GNSS USER TECHNOLOGY REPORT

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European Global Navigation Satellite Systems Agency

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FOREWORD

Dear Reader,

In recent years, GNSS technology, both on the side of global constellations and user receivers, has been developing considerably. European systems EGNOS and Galileo are increasingly present in GNSS receivers, providing enhanced performance to their users in Europe and worldwide. Despite increased deployment of other positioning technologies, GNSS remains at their core and is today the most widespread and cost effective source of location information. In view of the changing user needs in terms of expected positioning experiences, the appearance of new and modernised GNSS signals, and advances in semiconductor technologies, we felt the need to take a closer look at the impact these changes will have on user technology and the role of GNSS in positioning solutions of the future.

I am pleased to introduce the GSA's first GNSS User Technology Report. As a sister publication to our well recognised GNSS Market Report, this Report zeros in on the state-of-the-art GNSS receiver technology, along with analysing the trends that are sure to change the entire GNSS landscape.

In the following pages, you will get an in-depth analysis of GNSS user technology as it pertains to three key macrosegments: mass market solutions; transport safety and liability-critical solutions and high precision, timing and asset management solutions. In addition, we also provide a general overview of the latest GNSS receiver technology, common to all application areas, along with a supplement on location technologies that looks beyond GNSS in the positioning landscape.

This publication was written with the contribution of leading GNSS receiver and chipset manufacturers, and is meant to serve as a valuable tool to support your planning and decision-making with regard to developing, purchasing and using GNSS user technology. We look forward to receiving your feedback and working with you in continuing this exciting E-GNSS evolution.

Carlo des Dorides
Executive Director

The European GNSS Agency (GSA)
Prague, October 2016

The Technology in GNSS user equipment today is more diversified than ever before; ranging from miniaturised, low power chips found in IoT networks nodes to much larger, more powerful (and expensive) receivers fitted in passenger aircraft. Furthermore, **new models are being introduced at an unprecedented rate**, driven by the growing performance requirements of innovative applications, developments in the semiconductor industry and to take advantage of the enhanced capabilities offered by new and modernised GNSS systems and services.

In this rapidly evolving landscape, **three primary dimensions of change** can be identified for user positioning technology: **ubiquity** (continuous access to the location information everywhere), **automation and ambient intelligence** (e.g. enabling autonomous vehicles that can sense their environment and adapt to it) and the provision of **more robust, secure solutions** (resistant to interference and respecting the privacy of the users).

These drivers impact all aspects of receiver design, from antenna frequency range to signal processing channels. The implementation of disruptive techniques, such as vector and cloud processing, is making it possible to achieve greater performance while preserving battery life. Furthermore, **other positioning technologies and signals of opportunity are used alongside GNSS** to offer enhanced experiences. The sensor technology is advancing in parallel, making the vision of smart dust (a widely deployed network of low power, low cost microsensors) closer to becoming a reality. GNSS antenna designers are expected to complement the solution with more robust, smaller, multi-purpose antennas. Some of these innovations are already becoming accessible, as confirmed by leading GNSS technology providers, featuring their latest solutions in this report.

Changes in receiver design are not obviously affecting all application segments in the same way, or at the same pace. **GSA analysis of more than 400 receivers, chipsets and modules** currently on the market shows that **nearly 65% of them support multiple constellations**, and this percentage should reach nearly 100% of new devices within the next few years. Mass market receivers and high accuracy professional receivers are leading this trend, with **nearly 30% of them already capable of using the 4 available global constellations**. On the other hand, receivers targeting safety-critical applications, such as aviation, must wait for the new technologies to be proven and new standards or regulations to become available prior to implementing them.

In terms of **supported frequencies**, GSA analysis shows that **30% of all receivers implement more than one of them**, mostly in high precision. The adoption is lower than that of multi-constellation due to many factors, such as cost, complexity, power draw and the relative novelty of open signals on multiple frequencies. In the coming years, the ever increasing demand for a better resilience observed across all applications, and the higher accuracy and integrity needed for automation, will undoubtedly foster a much wider **adoption of dual frequency (E1/L1 + E5/L5) solutions**. This is supported by the fact that satellites broadcasting a high quality open signal on L5/E5 are launched at a faster rate and their promising performance in urban canyons is awaking growing interest for double frequency in mass market.

Finally, new capabilities are introduced at a GNSS system and/or receiver level to provide users with an improved performance in terms of robustness and accuracy to better serve applications that require it. Examples include **GNSS signal authentication**, which is expected to play an important role for liability critical applications; and triple frequency real time precise point positioning, such as found in the Galileo commercial service for high accuracy applications.

Industry and research organisations are the main actors of these developments. In mass market, the chipset supply chain is extremely consolidated with few players worldwide driving the innovation. In liability and safety, critical transport solutions, a consolidated industry with important European presence, is dominating innovation in automotive, maritime and aviation, while new players may emerge in new applications, such as autonomous vehicles. In high precision, timing and asset management, the suppliers are specialised in various professional fields (e.g. surveying, machine control, timing), however their products are based on a relatively low number of GNSS chipsets.

To conclude, the GNSS user technology is, now more than ever, **experiencing a rapid and exciting evolution**, answering to the needs of ubiquity, automation and secure positioning. This report explores in details of all these new developments, and how they will bring continuous accuracy, integrity and robustness to the main application domains.

TABLE OF CONTENTS

Welcome to the future

In the era of the Internet of Things (IoT) and Big Data, trends in geo-positioning and information technology (IT) are inseparable. After all, IoT is built on the premise that it will know where the 'things' are. In fact, already today nearly half of all available mobile applications use location information – a significance that will only continue to increase.

In writing this report, our goal was twofold. On the one hand, we have tried to foresee how location will be used in the years to come and, on the other, how it will influence the design of positioning systems. The future we see goes something like this: You will set your morning alarms based on real-time traffic estimates and your coffee will be brewed accordingly, ready and waiting for you as you head out the door. Gone will be the days of forgetting to send mom flowers on Mother's Day, as your phone will send an automatic reminder and provide your autonomous car with directions to the nearest floral shop. Or perhaps you don't have time to go to the shop? No worries, with just a simple command a drone will deliver the flowers for you.

But this 'future' can only become a reality if the positioning systems of the future provide:

- **Ubiquitous positioning:** the ability to choose the optimal combination of sensors and networks to become environment-independent. Here technology works in the background to provide seamless indoor and outdoor positioning and navigation at any time.
- **Automation and ambient intelligence:** sufficient reliability to enable such autonomous operations as driving, sailing, parking, landing, etc., by sensing the environment and adapting to it in real time.
- **Security:** not only in the sense of a solution's reliability and safety, but also by responding to growing concerns about privacy. If the positioning system knows where you and your assets are at all times, it better keep this information to itself.

No 'one-size-fits-all'

No single positioning method or technology, or magic combination thereof, can serve as 'the answer'. After all, the technology that's right for pedestrian navigation probably isn't the best fit for use with an unmanned vehicle. This is because all positioning requirements exist within a given context, including the physical and radio-electrical environment, user dynamics, and power, size and weight constraints. It is this context that determines what positioning technologies are required.

As a result, the most advanced positioning systems can evaluate the context of their intended use and deliver an optimised positioning solution.

Source: Thinkstock

Main areas of innovation

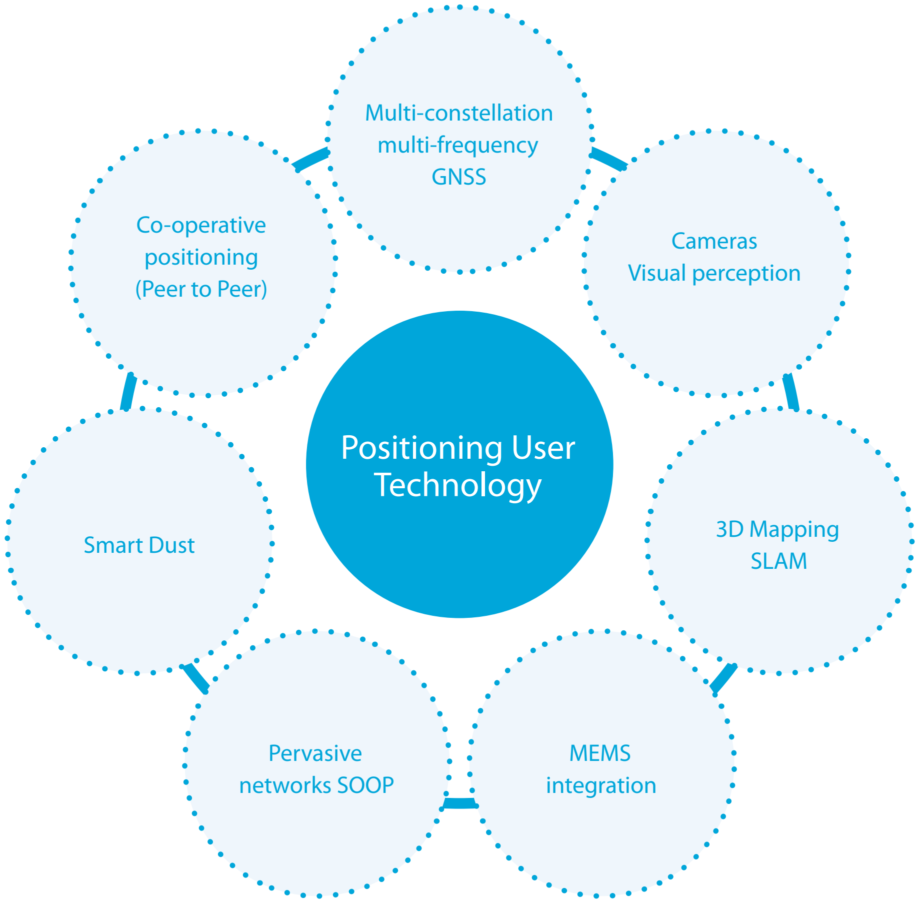
GNSS is by far the most cost-effective outdoor positioning technology currently available – and will remain so for the foreseeable future. Already today GNSS is the **main source for outdoor location information**, which is especially important for large scale applications and when working away from urban areas.

GNSS will not, however, be used as standalone solution. In order to work across an array of contexts, ubiquitous positioning requires the **use of several positioning networks and sensors**. For this reason, today's GNSS chipsets use other radio networks and Micro-Electro-Mechanical Systems (MEMS) to provide enhanced positioning, and dedicated networks like LoRaWAN, ZigBee and Sigfox to provide additional connectivity to IoT tags. The next generation of chipsets will allow users to simultaneously connect to several wireless access technologies (WiFi, Universal Mobile Telecommunications System (UMTS), Enhanced Data Rates for GSM Evolution (EDGE), smart-radio, among others) and to seamlessly move between them.

By 2020, all new GNSS receivers will be **multi-constellation capable**, providing sound benefits for product innovation and achieving enhanced performance in many GNSS applications. Based on a GSA analysis of more than 400 receivers, chipsets and modules currently on the market, already around 65% of receivers implement multi-constellation support, and more than 20% integrate four constellations into a single product. The most popular combination is GPS and Glonass, followed by GPS and Galileo. Although power consumption and processing capability may somewhat limit the number of satellites used, thus imposing a choice at the receiver level, advances in other technical fields will compensate for these issues.

Multi-frequency is already widely used by professional applications, with the mass market expected to follow. Overall, out of the 400 receivers analysed, 20% use double frequency, and 10% integrate three frequencies. This trend is fuelled by the need for greater accuracy in active driver assistance and for the additional protection against interference that frequency diversity provides. As to the latter point, the vulnerability of location services to interference or spoofing is a growing concern. However, the developments towards GNSS **signal authentication** may increase robustness against spoofing, and could even support applications using geo-fencing, such as mobile payments.

Innovation areas and emerging concepts likely to influence future positioning, navigation and timing (PNT) systems



How to read this report: many applications, three macrosegments

For your reading convenience, this report has been divided into three parts.

In the first part, we take a general look at the recent developments and future trends of GNSS user technology. Our focus is on receiver design, innovative signal processing techniques, changes impacting antennas, and GNSS vulnerabilities – and what is being done to mitigate them. We also take a close look at how changes in user needs, GNSS systems, and underlying technologies are all having an impact on receiver design.

In the second part, we present specific developments and solutions that are typical for a given application area. Like our Market Report, this report considers all GNSS applications in these segments: Location Based Services, Agriculture, Transportation (Aviation, Maritime, Rail, Road), Surveying and Timing*. We have further grouped these applications into three macrosegments:

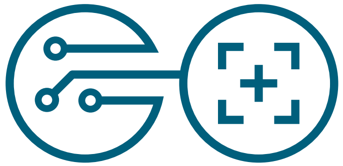
1. **Mass market consumer solutions:** high volume chipsets typically used in smartphones, tablets and other consumer devices, along with emerging solutions for IoT, in-vehicle navigation, consumer unmanned aerial vehicles (UAVs), general aviation Visual Flight Rules (VFRs) and solutions for leisure maritime. These solutions are characterised by requiring a fast time to first fix and high availability, but not being very demanding in terms of accuracy.
2. **Transport liability-critical and safety-critical solutions:** location solutions for Road User Charging, Emergency Caller Location (such as eCall), Advanced Driver Assistance, Smart Tachograph, Civil Aviation, Prosumer UAVs, Control Command and Signalling solutions in Rail, Ship Navigation in Maritime (including Vessel Traffic Management), and Anti-Collision systems. These applications are characterised by requiring more robust positioning and navigation information, secured by integrity and authentication. Solutions usually must comply with safety requirements and standards.
3. **High precision, Timing and Asset Management solutions:** Business to Business (B2B) technology solutions for tractor guidance; Variable Rate Technology in agriculture; geodesy and other surveying applications; all asset management solutions (e.g. container tracking, fleet management); and the timing and synchronisation solutions used by telecom operators, financial services and energy providers. High precision solutions are characterised by their demand for accuracy of both position and time.

In the final part, we provide a comprehensive overview of all positioning technologies, looking at what lies beyond GNSS in the positioning landscape. A closer look is taken at such augmentation systems as SBAS, PPP solutions, other radio location technologies (LPWAN, Wi-Fi, UWB) and non-radio positioning techniques such as vision-aided navigation.

** Defence and public utilities solutions are out of scope in this report. Search and Rescue solutions are only partially covered, providing basic information on SAR system architecture and the contribution of GNSS to SAR missions.*

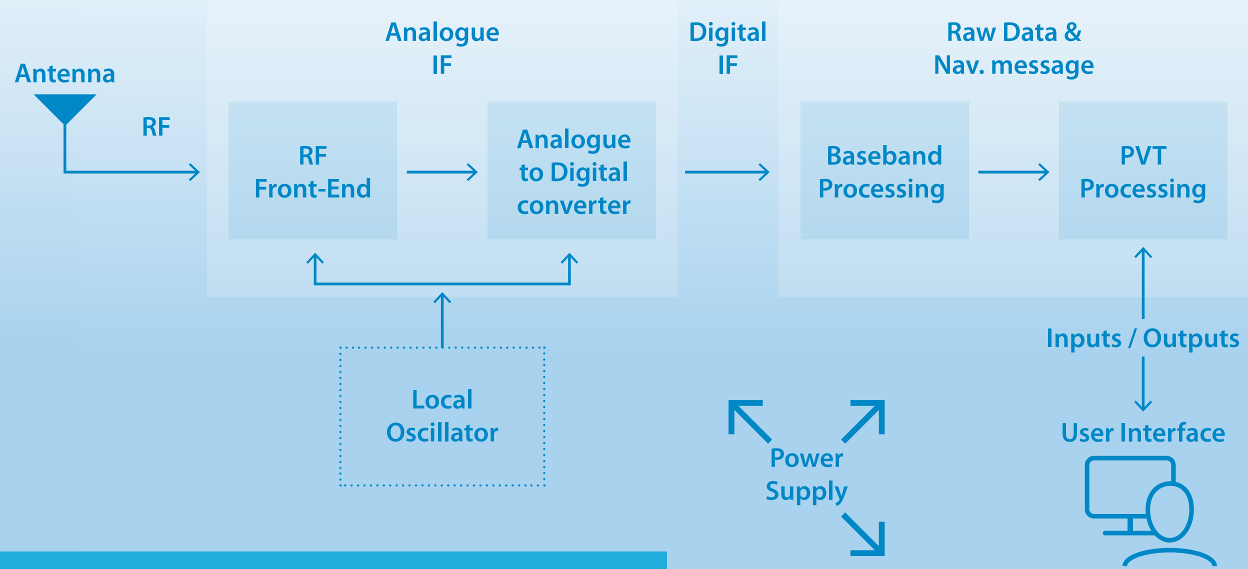
Mass Market
Consumer Solutions

Transport Liability-Critical
and Safety-Critical Solutions



High Precision, Timing and Asset
Management Solutions

GNSS user technology overview



The evolution of GNSS user technology is driven by user needs, GNSS infrastructure and underlying technologies

What differences can be found between GNSS receivers?

GNSS is used for many types of applications, each requiring different service levels. The type of technology used depends on such user needs as the desired quality of service. This results in a large variety of user terminals. Some key features of a receiver are:

- Supported GNSS constellation(s), frequencies and signals and augmentation system(s).
- Complementary technologies in use.
- Such factors as size, weight, power consumption, etc.

Factors affecting the evolution of GNSS user technology

The evolution of GNSS user technology is influenced by three major factors:

- **Changing trends in users' behaviour and expectations.**
- **Evolution of GNSS infrastructure, such as the appearance of new signals and frequencies.**
- **Evolution of underlying technologies, largely driven by the IT & Communications industries.**

The market drivers and trends derived from changing user needs are analysed in depth in sister publication **"GNSS Market Report"** (see next page). The other two factors impacting receiver design are discussed in following sections of this report.

TI-4100 NAVSTAR GPS Receiver, 1981
One of the first commercial GPS receivers.

Magellan NAV 1000 GPS, 1988
World's first handheld GPS receiver.

Benefon Esc!, 2001
World's first personal navigation phone with mobile maps.

BQ's Aquaris X5 Plus smartphone, 2016
First European smartphone with Galileo capability.

Fitbit Blaze, 2016
One of the most popular wearable devices, which includes GNSS, a heart rate monitor and a battery life of up to one week.

For many years, the most important evolution in GNSS receivers has been the reduction of their size, weight, power use and cost, to such an extent that GNSS is now considered a utility.

Although today's evolutions may not be as spectacular, they are nonetheless equally important. At the same size and cost, today's receivers deliver ever increasing capabilities for a better user experience. Thanks to the use of multiple constellations and new services, this includes not only improved availability and accuracy, but also improved confidence.

Changes in user needs define the innovation roadmap

The GSA continuously monitors and analyses changing user needs and market trends, thanks to the GSA's well-established internal market monitoring and forecasting process. The results of this process are published in the **GSA's GNSS Market Report**.

With in-depth information on specific market segments, the Market Report serves as a comprehensive source of knowledge and information on the GNSS global market and trends at the user level.

Whereas the GNSS User Technology Report focuses on the technology trends and drivers at the receiver level, the GNSS Market Report provides a deep insight into current markets and forecasts the future shipments, installed bases and revenues. Together, they form a comprehensive source of information on GNSS downstream sector.

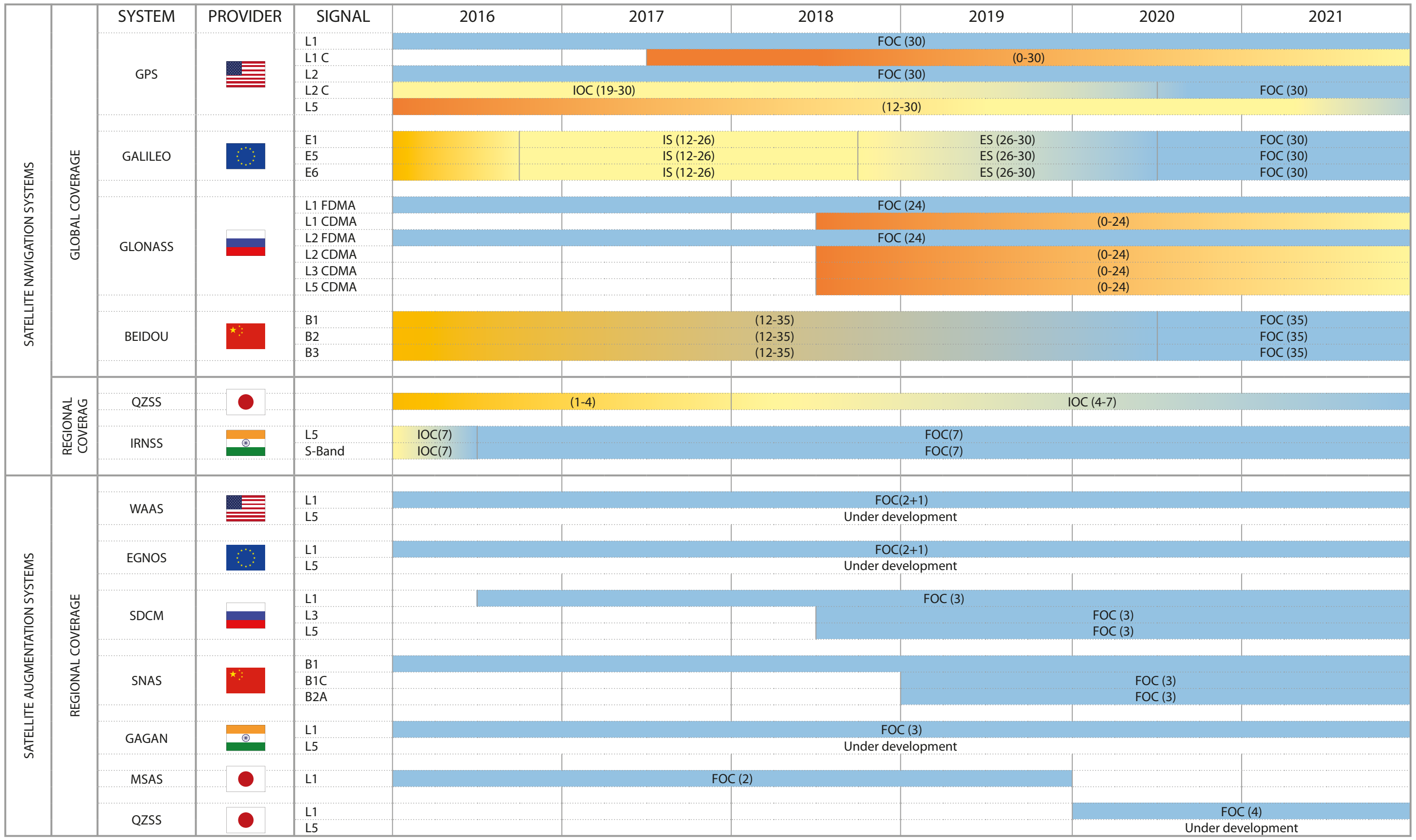
The current version of the GSA's GNSS Market Report **can be downloaded free of charge at: https://www.gsa.europa.eu/market/market-report**

The 5th edition of the GSA's GNSS Market Report is set for publication in 2017.

All GNSS infrastructure providers are developing new and improved services

All GNSS infrastructure providers are currently working on further developing their systems, either in terms of modernisation or initial deployment. For example, GPS and the Russian GLONASS navigation system, both operational, are currently being modernised, while Galileo is in the deployment phase and set to be fully operational by 2020. Meanwhile, China is in the process of expanding its regional BeiDou Navigation Satellite System into a global one, also by 2020. The Indian Regional Navigation Satellite System (IRNSS) and Japanese Quasi-Zenith Satellite System (QZSS), which provide regional coverage, are scheduled to become operational in the coming years.

As for the satellite based augmentation systems (SBAS), the American Wide Area Augmentation System (WAAS), the European Geostationary Navigation Overlay System (EGNOS) and the Indian GPS Aided Geo Augmentation Navigation (GAGAN) are all planning upgrades to improve performance, while the Russian System for Differential Corrections and Monitoring (SDCM) and the Chinese Satellite Navigation Augmentation (SNAS) systems are currently under development.



Disclaimer: Planning based upon publicly available information as of July 2016.

Development plans

The figures below show the current development plans for each satellite navigation system over the next five years. The signal sets, status and number of satellites are reported as follows:

Signal status | **Number of satellites (X)**

- No service
- Initial services (IOC: Initial Operational Capabilities, IS: Initial Services, ES: Enhanced Services)
- Full services (FOC: Full Operational Capabilities)

GNSS evolution offers enhanced performances, but also raises new questions

With the modernisation plans of GPS and GLONASS on one hand, and the deployment of Galileo and the Chinese BeiDou on the other, users will soon have access to a wealth of open signals broadcasted on multiple frequencies. This raises several questions, with no easy answers:

Which GNSS/ RNSS?

All systems, both GNSS and Regional Navigation Satellite Systems (RNSS) are designed to be interoperable and use the same frequency bands. Their signals, however, are different. As a result, some have a better immunity to multipath or measurement accuracy, while others provide faster acquisition or require less processing power. In other words, there is no "best" signal or combination of signals – only signals better suited for a particular use case or context.

How many satellites?

Soon there will be approximately 120 satellites broadcasting signals on L1/E1 – with even more on L5/E5 – meaning a GNSS receiver could potentially receive signals from as many as 50 satellites. Having this many visible satellites allows for further improvements, including the possibility to reject low quality measurements (non-line of sight, multipath contamination, low elevation, etc.) without compromising Geometric Dilution Of Precision (GDOP). The net overall effect is better position accuracy, and the key to achieving this is the capability to properly assess the quality of observations. To cope with this reality, GNSS receivers will have to implement selection (or rejection) strategies.

Which frequencies to use?

For many low to medium accuracy applications, one frequency is sufficient. This single-frequency is currently L1/E1, but as can be seen in the table, L5/E5 could be a viable alternative in the future.

High accuracy applications, however, often require the use of dual-frequency observations in order to compensate the ionospheric propagation delays and/or to resolve "carrier phase ambiguities" encountered in such specific processing strategies as Real Time Kinematic (RTK) or Precise Point Positioning (PPP). Currently, L1 + L2 observations are used, but L5 may soon become the "second frequency of choice" as it will be present on more satellites and is less prone to interferences. High accuracy applications can also benefit from a third frequency to facilitate the ambiguity resolution through techniques known as Three Carrier Ambiguity Resolution (TCAR) or Extra-wide laning.

For safety-critical applications, where redundancy and resistance to jamming is important, dual-frequency (L1/E1 + L5/E5) is undoubtedly the best choice.

Future GNSS/RNSS common frequencies, showing the potential of E5a/L5 and of E1/L1 combination

	L5 / L5OC / E5a / B2a	L2 / L2C / L2OC	E6 / LEX	L1 / L1OC / E1 / B1
GPS	30	30		30
GLONASS	24	24		24
Galileo	30		30	30
BeiDou	35		35	35
QZSS	3	3	3	3
IRNSS	7			
	129	← ARNS* Bands	→	122

Frequency band used by the system, with N = number of satellites

Frequency band not used by the system

** ARNS = Aeronautical Radio Navigation Service: Frequency bands allocated worldwide to GNSS on a primary basis, granting a better protection against interference*

Which services?

Some services offer unique features not available on all GNSS. For instance, Galileo offers:

- A Commercial Service that provides subscribed users with such enhanced performance as a very high accuracy or a signal authentication at the spreading code level.
- Navigation Message Authentication (NMA) on the Open Service (OS), an innovation that allows OS users to benefit from better protection against spoofing.

Developments in semiconductor technologies will directly impact GNSS receiver performance

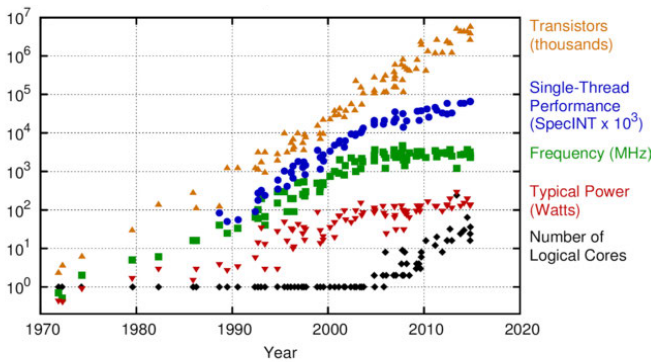
Advances in semiconductor technology

According to **Moore's Law**, "the number of transistors on a chip roughly doubles every two years." Over time, performance and power consumption have followed the same trend, thanks to a reduction in the transistors' feature size.

This is known as **"Dennard scaling"**, and it gives Moore's law its full strength since physically smaller areas require less power, can operate at higher frequencies as there is a lower delay; and more transistors can be squeezed into the same area.

This rapid evolution in chip size, density and efficiency has led to a huge increase in the capability of Application-Specific Integrated Circuit (ASIC) devices, enabling unprecedented increases in the complexity of such electronic products as smartphones and GNSS receivers.

40 Years of Microprocessor Trend Data



Source: https://www.karlrupp.net/2015/06/40-years-of-microprocessor-trend-data

Current and predicted slow down

Since around 2005, predictions of **Dennard scaling** could no longer be achieved at the previous rate, and the increase in transistors has been maintained only through a switch to multi-core processors.

The figure above perfectly illustrates this issue. One can see that growth in transistors count is constant, but only because the number of cores is increasing, whilst clock frequency and power consumption have plateaued.

Increased processing power

The reduction in transistor size directly leads to an increase in the number of transistors on a chip and in the clock rate of processors. Together, these two factors enable a substantial increase in processing power. However, as a result of the slowdown described above, two challenges confront any continued increase in performance:

- Development of software that can effectively deploy multi-core.
- Development of alternative technologies to the transistor in the longer term.

Better power efficiency

A reduction in transistor size also causes a significant decrease in power required for comparable processing power, as the power required by a processor stays in proportion to area, both in terms of voltage and current.

Over the last decade all types of electronics have enjoyed drastic reductions in power consumption, and the progress of GNSS modules power consumption reflects this trend. Whereas in the past a basic GPS chip may have consumed 200mW, a modern equivalent will consume 20mW and be capable of processing more channels over more constellations.

