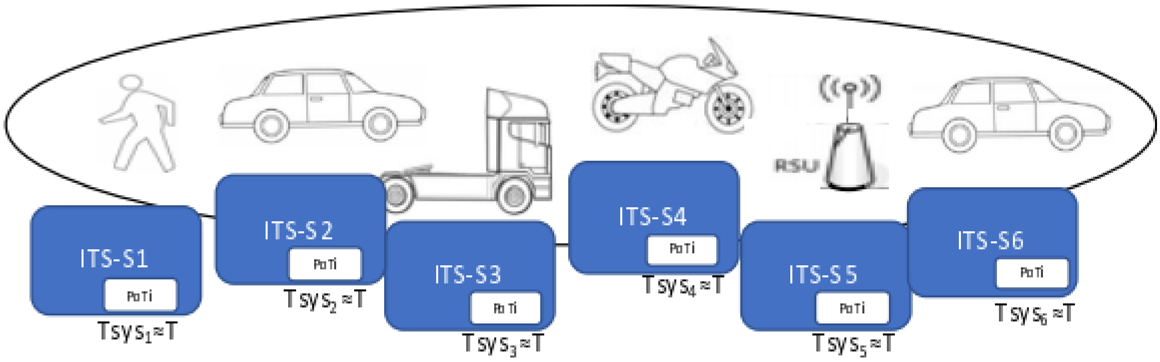

Figure 55: ITS stations [7]

To enhance position accuracy and integrity, a roadside RSU or ITS-S (e.g a traffic light – R-ITS-S) can be utilized in different methods [7].

7.2.7.2.1 Distribution of GNSS augmentation services

Corrections signals for GNSS based positioning, e.g. EGNOS, PPP-RTK, Galileo HAS, is broadcasted by satellite or internet. Similar to other terrestrial communication, ITS-S can be used to distribute these correction services [7].

7.2.7.2.2 R-ITS-S as a GNSS reference station

If R-ITS-S has a high quality GNSS receiver, this can operate as a GNSS reference station and distribute corrections to nearby ITS-S. This works as a traditional GNSS RTK service, and achievable accuracy is at cm level. In "ETSI ITS Part2: Position and Time management (PoTi)" this is described as a single baseline approach, RTK, where ITS-S always chooses the closest R-ITS-S. This means that ITS-S will change GNSS reference station when moving into a new area [7].

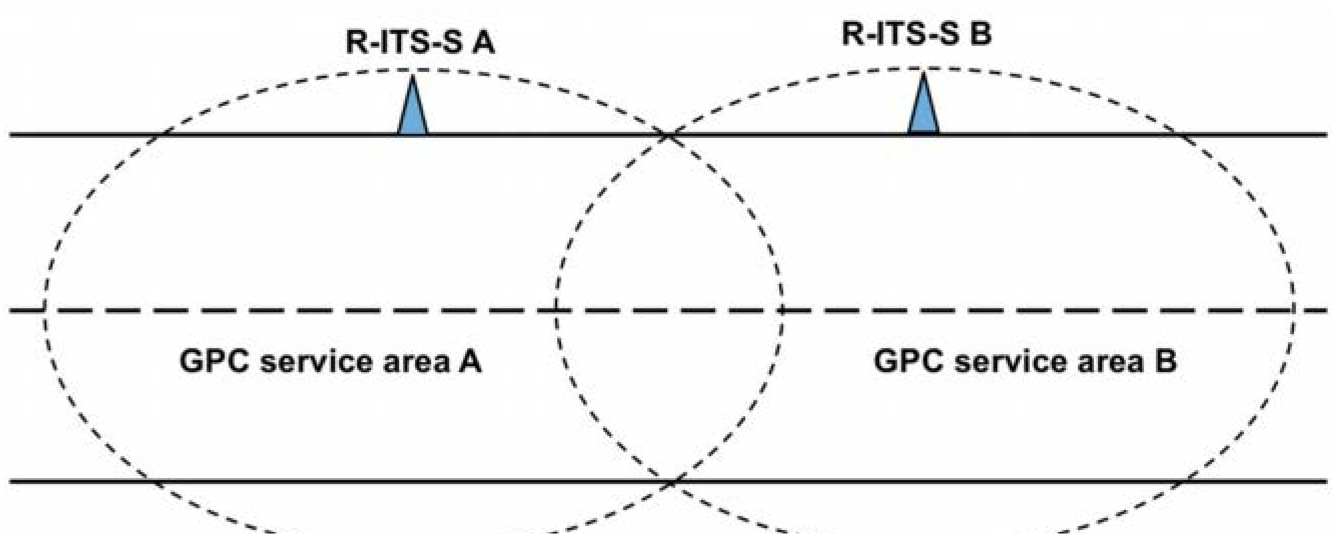

Figure 56: R-ITS-S as a GNSS single baseline concept [7]

7.2.7.2.3 R-ITS-S as a ranging augmentation service

A vehicle, or ITS-S, can measure range to an R-ITS-S directly and use that measurement to support other navigation sensors as e.g. GNSS or odometer from vehicle.

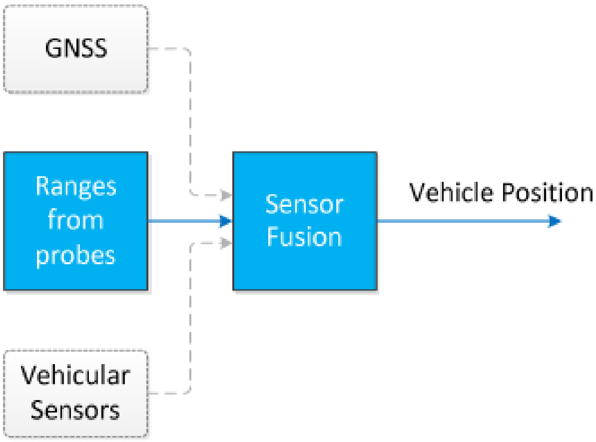

Figure 57: R-ITS-S range measurement in sensor fusion [7].

This is done by R-ITS-S broadcast a message announcing availability if range measurement is available or not. Then ITS-S "asks" for a range measurement based on time-of-flight to R-ITS-S, and then it responds back. Data in this measurement must contain, among others, 3D coordinates and ID of R-ITS-S. It noted that accuracy of station coordinates is important and should be better than 10cm, but there are no other indication of achievable accuracy for ITS-S [7]. These units use typical RTLS (relative radio based location systems) methods, and achievable accuracy is 0.1-1m [22].

7.3 Integrity and threats

There is more and more focus on integrity and threats since GNSS and sensor fusion are used in life-critical applications like autonomous driving. There is a lot of research within GNSS integrity today. TEAPOT project, WP2.4, covers integrity, and this subject is only briefly summarized here.

There are various methods for GNSS jamming and spoofing protection.

- Clean RF (Radio Frequency) environment, use of frequency bands are protected and regulation of this is a national responsibility.
- Antennas, two-antenna setup can disclose wrong signal directions.
- Authenticate GNSS signals, only the Galileo system is capable of doing this today by verifying broadcast messages and ranges to satellites.
- Sensor fusion, redundancy with other independent navigation sensors. E.g., a smartphones has many sensors that can provide redundant PNT or add constraint to position updates.
- Receiver techniques, various techniques are investigated at receiver design, but currently only available on high end receives.[6]

ITS standards describes different types of confidence [7]:

- Horizontal position
- Vertical position
- Heading
- Other ids available, like acceleration

- Accuracy estimations
- Relative positions
- Time information

7.4 Processing strategies

There are different methods for processing and calculating positions with GNSS both in real-time and post-processing. Different approaches are chosen from simplicity, cost, hardware, real-time or post-processing and need for accuracy. All common strategies are described briefly, and most focus on correction techniques applicable for navigation and autonomous driving.

7.4.1 SPP

SPP (Single Point Positioning) is the most common computation technique, as it only requires a cheap, basic GNSS receiver. It is a code-based computation and no correction methods are applied.

7.4.2 DGNSS

DGNSS (Differential GNSS) are quite similar to RTK described in chapter 7.4.3, but utilizes code signal instead of phase as for RTK. Most receivers capable of computing DGNSS or RTK can do both, and therefor RTK is often used.

7.4.3 RTK

RTK (Real Time Kinematic) is a relative positioning technique where at least two GNSS receivers simultaneously track at least four common satellites [3]. One receiver, the base station, has known coordinates and the rover, receiver with uncertain coordinates, is positioned relative to the base station.

When utilizing that both receivers have the same error sources, RTK remove or mitigate:

- Satellite orbit – satellite vehicles position in space
- Ionosphere – about 80 to 1000km above ground, reflecting radio waves.
- Troposphere – lowest layer in atmosphere, above 0 – 10km above ground, where all weather conditions take place.

RTK has the potential to measure absolute position with cm accuracy, corrections are distributed by radio VHF (Very High Frequency) or internet in real time. Similarity of the error sources decreases with distance between the receivers, and so the relevance of correlating the corrections, practical distance being 10 to 20 km.

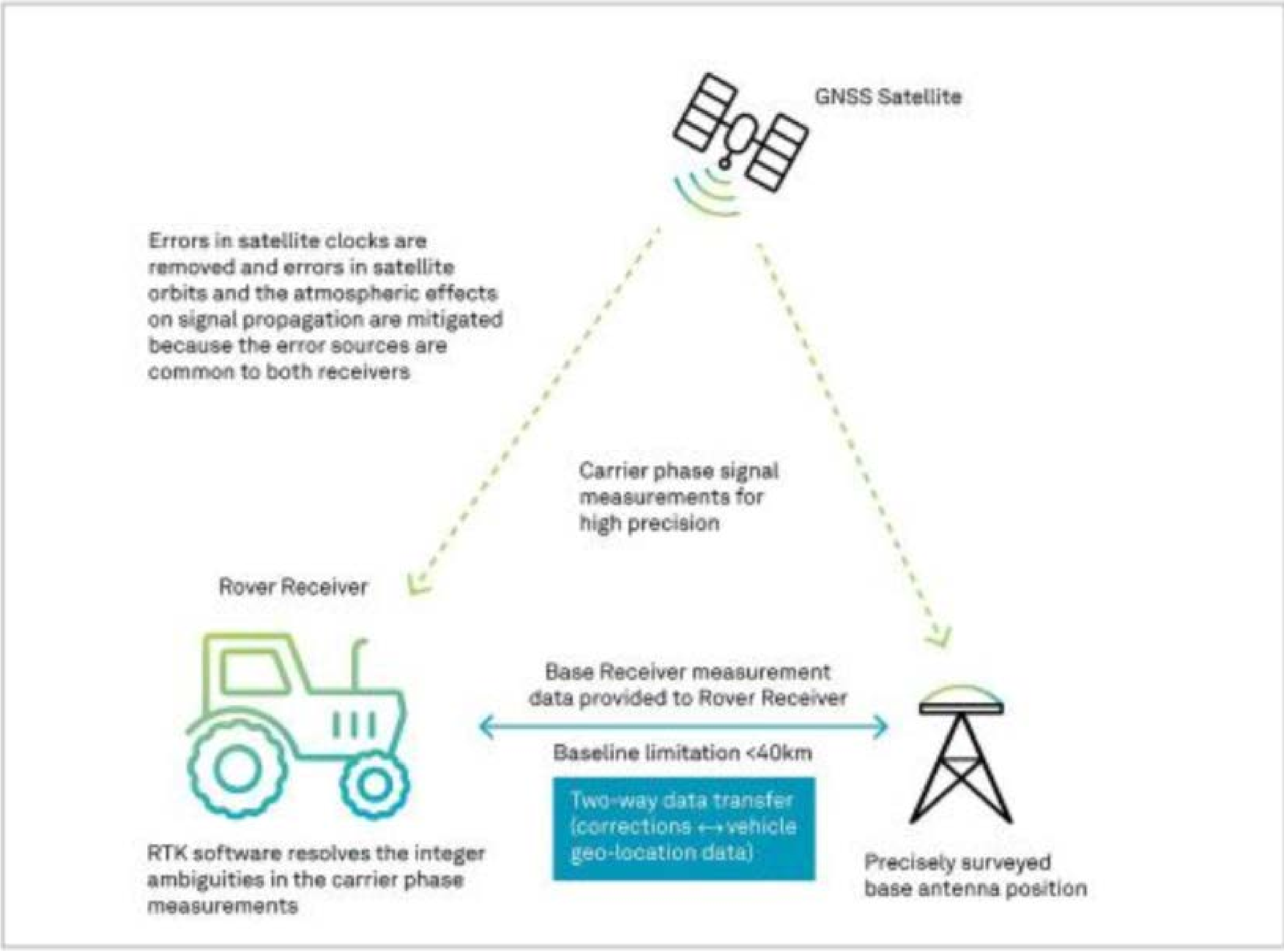

Figure 58: A diagram of a typical RTK system featuring a base receiver, a rover and GNSS satellite [2]

7.4.4 Network RTK

Network RTK is quite similar to RTK, but uses several base stations with longer baseline. Baselines are the distance between different base stations or distance between base station and user equipment. When using NRTK the idea is to generate a virtual base station close to the rover and generate corrections. In practice, the rover, receiver that needs corrections, send its position to the central processing facility and position for the virtual base station is established. Then interpolated corrections for that area are computed and sent back to the rover. Rover utilize corrections to compute a corrected position [3].

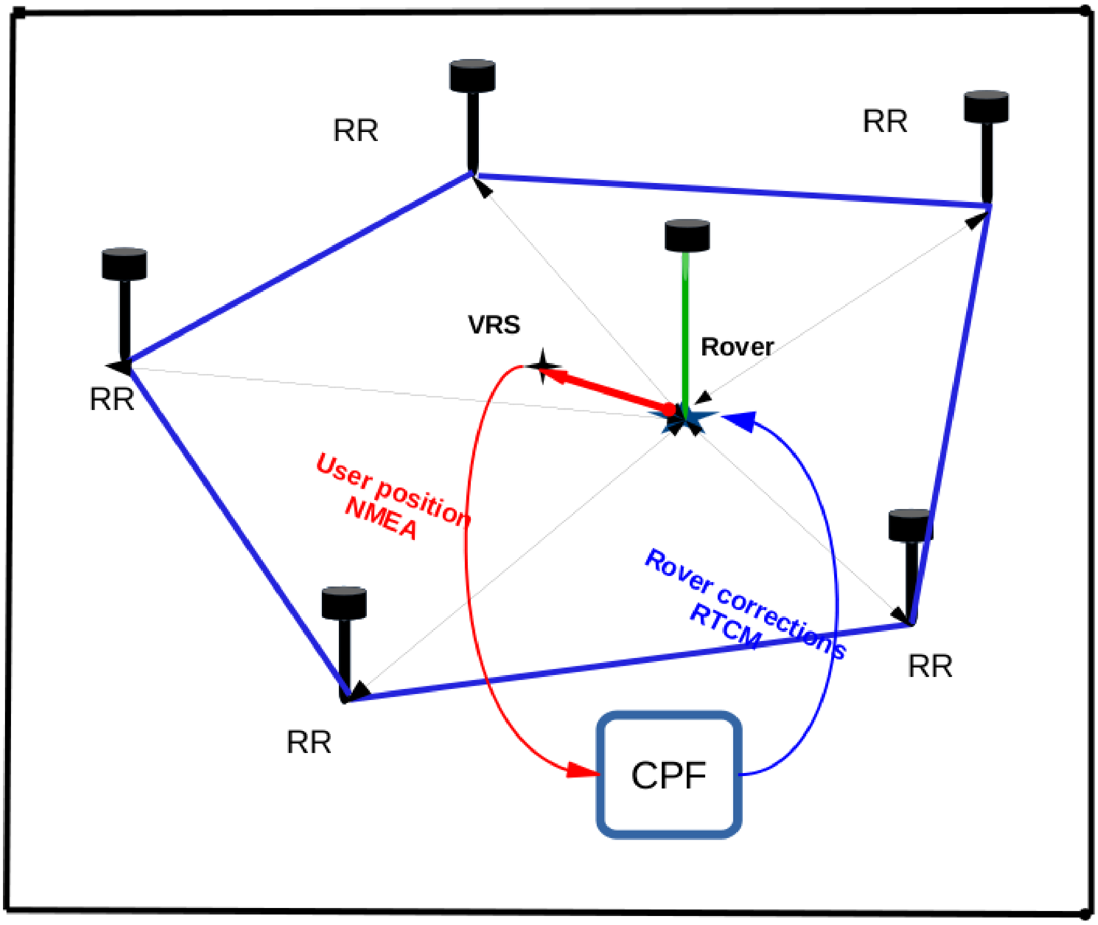

Figure 59: NRTK VRS concept. CPF - Central processing facility, RR - reference receiver/base station, VRS – virtual reference receiver/base station [3]. RTCM and NMEA are organizations that defines corresponding standard formats for GNSS and corrections.

The Norwegian Mapping Authority has a NRTK service, CPOS, with baselines from approximately 35 to 70km. Horizontal accuracy is 8mm in areas with 35km baseline, and 14mm in areas with 70km baseline [18].

	Areas with approximately 35km between base stations	**Areas with approximately 70km between base stations**
Horizontal EUREF89	8 mm	14 mm
Height EUREF89 (above ellipsoid)	17 mm	30 mm
Height NN2000	20 mm	36 mm

Figure 60: CPOS accuracy in areas with approximately 35km between base stations, and approximately 70km between base stations. Values are given as one standard deviation, it means that 66% of measurements will be better than stated values.

7.4.5 PPP

PPP (Precise Point Positioning) uses corrected precise satellite orbit and clock data, and can achieve position with cm accuracy. International GNSS Service (IGS) and Jet Propulsion Laboratory (JPL) distribute precise satellite orbit and clock data as products and Ultra-rapid products available in real-time [3]. With these products, PPP positions can be computed in real time or post processed. PPPs advantage is that it is cost efficient since it only needs one receiver and no other correction services, and it works worldwide. The downside is that this method needs convergence time of at least 20 minutes to achieve cm accuracy.

