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LOCALISATION WORKING GROUP (LWG)

Train Positioning Techniques' Comparison

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Table of Contents

1 List of references and acronyms

1.1 References

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[2] "Localization With Magnetic Field Distortions and Simultaneous Magnetometer Calibration," [Online]. Available: https://ieeexplore.ieee.org/document/9195842.

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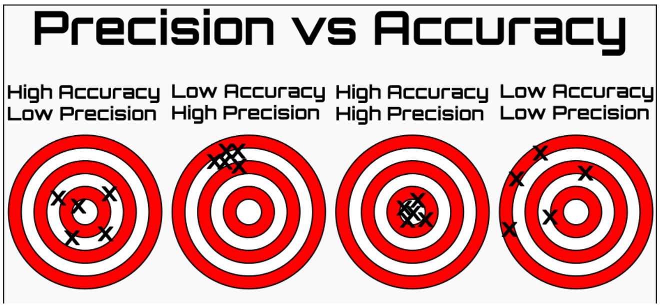
1.2 Acronyms

CCS	Control Command and Signalling
DGNSS	Differential Global Navigation Satellite System
DM	Digital Map
EDAS	EGNOS Data Access Service
EGNOS	European Geostationary Navigation Overlay Service
ERTMS	European Rail Traffic Management System
ESA	European Space Agency
ETCS	European Train Control System
EU	European Union
EUG	ERTMS Users Group
EUSPA	European Union Agency for the Space Programme
GBAS	Ground Based Augmentation System
GNSS	Global Navigation Satellite System
GPR	Ground Penetrating Radar
GPS	Global Positioning System
HAS	High Accuracy Service
IM	Infrastructure Manager
IMU	Inertial Measurement Unit

INS	Inertial Navigation System
IR	Infrared (Camera)
L1	Level 1 (referred to EGNOS versioning)
LIDAR	Laser Imaging, Detection and Ranging
LWG	Localisation Working Group
MIT	Massachusetts Institute of Technology
PPP	Precise Point Positioning
PRS	Public Regulated Service
RADAR	Radio Detection and Ranging
RCA	Reference CCS Architecture
RFID	Radio Frequency Identification
RTK	Real-time Kinematics
RU	Railway Undertaking
SBAS	Satellite Based Augmentation System
SIL	Safe Integrity Level
SiS	Signal in Space
SLAM	Simultaneous Localisation and Mapping
SoL	Safety of Life
SoM	Start of Mission (referred to ERTMS/ETCS procedure)
SP	System Pillar
SR	Staff Responsible (referred to ERTMS/ETCS mode)
UWB	Ultra-Wideband
VPS	Visual Positioning Systems
WARTK	Wide Area Real-Time Kinematics

1.3 Definitions

Accuracy	Accuracy is the proximity of measurement results to the accepted or true value
Precision	Precision is the degree to which repeated (or reproducible) measurements under unchanged conditions show the same results.  [1]

2 Scope of the document

2.1.1.1 The scope of this document is to investigate positioning techniques that are not yet in use or are still in an experimental phase for rail CCS applications.

2.1.1.2 Note: Eurobalises and wheel sensors (electronic, mechanical and/or electromechanical) are not considered in this document, as they are largely already in operation.

2.1.1.3 This document intends to provide:

- An overview of technical systems that are potentially able to fulfil the operational needs required by the “advanced train positioning” system (summarised in Chapter 3), typically in combination among them.
- A maturity comparison among the most promising techniques.

3 Operational needs affecting train positioning

3.1.1.1 In this chapter, the main functional operational needs affecting train positioning are derived from the main System Pillar common business objectives and summarised.

3.1.1.1.1 Reduce the size of the train confidence interval when rail operation needs it (with benefits for performance, grade of automation of the operation and safety only in release speed monitoring).

3.1.1.1.2 Improve the robustness of the localisation system by decreasing the influence of slip-and-slide phenomena and systematic errors (e.g., faulty configuration such as the wheel diameter).

3.1.1.1.3 Reduction of physical reference points in the form of Eurobalises.

3.1.1.1.4 Being an enabler for moving the track occupancy determination functionality from trackside to on-board (on-board centric approach).