From ever more processing power to lowest possible power usage

Possibly because of the end of Dennard scaling, the semiconductor industry has shifted its focus from "raw processing power" to concepts like MtM scaling, improving power efficiency and device utilisation. While the gains will be smaller than historically observed, they may also occur in more interesting areas. For GNSS receivers, this potentially means more progress on the RF side, more accessible Software Defined Radio (SDR) or a combination of both.

The short term: More than Moore (MtM) scaling

The goal of MtM scaling is to extend the same design principles that have driven digital device scaling for decades over to analogue circuitry and to integrate these technologies on-die within a System on Chip (SoC) or System in Package (SiP). The proposal behind MtM states that *it is the heterogeneous integration of digital and non-digital functionalities into compact systems that will be the key driver for a wide variety of application fields, such as communication, automotive, environmental control, healthcare, security and entertainment.* (European Nanoelectronics Initiative Advisory Council, ENIAC).

At the same time, MtM aims to convert analogue circuits to digital ones, bringing the benefits of Moore's Law to Radio Frequency (RF) circuits and, ultimately, making digital RF practical for SoC integration.

Developments towards software-defined GNSS receivers promise more flexibility

Advances in software and algorithms

A new trend, driven by advances in general processing power, is using software to approach problems that traditionally required dedicated hardware.

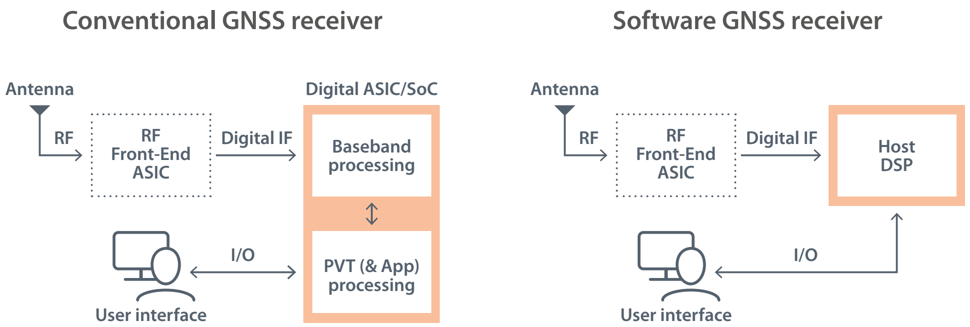
Advances in algorithms enabling new positioning techniques

Today algorithm designers have access to more sensors and data than ever before, enabling novel positioning techniques by fusing said inputs. Although these techniques can overcome the challenges of unfavourable contexts encountered e.g. in location based service (LBS), they pose a problem when it comes to quantifying performance. As such, they must first mature significantly before they can be used for any safety or liability-critical applications.

Software defined GNSS receivers & simulators

GNSS software receivers use the antenna and frontend hardware of a conventional receiver; and their host platform's digital computing capabilities to perform all other tasks (signal processing; navigation solution processing) usually performed by a dedicated GNSS Application Specific Integrated Circuit (ASIC). They can be seen as the GNSS receiver equivalent of a software-defined radio.

Software defined GNSS receivers offer significant increases in flexibility over hardware receivers, yet this comes at the cost of decreased efficiency (power usage and computational load on the host system). Thus, their use tends to be currently limited to development tools.



Along these same lines are GNSS simulators, which utilise Software Defined Radio for rapid prototyping of new positioning algorithms.

A key question in the near to medium term evolution of GNSS receiver technology is whether advances in digital signal processing will allow software receivers to go mainstream, meaning we will see GNSS functions switch from ASIC to a software implementation. Considering the evolution in semiconductor technology in the recent years, particularly those pertaining to digital processing, such a move seems rather likely – albeit probably not in the next five years.

Advances in sensors technology

The "More than Moore" revolution has happened, and semiconductor manufacturing processes are no longer exclusive to the integrated circuit (IC) industry. In fact, innovation in sensor technology is being driven by automotive positioning systems, smartphones and tablets. This is resulting in a proliferation of combined sensor packages (combos), sensor hubs (dedicated processors) and "intelligent sensors" (integrating sensor fusion software) and is benefiting such products as MEMS, sensors, LEDs, power devices, 3D assembly and heterogeneous integration solutions.

The largest share of the industry, at least for consumer products, is owned by inertial sensors (accelerometers and gyroscopes). These are most often integrated in 6 or, with the addition of magnetometers, 9 axis combos and named "motion sensors". As a result of a drastic decrease in their size, cost and power consumption, they have seen an increased uptake in smartphones, wearables and various IoT markets.

Besides inertial sensors, the automotive Advanced Driver Assistance Systems (ADAS) and developments in the driverless car foster the availability of cheaper and/or higher performance cameras, Infra Red, Complementary Metal Oxide Semiconductor (CMOS) image and ultra sound sensors. Still images and video cameras are not only found in our smartphones, many cars equipped with parking assistance or similar ADAS function also use these cameras as sensors – and they may well become one of the most widely used sensors for location purposes.

With respect to reference oscillators, Chip Scale Atomic Clocks (CSAC) are commercially available today, and research continues to improve their performance/cost ratio.

Along with the drastic reduction in the size and power of GNSS receivers, the energy density of batteries has increased, typically doubling every decade, with a parallel cost reduction. This combination means consumers can keep their hand-held devices on for days. Furthermore, these devices are also getting progressively smaller, which enables new applications – many of which are as yet unknown.

All components of GNSS receiver design are evolving

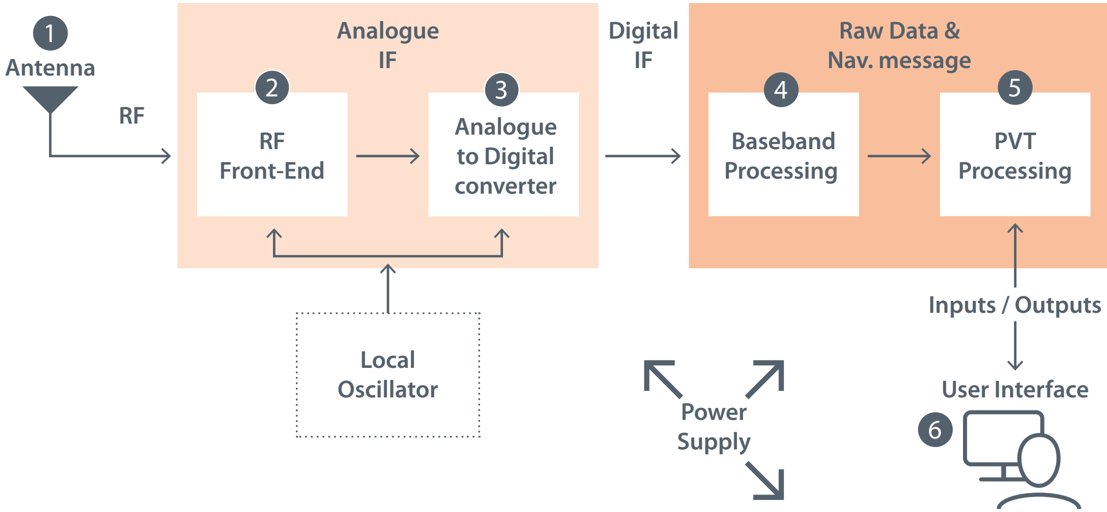
The evolution of receiver design has been driven forward by technological developments, including increased power to enable the processing of more GNSS channels and the development of low-cost MEMS sensors that allow tighter coupling with different sensors and bringing positioning to GNSS-deprived locations. Simultaneously, market pressures have exerted a pull towards increased accuracy, improved performance in difficult environments and reduced time to first fix (TTFF).

This diagram presents in a simplified manner the building blocks of a typical GNSS receiver, together with their main characteristics (the most important or rapidly evolving ones being highlighted in red).

1. Antenna (+ preamplifier)

Receives, amplifies and band-pass filters GNSS signals.
Dimensions:

- Selectivity
- Noise factor
- Gain
- Diagram
- Phase Centre
- Bandwidth
- Multipath rejection
- Single or multiple antenna inputs
- Jamming mitigation



6. Input/ Output interfaces

Converts data produced in internal formats into such recognised formats as NMEA. After reformatting, the data is output over a suitable data interface such as RS-232 Serial data, Ethernet, Bluetooth or a combination of several. The selection of the interface is often application domain specific.

2. RF down convertor

Down-converts and filters RF signals to an intermediate frequency (IF) compatible with analogue-to-digital converter (ADC) acceptable input.
Dimensions:

- Input frequency/ies
- Phase noise
- Linearity
- Automatic Gain Control (AGC)
- Isolation

3. Analogue to Digital converter

Converts the analogue IF signal into a digital replica.
Dimensions:

- Linearity
- Number of bits / Dynamic range
- Jitter
- Bandwidth
- Interface to baseband

4. Baseband processing

Acquires and tracks incoming signals, demodulates navigation data.
Dimensions:

- Number of channels
- Measurement rate
- Measurement noise (C/N0)
- Multipath immunity
- Signals/modulations processed
- Dynamics
- Interference cancellation
- Jamming mitigation

5. PVT (& Application) processing

Computes the estimated position and receiver time offset relative to the constellation's reference time.
Dimensions:

- Solution type (GNSS, Differential GNSS, Real Time Kinematic (RTK), Precise Point Positioning (PPP), …)
- Single or Multi constellation
- Update rate
- Latency

Innovative signal processing means integration of new signals and reduction of power usage

Signals and Bandwidth considerations

The specific signals that a given receiver supports will usually depend upon its targeted market. For example, a composite signal like Galileo E1 uses both Binary Offset Carrier (BOC) 1,1 and BOC 6,1 modulations, allowing receiver designers to choose whether to process the whole signal or just the inner BOC1,1 part. Their decision is driven by device complexity, power consumption and performance trade-offs, as the power consumption of a given receiver is generally proportional to the processing bandwidth and, hence, signal bandwidth. On the other hand, the use of higher processing bandwidths delivers more accurate observations and greater immunity to multipath. Thus, precision receivers, particularly those without power consumption constraints, tend to process the full signal bandwidth, whilst mass market receivers, such as smartphone GNSS receivers, tend to only process the necessary minimum bandwidth.

Vector tracking

Almost all GNSS receivers employ what we now call **scalar tracking**, a naming adopted to differentiate them from the more advanced design concept of **vector tracking**. In scalar tracking, carrier and code tracking takes place independently for each signal.

Vector tracking tracks all satellite signals in one navigation filter, and is seen as a promising approach to minimise the effect of multipath interference and aid Non Line of Sight (NLOS) detection, both major error sources when using GNSS in urban environments.

Vector tracking combines the signal acquisition and tracking function with the position solution function, all within one algorithm. Whilst significantly increasing the processing power needed through increased algorithmic complexity and a ten or more fold increase in the rate at which the position is computed, vector tracking is expected to further improve sensitivity, provide an ability to bridge short signal outages and provide a greater immunity to interference.

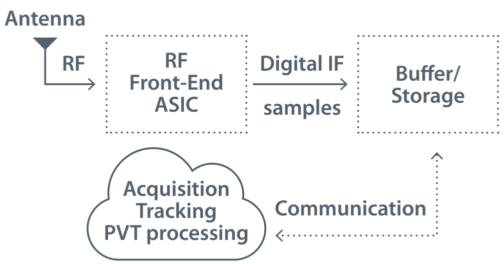
Despite its promised benefits, vector tracking has yet to be embodied into commercial products. It can however be expected that future generations of GNSS receivers will adopt this strategy once microprocessor capabilities have increased sufficiently to make it viable, which may take place in the next five years or so.

Cloud GNSS processing and snapshot receivers

Cloud GNSS processing is the ultimate evolution of the software GNSS receiver concept. Instead of using the host device's processing capabilities, cloud GNSS receivers use cloud based processing services, thus offloading (most) processing and energy consuming tasks to the cloud – where such resources are virtually unlimited.

Snapshot or single shot positioning is designed to work with only a few milliseconds of raw GNSS signal. A snapshot is a short recording of the raw data after signal conditioning (pre-amplification,

Cloud-based GNSS receiver architecture



This architecture enables the development of very advanced receivers – requiring a high computational load – that would otherwise be impractical, or very low power and low-cost entry level receivers, particularly when associated with GNSS snapshot techniques.

down-conversion, filtering and analogue to digital conversion) in the front-end. Snapshots are then passed to the host platform processor, (like a software receiver), stored for later processing (like a GNSS sensor/tracker) or sent to the cloud.

This technique is specifically designed for scenarios when continuous Signal in Space (SiS) tracking is not possible (e.g. indoors), not required or not desirable. Because snapshot positioning works with pure signal acquisition and no signal tracking, it does not permit navigation message extraction. For this reason, it is impossible to synchronise measurements to any time stamp of the navigation message, as in conventional GNSS positioning. However, via **coarse time positioning**, specific algorithms can derive a position solution from the snapshots and assistance data.

Snapshot positioning has many attractive features:

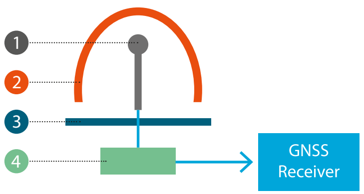
- The GNSS receiver's tasks are reduced to measuring the spreading code phases. Because they do not need to track satellites or decode navigation messages (all computationally intense and energy demanding tasks), power consumption is drastically reduced.
- Instead of tracking satellites for tens of seconds to decode the navigation message, only milliseconds of information are required. Therefore, the GNSS receiver can be aggressively duty cycled, further reducing energy needs.
- Galileo makes it possible to leverage pilot signals on E1. Pilot codes have improved cross-correlation protection for near-far situations (processing weak signals in presence of a strong one), allow for very long coherent integration times and therefore arbitrarily high sensitivity (only limited to the local oscillator stability), and ambiguity-free ranging (lifting the constraint of precise timing assistance).

By combining snapshot GNSS positioning and cloud based processing some researchers and vendors claim energy savings of several orders of magnitude – a very interesting combination for such uses as "drop and forget" and the Smart Dust concept.

Antenna designers must make trade-offs between antenna efficiency, bandwidth and level of miniaturisation

Antennas, which are responsible for capturing L-band signals transmitted from space, serve as the link between the GNSS Space Segment (satellite constellations) and User Segment (GNSS receivers). They are characterised by frequency range, gain, pattern, phase centre variations, capability to reject multipath and interference, and by size, shape and environmental constraints.

Scheme of GNSS Antenna



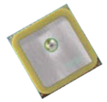
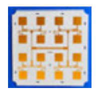
1. **The radiating element:** responsible for antenna bandwidth and radiating characteristics.
2. **The radome:** dielectric physical element that protects the radiating element.
3. **The ground plane:** conditions the radiation pattern shape, foremost at low elevation angles.
4. **The amplifier:** LNA (Low Noise Amplifier) that sets the receiver noise figure.

Typical applications for commercial GNSS antenna design

GNSS Antenna Type	Type	Form factor	Applications
Fixed Reference	External	Choke ring	Reference station Geological monitoring Other fixed location applications
High Performance	External	Spiral Array	Reference station (temporary and permanent) Surveying Ground mapping Agriculture Construction and mining
Certified Compact	External	Patch	Aircraft certified for navigation but suitable for any mobile application. Highly portable and suitable for a variety of environments and applications.
Compact	External	Patch	Road Railway Maritime
OEM	Embedded	Patch Monopole Dipole Helix	Road Railway Survey LBS, PND & IoT

As sensitivity and selectivity are key parameters for satellite navigation, antennas are usually active, meaning Low Noise Amplifiers (LNAs) and filters can typically be found very close to the radiating element feed.

GNSS antenna design examples and description

Design	Example	Description
Patch		Square microstrip patch antennas over high permittivity dielectric substrate to reduce the antenna size. Photo source: ec-portal.com
Helix		Quadrifilar helical antennas have monopole-like appearance without the need for a supporting ground plane, making them most useful for mobile and handheld devices. Photo source: orbanmicrowave.com
Array		Set of antenna elements arranged in an array pattern, usually designed to provide direction of arrival determination for cancelling or suppressing multipath or interferences. Photo: csr.com
Spiral		Planar spiral antennas are inherently circularly polarized and wideband with a hemispherical pattern. Photo source : toptech-mw.com
Dipole		Two orthogonal dipoles over a ground plane excited in quadrature produce a hemispherical CP pattern. Similar to the one obtained by a micro strip patch antenna, but with larger dimensions. Photo source: Taoglas.com
Choke ring		Central element with several concentric conductive rings, enclosed in a protective dome. The objective is to reduce the edge diffraction of a limited size ground plane to produce a better hemispherical pattern. Photo source: panbo.com
Monopole		Dielectric resonator antennas (DRA) consist of a block of ceramic material of various shapes, the dielectric resonator mounted on a metal surface, and a ground plane. Photo source: lte.com.tr

More robust, smaller and multi-purpose GNSS antennas are on demand

Advances in antenna design will pave the way for miniature, multipurpose antennas. Capable of operating with various types of receivers, these antennas should be used in heterogeneous applications and market segments, thus maximising the advantages of the economies of scale.

Miniaturisation

Antennas are most efficient when their dimensions are the same as the wavelength at the relevant frequency band (19 cm at E1). Although some applications (e.g. Aviation) allow, or even impose, technical specifications that focus on their radio electrical performance, the majority of GNSS antennas are designed to best meet the needs of GNSS integrators. As a result, they are well-suited to address automotive and LBS applications, for example, where size and cost are the main drivers – albeit at the expense of performance.

Miniaturisation techniques can be used to reduce antenna dimensions, such as the folding of the antenna wire or the use of antenna dielectrics with high permittivity. However, the drawback is the reduction of bandwidth wherein the antenna operates most efficiently.

Multiple-frequency antennas

The availability of new wider band GNSS signals, the possible migration of multiple frequency techniques towards mass market applications and the increasing need to offer better multipath and interference immunity are raising new demands on antenna characteristics, such as increased bandwidth. Such requirements may be in contradiction with the miniaturisation trend.

The challenge for antenna manufacturers is to achieve an optimal trade-off between antenna efficiency, bandwidth and miniaturisation.

More multipath & interference resilient antenna designs

Resilience against multipath and interferences is a demand for the whole GNSS reception channel, including the antennas. This aspect of antenna design is identified by the manufacturers as a most promising research area for professional applications, as well as for mass market ones.

The multi-frequency and multi-constellation concepts contribute to increasing this resilience thanks to the higher redundancy and diversity of the signals offered by the new constellations and bands. Within this context, adaptive antennas are positioned as a very powerful tool against jamming and non-intentional interferences. That being said, the commercial adaptive antenna landscape remains limited to military grade null-steering antennas. Innovative, concurrent designs compatible with civilian market needs will undoubtedly come to market in the coming years.

The use of independent antenna elements improves gain and allows Direction of Arrival (DoA) measurements. As a result, multiple input multiple output (MIMO) antenna designs already exist as mature technology for use in telecommunications and 4G LTE modems.

Summary of current status and trends of GNSS antennas

Multi-frequency	Mass market applications require single-frequency receivers in their large majority, explaining why single band antennas still account for nearly 60% of all antenna models. The percentage of antennas with multi-frequency capabilities has not significantly increased over recent years, although multi-frequency antennas are attracting a growing interest in professional applications.
Multipurpose	Recently, the GNSS downstream industry has shifted from designing antennas on a case-by-case basis to a scenario where antenna manufacturers supply modules that can be easily integrated into OEM manufacturers' proprietary products. On top of specifically designed antennas for niche applications, manufacturers now provide numerous embedded and compact antenna designs offering different form factors, choices of housing, mounting, connectors and supply voltage.
Miniaturisation	All classes of antennas have seen a move towards miniaturisation. For applications where miniaturisation is the main driver, such as LBS, miniature monopole-like solutions are much more widespread than patches and spirals. These applications require a very small and nearly omnidirectional antenna, and sufficient performance is achieved even with linearly polarised antennas. Approaches are based in incorporating Electromagnetic bandgap structured (EBG) or metamaterial inspired structures.
Robustness	There is a growing interest in using adaptive antennas as a countermeasure to jamming and non-intentional interferences. Adaptive antennas exploit spatial diversity and can discriminate received signals when they come from different directions than expected. Adaptive techniques cannot be supported solely by the antennas, which are limited to the radiating element and the LNA (Low Noise Amplifier), but require the use of additional electronic components that process the RF signal.
Basic performances	Antenna gain and noise figures have remained constant over recent years, and show no sign of needing improvement. Receiver sensitivity, however, has improved significantly, relaxing the pressure to have better antennas in many "low performance" applications, thus widening the use of miniature monopole-like antennas.
Integration with other antennas	GNSS devices are being increasingly integrated into devices supporting other wireless communication technologies, including short range data transmission (Bluetooth, WiFi, RFID) and cellular or satellite communication networks.

Multi-constellation feature becoming standard across all applications

The past decade has seen the emergence of GNSS receivers supporting multiple constellations – a trend that exists even in markets where cost is the dominant factor. However, due to developments in the underlying technologies, the lifecycle of a given generation of receivers is typically only a few years. As a result, manufacturers only seriously address each new constellation or signal when it nears its full operational capabilities (FOC) status.

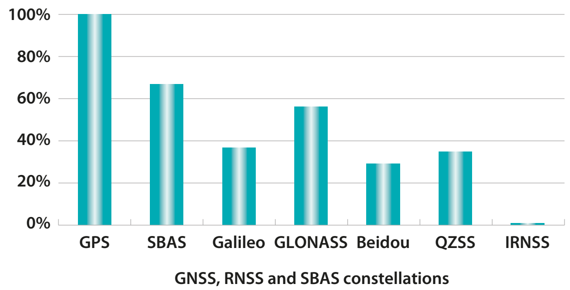
Nearly 65% of GNSS receivers available today are multi-constellation, with more than 20% supporting four constellations. The most common combination remains GPS+GLONASS, followed by GPS+Galileo.

More than 60% of receivers also include SBAS, either for higher accuracy or integrity. Regional systems, such as QZSS and IRNSS, are also becoming more common.

The benefits of supporting multiple constellations:

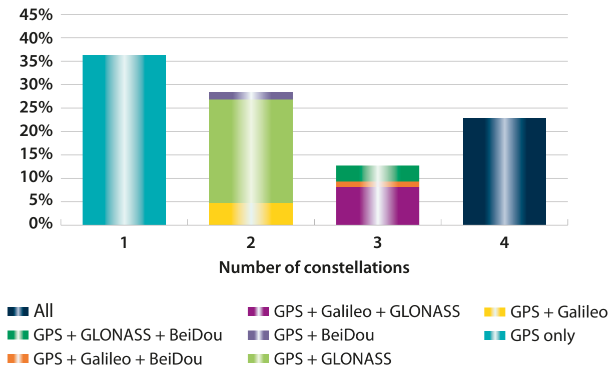
- **Increased availability:*** particularly in areas with shadowing.
- **Increased accuracy* and integrity:*** more satellites in view improves accuracy through a better GDOP and integrity through more efficient Receiver Autonomous Integrity Monitoring (RAIM) procedures.
- **Improved robustness*:** as independent systems are harder to spoof.

Constellation capability of GNSS receivers[1]



[1] shows percentage of receivers capable of tracking each constellation

Supported constellations by GNSS receivers[2]



[2] shows percentage of receivers capable of tracking 1, 2, 3 or all the 4 GNSS constellations

Analysis of GNSS receivers capabilities

The GSA independent analysis assesses the capabilities of nearly 400 receivers, chipsets and modules currently available on the market**. For the analysis, each device is weighted equally, regardless of whether it is a chipset or a receiver and no matter what its sales volume is. The results should therefore be interpreted not as the split of constellations utilised by end users, but rather the split of constellations available in manufacturers' offerings.

Disclaimer: The above graphs reflect manufacturers' publicly available claims regarding their products' domain(s) of use and NOT their actual suitability for specific applications as can be demonstrated e.g. by a certification (when standards and regulations are existing) or actual usage.

* The Key Performance Parameters are defined in Annex I
** For details see Annex IV

Multi-frequency common today only in high precision

From their inception, new GNSS like Galileo and BeiDou support open multi-frequency signals, which helps drive the introduction of dual and triple-frequency commercial receivers. Today, the adoption of multi-frequency tends to only be found in the high precision receivers that demand higher accuracy. There are several research activities happening around dual frequency receivers for mass market and automotive, however no real large scale deployment could be observed so far.

As a result, nearly 70% of GNSS receivers remain single-frequency (with the remaining 20% supporting two and 10% three frequencies). The most common combination is L1/E1 and L2, followed by L1/E1, L2 and L5/E5. Not surprisingly, all GNSS receivers use L1/E1 frequency. Furthermore, around 30% have L2 capability, 10% L5/E5, and 1% E6. (For more see charts below).

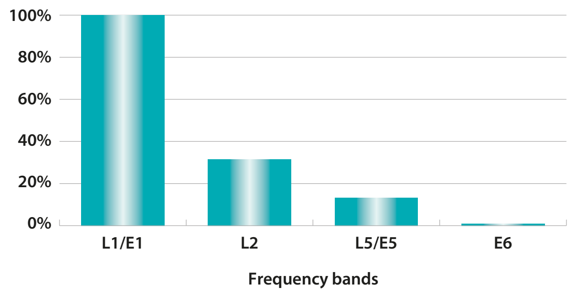
The benefits of supporting multiple frequencies:

- **Improved accuracy:** Dual-frequency capable devices can estimate and compensate for ionospheric delays.
- **Access to RTK and PPP techniques:** Although theoretically possible for single-frequency receivers, RTK or real time PPP techniques practically require dual-frequency receivers. Furthermore, the use of triple-frequency receivers will likely enable further improvement of the ambiguity resolution algorithms, e.g. through the TCAR technique.
- **Improved robustness:** Although rarely advertised, frequency diversity is a basic but very efficient protection against jamming.

New signal designs also bring significant benefits:

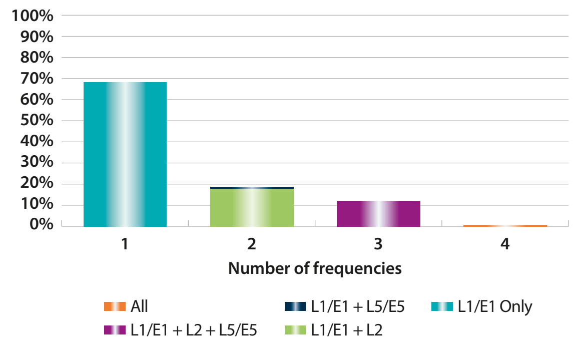
- **Improved accuracy:** New modulations and higher chip rates enable more precise range measurements.
- **Improved multipath mitigation:** New modulations and higher chip rates provide additional mitigation for multipath issues.
- **Improved sensitivity:** Pilot signals (i.e. dataless signals) enable higher sensitivity receivers through longer integration times.

Frequency capability of GNSS receivers[1]



[1] shows percentage of receivers supporting each frequency band

Supported frequencies by GNSS receivers[2]



[2] shows percentage of receivers capable of tracking 1, 2, 3 or all the 4 frequencies

Analysis of GNSS receivers capabilities

The GSA independent analysis assesses the capabilities of nearly 400 receivers, chipsets and modules currently available on the market*. For the analysis, each device is weighted equally, regardless of whether it is a chipset or a receiver and no matter what its sales volume is. The results should therefore be interpreted not as the split of constellations utilised by end users, but rather the split of constellations available in manufacturers' offerings.

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* For details see Annex IV

Galileo testing campaign demonstrates benefits of multi-GNSS

In preparation for the declaration of Galileo Initial Services, the GSA, along with the European Space Agency (ESA) organised a test campaign of GNSS chipsets to assess the readiness of consumer devices to support Galileo signals. The tests were executed between mid-2014 and early 2016, with participation of nine leading mass market manufacturers.

In addition to supporting the industry for testing and fine-tuning their Galileo capable products, the campaign also highlighted the performance improvements enabled by multi-constellation capability.

The test campaign included a mixture of simulator-based, RF-replay-based and live tests. Laboratory-based tests were based on either RF simulator signals conducted with "on the air" (OTA) RF testing or via scenarios recorded using an RF data recorder. This allowed for meaningful comparisons between receivers or between the various firmware versions of a given receiver.

As for receivers, several manufacturers used this campaign to compare and fine tune concurrent implementations of their Galileo and multi-GNSS functionality.

The test scenarios were designed to assess chipset performance under nominal (open sky) and degraded (sub-urban and urban) environments. They included both static and dynamic conditions, and used various combinations of GPS (used as the reference), GLONASS and Galileo signals. The main performance parameters evaluated were accuracy and Time to First Fix (TTFF).

Accuracy: The addition of one or two constellations to GPS only marginally improves accuracy in open sky conditions. However, as an environment becomes worse **(physically and/or radio electrically), Galileo's benefits become more obvious**. For example, in the urban scenarios, the addition of Galileo signals **always** improved accuracy, with an observed improvement of the Circular Error Probable (CEP) between 15 and 20%.

The best performing receiver reached a CEP of 3.9 m with GPS and Galileo.

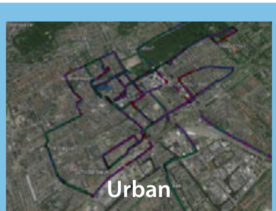
The combination GPS+GLONASS (with 7-8 GLONASS satellites) and GPS+Galileo (with only 2-3 Galileo In-Orbit Validation (IOV) satellites) led to a very similar average horizontal position error.

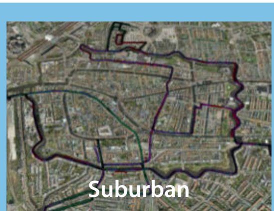
TTFF: TTFF was assessed in the same live environments used for accuracy. Like accuracy, improvements in TTFF are mostly visible in worst case (urban) scenarios. The average improvement among tested receivers was around 1s in hot start and 20s in cold start TTFF, with the cold start average TTFF expected to show significant reduction when the number of Galileo satellites in view becomes equal to or greater than four. However, as in the accuracy tests, some large differences between receivers were observed, most likely due to different implementation choices, acquisition strategies and allocation of resources.

