Galileo Satellite Navigation System

Space applications on earth

STUDY

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Galileo Satellite Navigation System: Space applications on earth

Study

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Abstract

This study explains the background necessary for an understanding of the Global Navigation Satellite System (GNSS) working principle, and highlights Galileo's properties in comparison to those of other competing GNSSs. It outlines Galileo's importance for the EU, emphasising the socio-economic and strategic benefits for Europe by providing a detailed view of a wide variety of applications across different domains. The study also considers the different requirements from the various application domains, which are based on commonly used Key Performance Indicators. It also identifies some of the gaps and challenges to reaching Galileo's final operational capability, expected in 2021. The study concludes with an examination of results, based on which different policy options are proposed in order to maximise the impact of the European GNSS in the near future and in the longer term.

The study is based on interviews with various experts throughout Europe involved in GNSS in general and Galileo in particular, and on an extensive literature review covering high-quality sources.

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List of abbreviations

ABAS	Aircraft Based Augmentation System
ADS-B	Automated Dependent Surveillance Broadcast
ARNS	Aeronautical Radio Navigation Service
CS	Commercial Service
DAS	Driver Advisory System
DG Grow	Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, European Commission
EGEP	GNSS Evolution Programme
EGNOS	European Geostationary Navigation Overlay Service
EU	European Union
GADSS	Global Aeronautical Distress Safety System
GBAS	Ground Based Augmentation System
GLONASS	Global Navigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSA	European Global Navigation Satellite Systems Agency
ICAO	International Civil Aviation Organization
ITU	International Telecommunication Union
JRC	Joint Research Centre
LTE	Long Term Evolution (4G cell phone network)
MEO	Medium Earth Orbit
NAGU	Notice Advisory to Galileo Users
NAVSTAR	Navigation System with Time and Ranging (same as GPS)
OEM	Original Equipment Manufacturer
OS	Open Service
PBN	Performance Based Navigation
PMU	Phasor Measurement Units
POI	Point of Interest
PPD	Personal Privacy Devices
PPP	Precise Point Positioning
PRS	Public Regulated Service
RFI	Radio Frequency Interference
RNSS	Radio Navigation Satellite Service
RTK	Real-Time Kinematics
SAR	Search and Rescue
SBAS	Space Based Augmentation Systems
SMEs	Small and medium-sized enterprises
UA	Unmanned Aircraft
UTC	Universal Time Coordinated

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Executive Summary

This study focusses on the European Galileo Satellite Navigation System, presents its current deployment status and discusses current and potential new applications of GNSS technologies in general and the Galileo system in particular. The study is also useful for understanding the basic principles of GNSS functioning. It points out Galileo's unique features, compared to the other GNSSs and also summarises the benefits for European citizens and the economy.

The study is based on the information gained during 13 interviews with various experts in the field of GNSS and is complemented by high-quality literature sources.

Domain-related assessment

The importance of GNSS and Galileo is discussed for the following domains of application: aviation, Location Based Services (LBS), timing and synchronisation, surveying, road, rail, maritime, agriculture, and public authorities and military.

In the aviation domain, GNSSs are used for navigation, surveillance and aircraft tracking (including drones). With Galileo, more satellites and frequencies are available, providing better service to the users. However, pending international harmonisation and certification, Galileo is not yet fully integrated into aviation navigation and surveillance.

Location Based Services (LBS) comprise very dynamic and diverse fields of GNSS applications and include navigation services, social networks and games, as well as fitness, sport and activity tracking, and a variety of professional commercial services. In this domain, interoperability between different GNSSs is particularly important to avoid costly adaptations to single-satellite navigation systems. Here, Galileo will provide more satellites in view for challenging reception scenarios, signal authentication for security sensitive applications, as well as improved accuracy and coverage with unique return link capability for Search and Rescue (SAR) operations.

In the timing and synchronisation domain, Galileo provides the EU strategic autonomy in providing information for critical infrastructure and the financial domain, but it is also a redundant timing source for increased robustness and resilience in general.

Land surveying is the process of determining the three-dimensional position of a fixed point on Earth relative to a certain reference frame. In this domain, Galileo provides more frequencies and satellites for improved accuracy and convergence times and is particularly useful in conjunction with the Copernicus Earth observation programme.

For road and autonomous driving, Galileo provides more satellites in view for challenging urban reception scenarios. However, GNSS positioning is generally not sufficient for autonomous driving. Galileo also provides a basis for improved traffic safety due to European eCall distress service.

In the rail sector, GNSS is used to a limited extent due to specific domain requirements. However, besides providing more satellites in view for challenging reception scenarios, it improves the efficiency by supporting the train driver advisory systems.

Galileo is already approved as maritime navigation aid internationally and it provides redundant navigation source to other navigation aids. It also improves maritime safety as the European contribution to worldwide SAR service.

In agriculture, Galileo enables high precision navigation service free of charge for precision farming thanks to more frequencies and satellites available for improved accuracy and efficiency.

Concerning public authorities and military, Galileo provides strategic autonomy from other countries' space assets. Encrypted service could be used for sensitive sovereign applications and the authentication feature increases safety even in disturbed environments. There are particular benefits for civil protection when Galileo is used in combination with data provided by the Copernicus Earth observation programme.

Advantages and challenges

Galileo has several technical features which are unique and not provided by other competing GNSS systems, for example, the Search and Rescue return data link for user notification and signal authentication for civil users. Both features represent important advantages which are expected to provide high added values both to EU citizens and to users throughout the world.

Although Galileo is behind its initial schedule, many application domains have already seen benefits from Galileo and expect additional benefits in the future. This can mainly be attributed to the fact that Galileo is interoperable with other GNSS constellations and therefore increases the potential number of satellites in view. This results in improved accuracies, more measurements for integrity monitoring and higher availability.

Another advantage of Galileo is the strategic autonomy of the EU regarding other countries' space navigation assets, especially since GNSS is being increasingly used in safety-critical applications and highly relevant infrastructures.

Galileo presents Europe's contribution to the world-wide satellite-based distress signal detection and localisation system Cospas-Sarsat, both by providing additional satellites, but also by significantly improving the coverage and accuracy of the located emergency positions.

Together with the geo-stationary satellite-based augmentation system EGNOS, Galileo is expected have a calculated cumulative value of approximately €130 billion in the period of 2014-2034. Immediate direct benefits are expected for the space industry as well as downstream markets for GNSS-based applications and services. On the other hand, the total Galileo-related costs from the early 1990s until 2020 amount to approximately €16 billion.

The study also highlights technical, communication and organisational challenges in working towards Galileo's full operational capability. These were mainly collected during expert interviews. Two major drawbacks of Galileo can be identified. Firstly, it currently cannot be used for certain safety-critical applications due to the fact that no approval or guidelines are in place. Certification of Galileo is often hindered by the fact that information has not been provided by the Galileo authorities, or that such communication has been inefficient. Secondly, some industry players lost faith in Galileo due to the overly-optimistic time schedules in the past. With the parallel modernisation of GPS, Galileo has missed the opportunity to be the first operational system with modern features for civil users. Therefore, Galileo is nowadays mostly seen as an additional source of measurements to be used in conjunction with the other GNSS constellations, but not as an independent alternative to GPS.

Policy options

At the end, based on the interviewees' feedback and the major findings from the literature, the study outlines eight policy objectives based on which it lists 12 policy options. The policy objectives include:

(1) Maximising the impact of Galileo by increasing the support for development of Galileo-based technologies and services;

(2) Maximising safety and integrity provided by Galileo and accommodating user needs for improved signal authentication;

(3) Maximising benefits from Galileo's Public Regulated Service (PRS), by for example increasing the support for SMEs in applying PRS for safety-critical infrastructures;

(4) Spreading the use of Galileo's services by facilitating easy integration and interoperability on a technical level;

(5) Analysing the strategic dependency on GNSS in general and investigation options for backup technologies;

(6) Counteracting Personal Privacy Devices generating radio frequency interference in order to prevent GNSS-based tracking, which is particularly affecting safety-critical GNSS applications;

(7) Supporting certification of Galileo for safety-critical applications in order to accelerate the incorporation of Galileo into such applications, which is especially relevant for the aviation sector; and

(8) Increasing the use of Galileo for research purposes.

1. Introduction

Global Navigation Satellite Systems (GNSSs) are defined as constellations of satellites providing signals which can be received by users to measure the distance to the transmitting satellite and to globally determine their current position. In general, GNSSs consist of three components:

1. Space segment: The space segment includes the satellites of a GNSS. Usually, GNSS satellites are in a so-called Medium Earth Orbit (MEO) at altitudes of about 20 000 km.
2. Control segment: The control segment or ground segment is located on Earth to monitor and control the space segment and generates navigation data which is broadcast along with the ranging signal by the space segment.
3. User segment: The user segment includes any user receiving and processing the GNSS signals. For this task, an interface control document defines in detail how a GNSS receiver is to use the signals broadcast in order to obtain a position solution.

All components have to be designed carefully in order to achieve a high level of performance. In addition to an interface control document, most GNSS systems also provide a performance specification document detailing the performance which users can expect under nominal conditions. Four GNSSs are currently available:

- NAVSTAR-GPS: The 'Navigation System with Time and Ranging – Global Positioning System', commonly denoted as GPS, is a military system operated by the Department of Defence of the United States of America. Developed as a military system during the Cold War, it has now spread into various civil applications and is currently undergoing a modernisation effort.
- GLONASS: The 'Globalnaja Nawigazionnaja Sputnikowaja Sistema' is the counterpart to GPS, operated by the Russian Ministry of Defence.
- Galileo: Plans for a European satellite navigation system have existed for decades. Galileo was agreed upon in 1994 and is now, after several setbacks and delays, foreseen to declare its full operational capability in 2021 [7]. It is operated by the European GNSS Agency (GSA) and the European Space Agency (ESA), with the programme oversight of the European Commission and the political oversight of the European Council and the European Parliament. Apart from the other GNSS constellations, Galileo has been designed to provide signals usable by civilians in different frequency bands, beginning with the initial planning.
- BeiDou: The Chinese BeiDou system (also called COMPASS) has been under development for several years and is operated by the China National Space Administration (CNSA). In the current generation of its evolution, the space segment not only consists of MEO satellites for global coverage, but also incorporates satellites in other types of orbits in order to improve availability in the Asia-Pacific region. The evolution of BeiDou is oriented towards changing it from a regional satellite navigation system to a global system.

Apart from these global systems, additional regional satellite navigation systems such as the Indian Regional Navigation Satellite System (IRNSS) and the Japanese Quasi-Zenith Satellite System (QZSS) have been introduced and are available for specific non-global service volumes.

Galileo is the only Global Navigation Satellite System (GNSS) operated under civil control. All other GNSS constellations are operated by organisations which have a military background. This means that, in the event of political tensions, the other GNSSs may become unavailable. Therefore, Galileo ensures Europe's strategic autonomy with respect to satellite positioning under all circumstances.

The space segment of each GNSS consists of multiple satellites. The number of satellites and their orbits differs slightly. Table 1 shows the nominal characteristics of the different GNSS MEO satellites, which are the minimum numbers of satellites expected to meet the respective performance specifications. It should be noted that the given number of satellites does not include backup satellites which may also be in orbit. Thus, the actual number of satellites is usually larger than the nominal number.

Table 1 - Nominal characteristics of the GNSS space segments

GNSS Constellation	Nominal Number of Satellites	Actual Number of Satellites [49]	Altitude	Inclination
GPS	27	31	20 180 km	55°
GLONASS	24	28	19 140 km	64,13°
Galileo	24	22	23 222 km	56°
BeiDou	27	25	21 528 km	55°

All GNSS satellites used in these systems transmit their signals in similar frequency bands. These bands have been allocated by the International Telecommunication Union (ITU) for the use of satellite navigation systems. The three predominant frequency bands used in satellite navigation are shown in Table 2.

Table 2 - Assigned GNSS frequency bands

Frequency Band	Common Name(s)
1164 – 1215 MHz	L5, E5, B2
1215 – 1300 MHz	L2, E6, B3
1559 – 1610 MHz	L1, E1, B1

GNSS receivers provide different observables based on the measurements of the received signals. Due to the similarity of all GNSS systems, these observables are available for all systems and for all signals:

- Pseudorange measurement: Pseudorange measurements are the main measurements used in positioning. They represent the distance between the user and the satellite and include additional error sources, such as clock offsets. At least four pseudorange measurements are needed to solve the unknown variables position (latitude, longitude, altitude) and time.
- Phase measurement: Modern GNSS receivers also output measurements of the signal's carrier phase, which can be measured more precisely than pseudoranges. Phase measurements can lead to very accurate positioning. However, as unknown ambiguities must be resolved by observing measurements over larger time spans, this positioning technique is especially useful for static or low dynamic applications.
- Doppler frequency shift measurements: The received frequency of a radio signal may differ from the transmitted frequency due to a relative velocity between transmitter and receiver. This effect is known as the Doppler Effect and results in a perceived frequency shift when receiving radio-frequency signals. This measured Doppler frequency shift is used to calculate the user's velocity.

Between the transmission of the signal by a GNSS satellite and its reception by a GNSS receiver, the signal may be affected by numerous factors, resulting in errors in the measurements. Such factors include (but are not limited to) errors due to the ionosphere (an upper layer of the atmosphere), the troposphere (the lowest layer of the atmosphere) or multipath reception at the user's antenna (i.e. receiving not only the direct signal from the satellite, but also signals reflected from structures near the user). The higher the desired level of GNSS performance is, the greater the effort required to correct all possible influencing factors.

The availability of GNSS signals on different frequencies is particularly important due to the influence of the ionosphere. The ionosphere, a layer in the Earth's upper atmosphere, can affect GNSS signals significantly, resulting in degraded positioning accuracy. Such ionospheric anomalies are almost impossible to predict. However, by means of GNSS signals measured simultaneously from the same satellite but on different frequencies, users can eliminate most of the ionospheric effects. Thus, especially for safety-critical applications, multi-frequency GNSS can improve the reliability of satellite navigation significantly. Galileo (and BeiDou) are the only systems which have been providing GNSS signals usable by civilians in multiple frequency bands since their inception. With Galileo and BeiDou and the modernisation of GPS and Glonass, all systems will provide such multi-frequency services in the future.

For users, the dominant influence on the achievable positioning performance is the number of visible satellites and their geometry in the visible sky. In order to calculate the position and the receiver clock offset as an additional unknown parameter, users have to receive signals from at least three satellites, plus one additional satellite for each GNSS constellation applied. When combining GPS and Galileo, for example, range measurements from at least five satellites are required for positioning. It follows that the more satellite measurements are available, the better the positioning performance is. For this reason, many applications do not use a single GNSS constellation exclusively, but multiple GNSS constellations jointly. With such a multi-constellation approach, the achievable accuracy improves, especially for situations in which reception is difficult.

Depending on the domain and application, the required performance of satellite navigation can differ significantly. If the intrinsically guaranteed performance of satellite navigation alone is not sufficient, it is possible to improve the overall performance using a variety of techniques.

One example is the use of differential corrections. For differential GNSS, a reference receiver at a static, known position is used in addition to the user receiver (whose exact position is unknown). Based on the known positions of the reference receiver and the satellites, the reference station can compare the received and expected range to a satellite. Based on this difference, the reference station calculates differential corrections which are transmitted to the user. Under the assumption that the reference and user receivers are subject to similar errors, this allows the user to improve the user positioning performance significantly.