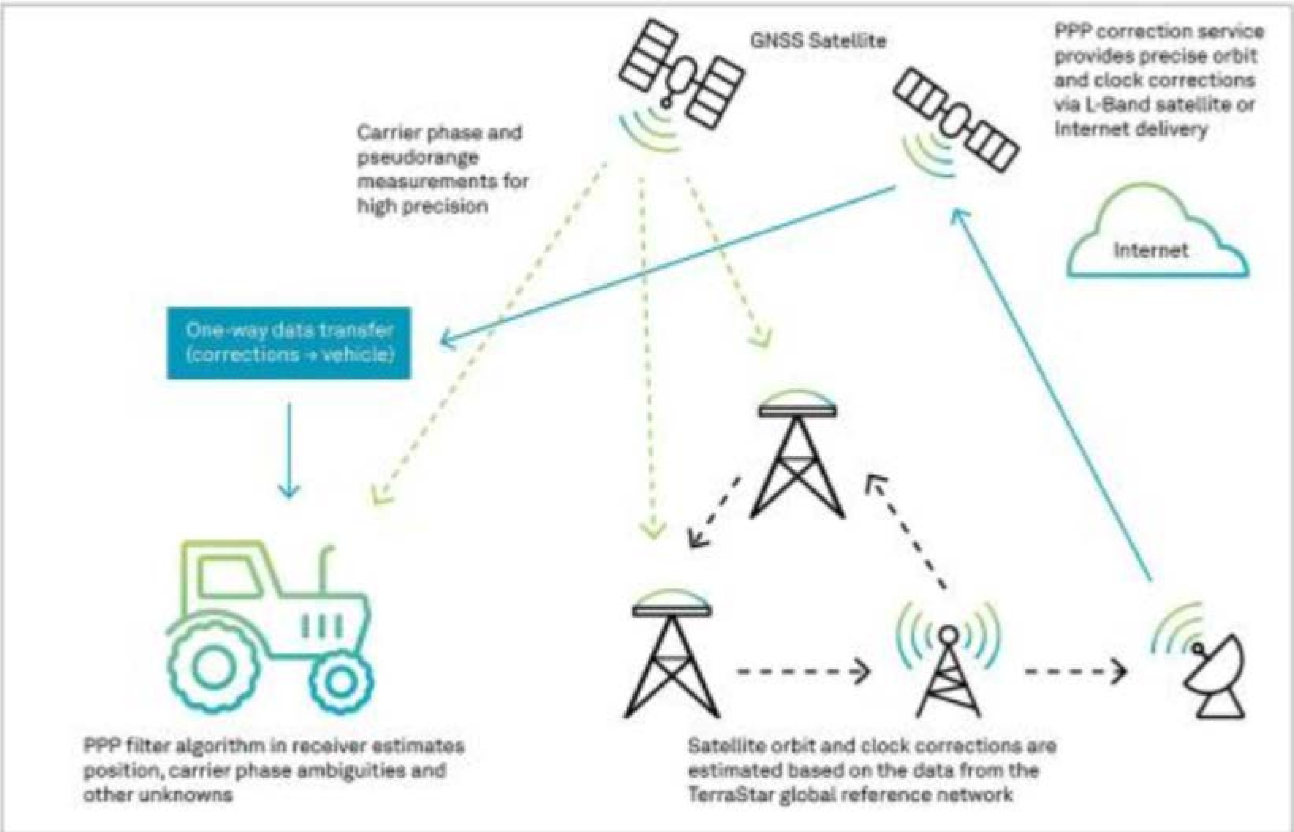

Figure 61: A diagram of a typical PPP system, with corrections from internet or satellite [2]

7.4.6 PPP-RTK

PPP-RTK can be regarded as the PPP augmented high-precision positioning service [3]. It uses corrections for orbits and clocks like PPP, and generates a troposphere and ionosphere model from base stations and RTK [6].

This method aims to have a better coverage and less infrastructure (base stations) than NRTK networks by not relying on relative (double differenced observations) measurements. NRTK services usually have a two-way communication with user equipment, but PPP-RTK can broadcast corrections to users and limits bandwidth need.

The downsides are longer TTFF than RTK, which also leads to reduced accuracy in challenging GNSS areas [4]. And PPP-RTK relies on a sparse network of base stations, so services get unavailable in rural areas [6].

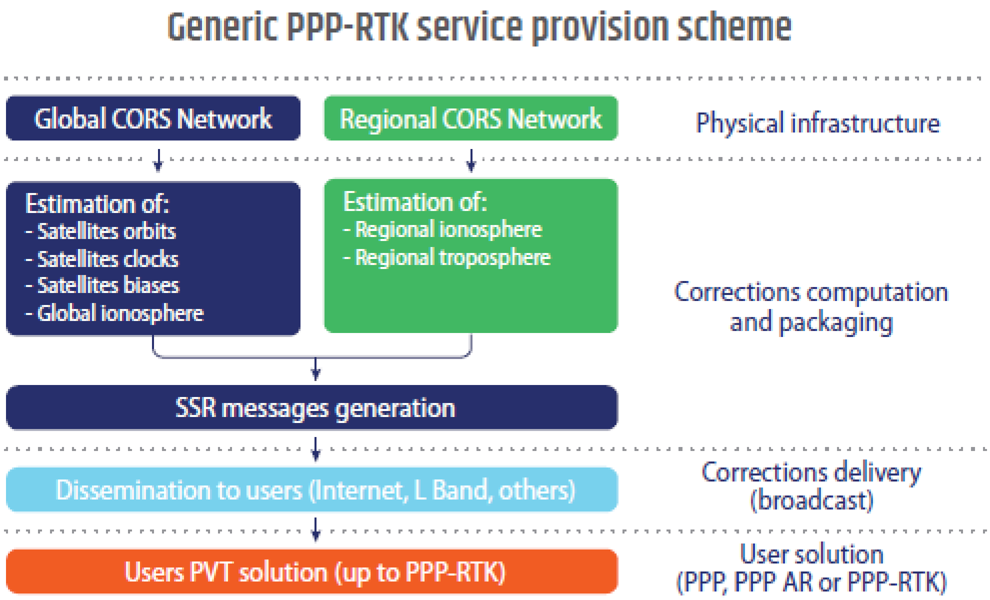

Figure 62: PPP-RTK overview [6]

PPP-RTK market today is narrow, and dominated by a few players where proprietary formats are used, unlike PPP and NRTK that have open formats and are supported by many sensors.

7.4.7 Galileo High Accuracy Service

Galileo will offer four high-performance services worldwide [1]:

- Open service - OS
- High Accuracy Service – HAS
- Public Regulated Service - PRS
- Search and Rescue Service – SAR

About trends in positioning within the transport sector the HAS is the most interesting service as it will provide corrected positions free of charge. HAS uses a real time PPP technique and aims for an accuracy below 20cm horizontal and 40cm vertical by broadcasting corrections, better satellite orbits, clocks and biases, distributed by satellite with the Galileo E6-B channel. Corrections can also be distributed by the internet. In Europe, it is planned to distributed atmospheric corrections as well to speed up initialization time [5].

Galileo HAS is currently in a testing phase, but HAS initial service is planned to roll out in the 2nd half of 2022 with PPP corrections to users in Europe. Later HAS full service will be enabled with two service levels. Service Level 1 allows PPP-AR globally with convergence time less than 5min. Service level 2 will add atmospheric corrections in Europe, being a regional service, and achieves convergence time of less than 100 seconds [5].

From tests started with Galileo HAS there has been a development in accuracy and this service is now, Figure 63, providing stable accuracy below 25cm.

It is important that Galileo HAS will support all Galileo frequencies, and in addition GPS L1/L5 and L2C.

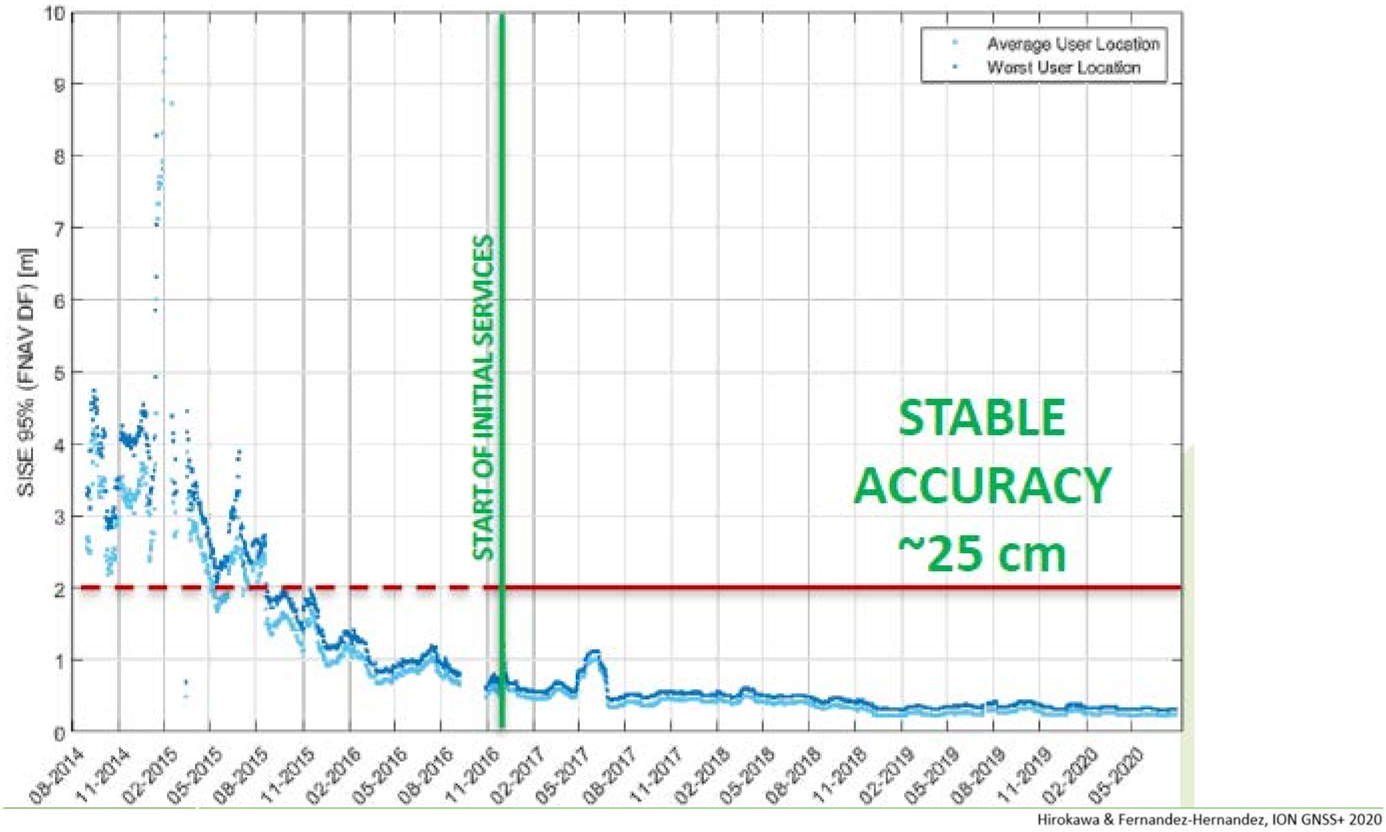

Figure 63: Development of Galileo HAS accuracy [5].

7.4.7.1 Other open PPP services

Not only the Galileo system are designing or developing a PPP service, there are initiatives from Japans QZSS, Beidou, Australias SBAS system and GLONASS.

Galileo HAS in context

High Accuracy services from RNSS Providers

System	Service	Satellite	Status	Data Rate per Sat	Format	Coverage
QZSS CLAS	PPP-RTK	IGSO/GEO	Operational (2018-)	2,000 bps	Compact SSR	Regional (Japan)
QZSS MADOCA	PPP	IGSO/GEO	Experimental (2017-)	2,000 bps	RTCM SSR	Regional (Japan)
Galileo HAS	PPP	MEO	Experimental (2020-)	~500 bps	Based on Compact SSR	Global
BeiDou PPP	PPP	GEO	Operational (2020-)	500 bps	SSR (PPP-B2bI ICD)	Regional (China), MEO/global plans
Aus/NZ SBAS	PPP	GEO	Development (2023-)	~250 bps	Under definition	Regional (Aus/NZ)
GLONASS PPP	PPP	GEO	Concept (2030-)	4,000 bps	RTCM SSR	Regional (Russia)

Hirokawa & Fernandez-Hernandez, ION GNSS+ 2020

Figure 64: Other PPP correction services [16]

The one who stands out is QZSS CLAS (Centimeter Level Augmentation Service), which is the only PPP-RTK. This service supports QASS, GPS, Galileo (GLONASS in future). They aim for an accuracy better than Galileo HAS which is an PPP service, see their specification for details regarding remarks on technical details. CLAS service is only available in Japan [17].

Positioning Type	Positioning Error		Remark
	Horizontal	Vertical	
Static	≤ 6cm(95%) (3.47cm(RMS))	≤ 12cm(95%) (6.13cm(RMS))	(*)(**)
Kinematic	≤ 12cm(95%) (6.94cm(RMS))	≤ 24cm(95%) (12.25cm(RMS))	(*)(**)

Figure 65: QZSS CLAS positioning accuracy

7.4.8 Overview of computation strategies

I table in Figure 66 is common GNSS computation strategies. The numbers are achievable accuracy in an open sky environment. [6]. Vertical accuracy is not listed, but it is often about 1.5 larger than horizontal accuracy due to satellite elevation and geometry.

Major GNSS position computation strategies

Method *	SPP	DGNSS	SBAS	RTK	PPP-RTK	PPP
Observable	Code	Code	Code	Carrier	Carrier	Code / Carrier
Positioning	Absolute (in the GNSS reference frame)	Relative	Relative	Relative	Absolute (in the tracking network reference frame)	Absolute (in the tracking network reference frame)
Comm Link	No	Yes	Yes (GNSS like)	Yes	Yes	Yes
Single Frequency (SF) Dual Frequency (DF) Triple Frequency (TF)	SF or DF	SF	SF current DF planned	Mostly DF	(SF) DF or TF	(SF) DF or TF
Time To First Fix (TTFF)	Rx TTFF	As SPP + time to receive corrections	As DGNSS	As DGNSS + time to resolve ambiguities	Faster than PPP, but slower than RTK	As RTK, but time to estimate ambiguities significantly higher (more unknowns)
Accuracy Horizontal	5-10 m DF 15-30 m SF	< 1 m to < 5 m	< 1 m	1 cm + 1 ppm baseline	< 10 cm	< 10 cm to < 1 m
Coverage	Worldwide	Up to 100s Km	Up to 1000s Km	Up to 10s Km	Regional	Worldwide

** Acronyms are defined in Annex 5.*

Figure 66: Major GNSS computation strategies [6]

The table in Figure 67 shows error mitigation for different computation strategies [6].

	OSR (Observation State Representation)		SSR (Space State Representation)		
	RTK	Network RTK	Carrier PPP	Code PPP	PPP-RTK
Error mitigation	Combined range correction		Orbits, clocks, biases		Orbits, clocks, biases, iono, tropo
Accuracy	~ cm		< dm	~ 3 dm	< cm
Time required	< 5 s		~ 20 min	< 1 s	< 5 s – 100 s(1)
Service area	local	regional	global	global/ regional	global/ regional
Single frequency capability	✓ receiver dependent		✓ receiver dependent	✓	✓ (2)
Required bandwidth	medium	medium-high	low	low	low-medium

(1) depends on update rate
(2) depends on the algorithm used

Figure 67: Overview of high accuracy real time methods [6]

7.4.9 Methods of GNSS corrections distribution

Traditional NRTK services uses a two-way communication, GNSS receiver with uncertain position sends its position to GNSS correction processing center that computes a lump sum correction valid for the receivers area. This method is called OSR (Observation State Representation) and is used by the CPOS service from the Norwegian Mapping Authority.

The development of real time global corrections services have forced new formats to be developed. With services like Galileo HAS or a PPP-RTK service, corrections have to be broadcasted to users with a one-way link to be scalable for unlimited number of users. This method is called SSR (State Space Representation) and decorrelate and estimate different error sources (states). Corrections for satellite- clocks, orbits and signal biases, and ionospheric and tropospheric delay are broadcasted. GNSS receivers compute corrections valid at their position, and information about statistical accuracy for correction sources are also transmitted [23].

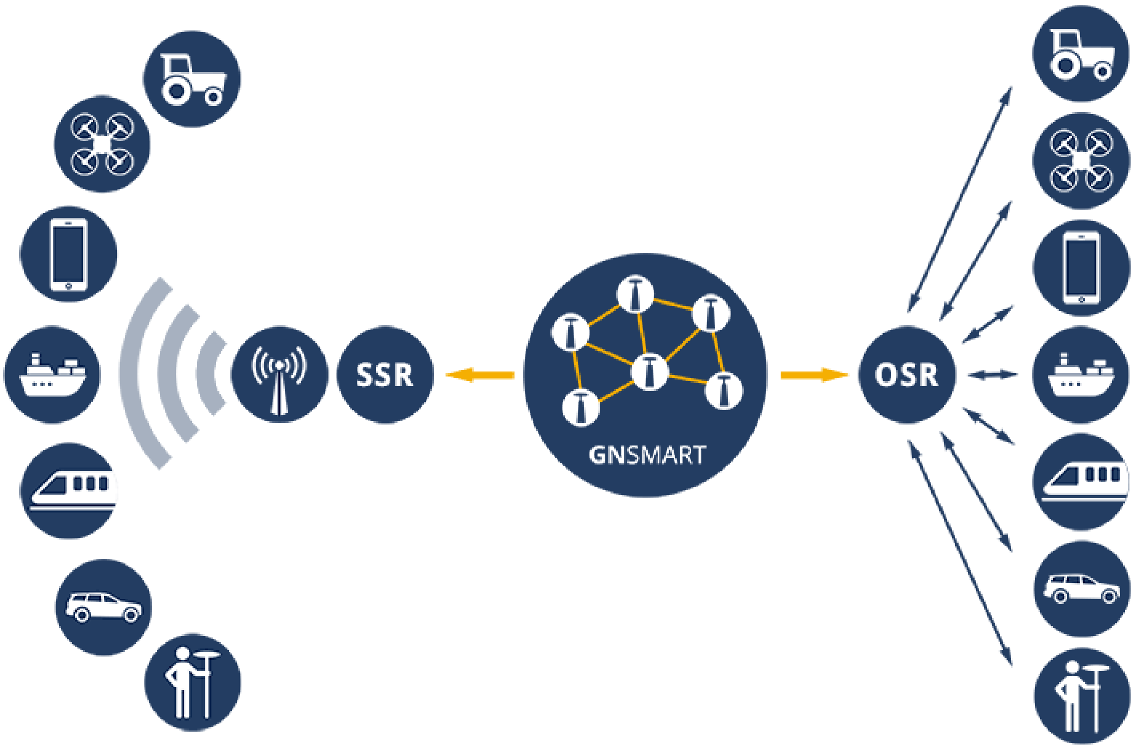

Figure 68: Principal differences between OSR and SSR. GNSMART is GNSS correction processing center [23]

Quick comparison of OSR and SSR are:

	OSR	SSR
Accuracy	Centimetre	Centimetre
Format	Open	Proprietary
Coverage	Regional/local	Global
Communication	Two-way	One-way
Bandwidth	High	Low
Maturity	Well established	New, not always implemented

7.4.10 Example of SSR correction data format – SPARTN

SAPCORDA has made their GNSS corrections service from scratch and a new format for distributing data was identified as a key feature. This format has similarities with the well known RTCMv3 (Radio Technical Commission for Maritime Services) format and use a SSR approach, but is designed for better low bandwidth, accuracy, availability, reliability and integrity for safety of life applications. SPARTN (Safe Position Augmentation for Real Time Navigation) are under continuously development and are available for everyone free of charge, aiming for this format to de adopted by the industry. Latest version, v2.0, was released in December 2020 with integrity message definition and additional signal and constellation support [8] [9].

7.5 Low cost mass marked equipment

Mass market sensors are produced in large volumes, applications are among others in smartphones, IoT, automotive, drones or sports tracking. These sensors, unlike professional receivers, are focusing on availability of position, low TTFF (Time-To-First-Fix) and low power consumption due to battery life [6].

Multi-constellation support seems now to be the standard as shown in Figure 69, and in 2018 the first smartphone with a dual frequency (adding L5/E5a) was launched and it is expected that this will become more common in the future [6].

With multi-constellations and -frequencies on mass market devices, numerous GNSS providers are releasing high-accuracy-services at a regional and global scale. In some countries, telecom operators have joined geospatial companies to utilize 5G technology. In Japan 5G base stations have been used as GNSS reference stations, and one company has installed 3300 5G GNSS base stations. In Germany 5G has been used to distribute PPP-RTK corrections quickly in real time [6].