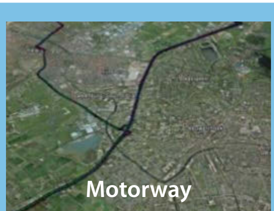


Source: ESA

LIVE scenarios executed to analyse different user environments







In an OPEN SKY environment, GPS-only acquisition and accuracy is as good as MULTI-CONSTELLATION.

In difficult to extreme live environments (e.g. bridges) the MULTI- CONSTELLATION solution always outperforms GPS-only, making it a MUST HAVE.

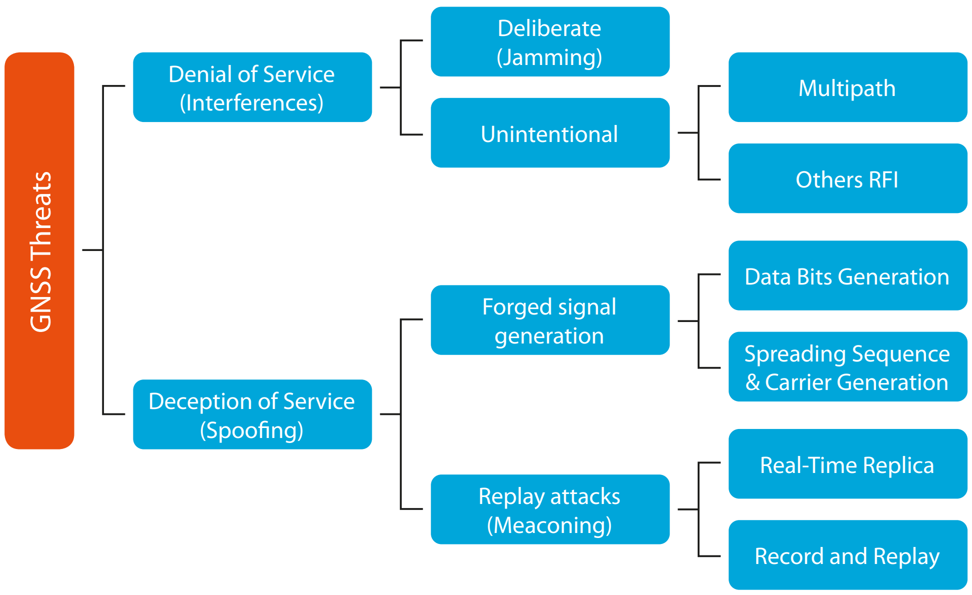
Jamming, spoofing and meaconing threaten GNSS signals and must be coped with

Due to the nature of GNSS (signals received with very low power level), these systems are vulnerable to either natural (e.g. ionospheric scintillation) or man-made (e.g. radio interferences of all sorts) phenomena that may severely disrupt their operation – up to a partial or total interruption of service.

*Such phenomena can be deliberate (**jamming** and **spoofing** attacks), but can also be unwanted (spurious radiation of other radio devices, GNSS multipath propagation).*

Regardless of their nature, these phenomena threaten GNSS and must be protected against.

A simplified taxonomy of man-made RF threats to GNSS



Spoofing is a more sophisticated and malicious form of attack than **jamming** (successful spoofing goes undetected). Although jamming is a well-known threat, the classification of deception interferences that affect GNSS signals is not straightforward, with the following parameters being vulnerable to attack (independently or not): *timing information, ranging information, ephemeris data, almanac data, corrections data, integrity data, service parameters and authentication data.*

Deliberate RF Interference (Jamming):

Although GNSS jammers are illegal to market, sell and use in most countries, they can nevertheless be bought by the public on the internet. A typical motivation for using a jammer is to fool devices used in asset tracking. However, such jammers often disrupt GNSS over a much larger area than advertised, transforming an alleged "privacy protection device" into a major public nuisance.

Unintentional RF Interference:

Multipath: a multipath effect is, by definition, a self-interference occurring when the direct path GNSS signal is combined with a delayed replica of itself. It affects phase as well as code measurements. However, by knowing the nature of the interfering signal one can devise specific mitigation strategies.

Other RF Interferences: These are unpredictable events, due to abnormal spurious adjacent band or harmonics radiations. Reported incidents have implied sources as diverse as microwave devices, airport radars and TV transmitters.

Generating a forged GNSS signal:

Data Bit Generation: There are two approaches to data bit generation, namely navigation messages replica and forgery:

- **Navigation messages replica:** data from space is replayed to reuse the authentic data and/or the ephemeris of the live signal.
- **Navigation messages forgery:** the attacker can theoretically forge the navigation message to achieve a desired PVT at the receiver. If message authentication is used, the authentication tag must also be forged.

Spreading code and carrier generation: a GNSS system modulates the data with direct-sequence spread spectrum (DSSS). For all open services, these sequences are published in the system's Interface Control Documents (ICDs), and may be used to construct a simulated signal. Such a forged signal may then be broadcast with or without synchronising the simulated and real-satellite spreading sequences and at various power levels.

Replay attacks (Meaconing):

Real-time signal replica: signals from space can be delayed and replayed with appropriate hardware, e.g. by using cables that introduce delays into the propagation times, allowing errors in the order of 100 to 200 metres to be introduced in the position solution. Even if this approach isn't sufficient to simulate a desired PVT or trajectory, a user might use it to cheat unprotected liability-critical applications (self-spoofing).

Record-and-replay: this attack is performed using already commercially available products. The typical architecture of these devices consists of a down-converter and analogue-to-digital converter (ADC), glue-logic, digital storage (hard disk), and a digital-to-analogue converter (DAC) and up-converter for the retransmission of the signal.

Mitigation of GNSS vulnerabilities is the subject of intense R&D

Anti-Spoofing

GNSS may implement several layers of defence against spoofing. The most widely known is to control access to the signals by encrypting the ranging codes ("NAVSEC") and navigation messages ("COMSEC"). This is what the **GPS Precise Positioning Service (PPS)** and **Galileo Public Regulated Service (PRS)** services do, only granting access to authorised users.

Another approach is *GNSS signal authentication*. Although here all receivers can process the authenticated signals, these signals include "markers" that can only be interpreted (and in some cases detected) by enabled receivers using a cryptographic feature. This authentication capability may theoretically concern the navigation messages, the ranging codes, or both.

In the near future, Galileo plans to implement such a capability:

- The Navigation Message Authentication (NMA) for the Galileo Open Service signals will be freely available to all users and will offer a "COMSEC" protection against spoofing.
- In addition to NMA, the Galileo Commercial Service will also offer an encrypted ranging code to subscribed users, thus adding "NAVSEC" protection.

Interference mitigation

All RF Interference

Detecting and mitigating jamming can be achieved by:

- Such antenna techniques as array-antennas and array processing algorithms:
  - Beamforming
  - Nullsteering
- Determining the signal of interest's DoA (Direction of Arrival) by exploiting available information from spatial separation.
- Determining the source of interference and spoofing (Direction of Interference – DoI).
- Front-end Techniques, such as detection techniques based on Compressed Sensing.
- Pre- and Post-Correlation Receiver Techniques, such as pulse blanker, Continuous Wave (CW) nulling, notch filtering, etc.

Multipath specific countermeasures

Multipath can be mitigated at different levels by using:

- Good antenna design: rejecting LHCP (Left Hand Circularly Polarised) signal because the GNSS signal is RHCP (Right Hand Circularly Polarised), including such specific antenna designs as the choke ring antennas (see page 19).
- Advanced correlator techniques that are now commonly used in higher performance receivers, such as the narrow correlator, Multipath Estimating Delay Lock Loop (MEDLL), double delta techniques and gating functions.
- Signal processing techniques that estimate the multipath and the ones that attempt to mitigate without estimating it. Carrier phase smoothing of code observations is one of the first methods that has been used.
- Improved navigation algorithms that employ post-processing methods to analyse receiver-satellite measurements or to correct the solution itself.

A testing campaign on GNSS professional receivers assessed their robustness against interference

European Commission

Source: Joint Research Centre, EC

Professional receivers are those requiring the highest accuracy, between decimetre and millimetre level – accuracies that require multi-frequency, multi-constellation standalone (Precise Point Positioning – PPP) or differential code and carrier phase processing. Here design is driven not by size, weight and power, but by the quality and specifications of analogue components and the computational capability of the digital processing units. Such GNSS receivers should be compared with calibrated RF laboratory instrumentation, and it is not uncommon to find them used as ground infrastructure to monitor and measure the performance of the space segment itself. As a consequence, the purity of the observations produced is just as important as their availability.

To assess the level of readiness and compliance of these professional receivers for Galileo Open Service signals (also in comparison with GPS, Glonass and Beidou) the Joint Research Centre (JRC) conducted an in-depth testing campaign in 2014 and 2015. The purpose of the campaign was not to benchmark the tested receivers, but to characterise their behaviour in the presence of a signal in space, both nominal and subject to such anomalies as interference and multipath, and to compare combined Galileo observables and positioning performance with standalone GPS figures.

The tests considered different types of radio frequency interferences (RFI):

- Continuous Wave (CW, typical of unwanted oscillator harmonics).
- Chirp (typical of low-cost jammers).
- Wideband noise (typical of leakage from neighbouring high-power signals).

Specific tests were carried out for each class of RFI on each band, with observations collected for both measurement level and the position domain. At measurement level, the degradation of Pseudo-Range (PR), Range Rate (RR) and Carrier Phase (CP) was observed through a comparison between the interfered/jammed measurements and the reference measurements obtained without interference. In the position domain, GNSS receiver performance was analysed in Single Point Positioning (SPP) mode in terms of mean and Standard Deviation (STD) for both horizontal and vertical components independently computing a classical least-squares PVT solution.

The tests showed that in a nominal scenario with no interference, the variance of the residuals is highest on GPS L1 C/A, and significantly smaller on Galileo E1B/C. However, the performance on L5 and E5a is similar, as the same BPSK(10) modulation is used by GPS and Galileo (similar performance is obtained with E6).

The campaign links well with the current adjacent band compatibility studies carried out in the US by the Federal Communications Commission (FCC) under the push of Ligado (formerly Lightsquared). In Europe, in the framework of the Radio Equipment Directive (RED), this work might be re-used (or re-produced) to provide scientific back-up to the application of the regulation to the precision-receivers market (e.g. surveying, construction, mapping).

Europe's industrial contribution to GNSS innovation

> "We see that there is a strong interest from European industry to provide solutions for European GNSS applications globally."
>
> "Notably, we see members of Galileo Services and Oregin that already have or are developing receivers for a broad range of applications, in particular building on Galileo differentiators,"
>
> Gard Ueland, GS Chairman.

European GNSS Downstream Industry

Since the early days of Satellite Navigation in the 2000's, European industry has shown a great interest in GNSS technology and markets for Galileo & EGNOS applications.

Today, European GNSS downstream Industry is at the forefront of technological innovation in many areas. It has been an outstanding actor in the transition from pure GPS to multi-GNSS multi-frequency solutions and more widely to connected PNT solutions leveraging hybridization or sensor fusion.

Europe industry ranges all domains, from chipset design to manufacturing, integration and certification of major systems and provision of innovative services. In particular, European industry has a leading position in GNSS security and resilience domains.

Galileo Services community

Galileo Services (GS) and Oregin federate the most active and representative players of GNSS industry and research supporting the Galileo and EGNOS Programmes.

This growing network includes actors from the whole GNSS value chain: R&D, equipment manufacturers, service providers, integrators, software developers, data content and map providers, chip producers, telecom manufacturers, etc. These organisations are excelling in all kinds of applications in all domains.

GS and Oregin members have made substantial investments in and have been conducting research projects on the development of E-GNSS applications for many years. They are also directly involved in the definition of E-GNSS services.

GS community works every day for an early and wide adoption of E-GNSS services in all domains.

Galileo Services (GS) is a non-profit organisation founded in 2002 to support the European GNSS downstream industry interest. GS network represents more than 180 member organisations ranging from SMEs to large companies and Academia.

For further information: www.galileo-services.org

Academic research in GNSS is very active in Europe

GNSS academic research is alive and well in Europe, making an impressive impact on global innovation. It involves many universities and institutes across all European countries, with some formalising their collaboration under the Satellite Navigation University Network (SUN).

Satellite Navigation University Network

SUN, which started in 2010, is now part of the GSA-supported Horizon 2020 e-KnoT project. Its objectives include:

- Bringing together providers of GNSS university education to facilitate the development of joint educational programmes.
- Increasing co-operation between partners and industry and between national and European organisations like the GSA, EC and ESA.
- Identifying the needs of GNSS education and improving its process and curricula.
- Developing strategies for the current network of GNSS universities exploring new educational programmes and methods.

Aalborg Universitet	Aalborg University conducts research on the applications of GNSS in surveying and mapping.
École Nationale de L'Aviation Civile (ENAC)	French Civil Aviation University's research activities on navigation and positioning focus on such critical transport applications as aviation, road and rail. It encompasses GNSS integrity monitoring, receiver signal processing, multi-sensor navigation and precise positioning.
Hochschule für Angewandte Wissenschaften München	Research at the Faculty of Geoinformatics at the Munich University of Applied Sciences comprises of UAV-Photogrammetry, Remote Sensing, Computer Vision, Navigation and Machine Learning. In particular, research is focused on object-based segmentation and classification for 3D vegetation mapping.
Institut Supérieur de l'Aéronautique et de l'Espace (ISAE)	GNSS education is part of the graduate and postgraduate programmes at ISAE's Aerospace Electronics & Communications Programmes. Short courses are organised for professional training. PhD and research activities focus on improving the performance of positioning systems in adverse environment (e.g. cities) via low-cost sensors fusion (e.g. MEMS), antenna processing, multi-constellation receivers, etc. ISAE is one of the founding members of the GNSS Test Laboratory GUIDE.
Istituto Superiore Mario Boella (ISMB)	The Navigation Technologies Research Area at ISMB focuses on GNSS software receiver technologies and algorithms. It co-organises the Specialising Master on Navigation and Related Applications with the Polytechnic University of Turin.
Politecnico di Torino (POLITO)	The Polytechnic University of Turin is involved in GNSS activities through the Department of Electronics and Telecommunications Engineering, where it is developing advanced signal processing algorithms for receivers, and through the Department of Environment, Land and Infrastructure Engineering where it is studying geomatics applications. Teaching of specific GNSS courses at the University is implemented at MSc level and at specialising masters level.
Sveučilište u Rijeci	University of Rijeka, Faculty of Maritime Studies (Navigational GNSS and Space Weather Laboratory), operates multi-GNSS performance and ionospheric dynamics observatories in Rijeka and Baška, and develops a regional space weather impact model and GNSS SDR applications.
Tampereen Teknillinen Yliopisto	The Tampere University of Technology focuses on signal processing for GNSS receivers, modulation design in GNSS transmitters, GNSS channel modelling, orbit predictions, implementation and simulation issues on GNSS receiver prototyping, and hybrid localisation solutions involving GNSS and non-GNSS.
Technische Universität Graz	The GNSS research at Graz University of Technology mainly focuses on GNSS-based trajectory determination (PPP, RTK), fusion of GNSS and INS, together with filtering (Kalman filter, particle filter).
Università degli Studi di Padova	University of Padova specialises in regional GNSS permanent networks for application to geodesy, mapping, deformation monitoring in seismic/subsident areas and research on multi-GNSS interoperability and receiver calibration. It is a regional provider of RTCM/RTK correction signals.
Università di Bologna	GNSS-related research at the University of Bologna focuses mainly on code acquisition subsystems; GNSS interference detection, localisation, and mitigation; cooperative algorithms; and integration between GNSS and inertial navigation systems.
Universität der Bundeswehr München	Activities at the Institute of Space Technology and Space Applications (ISTA) at the Federal Armed Forces University of Munich focuses on teaching and research in the areas of navigation, signal processing, satellite methodologies, satellite communication, geophysics and geodynamic. The university also has expertise and experience in GNSS and integration with INS.
Universitat Politécnica de Catalunya (UPC)	The GNSS-related activity of Research group of Astronomy and GEomatics (gAGE) at Polytechnic University of Catalonia includes new algorithms for Wide Area navigation and Fast Precise Point Positioning at the centimetre-level of accuracy using GPS/Galileo signals, SBAS and GBAS studies, and precise ionospheric and tropospheric sounding.
University of Nottingham	Nottingham Geospatial Institute (NGI) is a cross-disciplinary research and postgraduate teaching institute at The University of Nottingham. Fields of specialisation include satellite navigation and positioning systems, remote sensing photogrammetry, sensor integration, geospatial information science and location based services.

EU-funded GNSS downstream R&D covers receiver technology and application development

GNSS Downstream R&D programmes in Europe

To foster the adoption of Galileo and EGNOS-powered services across all market segments, the GSA supports two complementary R&D funding mechanisms:

Horizon 2020 (H2020) encourages the adoption of Galileo and EGNOS via content and application development. It also supports the integration of their services into devices, along with their eventual commercialisation.

Fundamental Elements focuses on supporting the development of innovative chipsets, receivers and other associated technologies that integrate Galileo and EGNOS into competitive devices for dedicated user communities/target markets.

Research programmes prior to H2020

From 2007 to 2013, European GNSS Downstream R&D was funded under the Transport Theme of the **7th Framework Programme for Research and Technological Development (FP7)**. The GSA managed a portfolio of **86 R&D GNSS projects**, with an average budget of € 1.2 million. The total budget for the period was **~€ 66 million**.

FP7 projects covered a wide range of market segments: Road, LBS, Precision, Professional and Scientific Applications, International Cooperation, Aviation, Rail, Maritime. There was a strong focus on SMEs, **with 40% of GNSS funds awarded to SMEs** amongst the **425 beneficiaries**.

Most importantly, the programme generated tangible results: 115 demonstrations of E-GNSS applications, 45 products, 80 prototypes and 13 patents/trademarks.

Information about all GNSS projects funded under FP7 can be found here:
http://www.gsa.europa.eu/r-d/gnss-project-portfolio

HORIZON 2020

Horizon 2020

Horizon 2020 is the current EU Research and Innovation programme, offering nearly **€ 80 billion** in funding for the 2014 – 2020 period. European GNSS applications are part of the Space Theme, having synergies with topics on societal challenges. **Two E-GNSS calls were successfully concluded with a budget of €38 million and €25 million respectively. A third call is planned to be open in November 2016 and run until March 2017.**

Actions under H2020-Galileo address the **development of innovative products, applications, feasibility studies and market tests** that will have a substantial impact on growing and strengthening European innovation and know-how, along with the economy and strategic sectors.

More information can be found here:
http://www.gsa.europa.eu/gnss-h2020-projects

Fundamental Elements

The Fundamental Elements of European GNSS

With a budget of **€ 111 million** for the 2015 – 2020 timeframe, "Fundamental Elements" aims to develop market-ready GNSS chipsets, receivers and antennas. The markets targeted by these end-products include, in varying proportions, all segments: Aviation, Location Based Services (LBS), Agriculture, Surveying, Rail, Road, Maritime, Timing and Synchronisation and PRS.

The financial instruments for funding Fundamental Elements-supported activities include **grants and tenders/procurements**. Grants are the preferred financial instrument, with funding generally provided to beneficiaries for up to 70% of the total budget of the grant agreements (up to 100% for the tenders/procurements).

More information can be found here:
http://www.gsa.europa.eu/r-d/gnss-r-d-programmes/fundamental-elements

Mass market solutions

Source: Thinkstock

High availability and low power consumption are key for mass market receivers

Characterisation of mass market solutions

This chapter discusses GNSS receivers dedicated to:

- Location Based Services (LBS): Smartphones/tablets, portable devices, wearable devices.
- Internet of Things (IoT): Autonomous devices that require long availability (years) but infrequent uses.
- Automotive in-dash navigation/infotainment systems.
- Portable Navigation Devices (PND) and other handheld devices for driving, walking, cycling and outdoors activities.
- Other consumer equipment used in:
  - Consumer grade drones
  - General Aviation (GA) operating under Visual Flight Rules (VFR)
  - Recreational sailing

LBS remains the predominant use in terms of volume and value, followed by IoT. PNDs are gradually losing ground to in-vehicle systems and smartphones. Meanwhile, other consumer devices which tend to benefit from technological developments in the three key application areas, generally do not justify specific designs at the GNSS core level.

Market acceptance of LBS devices is conditioned on the **availability** and cost of the service, which in turn constrains such location sub-systems as high sensitivity GNSS or hybrid GNSS/MEMS solutions that allow **indoor use**. On the other hand, the vast majority of these listed use cases imply the use of a **connected** device, thus facilitating the use of Assisted GNSS (A-GNSS) or, in the most extreme cases, of distributed receiver architecture with cloud based processing.

Another commonality seen here is that, in general, these devices are battery powered, meaning they must remain small and lightweight. Consequently, another priority for GNSS receiver design is to minimise **power consumption**.

Finally, with the notable exception of navigation applications, these applications require "on demand" rather than continuous location information. This often allows setting the GNSS receiver in idle or sleep mode to save energy, although this imposes a quasi-immediate availability (shortest possible TTFF) when the user or the application requests a position.

Key performance parameters for mass market*

- **Availability:** the positioning information is needed "everywhere, every time" and as quickly as possible when requested by the user or the application.
- **Power consumption:** most devices are mobile and restricted to battery power. As a result, low power consumption positioning technologies remain a priority.
- **TTFF:** typical usage is over a short period of time. As the user typically has other means of locating themselves, if the time to acquire their position is too long, they will not use the device.
- **Indoor penetration:** many applications are used indoors or in urban areas where there is restricted visibility or attenuated signals.

Key Performance Parameter (KPP)*	Mass Market
Availability	🟢
Accuracy	🔴
Continuity	🔴
Integrity	🔴
Robustness	🔴
Indoor penetration	🟢
Time To First Fix (TTFF)	🟢
Latency	🔴
Power consumption	🟢

🔴 Low priority 🟢 High priority

* The Key Performance Parameters are defined in Annex I

Mass market chipset supply is extremely consolidated, with few global players

Mass market receivers are produced in very high volume and sold at a limited price, with hundreds of millions of units going to smartphones and tablets and tens of millions for in-car GNSS systems every year.

Largely dominated by the LBS segment (IT industry model), mass market receivers have a relatively **short life cycle** (in the 10s of months). Although this gives them the advantage of being able to rapidly adopt new features, it also means that time to market is of essence. Adopting a new feature too early or too late, even if by just a few months, could impact the product's entire life cycle.

Mass market receivers also enjoy a very high **innovation rate**. For example, high-end consumer devices have been in the past early adopters of dual constellation capability, prior to deployment to entry level as well – and the same will undoubtedly holds true for the adoption of currently in deployment systems like Galileo. However, this trend towards innovation tends to be limited to a **few very large players** who can ensure sufficient economies of scale.

There are challenges, however. For example, particular to the design of mass market receivers is the requirement for a position to be available quasi-instantaneously and everywhere. This challenge is addressed by such techniques as:

- Reducing the signal level needed to acquire the signal (high sensitivity).
- Hybridisation with other radio technologies (Wi-Fi fingerprinting, cellular network positioning, use of Signals of Opportunity) or non-radio based ones (MEMS).
- Special techniques devised to provide a more accurate position estimate in the presence of severe multipath and/or non-line of sight (NLOS) signals.
- Use of vector tracking techniques.
- Advances in such algorithms as satellite shadow matching.

Clearly, the development, validation and deployment of such techniques require a **high investment**.

Furthermore, the power, size and cost constraints result in a high-scale integration of both the GNSS and the communications (Wi-Fi, Bluetooth, LTE, FM) into a single chip, to allows for high volume production and a minimal bill of materials for the LBS devices. This in turn has led to a **consolidation of the industry**, which has as principal actors only **eight companies** around the world (see table above). None of these actors is a "pure play" GNSS one, with all of them having a scope of activities encompassing at least wireless communication and positioning.

Leading components manufacturers		
BROADCOM	North America	www.broadcom.com
INTEL	North America	www.intel.com
MEDIATEK	Asia-Pacific	www.mediatek.com
QUALCOMM	North America	www.qualcomm.com
SPREADTRUM	Asia-Pacific	www.spreadtrum.com
STMICROELECTRONICS	EU28	www.st.com
TEXAS INSTRUMENTS	North America	www.ti.com
U-BLOX	Non-UE28 Europe	www.u-blox.ch

Disclaimer: Note that some key industry players do not appear in this list which does not include system or terminal integrators.

An important feature of mass market consumer solutions is that most receivers are connected ones, with a large proportion of them being smartphones or tablets. This in turn means that the supplier of the device's operating system has also an important role to play in the collection, aggregation, processing and delivery of location related information. Thus the description of the background industrial landscape would not be complete if it were to omit major players / influencers such as **Google** (for Android based terminals) and **Apple** (for iOS based terminals), although none of these companies is a supplier of GNSS components.

Multi-constellation improves performance in urban environments

Multi-constellations adoption

With Galileo, QZSS, BeiDou, GPS-L1C, and GLONASS-CDMA all on their way, the market continues to develop towards fully flexible, multi-constellation mass market receivers.

The uptake of multi-constellation receivers is driven by devices meant for use in urban canyons and indoors. Although cell/Wi-Fi and related positioning techniques provide some help, GNSS remains the core positioning technology within such environments. As a result, over 70% of all currently available mass market chipsets are multi-constellation capable.

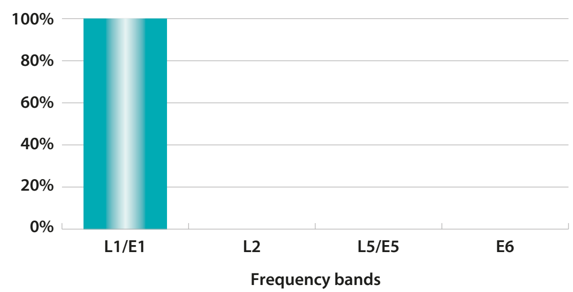
The main obstacles to multi-constellation adoption are the additional costs in terms of price, processing load and energy consumption it may add. Thus, designers must balance the benefits of multi-constellation capability against its costs and, based on this, find the optimal number of channels for the chipset. However, thanks to recent innovations, this choice has become easier. Through the use of architectures that allow a specific channel to process signals originating from different constellations, it is now possible to implement constellation-specific functionality into firmware. This allows the final product manufacturer to implement constellation-specific designs or to configure a given hardware implementation to function with different combinations of constellations as a means of targeting specific sub-markets.

It is also worth noting that 65% of these receivers support space based augmentation systems (SBAS), although this figure can be misleading as SBAS functionalities are activated in a much smaller proportion of the end products (due to their requirement for continuous operation, imposing a severe drain on battery operated devices).

Multi-frequency adoption

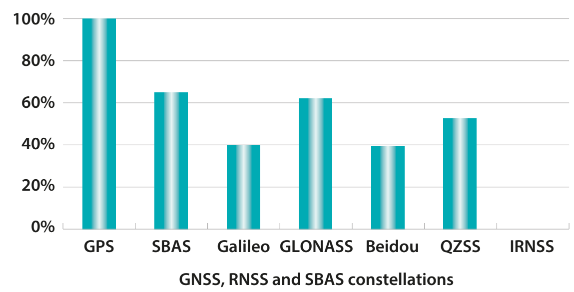
Although only the L1/E1 signals are currently used in mass market products, the uptake of E5/L5 signals is expected in the coming years as further explained in section "drivers and trends" on page 36.

Frequency capability of GNSS receivers[1]



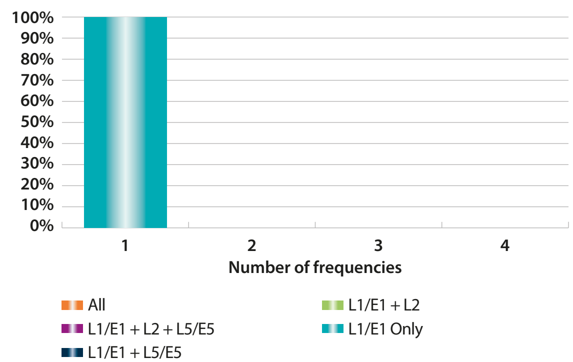
[1] shows percentage of receivers supporting each frequency band

Constellation capability of GNSS receivers[2]



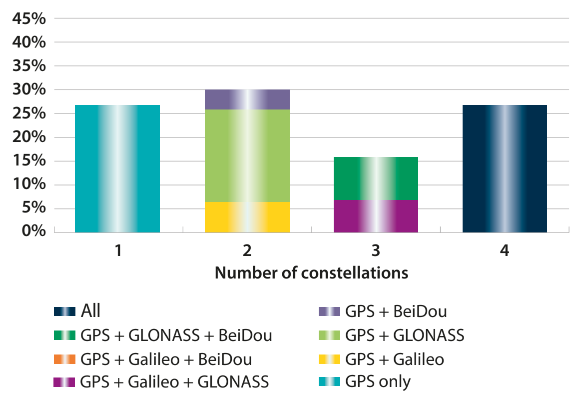
[2] shows percentage of receivers capable of tracking each constellation

Supported frequencies by GNSS receivers[3]



[3] shows percentage of receivers capable of tracking 1, 2, 3 or all the 4 frequencies

Supported constellations by GNSS receivers[4]



[4] shows percentage of receivers capable of tracking 1, 2, 3 or all the 4 GNSS constellations

Disclaimer: The above graphs reflect manufacturers' publicly available claims regarding their products' domain(s) of use and NOT their actual suitability for specific applications as can be demonstrated e.g. by a certification (when standards and regulations are existing) or actual usage.