One drawback to satellite navigation is that signals are received at very low power levels. GNSS receivers are highly susceptible to radio-frequency interference (RFI) and can be jammed very easily. Similarly to all other GNSSs, Galileo is highly susceptible to RFI, which is very difficult to mitigate. Intentional RFI, also known as jamming, already poses a serious threat to multiple applications, as it directly reduces GNSS availability. For reasons of privacy, many people currently use so-called personal privacy devices (PPDs). These are small yet powerful devices and can jam GNSS signals on different frequencies over larger distances. Even though their use is illegal, they are widely used in practice, significantly affecting various GNSS applications in several domains. As there is hardly any way to overcome these intentional interferences with GNSS alone, some domains are forced to use other input sources as fall-back solutions. PPDs are one of the major concerns for many GNSS users.

2. Purpose, methodology and study structure

2.1. Purpose of the study

The purpose of this study is to provide an overview of the current achievements and impacts of the Galileo programme in terms of the applications and services currently available, and those expected in the future. The study will also propose possible new services and applications, mainly resulting from interviewing users and operators across different domains. Furthermore, the study will cover challenges, gaps and benefits linked to the European GNSS programme in general, with a special focus on the Galileo programme. Finally, the study will provide potential policy options to address the gaps and challenges identified and to derive additional benefits from the Galileo programme.

2.2. Methodology

The methodology of this study is twofold. The first part summarises the most important findings based on high-quality references and publications from interdisciplinary domains. It reviews the state of the art, details the benefits derived from the Galileo programme to date, and provides an outlook of planned milestones and activities. Relevant literature was identified during an extensive literature review process or mentioned specifically during interviews with experts in the field.

The second part incorporates opinions and feedback from external experts. To this end, interview partners from various companies, associations, administrations and public authorities throughout Europe were asked to identify Galileo's socio-economic impacts and to emphasise users' technical needs and requirements. All interview partners were identified in a structured process that included all GNSS domains covered by this study. Another criterion was for the nationalities of experts to be represented equally, with focus on European stakeholders. Where possible, priority was given to associations over standalone companies to ensure a broad sample during the assessment. More than 20 experts and managers from different domains were contacted for this study. Thirteen of them agreed to provide feedback and were interviewed for this study (see the list of interviewees in the annexe). All interview outcomes are explicitly mentioned as such in the text.

The purpose of the literature review was to provide a rationalisation for time schedules, incidents, and performance analysis. The interviews complement this view by providing subjective feedback from the different application domains, by outlining user expectations and by rating Galileo's importance for each domain. In addition, the interviews provided updates on new applications and their development. The interviews also provided useful comments and suggestions on possible improvements which formed the basis for the policy options.

It should be mentioned that, because Galileo is not yet fully operational, most experts based their feedback on their extensive system knowledge and their expectations rather than on their experience with real data. This can be attributed to the simple fact that Galileo is about to become fully operational and is not yet widely used in daily applications. However, this will change in the near future.

2.3. Study structure

After a brief introduction in Chapters 1 and 2, Chapter 3 presents the current Galileo deployment status and outlines ongoing activities and capabilities currently under development for the next generation of the Galileo system. It also compares Galileo to other GNSSs, elaborates on additional advantages of using Galileo in combination with other GNSSs, and summarises the funding of the Galileo system. Chapter 4 presents the results of the literature review and expert interviews for the following fields of application: aviation, Location Based Services (LBS), timing and synchronisation, surveying, road and autonomous driving, rail, maritime, agriculture, and public authorities and military. Galileo's major benefits and potential challenges are identified in Chapters 5 and 6, respectively. Chapter 7 briefly summarises the conclusions of the study. Finally, Chapter 8 presents different policy options and outlines the rationale behind them.

3. The Galileo system

3.1. Current deployment status

As of March 2018, the Galileo system comprises 14 ready to use satellites, one satellite which is available but currently set to 'do not use' for maintenance purposes, two satellites in test mode unintentionally placed in elliptical orbits, one satellite which has not been available since May 2014 due to major frequency problems, and four satellites which were recently deployed and are currently being put into operation [4]. The above-mentioned pair of satellites were launched into an erroneous elliptical orbit due to a mishap of the Russian Proton rocket used for launch. The extent to which these satellites can contribute to the Galileo constellation, or whether they need to be replaced, is an issue which remains open [5]. In the case that these two satellites cannot be used for navigation purposes, there are other options to make them available for research, for example in the field of atomic clock behaviour on strongly elliptical orbits. In any case, these two satellites are not lost and will contribute to the European satellite navigation program. The launch of an additional set of four Galileo satellites is planned for 2018. The major Galileo milestones are summarised in Table 3.

Table 3 - Galileo milestones

Date	Milestone
May 1994	The European Parliament adopts a resolution calling "on the Commission to establish a European strategy for satellite navigation". [7]
28 December 2005	Launch of the first in-orbit validation satellite [26]
22 August 2014	Launch of the first full operational capability satellites
15 December 2016	Initial services become available[1]
End of 2018	Initial service of Galileo's Return Link Alert Service within the SAR capabilities is expected to be operational (see also Section 4.2.6). [2]
2021	Expected full operational capability [7]

The Galileo system provides four services:

- Open service (OS): Open and free-of-charge service for basic positioning and timing services.
- Commercial service (CS): Improved service with improved levels of guaranteed performance. CS offers the possibility for signal encryption in order to reduce the risk of active signals being disturbed or fabricated.
- Public regulated service (PRS): Service restricted to government-authorised users for sensitive applications which require a high level of service continuity. This service is intended for use by approved authorities only.
- Search and rescue service (SAR): European contribution to the international search and rescue distress alert detection system (Cospas-Sarsat), see Section 4.2.6.

An initial fifth service, the 'safety of life' service, was re-profiled in 2010 and abandoned in 2013. [7]

DG Grow of the European Commission confirmed that recently, parts of the former Commercial Service for improved positioning accuracy and integrity were re-profiled. This high precision service has a target

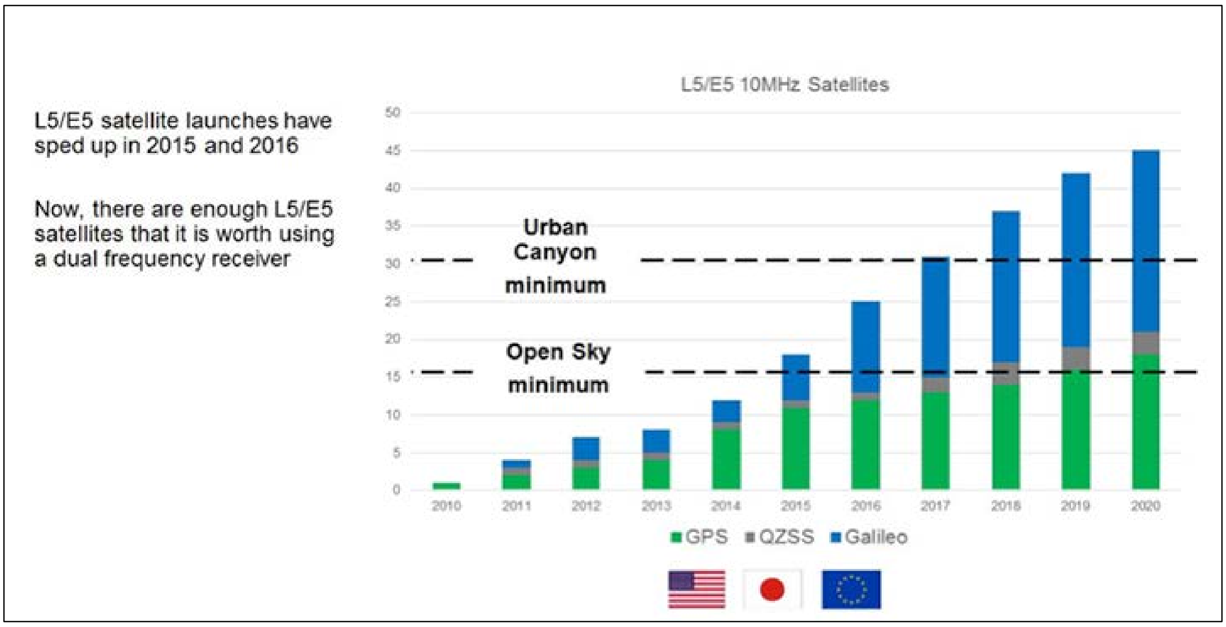
[1] The initial services included the Open Service, the Public Regulated Service (PRS) and the Search and Rescue Service (SAR). [3]

positioning error of less than two decimetres. Due to similar, free of charge services being planned by competing navigation satellite systems such as BeiDou (China) and QZSS (Japan), the European Commission agreed to take the initiative in providing a high-accuracy service free of charge. Having to pay a fee to access this high-accuracy service was considered to slow development in this field and hinder the expected growth of the economy, especially in the European Union. Additionally, a pay-for service would make it more difficult for the Galileo system to penetrate the global GNSS market, especially since competing free-of-charge services are expected to be released. For these reasons, this policy change was approved. The initial service is planned for 2019. [35]

One major benefit of Galileo is that it provides a second free-of-charge navigation signal in the E5 frequency band. Together with the legacy signal on L1, it allows for a more precise compensation of ionospheric effects, and can thus significantly improve positioning accuracy.

Although neither Galileo nor the GPS constellation with L5 satellites has been fully deployed, dual frequency has already demonstrated its usefulness: currently, around 30 satellites from different satellite navigation systems broadcast both frequencies; thus as stated by the Broadcom company, there are about eight satellites in view for a majority of locations around the world [32]. Figure 1 depicts the evolution of L5/E5-capable satellites over the past several years. This figure distinguishes between two scenarios: The first scenario is an ideal 'Open Sky' environment without any obstacles, for which a sufficient number of L5 satellites have been available since 2015. The second scenario is the challenging 'Urban Canyon' scenario, in which high buildings obstruct the view to a significant number of satellites, thus increasing the total number of satellites necessary for providing comparable performance.

Figure 1 - Why dual frequency now?



Source: [32]

3.2. Future plans for Galileo

This section briefly outlines further developments of the current European satellite navigation systems. The European GNSS Evolution Programme (EGEP) is an ESA programme supported by 17 ESA Member States and Canada. Its primary aim is to undertake research and development in and verification of technologies related to regional Space-Based Augmentation Systems (SBAS) and GNSSs satellite systems in order to ensure continuous development of European GNSS technology [6].

The EGEP identified potential goals for future evolution and improvements of Galileo [38], including accuracy improvements for positioning and timing, increased security and general service improvements. To this end, additional Galileo signals currently under investigation could be introduced.

Regarding Europe's satellite navigation overlay service (European Geostationary Navigation Overlay Service, EGNOS), plans exist to expand the EGNOS service to support Galileo in addition to the currently supported GPS. The expanded service will make use of new Galileo signals as well as new signals of the latest generation of GPS satellites in the L5 frequency band. In this way, position accuracy, integrity and robustness can be increased further and provide the level of performance necessary for safety-of-life applications. This second generation of the EGNOS is planned to enter service in 2025.

In additional to improving services for civil aviation, the new EGNOS will introduce new services for other domains such as maritime navigation and rail. Moreover, it will expand the current service coverage from the European continent to integrate seamlessly with other interoperable augmentation systems worldwide [27].

3.3. Comparison of Galileo to other GNSSs

Galileo is one of the four global navigation satellite systems currently available. In order to show the importance of Galileo compared to the other systems, a short overview about the other systems' characteristics is outlined in this section.

The **American GPS** is predominant in various domains. GPS was introduced as a military system in the 1970s and has since been operated and maintained by the US Department of Defence (DOD). It is currently being modernised to include additional navigation signals in multiple frequency bands. This modernisation will also include a new satellite generation as well as a new control segment. In order to ensure a smooth transition from the well-proven and established legacy, the different GPS generations will work in parallel for a long time.

The **Russian GLONASS** system is a second global navigation system. GLONASS overcame initial setbacks in the 1990s due to Russia's financial crisis and currently provides global navigation services. In contrast to the other GNSS constellations, the conventional GLONASS signals use Frequency Division Multiple Access (FDMA) for multiplexing, which means that each satellite transmits its signals on a slightly different frequency in order to distinguish between individual satellites. In the future, however, GLONASS will introduce new signals using Code Division Multiple Access (CDMA) for multiplexing the broadcast signals on the same carrier frequency, like the other GNSSs. Another difference compared to GPS is that GLONASS has been providing publicly accessible signals on two distinct frequencies from its inception in order to mitigate the ionospheric effects. For historical and technical reasons, GLONASS has not been used widely in all domains.

Over a timeframe similar to that of Galileo, the People's Republic of China developed its **BeiDou** system. This development is divided into three sequential phases, the latest of which will provide global GNSS services, albeit with a special focus on the Asia-Pacific region. To this end, the BeiDou constellation consists of satellites with three different types of orbits. In addition to Medium-Earth-Orbit (MEO) satellites (which are also used by the other systems), BeiDou will also include satellites in the Inclined Geo-Synchronous Orbits (IGSO) and Geostationary Orbits (GEO). This will complement the BeiDou constellation in the Asia-Pacific region by adding satellites which can be seen at high elevations and is expected to provide benefits particularly in urban scenarios.

Galileo applies techniques similar to those found in other GNSSs, and can therefore be compared to the other systems. One major advantage of Galileo compared to the other systems is its independence. As each of the other systems forms part of its country's military, each system may become unavailable during political conflicts. Since GNSS has become a critical infrastructure in many applications, it is of crucial importance that control of a satellite navigation system be sustained. In this way, all Galileo services can be used independently from the other GNSS implementations.

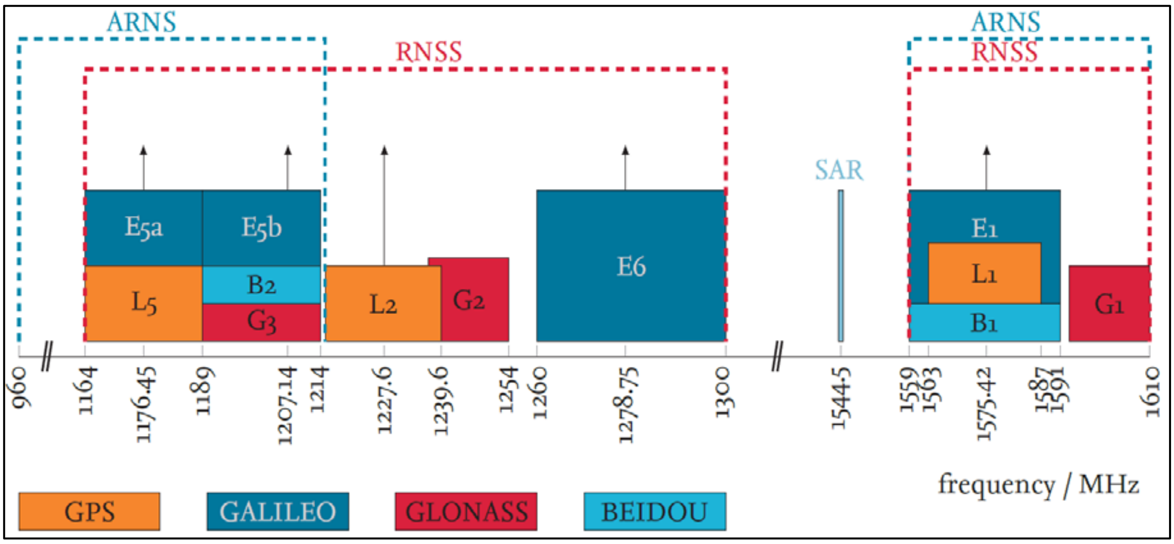
In addition, Galileo is ultimately expected to outperform the other systems, at least in specific domains. A great deal of effort was devoted to building satellite which have very accurate atomic clocks, digital signal processing and a long life-span. Together with its dense network of reference stations and its redundant control stations, Galileo has the potential to deliver better positioning performance than the other systems in future.