3.1.1.1.5 Improve flexibility and time-to-market for the introduction of new technologies.

3.1.1.1.6 Reduce the distances to be run in ETCS mode Staff Responsible after Start-of-Mission with an ETCS train position different from valid and without the need for additional ETCS physical balises.

3.1.1.1.7 No need for human intervention (unless for maintenance purposes and at the very first starting) and with a minimum start-up time.

3.1.1.1.8 To provide train positioning information to different on-board consumers having different safety and content requirements avoiding duplication of sensors to be installed.

4 Overview of positioning techniques

4.1.1.1 In this chapter, different positioning techniques, not or partially in use for rail safety applications, are described according to the information available in literature.

4.1.2 UWB

4.1.2.1 Ultra-wideband (UWB) is a radio frequency technology for transmitting information using short-range, high-bandwidth communication with low energy consumption.

4.1.2.2 UWB is used to transmit and receive small pulses to determine a location within a range of 1 to 50 meters.

4.1.2.3 UWB is based on the principle of measuring the travelling time of the radio signal. The transmitter and receiver operate best in an obstacle-free view to ensure the most optimal performance.

4.1.2.4 UWB needs to deploy a network of stationary radio bases.

4.1.2.5 UWB has the capability of transmitting information while the receiver can determine the distance to the transmitter.

4.1.2.6 Besides, ERTMS balises, UWB is the only other technology which is by the time writing fully mature and ready for railway application. A drawback is that the deployment on the full network is currently expensive and not standardized.

4.1.3 GNSS

4.1.3.1 A Global Navigation Satellite System (GNSS) is a satellite-based system that provides continuous positioning in open-sky conditions and involves a constellation of satellites in orbits around the Earth.

4.1.3.2 GNSS consists of three segments: a space segment, a control or ground segment and a user segment.

- The space segment comprises satellites strategically placed in orbit to ensure comprehensive coverage. Each satellite in a GNSS constellation broadcasts a signal identifying itself and providing, among others, its precise time, orbit location and system health status.
- The control segment consists of various ground-based facilities, including master control stations, monitor stations, and ground antennas. These ground facilities

play a crucial role in ensuring and maintaining the proper operation of the satellite system.

- The user segment consists of equipment designed to process the received GNSS signals, enabling the computation of location and time information. The equipment ranges from smartphone and handheld receivers to advanced and specialised receivers tailored for specific applications.

4.1.3.3 The GNSS positioning principle is based on the user's distances to a set of at least four visible satellites with known coordinates to calculate time and a position in the 3D space.

4.1.3.4 Note: less than four satellites can be sufficient if additional boundary conditions (e.g., rail track information, surface location, …) are available.

4.1.3.5 The performance of GNSS is subject to external, uncontrollable influences - due to environmental influences, structural conditions - and therefore requires supplementary approaches to overcome difficulties in such cases.

4.1.3.6 In locations where GNSS satellites are not visible, GNSS repeaters can be used to enable some GNSS satellite services to GNSS devices. GNSS repeaters provide at least their antenna location and satellite time to GNSS devices. For example, a building equipped by a GNSS repeater, a GNSS device inside the building has the location of the repeater antenna wherever the device is in the coverage area of the repeater, and an accurate satellite time information provided by the GNSS repeater.

4.1.3.7 GNSS error sources include:

- Satellite related errors (clock errors, orbit errors, instrumental hardware delay);
- Signal propagation related errors (ionospheric delay, tropospheric delay, multipath);
- Receiver related errors (receiver noise, clock bias, hardware and software errors);
- Intentional error sources (signal jamming, signal spoofing).

4.1.3.8 The performance of GNSS is assessed using four criteria:

- Accuracy: the difference between the estimated and the real value (position, velocity, time);
- Integrity: the measurement of the reliability and the system's capacity to provide a threshold of confidence and, in the event of an anomaly in the positioning data, an alarm;
- Continuity: the system's ability to be operational without unscheduled interruptions;
- Availability: the percentage of time the system fulfils the above accuracy, integrity and continuity criteria.

This performance can be improved by Ground Based Augmentation Systems (GBAS) and Satellite Based Augmentation Systems (SBAS), such as the European Geostationary Navigation Overlay Service (EGNOS).