Mass market chipsets can be classified into LBS, IoT and automotive with different specs

Typical state of the art receiver specifications for the mass market segment

Features		LBS	IoT	PND
Dimensions		15 x 15 x 3 mm	7 x 7 x 2 mm	10 x 10 x 1.5 mm
Weight		1.6 g	0.5 g	1 g
Temperature range	Operating temperature	-40 to +85°C	-40 to +85°C	-40 to +85°C
	Storage temperature	-40 to +105°C	-40 to +85°C	-40 to +85°C
Power supply		2.5 - 3.6 V	1.75 - 1.85 V	3.0 - 3.6 V
Current consumption	Hibernate	10 mA	28 uA	30 uA
	Acquisition	100 mA	56 mA	10 mA
	Tracking	100 mA	39 mA	8 mA
Number of channels		80	8	40
Time-To-First-Fix	Cold start	26 s	< 35 s	< 40 s
	Hot start	1 s	1 s	1 s
	Aided starts	2 s	N/A	2.5 s
Sensitivity	Tracking & Navigation	−167 dBm	−165 dBm	−159 dBm
	Acquisition	−160 dBm	−146 dBm	−146 dBm
	Cold start	−148 dBm	−130 dBm	−150 dBm
	Hot start	−156 dBm	−130 dBm	−150 dBm
Max navigation update rate		5 Hz	N/A	30 Hz
Velocity accuracy		0.05 m/s	0.01 m/s	0.03 m/s
Horizontal position accuracy	Autonomous	2.5 m	1.2 m	2 m
	SBAS	2.0 m		N/A
Accuracy of time pulse signal	RMS	30 ns		30 ns
	99%	60 ns		60 ns
Frequency of time pulse signal		0.25 Hz…10 MHz	N/A	
Operational limits	Dynamics	≤4 g		≤3 g
	Altitude	50,000 m		50,000 m
	Velocity	500 m/s		300 m/s

Disclaimer: The above specifications are reflecting manufacturers' commercial literature. Furthermore, they concern their most recent products. Consequently, discrepancies may exist between the installed receivers' characteristics and those stated above.

All chipsets or modules in the mass market consumer applications group are single-frequency (E1/L1) receivers (although with the IRNSS system reaching operational capability in 2016, some products supporting E5/L5 could appear). For increased sensitivity, shorter TTFF and lower power requirements, these chipsets are also all A-GNSS capable.

The latest GNSS modules coming from the **LBS segment** are designed with multi-constellation capability. They provide high sensitivity and minimal acquisition times while maintaining low system power. In addition, they are optimised for cost sensitive applications, providing optimal performance and easier RF integration. Furthermore, nominal form factor allows for easy migration, and sophisticated RF-architecture and interference suppression ensure maximum performance – even in GNSS-hostile environments. In the near future, expect to see an internal flash memory added to allow simple firmware upgrades to support additional GNSS features. Typically not pure GNSS modules, these systems on chip (SoC) often integrate communications (Wi-Fi, Bluetooth, LTE, FM) and MEMS accelerometers/gyros, along with other functions.

IoT chipsets are the world's smallest GNSS modules offering embedded flash and full GPS compliance (although other constellations may become supported, this uptake is limited by the extremely low power requirements of these devices which limits their number of channels). These chips are commonly provided with a plastic package designed to minimise their total footprint. Their low power-processing core delivers several customisable power-saving modes meant to optimise current draw for the desired use. IoT chipsets support both local and server-based A-GNSS, thus improving TTFF and minimising power requirements.

Portable Navigation Devices (PND) chipsets generally merge the satellite information with data from MEMS inertial sensors to provide continuous location information. These chipsets provide a unified platform comprised of navigation engines, 3D positioning capability and motion sensors. The firmware is usually loaded onto the receivers, with the option of being updated when additional features are needed. SBAS corrections from WAAS, EGNOS, MSAS, and GAGAN are normally supported at chipset level and can be used to increase positioning accuracy, according to user needs.

*Products dedicated to other consumer applications such as **recreational sailing** and **general aviation** typically benefit from chipsets developed for the **PND** market, which fully meet their needs.*

As smartphones connect us everywhere, the need for ubiquitous location increases

According to the GSM Association (GSMA), by 2020 four out of five people will have access to 3G/4G networks worldwide. Devices such as smartphones, tablets and wearables will increasingly serve as the primary interfaces for interacting with each other and with connected smart devices. This hyper-connected world will enable a tremendous range of applications, all based on context awareness and interaction with the environment – and location information plays a key role in this scenario. And for this, precise and truly ubiquitous positioning systems are still needed. The innovation is happening now for better ubiquity.

Ubiquity

Sensor fusion evolves for a better positioning experience

With the emergence of the smartphone, there's been an increasing demand for more sophisticated and more accurate LBS applications. In answer to this demand, smartphones are increasingly coming equipped with GNSS-complementary technologies that enable them to deliver a per-situation optimised positioning solution. As GNSS remains the main source of outdoor positioning information, these complementary technologies aim to expand the location capabilities in urban canyons and indoor environments.

Of course this dependency on GNSS alone increases the risks in the event that GNSS signals become unusable. To mitigate this risk, GNSS is oftentimes augmented by sensors (MEMS). With sensors, such inner variables as accelerometer biases, gyro drift and 3D inertial velocity are estimated by combining inertial navigation system (INS) information with an absolute external source that provides absolute reference information.

In addition, some indoor navigation systems rely on Signals of Opportunity (SOOPs) to aid an INS in the absence of GNSS signals, enabling a navigation solution with bounded errors. SOOPs are transmitted at a wide range of frequencies and directions, making them an attractive supplement to GNSS signals to improve the accuracy of a navigation solution.

An alternative approach involves the use of machine learning techniques. For instance, Simultaneous Location And Mapping (SLAM) algorithms allow a device to develop a consistent map of its environment while simultaneously determining its location within this map. This technique provides positioning in almost all kind of environments, and without the need for complementary infrastructure. As a fall-back solution, the data of the inertial sensor is used to bridge short distances where the algorithm cannot work.

Source: Thinkstock

Smartphone chipset manufacturers are incorporating chip-based indoor location positioning technologies

All available indoor location systems running on smartphones so far share a need for dedicated software to receive and process the signals to compute a location solution.

A notable improvement of CPU processing performance and power consumption in mobile phones could be achieved if the location algorithms were running inside the chipset. This would also enable a new generation smartphones to be factory-ready for indoor positioning anywhere.

There are already some chipsets on the market that incorporate these features, and many top chipset manufacturers are now working to include (or improve) indoor location technologies into their new chipset generations.

Some of these chips use an advanced form of Wi-Fi called 802.11mc, which supports a much more precise measurement of the distance between a wireless device and a Wi-Fi access point.

Other manufacturers are working to integrate motion sensing and location positioning. Here, the chipset would track location using GNSS up to the entrance of a building, at which point it would switch to inertial navigation for dead reckoning to maintain a 10 – 15 minute location estimate indoors.

As a result of these developments, new phone models equipped with universal location positioning capable chipsets will soon be on the market.

The demand for further accuracy drives technological development

The Benefon Esc! was the first commercially available cell phone to offer GPS functionality. Despite being a breakthrough in cell phone development history, its single frequency, single constellation receiver developed within a SiRFstar chip architecture presented features well below those currently available in modern smartphones. Nowadays as in the past, the main driver supporting the GNSS technological development in smartphones is accuracy. Judging from the software and hardware currently being developed, we are clearly on the cusps of an era of innovation. As a result, our smartphones will soon be capable of providing such accurate location that they will be used for a range of applications now served by high-end dedicated devices.

Accuracy

Innovative software developments promise enhanced accuracy to mass market users

The functioning of a GNSS chipset within a mass market device is often referred to as a 'black box'. Once GNSS measurements are received, the chipset outputs the complete PVT solution, possibly integrated with other information (e.g. the space vehicle number, the pseudorandom noise code, the azimuth and elevation of a given satellite). So far the possibility of providing "raw measurements", including pseudoranges, Doppler shifts/frequencies and carrier phase, was usually only featured in high-end receivers intended for professional applications, whereas most GNSS users are thought to be primarily interested in PVT information.

Despite pseudorange and carrier phase observables for all signals tracked are available at chipset level, traditional operating systems do not make them available for users. Although such an approach certainly satisfies the average user, it limits the extent to which an advanced user can make use of GNSS-derived location information. Fortunately, this limitation is being reconsidered in new operating systems releases (see box below). Having access to such additional information would allow sophisticated users and application developers to further close the already narrowing gap between the mass market and professional segments. For example:

- RTK precise positioning might be achieved by using just a simple smartphone as a device.
- Such SBAS corrections as those provided by EGNOS could be included in smartphones without the need for additional equipment.
- In general, many innovative applications could be developed/enhanced as a result of the increase in accuracy.

On the software side, similar developments are happening. For example, a team from the University of Texas recently demonstrated the possibility of achieving centimetre precision (in theory up to 2mm) by applying a carrier phase technique and using a normal smartphone antenna – well known to be subject to poor multipath suppression and irregular gain pattern. The solution envisaged the creation of a software that implements a sophisticated filter capable of removing the errors caused by multipath reception. Currently, such a solution would require the use of an external receiver, but if raw measurements were made available in smartphones, a truly handheld centimetre-accurate positioning could be achieved.

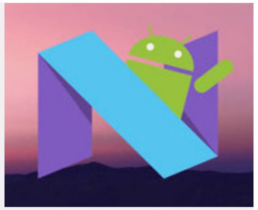
At the hardware level, developments in multi-frequency chipsets promise improved accuracy in urban canyons

As the demand for better location accuracy grows, we expect to see technologies from high-end commercial systems arrive on mobile phones. In fact, leading smartphone chipset manufacturers are already working to launch a new generation of GNSS receivers that exploit the more accurate and reliable positioning offered by dual-frequency signal processing.

Another benefit of dual-frequency receivers is their ability to effectively remove ionospheric error from the position calculation. The error, introduced by the ionosphere, is frequency dependent so it impacts the various GNSS signals differently. A dual-frequency receiver can correct the impact of ionospheric errors by comparing the delays of the two GNSS signals.

Finally, a dual-frequency receiver can quickly transition from code phase to carrier phase-based navigation, allowing it to confidently solve the carrier phase integer ambiguities on the fly (carrier phase tracking has been shown to provide centimetre level accuracy in positioning).

Raw GNSS Measurements from Android Phones



Google recently announced that raw GNSS measurements will be available to apps in the Android N operating system to be released later this year. This milestone marks a new era for the GNSS community: developers and phone makers will have access to raw Pseudoranges, Dopplers and Carrier Phase from a phone or tablet. Phone makers can make use of this data for performance testing while developers will have more resources to create innovative applications. The first phones to provide raw measurements will be launched next year after which more and more Android handsets will start to support this feature, as it will become mandatory in Android.

Testimonial provided by the company.

Galileo E5 is the most suitable choice for a second frequency

Signals available on the L2 and L5/E5 frequencies have common advantages: they both have a pilot channel for long coherent integration and therefore higher sensitivity.
However, L5/E5 has key features that make it a better option:

- With six fully deployed GNSS and RNSS constellations, there will be roughly twice as many satellites broadcasting on L5/E5 than on L2 (Galileo, BeiDou and IRNSS do not support L2).
- The L5/E5 signals offer superior multipath mitigation and better accuracy than the L2 ones thanks to the use of a 10x higher chipping rate (10.23MHz vs. 1MHz). This means the correlation triangle is 10x narrower in E5/L5 (30m instead of 300m in L2).
- The received power on L5/E5 is 3dB higher than on L2C, a very significant advantage for use in constrained environments.

IoT is driving power efficiency and miniaturisation at all levels: GNSS is not the exception

Since IoT devices are typically untethered, they must survive on either a battery or on power harvested from their environment. IoT devices typically require long lifetimes, further constraining power consumption. While larger systems can afford microwatt – milliwatt average power, millimetre-sized devices must survive on nanowatt power budgets. On the other hand, because of the real-time nature of their operations, GNSS receivers tend to require relatively high power consumption.

However, positioning is an increasingly important part of an embedded design as more and more devices become mobile. Adding this capability into equipment that has to be smaller, lighter and have longer battery life is a major technological challenge being addressed at all levels.

Innovation in all IoT dimensions

Sensing: Towards smart dust and sensor networks

Source: Thinkstock

Thanks to developments in silicon and manufacturing techniques, sooner or later sensors no larger than the size of a grain of sand will be in production. Called motes, smart dust or wireless sensing network, this technology is a collection of tiny objects equipped with sensors, computing circuits, bidirectional wireless communications technology and an independent power supply.

At their core is a small, low-cost, low-power computer linked to one or more sensors (temperature, light, sound, position, acceleration, vibration, stress, weight pressure, humidity, etc.). These computers are also connected via a radio link, allowing the mote to transmit information from a distance.

Motes have numerous potential applications. For example, engineers plan to mix them into concrete in order to internally monitor the health of buildings and bridges. Manufacturers can use them to detect defects by sensing out-of-range vibrations in industrial equipment, and hospitals can utilise motes to track patient movement. The technology continues to improve and new applications continue to arise.

The quest to reduce size and energy consumption use continues.

Connectivity: The deployment of Low-Power Wide Area Networks (LPWAN) fuels IoT growth

Source: Thinkstock

When it comes to range and bandwidth, different wireless technologies cover different applications. For example, the long-range applications with low bandwidth requirements that are typical for IoT and M2M scenarios are not well supported by such traditional technologies as 4G, 3G, Bluetooth, BLE, WiFi, or ZigBee.

LPWAN is a wireless wide area network technology geared towards interconnecting devices with low-bandwidth connectivity, focusing on range and power efficiency as required by many IoT applications. It is having a significant impact on the growth of IoT, allowing new applications to collect data and control devices in ways that were previously economically impossible.

Its main characteristics are:

- Range from 5 to 50 km in different environments.
- High autonomy of smart devices with battery lifetime of 10 years.
- Low throughput, typically a few hundreds bit/sec.
- Inexpensive radio modules and chipsets, depending on vendor, may vary from few Euro to 10s Euro.
- Inexpensive radio subscription cost in the order of 1€/device/year.
- Less number of base stations needed to cover a given area in comparison with other technologies.

Processing: Cloud processing reduces power consumption at device level

Source: Thinkstock

Cloud GNSS processing is the ultimate evolution of the software GNSS receiver concept. Instead of using the host device's processing capabilities, cloud GNSS receivers utilise cloud-based processing services, thus offloading most of the processing and energy-consuming tasks to the cloud – where such resources are virtually unlimited.

UBIGNSS™: A GNSS-based location technology suitable for low-power IoT applications

French start-up UBISCALE was named winner of the first GSA "IoT Solutions empowered by GNSS" award at the 2016 GEO IoT conference. At the centre of this winning concept is the UbiGNSS™ technology and service that enables true low-power GNSS-based services for IoT applications, overcoming one of the main barriers for GNSS adoption in IoT: power consumption.

The UBIGNSS™ solution's essential insight is that for tracking applications, the device itself does not need to know its position, although the service side tracking applications do. Best partitioning of the GNSS position computation between device and cloud enables optimisation of the power consumption thanks to a reduction of the activation time, light pre-processing in the device and minimised network connectivity.

Galileo improves performance in challenging urban environments

Mass market consumer applications require **high availability**, fast **TTFF** and the ability to **penetrate (light) indoor buildings** while simultaneously **preserving the battery life** of the device and keeping the cost of the receiver down.

Galileo, in combination with other GNSS in multi-GNSS mode, is capable of enhancing such basic GNSS performances as availability, TTFF and accuracy thanks to a higher number of available satellites. This is especially meaningful in challenging urban environments characterised by high buildings, helping achieve reliable positioning even in areas potentially affected by multipath.

Moreover, Galileo offers specific differentiators in respect to other GNSS. For example, its **navigation message authentication** could be used to enhance the quality of big data collection. It could even enable innovative, commercially sensitive applications that "link" a user's location to a payment for a service. The capability to operate in **light indoor environments** is also a differentiator provided by a specific feature of Galileo: using the pilot signal with a 100ms length for the secondary code, the sensitivity of the receiver is significantly improved.

EGNOS is usually not integrated into mass market solutions, since SBAS requires continuous operation and may drain the battery thus limiting the overall user experience. Nevertheless, some niche applications employ EGNOS in dedicated devices in order to take advantage of its enhanced accuracy and reliability.

Key Performance Parameter (KPP)	EGNOS contribution*	Galileo contribution*
Availability		●●
Accuracy	●●	●●
Indoor penetration		●
Time To First Fix (TTFF)		●●

* ●●● = major contribution, capable of enabling new GNSS applications, ●● = medium contribution, enhancing the user's experience so benefits (e.g. operational, at cost level), are achieved, ● = minor contribution, performances improved but no major differences at users' level

Using More Galileo Signals Renders Better Accuracy, Especially with Multipath – Broadcom's BCM4774 Proves It

Supporting more constellations improves performance because there are more satellites scattered about the sky, thus increasing the opportunity of being able to use only direct line-of-sight signals for the position computation, and removing most of the multipath errors in difficult urban environments.

BCM4774 is Broadcom's most recent combination of GNSS and Sensor Hub in a single chip. It supports all available GNSS constellations. When referring specifically to Galileo, improvements not only come because of the higher satellite count, but also because of the better quality of the distance measurements to each Galileo satellite.

A test carried out under multipath conditions compared the performance of the BCM4774 chipset configured in GPS only mode and GPS + Galileo mode. The results showed that the effect of multipath in Galileo is approximately 2x smaller than the effect of multipath in GPS. Thanks to Galileo's unique signal modulation (BOC), the more Galileo satellites chosen by the receiver for a position computation in a multipath environment, the better position estimate will be obtained.

Testimonial provided by the company.

Qualcomm enhances mobile Location experience by adding broad support for Galileo across its Snapdragon processor and modem portfolios

In challenging environments, such as urban canyons, Location experience can be affected by non-line-of-sight reception or multipath interference. Supporting the six satellite constellations concurrently is the state of the art to obtain better Location performance.

The addition of Galileo to a multi-constellation solution will give users of Qualcomm® IZat™ Location Platform the benefit of more than 80 different satellites when calculating global position for navigation or any location-based application. The result is more accurate Location, faster time-to-first-fix and improved robustness all over the world, particularly in challenging urban environments where the combination of narrow streets and tall buildings can degrade accuracy.

Support for Galileo and concurrent processing of six satellite constellations is integrated in the latest Qualcomm® Snapdragon™ 800, 600, and 400 processors and modems. This feature will be supported by smartphones and compute devices with the appropriate software release on Snapdragon 820, 652, 650, 625, 617, and 435 processors, automotive solutions leveraging Snapdragon 820A, and telematics and IoT solutions with Snapdragon X16, X12, X7, and X5 LTE Modems, and Qualcomm® Gobi™ 9x15 and MDM6x00 modems.

Testimonial provided by the company.

Transport safety* & liability** critical solutions

Source: Thinkstock

** **Safety-critical applications** are defined as those that possess the potential to directly or indirectly cause harm to humans (death or injury), destruction of the carrier vehicle, damage to external properties or to the environment.*

*** **Liability-critical applications** are defined as those applications for which undetected GNSS miss-performances can result in significant legal or economic consequences.*

High levels of confidence and resilience are required for transport safety and liability-critical solutions

Characterisation of the transport liability and safety-critical segment

This segment covers receivers and technologies used to cope with the stringent requirements of safety or liability-critical applications found in aviation, maritime, rail and road transport applications. However, it has to be noted that:

- Not all transport applications are liability or safety-critical. For instance, aftermarket in-vehicle navigation (PNDs) is dealt with in the "Mass Market" macrosegment, and fleet management in the "High precision, Timing and Asset Management" one.
- Some critical applications may arise in domains other than transport, although currently not considered in this report. The only exception is timing and synchronisation of critical infrastructures, which is dealt with in the next group within the "High precision, timing and asset management solutions" macrosegment.

There is a clear trend towards using GNSS as a position sensor in such liability-critical applications as road charging and even in safely-critical applications such as autonomous cars. Following this trend, road devices are gradually developing similarities with aviation, rail and maritime devices, and are therefore discussed together. Therefore, in-vehicle navigation, factory-fit GNSS receivers are included in this segment, despite their (current) predominant use in vehicle infotainment systems.

Applications considered in this segment range from relatively simple "positioning" to the most complex "control" of such things as autonomous vehicles, with an increasing level of criticality. Because of this criticality, these applications are often regulated or, for the emerging ones, likely to become regulated or subject to standardised design/performance requirements.

Key performance parameters*

Within this segment, all applications require a high level of confidence and resilience, which translates into the following performance parameters:

- **Integrity:** a failure in integrity could lead to catastrophic events for safety-critical applications, such as mid-air collision or controlled flight into terrain in aviation. It can also lead to erroneous charges/fines and undermine the entire application for liability-critical ones.
- **Continuity:** in combination with integrity, it is vital that safety-critical application systems function for the duration of the procedure. This is also highly important for liability-critical applications, as discontinuity may render certain applications inert (such as road tolling or insurance).
- **Robustness:** susceptibility to jamming or the inability to detect spoofing could lead to accidents or render the application useless.
- **Availability:** since the applications supported can be operated 24 hours a day, 365 days a year, it is important that the positioning technology supports it.
- **Accuracy:** some applications may require a high level of accuracy in order to function.

To summarise, with the exception of personal car navigation, all these applications share the following key parameters: **Integrity, Robustness, Availability** and **Continuity**. In addition, **Accuracy** may be required for some specific applications/operations.

Signal Authentication *is an important feature and, in some cases, a fundamental enabler of* ***Robustness****. However, here it is considered a "Signal Property" rather than a user's "Key Performance Parameter".*

Key Performance Parameter*	Safety & Liability Critical
Availability	● (High priority)
Accuracy	● (High priority)
Continuity	● (High priority)
Integrity	● (High priority)
Robustness	● (High priority)
Indoor penetration	● (Low priority)
Time To First Fix (TTFF)	● (Low priority)
Latency	● (Low priority)
Power consumption	● (Low priority)

● Low priority ● High priority

* The Key Performance Parameters are defined in Annex I

Whilst the safety-related GNSS industry is a mature and stable one, new applications or use cases are being proposed

Leading components manufacturers		
ACSS	North America	www.acss.com
AVYDINE	North America	www.avidyne.com
BROADCOM	North America	www.broadcom.com
COBHAM	EU28	www.cobham.com
ESTERLINE	North America	www.esterline.com
FURUNO	Asia-Pacific	www.furuno.co.jp
HONEYWELL	North America	www.honeywell.com
JRC	Asia-Pacific	www.jrc.co.jp
KATHREIN	EU28	www.kathrein.de
KODEN	Asia-Pacific	www.koden-electronics.co.jp
LAIRD	EU28	www.laird-plc.com
MEDIATEK	Asia-Pacific	www.mediatek.com
OROLIA	EU28	www.orolia.com
PULSE ELECTRONIC	North America	www.pulseelectronics.com
QUALCOMM	North America	www.qualcomm.com
ROCKWELL COLLINS	North America	www.rockwellcollins.com
SAMYUNG	Asia-Pacific	www.samyungenc.com
STMICRO-ELECTRONICS	EU28	www.st.com
TECHTEST	EU28	www.hr-smith.com
THALES AVIONICS	EU28	www.thalesgroup.com
U-BLOX	Non-UE28 Europe	www.u-blox.ch

Disclaimer: Note that some key industry players do not appear in this list which does not include system or terminal integrators.

Regulatory environment

Mature safety-critical applications are specifically concerned about regulation, and emerging ones are bound to become so as they reach maturity.

Liability-critical applications may not require as strict a set of standards as the safety-of-life applications, but are nevertheless possible only if and when the ad-hoc legal framework is in place.

This high reliance on regulation has a number of consequences on the receivers serving these applications, which include high development and certification costs, long life cycles and corresponding technological obsolescence issues, and slow adoption of new signals or services.

The road sector is currently less concerned by regulations specific to positioning, although with the introduction of such liability-critical applications as road charging, and safely-critical applications like autonomous cars, related standards and regulations will likely become necessary.

New applications and players are appearing

Whilst the safety-related GNSS industry is a mature and stable one, new applications or use cases are being proposed. These will potentially impact public safety, but are not yet fully or properly regulated, either because they are still at the development stage or merely because innovation is faster than regulation. Most notably, the trend to automation of unmanned vehicles (UAVs, unmanned vessels and driverless cars) is shaking this traditionally quiet landscape – not only because it has become the major source of innovation, but also because such innovation is brought by outsiders in a disruptive manner rather than by industry insiders in an incremental way.

Receiver Industry

Historically, each critical market such as aviation, maritime and rail, is served by a largely separate group of specialist manufacturers who have the necessary domain experience and maintain control of their own GNSS technology. Additionally, some integrators may have a significant market presence, such as Garmin in the avionics domain, while not controlling the GNSS chips or modules used in their products.

The automotive sector is somewhat different, with Tier 1 suppliers delivering in-vehicle navigation or infotainment systems to "traditional" car manufacturers, based on GNSS technology procured from major chipset manufacturers (who are mostly the same as for the consumer sector). In parallel with this conventional approach, newcomers from the IT industry, most notably Google and Apple, are taking a disruptive strategy, directly targeting future driverless cars as a new platform to deliver their services (after the home PC, and mobile phones or tablets). For such driverless vehicles to become a reality, a full navigation solution must exist that can satisfactorily answer the following challenges:

- Very high integrity
- GNSS deprived areas (e.g. urban canyons, tunnels, etc.)
- Dynamically changing obstacle environment
- Specialised precision requirements for path/lane keeping
- Additional inputs which must be obeyed (e.g. signage, lighting systems)

Therefore, the control systems must feature tight coupling between a wide variety of independent sensors and the use of complex data fusion algorithms, resulting in a complex situation for identifying liability issues. Full automotive control (autonomous cars) systems are currently being developed, the rate of innovation is high, but the legislation and infrastructure are not ready. GNSS is only one component of such future systems, and the receivers are currently of the same class as those used in mass market automotive applications. As the requirement for more robust and/or accurate location information strengthens, it is quite conceivable to see a move towards dual-frequency receivers, possibly with some kind of integrity and/or authentication functions.

Dual-frequency will be a key enabler of improved accuracy and integrity

Multi-constellations adoption

There are significant variations concerning the adoption of multi-constellations technology within the sub-markets. In aviation, for example, the requirement to comply with regulation, and lack of regulatory support for constellations other than GPS, means that the adoption of other constellations is not significant. Even if regulatory conditions change, adoption within aviation is unlikely to increase rapidly, as product lifecycles are long and retrofit costs are high.

Maritime, road and rail, on the other hand, all have comparatively high adoption rates. For example, an average of around 60% of device models serving these markets supports GLONASS. This uptake is driven by such factors as Russian government decisions to promote the use of GLONASS for several applications (PNDs, Aircrafts, Integrated Train Protection System).

With new GNSS such as Galileo and BeiDou nearing completion, it is clear that similar policies to allow or promote their use will foster rapid adoption. Already, some EU legislation such as the Smart Tachograph or the eCall are in place, both of which will undoubtedly facilitate the uptake of multi-constellation receivers including E-GNSS.

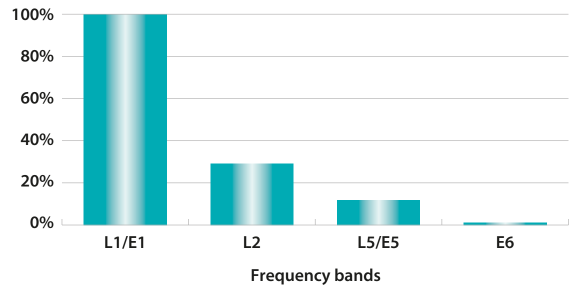
Multi-frequency adoption

All receivers support L1, whilst only a very small percentage supports L2, L5 or E6 frequencies. This is because the sector is dominated by the mature aviation and maritime markets, which currently only use L1 for regulatory reasons. An important issue that faces this segment is the vulnerability of GNSS signals to jamming and/or spoofing, and it can be expected that the use of dual-frequencies will go some way to mitigate this risk.

Furthermore, it is expected that dual-frequency will soon penetrate the automotive arena, as receivers are increasingly used for more advanced automation towards fully self-driving vehicles. Here, dual-frequency will be a key enabler of improved accuracy and integrity.

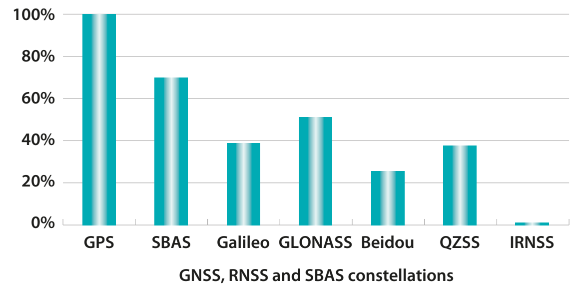
As soon as L5/E5 signals are provided by one or more of the major GNSS constellations, it can be expected that transport sub-sectors will adopt a dual L1/E1 + L5/E5 solution once the necessary standards have been put in place. Thus, a significant increase in the number of dual L1/E1 + L5/E5 capable receivers can be anticipated over the next five years.

Frequency capability of GNSS receivers[1]



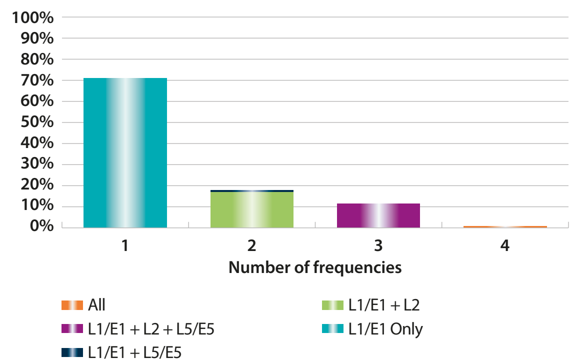
[1] shows percentage of receivers supporting each frequency band

Constellation capability of GNSS receivers[2]



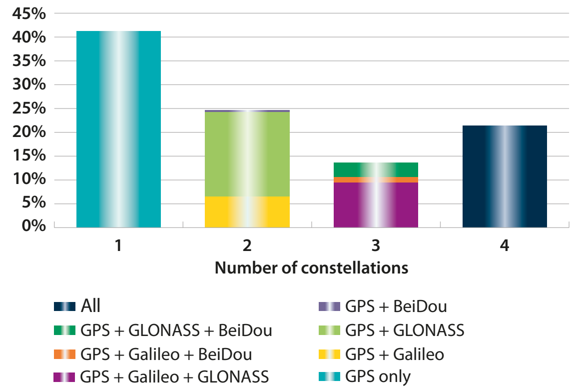
[2] shows percentage of receivers capable of tracking each constellation

Supported frequencies by GNSS receivers[3]



[3] shows percentage of receivers capable of tracking 1, 2, 3 or all the 4 frequencies

Supported constellations by GNSS receivers[4]



[4] shows percentage of receivers capable of tracking 1, 2, 3 or all the 4 GNSS constellations

Disclaimer: The above charts are reflecting manufacturers' publicly available claims regarding their products' domain(s) of use and NOT their actual suitability for specific liability or safety-critical applications as can be demonstrated e.g. by a certification (when standards and regulations are existing).
There is, consequently, an abnormally high adoption rate of multiple frequency receivers (that are currently not considered in any standard), which can be attributed to the inclusion in the statistics of high-precision receivers that can be used for non-regulated applications in a maritime, airborne or train environment.