Another benefit provided by Galileo is the increased number of satellites available for multi-constellation GNSS positioning. The use of more than one of the four GNSS core constellations has a direct influence on positioning performance, especially under less-than-ideal environmental situations such as urban canyon scenarios. The use of a multi-constellation GNSS could enable completely new applications, for which single-constellation GNSS cannot ensure sufficient performance.

Another strong advantage of Galileo compared to other GNSS constellations is the fact that all Galileo satellites transmit (open) signals usable by civilians in two frequency bands (both the L1/E1 and the L5/E5 bands). In this way, all Galileo users can benefit from a dual frequency GNSS, which is a method of mitigating most of the ionospheric influence on GNSS positioning by combining two measurements of one satellite on different frequencies. For most GPS satellites, for example, this is not possible, as not all GPS satellites currently provide dual-frequency GNSS signals usable by civilians. Figure 2 summarises different navigation signals of the four satellite-based navigation systems (GPS, Galileo, GLONASS and BeiDou). It also shows the frequency bands allocated to the Radio Navigation Satellite Service (RNSS) in general and the frequency band specifically allocated to the Aeronautical Radio Navigation Service (ARNS). Only the signals within the ARNS can be applied for aeronautical purposes.

Finally, Galileo differs from the other GNSS constellations because it has a wider variety of services available to civilian users. In addition to its open service (OS), Galileo also offers a commercial service (CS) for enhanced performance guarantees, a public regulated service (PRS) for governmental bodies, and a search and rescue service (SAR) for emergency responses. In this way, Galileo can support different applications in various domains which require specific performance levels.

Figure 2 - GNSS signals and their allocated frequency bands



Source: Institute of Flight Guidance of the Technische Universität Braunschweig / Bestmann derived work

3.4. Costs of the Galileo system

The estimated Galileo costs are summarised in Table 4 and include the EU as well as the ESA budgets which could not be further broken down from the sources available. Although the table lists only Galileo costs, it should be noted that same budgets may include contributions to EGNOS costs, as an exact break-down is not always possible.

Table 4 - Estimated budget for the European GNSS (in € million)

Year	Total	Purpose
1990 - 1999	42,5	System definition
2000	550	System development
2007 - 2008	2 967	System development and deployment
2013	4 930	System deployment and operation
FP[2]	603,5	Research related to the GNSS programmes
2014 - 2020	7 071,73	Combined costs for Galileo and EGNOS including operation, management, further development, sustaining and system modernising as well as procurement of new satellites
Total	**16 164,73**	

Source: [7] for the period 1990-2013 and the FP; [12] for the period 2014-2020

A unique feature of Galileo is its relatively low price per single satellite of approximately €40 million, not including launching costs. By comparison, while the cost to build one GPS satellite was still US$ 43 million in the early 1990s, the new GPS III satellite costs are estimated to be around US$ 500 million apiece [44]. The exact reasons for this difference in price are not publicly available, but are very likely due to additional military components on GPS satellites.

[2]FP: Budgets attributed under the framework programmes for research and innovation related to GNSS programmes: FP5 (1998 - €37 million), FP6 (2002 - €100 million), FP7 (2006 - €66.5 million) and Horizon 2020 (2013 - €400 million). FP4 (1994) also covered research projects for the development of EGNOS receivers, for which the costs were estimated at € 5-10 million (not included here) [7].

4. Domain-related assessment

This chapter presents different fields of application of GNSSs and emphasises beneficial contributions that Galileo can provide. It also summarises the feedback from the interviewees and indicates the special requirements, needs and concerns of each domain. The domains include: aviation, location based services (LBS), timing and synchronisation, surveying, road and autonomous driving, rail, maritime, agriculture, and public authorities and military. They were selected according to the ones listed in GSA's market report [2], with the addition of the public authorities' application domain by the study authors.

The requirements with respect to GNSS systems in general and Galileo in particular are expressed via common key performance indicators found in literature and briefly defined below.

Availability of a navigation system is the "ability […] to provide the required function and performance at the initiation of the intended operation. Availability is an indication of the ability of a system to provide usable service within the coverage area" [18]. It is a function of the physical and meteorological conditions and the technical capabilities of the equipment.

Continuity is defined as "the ability of a system to perform its function without interruption during the intended operation" [18].

Accuracy is the statistical difference between estimated and actual value. For the application in GNSS system, accuracy may refer to time, velocity or position measurements. By contrast, precision describes the deviation between repeated measurements of the same value. Within the scope of this document, accuracy also implies precision.

Integrity is a measure of trust which can be placed in the correctness of information supplied by the GNSS system [19]. It is based on monitoring mechanisms and should alert the user within an appropriate time that the GNSS outputs including position, velocity and time are corrupted [18]. Integrity is a key element in all safety-of life applications.

Time to Alert (TTA) is "the maximal allowable elapsed time from the onset of a [system] failure until the equipment annunciates the alert" [18].

Authentication is a well-known security technique to prove that data originate from the expected source. It is one of the key techniques to protect GNSS signals and the resulting position against intentional signal alteration, also named signal spoofing.

Robustness is the ability of a system to withstand intentional or unintentional disturbances.

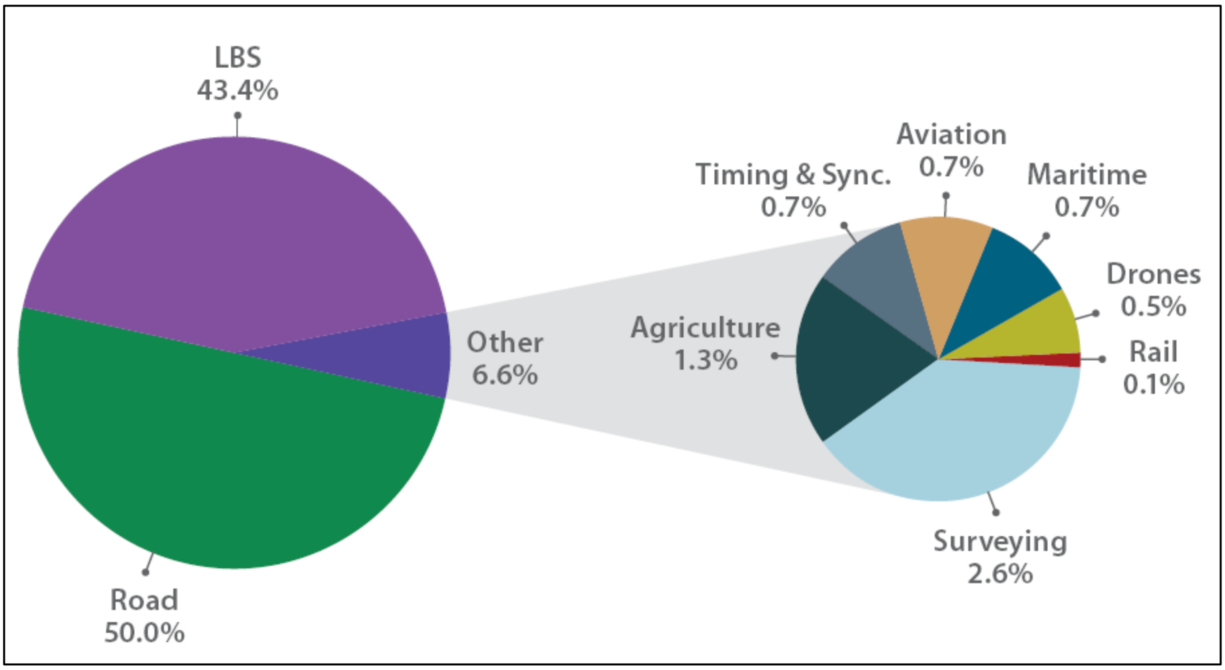
Resilience is the ability of a system to maintain service in the event of intentional or unintentional system faults.

Interoperability is a system's compatibility with other, different systems without the systems interfering with each other, for example, a GNSS receiver which can be used with different satellite navigation systems.

Time-To-First-Fix (TTFF) is the time duration required for a GNSS receiver to acquire satellite signals and navigation data, and to provide the position, velocity and time solution, also called a position fix. A time to first fix can refer to a system start from scratch (cold start) but also to an assisted GNSS start (warm start), during which GNSS receivers are supplied with orbit data and approximate position and time, for example, via an internet connection. This mechanism is widely used in smartphones.

The analysis shown in Figure 3 splits the cumulative GNSS revenue for the years 2015-2025 into the individual application domains (excluding the PRS), which are presented in the following sections.

Figure 3 - Cumulative GNSS revenue for 2015-2025 by domain of application



Source: [2]

4.1. Aviation

GNSS technologies are becoming more and more important for aviation and air traffic management. Although other radio navigation systems still exist, they are increasingly being replaced by satellite-based navigation techniques due to their improved accuracy, worldwide availability and reduced maintenance costs. The improved accuracy and integrity of GNSS positioning allows air traffic control to apply smaller separations between two aircraft, effectively increasing the capacity of the airspace. Furthermore, instead of having to follow fixed routes between ground navigation infrastructure, aircraft can now fly optimized routes based on GNSS, allowing for more direct routings, less flight time, and less fuel consumption, and thus a smaller environmental footprint. All this can be achieved with GNSS with the same level of safety as that available today [23].

Aviation has the special requirement that all navigation signals applied must be within the ARNS bands defined by the ITU [39]. This ensures that all signals used for aviation purposes are not affected negatively by other transmissions. As shown in Figure 2, this excludes all signals from the L2/E6 band from being used in aviation. Thus only signals in the L1/E1 and the L5/E5 frequency bands can be used in aviation. Compared to GPS, Galileo offers the clear advantage that all satellites transmit signals both in the E1 and the E5a/b frequencies, while GPS added L5 signals only recently to its newest generation of satellites. Subsequently, the use of Galileo is a key enabler for future dual-frequency services to be used in aviation.

4.1.1. Navigation

In the navigation domain, the shift from conventional radio aids to the new concept of Performance Based Navigation (PBN) opens the door to a greater number of GNSS airborne applications being used for area navigation. The PBN concept specifies aircraft navigation system performance requirements rather than requirements for different sets of navigation sensors. They are defined in terms of accuracy, integrity, availability, continuity and functionality, which are needed for the proposed operations in the context of a particular airspace concept. The PBN concept represents a shift from sensor-based to performance-based navigation and a major milestone for the introduction of GNSS-based navigation [25]. GNSS-based navigation sources are used today during all phases of flight, including ground operation, departure, cruise, approach, and landing. In order to meet the performance requirements for the different phases of flight, multiple augmentation systems are used. Three different types of augmentation systems are currently in use:

- Aircraft-based Augmentation Systems (ABAS): ABAS installations use redundant information available for airborne users for cross-checking in order to ensure sufficient integrity.
- Space-based Augmentation Systems (SBAS): SBAS systems provide differential corrections using geostationary satellites. Airborne users can receive these corrections with their SBAS-capable GNSS receivers and use them to improve the positioning performance.
- Ground-based Augmentation Systems (GBAS): In contrast to SBAS systems, GBAS is designed to provide precision approach services to airborne users. This is achieved by providing differential corrections of a local ground station installed at an airport via a datalink in the very high frequency band.

All components involved in air transport need to be approved and certified in order to be internationally harmonised. This approval process is based on different elements. The International Civil Aviation Authority (ICAO) ensures that all operational components are interoperable throughout the whole world. In order to simplify the approval of new equipment, approval associations define criteria for compliance. When following these, a manufacturer of new avionics can ease the approval process of this equipment with the responsible approval bodies. To date, Galileo has not been incorporated into these compliance criteria.

Due to this lack of certification guidance, no airborne GNSS equipment supporting Galileo currently exists. Even with existing certification guidelines it will take a long time until a notable equipage rate of Galileo receivers is available on airplanes. Nevertheless, Galileo is seen as one of the core global constellations (along with GPS, GLONASS and BeiDou) to be integrated into future aviation navigation receivers. In this way, Galileo will help to achieve ICAO's goals for future air transportation.

4.1.2. Surveillance

Surveillance of aircraft allows the air traffic control to apply small separations between aircraft and to ensure high capacity and throughput of the airspace. In addition to conventional radar systems, a new surveillance technique called Automated Dependence Surveillance Broadcast (ADS-B) has recently been put into operation.

With ADS-B, transmitters installed on board broadcast numerous parameters concerning the aircraft's state. These parameters include (but are not limited to) the aircraft's identification codes, current state (altitude, velocity) and intentions. These ADS-B transmissions are decoded by both air traffic control and other aircraft within range. In this way, not only air traffic control but also the pilots of other aircraft benefit from improved situational awareness. Starting in June 2020, ADS-B equipage will be required in European airspaces for all aircraft with a maximum take-off weight of more than 5700 kg or a maximum cruise speed exceeding 250 knots [50].

The main source for the position reported via ADS-B is currently the GPS system. Again, due to the lack of certification documents, Galileo is not currently used for ADS-B. As the required positioning accuracy is rather moderate, adding Galileo is not a high priority in this domain at the moment.

4.1.3. Remotely piloted aircraft systems

The integration of Unmanned Aircraft (UA), also known as drones, into the civil airspace is part of ongoing activities by the research community [20], governments and international organisations [24]. Although forecasts vary greatly among different sources, the civil drone market is expected to increase annually at a rate of 20-30% between 2015 and 2020 [20]. In order to exploit the economic potential of UA and maintain the current level of safety in aviation, it is essential to have a reliable and accurate position of all airspace users to ensure separation between the different participants. Moreover, technologies are currently being investigated to allow small drones to broadcast their position for monitoring and surveillance purposes. This is especially important since it is difficult for ground-based surveillance technology to detect and locate small drones because they are too small and fly too low for conventional primary radar. Other mass market drones already implement high-integrity geo-fencing that prohibits operation in restricted airspace or in other so-called no-fly zones such as airports, power plants or military bases.

Multi-frequency and multi-constellation GNSS is seen as a technology which is key to fulfilling this goal because it meets stringent requirements regarding accuracy, availability and (in particular) integrity. By adding another important GNSS constellation, Galileo will not only improve the multi-constellation benefits as described in chapter 3, but also strengthen the redundancy and resilience of positioning systems for UA. A European initiative is currently on the path towards a consistent European unmanned air traffic management system called U-Space [24].

4.1.4. Aircraft tracking and distress monitoring

In response to the Air France and Malaysian Airlines aircraft that went missing in 2009 and 2014, respectively, a new regulation for autonomous aircraft distress tracking came into effect and will become valid in November 2018. This Global Aeronautical Distress Safety System (GADSS) is based on continuous aircraft tracking, autonomous distress monitoring and a post-flight localisation and recovery strategy for missing aircraft. Prior to that date, no global aircraft tracking was required on an international level.

For GADSS, air operators have been required since March 2016 to track their aircraft at least over oceanic areas at intervals of 15 minutes or less. This includes a four-dimensional aircraft position (latitude, longitude, altitude and time) record [21]. In this way, search areas can be dramatically reduced in case an aircraft goes missing. Beginning in January 2021, aircraft will additionally be required to autonomously transmit information from which a location can be calculated once per minute.

Both position reporting features will be strongly supported by GNSS and in particular by Galileo, and will lead to a significant improvement in the effectiveness of search and rescue efforts and recovery operations in future [21].