4.1.3.9 Galileo is Europe’s own GNSS which provides high accuracy and guarantees global positioning service under civilian control. The Galileo system will comprise 30 satellites, which improves the overall availability and coverage of GNSS signals. Six to eight Galileo satellites will be visible from most locations, which combined with GPS signals, will make it possible to determine positions to within a few centimetres. Examples of high-performance services provided by Galileo are the High Accuracy Service (HAS) and the Public Regulated Service (PRS). The Galileo HAS will provide high-accuracy Precise Point Positioning (PPP) corrections free of charge and the Galileo PRS will provide restricted position and timing to government-authorised users and aims to ensure the continuous availability of the Signal-in-Space (SiS).
As Galileo's high-performance services are provided from the same satellites as all Galileo GNSS signals, it does not need to rely on ground stations and radio network, and therefore the reliability of these services depends only on the availability of Galileo satellites. The availability of Galileo satellite services is much higher compared to geostationary satellites, especially in northern Europe. Even though Galileo services are primarily provided by the satellites, some services are available also via the internet. In such use cases, the reliability of the service level depends highly on the radio network in use.

4.1.3.10 In addition to Galileo, examples of GNSS include the USA’s NAVSTAR Global Positioning System (GPS), Russia’s Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS) and China’s BeiDou Navigation Satellite System.

4.1.3.11 Different approaches involve the standard GNSS solution aiming to augment GNSS service:

- Differential GNSS (DGNSS) is a type of GNSS augmentation based on enhancing GNSS position determination using a network of ground-based reference stations with an accurately known position, but does not provide integrity information. There are several differential GNSS approaches implemented, such as the classical DGNSS (or DGPS), the Real Time Kinematics (RTK) and the Wide Area RTK (WARTK). These GNSS augmentation services are provided to users via different radio networks, and therefore the service level depends highly on the reliability of a radio network in use.
- The European Geostationary Navigation Overlay Service (EGNOS) is Europe's regional satellite-based augmentation system (SBAS) that is used to improve the performance of global navigation satellite systems (GNSSs), such as GPS and Galileo (source EUSPA). EGNOS V3.x, which will be implemented for multi-constellation, multi-frequency (MCMF) and therefore augment both GPS and Galileo in the L1/E1 and L5/E5 bands, will also provide additional SBAS service capabilities using a new SBAS channel on L5/E5 and will provide increased service availability within and outside the EU. The EGNOS, which consists of three geostationary satellites and an interconnected ground network of about 40 positioning stations and 2 mission control centres, is designed to improve the accuracy and reliability of GNSS information by correcting signal measurement errors and by providing information about the integrity of its signals. EGNOS offers three navigation and positioning services: Open Service, Safety-of-Life Service, and Commercial Service (EDAS). In ideal conditions, the position is determined with an accuracy of 1.5

metres.
The use of EGNOS on the ground, especially in urban areas, is limited due to the relatively low elevation of the geostationary satellites: about 30° above the horizon in central Europe and the North of Europe much less or even below the horizon. To address this problem, ESA has released an Internet service designed for the continuous delivery of EGNOS signals to ground users. In such areas the geostationary satellites are not visible, the augmentation is provided to the users via a radio network e.g., a mobile telecommunication network, and therefore the reliability of the augmentation depends highly on the reliability of a radio network in use.

4.1.3.12 GNSS is considered by most of the suppliers - so far even if not fully mature - as the best candidate for a solution. This is due to the proven usefulness in aviation and maritime applications.

4.1.4 LIDAR

4.1.4.1 Laser Imaging, Detection and Ranging (LIDAR) is a sensor that determines the distance to a reflecting target.

4.1.4.2 The measurement principle of LIDAR is to measure the time of flight of laser pulses. The distance is determined by emitting laser pulses toward a surface or object and measuring the time between the emission and the reflected signal. The accuracy ranges from a few millimetres to decimetres.

4.1.4.3 LIDARs generally produce 2D or 3D point cloud data as output values. The laser pulses are emitted in a circular or spherical pattern which yield a sampled 2D respectively 3D image of the surrounding.

4.1.4.4 In positioning and navigation systems, LIDAR sensor generally requires additional devices (generally a GNSS receiver and an Inertial Measurement Unit) and/or a digital map (DM) to determine position and orientation.

4.1.4.5 When a digital map of the environment is available, the LIDAR (or any other visual sensor) can be used to determine the position by relying on the georeferenced position of the detected object included in the digital map and the position of the sensor with respect to that object.