Integrity and continuity performance are determined by standards in regulated sub-markets

Typical state of the art receiver specifications for the safety / liability critical segment
No Rail receiver is included, since GNSS is currently only marginally used in this domain for critical applications.

Features	Aviation	Maritime	Automotive
Number of channels	12-24	12-32	32-52
Code / Phase processing	Code and carrier phase	Code and carrier phase	Code and carrier phase
Constellations / Signals	GPS L1	GPS (GLONASS) L1	GPS, GLONASS, (Galileo), (BeiDou), QZSS L1
Sensitivity (typical)	-135 dBm acquisition -140 dBm tracking	-130 dBm acquisition -135 dBm tracking	-147 dBm acquisition -162 dBm tracking
Multipath rejection techniques	Usually yes	Not documented	Usually yes
SBAS / A-GNSS readiness	SBAS (E)TSO 145/146	SBAS supported (non safety of life)	SBAS supported (non safety of life) / A-GNSS supported
Receiver connectivity	Per ARINC 429	RS422 / NMEA 0183 NMEA 2000	
TTFF	Cold Start: < 75s Warm Start: < 30s Re-Acquisition: < 3 to 10s	Cold Start: < 60 to 120s Warm Start: < 30s Re-Acquisition: < 1 to 10s	Cold Start: < 33s Warm Start: < 30s Re-Acquisition: < 1s
Horizontal Accuracy (95%)	GNSS: 5 – 15m DGNSS: N/A SBAS: 2 – 6m	GNSS: 2.5 – 13m DGNSS: 0.3 – 5m SBAS: 2 – 8m	GNSS: 2.5 – 13m DGNSS: 0.3 – 5m SBAS: 2 – 8m
Vertical Accuracy (95%)	GNSS: 10 – 20m DGNSS: N/A SBAS: 8m	Not documented	Not documented
Antenna	External	External	External active
Standards & *Certification*	RTCA DO-229D, DO-178C, DO-254, DO-160, ARINC 743 ***(E)TSO 145/146***	IEC 60945, 61108-1/2/3/4, 61162-1/3, 62288; NMEA0183/2000, RTCM SC104 ***USCG or Wheelmark (EC MED)***	AEC-Q100 ISO16750
Form Factor	Complete unit conforming to standard (e.g. 2 MCU) External Antenna Remote CDU	Complete unit with built-in or remote CDU & Ext. Antenna Alt. "Smart Antenna" incl. receiver with remote CDU	Receiver Chip or Module
Others:		Internal Radiobeacon DGNSS receiver	May include up to 6 axis mems

Disclaimer: The above specifications are reflecting manufacturers' commercial literature. Furthermore, they concern their most recent products. Consequently, discrepancies may exist between the installed receivers' characteristics and those stated above.

The aviation, rail and maritime market segments have their own standards that define such key issues as which signals are to be used from which constellation; accuracy, integrity, availability and continuity requirements; the position output formats and interface details; and the form and fit, power and environmental requirements.

As integrity and continuity performance are particularly crucial to these applications, the specific approach used is mandated by the appropriate standard. The form and fit for these markets is generally best satisfied by a conventional external antenna (with medium-to-high gain preamplifier to compensate for cable losses) and internal receiver configuration. As can be seen in the table on the left, these receivers are mostly "all in view", single-frequency, single constellation, SBAS capable.

Since maritime regulation includes all GNSS constellations, some dual constellation receivers are available, with a corresponding larger number of channels. Another characteristic of the maritime domain is the addition of an internal radio beacon receiver (dual MF channel) dedicated to receiving the IALA (International Association of Marine Aids to Navigation and Lighthouse Authorities) Differential GNSS (DGNSS) system.

The included automotive receivers are very similar to mass market chips or modules, although they are not as constrained in terms of power consumption. On the other hand, they are generally built to automotive performance requirements, for instance concerning temperature range or vibration. Such receivers are integrated in application-specific on-board units (OBUs) for such applications as Road Use Charging, Smart Tachograph or Pay-as-You-Drive insurance. It must be noted that any additional means used to ensure suitability of the location system for the safety or liability-critical functions are implemented mainly at the OBU level, with no impact at the GNSS chip level. This situation is likely to change with the planned introduction of authenticated GNSS signals, which will require dedicated processing at the GNSS chip level.

The same GNSS receivers are also found in the relatively simpler in-vehicle navigation or infotainment systems. Although their current use case cannot be considered critical, they are nonetheless included here.

As a result of this incremental introduction of GNSS related functions within a car, there is a tendency to use multiple GNSS receivers within a single car. However, it is anticipated that a more integrated approach will be adopted, whereby a single robust and accurate GNSS receiver will drive the many applications that work as a "location engine" via a suitable data bus. It is also anticipated that this single GNSS receiver will be tightly integrated with inertial sensors and digital mapping to provide a high performance positioning sub-system.

Connected vehicles pave the way to active Advanced Driver Assistance Systems (ADAS)

A connected car can optimise its own operation and maintenance, along with passenger convenience, comfort, and entertainment by using on-board sensors and internet connectivity. Connected cars include such features as Navigation, Automotive System Diagnosis and Prognosis, Gesture Control and Voice Commands, Contextual Help, Parking Assistance, Safety and Security, Fleet Management, Vehicle Tracking, Road Side Assistance, Wi-Fi hotspots and many others.

Vehicles can also connect with other home and office devices and interact with each other (V2V) and with the infrastructure (V2I) to get traffic updates, optimise trajectories and avoid accidents. (V2V and V2I are collectively known as V2X).

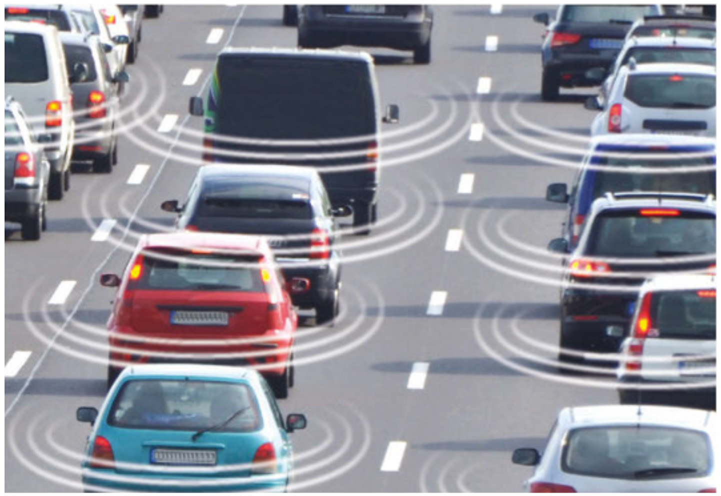
Long range connectivity is obtained via mobile telephony networks. Beyond infotainment, this helps enable numerous location and navigation features, providing timely access to, for example, landmark databases, detailed 3D maps, and information on routing, traffic and weather. It also enables A-GNSS and safety features such as emergency assistance, including the European eCall system.

Short range connectivity is obtained with ad hoc networking using the IEEE 802.11p standard, more commonly known as ITS-G5, which is the technical foundation of V2X. V2X is built on the assumption that vehicles, infrastructure elements, and other road users are location-aware and can communicate critical information to others around them. This opens the door to such innovative navigation methods as cooperative intelligent transport system (C-ITS) platforms and convoy navigation.

Furthermore, V2X may offer a ranging capability which can be used for position fixing. V2X lane level positioning accuracy has been claimed by some automotive suppliers, which is opening very interesting perspectives for combining GNSS with V2X ranging – as well as other sensors information – to ensure the security, accuracy, and reliability of positioning information in difficult urban environments. Because of its contribution to situational awareness, V2X is an essential building block to ADAS solutions. Soon vehicles will receive information from multiple sensors, including V2X, which will be combined/fused to generate a view of the surrounding environment.

In summary, active driver assistance requires equal measures of reliability, accuracy, and security – and no driver would sacrifice any of these. Accurate absolute and relative positioning – to other vehicles and infrastructure – is critical to the move towards semi- and fully-autonomous vehicles. In this respect, the fusion of V2X ranging and GNSS could offer the desired level of accuracy and robustness, albeit in areas where the infrastructure is deployed.

V2X technology is ready to be deployed in the near future. In the USA, a National Highway Traffic Safety Administration (NHTSA) mandate on new light vehicles is expected to start around 2020 as a phase-in plan, with completion around 2025. Regulations for aftermarket devices are expected to follow. In Europe, the Declaration of Amsterdam (April 2016) defined the framework for European cooperation in the fields of connected and autonomous vehicles, including the development of a shared strategy for research and innovation, the evolution through Cooperative ITS and the adaptation of the EU regulatory framework.



Source: Thinkstock

eCall Receivers Test Campaign

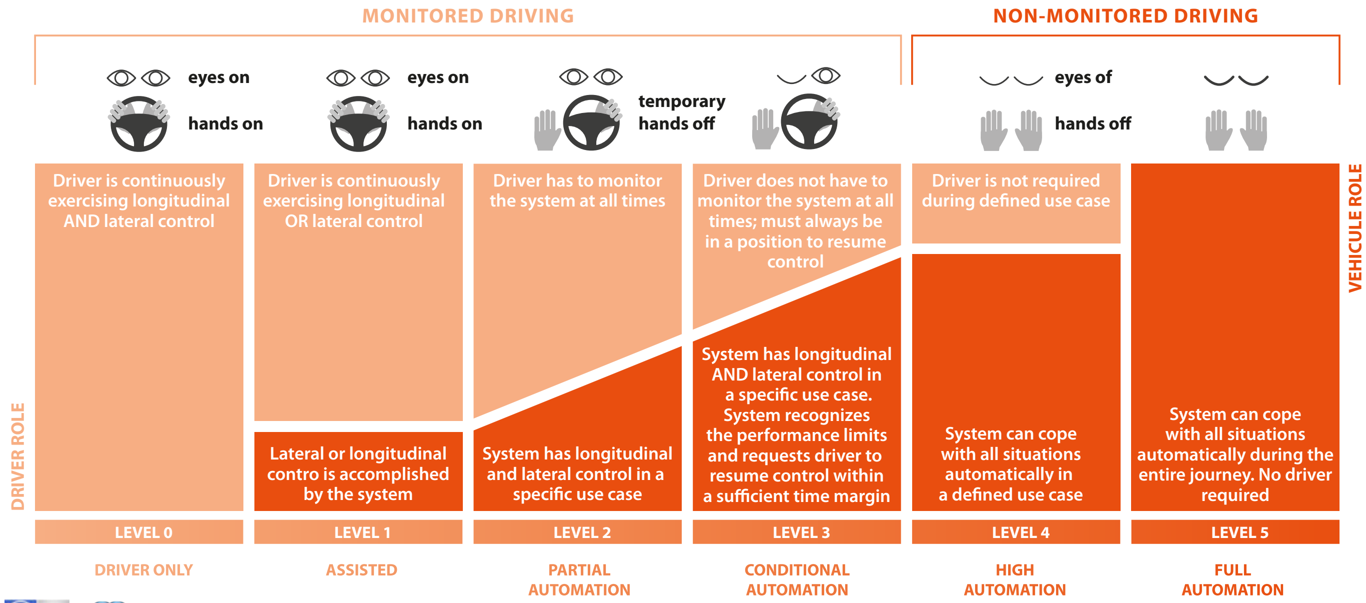
Source: Joint Research Centre

The eCall regulation requires that, as of April 2018, all new models of passenger cars and vans that will be commercialised in Europe be equipped with the automated emergency-Call. The European eCall system, which provides an accurate GNSS location of an accident by using EGNOS and Galileo, will significantly improve the response time of emergency services.

The GSA and the European Commission invite eCall manufacturers, such as modules or Tier 1 suppliers, to take part in a test campaign to verify the proper support of Galileo signals in eCall devices in view of the coming declaration of Galileo Initial Services. This campaign is undertaken in cooperation with the Joint Research Centre of the European Commission (JRC) and will consist of a series of tests making use of the state-of-the art Galileo facilities available at JRC's Ispra (Italy) site. The tests will verify the devices' eCall readiness, with a focus on the performance requirements for the reception of EGNOS and Galileo Open Service Signals.

The drive to automation is fuelling Research & Development in location technologies

All modes of transportation are witnessing a trend towards autonomous or robotic vehicles/crafts – a trend that is also extending to some professional applications (e.g. agriculture). The autonomous car is probably the most challenging of these concepts, and is also the area where most research and innovation is happening – both by "traditional" automotive players and the IT industry.



Author: Mike Lemanski

Autonomous Driving is the final step of a long evolution process

There are still many obstacles to achieving fully autonomous driving, some directly linked to the location system:

- Accuracy has to be improved to decimetre level.
- Better continuity in urban canyons must be ensured.
- Better reliability, and possibly authentication, is needed to prevent malicious attacks or facilitate liability mechanisms.

To advance the level of automation, GNSS receivers will soon have to evolve from their current multi-constellation, single-frequency form into a dual-frequency unit, triggering the birth of a new class of "dual-frequency, mass market" GNSS receivers.

Source: TAXISAT project

The Easy Mile EZ10, featuring enhanced vehicle-location capability with simultaneous localisation and mapping and robust GNSS systems.

Navigation solution developed in the TAXISAT project, funded by the GSA under the FP7 programme.

The ESCAPE project: Development of E-GNSS engine for safety-critical multi-applications in road transportation

Fundamental Elements

Source: Renault

The need to provide accurate and reliable positioning information is clearly emerging for safety-critical applications, and the most common approach is still to use multiple sources of data, some of which may be rather expensive (e.g. sophisticated radar based sensors, cameras, infrastructures mounted/sensors, differential techniques).

The ESCAPE project is developing a versatile solution to address the needs of such multiple safety-critical applications as:

- Advanced Driver Assistance Systems (ADAS)
- Anti-collision systems (based on V2X)
- Autonomous vehicles
- Dangerous goods transportation

The E-GNSS engine will deliver improved robustness, integrity and accuracy to the integrated location system. It aims to repetitively perform the location calculation, which will primarily be provided to the safety-critical applications, but also to an array of in-vehicle applications that improve the passenger's comfort and smarter mobility. The E-GNSS engine includes the GNSS chipset/receiver and additional software and hardware parts and vehicle standard interfaces that allow for final location calculation with accuracy and reliability suitable for the safety-critical applications.

More information can be found at: https://www.gsa.europa.eu/r-d/gnss-r-d-programmes/fundamental-elements

Better integrity and authentication will support the development of liability-critical applications

Development of a Galileo Open Service authentication user terminal

Unique to Galileo is its authentication capability delivered through an asymmetrical navigation data-based architecture – the Navigation Message Authentication (NMA) – broadcast via Galileo Open Service (OS) signals. This feature could become an added value for a wide variety of applications, including:

- **Road User Charging (RUC):** improving the trustworthiness of toll collection and associated ITS services, and tackling unwanted charging errors.
- **Smart Tachograph (DT):** improving the reliability of truck driver resting time monitoring by means of secure and free of charge GNSS signals.
- **Maritime in restricted waters and fisheries:** to establish fishing zones without territorial inclusion.
- **Other applications:** for which a liability risk or economic consequence would ensue in case of falsification of the signal (e.g. Multimodal transportation and transportation of valuable and dangerous goods handover, Vehicle tracking and Fleet Management Services (FMS), Authenticated time-stamping, etc.).

The to-be-developed **OS authentication user terminal** aims, by means of a valid public key, to continuously process the navigation data and inform users about the received signal's authenticity. Authentication can be also extended from the signal domain to the user position domain through appropriate technologies, thus ensuring the authenticity of the user's position. The user terminal includes the GNSS chipset/receiver, a suitable interface to receive the public key and a central authentication management software tailored for the selected target application.

More information can be found at: https://www.gsa.europa.eu/r-d/gnss-r-d-programmes/fundamental-elements

Source: Thinkstock

Receivers used in liability-critical applications (i.e. for monitoring) may be subject to regulation, albeit a less restrictive form than for those used in safety-critical cases. Here the reliability is driven by economic or legal interests and by the need to ensure cost efficiency of GNSS-based applications when compared to alternative technologies.

This market is considerably larger and more diverse than the safety-critical market, leaving room for products to differentiate themselves technologically and through innovative ancillary services. Devices containing receivers can also be easily fitted or replaced compared to those in safety-critical applications. It should, however, be noted that applications such as the insurance telematics currently use devices based solely on GNSS, with no particular attention given to potential vulnerabilities. This raises risk, as, for example, the widespread use of GNSS technology in applications involving payments (such as road user charging) may generate claims from users for undue charges, or even attempts to evade the payment by "self-spoofing" the GNSS-based on-board unit. As a consequence, both users and service providers must have sufficient trust in the location system to agree on its use for such payments. At the application and OBU levels, this means that position availability, integrity and robustness to intentional jamming or spoofing are key performance parameters.

There is currently no unified strategy to answer these requirements. Rather, system integrators are using a variety of means at the OBU level to cope. However, the potential capabilities of modern multi-constellation GNSS receivers such as integrity (RAIM like) and/or signal authentication could go a long way in supporting them, should adequate receivers/chips be available. Galileo in particular offers signal authentication capability, which is currently being trialled and demonstrated within the EC AALECS project (Authentication and Accurate Location Experimentation with the Commercial Service), paving the way for the more widespread development and operational use of "authentication enabled" GNSS engines. As this Authentication capability is new, there is currently a lack of compatible GNSS receivers/engines, which the GSA Fundamental Elements project "OS Authentication user terminals" is addressing.

GNSS Receivers for Liability- and Safety-Critical Automotive Applications

In 2016, STMicroelectronics is ramping up production of its latest Teseo III family of GNSS receivers, capable of managing all GNSS signals and supporting multi-constellations based on Beidou, Galileo, GLONASS, GPS and QZSS systems. The new receivers support industrial and automotive GNSS applications with automotive grade and extended temperature range, and are compliant with all published GNSS system-level specifications, including Russia's ERA-GLONASS and European eCall system requirements.

While these single-frequency, multi-constellation GNSS solutions are a good fit for traditional Infotainment applications, the emerging Intelligent Transportation Systems (ITS) and Advanced Driver Assistance Systems (ADAS) applications are raising the performance and integrity requirements for GNSS receivers. These liability- and safety-critical applications are creating demand for new advanced GNSS solutions. A new breed of mission-critical GNSS receivers is needed, aimed to work in conjunction with correction data available from different sources in order to provide sub-meter accuracy, and combined with different indicators allowing effective use of GNSS information in the system solution.

As a leading supplier of Smart-Driving solutions, STMicroelectronics is committed to developing high-precision GNSS solutions to serve the new automotive applications.

Testimonial provided by the company.

The move to Performance-Based Navigation drives GNSS uptake in aviation

The trend in requirements focuses on extending the utilisation of GNSS for an increasing number of more demanding applications:

- Transition from conventional to GNSS navigation solutions for all phases of flight.
- New advanced Communications, Navigation and Surveillance (CNS) applications are expected with the use of multi-frequency and multi-constellation navigation capabilities (GNSS timing reference, ADS-Out positioning source, etc.). A new concept of operations is being developed to take advantage of this new GNSS scenario.
- The new Galileo-enabled multi-constellation environment adds robustness to the GNSS system, increasing safety and satisfying one of the main goals of the International Civil Aviation Organisation (ICAO) Global Air Navigation Plans.
- With the use of additional constellations, the availability of GBAS CAT II/III will be significantly improved.
- The development of Advanced RAIM (ARAIM) enabled by Galileo will enhance autonomous on-board integrity monitoring, which allows for the use of the RAIM functionality up to CAT I approach operations.

As previously stated, the aviation market is specifically constrained by regulation. Given the recent decision by the SBAS Interoperability Working Group (IWG) to adopt a transmission on the L5 frequency, it is expected that this market will transition to dual-frequency support. Furthermore, within the next five years, it is expected that the standards for regulated use of multi-frequency and multi-constellation receivers will be finalised, paving the way for a gradual increase in the number of these receivers used within mainstream aviation.

However, a standard cannot be adopted until it is fully proven both technically and operationally. Only once the standards are in place can the receiver manufacturer finalise and certify their products. The GSA Aviation DFMC (Dual-frequency Multi-Constellation) SBAS Receiver prototype project targets the early development of an E1/E5 receiver, allowing for work on the standard to start early and thus accelerate the entire standardisation and adoption process.

The new generation of TopStar GNSS receiver relies on dual-constellation benefits

THALES

The future of GNSS in the aviation sector lies in the combined use of GPS and Galileo. A dual-mode system, with a second constellation, effectively eliminates any common modes of failure with GPS, improving dependability by a factor of 1,000 or more. Sensor hybridisation and data fusion techniques will also be extended with the introduction of Galileo, significantly improving dependability and performance in line with the latest ICAO recommendations on the prevention of signal interference and jamming.

Aviation is paving the way for a new generation of positioning and navigation solutions for safety-of-life applications, with GNSS certified products providing guaranteed signal integrity. These solutions are vital for a wide range of applications, including ground transportation, with the development of autonomous systems. Benefits include precision and integrity, combined with small form factor and low cost. Building on the experience gained in the aerospace sector, GNSS architectures using GPS and Galileo receivers are now entirely conceivable for emerging applications such as driverless cars as well as for public transportation (buses, trams and trains), professional UAVs, shipping and future generations of robotics.

The next-generation TopStar dual-constellation GPS and Galileo-based solution from Thales Avionics is thus set to play a crucial role in the development and testing of safety/liability critical solutions for all forms of transportation.

Aviation DFMC SBAS Receiver Prototype

Fundamental Elements

Source: Airbus

The EGNOS Safety-of-Life (SoL) service, declared operational on the 2nd March 2011, is openly available and freely accessible without any direct charge, and is tailored to safety-critical transport applications in various domains and, in particular, for aviation.

EGNOS v3 will continue to offer this legacy service with the addition of two new features: the augmentation of the Galileo positioning service (i.e. Dual Constellation capability with GPS and Galileo) and providing correction data and integrity information with a second signal in the GPS L5 and Galileo E5a frequency band.

Several aviation receivers' manufacturers have developed user terminals compatible with the current applicable standards and, in order to have Dual-frequency Multi-Constellation (DFMC) receivers ready before the DFMC SoL service becomes operational in 2021, a new generation of user terminal needs to be developed in parallel with (and in support of) the definition of the new standards for DFMC.

The purpose of the **Aviation DFMC SBAS Receiver Prototype** project is to design, develop and test a DFMC SBAS user terminal prototype for the aviation SoL service, augmenting GPS and Galileo capabilities. The developed receiver, besides having SBAS DFMC functions, will also include RAIM (Receiver Autonomous Integrity Monitoring) and Horizontal-ARAIM (Advanced RAIM). Furthermore, the Vertical-ARAIM will be taken into account for the purpose of dimensioning the computational capabilities in the design and developing the prototype receiver.

More information can be found at: https://www.gsa.europa.eu/r-d/gnss-r-d-programmes/fundamental-elements

The need for safety, reliable performance and accuracy will drive the adoption of multi-frequency for commercial drone operation

Commercial use of drones is exploding

Although the commercial and professional use of drones is raising a lot of interest, full market potential will be limited until the regulatory framework is put in place. However, there is no doubt that especially for non line of sight operation these drones demand a location system offering the same level of availability, integrity, continuity and robustness performance as those encountered in other safety-of-life applications.

Depending on their intended use, drones can be equipped with many different kinds of sensors, from visible light, thermal, multispectral, hyperspectral, near infrared cameras to Lidar sensors. As a drone's payload directly affects its overall endurance and performance, the miniaturisation of all components is desirable.

Lighter and smaller sensors significantly help operators improve quality and efficiency in their daily operations. As such, improved battery life remains an essential characteristic that allows for the performance of long-lasting and more complex applications, in addition to supporting highly sophisticated technology (multi-constellation, multi-frequency GNSS, Inertial Measurement Units (IMUs), etc.).

In addition, many new features are under development, including collision avoidance, the return-home function and autopilot systems. Some of these features are incrementally required to reduce potential risks for damages and pilot liability.

Source: Thinkstock

GNSS technology in drones

GNSS is the backbone of commercial drones, informing drone operators about the drone's position and allowing for safe navigation.

Regarding the **professional use of drones**, about 70% of all GNSS receivers produced to equip drones in agriculture and surveying are multi-frequency (L1 + L2) and multi-constellation enabled. The need for highly accurate and reliable performance, and hence the necessity of multi-constellation receivers, depends on the kind of application being deployed. It is likely that an increase in the use of multi-constellation receivers will take place, although this depends on advancements in improved battery life. Around 50% of GNSS receivers are also SBAS enabled. On the contrary, IMU, a sophisticated and still expensive technology, is not widespread, although its uptake will likely increase with a general advancement of GNSS-based solutions and lower prices.

For lower accuracy professional applications such as parcel delivery and video recording or others, dual-frequency is not required.

*However the increasing pressure for better safety, reliability and jamming immunity will likely foster the uptake of **dual-frequency multi-constellation** solutions, as in the case of conventional (manned) aviation.*

Non-professional drones are generally equipped with entry-level GNSS receivers, which typically fulfil user requirements (photography geotagging / homing functions).

Source: Thinkstock

Source: Thinkstock

Regulations

The increasing use of drones poses a regulatory challenge, not only because today's aviation safety rules are not adapted, but also because of the many types of drones and of operating conditions. Even for small drones (below 25 kg) flying in lower airspace (up to 150m above ground), well separated from manned aviation, there are legitimate concerns related to operational safety, privacy, data protection, security, liability, insurance and environment.

Current regulations are very fragmented, with each country having its own policies on authorisation, certification, vertical and horizontal limitations and pilot qualifications. These differences (even between the EU Member States) create barriers to the development of commercial use drones. In fact, it is often impossible to undertake some drone applications due to vertical or visual line-of-sight flight restrictions, limiting missions requiring a drone to fly long distances and often beyond the pilot's visual line of sight.

Given the promised economic benefits of drones, the responsible authorities are working on a new regulatory framework at the national and international levels. For example, the US Federal Aviation Administration (FAA) has issued rules (Part 107) for operating small drones, and the Russian Federation issued similar legislation earlier this year. In the EU, EASA (European Union Aviation Safety Agency) is targeting a formal agreement on drone regulation in 2017, with partial guidelines available by mid-2016.

Virtual balise in railway signalling can offer significant cost savings, unmanned ships and port applications to come in maritime

Different levels of maturity for GNSS consideration in future Rail applications

European railway signalling is undergoing a challenging transition from multiple signalling solutions in different Member States to a unified pan-European solution. The European Rail Traffic Management System (ERTMS) provides positioning via balise, a physical device mounted on the sleepers of a railway track and capable of delivering precise positioning information to the Euro Vital Computer (EVC) on board of the train.

Currently, engineering teams from major signalling companies, through EU-funded R&D initiatives, are working to establish an architecture that would, in the frame of the ERTMS, allow the replacement of physical balises with virtual ones based on a GNSS signal. GNSS, together with additional sensors such as SIL4 odometer or Doppler radar, could replace the more expensive physical balise technology in particular operational scenarios. Receivers with specific requirements related to railway safety needs will likely have to be developed in the near future, taking advantage of E-GNSS' dual-frequency, multi-constellation and SBAS features.

Unmanned ships and port applications in maritime will increasingly rely on GNSS

Maritime standards for all single constellation GNSS are already in place, and "performance standards for multi-system shipborne navigation receivers" were adopted in 2015. The maritime community is promoting the concept of "Resilient PNT" that, in terms of GNSS technology, is fully consistent with the use of multiple GNSS constellations, SBAS (current and future), and multiple frequencies. Much technology convergence can be expected between this domain and Aviation.

Unmanned merchant ships will soon become a reality, with the autonomous ship serving as an important next step in the evolution of sustainable maritime transport. The EU Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) project addresses the feasibility of an autonomous and unmanned vessel, and aims to develop its individual components in a way that existing ships can be retrofitted.

Finally, GNSS usage in ports is forecast to grow rapidly due to increasing congestion in and around ports, combined with the ever-increasing size of vessels. Two significant applications with even more stringent requirements than ship navigation are:

- **Portable Pilot Units (PPUs):** GNSS-enabled specialist navigation aids used to enter port.
- **Port Automation:** such as the tracking of shipping containers and other goods.

HORIZON 2020

STARS SATELLITE TECHNOLOGY FOR ADVANCED RAILWAY SIGNALLING

Galileo potential: STARS project supports inclusion of E-GNSS into ERTMS

The Horizon 2020 Satellite Technology for Advanced Railway Signalling (STARS) project paves the way for future deployment of E-GNSS in safety-relevant railway applications. By further developing the ERTMS standard by implementing satellite positioning, it will be possible to reduce the cost of future railway signalling systems. The project focuses on three main topics:

1. Elaboration of reference data and characterisation of the railway environment through a measurement campaign.
2. Assessment of E-GNSS performances achievable in the railway environment, with the determination of the applicable requirements for the positioning system and the necessary evolutions of E-GNSS services and ERTMS/ETCS functions.
3. Quantification of the economic benefits and specifying the possible roadmap for implementing E-GNSS on railways.

The project is closely linked to other initiatives and actions related to the same topic. In order to feed directly into the ERTMS standardisation work, project partners cooperate closely with UNISIG. Moreover, the project will actively interact with Next Generation Train Control project (NGTC), with the results being directly implemented by SHIFT2RAIL, providing practical demonstrators for different categories of railway tracks.