Galileo's impact in aviation

- With Galileo, more satellites and frequencies are available
- Galileo provides dual frequency signals in the aeronautical radio navigation service band
- International harmonisation and certification pending, Galileo not yet fully integrated into aviation navigation and surveillance

4.2. Location Based Services

Location Based Services (LBS) cover a broad range of emerging GNSS-related applications and services, mainly utilising portable devices such as mobile phones, tablets and smart watches. LBS comprise very dynamic and diverse fields of GNSS applications and include navigation services, social networks and games, as well as fitness, sport and activity tracking, and a variety of professional commercial services. If Galileo is used in LBS, it will be predominantly based on Galileo's Open Service and Search and Rescue Service.

Galileo will contribute to the development of further LBS applications in a growing market. LBS are increasingly being used in daily life and arguably represent the most prominent form of GNSS among civil end users. European developers continue to perform strongly in app development. Of the 5.7 million app developers worldwide, over 22% work in the EU. By 2018, the European app economy is forecast to contribute €63 billion to the EU economy and employ 4.8 million people [2].

4.2.1. Pedestrian navigation

Conventional uses of LBS can be found in well-known car and pedestrian navigation programs, for which step by step instructions lead to arbitrary points of interest (POIs). LBS are also a key enabler for assisted and autonomous driving, two functions that are separately covered in Section 4.5. Augmented reality apps provide immediate information on buildings and other POIs. In return, POIs are generated based on other users' behaviour and their reported position data. Digital maps are increasingly being generated by collecting crowd data, either by having users report map details such as restaurants or by automatically collecting data. In both cases, precise positioning data is needed for maps that generate high added value for other users later. The annual revenue from GNSS-based LBS device sales and services is growing and expected to exceed €115 billion by 2025 [2].

GNSS positioning data is being increasingly used for Geo marketing and advertising that is adapted to the user's current position. Additionally, various social media apps allow the user's current position to be shared with friends and provide users with location-based games such as Geocaching and PokemonGo.

4.2.2. Health and emergency

Relatively new smart watches and other wearable devices make use of GNSS for health and fitness apps and for convenient, automatic adaptation to time zones. The segment of wearables comprises fitness wrist wear equipped with sensors, activity trackers which measure and analyse physical activity and body functions, and smart clothes, eyewear and other wearables that measure body functions. According to current market analyses [28], the revenues in the wearables segment will total US$ 1.095 million in 2018 for Europe with an annual growth rate of 5.1%.

An increasing number of health apps and devices make daily life easier for persons with disabilities. GPS SmartSole® is one of several products specifically designed for the visually impaired, for persons who suffer from Alzheimer's, dementia, autism, traumatic brain injuries and other memory disorders, and persons who have a tendency to wander. The device provides ubiquitous location in the form of small and affordable shoe inlays and allows such persons to be continuous monitored [22].

Many emergency and distress call systems rely on location-based services. Here, GNSS, in combination with network or satellite-based communication, is used to provide fast and accurate emergency caller locations. These systems are described in greater detail in sections 4.2.5 and 4.2.6.

4.2.3. Position monitoring

LBS are also used for fleet tracking and the efficient dispatch of single units. Used by shipping companies, parcel services and other logistics-related domains, they provide seamless information on the current position of vehicles and goods in real-time. This ensures timely and reliable delivery and generates special added value for the transport of expensive or hazardous cargo. For this purpose, low power GNSS receivers were developed whose functions include tracking cargo containers over several years autonomously via battery or solar power supply [37].

Good GNSS positioning accuracy in urban environments and a fast time to first fix are the most important requirements for many LBS applications. During the interviews, one equipment manufacturer emphasised the importance of an upcoming KPI that will be a 'Time to authentication fix'. This time span addresses the time needed to confirm that the authentication of the signal would influence all applications in which successful signal authentication must be performed before the GNSS position and timing solution can be used.

There are also other applications in which security, robustness and signal authentication play important roles. These include prisoner tagging and other personal tracking devices that trigger an alarm when the target leaves the configured perimeter. Other examples include anti-theft tracking systems for cars and other items. GNSS is also used for tracking pets and endangered animals in their habitat. There are other applications for LBS in GNSS-based road tolls and insurance fees, for which signal authentication and protection are important. In these applications customers are charged based on their real driving behaviour or mileage, which again are determined by LBS.

Improved accuracy with the help of multi-constellation satellites and interoperability between different GNSS systems are the two most important requirements for Galileo in LBS applications. Especially for the low-cost GNSS market, interoperability is the key requirement because costly adaptations to single-satellite navigation systems cannot be justified compared to the benefits they are expected to provide.

4.2.4. Smartphones/Tablets

Currently, more than 34 different smartphone and tablet models are already ready to use Galileo signals (see [16] for a complete list). With Galileo as an additional satellite navigation system, the positioning information provided by smartphones, tablets and smartwatches is more accurate and reliable – particularly in urban environments where narrow streets and tall buildings often block satellite signals and degrade the usefulness of many mobile services.

Mobile devices are increasingly using raw measurements provided by GNSS instead of the ready-to-use GNSS solutions. This deep integration allows app developers to adapt the GNSS information to their needs and to provide improved services with increased accuracy and integrity. A white paper on using GNSS raw measurements on Android devices was recently published by the GSA to support those activities [41].

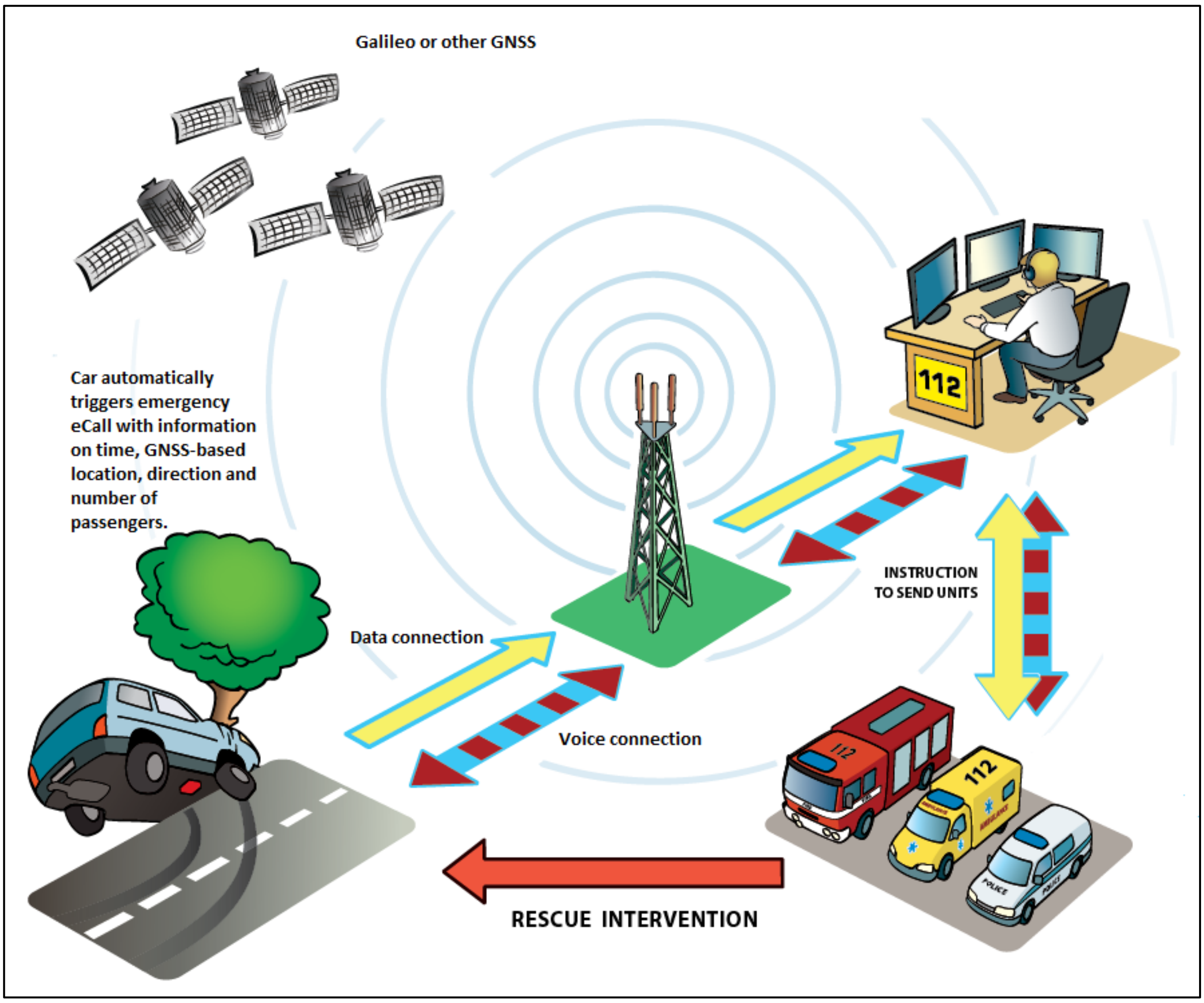
Singapore-based company Broadcom Limited recently released the first integrated circuit for smartphones and tablets that makes use of the signals from Galileo and GPS in the L1/E1 and L5/E5 frequency bands. This chip will normally be able to provide a positioning accuracy of around 30 centimetres [29], [30], [31].

4.2.5. eCall

Emergency Call (eCall) is an automatic emergency call system specifically developed for motor vehicles. In case of an accident, this system can automatically alert rescue services via 112, the standardized European emergency telephone number. All new passenger cars delivered after March 31st 2018 are required to be equipped with an automatic distress system to alert emergency services in case of an accident. In addition to the above functions, eCall automatically reports the location of the sender obtained by Global Satellite Navigation. Each eCall implementation must be compatible with Galileo and can optionally include other GNSS constellations such as GPS and GLONASS [17].

Current eCall systems use more than one GNSS constellation to achieve better positioning accuracy and exploit the redundancy, which strengthens the robustness of the total eCall system. Generally it can be concluded that the more satellites are used, the better the positioning accuracy is, especially for challenging environments such as mountainous regions. Therefore, it makes sense to use other GNSS in addition to Galileo. A schematic system overview is depicted in Figure 4, which is adapted from [42]. eCall is expected to contribute to a fast and efficient coordination of necessary rescue operations, thereby lowering the total number of traffic deaths. According to a study conducted within the scope of the HELP112 project, improved emergency caller location could save 800 lives annually and up to €100 billion in rescue operation costs over the next decade [2].

Figure 4 - eCall: Schematic overview



Source: Adapted from [42]

4.2.6. Cospas-Sarsat

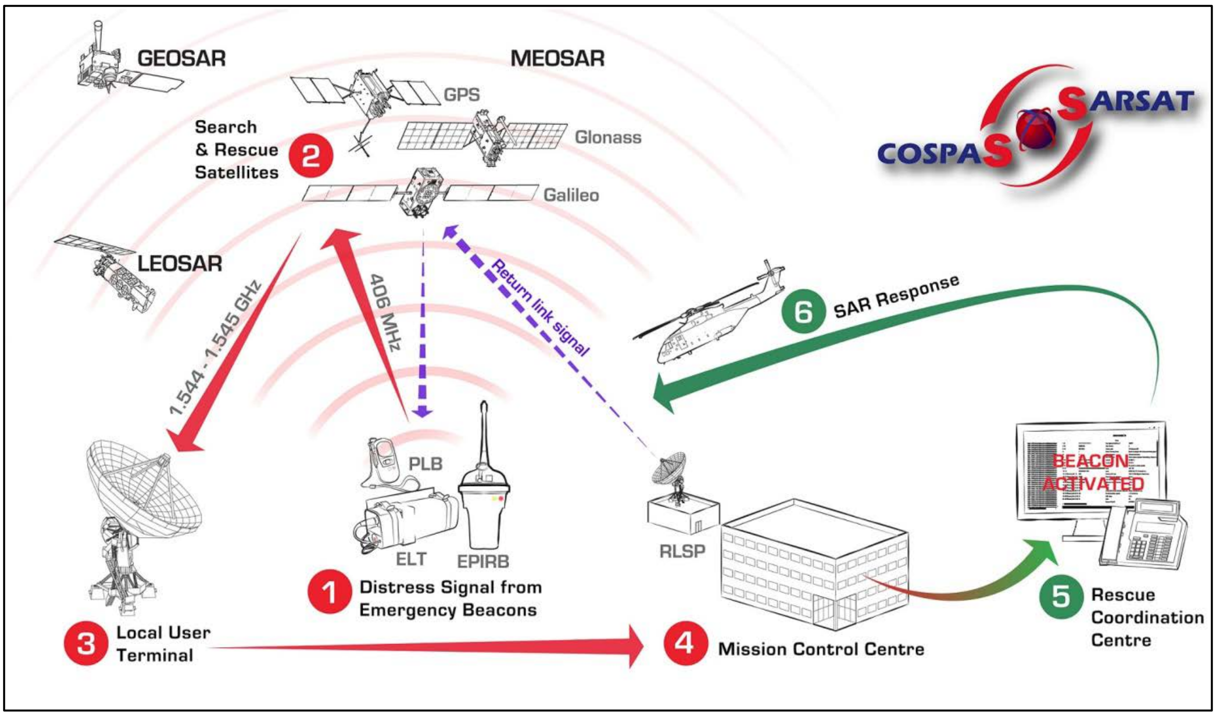
Whilst eCall is an automobile-specific system that is limited to the European region and requires mobile connectivity for making emergency calls, another international satellite-based system exists for detecting and locating emergency radio beacons - Cospas-Sarsat. Initiated at the end of the 1970s by the USA, Canada and France as Sarsat, this system was later combined with the Russian Cospas system. Today, more than 44 countries and organisations are part of this intergovernmental, non-profit programme [51].

Galileo's SAR service will help in distress signal localisation and represents Europe's contribution to the worldwide Cospas-Sarsat system [14]. Before Galileo was introduced, distress signal detection and localisation were performed only by US and Russian satellites. The system can receive distress signals at 406 MHz from different types of emergency beacons, namely:

- Personal Locator Beacons (PLBs), which are carried by hikers and commercial expeditions to call for help in areas with poor mobile phone coverage.
- Emergency Locator Transmitters (ELTs), which are used in aviation for large commercial aircraft but also for smaller general aviation aircraft.
- Emergency Position-Indicating Radio Beacons (EPIRBs), which are designed specifically for reporting distress at sea in maritime applications.

Figure 5 gives an overview of the basic Cospas-Sarsat architecture and the facilities involved.

Figure 5 - Cospas-Sarsat system overview



Source: [14]

Galileo is currently the only GNSS that provides a backward channel to inform the user that the distress call has been registered and emergency rescue teams are on their way. SAR 406 MHz beacons including Galileo's return link service capability, are being tested under several H2020 programme projects: HELIOS, GRICAS and SAT406M [16]. When fully operational, Galileo's SAR service will reduce the time it takes to detect a person lost at sea or in the mountains from 3 hours to just 10 minutes after a distress beacon has been activated, thus facilitating rescue operations and saving lives [16].

Galileo's impact for Location Based Services

- More satellites in view for challenging reception scenarios
- Interoperability between different GNSSs also important to avoid costly adaptations to single-satellite navigation systems
- Signal authentication will be available for security sensitive applications
- Search and Rescue: improved accuracy and coverage with unique return link capability

4.3. Timing and synchronisation

In addition to positioning information, each GNSS also provides very accurate timing information. To this end, Galileo also provides precise timing information and synchronisation techniques for Coordinated Universal Time (or Universal Time Coordinated, UTC), which is the primary time standard by which the world regulates clocks and time. In this way, Galileo allows timing and synchronisation to take place over great distances at minimal costs. This feature is increasingly being used in various domains and often finds its way into critical infrastructure. Although the latter is currently required to incorporate back-up synchronisation mechanisms, it appears that such mechanisms are subject to degraded performance and limited capacity when in back-up mode. Hence, GNSS timing is becoming increasingly important.