4.1.4.6 LIDAR is generally used as a sensor for Simultaneous Localization And Mapping (SLAM) algorithms. LIDAR-based SLAM algorithms allow mapping an area while keeping track of the location of the device within that area. This process can work in both outdoor and indoor environments.

4.1.4.7 Using LIDAR as a standalone positioning method, LIDAR needs a sensor map or reference map with well-defined features that a LIDAR-based positioning system uses to determine its location.

4.1.4.8 LIDAR using point cloud matching is considered by some suppliers, but the safety case has not worked so far and will increase a lot the size of the digital map.

4.1.4.9 Besides positioning, LIDAR can be used for other purposes as well, such as obstacle detection.

4.1.5 RFID

4.1.5.1 Radio Frequency Identification (RFID) technology uses radio signals to identify and track tags attached to objects.

4.1.5.2 RFID tags can be either active with their own battery and periodically transmit their ID signal, or passive by the usage of the radio energy transmitted by the reader. An active tag usually enables a larger amount of information than a passive tag.

4.1.5.3 Active tags need to be maintained, like battery changes, whereas passive tags are basically free of maintenance. In RFID-based positioning systems, the possible corruption of information in RFID tags must be considered, for example by duplicating tags.

4.1.5.4 Note: passive tags are maintenance-free if the information is checked to be correct (environmental conditions may affect passive tags behaviour anyway). Active tags may have more information, but they need to be maintained which increases the cost.

4.1.5.5 RFID is based on the principle of transmitting and receiving radio signals but is not able to estimate the distance. However, if every sleeper or following sleepers have passive RFID tags, the train accuracy and location can be determined based on the distance between the sleepers and the RFID tags recognized by the RFID reader.

4.1.5.6 RFID can utilize the identification of discrete objects where the RFID tags are installed. Cross ties/sleepers, catenary poles, switches, marker boards etc are examples of discrete objects in this context. The objects must have a known location in a track map/database to translate the identified RFID reading into a position.

4.1.5.7 Passive tags cannot be read very far away and can therefore give a position in many cases within the range of some metres.

4.1.6 IMU

4.1.6.1 The Inertial Measurement Unit (IMU) is a device capable of measuring specific forces and angular rates in three dimensions using a combination of an accelerometer and a gyroscope. Some IMUs also include a magnetometer which is commonly used as a heading reference. Typical configurations contain one accelerometer, gyroscope, and magnetometer per axis for all of the three principal axes.

4.1.6.2 The three dominating technologies for gyroscopes are:

4.1.6.2.1 MEMS: Micro electro-mechanical systems

4.1.6.2.2 FOG: Fibre optic gyroscopes

4.1.6.2.3 RLG: Ring laser gyroscopes

4.1.6.3 The main characteristic of an IMU is its gyroscope's bias instability describing the angular drift ranging from $2*10^{1}$ to 10^{-4} degrees per hour. This is reflected in the prices for an IMU starting from several Euros and ending at several 100k Euros.

4.1.7 INS

4.1.7.1 An Inertial Navigation System (INS) generally consists of a computational unit, an Inertial Measurement Unit (IMU) and other sensors. A standard approach is sensor fusion using a GNSS receiver and an IMU.

4.1.7.2 INS are used to continuously compute by dead reckoning the position, the orientation, and the velocity (direction and speed of movement) of a moving object without the need for external references.

4.1.7.3 The integration of IMU drift: small errors in the measurement of acceleration and angular rate are integrated into progressively larger errors in velocity, which are compounded into still greater errors in position. Therefore, the position must be periodically corrected by external input such as the GNSS position and velocity.

4.1.7.4 An INS often consists of a GNSS receiver and makes use of estimation methods (e.g. Kalman Filter, Particle Filter) to deal with the integration drift. GNSS results are processed and used to correct accumulated errors of the inertial system and vice versa where the IMU compensates local effects of the GNSS receiver.

4.1.7.5 INS are used for aviation, maritime, military and civilian applications.

4.1.7.6 The performance and capabilities of the INS mainly rely on the algorithm technique and the quality of the IMU which are described in the paragraph above.

4.1.8 RADAR

4.1.8.1 Radio Detection And Ranging (RADAR) technology uses radio waves to detect objects and determine the distance, angle, or speed of those objects.