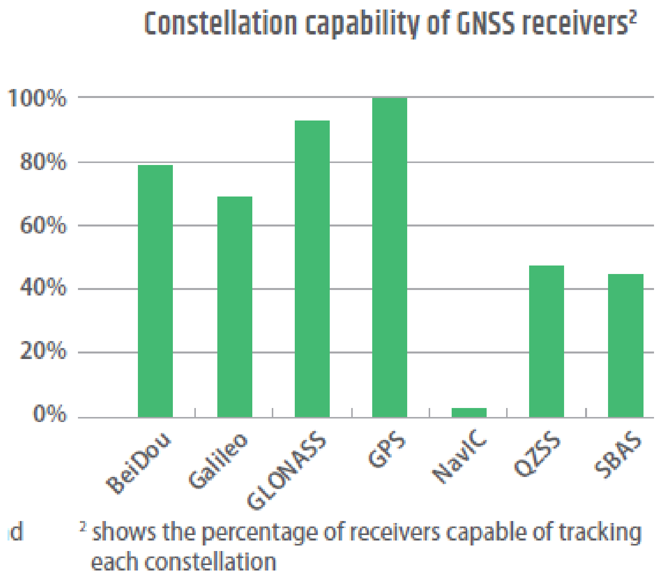

Figure 69: Mass market receivers capable of using GNSS systems [6]

Mass market equipment is often combined with other sensors as for example in smartphones. IMU (Inertial Measurement Unit), WiFi RTT (Round Trip Time), Bluetooth or UWB (Ultra Wide Band) are technologies that can be used for positioning for example indoors. These technologies can be used for positioning quite similar to GNSS, where some devices are described as pseudo-satellites with known coordinates [6].

To give an example of maturity of mass marked equipment, the Norwegian Mapping Authority conducted in 2020 a dynamic performance test of GNSS receivers at different price levels. Among these was uBlox F9P (GNSS receiver) and F9K (GNSS receiver with IMU) evaluation kits with a low price level compared to high end GNSS receivers. All sensors were connected to NRTK service CPOS, and cumulative position error for different sensors from this test are shown in Figure 70. CPOS is results for Trimble NetR9 receiver and geodetic antenna Trimble Zephyr Geodetic 2 using CPOS service, GR (GPS,GLONASS) to GREC (GPS, GLONASS, Galileo, Beidou) describes which constellation that is used. RTX-GREC is Trimble NetR9 receiver and geodetic antenna Trimble Zephyr Geodetic 2 which uses Trimble's PPP-RTK service Trimble RTX Center Point.

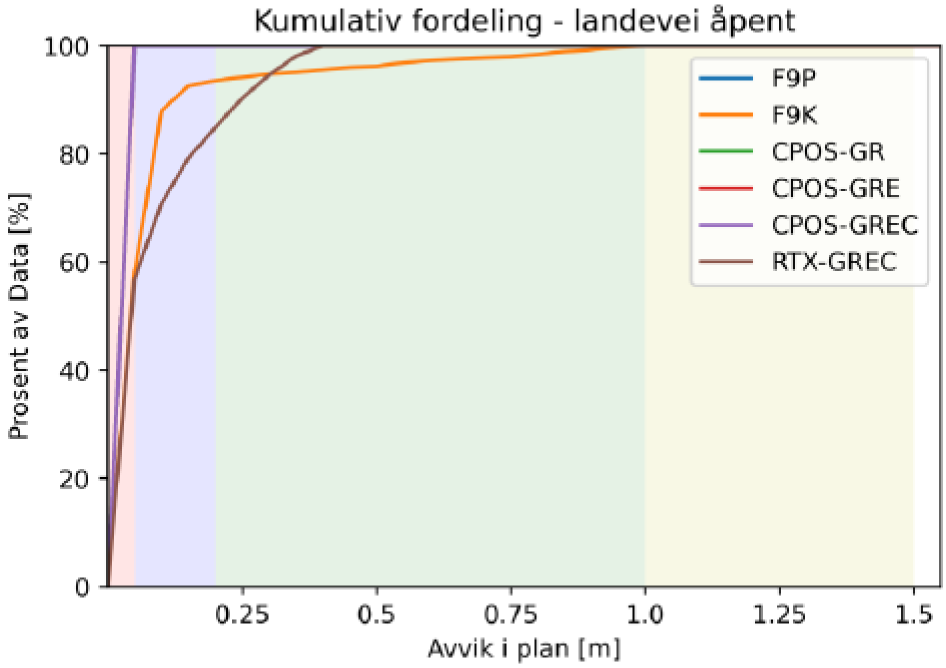

Figure 70: Cumulative plot for deviation on x-axis and percentage of data on y-axis. Area is a countryside road with no obstructions to satellites.

uBlox F9P got 94.4% of positions within 5cm, and CPOS performance with professional receiver is about the same level with 97.2% of positions within 5cm. Trimbles RTX Center Point service is also tested, and this corrections technique performs worse than uBlox receivers using CPOS. High end equipment is only performing better in challenging areas for GNSS measurements, f.ex. urban canyons [4].

7.6 Positioning for life-critical applications

Users that operate life-critical systems, often used for autonomous operation, have high demands for positioning, and their priority of key performance indicators are shown in Figure 71 [6]. As can be seen, only indoor penetration and power consumption do not have a high priority (** refers to drone applications, where power consumption is important).

Safety-and Liability-Critical Devices Key Performance Parameters

Key Performance Parameter (KPP)*	Safety - and Liability- Critical Devices
Accuracy	⬢⬢⬢
Availability	⬢⬢⬢
Continuity	⬢⬢⬢
Indoor penetration	⬢⬡⬡
Integrity	⬢⬢⬢
Latency	⬢⬢⬢
Power consumption**	⬢⬢⬡
Robustness	⬢⬢⬢
Time-To-First-Fix (TTFF)	⬢⬢⬢

⬢⬢⬢ High priority ⬢⬢⬡ Medium priority ⬢⬡⬡ Low priority

Figure 71: Safety Key Performance Indicators [6]

GNSS receivers for safety applications, traditionally focused on marine and aviation, are produced to meet demands in certification. This leads to innovation in other sectors, then standards are updated and manufacturers produce receivers after new standards. This is apparent when EGNOS, which has an integrity message, only uses GPS. But today multi-constellations and -frequencies are common practise in sectors that don’t require integrity [6].

There are different approaches to ensure integrity, availability and robustness. EGNOS is already mentioned, receivers use RAIM, Galileo has Navigation Message Authentication (OS-NMA) and of an encrypted navigation signal on E6, the Commercial Authentication Service (CAS). These functions offer the first protection against spoofing available to civilian GNSS – Galileo. Sensor fusion can be used for comparing independent measurement methods, and uses strengths from different sensors or redundancy.

Integrity methods and concepts are elaborated further in WP2.4 of this project.

7.6.1 GNSS correction services aimed for life-critical situations

Several GNSS correction services released are aiming for autonomous operations like agriculture, robotics or vehicles on public roads. However, they can of course also be used for non-critical applications. These services focus on KPIs listed in Figure 71 to keep safety as a key factor. But also to provide service at a regional or global at a low enough cost to be adopted by the mass market.

7.7 Business models

With respect to positioning and the automotive industry, this is an emerging business and there are different approaches. Some are providing a GNSS correction service only, some hardware providers are building own correction service, hardware and software, while others provide modules to be integrated in a navigation system.

7.7.1 Correction services

The Norwegian Mapping Authority runs a network of base stations to provide NRTK service CPOS covering the entire Norway. Private companies can stream data from these base stations to generate either PPP-RTK or NRTK services. This implies that several private companies are using the same infrastructure to produce competitive services, their benefit is that they do not have to operate and maintain their own base stations and can reduce cost and complexity. In Sweden the Swedish mapping, cadastral and land registration authority runs a service similar to CPOS [19]. In Finland services run by private companies and National Land Survey of Finland [21]. In Denmark there are private companies running NRTK services. Private company Hexagon SmartNet has a service in Norway, Sweden, Denmark, Finland and most of Europe [20].

For PPP-RTK services two of the largest companies, Trimble and Novatel, have restricted this to their hardware. Sapcorda on the other hand has service open for all, but their format SPARTN must be implemented. Mentioned companies distribute corrections by satellite and internet. Swift Navigations Skylark service is independent of hardware and OEMs can implement this service. Corrections are distributed by the internet. There are probably other providers not mentioned here that run similar services. These PPP-RTK services have different service levels where the most basic is a PPP solution with reduced performance with respect to initialization time and accuracy. In the case of Sapcorda, only the most advanced service provides integrity messages. Galileo High Accuracy Service, described in chapter 7.4.7, is a free PPP-RTK service implemented in Galileo system design. When operative, this will be a competitor to private services. Japan has a Regional Navigation Satellite System, RNSS, named QZSS. It is now broadcasting an open Centimeter Level Augmentation Service, CLAS, on QZSS L6 signal. This service is only available in Japan [10].

Some of the largest companies are running NRTK networks in several countries. Hexagon, Trimble and Topcon have an operative service in Norway. The same network also covers other countries in Europe, parts of the USA and Australia. NRTK demands more ground infrastructure than PPP-RTK, but provides better accuracy.

HERE technologies and their service HD-GNSS aims to bring together the data providers and the sources and do the service distribution through the HERE platform. HERE offers a market place where RTK providers and owners of base stations can link their data to the platform, HERE distributes data to end-users via the internet, and they deliver in open formats well known in the industry. This service aims for a sub-meter accuracy, even with mobile devices with no other hardware [15].

7.7.2 Software libraries

Trimble supports automotive industry by their RTX Auto library, with this library Trimbles positioning services can be implemented with any GNSS receiver [11]. This is a different approach compared to when a user wants to use a standalone GNSS receiver, then their positioning services are restricted to their hardware only.

Hexagon has a position engine which is designed for automotive applications. It can take input from GNSS receivers of different brands, IMU, odometer or even LiDAR. It is customizable for sensors from different brands [12].

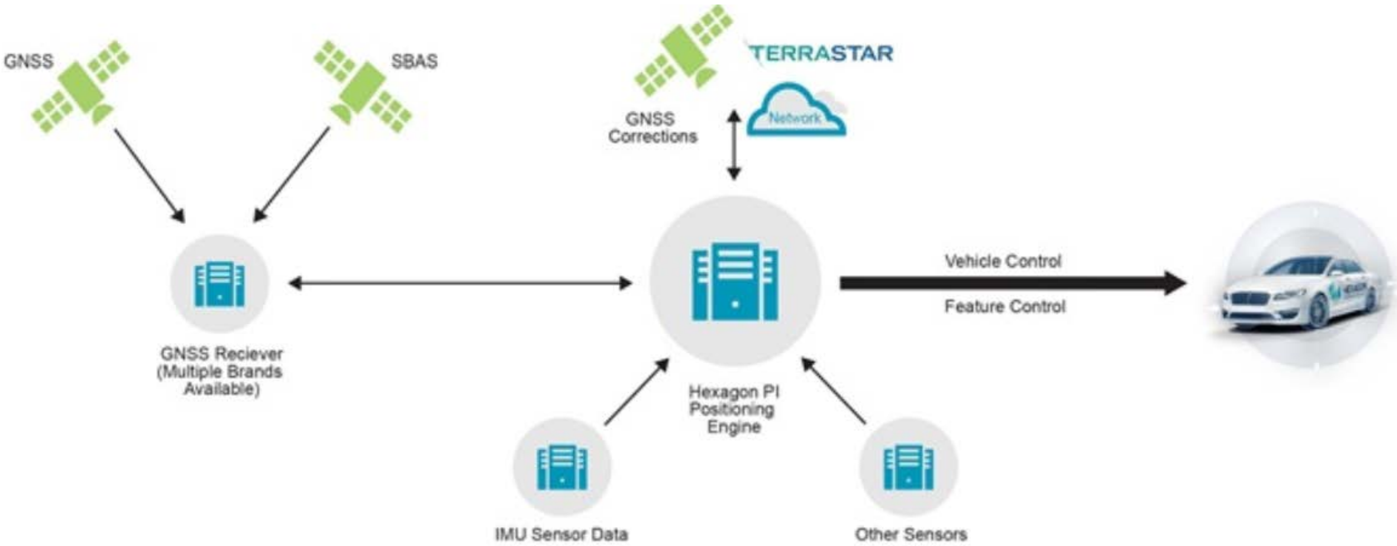

Figure 72: Hexagon position engine [12]

7.7.3 Embedded systems and engineering support

Trimble provides GNSS boards, modules, chipset to automotive OEMs for implementation of positioning and RTX services.

Hexagon provides engineering services and support for implementation of software and equipment selection. This is an approach to help clients to an easier implementation and shorter time to market. https://hexagonpositioning.com/autonomous-x/automotive-positioning/serial-production/engineering-and-integration-services

U-blox, one of the companies behind Sapcorda, produces modules designed for automotive mass market and easy implementation. These modules can receive any GNSS correction service, including SPARTN, and give in lane accuracy [13].

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8 Technological approaches and challenges

Morten Taraldsten Brunes and Samuel Schiess

8.1 Introduction

Autonomous vehicles use various sensors to navigate and position themselves, however these sensors have their pros and cons and they must be implemented with that in mind. These vehicles can also be supported by roadside infrastructure to achieve autonomy.

Autonomy is an emerging business sector and this paper highlight how different car and autonomous vehicle developers are approaching this challenge. A substantial part is Nordic conditions with snow and harsh weather.

8.1.1 Abbreviations and Definitions

ADAS	Advanced Driver Assistant System	Systems to help drivers
AI	Artificial Intelligence	Intelligence demonstrated by machines
API	Application Programming Interface	To give software developers a connection between computers or between computer programs
AV-maps	Mobileye's version of HD-maps	Less information than HD-maps specifically for Mobileye
CCAM	Cooperative, Connected and Automated Mobility	
CEN	European Committee for Standardization	Standardization organization
CNN	Convolutional Neural Network	Subset of artificial intelligence
GNSS	Global Navigation Satellite System	Common name for all navigation systems
GPR	Ground Penetrating Radar	Sensor that use radar pulses to image the subsurface
HD-maps	High Definition maps	Detailed maps along a road often used for autonomous vehicles
IMU	Inertial Measurement Unit	Sensor that measures acceleration and orientation
INS	Inertial Navigation System	Navigation device that uses a computer, motion sensors (accelerometers) and rotation sensors (gyroscopes)
ISO	International Organization for Standardization	Standardization organization
LGPR	Localizing Ground Penetrating Radar	Special type of GPR used for localization
LIDAR	Light Detection and Ranging,	Laser scanner sensor
MIoU	Mean Intersection over Union	Statistical measure

NMA	Norwegian Mapping Authority	National mapping agency Norway
NRTK	Network Real Time Kinematic	GNSS correction method where positioning is relative to multiple GNSS receivers
OTA	Over The Air	Updates to vehicle software downloaded and installed at home
RTLS	Real-Time Locating Systems	Short range local positioning system
SAE	Society of Automotive Engineers	Defines levels of automation for vehicles
SDK	Software Development Kit	Collection of software development tools in one installable package

8.2 Sensors on the vehicle

Autonomous vehicles from different manufacturers are often based on the same navigation sensors, and there are different approaches to software and how to utilize information from each sensor Figure 73 shows a simplified sketch of a vehicle with different sensors.

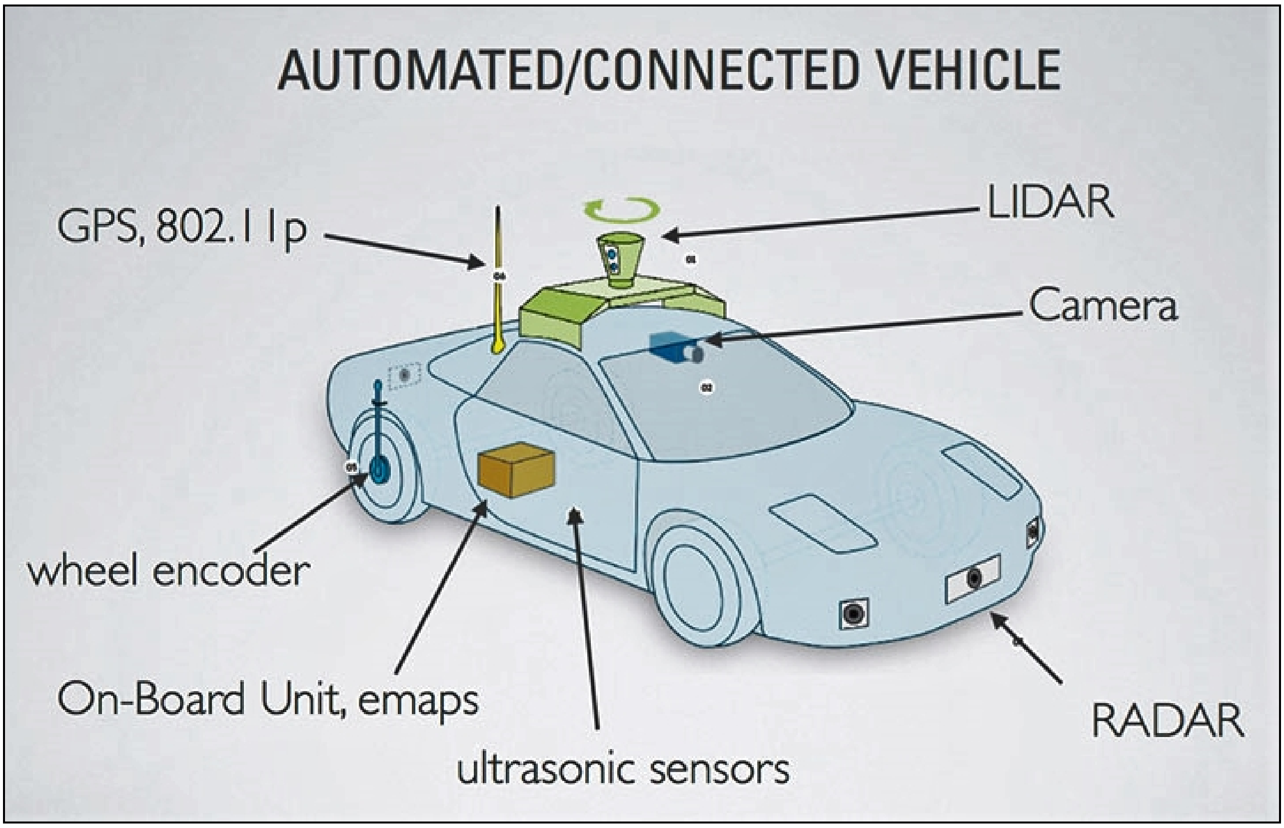


Figure 73: Typical sensors of an autonomous car [2]

8.2.1 Odometer

Odometers, or wheel encoders, measure the rotational rate of a vehicle wheel. Most common are mechanical, rotary encoders. Rotary encoders' measurement resolution is given by pulses per rotation, and with knowledge of wheel circumference the speed and distance can be computed. These odometers often measure incremental with a quadrature technique. Incremental means that the odometer use two signals, A and B, to report real time changes in velocity and direction, but have to be used in a sensor fusion algorithm to report absolute position. Signal A and B are quadrature encoded, shown in Figure 74, meaning that signals are 90° phase difference between A and B. Encoders direction, vehicle driving forward or backward, is determined by sign of A-B phase and instrument set up on vehicle [1].