4.3.1. Network synchronisation

Telecommunication is a field with high demand for time slot, frequency and phase synchronisation. Synchronisation is important for the efficient use of the available data bandwidth and enables multiple sending devices to be used on the same communication channel. To this end, GNSS timing can be used in various ways for different types of telecommunication networks:

- **Satellite Communication** (SATCOM) covers data and voice communication via satellites in space. Typical applications can be found in satellite phones or in aircraft satellite data modems.
- **Digital Cellular Network** (4G, 5G) is the backbone for connecting mobile devices.
- **Public Switched Telephone Network** represents the conventional telephone network and includes analogue and digital fixed line communication. Although being increasingly replaced by Voice Over IP (VOIP) technology, it is still required for certain life-critical applications, for example in rescue coordination centres.
- **Small Cells** are a special implementation of digital cellular networks characterised by low-powered radio access nodes that operate in licensed and unlicensed spectra. These spectra have a range of several metres to 1-2 kilometres and represent the backbone of Long-Term Evolution (LTE) networks. LTE networks are state-of-the-art high-speed networks for mobile data used by smartphones, tablets and portable computers. Due to their relatively low cost, they are part of a rapidly growing market, with around 10 million small cells being deployed worldwide as of 2015 [1].

Another important application of GNSS timing is power net monitoring via Phasor Measurement Units (PMUs). PMUs determine the momentary voltage and power flow at different locations in alternating current networks and allow energy flows to be calculated within the network. Such measurements are vital for power net monitoring and control, and form the basis for stable power supply.

4.3.2. Distributed applications

Typical applications for timing and synchronisation can be found in the finance domain, in which high frequency banking and stock exchanges require accurate time stamping. In this context, Galileo can contribute to the time accuracies required for the new EU regulatory frameworks; here, financial operators will be required to achieve UTC traceability with microsecond timestamp resolution [52].

In general, synchronisation of clocks is a requirement in a variety of domains, especially for recording measurements with very accurate time stamps. Clocks usually contain oscillators which provide periodic timekeeping signals. For having the exact same time at different clock locations, these oscillators must be kept aligned by active control techniques. This process is called disciplination.

GNSS time synchronisation is widely used today for the disciplination of local oscillators. As the current local clock error is determined as part of the positioning algorithms, the local clock can be controlled to minimize the clock offset. This way, clocks at different locations can be synchronized very precisely. Compared to other synchronisation techniques, GNSS represents a low-cost and easy-to-use approach. With specific algorithms, synchronization accuracies in the range of a few nanoseconds can be obtained [53].

With such accurate clock synchronisations, GNSS is also used for multilateration. Multilateration presents an alternative to conventional primary radar systems and allows tracking of aircraft based on random emissions for surveillance, see section 4.1.2. It uses a network of receiving stations which need to be synchronized closely. Using Galileo with the other GNSS systems could improve the achievable synchronisation accuracy in order to allow multilateration systems to be used over wide areas.

Finally, GNSS synchronisation is used in less critical applications such as the synchronisation of anti-collision lights on wind power generators. This is a very simple application but can represent a remarkable added value for the local population by avoiding disturbing, unsynchronised blinking lights. According to the interview outcomes, other applications of GNSS based time synchronisation can be found in traffic control and information systems, for example the synchronisation of traffic light systems.

The interview furthermore outlined the demand for reliable GNSS-based timing and synchronisation capabilities and emphasised Galileo's role as an additional independent provider of timing information. In this context, Galileo's timing capabilities are not only suitable for satisfying the state of the art requirements but are also seen as a driver and enabler for new technologies such as 4G or the upcoming next generation 5G mobile data networks [2].

The study further indicated a heavily increasing need for PMU in power networks due to planned power grids and the increasing number of power generating/buffering nodes. To this end, GNSS timing and Galileo's contribution will play a significant role in the success of transition to renewable energy sources.

Galileo capable timing and synchronisation systems are already available. Moreover, it shall be noted that a majority of the timing equipment already installed can be retrofitted by simply replacing the GNSS receiver card with Galileo-compatible receivers.

The expected Galileo benefits regarding timing and synchronisation are the delivery of a free, stable and very accurate time and frequency source worldwide that emphasises European autonomy and increases the resilience of critical infrastructures such as power networks, finance trading and telecommunication. One expected Galileo benefit was already observed during the GPS anomaly on 26 January 2016, when the UTC time provided by GPS was corrupted due to a system failure, while the independent UTC time provided by the European EGNOS remained stable [12], [2], [33].

The interview revealed that, currently, timing and synchronisation applications mainly envisage the use of Galileo's OS. However, this may change in the near future with upcoming applications in key sectors of the economy and the need for additional security mechanisms. For these cases, timing applications would at least make use of Galileo's authentication feature for the OS or even rely on Galileo's PRS for improving timing accuracy and increasing robustness against signal spoofing and jamming. Furthermore, there are also a small number of military timing applications that envisage incorporating PRS in the future. Both signal authentication of the OS signal and the possible use of PRS for timing applications in public authorities are two unique features of the Galileo system that no other GNSS can provide to EU countries.

Another important benefit of Galileo as a worldwide timing source was mentioned during the interviews: certain customers have reservations about using a time source controlled by the US military and would prefer to use Galileo as a GNSS time source under civil control. This has the potential for further business developments and an improved EU market share of the timing and synchronisation domain.

Both interview partners emphasised Galileo's importance for European Small and Medium Sized Enterprises (SMEs) in the timing, synchronisation and time dissemination sector. Most equipment manufactures and integrators for timing and synchronisation belong to the SME category. The manufactures of timing equipment are subject to significant market growth rates (more than 20% in 2017).

Galileo's impact for timing and synchronisation

- Strategic autonomy in providing timing and synchronization information for critical infrastructure and financial domain
- Redundant timing source for increased robustness and resilience
- Authentication of the signal as part of the free-of-charge Open Service

4.4. Surveying

Land surveying is the process of determining the three-dimensional position of a fixed point on Earth relative to a certain reference frame. Satellite navigation has been used in surveying for decades due to its positional stability. For most surveying applications, it is not overly crucial for positioning results to have a high update rate. Long measurement periods are used in order to ensure accuracy and repeatability. The main challenge here is to determine the height accurately. In satellite navigation, vertical positioning is always less accurate compared to horizontal positioning, but is crucial for all kinds of surveying. Thus, two different primary GNSS-based techniques are currently used.

The first technique uses differential GNSS corrections and is named Real-Time Kinematics (RTK). RTK allows very precise fixed positions to be calculated by processing not only the pseudorange measurements but also the phase measurements of the satellites (see explanation of measurements in chapter 1). This also requires a base station with a GNSS receiver at a known reference position near the user, as the achievable accuracy depends on this baseline. Using the measurements of both the reference receiver and the user receiver, as well as models of different GNSS error sources, the phase ambiguity can be resolved, resulting in very accurate position solutions at the millimetre level. Aside from a dedicated reference station, different service providers operate networks of GNSS reference receivers. Based on their reference receivers, these networks can generate differential corrections for virtually all positions. In any event, users require a data transmission channel in order to receive the differential corrections in real time. Mobile communication networks (4G) are mainly used for this purpose when available.

The second technique is called Precise Point Positioning (PPP). PPP is different from RTK as it does not use differential corrections. Instead, it uses reference parameters calculated from a global network of GNSS receivers. These reference parameters include precise orbits and satellite clock corrections as well as different parameters for modelling all GNSS influence factors. The achievable performance is in the range of few centimetres. The precise parameters are generated by different GNSS networks based on dual-frequency GNSS measurements. However, as the final orbits for precise positioning are available only some days later, PPP cannot currently be used in real time (even though real-time PPP is part of current research).

The disadvantage of both techniques is the need for significant convergence times prior to achieving the desired level of accuracy and reliability. This convergence period depends on the number of satellites in use as well as on the signal frequencies used. For this reason, geodetic engineers have been using measurements provided by GPS and GLONASS for many years. However, Galileo could further accelerate surveying by adding not only more satellites but also new and freely accessible frequency combinations.

In addition to single and dual-frequency capability in the Galileo Open Service, Galileo E6 is available for ranging. This high-quality signal adds an option for the third frequency required for the linear combination of GNSS observations made on three frequencies (e.g. for faster and more reliable ambiguity resolution in RTK and PPP processing) [2]. Especially triple-frequency combinations possible with Galileo could help to reduce convergence periods significantly. Galileo is also assumed to significantly improve the positioning performance for surveying due to its reduced code noise and better multipath characteristics.

GNSS receivers for surveying applications are professional-grade solutions and are integrated into a specific workflow. In the interviews, it was stated that most of the GNSS receivers used are already capable of including Galileo satellites along with the other GNSS satellites, and can support signals in all frequency bands. Some manufacturers limit the operational capabilities of their receivers based on a licensing model. However, in Europe, most solutions are sold with activated Galileo support.

The manufacturers of Galileo-capable surveying GNSS solutions are thus very well prepared for the inclusion of Galileo along with other GNSS systems. However, the interviews revealed that at least some parts of the industry have lost faith in the Galileo programme due to the delayed time schedule, even though they acknowledge the technical advantages of Galileo. On the one hand, this is due to the industry’s decision to include Galileo being made very early based on overly optimistic, and ultimately unfulfilled, assumptions.

In addition to other benefits, the interviews revealed that the introduction of Galileo gave a boost to the awareness of GNSS in geodesy applications. Furthermore, the interview outlined Galileo’s added value in conjunction with other European space systems such as the Copernicus Earth observation program. Here, both programmes benefit from having open communication strategies and the same European origin.

GNSS also play an important role in offshore oil and gas activities [2], which are described in detail in Section 4.6 on maritime applications. Here, Galileo is mainly used in conjunction with other GNSS systems.

Galileo's impact in surveying

- Multi frequency, multi constellation for improved accuracy and convergence times
- Surveying solutions manufacturers well prepared for the inclusion of Galileo thanks to the open communication policy
- Added value in conjunction with the Copernicus Earth observation program

4.5. Road and autonomous driving

In order to address the importance of GNSS for automotive applications, it is necessary to distinguish between conventional road navigation and functions for assisted or autonomous driving. For the first use, GNSS accuracy and availability are very important performance features for which degradation directly affects the user experience. By contrast, safety, integrity and signal authentication are negligible because road navigation is not considered to be a safety-critical function. Similar to other applications in the LBS domain, Galileo is expected to provide additional benefits when being used in combination with other GNSS constellations, simply by having more satellites for positioning. Hence, accuracy and availability can profit from Galileo, especially in urban canyons, narrow streets and mountainous regions.

Autonomous driving, on the other hand requires very accurate positioning with a high level of integrity. In the past, it was revealed that sufficiently accurate lane positioning could not be achieved with standalone GNSS solutions. For this reason, the automotive industry follows other technical approaches by combining GNSS with other sensors and cameras. Another alternative is the use of differential GNSS. It is not assumed that Galileo will make relevant contributions to this use. There will still be many scenarios for which the GNSS technology will not meet the required performances, such as in alleys, tunnels and other challenging reception situations.

Besides road navigation, other technologies are emerging which will be enabled with the help of GNSS. The new European Smart Tachograph is a technology for better enforcement of driving and resting times of heavy-vehicle drivers to maximise road safety. Developed by the Joint Research Centre (JRC), it requires all heavy vehicles in traffic from 2019 on to be equipped with a new generation of Smart Tachograph as an improved version of the current digital technology [14]. It monitors and records the driving and resting times of professional drivers, with the help of GNSS. The system is designed to be compatible with the Galileo and EGNOS services [15]. Remote data download and checking are two features of the new system, which will make it easier for authorities to track and identify any potential offenders and detect fraud, misuse or device manipulation [13]. The Smart Tachograph is the first EU transport regulation anticipating the use of Galileo's Open Signal authentication feature whenever it will be available [15].

Another direct benefit of GNSS technology for automotive applications is the eCall system which was specifically developed for automated emergency calls in road vehicles. Here, Galileo is paving the way for an independent European distress service. Moreover, Galileo will improve the reported emergency location by increasing the number of satellites available in mountain or urban canyon areas. The eCall system is explained in detail in Section 4.2.5.

Galileo's impact for road and autonomous driving

- More satellites in view for challenging urban reception scenarios
- Improved traffic safety due to European eCall distress service
- GNSS positioning generally not sufficient for autonomous driving

4.6. Rail

GNSS technology is used in the rail sector, but only to a very limited extend. This is due to the fact that all safety systems in the rail domain have very high requirements in terms of safety, integrity, continuity and availability, which are difficult for GNSS to fulfil on its own. Other technical monitoring systems have been developed specifically for the rail domain in the past which also provide reliable performance in tunnels, covered railway stations and dense urban areas. The drawbacks of these conventional technologies are their relatively high installation and maintenance costs.

Whilst GNSS is not used for main line command and control systems at least in the EU and the United States, it can be found in low density line command and control systems, which provide full signalling capabilities supported by GNSS technology on lines with low to medium traffic. Usually, these lines are located in rural areas, where cost savings are crucial for the viability of a service [2].

However, other new applications of GNSS in the railway sector are emerging which, while not safety–relevant, increase the efficiency of the railway system. Driver Advisory Systems (DAS) use real-time positioning to support train drivers in operating their trains in optimum working points, thus optimising the traffic flow and saving energy and money. They have been deployed mainly for freight traffic in Europe in France, Germany, Sweden, Norway and Spain. Additionally, DAS systems are used in the UK for diesel and electric high-speed passenger trains and freight trains. In Denmark, 75% of all passenger trains have already been equipped with DAS [2].

Another non safety critical application of GNSS in the rail domain can be found in passenger information systems on-board trains, which show the real-time location of a train along its route. Increasingly, the GNSS location is also a supporting input for other online passenger information services, such as the indication of current and expected train delays and route planning services [2].

Finally, important applications of GNSS are widely used in seamless asset tracking of goods wagons, which is a conventional Location Based Service and described in detail in Section 4.2.

Galileo's contribution to the rail sector is similar to that of other LBS applications. By providing additional satellites, Galileo will improve the positioning performance in combination with other GNSS. It also provides a reliable long-term navigation source under civil control, thereby easing the way for long-term developments in the rail sector.

The interviews revealed that for a potential application of Galileo in the rail sector, the industry is waiting for the next generation of EGNOS. This is expected to provide the necessary integrity augmentation so that Galileo can be applied for safety-critical applications in the rail sector. Currently, EGNOS only supports GPS.

Galileo's impact in the rail sector

- More satellites in view for challenging reception scenarios
- Improved efficiency by Galileo-enabled train driver advisory systems
- GNSS positioning predominantly used as backup due to limited availability

4.7. Maritime

Currently, GNSS is the main navigation source for ships to ensure safe navigation at open sea as well as in inland waterways. Cargo ships larger than 500 gross tonnages or larger than 300 gross tonnages if engaged on international voyages are regulated and operate under the International Convention for the Safety of Life at Sea (SOLAS). For these types of ships at least three different GNSS devices are typically fitted on vessels for redundancy reasons. Additionally, Non-SOLAS vessels also use GNSS-based systems for maritime navigation and can be found not only in commercial vessels, but also in recreational vessels [2].

The use of GNSS for the marine field is regulated by the International Maritime Organization (IMO), which defines requirements for GNSS applications [8]. It recognised Galileo as part of the World Wide Radio-Navigation System in May 2016 [9]. Since then, it has been possible to use Galileo for maritime applications at the same level as GPS, GLONASS or BeiDou [2].