4.1.8.2 RADAR principle consists of emitting a pulse of electromagnetic radiation in a specific direction and reflecting part of the pulse energy in return to the radar unit. RADAR can be used to determine the distance of an object by measuring the time it takes for the radio waves to return with a range from millimetres to metres.

4.1.8.3 Using RADAR as a standalone positioning method, RADAR needs a sensor map or reference map with well-defined features that the RADAR-based positioning system uses to determine its location.

4.1.8.4 Besides positioning, RADAR can be used for other purposes as well, such as obstacle detection.

4.1.9 GPR

4.1.9.1 Ground Penetrating Radar (GPR) technology uses radar pulses to create an image of the subsurface.

4.1.9.2 The GPR principle is based on a transmitter that sends electromagnetic energy to an object and a receiver that detects the reflected waves with a range from decimetres to metres.

4.1.9.3 Using GPR as a standalone positioning method, GPR needs a sensor map or reference map with well-defined targets that the GPR-based positioning system uses to determine its location. Because the structure of the subsurface varies according to the seasons, it is unclear whether separate maps are needed for different seasons. This applies especially to areas where the structure of the ground changes in different seasons because of freezing and thawing. On the other hand, the sensor can use sleepers, switches, and other track components to determine the location.

4.1.9.4 An issue to be considered is the fact that locomotives may not have enough space underneath to install GPR.

4.1.9.5 Another issue to be tested is the interference between GPR and balise antennas if they are installed close to each other.

4.1.10 VPS

4.1.10.1 Visual Positioning Systems (VPS) use a combination of computer vision algorithms and a database of known locations or features to determine the device's position and orientation. The device captures images with a camera or other visual sensor, and the VPS software processes these images to identify visual features in the environment. These features are then compared against a database of known features together with their location to determine the device's position. In some cases, the device may also use additional sensors, such as inertial measurement units (IMUs) or lasers, to help refine its location and orientation.

4.1.10.2 In addition to their ability to work in urban environments, VPS systems can be very accurate, with some systems capable of providing sub-centimetre precision. They also do not require any special infrastructure, such as GPS satellites or beacon transmitters, to work. This makes them easy to deploy and operate in a wide variety of locations.

4.1.10.3 VPS systems have the following limitations: the cameras can be sensitive to lighting conditions and can be disrupted by occlusions, such as objects blocking their view of the environment. They also require a database of known features and locations to work, which can be time-consuming and expensive to identify, create, build and maintain.

4.1.10.4 Visual camera systems shall comply with the General Data Protection Regulation (GDPR), which is a Regulation in EU law on data protection and privacy. This means e.g., that the camera system shall make persons or vehicles unidentified especially if the photos or videos are saved even for a short period.

4.1.10.5 Besides positioning, the cameras used for VPS can be used for other purposes as well, such as security, safety and obstacle detection.

4.1.10.6 Other camera technologies can be considered to work like visual camera systems, such as Thermal cameras/IR cameras.

4.1.11 Thermal cameras/IR cameras

4.1.11.1 Thermal cameras are a type of vision sensor technology that can be used for positioning and other purpose like obstacle detection for safety.

4.1.11.2 Thermal cameras and IR cameras use infrared light to create a thermal image. IR cameras create their own IR light and illuminate the objects which are recorded by the IR camera. Thermal cameras only record the passive IR light created by every object. Due to thermal cameras working with longer wavelengths compared to IR cameras, they are not obstructed by oncoming headlights from other vehicles, dust, smoke, fog etc.

4.1.11.3 The accuracy of thermal cameras ranges from decimetres to metres.

4.1.11.4 Even if it is very dark outside, the temperature of the picture can be used to compare the image with the database.

4.1.11.5 External fixed elements are needed to support the system, as signals or bridges. The Digital Map Object Catalogue of RCA defines which kind of object could be used for reference points.

4.1.11.6 Two cameras in a stereo setup are needed to create a 3D view using triangulation. If the distance can be measured, then the location might be known.

4.1.11.7 The use of other sensors such as IMUs is needed to support the vision sensors in some scenarios like tunnel environments.