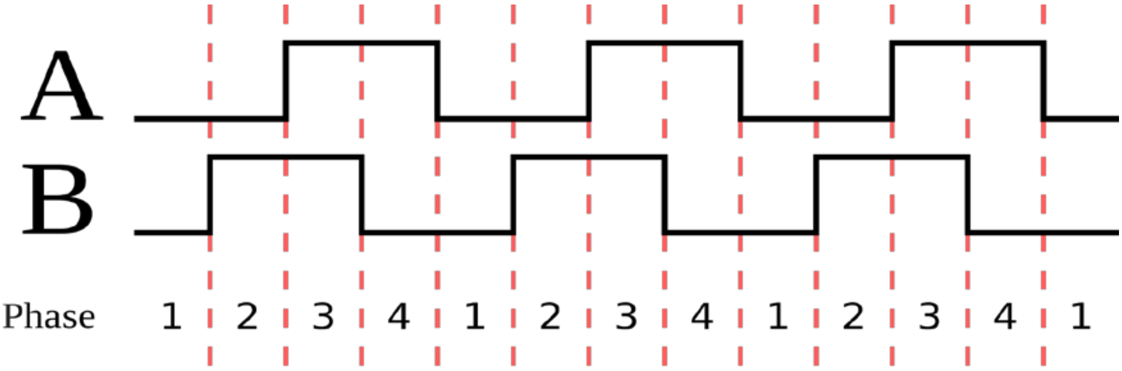


Figure 74: Quadrature encoder, A and B signal.

Quadrature measurement technique also yields that it is possible to measure four times per pulse, so if the encoder has 128 pulses per revolution, 512 measurements per revolution are measured. A typical vehicle wheel diameter is approximately 65cm, which gives a measurement approximately every 4mm [1].

Figure 75: Pegasem WSS2, a mechanical rotary and incremental odometer, mounted on the Norwegian Mapping Authorities car.

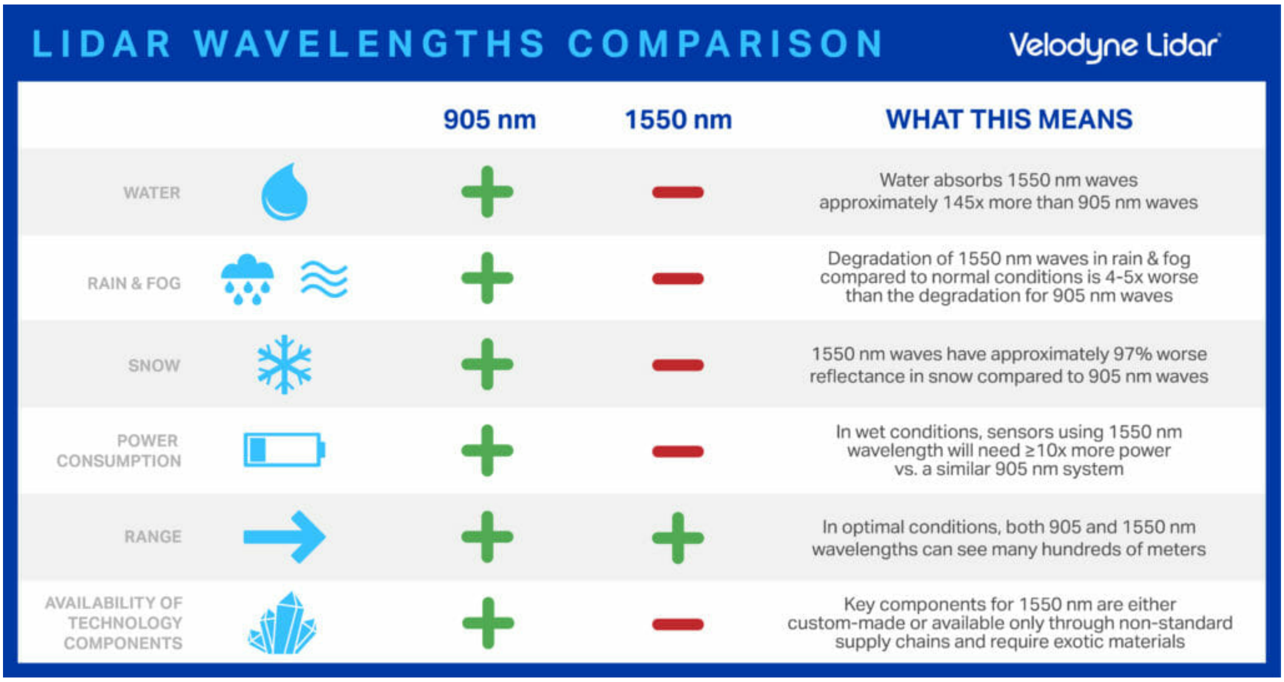
Figure 75 shows an odometer, Pegasem WSS2, with 128 pulses per rotation mounted on the Norwegian Mapping Authorities car.

Odometers measure a relative distance from a starting point along the travel direction. If the wheels skid on f.ex. ice it will lead to errors in the measurements. It is common in Kalman Filters to apply an uncertainty to these measurements for a weighting of the different sensors. When GNSS reception is good, the GNSS positioning can be expected to be so precise, that the odometers are neglected. The odometer is most valuable to sensor fusion in GNSS denied areas like tunnels or urban canyons.

8.2.2 LiDAR

LiDAR is an abbreviation for Light Detection and Ranging. The measurement principle is that the sensor emits light that bounces off an object and reflects back to the sensor. Since LiDAR emits light it is denoted as an active sensor, in contrast to a camera that capture light and is a passive sensor. Therefore, LiDAR works well in low light conditions where cameras can struggle. Modern sensors applicable for autonomous cars measure 360° horizontally around the vehicle, and have a vertical measurement angle depending on the sensor in use. Vertical measurement angle means that a sensor measure multiple layers or channels with a fixed angle between each channel. Depending on sensor type and configuration, these LiDARs have 16 – 128 channels and measure from approximately 300 000 – 2 600 000 points per second at 10 or 20Hz. With a high density point cloud, it is possible to do object classification.

All LiDARs for autonomy must comply with IEC/EN 60825 which denote that sensors must be eye safe, and are usually within the wavelength of 865nm and 1550nm. Ouster use 865nm [45], while Velodyne use 905nm for their LiDARs [44].


LIDAR WAVELENGTHS COMPARISON — Velodyne Lidar

	905 nm	1550 nm	WHAT THIS MEANS
WATER	+	−	Water absorbs 1550 nm waves approximately 145x more than 905 nm waves
RAIN & FOG	+	−	Degradation of 1550 nm waves in rain & fog compared to normal conditions is 4-5x worse than the degradation for 905 nm waves
SNOW	+	−	1550 nm waves have approximately 97% worse reflectance in snow compared to 905 nm waves
POWER CONSUMPTION	+	−	In wet conditions, sensors using 1550 nm wavelength will need ≥10x more power vs. a similar 905 nm system
RANGE	+	+	In optimal conditions, both 905 and 1550 nm wavelengths can see many hundreds of meters
AVAILABILITY OF TECHNOLOGY COMPONENTS	+	−	Key components for 1550 nm are either custom-made or available only through non-standard supply chains and require exotic materials

Figure 76: Lidar wavelengths comparison [44]

Figure 76 shows a comparison of 905nm and 1550nm wavelength. 905nm wavelength has less signal absorption in water, snow, rain and fog, and components to produce sensors are cheaper for the lower end wavelength. With 1550nm it is possible to increase power output to gain more range, but the drawback is obviously more power consumption [44]. Ouster use wavelength 850nm, benefits are pointed out to be better sensitivity for low cost CMOS detectors (two times better compared to 905nm wavelength), better ambient measurements, and lower power consumption [45].

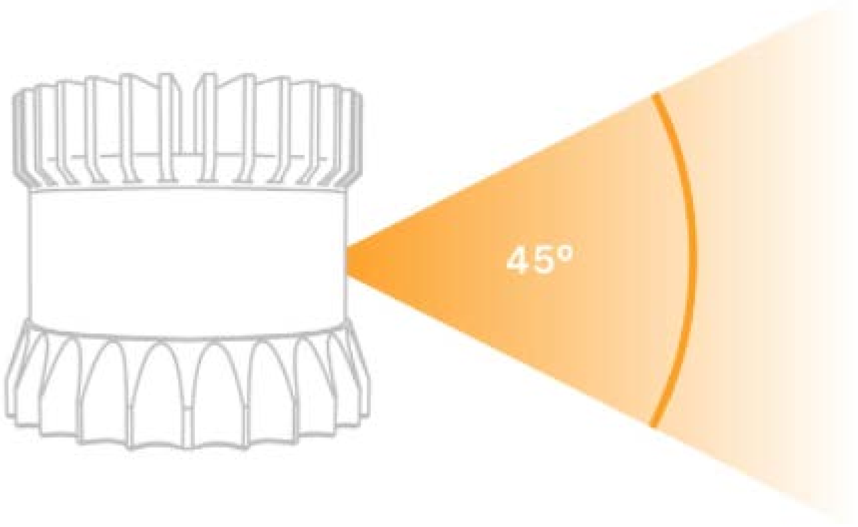


Figure 77: Vertical measurement angle of LiDAR sensor, channels are distributed within the vertical angle [3]

A single point is calculated by knowing the signals' emitted angle in both horizontal and vertical plan, and the distance which is half the travel time of speed of light.

LiDARs measure a detailed model, a so-called point cloud, of the surroundings as points in a local coordinate system of the sensor. Figure 77 shows a road intersection measured with a 64 channel sensor, where the vehicle has entered from the left and turns right (down in image).

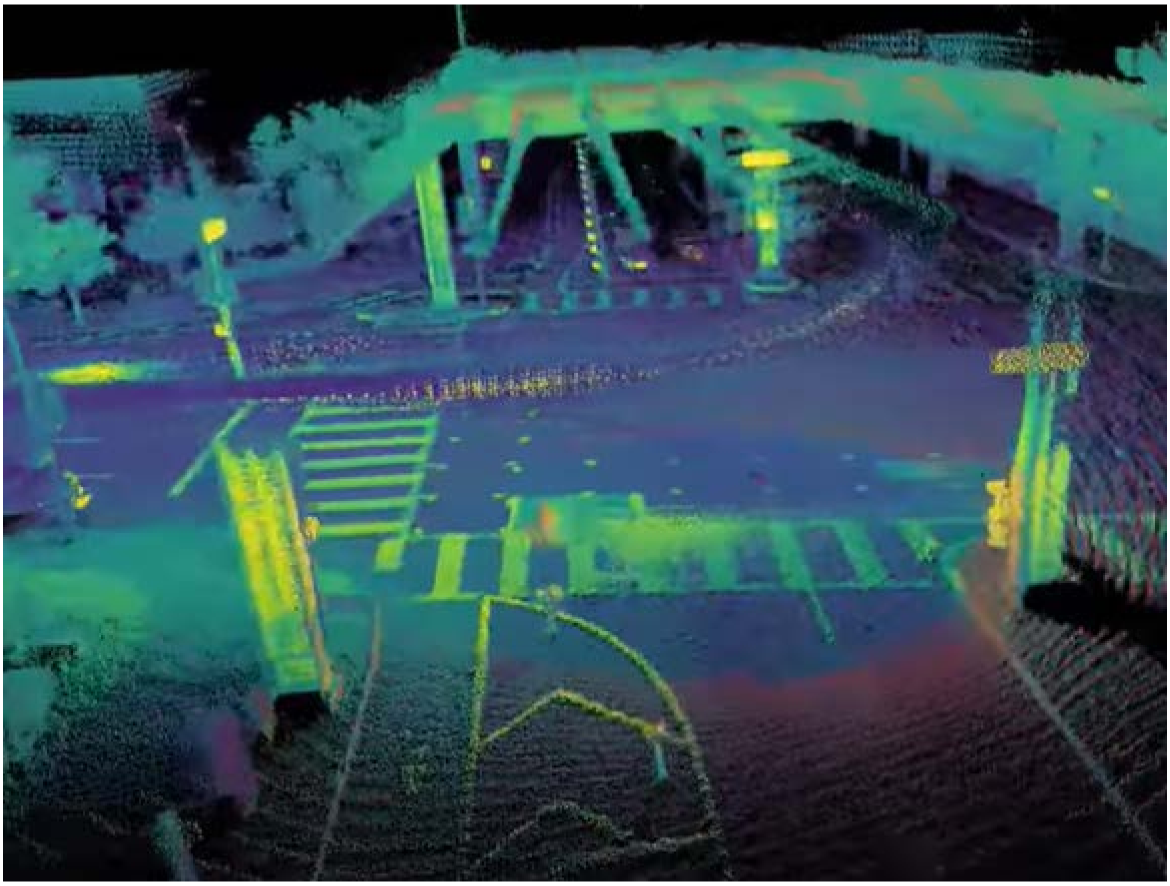


Figure 78: LiDAR measurements, point cloud, from a road intersection measured with Ouster OS1-64 sensor (64 channels) [4]

Point clouds from a LiDAR are used for two different purposes: mapping and navigation (including crash avoidance).

Mapping LiDARs are coupled with GNSS and other navigation sensors, and point clouds get absolute coordinates in a reference frame and map projection. Objects that are of interest for mapping are extracted from the point cloud.

Navigation with LiDAR has two approaches: a relative scan to scan method of determining a position relative to an existing point cloud.

In the relative method, one rotation for the LiDAR at one epoch is measured and compared to measurements from the next epoch. This is described from a very simplified perspective in Figure 78. If LiDAR at position and timestamp 0 (black circle at t0) measure 1m to left wall and 6m to right wall, and then at next timestamp t1 measurements are 4m to left and 3m to right wall. Then a computation gives a position change of 3m to the right. This is obviously an oversimplified example compared to the real world, but this gives an idea of scan to scan navigation. Final computed position is based on incremental measurements, which yield that errors add up and calculated position will drift from true position.

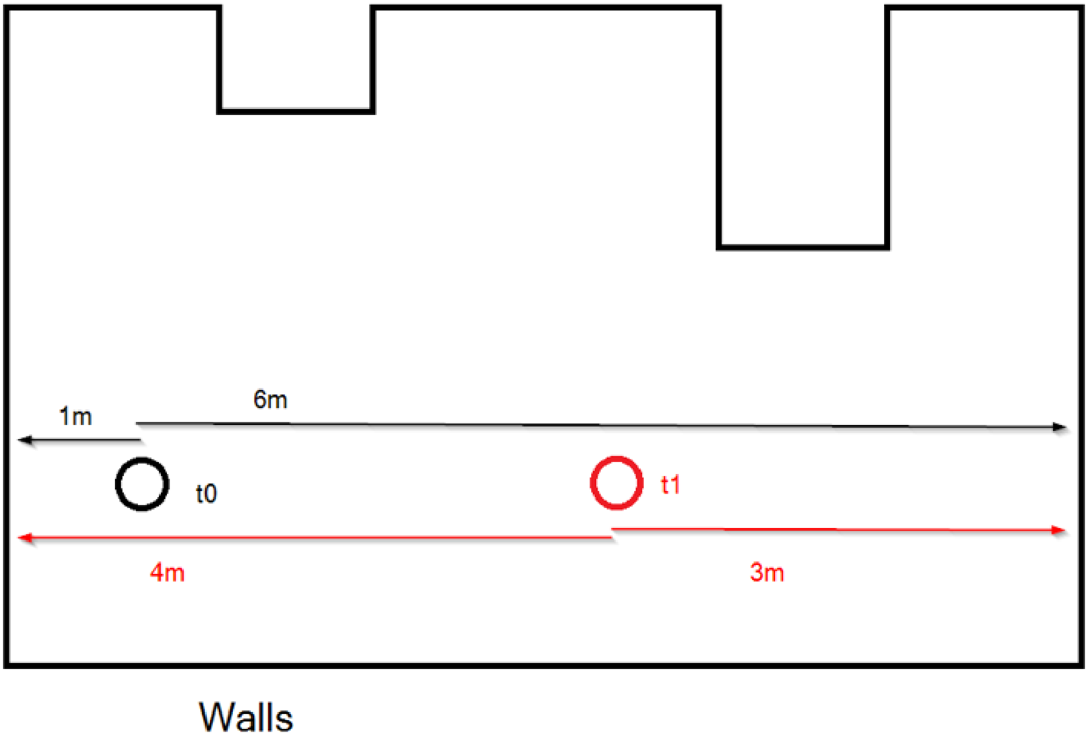


Figure 79: Simplified principle of scan to scan measurements

Positioning relative to an existing point cloud (often a 3D surface model generated from the point cloud) demands that the area already is mapped with a LiDAR so it exists a point cloud with absolute coordinates. The vehicles' LiDAR measures relative to the existing point cloud and positions itself with respect to that. This gives the vehicle absolute map coordinates, even from a relative measurement.If computed LiDAR position is compared with high precision GNSS position and they coincide it is a strong indication of a correct position. Since a single scan from each epoch is continuously compared with the existing point cloud, challenges with drift is non-existent compared to scan to scan navigation. The drawback is that the vehicle can only navigate in an area that is already mapped and a 3D model must be available.

When LiDAR measurements are used to navigate a vehicle, Velodyne has shown that they can classify objects in real time from a point cloud. In this way it is possible to tell which points are part of moving objects (crash avoidance) and which points are static ones and therefore usable for navigation purposes [10].

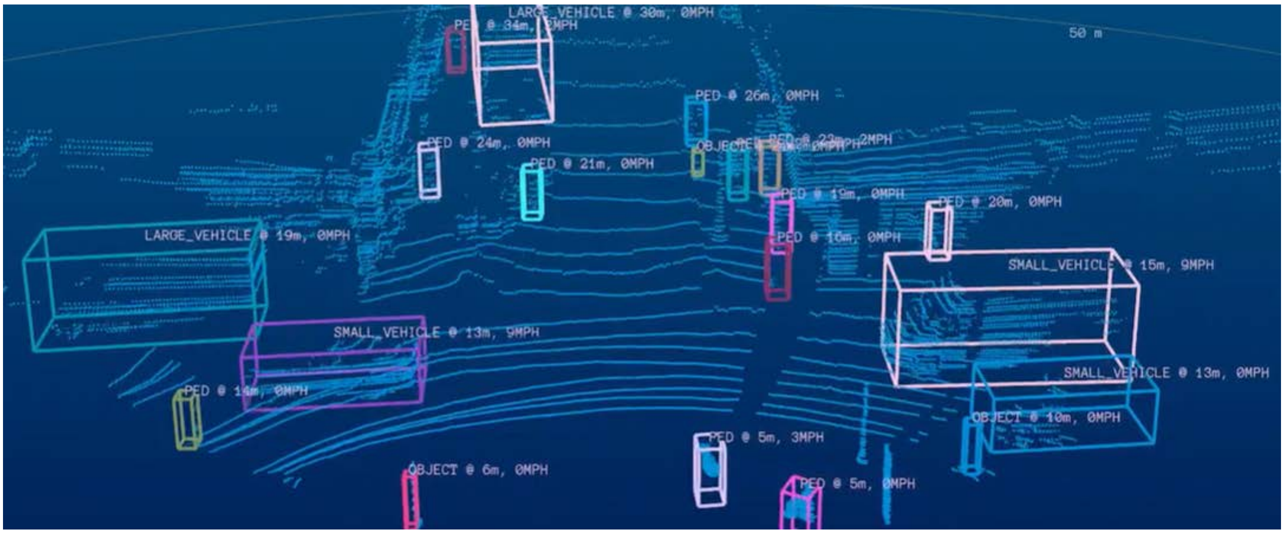


Figure 80**: Snapshot from Velodyne VDK homepage, which shows classification of objects from a point cloud in real time [10]**.