SEVENTH FRAMEWORK PROGRAMME

MUNIN

MUNIN: Maritime Unmanned Navigation through Intelligence in Networks

MUNIN aims to develop and verify a concept for the autonomous ship by achieving a number of objectives:

1. Develop the technology concept needed to implement the autonomous and unmanned ship.
2. Develop the critical integration mechanisms, including the ICT architecture and the cooperative procedural specifications, which ensure the technology works seamlessly and enables safe and efficient implementation of autonomy.
3. Verify and validate the concept through tests run in a range of scenarios and critical situations.
4. Document how legislation and commercial contracts need to be changed to allow for autonomous and unmanned ships.
5. Provide an in-depth economic, safety and legal assessment to show how the results will impact European shipping's competitiveness and safety.
6. Show how the concept gives such direct benefits as reduced off-hire due to fewer unexpected technical problems, and how it provides efficiency, safety and sustainability advantages for existing vessels in the short term, without necessitating the use of autonomous ships.

In order to achieve these objectives, several elementary developments are first needed. Together, they will enable autonomous ships on a conceptual level. However, in practice, full autonomy could be difficult to realise in the near future. Nevertheless, the research conducted within MUNIN will have an impact on maritime transport.

EGNOS and Galileo complement each other to address all key performance parameters

Confidence and resilience are key features in "liability-, safety- (and control-) critical solutions". Galileo and EGNOS help fulfil user needs by enhancing the capability of the receiver to derive a precise and reliable location.

Galileo

Used in conjunction with other GNSS, Galileo will increase the number of available satellites in view. This is expected to significantly improve the **availability** and **accuracy** of the provided location – especially important in such challenging environments as urban canyons. As a result, Galileo will make the computed location reliable enough to be used in liability/safety-critical solutions, including connected vehicles and autonomous cars.

Galileo also ensures the computed location is more robust, both in multi-GNSS mode (as the addition of different signals and frequencies makes spoofing and jamming easier to detect) and in standalone (as the presence of Galileo signal authentication allows one to verify the authenticity of the SiS).

EGNOS

EGNOS also improves **accuracy**, thanks to the differential corrections broadcast. Moreover, its distinguishing features of integrity and continuity make it an essential addition to maritime and aviation solutions.

Key Performance Parameter (KPP)	EGNOS contribution*	Galileo contribution*
Availability		●●
Accuracy	●●	●●●
Continuity	●●●	
Integrity	●●●	
Robustness		●●●

* ●●● = major contribution, capable of enabling new GNSS applications, ●● = medium contribution, enhancing the user's experience so benefits (e.g. operational, at cost level), are achieved, ● = minor contribution, performances improved but no major differences at users' level

EGNOS best practice: how aviation community benefit of EGNOS

Source: Thinkstock

By augmenting existing GPS signals to offer enhanced vertical precision and integrity, pilots can rely on EGNOS for a safe approach to aerodromes in weather conditions that have previously rendered landing unsafe or impossible. In a nutshell, EGNOS provides:

- **Improved safety and accessibility:** increased vertical accuracy and integrity, allowing the decision height to be lowered (APV-I) to as low as 200ft. Non-ILS equipped airports with a challenging geography, or suffering from bad weather, become much more accessible, and the number of controlled flights into terrain decreases.
- **Enhanced flexibility:** Area navigation (RNAV) and performance based navigation (PBN) for advanced arrival, approach and departure procedures are enabled by EGNOS.
- **Better cost efficiency and environmental safeguard:** More accessible runways reduce delays and diversions due to bad weather. Shorter approaches enabled by EGNOS result in reduced fuel consumption and CO_2 emission.

HORIZON 2020 GALILEO InDrive

Source: BMW

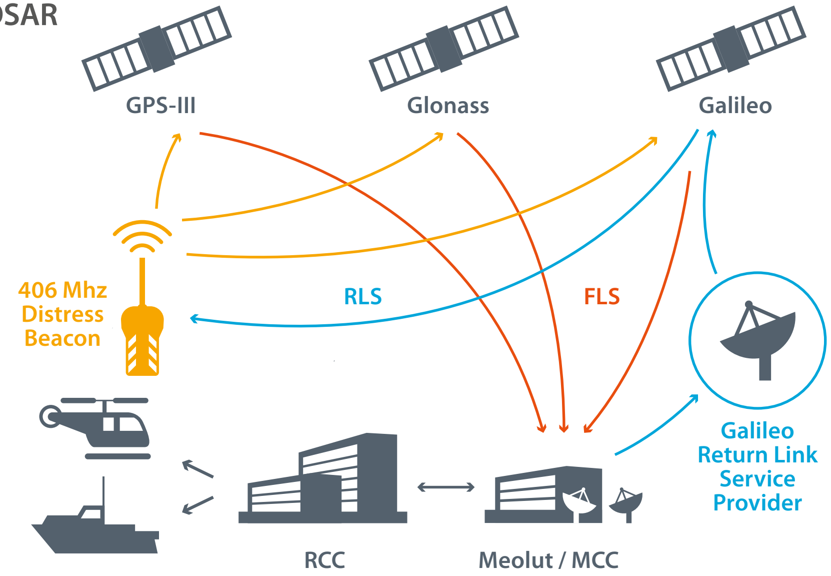
Galileo potential: InDrive leverages European GNSS to enable autonomous driving

The Horizon 2020 InDrive project aims to develop an automotive enhanced positioning platform, based on the integration of E-GNSS and other on-board sensors, that meets the requirements of safety-critical applications within the context of innovative but close-to-market solutions for autonomous driving. Leveraging on E-GNSS signal properties, InDrive will create a framework that specifies the requirements for data acquisition, signal tracking and data fusion to guarantee the proper handling of positioning data. Such an approach introduces an innovative integrity framework, which allows the applications to guarantee compliance in terms of false alarm rates and accuracy.

For example, when the position confidence elaborated by the solution is high, driving instructions can be very precise and safety-critical applications, such as emergency breaking, can operate. On the other hand, when position confidence is low and ambiguous, only the requirements for less demanding applications will be met, with the system operating accordingly.

GNSS enhances SAR mission performance

MEOSAR



COSPAS-SARSAT overview

The International Cospas-Sarsat Programme provides distress alert and location data to help Search and Rescue (SAR) authorities assist persons in distress. Operating since 1982, the system has achieved world-wide recognition. It is composed of:

- Distress radio beacons (ELTs* for aviation, EPIRBs** for maritime, and PLBs*** for personal use) that transmit signals during distress situations.
- Instruments on board satellites in GEO and LEO orbits that detect the signals transmitted by distress radio beacons.
- A ground segment made of Local User Terminals (LUTs), which receive and process the satellite signals and forward alerts to Mission Control Centres (MCCs) for use by SAR authorities.

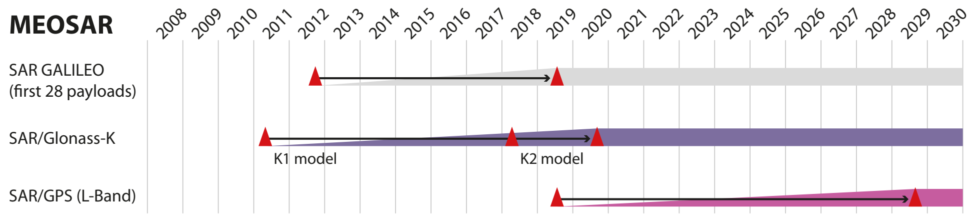
The use of Cospas-Sarsat 406 MHz distress beacons, whether mandated by administrations or as a result of voluntary use by individuals at risk, is becoming increasingly widespread.

(*) Emergency Locator Transmitter
(**) Emergency Positioning Indication Radio Beacon
(***) Personal Location Beacon

GNSS and SAR

There are three ways in which GNSS adds and contributes to SAR missions:

1. By providing more satellites carrying a SAR payload relaying the Forward Link Service (FLS), thus enabling the build-up of the MEOSAR system that is expected to replace the aging LEOSAR system. The MEOSAR will be backward-compatible and is expected to provide enhanced performance for all 406 MHz beacons currently in operation, to include global, near-instantaneous alerting and locating capabilities, and provide greater resilience to beacon-to-satellite obstructions. The MEOSAR Full Operational Capability is planned for 2018-2020.



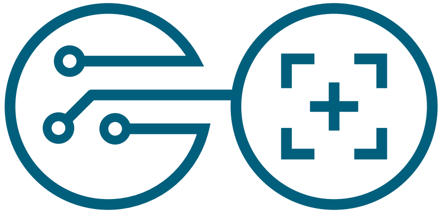
2. By providing position information to the "Location Protocol" (LP) enabled distress beacons. Although not compulsory (the GNSS position is only used as secondary) this is a very useful feature, all the more so as the GEOSAR system cannot independently compute the position of the distress caller (whereas LEOSAR can).
3. In the case of Galileo satellites, by providing a Return Link Service (RLS) in addition to the Forward Link Service, thus acknowledging the receipt of the distress call to the beacon (within 15 minutes), enabling the possibility of detecting false alarms and reducing the stress of people awaiting rescue (PLBs). The RLS is planned to be operational by 2018.

SAR KEY TRENDS:

- MEOSAR will replace LEOSAR within five years.
- Cospas-Sarsat 406 MHz distress beacons will increasingly include an internal GNSS receiver. This is enabled by the "ever smaller, ever less power" trend of GNSS chipsets.
- Galileo's unique Return Link Service is expected to meet public interest and foster the adoption of Galileo in ELTs, EPIRBs and PLBs. In fact, the Return Link is already part of the Cospas-Sarsat beacon specification.
- Remote activation of ELTs is being considered at ICAO level.

High precision, timing and asset management solutions

Accuracy is the key performance parameter for high precision solutions



Characterisation of the macrosegment

The high precision, timing and asset management solutions macrosegment includes receivers and technologies with various desired key performance parameters for each specific segment. Those that require high positioning accuracy include agriculture, surveying and construction. Users of these segments largely rely on one or more of the well-established augmentation techniques (RTK, PPP, etc.) in order to provide the required level of accuracy. Applications in the GIS/Mapping domain, on the other hand, requiring a level of accuracy ~1m utilise the free SBAS services or DGNSS.

The other segments include asset management and timing and synchronisation for which single-frequency receiver based products are used, as they offer satisfactory performance. The exception is timing laboratories, which use very high grade metrology GNSS receivers.

Key performance parameters*

The most critical parameters within the macrosegment vary significantly, depending on the segment involved.

For agriculture, the most important parameters are:

- **Accuracy:** many agricultural applications require very high accuracy to deliver their benefits, such as machine control (seeding and variable rate application). Applications requiring precision benefit from the mitigation of such issues as multipath and signal shadowing.
- **Availability:** certain agricultural practices have to happen at specific times and on specific dates, an outage during these times would be extremely detrimental.
- **Robustness:** there is a safety-critical element to applications involving active machine guidance, so protection against potential spoofing or jamming is desirable.

For asset management and GIS/mapping, the most important parameters are:

- **Integrity:** failures in integrity could lead to erroneous charges/fines and undermine the entire application.
- **Robustness:** susceptibility to jamming or inability to detect spoofing may render the application useless.
- **Availability:** the achieved availability is important in GIS/mapping, as lack of signal availability can result in costly delays.

For surveying, the most important parameters are:

- **Accuracy:** depending on the specific application, centimetre level accuracy may be required.
- **Integrity:** depending on the application, a failure to detect erroneous measurements could be extremely costly.
- **Robustness:** certain applications could benefit from being able to authenticate the recorded positions (for example, surveys linked to the Common Agricultural Policy).
- **Availability:** lack of sufficient signal availability could result in costly site re-occupations.

For construction, the most important parameters are:

- **Accuracy:** depending on the specific application, centimetre level accuracy may be required.
- **Integrity:** depending on the application, an integrity failure could be extremely costly.
- **Robustness:** for the same reasons as integrity.
- **Availability:** a lack of signal availability could result in costly delays.

For timing & synchronisation, the most important parameters are:

- **Availability:** access to timing services must be assured on a 24/7 basis.
- **Robustness:** there is a safety-critical element to some applications, which means that protection against potential spoofing or jamming is desirable. This is particularly true for the synchronisation of critical infrastructure networks in:
  - Telecommunications networks
  - Finance
  - Power distribution systems
- **Integrity:** applications requiring accurate time stamping for legal purposes.
- **Accuracy:** although accuracy requirements for these applications are generally met even by entry level receivers, there is an emerging need for a significantly better synchronisation accuracy in 4G (and 5G) telecommunications networks, as well as for 4K Digital Video Broadcast (DVB). As for Timing laboratories, accuracy is obviously the primary parameter, as stability and precision must be kept at the levels provided by atomic clocks.

Key Performance Parameter*	High precision, Timing and Asset Management solutions
Availability	🟢
Accuracy	🟢
Continuity	🔴
Integrity	🟢
Robustness	🟢
Indoor penetration	🔴
Time To First Fix (TTFF)	🔴
Latency	🔴
Power consumption	🔴

🔴 Low priority 🟢 High priority

** The Key Performance Parameters are defined in Annex I*

GNSS receiver modules for professional grade receivers are delivered by a few specialised suppliers

Leading components manufacturers		
AERONTENNA TECHNOLOGY INC	North America	www.aeroantenna.com
AGJUNCTION	North America	www.hemispheregps.com
AMAZONEN-WERKE	EU28	www.amazone.de
BEIJING BDSTAR NAVIGATION CO LTD	Asia-Pacific	www.navchina.com
DEERE & CO (NAVCOM)	North America	www.deere.com
FURUNO	Asia-Pacific	www.furuno.co.jp
HEXAGON (LEICA GEOSYSTEMS, NOVATEL)	EU28	www.hexagon.se
HOLUX TECHNOLOGY, INC	Asia-Pacific	www.holux.com
JAVAD GNSS	Non-EU28 Europe	www.javad.com
LAIRD	EU28	www.laird-plc.com
NAVIS	Non-EU28 Europe	www.navis.ru
NAVCOM TECHNOLOGY, INC.	North America	www.navcomtech.com
PULSE ELECTRONICS	North America	www.pulseelectronics.com
SEPTENTRIO	EU28	www.septentrio.com
SHANGHAI HUACE NAVIGATION TECHNOLOGY	Asia-Pacific	www.huace.cn
STM	EU28	www.st.com
TOPCON	Asia-Pacific	www.topcon.co.jp
TRIMBLE	North America	www.trimble.com
U-BLOX	Non-EU28 Europe	www.u-blox.ch
YAGEO CORPORATION	Asia-Pacific	www.yageo.com.tw

Disclaimer: Note that some key industry players do not appear in this list which does not include system or terminal integrators.

Receiver Industry

Although complex, the product offering for professional-grade receivers can be subdivided into the following:

- Surveying receivers (geodetic-grade reference station receivers and survey-grade receivers).
- Machine control receivers (being agriculture and construction receivers).
- General purpose receivers for GIS/mapping.
- Tracking and monitoring receivers (asset management).
- Timing receivers.

Whilst each of these segments use receivers designed for each specific use and are produced by a wide range of manufacturers, they are based on a relatively small number of GNSS receiver modules produced by a few manufacturers, which in turn are based around an even smaller number of chipsets. Generally, these chipsets are proprietary designs, with their evolution driving the evolution of most of the market place. Typically, each new generation of chipset will be based on the latest generation of ASIC technology, with each chipset designed to satisfy as many applications as possible and to allow extensibility at the module level.

Modules, especially low-end models, will typically not utilise all of a chipset's functionality. Since modern chipsets almost always include powerful microprocessor capability, each module can be further customised by using different versions embedded in firmware containing market-specific features. This allows many modules to be upgraded post-purchase using some form of authentication key supplied by the manufacturer.

Professional grade receivers are used for a wide range of applications

Geodetic reference station and surveying receivers

Geodetic-grade reference station receivers are primarily used in permanent networks (commercial, institutional or scientific) supporting a diverse range of applications ranging from day-to-day boundary surveying to crustal deformation monitoring. The operators of such permanent GNSS networks are often the first adopters of new constellations, as they want to have receivers in place at the same time or before the first satellites in a new constellation are launched.

Due to advances in ASIC and battery technology, it has recently become possible to sufficiently reduce power consumption to allow the design of man-portable combined antenna and receiver packages, often referred to as the "smart antenna" format. This format has proved popular for mobile surveying receivers, as it leads to significant operational benefits.

Such receivers are produced and marketed by a small number of manufacturers offering vertical integration with other (non-GNSS) geoscience instrumentation. These "key" manufacturers also sell their GNSS technology to integrators.

Machine control receivers

Machine control receivers are used in machine guidance applications, mainly in the civil engineering and agricultural sectors. The significant potential market size for these products means products are designed to be sector-specific. As with survey receivers, here too the smart antenna format has become very popular, as it greatly eases the installation of the product on the host vehicle. However, in this case, power consumption is not a primary consideration due to the availability of power from the host vehicle.

Machine guidance receivers are also used in conjunction with an external controller (providing the human-machine interface), the industry-specific control software, and with the interface to the vehicle control systems. Due to the complexity of these guidance systems, they are most commonly purchased fully installed and integrated with the host vehicle. However, particularly within the agricultural sector, it is not uncommon to move a key component like the smart receiver from machine to machine as dictated by the growing season.

The "core technology" used in such products is produced by the same manufacturers as in the surveying sector, although the products can be packaged, integrated and marketed through different channels (e.g. agriculture machinery providers).

General purpose receivers for GIS/mapping, tracking and monitoring

General purpose receivers for GIS/mapping, tracking and monitoring require metre level accuracies, meaning single-frequency standalone or SBAS receiver based products can meet these requirements. For mapping applications requiring decimetre accuracies, survey-grade receivers are used.

Receivers targeting the general purpose mapping and/or data gathering market will also use the smart antenna format, or even smaller handheld formats, whenever practical. Such products are developed and marketed by the same small group of companies, who for this segment are joined by integrators generally specialised in rugged mobile computing.

As tracking and monitoring applications require 1 to 10 m accuracy, they can use lower cost single-frequency GNSS modules. The chosen form factor and peripheral capabilities are dependent on the specific application and system in which the tracking unit will be used. For this reason, this market is very fragmented and is typically served by the smaller manufacturers integrating their products on modules produced by the larger GNSS receiver and communications module manufacturers. These units often have special requirements, such as anti-tamper construction, in order to satisfy the needs of the host system.

Timing receivers

Timing reference receivers used, for example, in UTC(k) laboratories, are expensive pieces of equipment, designed and manufactured to the highest achievable standards by a handful of specialised manufacturers (Septentrio) and OEM suppliers (Javad), or domain-specific integrators (Piktime, MESIT).

General purpose Timing receivers (boards / modules / smart antennas) are offered by most GNSS technology providers or components manufacturers (Novatel, Trimble, Javad, U-blox, etc.). These receivers are often integrated in dedicated T/S terminals (with all required interfaces) by domain specialist companies, especially when dealing with products targeting critical infrastructure synchronisation. Major actors in this domain include Microsemi, Meinberg and Spectracom (OROLIA).

Prototype timing receiver for critical infrastructure

Fundamental Elements

GNSS timing is essential for interconnected systems that monitor, control, produce, track, or transact, and that require synchronisation of geographically dispersed sites. Applications of GNSS timing include, but are not limited to, aviation, telecommunications and computer networks, energy generation and distribution, time labs and other government functions. All of these applications use infrastructure that relies on essential GNSS timing in order to synchronise their networks and monitor sites.

The purpose of the **Prototype timing receiver for critical infrastructure** project is the development and testing of a Galileo timing receiver.

The envisaged outcome is a low-cost, robust and jamming-resistant Galileo receiver capable of determining timing with high accuracy in bias and drift. Some features of this prototype receiver could include 1 pps and 10 MHz signals outputs and interfaces implemented through the time code formats NTP (network time protocol) and IRIG-B (inter-range instrumentation group, time code B).

More information can be found at: https://www.gsa.europa.eu/r-d/gnss-r-d-programmes/fundamental-elements

Multi-constellation and multi-frequency are widely adopted to fulfil stringent accuracy requirements

Multi-constellation adoption

The constellations supported within the professional segment are the most wide-spread in comparison to the other two segments.

Due to the surveying, GIS/mapping, construction and agriculture markets being relatively small and products having a longer lifecycle, the evolution in receiver design is more forward-looking and long-term than in the mass or transport markets. This, together with demand for high performance (be it accuracy, integrity, or otherwise), results in early support for constellations.

Most products currently in a manufacturer's product line support two or more constellations. However, the longer product lifecycle means many older products only supporting GPS remain in use. Due to cost and power considerations, fleet and asset tracking applications typically use GPS-only products, whereas lower accuracy GIS/mapping receivers are equipped with SBAS capability.

To frame this overview within the timing and synchronisation segment, new chipsets and receivers are already multi-constellation capable.

Multi-frequency adoption

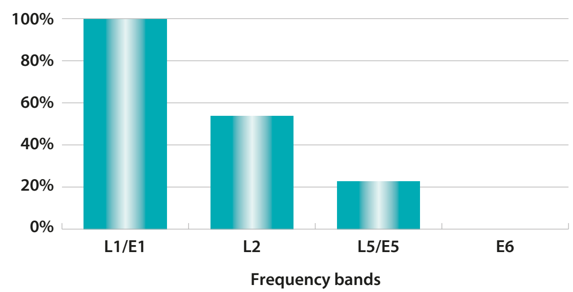
In surveying, dual-frequency capability is needed to support the sector's high accuracy requirements (<5cm). In the future, triple-frequency capability will almost certainly become more important. Permanent reference station receivers tend to be "all satellites, all open signals in view" in order to support all types of processing and mobile receivers.

In agriculture, especially for such applications as machine control, high accuracy is required, meaning that for all practical purposes dual-frequency is mandatory. If the Galileo CS is adopted within the market, it is likely that triple-frequency receivers will become common place.

Due to cost considerations, receivers used for GIS/mapping, tracking and monitoring are most often single-frequency only. For trackers, which may rely on integrated power supplies, minimal power requirements are an even more important driver.

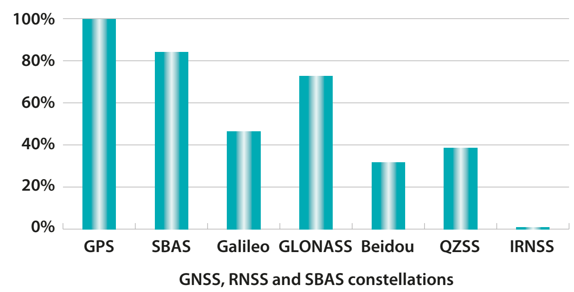
In the timing and synchronisation segment, the substantial majority of receivers are single-frequency. The exceptions to this rule are the time transfer laboratory receivers (metrology equipment), which tend to use all available frequencies/signals.

Frequency capability of GNSS receivers[1]



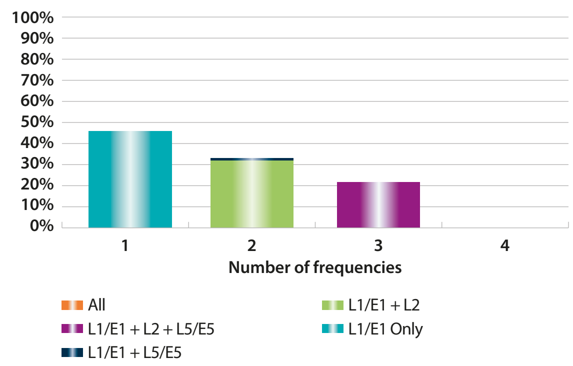
[1] shows percentage of receivers supporting each frequency band

Constellation capability of GNSS receivers[2]



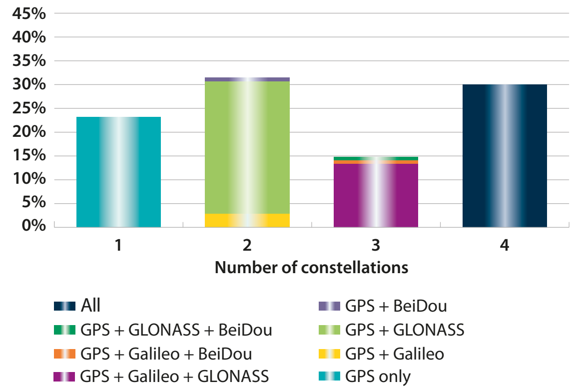
[2] shows percentage of receivers capable of tracking each constellation

Supported frequencies by GNSS receivers[3]



[3] shows percentage of receivers capable of tracking 1, 2, 3 or all the 4 frequencies

Supported constellations by GNSS receivers[4]



[4] shows percentage of receivers capable of tracking 1, 2, 3 or all the 4 GNSS constellations

Disclaimer: The above graphs reflect manufacturers' publicly available claims regarding their products' domain(s) of use and NOT their actual suitability for specific applications as can be demonstrated by, for example, a certification (when standards and regulations are existing) or their actual usage.

Accuracy is achieved by increasing the number of GNSS channels supported and the use of augmentation services

Typical state of the art receiver specifications for the high precision, timing and asset management segment

Features	Surveying	T&S (for critical infrastructure)
Number of channels	Hundreds (in average 200)	Up to 100
Code / Phase processing	Code and carrier phase	Code and carrier phase
Constellations	Multi-constellation	Single or multi-constellation
"Quality" of observables	Unsmoothed pseudorange, carrier phase measurements	Typically Carrier phase, Code pseudo-range and Doppler
Multipath rejection techniques	Usually yes	-
SBAS / A-GNSS readiness	SBAS and A-GNSS supported	SBAS and A-GNSS supported
Receiver connectivity	Examples: Wi-Fi, Bluetooth, USB, 3.5G, NMEA, RTCM	Examples: UART, USB, SPI, DDC
Frequencies	Dual, exceptionally triple frequency	Single or dual frequency
Typical sensitivity	-135 dBm acquisition -140 dBm tracking	-135 dBm acquisition -140 dBm tracking
TTFF	Cold Start: < 60s Warm Start: < 30s Re-Acquisition: < 15s	Cold Start: < 30s Warm Start: < 5s Re-Acquisition: < 2s
Form Factor	Receiver	Receiver Chip or Module
Antenna	External, active and passive supported	External, active and passive supported

Features	Agriculture	GIS/Mapping and Asset Management
Number of channels	Up to 100	Tens
Code / Phase processing	Code and carrier phase	Code
Constellations	Multi-constellation	One or two constellations
"quality" of observables	-	-
Multipath rejection techniques	Usually yes	-
SBAS / A-GNSS readiness	SBAS supported	SBAS supported
Receiver connectivity	Examples: RS-232, NMEA	Examples Asset/Fleet Management: Sub-D, CAN Examples GIS/mapping: Wi-fi, Bluetooth, USB
Frequencies	Dual, exceptionally triple frequency	Single frequency
Typical sensitivity	-135 dBm acquisition -140 dBm tracking	-135 dBm acquisition -140 dBm tracking
TTFF	Cold Start: < 60s Warm Start: < 35s Re-Acquisition: < 2s	Cold Start: < 60s Warm Start: < 35s Re-Acquisition: 2s
Form Factor	Receiver	Asset/Fleet Management: Receiver Chip or Module GIS/Mapping: Receiver
Antenna	Internal or external	External

Disclaimer: The above specifications are reflecting manufacturers' commercial literature. Furthermore, they concern their most recent products. Consequently, discrepancies may exist between the installed receivers' characteristics and those stated above.

Number of GNSS channels

In a typical architecture, a receiver assigns a channel to each tracked signal (representing an individual-frequency and signal component from an individual satellite). Although historically devices supported around 12 channels, there has been an increasing trend for larger numbers of supported channels. This trend is largely driven by the ever-increasing capability of semiconductor technologies. As a result, today some surveying receivers are capable of processing up to 864 channels, although typical values are in the order of 200. This enables a receiver to support all current and planned constellations and frequencies, including SBAS systems.

Receivers benefit from multi-frequency signal processing for the removal of the frequency-dependent errors that are present in GNSS signals, hence improving receiver accuracy. The most important example of this is the correction for ionospheric delays, as these usually represent the main contributors to the overall measurement error. However, there are trade-offs implied between cost, size, power consumption, performance, signal and band filtering, and analogue circuitry quality.

Augmentation services

From a technology perspective, the incorporation of commercial GNSS augmentation services is driven by the need to meet key performance parameters required by users. For example, the accuracy for agricultural machine guidance or survey applications simply cannot be achieved without some form of augmentation beyond what is publicly available. This has historically been met by RTK, but will increasingly be met through PPP techniques. This means professional GNSS receivers now include L-band data link receivers that allow for the reception of commercial DGNSS services; and/or Ultra high frequency (UHF) data link or cellular radio modules to allow the use of RTK and Network RTK services. The associated additions to the position solution algorithms, along with any conditional access functionality, have to be included in firmware to complete the capability.

Power and on-board communication

Unlike the mass market, professional application receivers often have access to a power source, making power consumption less of an issue. This allows the receivers to process considerably more GNSS channels without thought to power consumption. The main exception to this are professional receivers targeting portable land surveying devices, the setting out and GIS/mapping market, and some asset management modules not mounted on an object with a powerful energy source.

To support RTK, Network RTK (N-RTK) and satellite-delivered real-time PPP services, modern GNSS receivers designed for these markets (e.g. survey, agriculture) also provide an integrated data link capability in the form of one or more of the following: an UHF data link modem, a 3G or 4G cellular data link module or an L - band mobile satellite services (MSS) data link receiver.

Antennas

Typically surveying, reference-grade or machine control receivers will utilise an externally mounted antenna, which often includes an LNA and some RF filtering to overcome associated feeder cable losses. They may also employ various techniques designed to mitigate multipath interference. In the future, complex null steering in phased array antennas could become widespread as a way to overcome the effects of intentional or unintentional jamming. In the case of portable units, the antenna is often integrated within the GNSS receiver.

Technology developments will soon enable low-cost receivers capable of cm-level precision

Trends and Prospects

The main technological trends and prospects for the use of GNSS for high precision and timing and asset management solutions are driven by:

- Significant improvements in High-Accuracy solutions (e.g. multi-constellation, multi-frequency, Galileo CS High Accuracy (CS-HA)).
- Increased availability of low-cost equipment (e.g. performant handheld devices, SBAS-enabled devices, more affordable GNSS RTK solutions).