4.1.12 SLAM

4.1.12.1 Simultaneous Localisation and Mapping (SLAM) describes an approach in which a map is built continuously by the same sensor setup as the one used to locate itself with respect to this map. The features can be dynamic and artificial in the sensed environment. The process of building the map of the environment is executed simultaneously with the process of positioning/orientating the object. These processes do not require prior knowledge of the environment.

4.1.12.2 A crucial prerequisite for SLAM is invariant features which describe observable and derivable characteristics being as robust as possible against unavoidable changes in the point of view or environmental disparities.

4.1.12.3 A generic method includes the assignment of newly recorded features with previous and stored observations. A typical sensor setup for SLAM consists of an IMU and a LIDAR or one or multiple cameras.

4.1.12.4 SLAM is widely used in mobile robotics, whether they are ground-based vehicles or indoor drone applications. Augmented reality uses SLAM for the mapping and localisation of the user in the open space as well.

4.1.12.5 Noteworthy implementations of SLAM methodologies using two or three-dimensional laser scanners are Cartographer and mapping. As the prices for cameras have strongly decreased in past decades, visual-based SLAM techniques have been extensively researched. Examples of implementations are ORB-SLAM and DynaSLAM.

4.1.12.6 ORB-SLAM is an accurate monocular SLAM solution that computes the camera trajectory and a sparse 3D reconstruction using ORB features in image. ORB-SLAM is able to detect loops and perform relocalisation in real time.

4.1.12.7 DynaSLAM is a visual SLAM system based on ORB-SLAM that adds dynamic object detection and background inpainting capabilities. DynaSLAM is able to detect moving objects using multi-view geometry and/or deep learning.

4.1.13 Telecommunication Network positioning

4.1.13.1 Network positioning in telecommunication networks like 4G and 5G networks is based on determining a mobile phone's position by interpolating signals between nearby base stations as the phone is continuously communicating with the nearest base station.

4.1.13.2 The signal can be measured by parameters based on direction or distance.

- The direction parameter is related to the angle of arrival or departure of the signal.
- The distance parameter can be determined by time-based (measuring the arrival or round-trip time of the signal) or signal-based (linked to the strength of the received signal).

4.1.13.3 5G network improves the 2G-4,5G networks as 5G has less latency and more data traffic, available spectrum and connection density than the others. In terms of accuracy, 2G-4,5G networks have a range from metres to kilometres and 5G networks have a range from decimetres to kilometres.

4.1.13.4 The accuracy of network positioning is mainly influenced by the density of cells and the radio frequency. More cells require more antennas and therefore reference locations which improves the user's positioning. The radio frequency used by the network shall be bounded to the cell to minimize the effect of interference between different stations.

4.1.14 Ultrasonic positioning

4.1.14.1 Ultrasonic positioning technique determines the position, distance and movement within a specific space using ultrasound waves.

4.1.14.2 The ultrasonic sensors emit ultrasonic waves and transmitters receive them. Position is determined by measuring the time-of-flight of the wave from the sensor to a surface or object and back.

4.1.14.3 For positioning applications, multiple ultrasonic sensors with known positions must be placed in the environment. The position of an object can be determined through triangulation or trilateration calculations.

4.1.14.4 The accuracy of ultrasonic sensor is determined within a range from millimetres to decimetres and depends on quality of transducer, environmental conditions, obstacles presence or reflective surfaces.

4.1.15 Magnetic field sensors

4.1.15.1 Magnetic fields can be measured using the principle of electromagnetism: a current induces a magnetic field and vice versa.

4.1.15.2 There exist multiple strategies to make use of magnetism for localisation: measuring the characteristic distortions of the Earth's magnetic field or the specific influence of solids such as iron on magnetic fields. [2] [3]

4.1.15.3 To estimate a position, both methods require a map of reference values to locate their measurements with respect to it.

4.1.15.4 The accuracy of magnetic field sensors has been reported between several centimetres up to a few metres in literature.

4.1.15.5 The main weakness of magnetic field sensors is the reliability of magnetic fields as they are subject to electromagnetic waves and ferromagnetic solids like iron which is heavily used in railways.