In addition to navigation, GNSS is also used for surveillance and tracking of vessels. Like the aircraft ADS-B system (see section 4.1.2), ships broadcast their current position based on GNSS techniques. Such systems are commonly known under the names Automatic Identification System (AIS) and Long-Range Identification and Tracking (LRIT) and are used both in sea and in inland waters.

Search and Rescue is another important topic in which GNSS is seen as a main enabler for providing timely help to people in distress or danger. Different types of devices are available that apply GNSS positioning for submitting distress signals, such as Emergency Position Indicating Radio Beacons (EPIRBs). Other beacons are being developed such as a wrist-worn satellite Personal Locator Beacons for maritime users that was specifically designed for anybody performing outdoor, remote and often risky activities including sole mariners. This affordable device was developed within the scope of the SAT406M project, funded by the Horizon 2020 programme. The device is Galileo capable and specifically makes use of the Galileo Return Link Message to notify the user that the distress call has been registered.[3]

The distress signals can be detected worldwide by satellites of the Cospas-Sarsat system, to which Galileo represents the European contribution. More details on the Cospas-Sarsat system are available in Section 4.2.6. Another distress system distributes distress calls via very high frequency range and transmits a GNSS-based emergency location to alert other ships within the radio frequency range.

Other applications of GNSS in maritime domains can be found in fishing vessel control, where GNSS positioning enables Vessel Monitoring Systems to check their position, for example during time spent in international and foreign waters as well as in protected marine areas.

Another important field of application is marine engineering. Here, satellite-based navigation techniques are used to support marine construction activities such as cable and pipeline laying. Additionally, GNSS provides a highly accurate, repeatable and reliable position solution as needed for seafloor mapping and for searches for shipwrecks and missing aircraft. Without GNSS, massive search operations such as that undertaken for the Malaysia Airlines MH370 aircraft, which presumably went missing in the Indian Ocean, would not have been possible.

Many port operations also rely on GNSS for improved docking and loading-unloading operations. All operations can be monitored by GNSS, in order to facilitate the operation itself and improve the efficiency in the long term.

GNSS is also a key element for oil and gas platforms. While in operation, they follow extremely stringent safety regulations according to which they need to use two independent GNSS systems. This is to ensure redundancy at all times and to enable dynamic comparison between both systems for integrity. All of these requirements exist in order to ensure maximum safety for operators, equipment and environment. Due to these stringent requirements, all current market solutions rely on the full use of all available GNSS constellations. Once Galileo is fully operational it will provide increased availability contributing to a resilient position solution [2].

According to the interview for the maritime domain, Galileo represents an additional means of navigation without being expected to provide a significant improvement to the state of the art. However, the interviewees emphasised the importance of Galileo's SAR service combined with the new return link capability (see section 4.2.6.).

With more than three million commercial vessels worldwide and over 30 million recreational vessels, for which the current penetration rate of GNSS devices on-board is around 22%, there is still a high market potential for the adoption of GNSS equipment and improved GNSS-based navigation functions such as autopilots for sailing ships [2].

[3] SAT406M was a 2014 regional winner of the European Satellite Navigation Competition. More information can be found on: http://www.sat406.com/

Galileo's impact in the maritime sector

- Galileo already approved as maritime navigation aid internationally
- Redundant navigation source to other navigation aids
- Improves maritime safety as the European contribution to worldwide SAR service

4.8. Agriculture

Precision agriculture is seen as one of the key approaches to improve agricultural production in order to meet the world's future demand for food. High-precision satellite navigation is one of the main enablers for precision agriculture, allowing for an increase in crop yields while minimising its environmental footprint [2].

Precision agriculture is supported by global navigation satellite systems in various ways. Agricultural applications supported by GNSS include farm machinery guidance, automatic steering, variable rate application as well as monitoring. Guidance of farm machinery is one main factor in the more efficient use of soils. By providing precise guidance and digital maps to the drivers of farm machinery, the path driven can be optimised to reduce overlaps and the distance driven. Another application of GNSS for precision agriculture is the use of automatic steering. If the level of accuracy and integrity is sufficient, farm machinery could operate automatically with the driver merely monitoring the system.

Monitoring of the soils and the yield is very important in order to ensure that the yields remain productive for the future. With satellite navigation systems and additional sensors, farm machinery could automatically collect all data necessary for planning the use of agrichemicals. In this way, the environmental footprint could be reduced to a minimum.

GNSS technologies are also used in forest management. This allows damages and areas under stress to be precisely mapped as early as possible in order to take preventive actions as quickly and effectively as possible.

Different GNSS-based technologies are presently in use for precision farming. First, phase-differential GNSS (also known as real-time kinematics, RTK) is used intensively. This technique requires mobile data from a network of nearby reference stations, but allows for centimetre-level accuracy. Alternatively, Precise Point Positioning (PPP) is used. While conventional PPP solutions were only available a few days later (due to the processing of the broadcast signals), modern PPP providers allow for a real-time service. However, the accuracy achievable depends on various factors. As both techniques require a stable data link for external information, the availability of modern mobile data networks in remote areas is crucial for agricultural applications. These 2 techniques were also discussed in section 4.4.

Galileo is seen as an additional source of GNSS measurements. It is not expected to be used as a stand-alone system in this domain, but only in combination with other GNSS systems. Galileo differs from the other GNSS constellations as it provides civil usable signals in three different frequency bands. This enables triple-frequency combinations to be calculated with Galileo satellites, which could help to improve the level of achievable accuracy significantly in the future. As a challenge, Galileo will compete with existing commercial SBAS services in this domain which have been widely used in precision framing for many years.

Galileo's impact in agriculture

- High precision navigation service free of charge for precision farming
- Multi frequency, multi constellation for improved accuracy and efficiency
- Galileo directly competes with other commercial services in this domain

4.9. Public authorities and military

The use of satellite navigation is essential to supporting rescue teams in emergency situations by facilitating the location and dispatch of the single teams. Especially during stressful and dangerous situations, GNSS can provide a huge benefit to help bringing specialised units to the location where they are needed as quickly as possible and under minimal risk.

Galileo's PRS provides a robust and authenticated navigation signal to rescue services. In this way, reliable navigation and localisation can be ensured even in the presence of intentional and unintentional signal perturbation.

Galileo can also provide pre-emptive benefit for civil protection, for instance, in facility, dam, or bridge monitoring. For this purpose, GNSS devices are permanently attached at dedicated points of interests. When combined with precise data from the Copernicus Earth observation programme, movements in the centimetre range can be observed over longer time periods. Thus, potentially critical situations such as dangerous settlements due to soil erosions can be identified far in advance and appropriate countermeasures can be triggered.

Although, in sharp contrast to other GNSS constellations, Galileo is a civilian system never conceived for military use nor funded by military budgets, it will still benefit military applications due to its dual-use nature. Exact requirements from the military domain are not publicly available. However, for the sake of completeness, potential military requirements and concerns are briefly mentioned in this section. No explicit interviews were conducted in this domain.

Typical military applications include the positioning of forces, especially close to borders, their efficient dispatch to perform specific tasks and the fast coordination of their movements. In addition, the relatively new technology of unmanned aerial and ground vehicles partially relies on GNSS for safe operation 24/7 at any location in the world. Another application is the precise delivery of cargo not only for combat missions but also for relief shipments. Other specific military uses include the precision guidance of munitions to improve strike effectiveness and reduce the risk of friendly fire and collateral damage. For all of the above-named applications, and given the time constraints of military programmes in general, it is essential that the appropriate GNSS services be ensured over the long term. Military GNSS requirements directly result from the above-named applications and include integrity and a very high level of accuracy and continuity of service. Furthermore, one major difference between military and civilian GNSS requirements was identified as security requirements and signal resilience [11]. Also, military opponents are expected to have highly developed technologies and capabilities for signal manipulation, which means the risk of spoofing and jamming from hostile actors is far higher and potentially far more harmful for military applications [11]. Summarising the publicly available military requirements, it seems that the PRS provides a good technical basis for these applications. Additionally, for less stringent requirements, the OS may prove to be appropriate for military operations as well.

Galileo's impact for public authorities and military

- Galileo provides strategic autonomy from other countries' space assets
- Encrypted PRS could be used for sensitive sovereign applications
- Authentication for different services increases safety even in disturbed environments
- Particular benefits for civil protection when used in combination with data provided by the Copernicus Earth observation programme

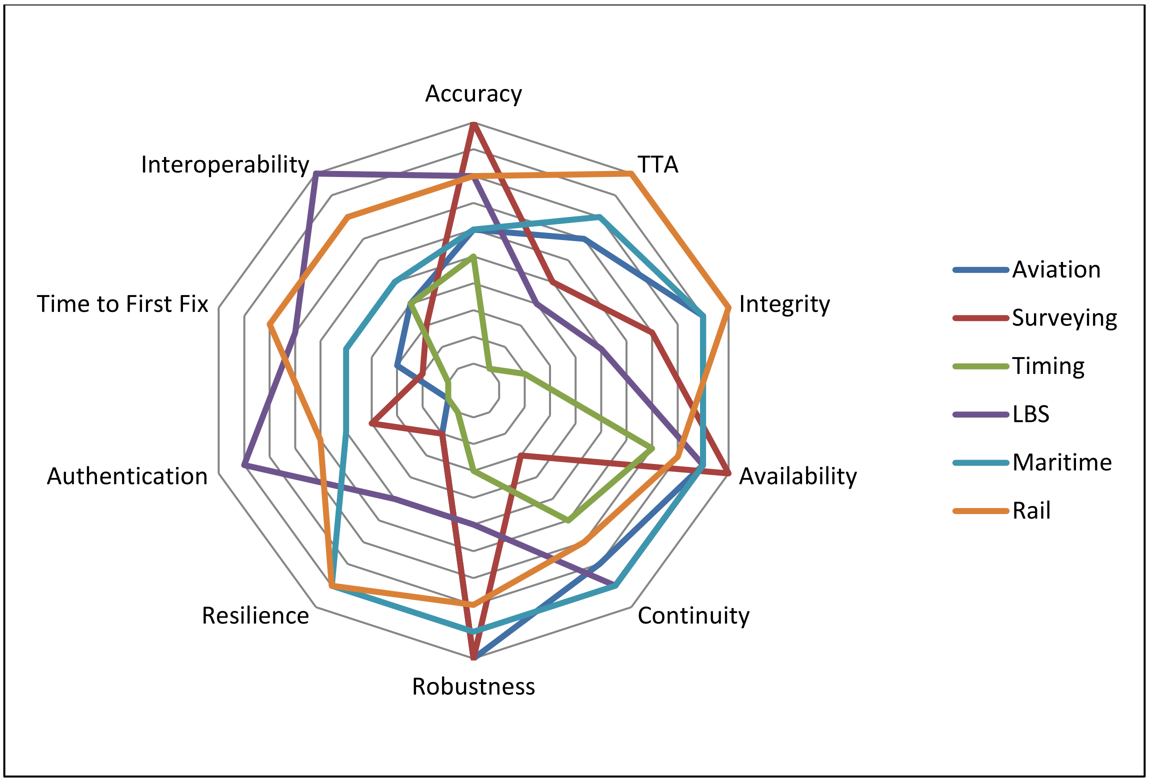
4.10. Summary across domains

The importance of the KPIs (defined for this study at the beginning of chapter 4) was evaluated during the interviews with experts in the different domains.[4] To this end, the interviewees were asked to rate the importance of the KPI for their domain on a subjective scale from 1 (low priority) to 10 (high priority). This approach outlines general common tendencies but also opposing trends between the different domains.

[4] The interviews did not cover all application domains, therefore not all domains appear in the figure.

Below, Figure 6 summarises the results. It should be noted that the interpretation of specific indicators can sometimes differ between the single domains and is subjective in some cases.

Figure 6 - Performance indicators for GNSS in different domains



Source: Compiled by authors

The following aspects can be noted:

- The general requirements for GNSS applications are very different and largely depend on the given application.
- There is a tendency towards safety relevant performance indicators such as resilience, authentication and integrity. This can be attributed to the fact that GNSS is being increasingly used for applications that are considered safety relevant or at least rated as very important infrastructure elements for major parts of the economy or the daily lives of EU citizens.
- Accuracy is a very helpful property but is not always rated as very important. It can be assumed that this is because, for many applications, the current GNSS performance is already acceptable, or because the accuracy could already be improved via other augmentation systems such as SBAS, GBAS or other commercial correction services.
- Availability of satellite navigation is a major concern for various domains and applications. However, each satellite navigation system is susceptible to radio frequency interference (RFI). With increasing occurrences of intentional and unintentional interference, the mitigation of this threat is crucial for such applications and should be assessed continuously. In addition, mitigation efforts could be included in the Galileo reference documents. This might include complementary navigation inputs.
- Every defined KPI is of great importance for at least one specific domain. Consequently, it would not be beneficial to sacrifice one KPI for another.

5. Major advantages of the Galileo programme

The Galileo navigation system creates multiple benefits both within Europe and throughout the world. Galileo provides socio-economic and strategic advantages and offers several unique features which are not found in other, competing GNSS constellations. The key advantages are summarised in the following list and explained in detail below:

- Civil governance, open communication policy;
- Strategic autonomy of the EU;
- Key enabler of various added socio-economic values;
- Envisaged to provide signal authentication for open signals;
- Promoter of new GNSS technologies and of the development of associated downstream markets within the EU;
- Improved accuracy;
- European contribution to worldwide Cospas-Sarsat system, provides a unique technical feature to announce that rescue forces are on their way.

5.1. Civil governance

Having been developed primarily as a civil system under civil governance of the EU, Galileo can provide several benefits that other competing GNSS cannot.

First, certification processes can be facilitated by open communication of the relevant system design specifications. For GPS, which is basically a military system under military control, only vague information on system architecture and guaranteed performance is available. This can be a problem for the certification process of life-critical technologies, for example, which require detailed knowledge of the complete system architecture. As such information is not available, costly backup strategies must be developed. By contrast, Galileo was specifically designed for civilian use and can provide the relevant documentation. This enables the development of additional applications and facilitates their certification process. Additionally, this open communication helps to promote trans-European infrastructure activities in transportation, telecommunication and energy.

Nevertheless, although Galileo is primarily a civil system, it can provide useful services for public authorities such as rescue services, police, civil protection, and border protection as well [12].

5.2. Strategic autonomy of the EU

Especially given that GPS and other GNSS constellations are under the control of the defence or other military departments, there is always the concern that navigation signals might be rejected or degraded for civil use. Similar to Selective Availability, a feature that intentionally reduced the quality of GPS' open signal until 2000, new technologies have been developed since then which allow for a regional degradation or even complete rejection of navigation signals. Although those techniques were rarely used in the past, their potential application can never be completely precluded.

These circumstances pose a potential risk to all critical GNSS applications and increase the dependency on other countries' GNSS constellations. Moreover, they represent a handicap to all long term investments in GNSS-based technologies which, even if not normally critical, would run into serious acceptance problems if GNSS signals are artificially degraded or completely removed.

Having Galileo as an independent civil European navigation system leads to the strategic autonomy of the EU and its member states and avoids the above named dependencies and risks. With Galileo, the EU can actively influence the GNSS strategy and pave the way for long-term investments and technologies.

The interviews outlined the importance of Galileo's advantage to provide civil signals in different frequency bands. This fact has the potential to increase the robustness of all positioning and timing applications and decreases the risk of intentional or unintentional disturbances. In the long-term, this will lead to safer and more reliable GNSS services for EU citizens.