With regard to high precision solutions only:

- Uptake of PPP.
- Integration of GNSS with other complementary technologies (Lidar, laser scanners, Remote Sensing, and robotics) within farm management systems.

Emerging multi-frequency and multi-constellation support

In the professional area, high accuracy is the most stringent demand across practically all applications. Multi-constellation greatly contributes to ensuring such accuracy in most circumstances. The vast majority (85%) of receivers used in the professional applications sector is already equipped with software that can track - at minima - two constellations (40% can track all four global constellations).

Furthermore, the introduction of the Galileo Commercial Service and GPS L5 will allow high accuracy users to benefit from triple-frequency solutions. This is expected to significantly reduce convergence time for PPP and differential techniques.

In the future, **Geodetic reference station, survey and machine control receivers** with triple-frequency capability will almost certainly increase in importance. As these receivers are used in conjunction with augmentation services, it takes some time for service providers to upgrade their networks, their correction formats and algorithms, and thoroughly test them prior to the launch of a new service. This is why network operators have already started to upgrade their equipment in several countries, ensuring they are ready when a new constellation approaches a sufficient size to offer clear benefits and foster end-users demands.

In the domain of **general purpose receivers for GIS/mapping**, professional users tend to use consumer-grade handheld devices such as smartphones or tablets to perform the data acquisition and asset management tasks. Alternatively, the connection of such devices with professional receivers offers comfort and friendliness while preserving high precision and ruggedness, and saves battery for the phone/tablet. The reduction of GNSS receiver prices and increase in accuracy are transforming mapping into a more accessible activity: democratisation of mapping.

The **asset/fleet management receiver** market is well established and has limited performance requirements, with single-frequency GNSS-based implementations being dominant. However, it is expected that in the future dual-frequency receivers and authentication capability will become more affordable and thus likely widespread.

Timing laboratories receivers, meanwhile, will continue to share many commonalities with geodetic ones (all signals). And **T/S receivers used in critical infrastructures** will likely migrate to multiple constellation and (for reliability reasons) even possibly dual-frequency (E1/E5), along with adopting authentication. Finally, the demand for higher accuracy (4G and 5G telecoms, DVB-T) will most likely lead to adoption of dual-frequency (E1/E5).

Development of high-end professional receivers and corresponding antennas

Fundamental Elements

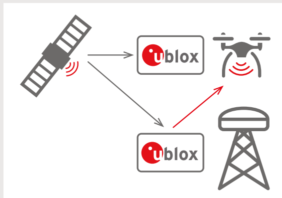
When it comes to navigation and positioning, professional users require high accuracy, high availability, high tracking sensitivity and high performance multipath rejection techniques. The exploitation of multi-constellation signals modulations, offer immediate benefits to address these requirements – pushing forward the development of state-of-the-art high-end E-GNSS receivers. Typical professional applications requiring high-end receivers include surveying (cadastral, construction, machine control, etc.), precision agriculture (automatic steering, Variable Rate Technologies), oil and gas platform management, etc.

The objective of this **development of high-end professional receivers and corresponding antennas** is to further advance GNSS technology for professional applications and, more specifically, investment in E-GNSS differentiators targeting high-precision, ultra-performant, cost-competitive professional receivers and corresponding antennas.

The end result will be three integrated products, each one designed for a dedicated professional use. These integrated products will ensure optimal performance in the specific operational conditions and respond to the specific needs of the end user in terms of accuracy, time-to-first-fix and power-consumption.

More information can be found at: https://www.gsa.europa.eu/r-d/gnss-r-d-programmes/fundamental-elements

U-blox brings low-cost centimetre-level precision GNSS technology to the market



RTK technologies have been used for some time in low- volume niche markets, such as surveying and construction. Due to high costs and complexity, this enhanced positioning technology has been inaccessible for most other uses. Emerging high volume markets, such as unmanned vehicles, require high precision performance that is energy-efficient and low in costs. Other application areas include agriculture and robotic guidance systems, such as tractors or robotic lawnmowers.

The new u-blox's NEO-M8P is the smallest high precision GNSS RTK (real time kinematic) module available on the market based on GPS and GLONASS satellite-based navigation systems. The rover with the u-blox NEO-M8P-0 receives corrections from the u-blox base receiver NEO-M8P-2 via a communication link that uses the RTCM (Radio Technical Commission for Maritime Services) protocol, enabling centimetre-level positioning accuracy. The RTK algorithms are pre-integrated into the module. As a result, the size and weight are significantly reduced, and power consumption is five times lower than existing solutions, thus cutting costs and improving usability dramatically.

Testimonial provided by the company.

PPP and integration solutions are emerging in agriculture and surveying

Uptake of PPP

The landscape of RTK is changing with:

- The proliferation of RTK GNSS receiver "boards".
- Massive uptake of RTK solutions in fast-growing markets such as China, which lies in the so-called GNSS hotspot of satellite visibility.
- The widespread availability of active and passive reference stations and RTK reference station networks operated by several national mapping agencies and commercial vendors.
- Significant decrease in the price of RTK GNSS receivers, due to a congested market and the competitive pressure from emerging PPP solutions.

These elements drive the trend towards low-cost, dual-frequency (L1/E1 and L5/E5) receivers capable of cm-level horizontal/vertical precision. As these become widely available they will enable the proliferation of RTK for a range of high accuracy applications. At the same time, and despite the challenges in delivering PPP solutions, particularly in a real-time environment, they are increasingly seen as a viable alternative to DGNSS solutions and are becoming popular amongst users who need sub-decimetre accuracy. This is especially true for users operating in environments where RTK is not an option (further from the coast), but also in areas where permanent networks are not available and the investment required for a full RTK system (2 receivers + a data-link) has to be compared with the lower cost of a PPP solution (1 receiver). Thus, in the context of centimetre accuracy applications, while RTK remains the premium option and offers immediate solution convergence, the minimal equipment needs and global accessibility make PPP an interesting alternative.

Integrated solutions with GNSS and complementary technologies

Driven by rigorous demands, the professional segment (surveying, construction) has traditionally been forward-looking in regards to adopting innovative technologies. In the past few years, several "tools" have been added to the arsenal of high accuracy users:

- **3D laser scanners:** by scanning a horizontal and vertical field from a static location, 3D laser scanners allow for the collection of dense clouds of points used to create digital 3D models of buildings or land.
- **Total Stations:** theodolites used to electronically calculate distances to centimetre accuracy, using a laser or infrared beam and with electronic data logging systems. Robotic versions of total stations are available, allowing surveyors to remotely operate them.
- **Lidar and photogrammetric cameras:** usually mounted on board aircrafts, Lidars are used to measure distances by illuminating different targets and calculating the backscattering of light. Using different wavelengths Lidars create elaborate 3D point cloud models of the landscape, with detailed representation of different elevations.

GNSS receivers are integrated together with these technologies to provide the coordinates of the sensor performing the measurement – both for the required initial known position and for any further coordinate measurements. This is applicable to, for example, hydrographic surveying (MBES (Multi-beam echo sounder) + IMU + GNSS), infrastructure visualisation of oil and gas pipelines (Lidar + GNSS + IMU), cadastral surveying (total stations + GNSS) and geo-referenced laser scanning data collection (terrestrial, airborne, and mobile).

Technology fusion by Trimble

Trimble creates new combinations of technologies that produce additional value along the data chain ecosystem. However, the benefits are not not fully realized until the data is transformed into information that can be put to work. This added value is where blended geospatial technologies are opening new doors for what can be achieved.

The data sources can be based on very different, but complimentary technologies. For example, the Trimble MX8 mobile mapping system fuses data from GNSS, inertial, LiDAR, imaging and vehicle speed sensors to capture georeferenced points and imagery of streets and other sites.

The Trimble V10 imaging rover with Trimble VISION™ technology leverages calibrated imaging sensors that allow digital images to be captured directly from a survey pole. The Trimble V10 precisely captures 360-degree digital panoramic images for efficient visual documentation and measurement of the surrounding environment. This solution works standalone or can be seamlessly integrated with the Trimble R10 GNSS receiver or Trimble S-series total stations to combine panoramic images with high-accuracy positions to produce an accurate and comprehensive geospatial dataset.

These are just a few examples of the many applications that benefit from Trimble integrated technologies and solutions.

Testimonial provided by the company.

GNSS a pillar of integrated farming management

One of the most clearly emerging trends in technology-driven agriculture is that of integrating data and technologies into all-around solutions. A number of solutions that complement each other have already come to market, ranging from **satellite remote sensing techniques**, the **use of drones** for a number of farming practices, to the **connectivity** (deployment of **Big Data analytics, IoT and future internet solutions** found in a highly digitised and interconnected framework).

Integrated Farm Management (IFM) collects, processes, stores and provides the data needed to manage a modern farm. GNSS plays a significant role here, linking the data to specific geographical coordinates, and providing geolocation, tracking and positioning. As a result, most of the technologies described below either rely on or complement GNSS.

The deployment of different technologies capturing data on spatial and temporal variability of crops across farms enables informed **decision-making and elaboration of a management strategy for farmers**. In this context, IFM solutions combine real-time modelling and data collection. This integrated approach enables farm advisers to develop tailored practices that help individual farms or groups thereof make better decisions. GNSS constitutes a key component of such integrated management systems as it enables the "site-specific" dimension of the collected data that is then infused into management strategies.

A short description of the most important technologies supporting this integrated solution framework is provided below.

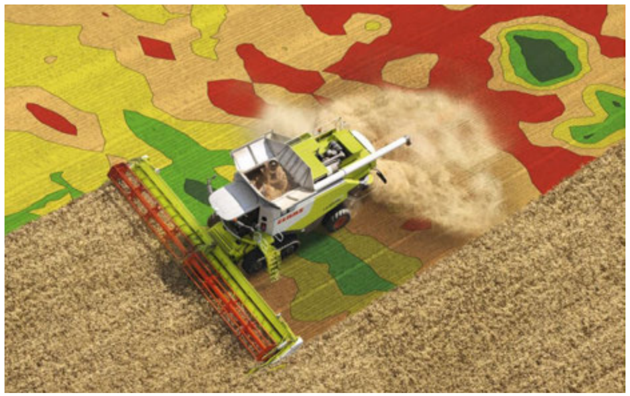
Earth Observation

Remote sensing techniques have been contributing and can further contribute to providing timely and accurate data on a number of aspects related to agricultural production. This includes everything from yield mapping and yield forecasting to monitoring weather and climatic variables, soil mapping and land cover changes. In the context of remote sensing, agricultural monitoring relies on a combination of satellite imagery, meteorological data, agrometeorological and biophysical modelling and statistical analyses.

Copernicus, which offers vast amounts of free and open data via the Sentinel missions, will significantly contribute to advancing the use of remote sensing techniques in precision agriculture. Additionally, the use of Earth Observation, in combination with GNSS, will foster the development of integrated and innovative applications with added value created by the synergies and complementarity of geolocation services and earth observation services (Galileo and Copernicus, both applications and services).

Drones

The utilisation of drones in precision agriculture marks an ongoing trend characterised by a number of dedicated R&D efforts, an increasing number of commercial solutions being launched and a strict regulatory framework constraining their uptake. Drones are used either as an alternative to high-resolution imagery from satellites or as farming equipment (e.g. crop-sprayers). Their range of applications covers surveying flights in the planning stage of an agricultural project, yield mapping, crop-cutting records and field management.



Source: Claas

Robotics

Another trend worth watching is the increased use of robots on a number of farming practices. Fully autonomous or robotic field machines are being increasingly employed in small-scale, high profit-margin agriculture settings such as wine grapes, nursery plants and some fruits and vegetables. In general, robotised precision farming promises to increase yields by optimising growth and harvesting processes while also helping to lower fertiliser and pesticide usage and improve soil quality through more targeted interventions. The autonomous operations performed by in-the-field robots are enabled by automatic steering technologies and high-precision positioning offered by GNSS solutions.

Connectivity

Connecting all devices used on a farm within the IoT concept is another trend to keep an eye on. By combining different technologies with fast internet access, farmers can obtain results from crop sensing activities in (near)-real time, supporting them in farm management decision-making. In this context, big data analytics will support the processing of large numbers of site-specific, geo-referenced data from various sensors and enable integrated decision support tools. IoT, Big Data and Future Internet will be a core part of the "Smart Farming" solutions of the (near) future.

Despite the increasing trend for such integrated solutions, several challenges exist. These range from the need to develop new business models on data management to developing sharing and open-data sources, addressing data ownership issues and building IT infrastructure (cloud solutions) for data storage.

European GNSS enhances key performance parameters for high precision

In light of the demanding performance requirements of most of the applications included in the "high precision, timing and asset management solutions" macrosegment, EGNOS and Galileo represent a great addition for users.

Accuracy

Applications where meter accuracy is adequate can benefit from EGNOS. This includes such applications as precision farming (cf. box on the right), mapping and thematic mapping for small and medium municipalities, forestry and park management, and the surveying of utility infrastructures. Most GNSS receivers used for mapping are now EGNOS ready. Besides professional users, EGNOS also allows non-professionals to access GNSS mapping technologies, thanks to its affordable and easy-to-use solutions.

Along with its single or dual-frequency OS, Galileo will also offer a Commercial Service (CS) dedicated to high precision applications. CS-HA will deliver PPP corrections globally via Galileo E6 for high accuracy users across all segments. Moreover, CS-HA will offer triple-frequency with faster convergence time and RTK-comparable accuracy for surveying applications. Additionally, users can benefit from using the E6B signal for tri-laning for greater reliability and accuracy.

NOTE: The final allocation of signals to services concerning E6-B/C is still under approval.

Availability

Used in conjunction with other GNSS, Galileo clearly increases the availability of precise location in general, and makes precise location achievable in challenging environments. This is representative of an added value when it comes to professional applications, including most of the ones in this macrosegment. Moreover, for timing applications, the capability of also receiving the Galileo signal would ensure continuous service provision even when another GNSS signal is not available.

Integrity

The need to be able to trust that a measurement is correct is extremely important in such applications as timing and asset management. EGNOS satisfies this need by adding a level of confidence to the provided positioning and timing information.

Robustness

As nearly all the applications in this group relate to a professional activity, Galileo's capability to mitigate such external interferences as spoofing (via Galileo authentication) is a welcome development. The Galileo CS Authentication service, the first-ever GNSS spreading code encryption capability for purely civil purposes, increases the security of professional applications by giving users confidence that they are using signals and data from actual satellites and not from another source.

Key Performance Parameter (KPP)	EGNOS contribution*	Galileo contribution*
Availability		●●
Accuracy	●●	●●●
Integrity	●●●	
Robustness		●●●

* ●●● = major contribution, capable of enabling new GNSS applications, ●● = medium contribution, enhancing the user's experience so benefits (e.g. operational, at cost level), are achieved, ● = minor contribution, performances improved but no major differences at users' level

EGNOS best practice: how EGNOS enables precision agriculture at low-cost

Precision farming is the use of various technologies and solutions to make the cultivation of agricultural land more efficient, thus enabling farmers to reap substantial savings and reduce their environmental impact. Using differential corrections broadcast by EGNOS in SBAS-capable GNSS receivers significantly improves the location accuracy and keeps costs on an effective level in comparison to RTK positioning systems. The level of accuracy achieved by EGNOS is typically below one meter, while pass-to-pass accuracy is typically 20 cm.

Traditionally, the barrier to precision agriculture has been the need for a substantial investment in equipment and costly ongoing subscriptions. EGNOS changed this equation by offering an affordable precision solution that helps eliminate waste and over-application of fertilisers and herbicides, saves time and fuel, reduces fatigue, optimises crop yields and increases profit margins.

Galileo potential: Demetra to demonstrate Galileo time dissemination capabilities

DEMETRA (Demonstrator of E-GNSS Services based on Time Reference Architecture) is a Horizon 2020 funded project that aims to develop and experiment time services based on Galileo by utilising an operational demonstrator and conducting tests with pilot applications. DEMETRA looks to become a prototype of a European time dissemination service based on Galileo and complemented with such features as certification, calibration and integrity – all of which could be of interest to end users like telecoms, power transmission companies, banks, and TV broadcasting networks.

Within the project's 24 month duration, nine different time services will be disseminated through different channels. Two validation test campaigns are also foreseen in order to validate the time dissemination performances and to test the real advantages and feasibility of the proposed services. The tests will feature user terminals located in a real user environments.

Editor's special: GNSS and other positioning technologies

Source: ESA

GNSS signals are provided by a variety of satellite positioning systems

Satellite navigation systems

Global Navigation Satellite System (GNSS) is the infrastructure that allows users with a compatible device to determine their position, velocity and time by processing signals from satellites. GNSS signals are provided by a variety of satellite positioning systems, including global and regional constellations and Satellite-Based Augmentation Systems:

- **Global constellations:**
  GPS (USA), **GLONASS** (Russian Federation), **Galileo** (EU), **BeiDou** (PRC).
- **Regional constellations:**
  QZSS (Japan), **IRNSS** (India), and **BeiDou** regional component (PRC).
- **Satellite-Based Augmentation Systems** (SBAS): WAAS (USA), EGNOS (EU), MSAS (Japan), GAGAN (India), SDCM (Russian Federation) and SNAS (China).

GNSS constellations main parameters

Parameter	GPS	GLONASS	Galileo	BeiDou
Orbital Period	11hrs 58 min	11hrs 15mins	14hrs 04mins	12 hrs 37min
Orbital Height	20,200 Km	19,100 km	23,222 km	21,150 km
Inclination	55^0	64.8^0	56^0	55^0
Number of Orbital Planes	6	3	3	6
Number of satellites	24 operational + 6 spares	21 operational + 3 spares	24 operational + 6 spares	27 MEOs + 5 GEOs + 3 IGSOs
Reference frame	WGS-84	PZ90	GTRF	CGCS2000
Reference time	GPS Time (GPST)	GLONASS Time (GLONASST)	Galileo System Time (GST)	BeiDou Time (BDT)

Despite concurrent designs, the similarities of GPS and GLONASS (1st generation) allowed the development of combined receivers. Galileo, BeiDou and modernised versions of GPS and GLONASS are designed to more easily allow interoperability.

Global constellations

There are currently two fully operational GNSS and two in the deployment phase:

- **GPS:** the first GNSS, fully operational since 1995, is managed by the US Department of Defence.
- **GLONASS:** the Russian GNSS, completed in 1995 and fully operational since 2011, is managed by the Russian Aerospace Defence Forces.
- **Galileo:** the European GNSS, currently under deployment as the only civil GNSS and due to start Initial Services in 2016, is owned and managed by the European Union.
- **BeiDou (Phase 3):** the Chinese GNSS (also known as **"BDS"**), set to supersede the current regional system, is managed by the governmental China Satellite Navigation Office.

GNSS are intended to provide global coverage, and make use of similar types of constellation. Each constellation consists of a minimum number of satellites which are each placed in circular, inclined Medium Earth Orbit (MEO), a fully operational constellation may have up to 32 operational satellites at any one time in order provide guaranteed minimum number of satellite specified in the event of multiple satellite failures.

Regional constellations

Regional Navigation Satellite Systems (RNSS) employ a small number of satellites in geostationary (GEO), or highly inclined, elliptical geosynchronous (IGSO) orbits. The parameters of these orbits are carefully selected to ensure a minimum of four satellites are visible at any one time over the specified regional coverage.

There are three RNSS:

- **QZSS:** Japan's RNSS, currently under development, is managed by the Cabinet Office of Japan.
- **IRNSS:** The Indian RNSS, fully deployed in April 2016, is managed by the governmental Indian Space Research Organisation (ISRO). The system has been renamed (or co-named) as Navigation Indian Constellation, or **NavIC**.
- **BeiDou (Phase 2):** The Chinese RNSS, formerly known as COMPASS, deployed from 2004 to 2012 as the second phase of the BeiDou programme.

SBAS

Satellite Based Augmentation Systems are discussed in detail on page 65.

GNSS broadcast signals within specific frequency bands to provide positioning services

Like all radio systems, GNSS must operate within specific parts of the radio spectrum as allocated by the International Telecommunication Union (ITU) to the Radio Navigation Satellite Service. Furthermore, when the signals are used by the aviation community, the frequency band should also be shared on a co-primary basis with the Aeronautical Radio Navigation Service (ARNS).

Frequencies

Frequencies in the range of 1 to 2 GHz (known as L-band) are suitable for mobile satellite systems as they suffer from little rain loss and offer lower path losses. Thus, all GNSS use signals in the lower parts of L-band. It should be noted that only the L1/E1 and L5/E5 signals use frequencies allocated to the ARNS.

Signals

GNSS satellites continuously transmit navigation signals in two or more frequency bands. These signals contain ranging codes that allow receivers to compute their travelling time from satellite to receiver, along with navigation data, in order to know the satellite's position at any time. The main signal characteristics are:

- Carrier frequency.
- Ranging (or spreading) code: A pseudo random sequence of 0s and 1s that allows the receiver to measure the travel time of the signal from satellite to receiver. Often referred to as Pseudo-Random Noise (PRN) codes.
- Type of modulation (generally BPSK* or BOC** or variants of these) and the chip rate.
- Navigation message: A binary-coded message providing information on the satellite ephemeris, clock parameters, almanac, health status and other complementary information. Some signals, known as "pilot signals", lack this component, thus offering better acquisition and tracking performances.

A multiple access scheme is used to allow the harmonious sharing of a frequency band by several satellites. For GLONASS, this is the Frequency Division Multiple Access (FDMA) technique, where satellites use a single spreading code but a different carrier frequency. For all other GNSS, the Code Division Multiple Access (CDMA) technique is used, with all satellites using the same carrier frequency but different spreading codes. Future GLONASS satellites will broadcast CDMA signals as well, for an improved interoperability between various GNSS.

Services

GNSS services are delivered by granting users access to one or several signals, allowing them to determine their position (or time) with a given level of performance.

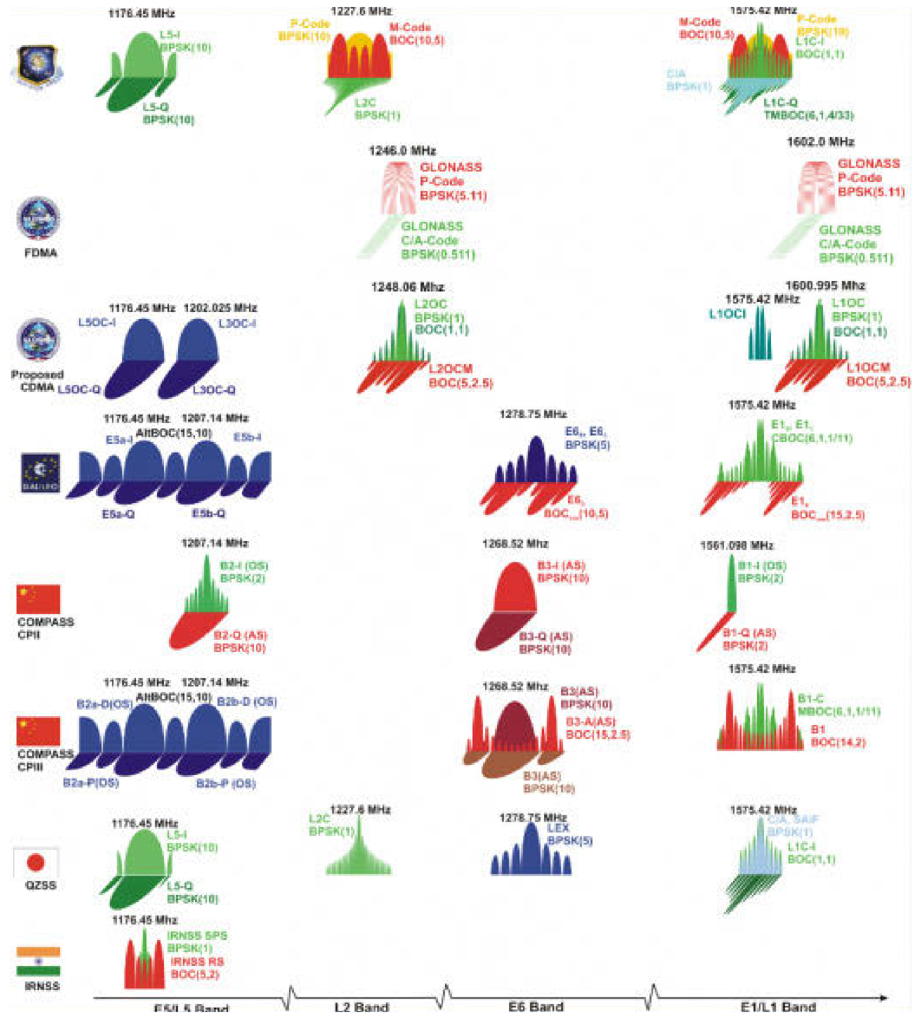
Some services are freely available for all users equipped with a suitable receiver, e.g. the GPS "Standard Positioning Service" (SPS) or Galileo's "Open Service" (OS).

Others have a controlled or restricted access. This is the case of GPS "Precise Positioning Service" (PPS) or of Galileo "Public Regulated Service" (PRS) which are reserved for governmental use, but also of Galileo "Commercial Service" (CS), intended to provide enhanced performance to subscribed users.

Finally, some GNSS satellites (Galileo, GLONASS) may carry a Search and Rescue payload to contribute to the COSPAS-SARSAT service (see page 51).

* Binary Phase Shift Keying modulation
** Binary Offset Carrier modulation

GNSS frequencies & signals



Source Navipedia http://www.navipedia.net/index.php/GNSS_signal

SBAS improves GNSS accuracy, provides integrity control

What are SBAS?

Satellite Based Augmentation Systems (SBAS) were developed in the 1990's for the aviation community in order to improve the accuracy of the GPS Standard Positioning Service (SPS) and, more importantly, to meet the integrity requirements of Civil Aviation that no single GNSS can currently satisfy.

SBAS systems allow compatible GNSS receivers to compute position estimates with improved accuracy and associated integrity warnings. This is achieved through the transmission of clock and ephemeris corrections for the GPS satellites in view and of ionospheric delay estimates in a message embedded in a GPS look-alike signal broadcast by geostationary communications satellites on the GPS L1 frequency. To support the integrity capability, the navigation message also contains estimates of the error associated with each of the basic corrections and ionospheric delay data.

There are currently four operational SBAS (WAAS, EGNOS, MSAS, GAGAN) and four in various phases of development. Their main characteristics are listed in the table on next page.

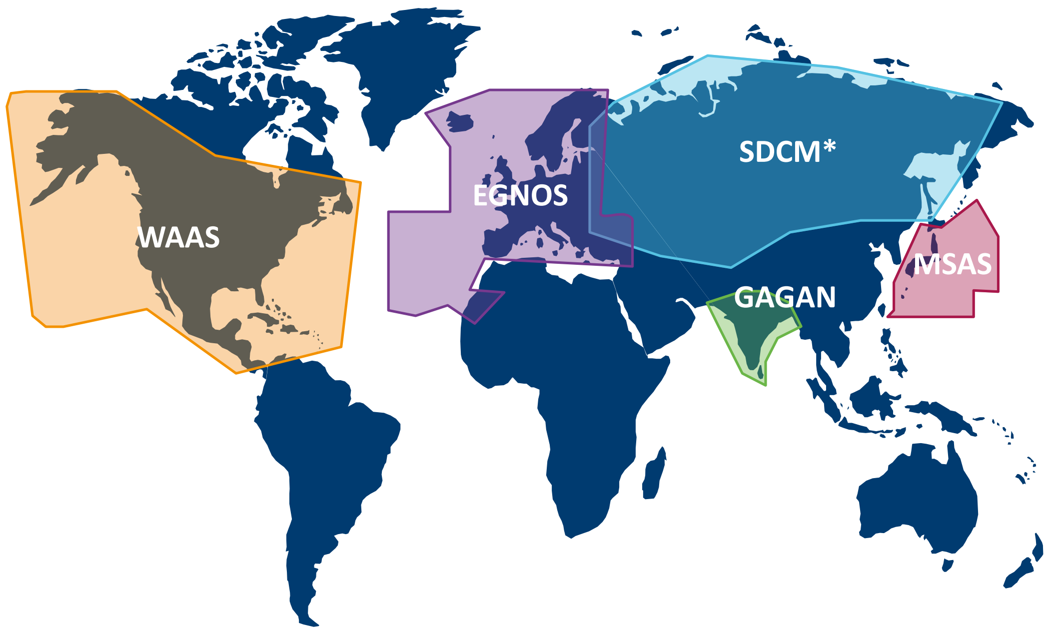
Who benefits from SBAS?

Besides aviation, SBAS has been widely adopted by many other user segments, including agriculture, mapping and road. As a result, most GNSS receivers are capable of providing SBAS-corrected position estimates when operating within an SBAS coverage region. These receivers normally don't use the integrity information and thus do not need to comply with any standards or guidelines. In Europe, this is formally known as the EGNOS Open Service. In addition, EGNOS correction data are also made available via the internet through the EGNOS Data Access Service (EDAS).

The maritime community makes use of SBAS improved accuracy to support navigation and positioning applications, both at sea and inland waterways. However, as there currently is no standard for implementing SBAS in maritime receivers, the integrity information is not used. In this respect, the European Commission, the GSA and the ESA are jointly working on manufacturing guidelines for implementing SBAS in shipborne receivers. These guidelines will facilitate a formal recognition of SBAS as a component of the International Maritime Organisation (IMO) World Wide Radio Navigation System (WWRNS) – allowing maritime users to benefit from SBAS integrity features.

In road transportation, regulations for eCall and Smart Tachograph will enable the use of EGNOS for new models of vehicles sold in the EU after 2018.

SBAS indicative service areas as of June 2016



The * sign denotes a system not yet certified for civil aviation

Several SBAS service providers operating in different regions

SBAS Evolution

The future development of SBAS has been a topic for much work over recent years which has culminated in the acceptance by the **SBAS Interoperability Working Group (IWG)*** of a new message definition for a second SBAS channel transmitted on L5 in April 2015. This allows future (second generation) SBAS systems to support both dual- and single-frequency operations, along with supporting correction data for signals originating from multiple GNSS constellations.