5 Maturity evaluation of the different techniques

5.1.1.1 The different techniques reported in Chapter 4 are compared on a qualitative basis according to the following conditions:

- Accuracy, the proximity of measurement results to the accepted or true value.
- Snow, this is how the technical system performs in snowy and cold environments.
- Fog, this is how the technical system performs in a foggy environment.
- Heavy rain, this is how the technical system performs in heavy rain conditions.
- Bright sunlight, light conditions may influence how the technical system performs when exposed to intense solar radiation.
- Open sky obstruction, this is how the technical system performs in an environment where the sky is obstructed, such as a tunnel.
- Susceptible to interfere, this is how easy the technical system performances can be affected by interferences which may be intentional or unintentional.
- Infrastructure requirements, this is if the technical system need specific additional infrastructure (such as base station, servers, tags, software elements) to perform.
- Sensor cost, the price range of the technical system.
- Infrastructure cost, the price range of the possible needed specific additional infrastructure (e.g., base stations).
- Technical maturity, this is how mature the technical system is. This does not refer to rail CCS application, but whether the technique is already in operation or even at an early stage of development.
- Certifiability maturity, this is how mature the technical system is for achieving a certification.
- Indoor/outdoor, this is whether the technical system is mostly able to perform indoor or outdoor.

5.1.1.2 The following table reports the meaning of the keys used in the comparison table below.

Criteria	Criteria id	Description
Accuracy	km	Kilometer
	dam	Decameter
	m	Meter
	dm	Decimeter
	cm	Centimeter
	mm	Milimeter
	(1)	Positioning accuracy in 5G networks depends largely on the frequency. In higher frequencies the accuracy is in dm level, although the number of base stations is very high to cover the whole railway network, and therefore the cost is huge
Snow	+	Good performance
	-	Bad performance
	(2)	GPR technology is rather new positioning method invented in MIT (Massachusetts Institute of Technology). No information currently how GPR works in different seasons as the ground is icy or wet or dry.
Fog	+	Good performance
	-	Bad performance
	(3)	Thermal sensors cannot be used for precise positioning in dense fog.
Heavy rain	+	Good performance
	-	Bad performance
Bright sunlight	+	Good performance
	n/a	Not available or not applicable
Open sky obstruction	+	Good performance
	(4)	If network is available in tunnels
	(5)	Only with repeaters
Susceptible to interfere	yes	Susceptible to both, intentional (with the purpose of sabotage, for example spoofing or jamming) or unintentional (such as malfunctions, human errors or effect of the environment) interference

	no	Robust to both intentional and unintentional interference
	unintent	Susceptible to unintentional interference, such as malfunctions, human errors or effect of the environment
Infrastructure requirements	yes	Specific additional infrastructure elements are needed
	yes*	Specific additional infrastructure elements are needed, network coverage is required
	no	No need for specific additional infrastructure elements
Sensor cost	€€	Tens of Euros
	€€€	Hundreds of Euros
	€,€€€	Thousands of Euros
	€€,€€€	Tens thousands of Euros
Infrastructure cost	(6)	Infrastructure elements are needed, such as base stations, servers, and software elements. Price level for a small positioning track maintenance area is around €,€€€-€€,€€€. If the technology is used in train or shunting operations, the whole network needs to be covered by the network, and therefore a huge number of fixed base stations are needed. To get the optimal accuracy, the maximum distance from a base station to a UWB positioning device is 50m.
	(7)	EGNOS needs base station network in the areas where the EGNOS satellites are not visible, for example in norther Europe. DGNSS needs a base station network where the service is used. DGNSS base station prices at 2€,€€€ - 5€,€€€ -level. If an own network is needed then the price will be €€€,€€€ - €,€€€,€€€. Needs also for other infrastructure elements.
	(8)	RTK-GNSS needs an RTK augmentation network. If commercial augmentation is available, then there will be a monthly cost. Base station prices at 2€,€€€ - 5€,€€€ -level. The accuracy depends on the distance of the base station, e.g., some GNSS devices for <30 cm accuracy require the distance between base stations to be less than 100 km. If an own network is needed, then the price will be €€€,€€€ - €,€€€,€€€. Needs also for other infrastructure elements.
	(9)	RFID system needs RFID tags in the infrastructure. The accuracy depends how dense the tag network is. For tag network, the highest price comes from installation as tags are at € - €€ price level. For example, to achieve the minimum accuracy requirement (5m +5% s) to the whole Finnish railway network (5926 km at the end of year 2018), there shall be nearly 1,2 million tags assembled to the