Navigation with LiDARs is a relative measurement method, but gives relative measurements if scan to scan method is applied and absolute coordinates if compared to an existing point cloud. Relative scan to scan accuracy will drift over time depending on quality of LiDAR, environment (easier with buildings along the road than open land with nothing to measure on) and noise like precipitation and moving objects. Drift is not crucial when using an existing point cloud, but the point cloud must be continuously updated.

8.2.3 IMU

IMU, Inertial Measurement Unit, is a relative measurement method that reports acceleration leading to velocity and angular rates leading to orientation in space (roll, pitch, heading/yaw). An IMU consists of 3 axis accelerometer, 3 axis gyroscopes and sometimes 3 axis magnetometer [5].

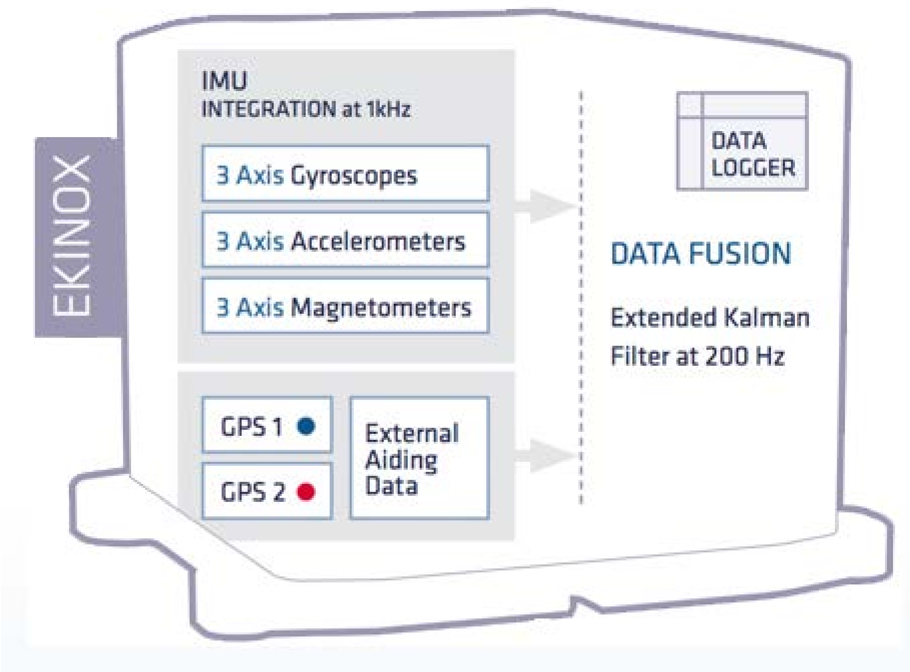


Figure 81: Inertial navigation system, sensors in an IMU is the grey box upper left in image [5]

Accelerometers measure acceleration felt by people and objects, meaning that an object in rest will measure 1g in the direction of the gravitational force. For navigation purposes, acceleration is measured with respect to the earth, and 1g or even more precise calibrated for local gravitation force must be compensated [6].

Gyroscopes measure angular velocity and orientation of an object [7].

Magnetometer measures the earth's magnetic field, in principle like a compass, to determine heading on an object. For navigation this measurement method is vulnerable to ferrous metals in the earth's surface and other objects, but these are not vulnerable for jamming [8].

IMUs give relative measurements from the starting point, measure with high frequency and are accurate over short periods. However, accuracy drift exponentially over time after about one minute depending on the model and quality.

8.2.4 GNSS

GNSS, Global Navigation Satellite Systems, is a satellite positioning method capable of measuring an absolute position down to centimetre accuracy. GNSS is thoroughly described in TEAPOT WP 2.1 and WP2.2, and will not be further discussed here.

Augmented GNSS gives an accuracy down to 1-2cm in open areas with absolute coordinates.

8.2.5 Camera

Cameras are a reliable method to visualize the surroundings, and algorithms perform well with respect to object detection or classification. For example in Figure 82 pedestrians at a crosswalk are identified and the car can slow down.

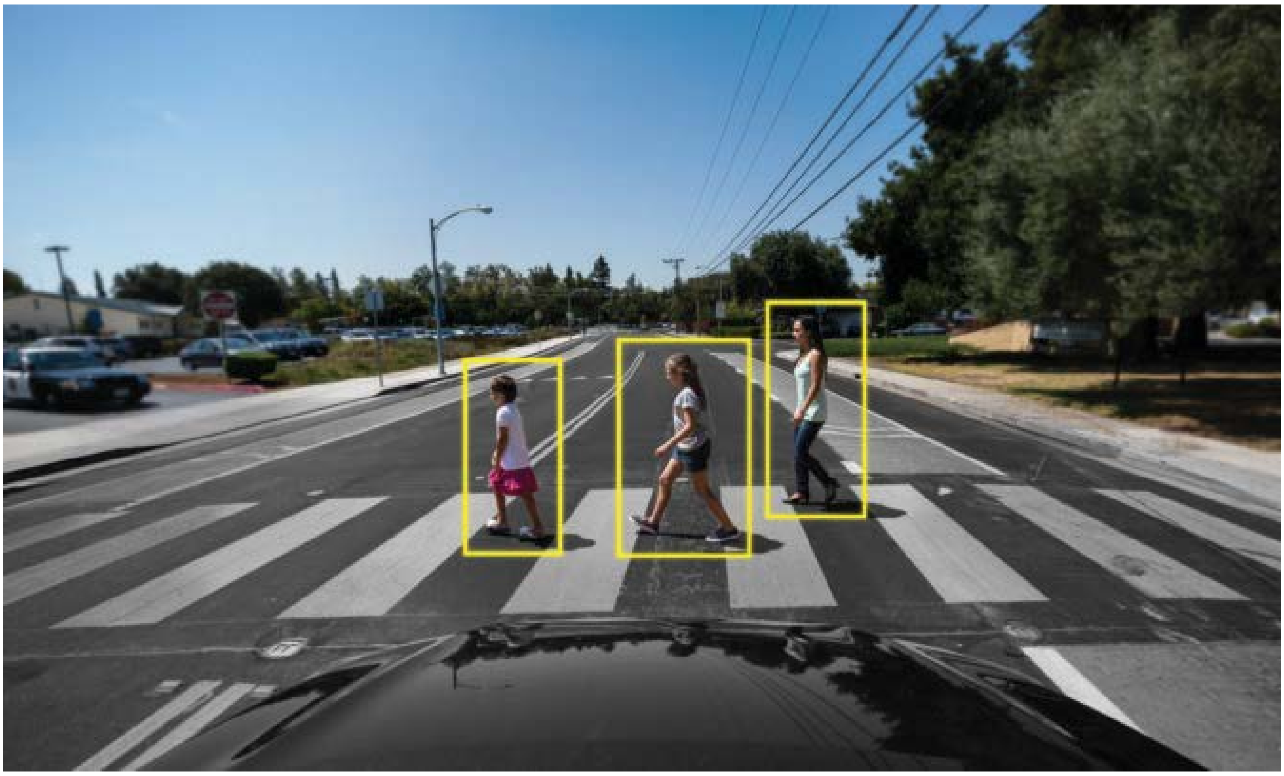


Figure 82: Camera object detection [9]

Most autonomous vehicles have cameras around the vehicle to get a full 360° view.

Performance of cameras are strongly dependent on the environment. Sun glare, precipitation, fog or low light conditions like night-time or poorly illuminated tunnels affects camera performance negatively. Distances to objects can be computed, but with higher computational effort and less accurate than LiDARs [9].

Cameras gives a relative position to an object, f.ex. road marking. If it is used with HD maps (section 8.4.1), absolute coordinates can be computed.

8.2.6 RADAR

Radar transmits electro magnetic waves in pulses and provides distance, speed and location of an object. This sensor can measure in any conditions, which is a benefit compared to other sensors. With relevant algorithms applied radars can classify objects [11].

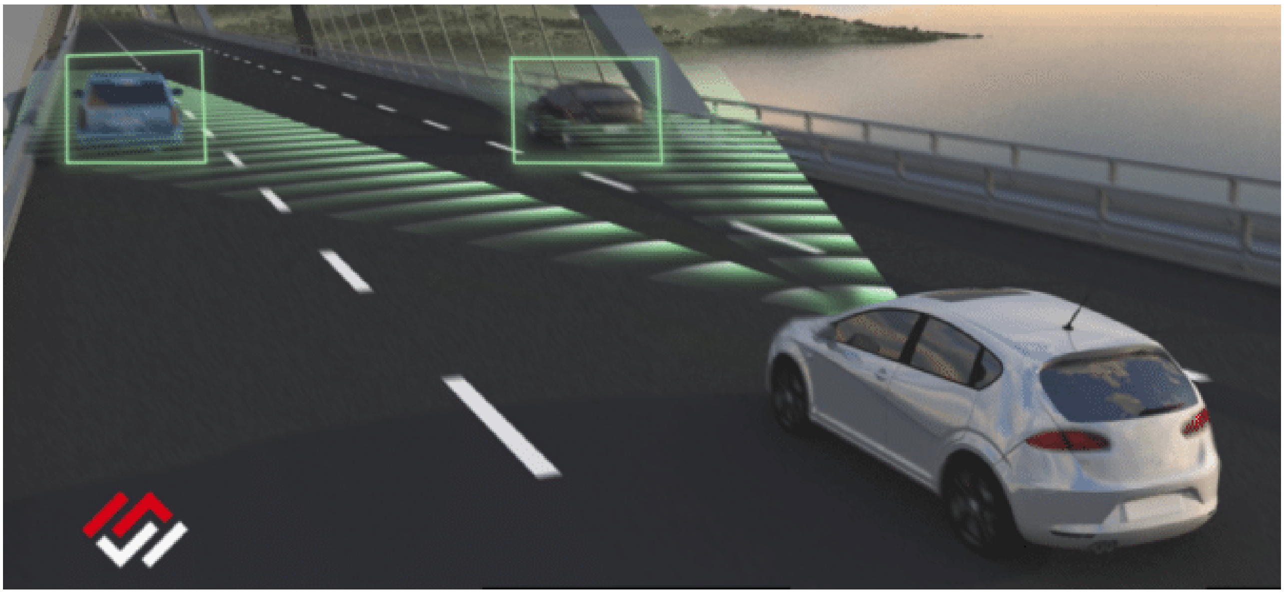


Figure 83: Radar distance measurements [9]

Radars give a relative distance measurement to objects, and are mostly used for collision avoidance, acceleration and braking.

8.2.7 Ultrasonic

Ultrasonic sensors emits sound waves and measure the distance to objects, they cannot measure directions and velocities. The sensor works in low light conditions, but are disturbed by rain, snow and dirt [11]. In Figure 84 pros and cons of radar, camera and ultrasound is listed in a table.

Radars give a relative distance measurement to objects, and are mostly used for crash avoidance, acceleration and braking. Ultrasonic sensors have shorter measurement range than RADAR.

	Radar	Camera	Ultrasound
ENVIRONMENTAL CONDITIONS			
Day/night	✓✓	neutral	✓✓
Shadows cast by sun	✓✓	✗	✓✓
Rain	✓✓	neutral	neutral
Fog	✓✓	✗✗	neutral
Snowfall	✓	✗	✗
Dirt	✓	✗	✗
TECHNICAL CRITERIA			
Range	✓✓	✓✓	✗
Resolution	✓	✓✓	✗
Measurement of velocity	✓✓	✗	✗✗
Measurement of distance	✓	neutral	✗
Detection of objects	✓	✓✓	✓✓
Classification of objects	✓✓	✓✓	✗✗

Figure 84: Comparison table between radar, camera and ultrasound. Criteria range from very good (vv) to very poor (xx) [11]

8.2.8 Sensors vulnerability to weather conditions

"Under ideal operating conditions, the perception systems provide enough information to enable autonomous transportation and mobility" [42]. But precipitation and weather conditions can affect sensors to work sub-optimal.

Figure 85 show a spider diagram for LiDAR, radar, ultrasonic and cameras for various sensor attributes, most interesting regarding autonomous operation in weather are "Works in dark", "Works in bright" and "Works in Snow/Fog/Rain". LiDAR perform well in dark and bright but can have trouble with heavy precipitation and f.ex. snow on the sensor. Both radars and ultrasonic sensors work well in all weather conditions. Cameras only work only in daylight and can be affected negatively by sun glare, heavy precipitation also negatively influence objects detection [42].

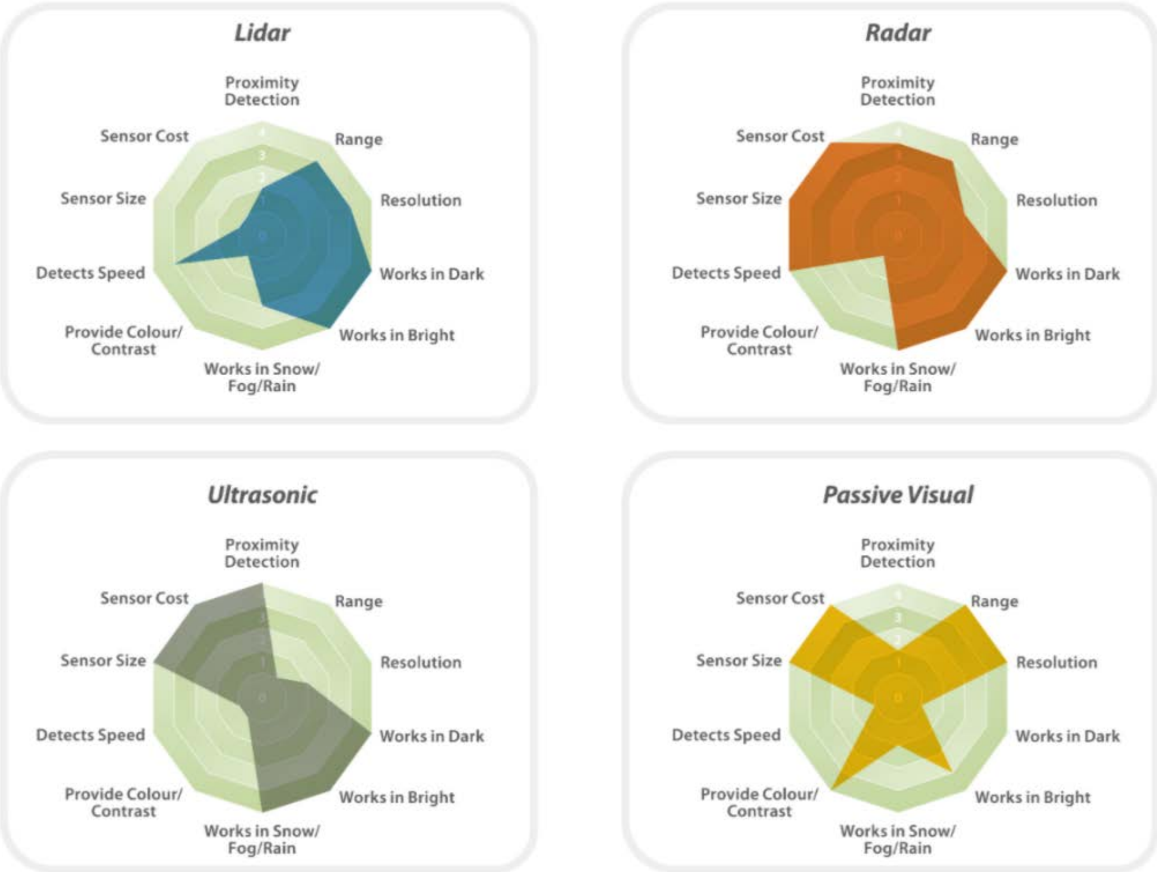


Figure 85: Strengths and weaknesses for sensors (Passive visual is camera) [42]

8.3 Roadside infrastructure

Roadside infrastructure can assist autonomous vehicles to navigate safely, both as a positioning technique and as communication and data transfer.

8.3.1 Mobile Network - 5G

The upcoming 5G technology has enhanced positioning capabilities - accuracies down to meter, decimetre and centimetre will be possible. Ericsson has identified use cases, with requirements and solutions for 5G positioning in Figure 86 where automotive is specifically mentioned [16].

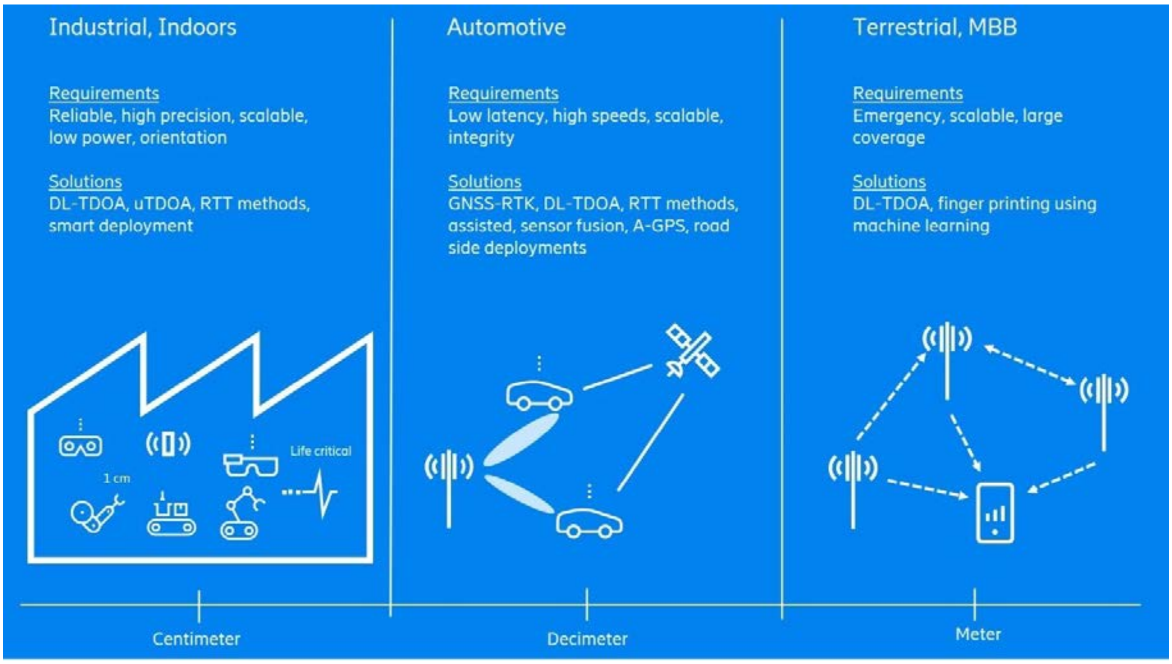


Figure 86: Requirements and specific solutions of 5G use cases with possible 5G positioning accuracy range [16]

For outdoor use a hybrid GNSS and 5G positioning service are expected to be relevant for the mass marked. 5G are also pointed out as an indoor positioning system, which for automotive use is applicable for instance in tunnels and when coming out in open air where it takes some seconds before GNSS converge to cm accuracy [16].

Current 3GPP release is 15, and more advanced positioning features are planned in release 16 and 17, see Figure 87.