5.3. Social benefits

A variety of applications for GNSS and Galileo are outlined in Chapter 4. It is obvious that GNSS technology has found its way into a significant number of applications in daily life. Additionally, it can be noticed that these applications are increasingly rated as important services or even present the backbone for other critical infrastructure such as telecommunication, power distribution and finance trading. Moreover, the availability of GNSS presents various advantages in almost all disaster management activities and is essential for worldwide distress signal detection and different EU initiatives like eCall and E112.

5.4. Signal authentication

Galileo is the only GNSS that is planning to offer signal authentication for open-service, free-of-charge signals [10]. This unique feature is being strongly anticipated by many users, manly those involved in critical or safety-relevant applications. Signal authentication is a technical mechanism to verify that the received navigation signals actually originate from the source stated. It helps to mitigate intentional signal manipulation and will increase the security for Galileo-based timing and positioning applications. Galileo is expected to start transmitting the Open Service Navigation Message Authentication in mid-2019 [45].

In the United States, no civil signal authentication is currently available via GPS and, according to the Director of the US National Coordination Office for Space-Based Positioning, Navigation and Timing, Harold Martin, there are no plans to change this in the next-generation GPS. Martin did note, however, that the US remains interested in EU developments in this area and is continuing to explore possibilities for future authentication [45].

5.5. Economic benefits

Galileo boosts European innovation, contributing to the creation of many new products and services, creating jobs and allowing Europe to own a greater share of the EUR 175 billion global GNSS market [2]. Additionally, there are indirect benefits that can be derived from the emergence of new applications and technology transfers, leading to new markets and efficiency gains. Moreover, public benefits will be created as well, for example, due to a reduction in pollution or improved levels of safety, for example, in aviation [12].

Together with EGNOS, Galileo is expected to provide advantages to the EU economy and EU citizens, with a calculated cumulative value of approximately EUR 130 billion for 2014–2034 [12]. Immediate direct benefits result from the growth of the EU space industry and downstream markets for GNSS-based applications and services.

DG Grow of the European Commission emphasised that the Galileo programme is a key enabler for market growth in various GNSS-related domains. This is achieved not only by powerful development programs such as Horizon 2020 and Galileo Masters, but also by workshops and organisational help for companies and SMEs to facilitate the development and implementation of new technologies and business cases.

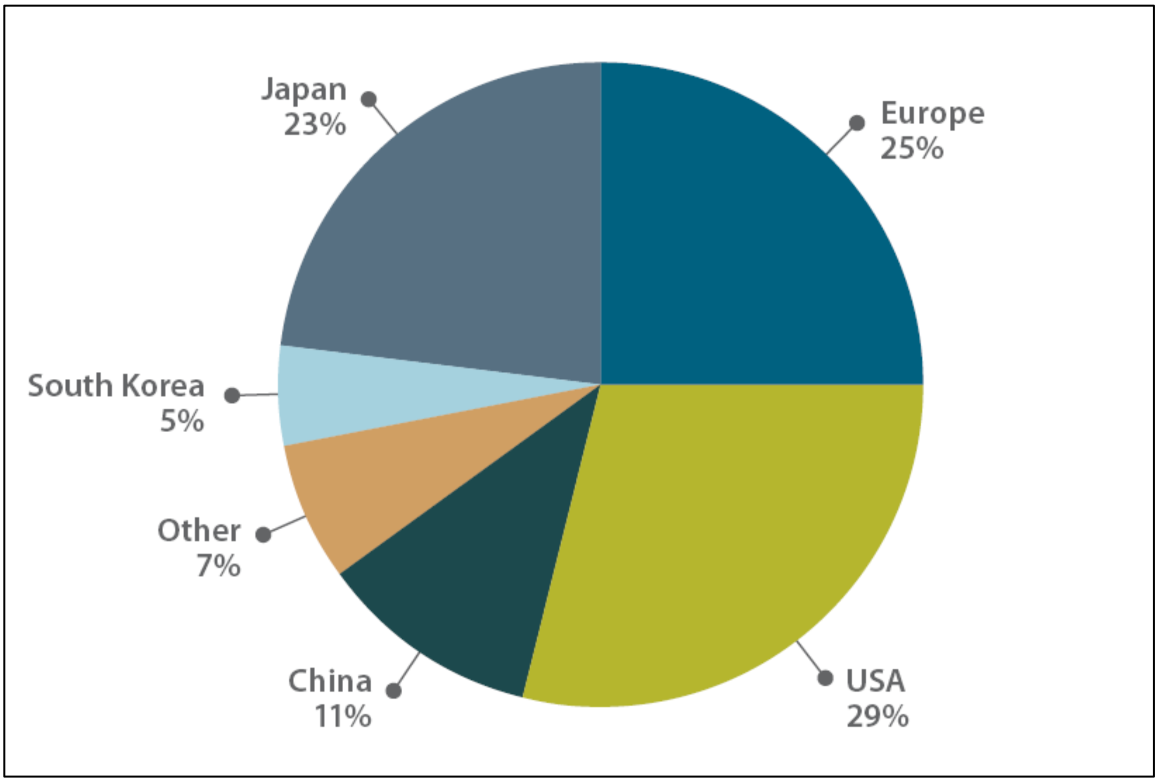
Furthermore, DG Grow emphasised Galileo's importance for international cooperation. Following the GNSS trend, more and more GNSS receivers are making use of multiple constellations for positioning; this requires close coordination between different international navigation service providers. In this context, Galileo is the European entry point for actively designing future GNSS technologies and trends in international working groups.

The analysis of the global revenue generated in the GNSS industry in 2015 is depicted in Figure 7. The analysis outlines the tendency that GNSS revenue is basically generated by the countries that operate GNSSs. The European market share is 25%.[5]

[5] In the analysis, Europe is defined as EU28 plus Norway and Switzerland.

Galileo is a main enabler for GNSS-related developments for European companies. The interview outcomes identified SMEs in particular as potentially profiting from the European Navigation Satellite System, for example, manufacturers of time and frequency synchronisation equipment.

Figure 7 - Revenue generation in the GNSS industry by key countries in 2015



Source: [2]

Recently, EU legislation required mandatory support of Galileo for safety-relevant systems such as the European eCall, the Digital Tachograph and future electronic toll collection systems. The Communication on Space Strategy for Europe published in 2016 contains ideas for legal enforcement of Galileo-capable timing and synchronisation devices for mobile phone networks and other critical infrastructures. These ideas still present possible options for the future.

5.6. Improved accuracy

The interviews revealed the improved accuracy of Galileo's open positioning service compared to GPS. They confirmed that, even though Galileo has not yet reached its final expansion state, its accuracy is comparable to that of GPS. This leads to the expectation that, once Galileo is fully operational, its accuracy will exceed that of GPS.

Another aspect to be highlighted is the very open communication strategy of GSA regarding system architecture, satellite metadata and planned activities. The GNSS community explicitly acknowledged Galileo's advantage of open communication that would not only facilitate further developments but also immediately result in improved positioning and timing services. For instance, the detailed satellite metadata leads to an improved localisation of the satellites, thereby leading to an improved user position. Furthermore, as with GPS, planned manoeuvres for Galileo satellites are indicated far in advance. This is not always the case for the competing GLONASS and BeiDou systems.

5.7. Distress signal detection and localisation

Since it has specialised distress signal receivers on-board every satellite, Galileo can receive and localise distress signals from various emergency beacon types all over the world. With this capability, Galileo represents Europe's contribution to the worldwide Cospas-Sarsat system, an international satellite-based emergency system. Galileo contributes to increasing the coverage and the localisation accuracy of the entire Cospas-Sarsat system. Additionally, Galileo adds a new and unique feature, which is the notification of the person in distress via a new return data link. Hence, emergency centres can confirm that the distress call has been detected and notify the user that rescue forces are on their way.

Furthermore, Galileo enables other local emergency services to function such as the European eCall system for road vehicles, for which Galileo is mandatory according to EU legislation. In case of an accident, eCall-equipped vehicles automatically issue an emergency call and provide an accurate GNSS position together with detailed information on the vehicle type, number of passengers and lane direction. The additional benefit which Galileo can provide is an improved multi-constellation position in challenging mountain or urban canyon scenarios and the strategic autonomy regarding the use of other countries' GNSS systems.

6. Challenges for Galileo

The interviewees mentioned several challenges Galileo is currently facing. These challenges have been collected and categorized in this section. It should be noted, however, that some of these challenges do not affect Galileo alone but apply to all GNSS systems.

Due to the increasing use of GNSS for strategic purposes, satellite navigation systems are becoming a sensitive infrastructure which could be susceptible to malicious use and therefore require adequate security and protection mechanisms [12]. The importance of GNSS systems for the EU today has been analysed in a study conducted for the European Commission and entitled "Dependence of the European Economy on Space Infrastructures - Potential Impacts of Space Assets Loss" [36]. It outlines the importance of the space assets in general and the space navigation system in particular, not only for the European downstream market but also with respect to the dependence on third countries space infrastructure. Regarding a loss of space navigation capability, no matter how it is caused, the study summarises highly probable social, environmental and strategic impacts. The study suggests identifying risks associated with dependence on critical space assets and developing suitable mitigation strategies. According to the study's conclusion, this could be achieved by continual development of space assets but also ground-based backup navigation systems [36].

Three different categories of challenges for Galileo have been identified in this study. Technical challenges cover all aspects related to technical details. Communication challenges refer to public information provided by the operators of Galileo. Organisational challenges describe the general shortcomings identified by the interviewees.

6.1. Technical challenges

In general, the susceptibility of GNSS to radio frequency interference (RFI) is a major threat for all domains. As all satellite navigation systems work in similar frequency bands with similar techniques, all systems are affected equally by RFI. Having GNSS signals available in multiple, distinct frequency bands (like Galileo) could help in situations where only one frequency band is affected, but cannot ensure safe operations for broad-band RFI events. RFI can be created by a magnitude of sources, including lightning, nearby malfunctioning electronic circuits, arbitrary high frequency transmitting systems or intentional jamming devices. Thus, protecting the GNSS bands properly is crucial for reliable satellite navigation. With upcoming demands for wireless communication, the pressure is increasing from certain industries to use nearby frequencies for their services without ensuring adequate GNSS signal protection. This could eventually lead to a degraded overall GNSS performance.

Regarding timing applications which are subject to national regulations, the compliance of Galileo derived timing is feasible from a technical point of view. However, the formal verification process for the traceability from Galileo time to local national times is still to be defined [34]. This traceability between the various GNSS times and the realisations of the national UTC times is important for certification and the aspect of liability.

Not only the timing community but also other application domains would like to encourage the GSA to proceed and make the signal authentication feature available as one of the most important unique features of Galileo. This could open new market segments and generate added value for customers that use GNSS-based timing in safety-critical applications. When EU-based companies are involved in an early-stage test process of these new features, this could foster their position on an international market level and attract new customers with new applications, thereby potentially increasing the EU market share. Policy actions should support the timely introduction of signal authentication.

6.2. Communication challenges

In general, the publicly available documentation of Galileo has been regarded as well written. However, multiple interviewees noted that the documents lack certain information needed in their domain. This includes the following points:

- The Galileo documentation does not cover differential corrections and their requirements whatsoever. This is particularly important for safety-critical applications which mostly depend on differential augmentation systems. For differentially corrected GNSS it is crucial to ensure that identical navigation data is used for generating and applying the differential corrections. For the certification of such services it is necessary to know exactly how the control segment uses the provided parameters. These rationales are not given in the Galileo documents.

- All GNSS satellites have a certain probability of failure, the exact value of which is needed for safety-critical GNSS applications. Even though performance reports are available for Galileo, the public documents do not include specific guarantees for this risk.
- The algorithm for modelling the ionosphere given in the Ionospheric Correction Algorithm for Galileo Single Frequency Users is very complex and hard to implement. In addition, the ionospheric parameters are not covered by any issue-of-data. Thus, if satellites broadcast different ionospheric parameters, users cannot decide which data set is the newest and should be used.

In addition, some of the Galileo reference documents are subject to Intellectual Property Rights (IPR) and patents. This is a serious challenge for any international harmonisation.

These shortcomings in the publicly available documentation impede the approval of Galileo for safety-critical applications. In aviation, for example, neither certification guidelines nor international harmonisation documents are presently available for Galileo. Galileo-capable GNSS receivers for air transport are thus not available either. As development, certification and approval of novel equipment has to be completed prior to installation in operationally used aircraft, it will take a significant period of time for Galileo receivers to be integrated in commercial air transport aircraft.

Multiple interviewees addressed the current status indications given by the Galileo operators in the form of 'Notices Advisory to Galileo Users' (NAGU). NAGUs are issued to notify Galileo users about any changes in the satellite constellation which might affect them. This includes, for example, when a satellite is taken out of service for maintenance purposes or a new Galileo satellite is available. However, in the past, some incidents were not covered sufficiently in the NAGUs. One interviewee mentioned a problem that occurred on 14 March 2017, when navigation messages could not be refreshed for all satellites due to a problem in the ground station. The corresponding NAGU (#2017015) was issued only the next day. During another incident on one of the clocks of Galileo satellite GSAT-0203 in June 2017, broadcast signals experienced large ranging errors nearly 24 hours before the signals were declared unhealthy [47]. This circumstance was beyond the specified notification limits and created a series of not specifically mentioned problems. Regarding this issue, the quarterly Galileo performance report stated only that "changes have been implemented in the operational procedures to avoid any future occurrence of analogous situations." [47]. Due to these incidents, the maturity of Galileo's technical infrastructure was questioned by some interviewees.

In addition, NAGUs are to be used as inputs for certain systems necessary for specific applications. Airborne users, for instance, are required to check the availability of the satellite constellation prior to the flight. Therefore, availability prediction services already exist today, taking 'Notice to Navstar Users' (NANU) issued for GPS into account. In order to introduce a similar service for Galileo, one interviewee suggested also providing NAGUs via other communication channels and in other formats, for example using the internationally harmonised Aeronautical Information Exchange Model (AIXM) format. In this way, future Galileo services could use the NAGUs directly without needing to parse them, simplifying the approval of such a procedure.

Galileo performance reports are issued quarterly by the GSA which is highly appreciated by the majority of interviewed experts. However, some of the aforementioned flaws of the Galileo systems are not reflected in the corresponding reports. One interview partner suggested including not only absolute measurements but also their estimations of uncertainty in the performance reports. In addition, the report would not specifically mention the metrology organisations which were involved in the single performance evaluation tasks.

6.3. Organisational challenges

The Galileo system schedule was identified as a major challenge in multiple domains. Reliable schedules are crucial for investment of companies in Galileo-related technologies. Galileo still suffers from its overly optimistic early schedules and promises in the past. Due to the delays in the Galileo programme, many companies have lost faith in the Galileo system, expressing that Galileo has missed its chance to be the first operable GNSS to provide civil-usable GNSS signals in two different frequency bands. During the interviews, this was considered a missed opportunity for adding Galileo functionalities to different applications.

Multiple interviewees complained about the lack of openness of the Galileo operators. They felt that their technical needs and demands concerning Galileo had not been taken seriously, nor their complaints taken into account. Especially for safety-critical GNSS applications, it is crucial to also report shortcomings and failures openly to the public instead of handling such flaws internally. For example, some of the atomic clocks on-board of Galileo satellites failed recently. However, no public information about the source of these failures or the mitigation actions taken by the Galileo operators was provided. As long-lasting Galileo performance data is not available, and since not all risk probabilities have been made available in public documents, these applications suffer from overly conservative assumptions introduced to cover the unknown uncertainties.