		infrastructure. If RFID tags are in each sleeper, about 50 cm accuracy can be achieved. This means that in Finland nearly 12 million tags are needed in the infrastructure.
	(10)	If infrastructure requirements needed, the price will be higher than €€€,€€€
	(11)	Depends on whether the teleoperators used offer network positioning. The operational cost is usually based per transaction, which might rise the operational costs very high. The pricing model should be monthly based, not by transaction. If an own mobile network is used, the main cost comes from the positioning components of the mobile network elements. Price estimation: €€€,€€€ - €,€€€,€€€
	n/a	Not available or not applicable
Technical maturity	1	The technical system is at a very early stage of development, still low confidence that performance objectives can be achieved
	2	The technical system is at an intermediate stage of development (prototype and field test already performed), sufficient confidence that performance objectives can be achieved
	3	The technical system is at a mature stage of development, or it is already in operation for rail SoL applications or similar
Certifiability maturity	1	There is not yet evidence of the possibility to certify the technical system for safety application or in a safety relevant context
	2	There is at least a sufficient confidence of the possibility to certify the technical system for safety application or in a safety relevant context
	3	The technical system is already certified for rail SoL applications or similar or there is anyway a high confidence of the possibility to certify the technique in a safety relevant context
Indoor/ outdoor	in/out	Mainly used for indoor applications. Some of these technologies are suitable for outdoor positioning in certain limited area depending on the outdoor prerequisites, such as additional infrastructure requirement like a base station network solution and therefore the price of the system
	in	Used in indoor positioning techniques
	out	Used in outdoor positioning techniques
	n/a	Not applicable, independent of indoor/outdoor usage

5.1.1.3 The following table summarises the result of the comparison.

Positioning techniques / Criteria	UWB	GNSS					LIDAR	RFID	IMU	RADAR	GPR	VPS		Telecom		Ultrasonic	Magnetic field sensor
		Classical	DGNSS	RTK	EGNOS V3.x	Galileo HAS						Camera	Thermal/ IR Camera	2G-4,5G	5G		
Accuracy	dm	m - dam	m	cm - dm	dm	dm	mm - dm	m	cm - m	cm - dm - m	dm - m	dm - m	dm - m	m - km	dm - km (1)	dm - m	cm - m
Snow	+	+	+	+	+	+	-	+	+	+	(2)	-	-	+	+	+	+
Fog	+	+	+	+	+	+	-	+	+	+	+	-	(3)	+	+	+	+
Heavy rain	+	+	+	+	+	+	-	+	+	+	+	-	-	+	+	+	+
Bright sunlight	+	+	+	+	+	+	+	+	+	+	+	n/a	n/a	+	+	+	+
Open sky obstruction	(4)	(5)	(5)	(5)	(5)	(5)	+	+	+	+	+	+	+	(4)	(4)	+	+
Susceptible to interfere	no	yes	yes	yes	yes	yes	no	no	no	no	no	no	no	no	no	unintent	unintent
Infrastructure requirements	yes	no	yes	yes	yes	no	no	yes	no	no	no	no	no	yes*	yes*	no	yes
Sensor cost	€€ - €€€	€€ - €,€€€	€€€ - €,€€€	€€€ - €,€€€	€€€ - €,€€€	€€€ - €,€€€	€,€€€- €€,€€€	€€€ - €,€€€	0 - €€€	€,€€€- €€,€€€	€,€€€- €€,€€€	€€€	€€€	€€€ - €,€€€	€€€ - €,€€€	€€€	n/a
Infrastructure cost	(6)	n/a	(7)	(8)	(7)	n/a	n/a	(9)	n/a	n/a	n/a	(10)	(10)	(11)	(11)	n/a	n/a
Technical maturity	3	3	3	3	1	2	3	3	3	3	2	3	2	3	2	3	2
Certifiability maturity	2	3	3	3	3	3	2	3	3	2	3	1	1	2	2	2	2
Indoor/outdoor	in/out	out	out	out	out	out	in/out	in/out	n/a	in/out	out	in	in/out	in/out	in/out	in/out	in/out

5.1.1.4 Note: the table above is a maturity evaluation of all the positioning techniques presented in Chapter 4, except for the INS and SLAM techniques. These two are algorithm techniques fusing the results of different technologies and are therefore not considered to be necessary to include them in the comparison table.