4G LTE based positioning — 5G NR based positioning / 5G Inter-RAT based positioning

3GPP Releases	Release 9	Release 11	Release 13	Release 14	Release 15	Release 16	Release 17	Release 18
Key positioning features	Support for LTE positioning	UTDOA support for LTE	Study LTE enhancements to cover FCC reequirements for indoors	Indoor positioning enhancements, LTE-M, NB-IOT support	GNSS RTK and NSA NR support, sensor measurement reporting	Positioning framework with NR	Industrial IOT, integerity for positioninig	TBD

Figure 87: Evolution of 3GPP standards and 5G releases [16]

The 5G network uses frequency band from a bit below 6GHz to 100GHz (Figure 88) and current deployed equipment are at the lower side. Potential position accuracy is believed to be around 20m for 5G with sub-

6GHz frequency, and higher end of mmWave bandwidth implies lower than 1m [17] and down to centimetres [16].

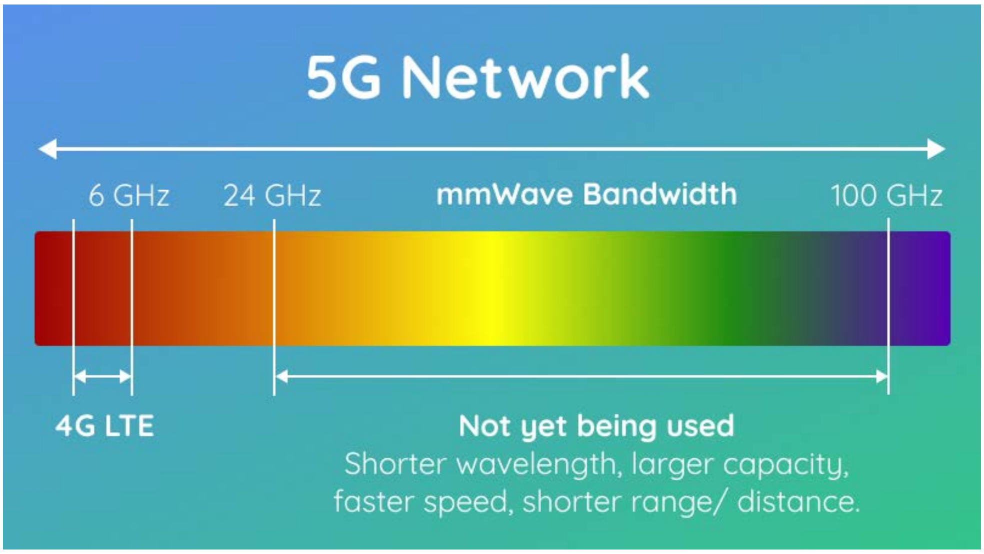


Figure 88: 5G frequency spectrum [17]

The Norwegian Mapping Authority, SINTEF, Telia and Ericsson received funding from the Research Council of Norway for their project HyPos (National Hybrid Positioning service for the future digital and autonomous society). The project goal is to research both technical and business aspects for a scalable GNSS correction service and positioning within the 5G technology, and how these technologies can be fused together.

8.3.2 ITS roadside equipment

ITS roadside equipment, ITS stations, are elaborated in TEAPOT WP2.2 – Trends, section 2.7.2.

8.3.3 Real-time locating systems

Real-Time Locating Systems, RTLS is a common term for positioning systems using some kind of radio frequency (RF) communication. Most common are Bluetooth, WiFi and UWB (Ultra Wide Band). It is usually used indoors for tracking items or people in warehouses, hospitals etc. Indoor positioning with RTLS can be applicable for autonomous cars in tunnels or parking garages. In Bjørnegårdstunnelen in Sandvika, close to Oslo, the Norwegian Road Administration mounted a RTLS system called Waze. With this system even regular mobile phones (tag) can get position in the correct lane inside the tunnel [19]. But with these RTS systems several anchors with known coordinates must be deployed, and they require regular maintenance.

RTLS systems have anchors and tags. Anchors are transceivers usually mounted on the wall or roof and their position, coordinates, must be known in a local or global coordinate system. Tags are devices that are mounted on the object that needs to be tracked with a position. If a tag measures to three or more anchors, it can calculate a 3D coordinate with different techniques:

- Angle of Arrival – AoA
- Angle of Departure – AoD
- Line of Sight – LoS
- Time of Arrival – ToA
- Time Difference of Arrival – TdoA
- Time of Flight – ToF
- Two-Way ranging - TWR

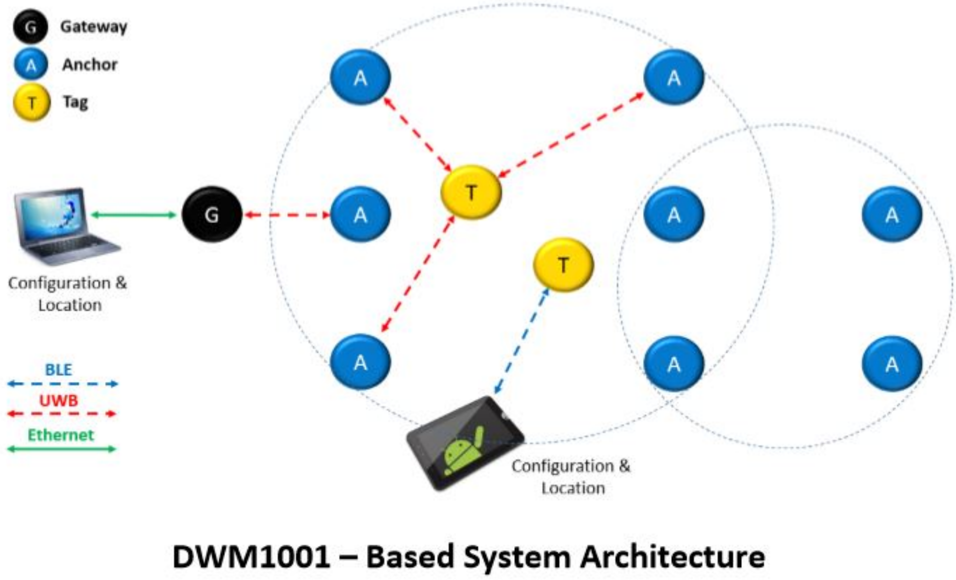


Figure 89: Anchors and tags in an RTLS system. A gateway is used to configure anchors. Red dotted line describes UWB communication and positioning, BLE describes Bluetooth connection to configure a tag or see tag position [20]

Number of anchors depend on signal penetration and needed accuracy, f.ex. thick concrete walls dampen the signal far more than a thin wall of wood. Due to needed infrastructure these systems are mostly used in small areas.

8.3.4 Connected vehicles

The futures' transport is expected to be depending heavily on communication infrastructure so vehicles can exchange information with other vehicles, roadside infrastructure or upload and download other relevant data. This is known as "Cooperative, Connected and Automated Mobility" (CCAM), this demands an infrastructure for communication with reliable bandwidth, latency and robustness.

There are two relevant communication techniques, 5G from the telecom sector and ITS-G5 which is a short distance communication included in roadside infrastructure. 5G has an advantage since the infrastructure will be built anyway by telecom companies and cover large areas, but ITS-G5 might be the solution where 5G don't have reliable signals. The Lambda Road project research how both technologies can be used together in an optimal way to create a hybrid communication solution [35].

Relevant data for vehicle communication are information about traffic jams, road conditions, GNSS corrections, map updates, traffic light status, etc.

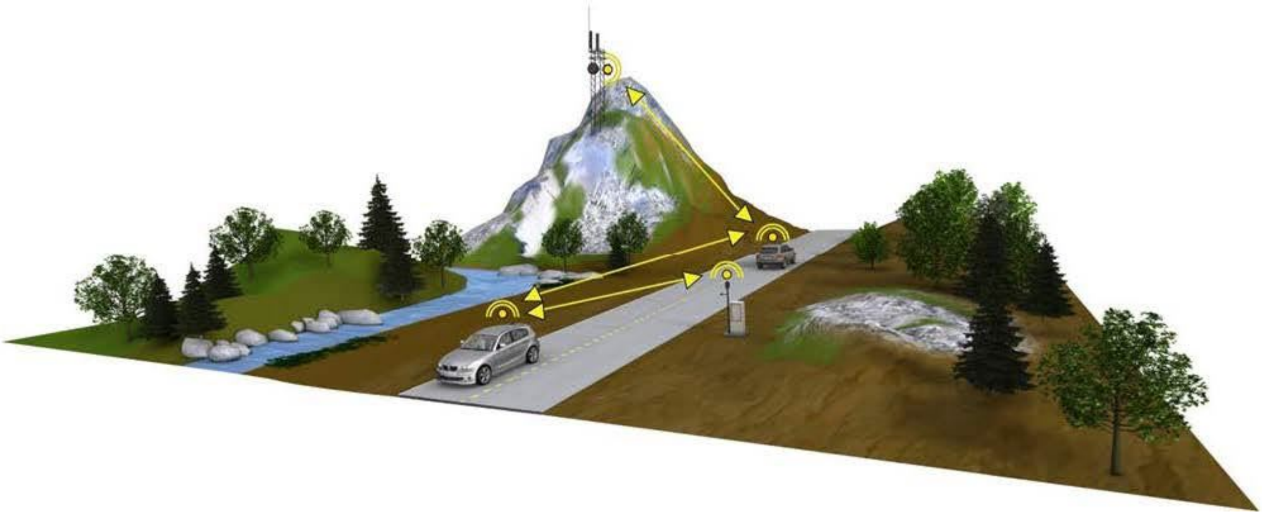


Figure 90: Communication for CCAM with 5G and ITS-G5 [35]

8.4 Digital infrastructure

Digital infrastructure are maps or point clouds that represent a digital twin of the physical infrastructure. Some navigation sensors are able to use the digital representation for navigation purposes.

8.4.1 HD maps

HD (High Definition) maps are highly accurate and detailed maps with more information than traditional large scale maps, emphasized on what is important for a vehicle along the road [15]. Autonomous vehicles use the map to position itself within the road and plan the route ahead. These maps complement on-board sensors so the vehicle has information about the surroundings beyond sensor measurement range, metadata like traffic rules and road conditions can be added to map elements [12].

The autonomous vehicle compare and validate the HD map with sensor readings in real time, this means that the vehicle is positioned on the map with global coordinates andcan use metadata to plan the trajectory. Redundancy is also a key merit, as position from other sensors like GNSS can be validated [12].

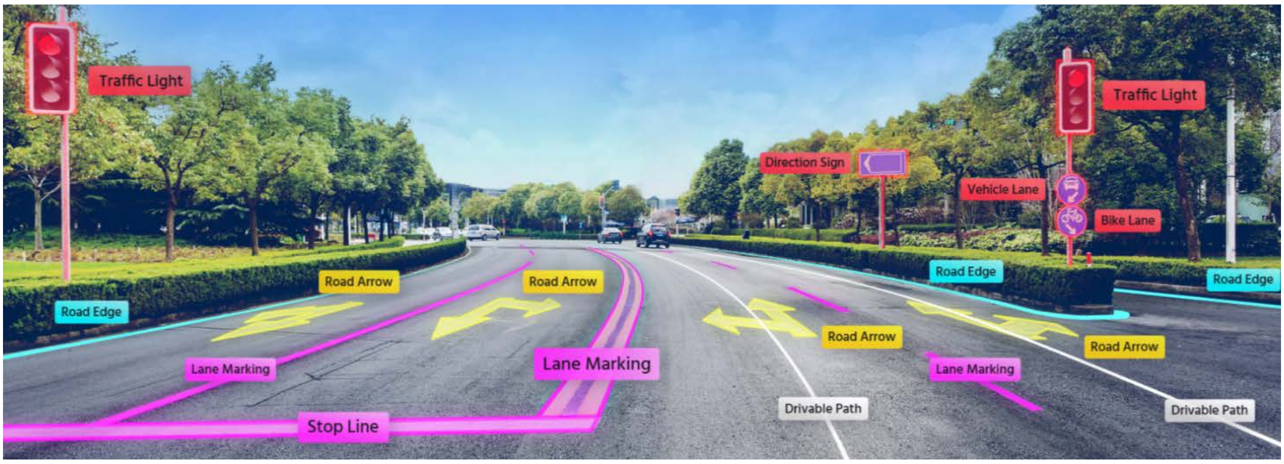


Figure 91: HD/AV map example overlay on image from Mobileye [13]

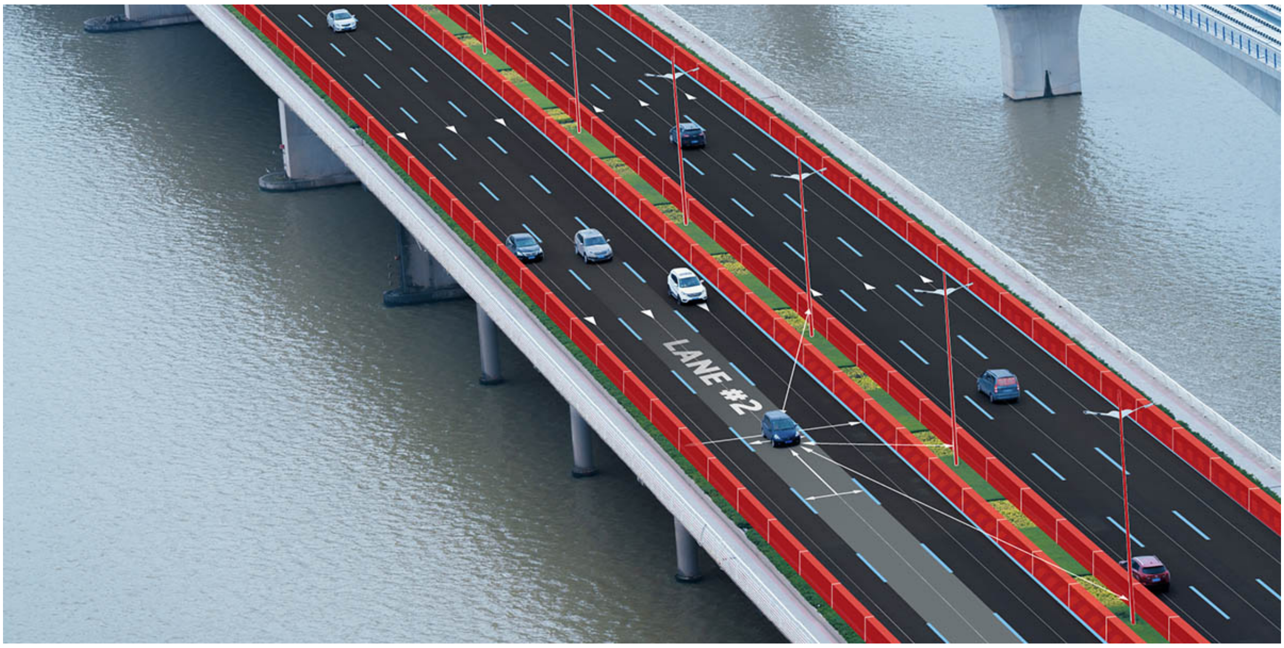


Figure 92: HD map example from Tom Tom [14]

8.4.1.1 AV maps

MobileEye introduce the term AV maps, that are specially designed for autonomous vehicles. From their point of view, HD maps contains a lot of information that is not needed, while some other information is missing. AV maps offer more metadata, or semantic information, to tell the vehicle how to drive, not limited to the global coordinates of the vehicle on the map. For example which traffic light belongs to which lane, where to stop at an intersection to have unobstructed view orwhich lane has right-of-way at an intersection" [13].

8.4.2 Continuously updated maps

Traditional static maps can be many years old and have crucial errors when an intersection, or even a road section is rebuilt. Safety of life applications like autonomous vehicles cannot rely on old data, and their HD maps must be updated in real life to have relevance. HERE technologies approaches this challenge with their "self-healing" maps. They update maps from several sources, like satellite imagery and OEM vehicles in real time to keep maps continuously updated [12]. Other providers of HD maps, like Mobile Eye [13] and Tom Tom [14] use the same concept for real time updated maps.

8.4.3 Point cloud

Point clouds are millions of points in 3D, representing the real world with global coordinates. These data can be used in the same way as a HD map, so the autonomous vehicle has information about how the surroundings are around the next corner and can plan its travel path.

Point clouds are captured with a LiDAR and further described in section 8.2.2.

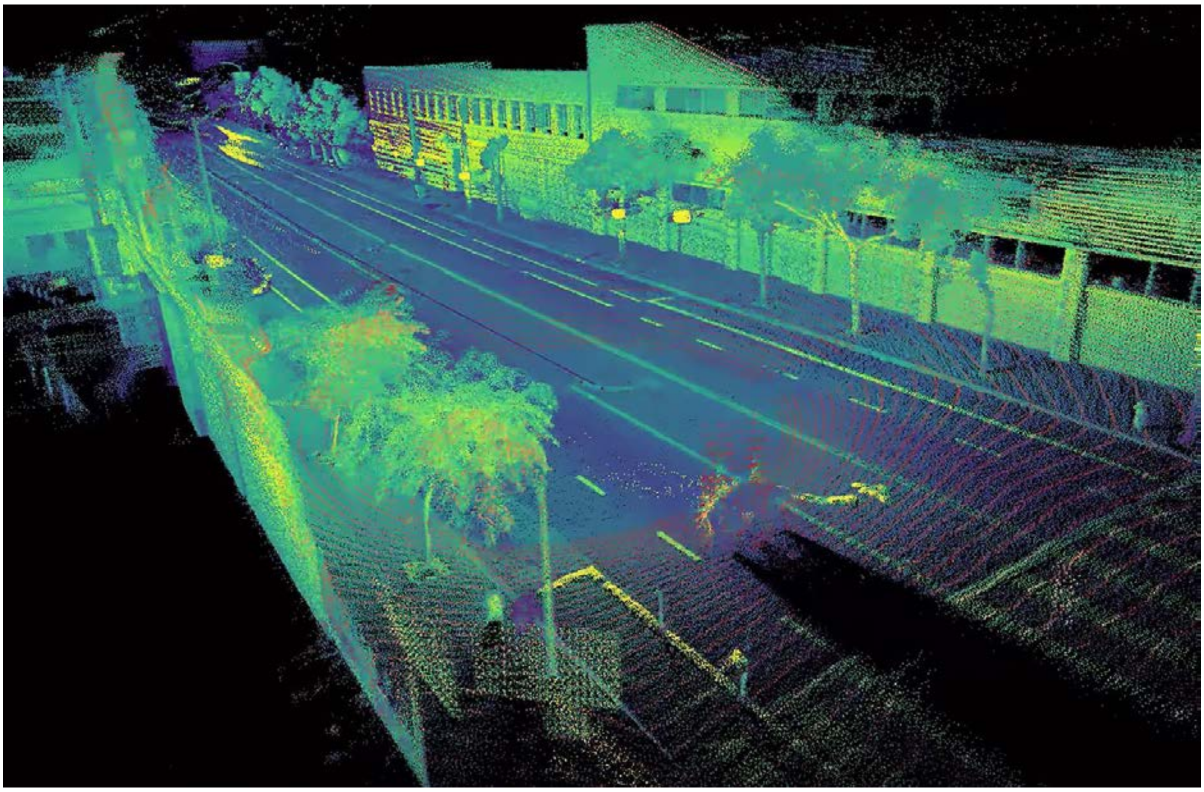


Figure 93: Point cloud of a road captured with an Ouster sensor [18]

8.5 Sensor Fusion

All described sensors on a vehicle are used together to give the most reliable, safe and trustworthy navigation. Different information like distance, speed and type of object are used to determine how the vehicle should react in different situations. Redundancy and integrity of sensors are highly important in safety critical applications. As an example, if both LiDAR and cameras identify a pedestrian at the same position and with the same speed, the vehicle has more redundancy to make the correct decision for how to navigate [9].