7. Conclusions

Galileo has several technical features that are unique and not provided by other competing GNSS, such as the Search and Rescue return data link for user notification and signal authentication for civil users. Both features represent important technologies that are expected to provide high added values to EU citizens in the first place but also to worldwide users. Especially the importance of signal authentication was emphasised by various experts working in the field of safety critical applications of GNSS.

Although Galileo is behind initial schedule, a lot of application domains already see benefits from Galileo and expect additional benefits in the future. This can mainly be contributed to the fact that Galileo is interoperable with other GNSSs and therefore increases the number of satellites potentially in view. This results in improved accuracies, more measurements for integrity monitoring and higher availability.

Another advantage of Galileo is the strategic autonomy of the EU regarding other countries' space navigation assets. Especially since GNSS is increasingly used in safety critical applications and highly relevant infrastructure, the fact of having an independent European navigation system under civil control is an important contribution to national security of the EU member states and their associated partners. It further represents a clear signal for a reliable open navigation source; a fact that encourages the development of new technologies and applications in the long-term.

Galileo presents Europe's contribution to the world-wide satellite-based distress signal detection and localisation system Cospas-Sarsat. It is the only system of this kind and the base for providing help to people in danger in many different sectors, such as aviation, vessels, sailors, world-wide expeditions, and private persons equipped with personal locator beacons. The Galileo system not only complements the Cospas-Sarsat system with additional satellites: the interviews also revealed that Galileo significantly improves the coverage and accuracy of the located emergency position.

Together with the geo-stationary satellite-based augmentation system EGNOS, Galileo is expected to provide advantages for the EU economy and EU citizens having a calculated cumulative value of approximately €130 billion in the period 2014–2034. Immediate direct benefits are expected for the space industry as well as downstream markets for GNSS-based applications and services. On the other hand, the total Galileo-related costs from the early 1990s until 2020 sum up to approximately €16 billion.

However, next to these benefits, Galileo also suffers from certain shortcomings. For example, it currently can't be used for certain safety-critical applications due to missing approval and guidelines. Certification of Galileo is often hindered by missing information by or inefficient communication with the Galileo authorities. In addition, some industry players lost faith in Galileo due to the overly-optimistic time schedules in the past. With the parallel modernisation of GPS, Galileo has missed the opportunity to be the first operational system with modern features for civil users. Therefore, Galileo is nowadays mostly seen as an additional source of measurements to be used in conjunction with the other GNSS constellations, but not as an independent alternative to GPS.

8. Policy options

This section presents different policy options developed based on major findings of the study. All options were either directly derived from the feedback of the interviewees or identified during the literature review.

Policy objective 1: Maximising the impact of Galileo

Promote Galileo towards becoming a major worldwide GNSS, thereby maximising its impact and reducing dependency on other countries' space assets.

Option 1.1: Further efforts by the EU to increase the development of Galileo-based technologies and services to ensure that additional benefits are provided to EU citizens. Although a very efficient funding instrument has already been established in the form of Horizon 2020 Programme for Research and Innovation [46], there is still the need for further development to accelerate the uptake of Galileo and ensure continuous adaptation of technologies developed so far. This is especially important since Galileo is already years behind initial schedule. It this does not take place, users may base their technologies on other competing GNSS systems, thereby reducing Galileo's impact and increasing users' dependency on other countries' GNSS systems.

Policy objective 2: Maximising safety and integrity provided by Galileo and accommodating user needs for improved signal authentication

Accelerate and increase the efforts regarding the introduction of Galileo's signal authentication feature as a unique selling proposition for new safety-relevant timing applications. In contrast to GPS and other concurrent GNSS systems, Galileo could make a real difference here, creating new business cases for safety-critical timing and synchronisation applications.

Option 2.1: Accelerate and promote the introduction of Galileo's Open Signal authentication. Support users from the various application domains in implementing authentication for their applications.

Option 2.2: Investigate the feasibility of further developments towards a strengthened authentication feature which goes beyond the capabilities currently planned. Feedback from the OEM domain indicates that security could be further increased by analysing whether the envisaged authentication feature could be implemented on a signal level rather than on a message level. This could provide added value for many safety-relevant GNSS applications. Possible side-effects of this function are beyond the scope of this study and need to be addressed separately.

Policy objective 3: Maximising benefits from Galileo's Public Regulated Service

With increasing demand for GNSS positioning and timing for critical infrastructures, investigations should address the opportunity to use Galileo's Public Regulated Service for these purposes.

Option 3.1: Increase support for SMEs in beginning to apply PRS for safety-critical infrastructures and other applications by public authorities. This support is less a form of financial support and more organisational in nature for SMEs in the process of obtaining access to PRS for their applications. Furthermore, SMEs should be supported in the process of obtaining clearance for PRS technology and be given clear indications on how and under which circumstances access to such confidential data is possible. This will enable the creation of new technologies and generate further applications; for example, Galileo's PRS can be used for safety-relevant timing applications.

Policy objective 4: Spreading the use of Galileo's services by facilitating usage

A key factor for the success of Galileo is its easy integration and interoperability with other GNSS systems. Especially since other competing GNSS constellations are available, it is crucial that users be able to apply Galileo signals with no or only minimal hardware adaptations. This is most relevant for the LBS domain, which has a very high number of GNSS receiver devices. In LBS, Galileo's benefits are in strong competition with low receiver chip prices.

Option 4.1: Regarding Galileo's future high-precision service, the suggestion was made to shift from the currently planned E6 frequency to the more common E1 or E5 frequency bands. The reason for this is that many manufacturers prefer to avoid high-frequency signal reception hardware for E6, which entails high technical costs compared to the rare use of E6 for satellite-based navigation systems. The technical working groups should consider whether this could be an option for future updates of Galileo.

Policy objective 5: Analysing the strategic dependency on GNSS in general and the benefit of backup technologies

With the old terrestrial backup navigation system LORAN being shut off in the last decade, various experts have suggested addressing other dissimilar navigation backup systems which are complementary to GNSS and might serve as an appropriate backup. They emphasised the similar working principle of all GNSS systems, which is good for their interoperability but makes them vulnerable to common error sources such as jamming or spoofing. Therefore, different communities recommend analysing the need for an independent navigation and timing backup system. For instance, terrestrial navigation systems such as LORAN transmit their signals with very high power and are thus less susceptible to RFI.

Option 5.1: Analyse the potential threats and impacts that would result from a complete loss of all GNSS signals.

Option 5.2: Investigate suitable backup strategies including terrestrial navigation systems which would be useful in mitigating the effects mentioned above.

Policy objective 6: Counteracting Personal Privacy Devices

Personal Privacy Devices (PPDs) are small yet powerful devices which generate RFI in order to prevent GNSS-based tracking. Such devices are currently readily available and are predominantly used in cars and trucks due to privacy concerns of the drivers. The use of PPDs is illegal, as this not only prevents tracking of the vehicle but also affects GNSS applications in various domains in the vicinity. Nonetheless, they are used extensively in practice and affect different GNSS-based applications negatively. Especially safety-critical GNSS applications suffer from reduced availability for this reason. In order to counteract these effects, two options could be explored.

Option 6.1: Establish a European strategy for detection and localisation of PPDs, for example via a European RFI detection network. Such a network could help law enforcement to identify, track and fine PPD users.

Option 6.2: Investigate legislative changes to strengthen the privacy of commercial drivers. This could help to reduce the demand for PPDs among this group.

Policy objective 7: Supporting certification of Galileo for safety-critical applications

Galileo cannot currently be used for safety-critical applications in different domains. This is mainly due to certification guidelines and performance information not being publicly available. One example is air traffic navigation which is currently limited to the use of GPS. As international harmonisation on the International Civil Aviation Authority level and the generation of certification guidelines take long periods of time, it is currently not foreseeable when Galileo could be incorporated here.

Option 7.1: Increase political support in order to accelerate the incorporation of Galileo into safety-relevant applications. This would foster the contributions that Galileo can offer for a more efficient air transport system in the future. As avionic equipment is typically used over a very long period of time, it can be assumed that the equipage percentage of Galileo capable equipment will increase very slowly only once certified products are available. Hence it is crucial to have the standardisation documents in place as early as possible.

Policy objective 8: Increasing use of Galileo for research purposes

Galileo as a system under civilian control should continue its open policy with regard to the research community. By getting the research community involved, Galileo can gain additional benefits, leading to a better understanding for the next generation of the Galileo system and a more detailed knowledge of the system behaviour in nominal and abnormal situations. To this end, detailed information from the two satellites which were accidentally launched into erroneous elliptical orbits are of special interest for the research community, mainly because their atomic clocks on board are subject to significant variations of speed and gravity.

Option 8.1: Provide detailed information on the two satellites on elliptical orbits to the research community. This will maximize the insights that can be derived from those accidentally deployed satellites potentially leading to a better understanding of the satellite behaviour. This would lead to the deep insights into Einstein's relativity effects on satellite clocks and satellite orbits.

Option 8.2: Provide the opportunity to the research community to suggest test setups to be conducted in close coordination with the GSA. This would allow for totally new applications of the two elliptical satellites, not necessarily in the field of satellite navigation, but for a wider research perspective instead. This option could maximise the benefit gained from the accidental launch.

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Annexe

External contribution from experts

The authors of this study acknowledge and would like to thank the following external experts for their contributions to this report. It should be emphasised that all interview contributions reflect the opinion of the respective interviewees and do not necessarily express the opinion of the organisations behind them.

Dr Andreas Bauch, Head of Working Group Time Dissemination

Physikalisch-Technische Bundesanstalt (PTB), the German National Metrology Institute, Germany

Expert for GNSS based time dissemination, Galileo's timing performance and properties of Galileo system time.

Interviewed on 2 March 2018

Mr Bernhard Richter, GNSS Business Director

Leica Geosystems AG, Switzerland

Expert for surveying domain and manufacturer of equipment for geodesy, construction and surveying.

Interviewed on 9 March 2018

Mr Heiko Gerstung, CEO

Meinberg Funkuhren GmbH & Co. KG, Professional Time and Frequency Synchronization Solutions, Germany

Director of a major SME manufacturer of timing and synchronisation equipment.

Interviewed on 9 March 2018

Mr Stefan Naerlich, Head of Navigation Services

Deutsche Flugsicherung (DFS), Germany

Expert for the aviation domain and use of Galileo for safety of life applications.

Interviewed on 14 March 2018

Mr Alessandro Coda, Chief Technology Officer

European Association of Automotive Suppliers (CLEPA), Belgium

Representative for the automotive domain.

Interviewed on 15 March 2018

Mr Andreas Lipp, Navigation Expert

Eurocontrol Experimental Centre, France

Expert for the aviation domain and use of Galileo for safety of life applications.

Interviewed on 15 March 2018

Mr Christoph Kautz, Deputy Head of Unit

DG Grow, European Commission

Expert for the Galileo system, the current status of Galileo services, and views on benefits for SMEs.

Interviewed on 22 March 2018

Mr Samuli Pietila, Senior Product Manager, Positioning

u-Blox Espoo Oy , Tampere, Finland

Expert for the LBS domain and views of OEMs in general.
Interviewed on 23 March 2018

Dr Benjamin Männel, Head of our IGS Analysis Center
Helmholtz-Zentrum Potsdam, Deutsches Geo Forschungs Zentrum GFZ, Germany
Expert for the surveying domain, the Galileo reference system and expected performance.
Interviewed on 23 March 2018

Dr Alain Grant, Principle Development Engineer
General Lighthouse Authorities of the UK, UK
Expert for the maritime domain.
Interviewed on 26 March 2018

Dr Rita Markovits-Somogyi, Development Support Engineer
Imre Bányász, Head of En-Route NAVAID, TWR Communications Systems
Hungarocontrol, Hungary
Expert for the air traffic management domain.
Interviewed on 4 April 2018

Mr Jose Bertolin, Technical Affair Manager
UNIFE - the European Rail Industry
Representative of the European Railway Association
Interviewed on 13 April 2018

Mr Alberto Fernández Wyttenbach
Market Innovation Officer
Galileo Space Agency
Interviewed on 2 May 2018

Questionnaire

General Information:

Name:

Affiliation:

Domain:

Position/Role:

Experience:

Anonymous (yes/no):

1) What is your business sector in general?
2) What are the benefits for EU citizens that can be derived from your business sector?
3) Which of the business sectors are based on GNSS technology in general?
4) Do you perform any activities regarding the use/incorporation of Galileo for your applications?
5) Which of the following Galileo Services might find its way into your domain? Please comment on
    a. Open Service
    b. Commercial Service
    c. Public Regulated Service
    d. Search and Rescue Service
6) When Galileo will become operational in the near future, what are your expectations regarding its benefits?
7) Please rate the importance of the following Galileo Key Performance Indicators (KPIs) according to your opinion on a scale from 1 (low) to 10 (high):
    a. Availability
    b. Continuity
    c. Accuracy
    d. Integrity
    e. Time to Alert
    f. Authentication
    g. Robustness
    h. Resilience
    i. Interoperability
    j. Fast Time-To-First-Fix (TTFF)
8) Are there any additional specific Key Performance Indictors (KPIs) in your domain?
9) Have you worked with the published Galileo documents in the past? Were you able to use these documents efficiently for integrating Galileo into your application(s)?
    a. Signal-in-Space Interface Control Document (SIS-ICD)
    b. Service Definition Document (SDD)
    c. Ionospheric Correction Algorithm for Galileo Single Frequency Users

10) Regarding your opinion, are there any shortcomings of the Galileo system with respect to your planned application?

    (System release schedule, agreed service levels, architecture design, signals, interface control documentation)

11) What could make Galileo more attractive regarding your requirements?
12) How do you judge Galileo's potential for increasing the EU market share of the services or products that you supply?
13) What immediate social benefit could arise from Galileo services for EU citizens?
14) What long-term social benefit could arise from Galileo services for EU citizens?
15) Would you agree that the Galileo system is an enabler for the development of new GNSS technologies and applications in Europe? If yes, which applications do you have in mind?
16) What is the estimated share of small and medium-sized enterprises (SMEs) in your domain?
17) How would you rate Galileo's potential to support SME's market growth?
18) Can you quantify the growing GNSS market (not only Galileo but all GNSS systems in general) with public figures for your domain, e.g. numbers of GNSS devices sold during recent years, turnover in GNSS market, revenue from GNSS applications, number of GNSS installations etc.?
19) Do you see potential new Galileo related applications in your domain, for which EU funding could leverage their breakthrough? If yes, which ones?
20) Do you suggest any policy changes or corrective actions for the current or the future Galileo system?
21) Do you see any shortcomings in the existing GNSS services/constellations?
22) What would you like to see in future GNSS services?
23) Do you have any further comments, questions or critique on Galileo, or anything else?
24) Would you like us to treat this interview anonymously?

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This study explains the background necessary for an understanding of the working principles of a Global Navigation Satellite System (GNSS), and highlights Galileo's properties in comparison to those of other competing GNSSs. It outlines Galileo's importance for the EU, emphasising the socio-economic and strategic benefits for Europe, by providing a detailed view of a wide variety of applications across different domains for which Galileo will make a difference. It also identifies some gaps and challenges to reaching Galileo's final operational capability, expected in 2021. The study summarises the current Galileo time schedule as well as the associated costs. It also mentions the different requirements from the various application domains, which are based on common Key Performance Indicators. The study concludes with an examination of results, based on which different policy options are proposed in order to maximise the impact of the European GNSS in the near future and in the longer term.

The study is based on interviews with various experts throughout Europe involved in GNSS in general and Galileo in particular, and on an extensive literature review covering high-quality sources.

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