8.5.1 Kalman Filter

Kalman filters are applicable where you have “uncertain information about some dynamic system, and you can make an educated guess about what the system is going to do next [32]”, and are memory and computationally efficient since only measurements from current epoch and previous state (position, velocity, etc.) are needed [32]. These fundamental characteristics make Kalman filters widely used in robotics and autonomous vehicles for navigation in real time.

The basic idea of Kalman filters in navigation are to use different sensors, like those described in chapter 0, with different advantages and disadvantages to calculate a precise position. These sensors have varying measurement accuracy for different environments. For example in urban canyons GNSS measurements are poor or even unavailable, but LiDAR can measure to buildings with good accuracy. In this situation the algorithm relies mostly on LiDAR sensor, but it will be the opposite in an open area where GNSS measurements calculates a precise position.

This leads to a relationship between sensors and measurements. In an urban canyon the velocity and distance travelled computed from a LiDAR has low uncertainty and measurements from GNSS has high uncertainty - this leads to the fact, that the distance travelled with GNSS can’t exceed the distance computed with LiDAR including the standard deviation. Correlation gives the Kalman filter more information, measurement from one sensor tells the algorithm what measurements from other sensors could be [32].

Kalman filters adds uncertainty in the calculation as measurement noise from sensors, but also unmodelled errors can be added as a constant. An odometer can be used as an example of an unmodelled error, if a wheel slips on an icy road the odometer will calculate a longer distance travelled than it really should. In the initialization phase, the Kalman filter tries to estimate and model the errors from each sensor through an iterative process. For this initialization phase, sensor fusion systems are dependent on good GNSS signals in the start-up phase. Most sensor fusion systems stores the error model to be used next time the system power up, so the initialization phase is not needed every time.

8.5.2 AI and machine learning as alternative to Kalman Filter

Research papers are investigating how to utilize AI (Artificial Intelligence) to achieve better sensor fusion algorithms for GNSS and INS, especially for low-cost receivers that are used in massmarket driver assistance technology, routing and auto-drive systems. However, low-cost INS sensors have nonlinear noise and this leads to error propagation for the computed position. Artificial Neural Networks have been used to model INS nonlinear errors to generate a more precise Kalman filter model. This is done by training the neural network when GNSS data is available, GNSS is then used as reference data and trajectory for the INS and how it should model the nonlinear errors to compute an optimal position. When there are a GNSS outages, the trained model is used to calculate and predict a position. Results show that positon estimation error are reduced by 67% by using the artificial neural network model [29]. A similar approach using reinforcement learning has shown significant improves compared to more standard Kalman filter approaches [30].

Even for mass marked equipment, like mobile phones, machine learning is used to compute a more accurate position in urban areas. The normal approach for GNSS is a line of sight measurement from satellite to user equipment, and with IMU a Kalman filter is applied. Instead a grid is applied in the area you know you should be in,.Then, residuals are computed for each cell or possible position for the whole grid. Residuals are measured minus the expected range to the satellites and the correct position is along the white line in Figure 94, where residuals are close to 0.

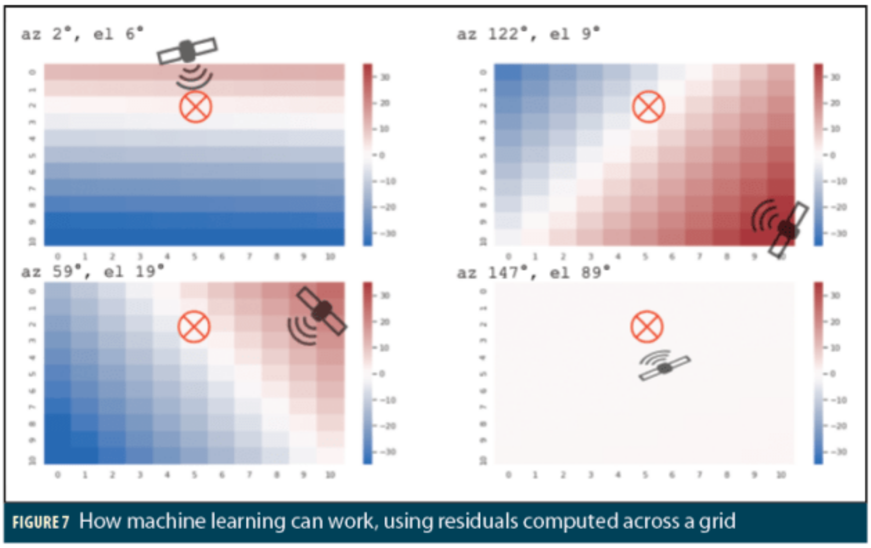


Figure 94: Concept for computing residuals across a grid for a satellite [31]

Afterwards, machine learning is applied to find the optimal position calculated for intersection of white lines for measurements to many satellites. The basic concept is described with residuals, but even more information like signal-to-noise (C/N0), constellation and signal type can be included in the model. Also, for the urban example, the grid concept is projected on a 3D model of the city. Tests from Berlin show improvements for a mobile phone, in Figure 94 grey dots are ground truth, red dots are regular positions from a phone and blue dots are positions from the approach with machine learning and 3D model which yields a significant improvement [31].

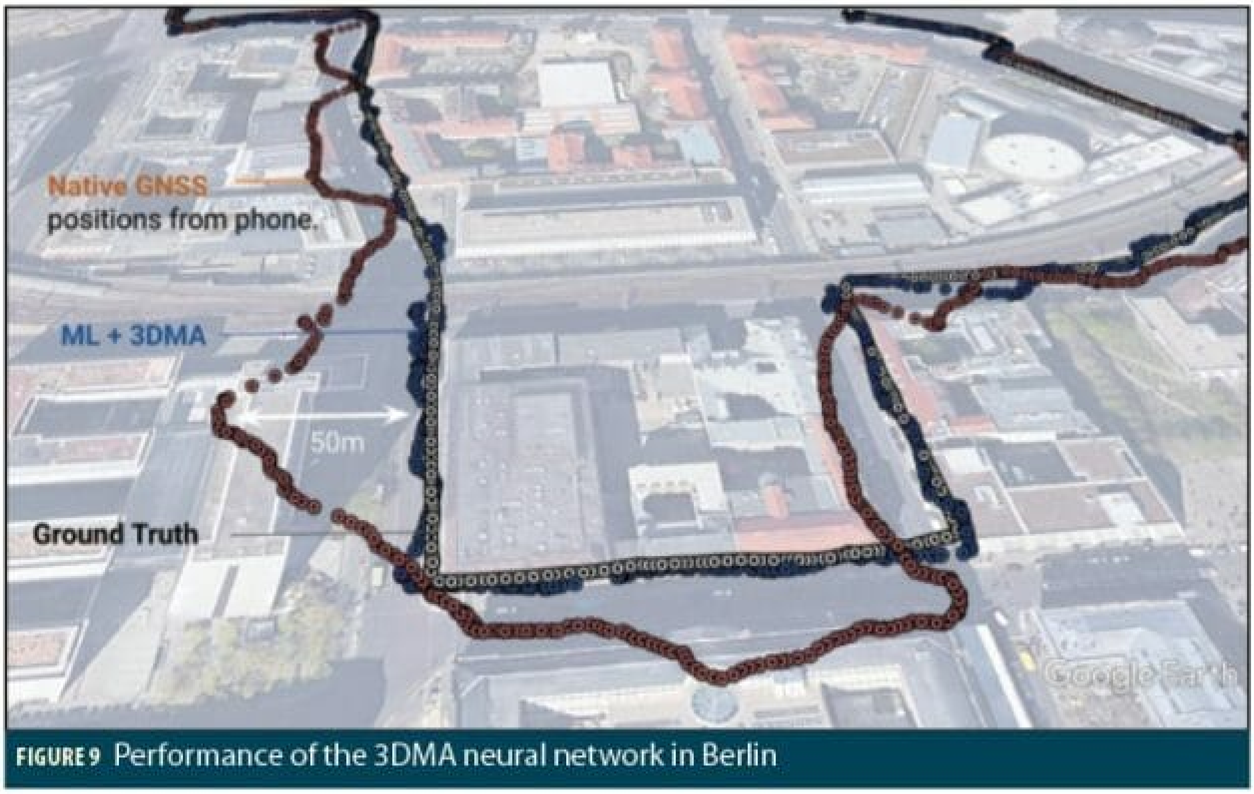


Figure 95: Improvements with machine learning approaches for GNSS position calculations

8.6 Approaches from providers of autonomous vehicles

Developers and providers of AVs have slightly different approaches, but detailed information about their hardware and software are hard to find.

8.6.1 Mobileye

Mobileye illustrates a "true redundancy" approach for their AV development. Their production AV is navigating on the camera system, while the radar/LiDAR system is running as a secondary system to provide redundancy as pictured in Figure 96. This system calculates two independent positions and trajectory based on different sensors, while a more traditional approach is to fuse data from all sensors to one position and trajectory [21]

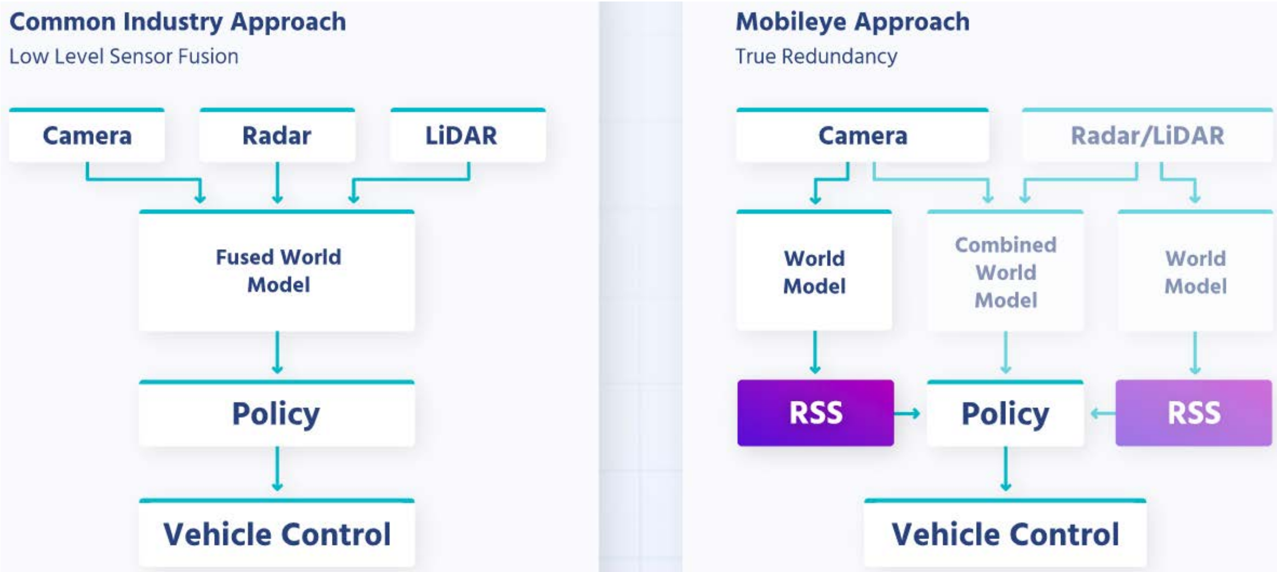


Figure 96: Mobileye true redundancy [21]

A core element of Mobileye system is a highly detailed AV map, section 8.4.1.1, their camera based system positon itself relative to the AV map. There are not much information about the radar/LiDAR approach, probably because the camera system is their main system and has existed for a longer time. Mobileye do not use high precision GNSS and don't emphasize global accuracy in their AV maps. The main idea is completeness and correct information in their AV map, any they only navigate relative to the HD-map.

Mobileye provide a camera only solution with 7 long range and 4 short range cameras named Mobileye SuperVision, but this is an ADAS system. However, it is marketed as "Hands-free for highway and up to urban with navigation, driving policy, and OTA (Over The Air) updates" [21].

Figure 97 shows a snapshot from Mobileyes software, where map, computer vision and actual situation is shown.

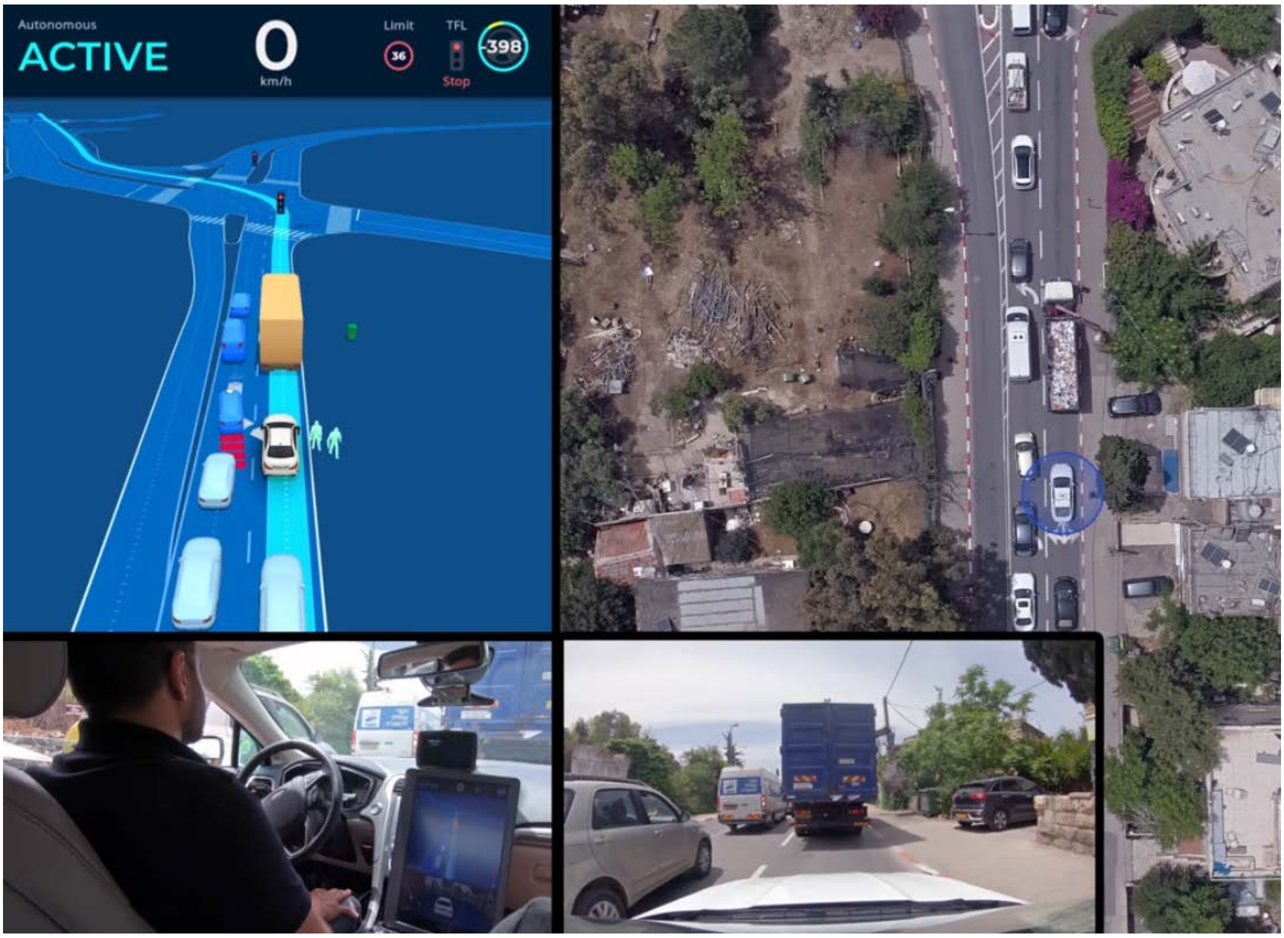


Figure 97: Snapshot from video on Mobileyes homepage [21]

8.6.2 Tesla

Tesla vehicles are equipped with side and forward facing cameras, forward radar and ultrasonic sensor with 360° view as shown in Figure 98. Tesla use big data collected from their vehicles to train a neural network for their self-driving software [22]. Tesla's aims for a software that supports autonomous driving, but at the moment their system is only an advanced ADAS system.

Unlike many other developers of autonomous driving, Tesla don't use LiDAR, HD maps or high precision GNSS [22]. Tesla aim for software in private vehicles, and aims to keep sensor cost at a minimum.

Figure 98: Sensors on a Tesla vehicle [23]

8.6.3 Mercedes Drive Pilot

Mercedes-Benz release Drive Pilot for compatible vehicles, this solution can drive without driver paying attention under certain conditions, this means SAE Level 3. These conditions are fulfilled when vehicle speed is below 60km/h, traffic situation not to complex and land marking are clear. The driver must sit in the driver’s seat and the system will alert when the driver must overtake control of the vehicle.

In addition to radar, cameras and ultrasonic sensors, which most of vehicles are equipped with today, differential GNSS with cm accuracy and HD-maps are also needed.

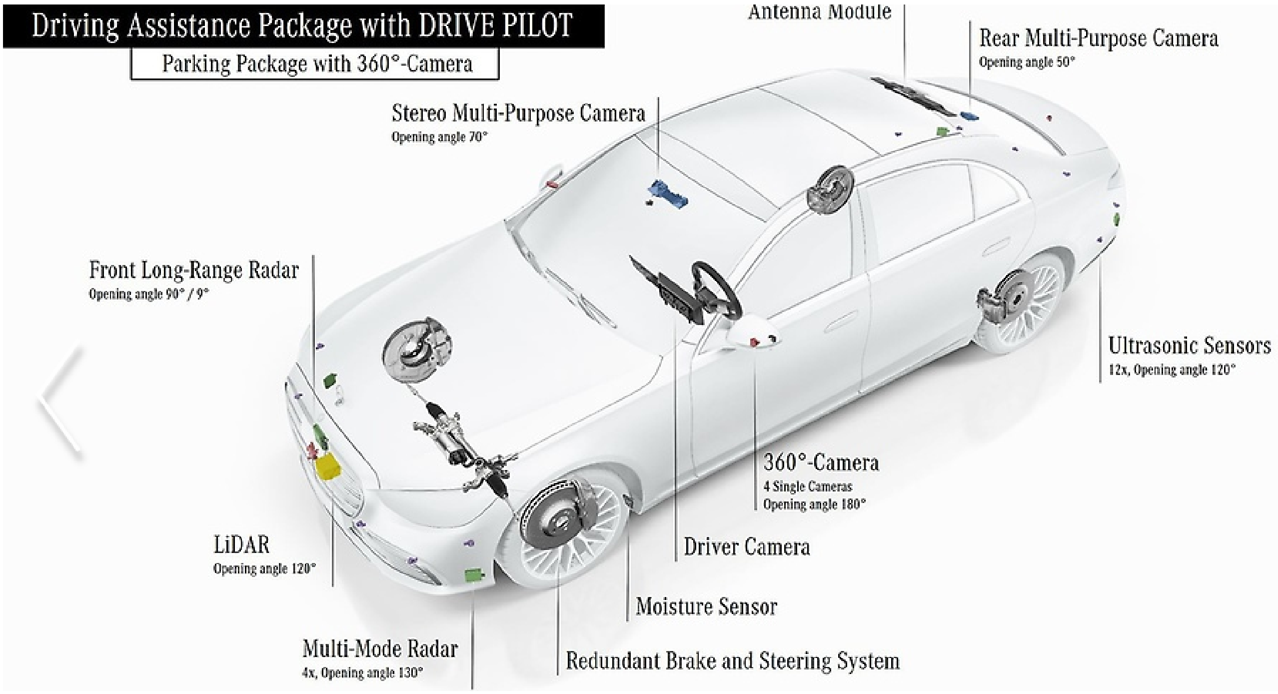


Figure 99: Sensors used with Mercedes Drive Pilot

8.6.4 Waymo

Waymo started as a Google project for self-driving cars in 2009, and they develop Waymo Driver hardware and software package that can be used on different vehicles. Hardware sensors are LiDAR, cameras and radar. Waymo do mapping to their proprietary standards, HD map, before vehicles can drive autonomously. Data from approximately 30 million km of real world driving and 30 million km of simulated driving are used to train their software [24].

Figure 100: Waymo hardware on a roof rack [24]

8.6.5 Sensible4

Sensible4 is a company that aims to develop software for all-weather autonomous vehicle and are based in Helsinki, Finland. They provide their customers with software and hardware so any vehicle can turn into an autonomous vehicle. So far, they have worked in strong partnership with other companies to test, develop and facilitate autonomous buses. In 2022 they aim to release commercial SAE level 4 autonomous shuttle bus software. At level 4, no safety driver is needed on-board [25]. In cooperation with Ruter, their system is operating on two Toyota vehicles in Ski south of Oslo [26].

The key element of their position engine is the LiDAR sensor, and an existing point cloud of the area that Sensible4 processes to a “volumetric probabilistic distributions”, or 3D map (surface model). In more detail the point cloud are processed sections of a cubic meter. Points in each cube are generalized to a normal distributed probabilistic distribution represented as an ellipsoid, as seen in Figure 101 and Figure 102, so computational effort is minimized. Measurements from the LiDAR are compared to the 3D map to derive the vehicle’s position. The probabilistic approach tolerates noise like snow, rain, parked vehicles, etc. Sensible4s software also utilize high precision GNSS, radar and “other methods” [25].

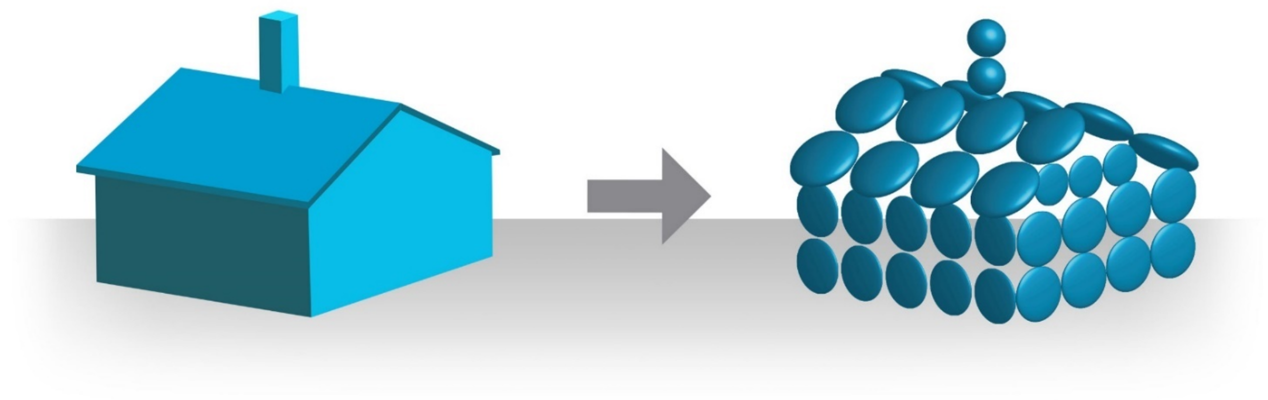


Figure 101: Principle of Sensible4s 3D map, or surface model [25]

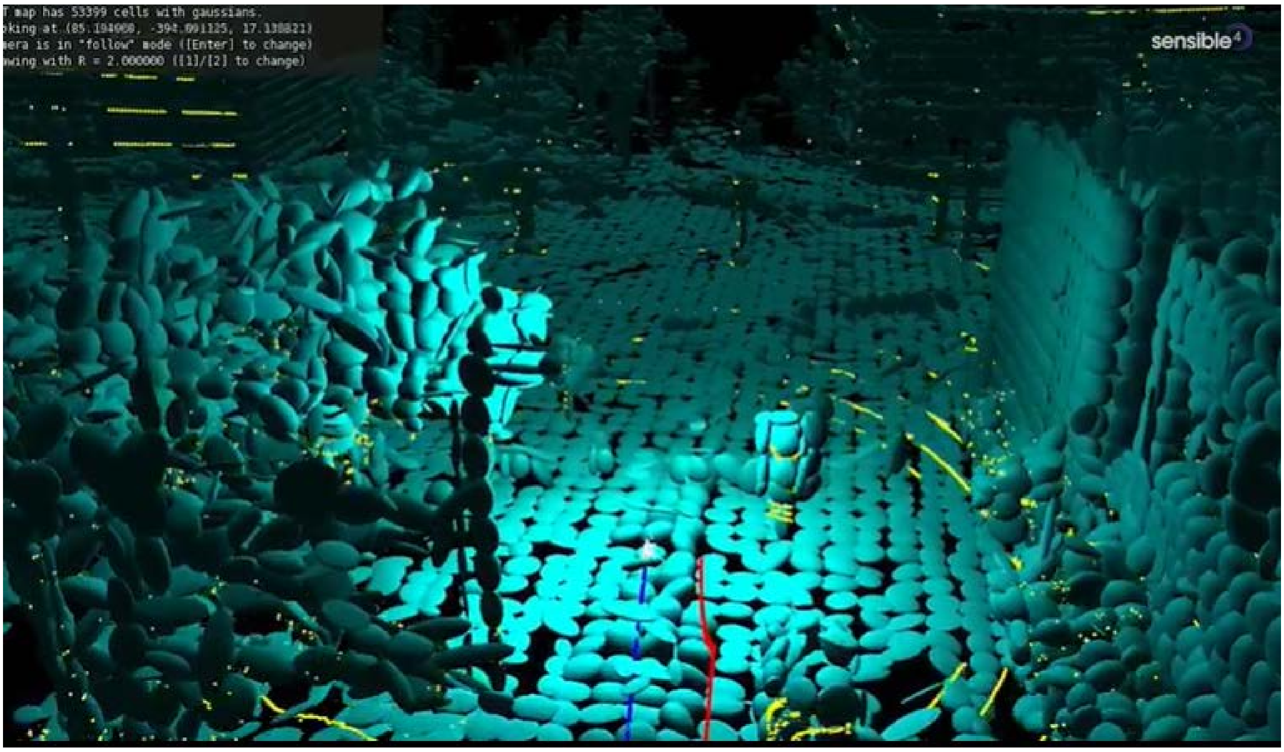


Figure 102: 3D map from Sensible4. Cyan ellipsoid represents the 3D map, yellow dots are real time LiDAR measurements that position the vehicle [25]

8.7 Nordic conditions and harsh weather

Nordic conditions and snow are a severe challenge for autonomous systems. Snow on the ground change the landscape so HD-maps and point clouds are more difficult to use a navigation source, and falling snow makes object detection harder and sensors becomes covered. As of today, no autonomous systems can be used and are reliable in all kinds of weather applications, however there are a lot of research ongoing to mitigate this challenge and some examples are elaborated.

8.7.1 Machine learning to detect drivable path on snowy roads

A research paper from Michigan Technology University trained a Convolutional Neural Network (CNN) with open data from the Dense Project. These data include LiDAR, images and radar from harsh weather conditions, and research are performed to find drivable path for a vehicle. Drivable path is defined as streets, parking lots, entrances and disregard lane markers, tramway tracks and other lines.

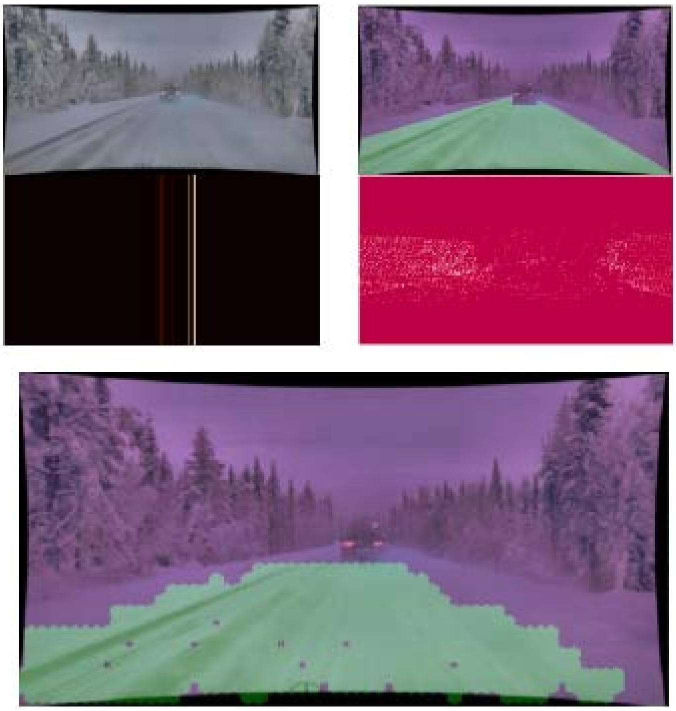


Figure 103: Input and output for CNN algorithm for drivable path. Top left – image, bottom left – radar output, top center – ground truth, bottom center – LiDAR, right – output. Green is drivable path [39].

Performance of the model is given by different metrics:

- Pixel accuracy – 95.04%
- MIoU drivable path – 81.35%
- MIoU non driveable path – 93.58%

Pixel accuracy are ratio of correctly identified positives and negatives to the size of the images. MIoU are Mean Intersection over Union which is the ratio between the intersection of the target mask and the prediction mask to the union of the target mask and the prediction mask.

Results show that the model can give a general area for drivable path without using lines on the road and handles fog and poor visibility. However, the model segmentation boundaries are rough and with low resolution and does not avoid pedestrians perfectly [39].

8.7.2 Localizing ground penetrating radar

At a research level, because these sensors are not commercially available, a Localizing Ground Penetrating Radar (LGPR) has been proposed as a sensor for autonomous vehicles. The hardware is specially designed with high cross-track resolution with low frequencies to measure deeper into the soil where ground is more stable.

The basic idea is that underground features are stable over time and less affected by surface conditions. Meanwhile, the road must be mapped with GPR so the autonomous vehicle can position itself relative to the GPS map.

The background map in Figure 104 visualize the concept of matching LGPR measurements to an existing background map, colours of the circles represent depth. Note that the process is done in 3D, so the visualization is a simplification.

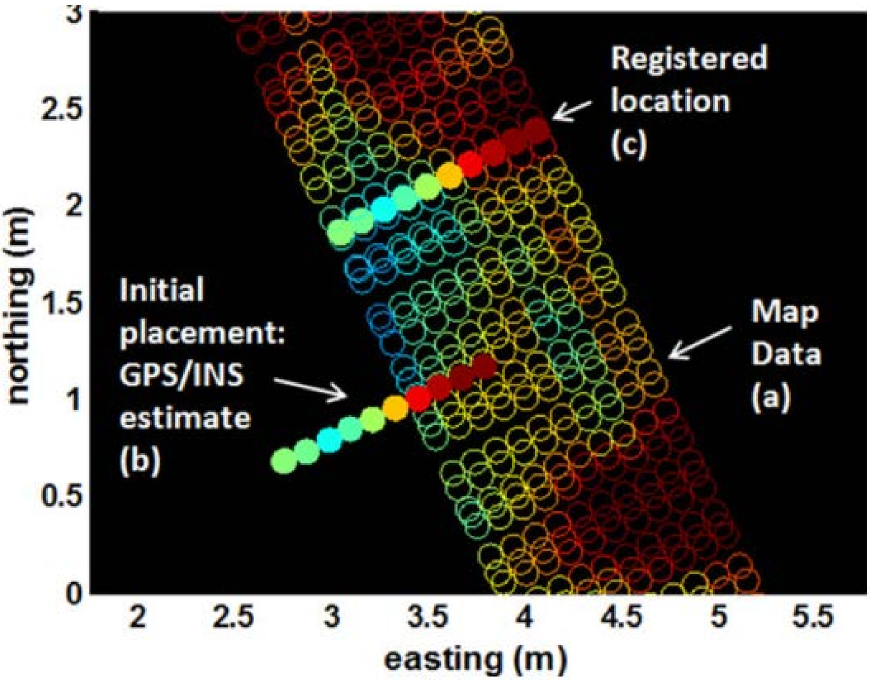


Figure 104: Visualization of measured LGPD data with background map and registered location [41].

Early experiments show that LGPR navigation has a cross-track accuracy of 4.3cm and an along-track accuracy of 11.9cm compared to a NRTK GNSS trajectory [41].

There are some risks that are identified in this early research for this navigation method:

- Subsurface map stability – surface weather condition like snow and rain can influence moisture in the ground which affects signal propagation [40].
- The need of pre-mapped roads
- All-weather operation is the key advantage for LGPR, but tests have to be performed to show the reliability
- Vehicle chassis – signals might be a little disturbed by vehicle chassis. It is believed that this is neglectable, but it must be verified in future studies.
- Antenna polarization – current antenna design gives data dependant on the orientation of the vehicle.
- Miniaturiation – antennas and hardware must become significantly smaller to be adapted by consumer marked.
- Cost – must be reduced for consumer marked [41].

In 2021 MIT shared their LGPR data for other researchers to further develop this concept [40].

8.7.3 GNSS in harsh weather

GNSS are in general not affected by local weather conditions with their operating frequency at approximately 1575GHz [42]. GNSS and troposphere are elaborated further in TEAPOT WP2.1 - Challenges of GNSS in the North.

High precision GNSS with cm absolute accuracy can be used as a reliable source for autonomous driving even with heavy precipitation. But if used with HD-maps or point clouds, these must have the same absolute accuracy to ensure correct sensor fusion and reliability for safe navigation.

8.8 Standardization for ITS and geospatial data

The business around autonomous vehicles is an evolving industry and companies that develop autonomous systems or related data started from scratch with no existing standards like it is in an established industry. As far as the authors of this document know, there are no standards for point clouds applicable for autonomous vehicles, however there are evolving standards for HD-maps.

8.8.1 Report from Ordnance Survey

In 2019 Ordnance Survey (Great Britain's National Mapping) agency, and Zensic (UK hub organization for self-driving vehicle development) has addressed the issue that there are no "consensus, standardization, and collaborative initiatives" for HD maps. There are no authoritative source for HD maps, and companies developing AV systems either map an area before operation starts or crowdsource maps to their needs and specifications. Ordnance Survey states that "We believe that consistent, authoritative and trusted data provides a framework for safe operation, interoperability, and open standards development. It will also enable innovative solutions from a wide range of providers who will bring new and exciting solutions to the U.K. mobility sector" [28]. They point out that authoritative standardization is needed to collaborate and share data for HD maps to scale up deployment of autonomous vehicles

8.8.2 Authoritative standardization

There are work related to ITS, maps, spatial data and position in the standardization organizations CEN and ISO. The CEN and ISO standardization organization covers Europe and globally [27].

CEN/TC 278 WG 7 ITS spatial data group focuses on "how to handle changes in road attributes from road authorities and operator, to actors who need these data (like map makers)".

ISO/TC 204 ITS – WG 3 ITS database technology group focuses on electronic maps relevant for ITS, and the GDF format (Geographic Data Files). GDF is used to "model, describe and transfer road networks and other geographic data".

TN-ITS are aiming to exchange information in real time about change in static road attributes, such as speed limit signs that are more or less at a permanent location but occasionally are moved. This change can be done by authorities or private companies. Members are authorities from Sweden, Belgium, Norway, Ireland, Finland and United Kingdom and the private map maker companies TomTom, HERE and Geojunxion [43].

8.8.3 Navigation Data Standard

Navigation Data Standard (NDS) is an association of members from automotive OEMs, map data providers, and navigation data providers. The format they developed is standardized for automotive-grade databases. NDS primary goal is to separate navigation software from navigation data by a standardized format for easy exchange of data between different companies. Members of the association compete among themselves on quality and completeness of map data (HD-maps), or end user experience as a navigation system in a vehicle.

It is important to note that this is an industry driven format and standardization organization, unlike standardization work in ISO and CEN. The format continuously develops by agile work method by talking together and bringing issues to the table.

8.9 Data exchange of geospatial data

Developers of autonomous vehicles have different needs for data and sensors depending on which level of autonomy they aim at. Pilot projects with systems aiming for full autonomy need point cloud, HD-maps and high precision GNSS for a small area and the roads they operate on. Systems aiming for developing ADAS systems for private consumers seldom use point cloud or high precision GNSS, hence they only use HD-maps. In general developers of fully autonomous systems use all sensors and data they need, while development of systems for private vehicles adapt to opportunities that available technology for large areas and at low cost gives them. This results in emerging standardization and data exchange for HD-maps aiming for private vehicle systems, while fully autonomous systems do their own mapping and data collection.

8.9.1 HERE platform

HERE technologies have a platform for location data where a customer can easily get started with geographic data. Examples are to visualize data and generate insights with web tools. With API and SDK it is possible to build applications, develop services and make maps. There is also a possibility to upload your geographic data to a marketplace so other companies can buy your data via this platform [33].

At CES 2022 HERE announced that they added point cloud data along roads on their platform, they have "millions of kilometres of roadways and their surroundings in high-fidelity across more than 50 countries and territories» [34].

HERE collects data from a variety of sources from different countries, some data they capture themselves and others are from 3rd party sources like other private companies or the public sector. This leads to data in many different formats and HERE puts a lot of effort into harmonizing all these data into one single end user product that will be used in different countries and in cross border applications like automated driving.

HERE is a member of Navigation Data Standard Association, see section 8.8.3.

8.9.2 Hexagon Content Program

Hexagon Content Program offers geospatial data from large parts of USA, Canada and Europe, type of data are aerial imagery, digital surface models and point clouds. This platform is organized with authorized resellers of data and companies that do data capture all over the world [36].

They do not share data from mobile mapping vehicles, but seen in relation with section 8.9.1 there is a trend that existing geospatial are more available than before.

8.9.3 Data from public sector

The public sector in Norway has an ambition to share and give open access to data to other public sectors and private companies so better solution and products can be created for the community and end users.

8.9.4 Data from the Norwegian Mapping Authority

The Norwegian Mapping Authorities, NMA, share data and most of them are relevant for the transport sector. Some examples are property and address information, digital terrain models, and maps specifically for roads.

NMA also operates an NRTK GNSS system which makes it possible to measure positions with cm accuracy [37].

8.9.5 Data from the Norwegian Public Road Administration

The Norwegian Public Road Administration operates and maintains the public roads in Norway and shares open data about road and transportation. There are relevant data about accidents, real time travel times, public transport, timetables and more. Access to such data are mandatory for all European countries stated by the ITS directive from EU [38].

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