Although the IWG accepted the new dual-frequency, multi-constellation message definition, as of August 2016 it has not received the endorsement of the **International Civil Aviation Organisation (ICAO)** or the **Radio Technical Commission for Aeronautics (RTCA)**.

** The **SBAS IWG** first convened in 1997 between WAAS and EGNOS experts, and has since become the forum for all SBAS service providers to discuss interoperability issues.*

Current and planned SBAS: summary of characteristics

SBAS Name	Space Segment	Operations supported	Operational since	Evolutions planned
EGNOS (Europe)	3 Geostationary satellites: • Inmarsat AOR-E (15.5° W) • SES-5 (5° E) • ASTRA 5B (31.5° E)	Open service (OS) ~1m accuracy	2009	Guaranteed operation until 2030 in compliance with ICAO SBAS SARPS. 2021 and beyond: EGNOS 'V3', including SBAS L1 and L5 (dual frequency), Galileo support and extended coverage
		Safety of Life (SoL) LPV-200	2011	
		Data Access (EDAS) ~1m accuracy	2015	
WAAS (USA)	3 Geostationary satellites: • Inmarsat AMR (98° W) • Galaxy 15 (133° W) • Anik F1R (107° W)	LPV-200	2012	Support for L1 legacy until 2028 Transition to L1/L5 to provide a dual frequency service
MSAS (Japan)	2 Geosynchronous satellites: • Himawari-8 (140.7° E) • Himawari-9 (140.7° E) launch in 2016	NPA	2003	Incorporation of L5 signal
GAGAN (India)	3 Geostationary satellites • GSAT-8 (55° E) • GSAT-10 (83° E) • GSAT-15 (93.5° E) launched Nov 2015	APV-1	2007	
SDCM (Russia)	3 Geosynchronous satellites: • Luch-51 (167° E) • Luch-5B (16 ° W) • Luch-5C (95° E)	APV-2	2013	Aiming for certification for APV-2 over Russian territory
KASS (Korea)	In development	Aviation	2016	L1/L5 and L1/L3 (GLONASS) by 2018
SNAS (China)	In development	<1m accuracy	2022	Collaboration with GAGAN
SACCSA (South America)	Feasibility study	APV-1	2020	Multi-constellation and dual frequency support intended

In addition to SBAS, there are other augmentation systems and services that improve GNSS performance

*Augmentation systems and services improve some performance parameters of a stand-alone GNSS when such parameters are not satisfactory for a given application. Historically, the targeted performance parameter has primarily been **accuracy**, which has been improved through the use of differential techniques. However, **integrity** and **availability** are also of paramount importance for numerous applications, justifying the development of other augmentation types:*

- *SBAS and the IALA differential GPS (DGPS) system are examples of augmentation dedicated to improving both GNSS **accuracy** and **integrity**.*
- *PPP (see below) and RTK (next page) improve accuracy down to the centimetre level.*
- *A-GNSS (next page) supports better **availability,** shorter **TTFF** and lower **power** requirements.*

PPP

Precise point positioning (PPP) is an emerging alternative to differential methods for precise positioning using GNSS. High accuracy is achieved by replacing the broadcast navigation message (satellite positions and clocks) with precise values, and by either modelling or estimating all residual errors at the receiver level. PPP does not require local or regional reference stations, but rather provides a homogenous world-wide high accuracy solution. This is contrary to DGNSS and RTK, which heavily depend on the distance to the base station(s). Instead, PPP depends on the availability of very precise orbits and clock estimates computed by the service provider or sourced from, for example, the International GNSS Service (IGS). Real time PPP involves the delivery of these data to the users in a timely manner, usually through L-Band geostationary satellites.

Initial PPP algorithms provided accuracies of the order of 5 to 10 cm (95%) horizontal and relied upon the estimation of floating point phase observation integer ambiguities. Thanks to recent developments, PPP accuracy has improved to 2 to 3cm horizontal through the use of full fixed point integer ambiguities. PPP, however, is burdened by long convergence initial times. Although these times have been reduced through the use of multiple constellations and improved algorithms, they still reach 10 or so minutes. However, this crucial convergence time will be further reduced through the development of new and improved algorithms that benefit from:

- More processing power in receivers
- Three frequencies
- Triple or quadruple GNSS constellations

Main world-wide commercial augmentation services

Name	Service	Stated performance	Supported Constellations	Method	Owned by
OmniStar	VBS	<1m	GPS	DGNSS	Trimble
	HP	10cm	GPS	LR-RTK	
	XP	15cm	GPS	PPP	
	G2	<10cm	GPS + GLONASS	PPP	
RTX	ViewPoint	<1m	GPS + GLONASS + BDS	PPP	Trimble
	RangePoint	<50cm	GPS + GLONASS + BDS	PPP	
	FieldPoint	<20cm	GPS + GLONASS + BDS	PPP	
	CenterPoint	<4cm	GPS + GLONASS + BDS	PPP	
StarFix	HP	10cm	GPS	Phase DGNSS	Fugro
	G2	10cm	GPS + GLONASS	PPP	
	G2+	3cm	GPS + GLONASS	PPP	
	G4	5-10cm	GPS + GLONASS + BDS + Galileo	PPP	
	L1	1.5m	GPS	DGNSS	
	XP2	10cm	GPS + GLONASS	PPP	
Atlas	H100	1m	GPS + GLONASS + BDS	PPP	Hemisphere
	H30	30cm	GPS + GLONASS + BDS	PPP	
	H10	8cm	GPS + GLONASS + BDS	PPP	
StarFire	SF2	5cm	GPS + GLONASS	PPP	John Deere
C-Nav	C1	5cm	GPS	PPP	Oceaneering international
Veripos	C2	5cm	GPS + GLONASS	PPP	Hexagon AB
	Apex	10-20cm	GPS	PPP	
	Apex²	5cm	GPS + GLONASS	PPP	
	Ultra	15cm	GPS	PPP	
	Ultra²	8cm	GPS + GLONASS	PPP	
	Standard	1m	GPS	DGNSS	
	Standard²	1m	GPS + GLONASS	DGNSS	
TerraStar	TerraStar D	10cm	GPS + GLONASS	PPP	Hexagon AB
	TerraStar M	1m	GPS + GLONASS	DGNSS	
	TerraStar C	2-3 cm	GPS + GLONASS	PPP	

Source GSA, 2016

Augmentation systems are tailored to meet varied users requirements

Professional DGNSS systems and services

Differential GNSS (DGNSS) is a relative positioning technique based on the principle that most errors affecting GNSS measurements are spatially and temporally correlated and, consequently, will cancel each other out when differencing simultaneous observations made by two or more nearby receivers. This requires a reference receiver set-up at a known location (to generate pseudorange corrections), a datalink (either terrestrial or satellite) to transmit these corrections to users, and a DGNSS receiver that applies these corrections to its own observations and computes its position relative to the reference one. When these observations are code observations (usually smoothed with carrier phase) this technique is called DGNSS, and when they are the carrier phase, it is called Real Time Kinematic (RTK). In both cases, one can use either a single reference position or multiple ones to produce so-called multi-reference or network solutions.

DGNSS

DGNSS services were first introduced as maritime DGPS services for the safety of navigation (United States Coast Guard (USCG), IALA) and further developed – notably regarding multireference and satellite delivery - by commercial service providers to serve the specific high accuracy applications demanded by the offshore oil and gas industry. Whilst the typical accuracy of the (free) IALA DGPS is below 5m (95%) in a range up to 200nm (370km) as stated in IALA guidelines, the (subscribed) commercial services can provide accuracies of 1 to 2m horizontal over baselines of up to a 1000km.

With a continent- or even world-wide infrastructure of reference stations in place, commercial providers turned in the late 90's to less demanding markets, including precision agriculture, with new services based on the "Virtual Base Station" (VBS) concept (also called "Virtual Reference Station"). This concept uses data from multiple reference stations combined at the network level to compute a single set of corrections optimised for a position in the vicinity of the user (VRS), delivered to the user and used as a conventional single reference DGNSS set of corrections. These services provide accuracies equivalent to the sophisticated multi-reference ones, albeit as a "black box" solution. However, the termination of GPS Selective Availability and the deployment of SBAS have rendered these commercial offerings much less attractive, meaning these legacy DGNSS services are kept in operation either as back-up systems or to provide an integrity monitoring function (IALA system). Other services have evolved either into PPP or RTK systems.

RTK and Network RTK

Surveying or precise positioning typically uses the carrier phase observations to accurately determine a vector (baseline) between a stationary reference station and a mobile (roving) receiver, as in DGNSS. The key challenge for reaching centimetre level accuracies is the resolution of the integer ambiguity inherent in the carrier phase observations. However, these ambiguities can be resolved in real time over baselines of tens of kilometres, and the availability of triple-frequency signals will allow for significantly longer baselines thanks to techniques known as "Triple Carrier Ambiguity Resolution" (TCAR).

To function, an RTK system needs a base station receiver located at a known position, a rover receiver located at the unknown position, and a radio data link between the two receivers. The accuracy of such systems is typically 1 to 2cm over a baseline of approximately 10km.

Over the years, public or commercial operators have deployed networks of GNSS reference stations to offer what is known as Network RTK (N-RTK) services to the wider professional markets (surveying, precision agriculture). The radio link is generally provided by a dial-up mobile phone data service. A recent trend is for manufacturers of high-grade GNSS equipment to become providers of such services, either through alliances with existing service providers or via the deployment of their own reference network. Such services are widely available, with European examples including OS Net, SmartNet and SAPOS.

Assisted GNSS

Assistance is a technique where information useful for positioning is provided to the GNSS receiver via a separate communications link, which would otherwise need to be acquired either from the Signal in Space (SiS) or stored in the user equipment. It is particularly valuable when access to satellite broadcast data is impaired.

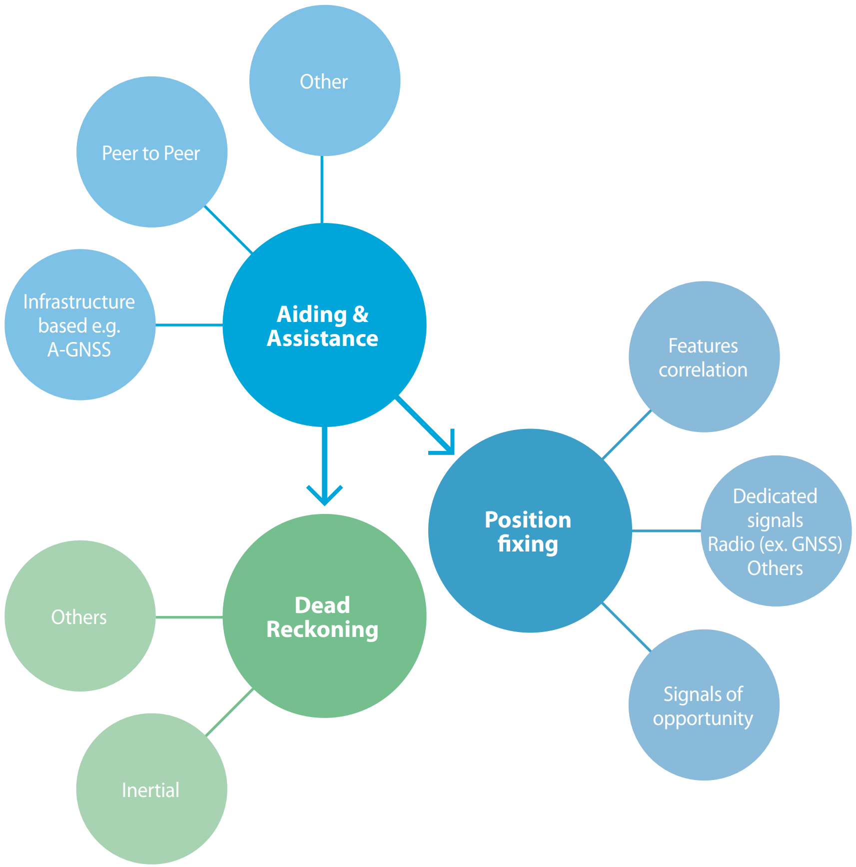
Satellite positions, approximate user position, and timing information is delivered to the A-GNSS user for a faster position fix or when reception of the positioning signals is poor. The received information allows the chipset to be set to a hot-start equivalent mode, thus drastically reducing the TTFF and improving performance in urban canyons and indoors. It further enables high sensitivity modes for GNSS that do not have pilot signals. As a side effect, A-GNSS boosts the receiver's power efficiency.

Assistance, however, can also be understood in a wider perspective and include other information useful to improving the performance of the receiver's navigation tasks. A simple example of this can be found in the use of traffic information for optimal routing in road navigation. Assistance data are commonly provided by such infrastructure/network operators as mobile phone companies.

Indeed, thanks to the data rates achievable since 3G, ephemeris data for full GNSS constellations can be transmitted in very little time, helping A-GNSS to become the standard it is today. Furthermore, assistance is also at the heart of emerging **peer-to-peer** cooperative positioning techniques, where nearby users can exchange information directly over a short range communications link (e.g. an indoor/outdoor cooperative scenario).

Position fixing and dead reckoning are the two positioning method categories

A taxonomy of Positioning Techniques



Positioning methods & strategies

There are numerous ways to determine one's position, but all methods fall in two categories:

- **Position Fixing**, which makes use of external information to directly compute a position.
- **Dead Reckoning**, which determines the change in position by integrating displacements, and therefore requires an initial position to compute the current one.

These two techniques are indeed very much complementary, and are used together in many hybridised or integrated navigation systems (e.g. GNSS based car navigation systems).

Position Fixing

Position fixing can use dedicated signals, as is the case for GNSS, or signals that are originally not intended for positioning (Signals of opportunity). Such signals may be radio, optical, or acoustic.

Alternatively, position fixing can be performed by correlating observed "features" with a georeferenced database of such "features". Examples of this technique include Wi-Fi fingerprinting, Terrain Relative Navigation, GNSS shadow matching and many more.

In all cases, signals or features must be unambiguously identified, and the positions of the transmitters known, or an a priori map of the features available.

Dead Reckoning

Dead Reckoning measures the distance and direction travelled, using sensors available on a given carrier (e.g. a ship's log and compass). There is indeed a very wide variety of such sensors, depending on what the object to be positioned is (a car, a plane, a pedestrian, a ship…).

A particular case is that of Inertial Navigation Systems, where the sensors are 3 accelerometers and 3 gyroscopes, composing an Inertial Measurement Unit (IMU).

Dead Reckoning systems can be totally independent of external infrastructure. They allow continuous operation. However, they require initialisation, and their errors are cumulative.

Aiding & Assistance

Assistance is the use of a separate communications link to provide the navigation system with information about the signals and environmental features available for positioning. For GNSS this can be the satellites ephemeris and clocks; for Terrain Relative Navigation a DTM (Digital Terrain Model).

Aiding can take a variety of forms. It consists in supplying the navigation system with extra information to enable it to better perform its functions. This can be independent velocity, attitude, time or height information. This also encompasses corrections and integrity data.

Many radio technologies can be used for positioning with specific range coverage and accuracy

Where GNSS is unavailable, alternative means of navigation must be employed. For example, GNSS isn't available underwater, underground and indoors. Sometimes it's even unavailable outside, such as when the GNSS receiver experiences radio interference or cannot obtain a clear view of the sky (e.g. dense urban environments).

Below is an overview of such complementary techniques, beginning with those that are usually considered first, i.e. other radionavigation systems.

Dedicated radionavigation systems

Most terrestrial radio navigation technology has its origins in the 1940s & 1950s, when the first hyperbolic systems such as Loran or Decca were developed. Only few systems have evolved and continue to currently operate. These include VOR*, DME**, Beacons used for direction finding; and in some areas eLoran, an upgraded version of Loran C. These systems are long range ones (hundreds of km, or even over 1000 km for Loran).

Although these systems do not offer the same coverage or accuracy as GNSS and are limited to only providing horizontal position, they do serve as a useful backup to GNSS for safety-critical applications.

More recent developments in terrestrial radio navigation technology focus on short range systems capable of operating indoors and in urban canyons. There are only a few such systems available, including Pseudolites and dedicated ultra-wide band (UWB) systems. Instead, the bulk of innovation today lies in the exploitation of existing communications and broadcasting signals for positioning purposes; i.e. in radio positioning using non dedicated systems.

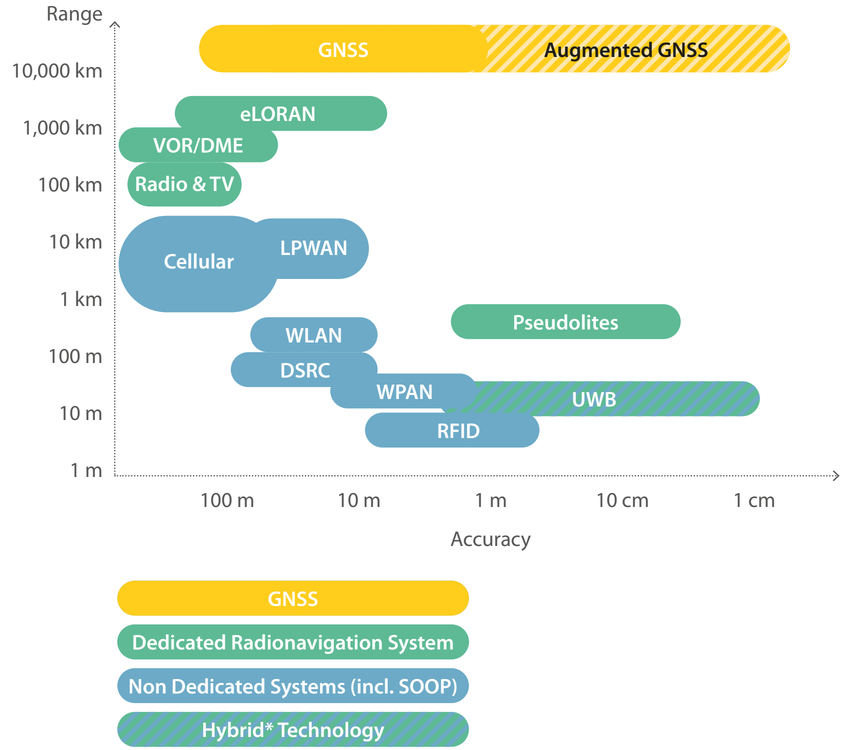
Use of other radio signals

All kinds of radio signals are used for positioning, with or without the cooperation of the network operator. In the latter case, such signals are called signals of opportunity (SOOP). Among the most widespread signals are:

- Mobile phone signals
- WLANs (Wireless Local Area Network) or Wi-Fi
- WPANs (Wireless Personal Area Network) such as Bluetooth and ZigBee
- LPWANs (Low-Power Wide-Area Network) such as LoRa, SigFox or others deployed for the IoT
- RFID (Radio-frequency identification)
- DSRC (Dedicated Short Range Communications)
- UWB (Ultra-Wide Band) communications
- Television signals and broadcast radio

(*) VHF Omnidirectional Range
(**) Distance Measuring Equipment

A comparison of GNSS and terrestrial radio positioning techniques



**Can be used either as a dedicated positioning system, or as a communications one*

Strong synergies exist between communication and positioning

Communications and Positioning

Although radio communication and radio navigation have always been "sister" technologies, over the last 10-15 years they have become even more intrinsically complementary. On the one hand, signals designed for communication purposes are now also widely used for positioning, with cellular phone signals and Wi-Fi positioning being examples of this trend. On the other hand, communication signals can and do provide GNSS devices with the assistance information they require to enhance their performance in constrained environments. More generally, communication is needed to provide the positioning system with information other than just A-GNSS, such as 3D maps for GNSS shadow masking or local field intensity maps for Wi-Fi positioning.

The characteristics of a number of communication systems usable as SOOP are shown in the table below.

Communication systems usable as SOOP

Name	Frequency	Range	Data Rate	Standard
Cellular Radio	800, 900, 1800, 2100 or 2500 MHz	Up to 10 km	32 Kbps to 100 Mbps	GSM, LTE etc.
Wi-Fi	2.5 and 5.5 GHz ISM bands	Up to 100m	1 to 760 Mbps	IEEE 802.11
Bluetooth	2.5 ISM band	Up to 10m (Class2)	1 to 3 Mbps	IEEE 802.15.1
Bluetooth Low Energy (BLE)	2.5 ISM band	Up to 10m (Class2)	1 to 3 Mbps	Bluetooth Core Spec., V4.0
ZigBee	868 MHz and 2.5 GHZ ISM bands	Up to 10m	20 to 250 kbps	IEEE 802.15.4
LoRaWan	EU 863-870 MHz ISM Band S 902-928 MHz ISM Band China 779-787 MHz ISM Band	2-5k (urban), 15k (rural)	0.3 kbps to 50 kbps	LoRaWAN standard
Sigfox	868 MHz/ 902 MHz ISM Band	3-10k (urban), 30-50k (rural)	100bps for 12 bytes messages Up to 140 messages / day	Proprietary
Dedicated short-range communications (DSRC)	5.8 GHz	Up to 1000m	30 to 500 kbps	EN 12253:2004

Many communication protocols were not designed with positioning in mind, thus limiting their accuracy as ranging signals of opportunity. As new communications standards are introduced (e.g. for IoT), they often incorporate ranging protocols, thus improving their usability as SOOP. As a result, the primary limiting factor will become the propagation channel: non-line-of-sight reception and multipath interference.

Mobile Telephony

Cellular telephony undoubtedly has a central and dominant position among all systems used to complement GNSS. Today there are more GNSS chipsets used in smartphones than in any other area of application, and cellular networks around the world distribute A-GNSS data. This trend was, in large part, triggered by a 1996 US FCC regulation requiring wireless carriers to determine and transmit the position of callers who dial the 911 emergency number. This regulation led to parallel developments of "network-based" and "handset based" (GNSS followed by A-GNSS) positioning methods.

Cellular network generations have appeared about every 10 years, each characterised by new frequency bands, higher data rates and non–backward-compatible transmission technology. Network-based positioning methods may then depend on the generation. We are currently using the 4th generation and planning for the 5th. It was with the introduction of 3G in 2001 that we achieved the data rate needed for A-GNSS to become the reality it is in most cellular phones today.

Network-based positioning

Positioning methods are based on time measurements of signals between the network Base Transceiver Stations (BTS) and the Mobile Station (MS).

- Cell-ID (Cell global identity) is a **proximity** method. The mobile position is within the serving cell or node, which can be refined with range and/or azimuth to the BTS when available.
- Enhanced Observed Time Difference (E-OTD) is a **ranging** method involving time difference measurements being made in the handset.
- Time Difference of Arrival (TDOA) is another **ranging** method involving time difference measurements being made at multiple Base Stations from signals transmitted by the handset.

Network-based positioning accuracy suffers from negative impacts caused by non-line-of-sight, multipath effect and various interference noises, and is varying in most cases from some tens of metres to 1km.

Positioning under particular environmental conditions is supported by alternative technologies

There are cases when radio signals cannot be used and must be replaced by other technologies. An obvious example is underwater, where due to poor penetration, they are commonly replaced by acoustic ones. Other environments will lead to different choices, including acoustic, infrared, optical and ultrasound.

An interesting example for indoor positioning is that of Visible Light Communication (VLC), which uses visible light from Light Emitting Diodes (LEDs) as a medium for data communication. A LED-based lighting system creates a positioning grid sending invisible codes to a smartphone's camera that correlates with the LED's location, allowing a position to be calculated.

There also exist cases when a sensor or a component (atomic clock, barometric altimeter) supports a positioning system by providing a direct estimation of one of the unknown parameters, effectively reducing the number of required observations (visible satellites for GNSS).

Finally, this extra information does not necessarily need be measured, but can be known a priori. A good example of this is a terrestrial vehicle where the altitude can be set equal to that of a Digital Elevation Model.

Mapping

High resolution mapping

As we move towards the autonomous vehicle, the high definition mapping of environmental features becomes increasingly important. Digital map is the tool used to provide the vehicle with information about such features as altitude, road curvature, number of lanes, tunnels, signs, exits, etc. In many cases, the accuracy requirement for this information is at the sub-decimetre level.

3D Mapping

3D city mapping can revolutionise positioning in challenging urban areas. Adding height information to street maps can be used to aid GNSS positioning. In fact, accurate 3D building models are used to predict blockage and reflection of GNSS and other radio signals – information that can be used to select the most accurate ranging measurements and for the so-called Shadow Matching technique.

SLAM

Accurate georeferenced databases of features essential for many position fixing techniques (e.g. vision aided navigation, image correlation, Wi-Fi fingerprinting) are generally not readily available or up-to-date. SLAM (Simultaneous Localisation And Mapping) is a technique whereby a location system explores its environment, observes features and builds/updates its own features database. As a result, SLAM provides the ability to continuously monitor and capture changes in the environment.

Crowd sourcing

Combining SLAM and connectivity allows one to continuously enrich remote, cloud-based feature maps by crowd sourcing. As a result, not only does a user (e.g. a connected car with advanced ADAS features and sensors) improve its own local database, it also contributes to the remote database maintenance.

Vision-based and vision-aided Navigation

Although visual-based navigation systems have been around for over 20 years, the cost of their sensors and their required processing power have generally limited their adoption to specific professional cases. However, these two obstacles have recently been surmounted as a result of the computational capacity of mobile platforms dramatically increasing and the availability of cheap yet powerful digital cameras (e.g. on every mobile phone) coming onto the market.

These cameras are basically angle sensors and can be used for navigation in a variety of ways, including:

- Visual odometry uses the correlation of successive camera images and can provide highly accurate velocity measurements (e.g. to a dead reckoning system).
- Feature recognition and correlation with stored images allows for direct position fixing. This technique, however, requires comparison with stored information and, as a result, is practical only when an approximate position is available.
- Stereo-photogrammetry is also a well-known technique requiring the use of two cameras (or two positions of one camera), which provides three-dimensional positions of points in local coordinates system.

Today, cameras are standard equipment on mobile phones and becoming widely found in cars, albeit not for navigational purposes. Interfacing the camera(s) that are already there with the navigation system should not raise major difficulties. The challenge lies in the optimal exploitation of this new potential source of information.

The trend towards automation creates a sensor-rich environment

As GNSS-enabled applications become more demanding and move towards full automation, not only of specialised robots in a controlled environment but also of individual vehicles driving on the roads, more complex safety-related problems arise. For example, an autonomous vehicle must not only determine its absolute position with very high accuracy and integrity, it is also compulsory to know this position with respect to the always changing environment, composed among other "things" of other vehicles and of human beings.

Thus, the questions of relative navigation, collision avoidance and feature recognition are becoming more important than the "relatively simple" problem of position fixing. To address these questions, researchers and industry are looking to a wide variety of sensors that were not previously found in vehicles, including Radars, Lidars and cameras – to name a few. Although such new sensors are primarily deployed for other purposes (e.g. radar for anti-collision), they are a source of potentially useful information for the "integrated navigation system".

The tables in Annex III of this report attempt to provide an overview of systems, sensors and sources of information that may be used to complement GNSS, including their context of use and their usefulness/contribution to a positioning system.

ANNEXES

ANNEX 1: Definition of key GNSS performance parameters

Availability: the percentage of time the position, navigation or timing solution can be computed by the user. Values vary greatly according to the specific application and services used, but typically range from 95-99.9%. There are two classes of availability:

- **System:** the percentage of time the system allows the user to compute a position – this is what GNSS Interface Control Documents (ICDs) refer to
- **Overall:** takes into account the receiver performance and the user's environment (for example if they are subject to shadowing).

Accuracy: the difference between true and computed position (absolute positioning). This is expressed as the value within which a specified proportion of samples would fall if measured. Typical values for accuracy range from tens of metres to centimetres for 95% of samples. Accuracy is typically stated as 2D (horizontal), 3D (horizontal and height) or time.

Continuity: ability to provide the required performance during an operation without interruption once the operation has started. Continuity is usually expressed as the risk of a discontinuity and depends entirely on the timeframe of the application (e.g. an application that requires 10 minutes of uninterrupted service has a different continuity figure than one requiring two hours of uninterrupted service, even if using the same receiver and services). A typical value is $1x10^{-4}$ over the course of the procedure where the system is in use.

Integrity: the measure of trust that can be placed in the correctness of the position or time estimate provided by the receiver. This is usually expressed as the probability of a user being exposed to an error larger than alert limits without warning.

The way integrity is ensured and assessed, and the means of delivering integrity related information to the user are highly application dependent.

For safety-of-life-critical applications such as passenger transportation, the "integrity concept" is generally mature, and integrity can be described by a set of precisely defined and measurable parameters. This is particularly true of civil aviation. For less critical or emerging applications, however, the situation is different, with an acknowledged need of integrity but no unified way of quantifying or satisfying it.

Throughout this report, "integrity" is to be understood at large, i.e. not restricted to safety-critical or civil aviation definitions but also encompassing concepts of quality assurance/quality control as used by other applications and sectors.

Robustness to spoofing and jamming: robustness is a qualitative, rather than quantitative, parameter that depends on the type of attack or interference the receiver is capable of mitigating. It can include authentication information to ensure users that the signal comes from a valid source (enabling sensitive applications).

Note: for some users robustness may have a different meaning, such as the ability of the solution to respond following a severe shadowing event. For the purpose of this document, robustness is defined as the ability of the solution to mitigate interference or spoofing.

Indoor penetration: ability of a signal to penetrate inside buildings (e.g. through windows). Indoor penetration does not have an agreed or typical means for expression. In GNSS, this parameter is dictated by the sensitivity of the receiver, whereas for other positioning technologies there are vastly different factors that determine performance (for example, availability of Wi-Fi base stations for Wi-Fi-based positioning).

Time To First Fix (TTFF): a measure of a receiver's performance covering the time between activation and output of a position within the required accuracy bounds. Activation means subtly different things depending on the status of the data the receiver has access to:

- **Cold start:** the receiver has no knowledge of the current situation and thus has to systematically search for and identify signals before processing them – a process that typically takes 15 minutes.
- **Warm start:** the receiver has estimates of the current situation – typically taking 45 seconds.
- **Hot start:** the receiver knows what the current situation is – typically taking 20 seconds.

Latency: the difference between the time the receiver estimates the position and the presentation of the position solution to the end user (i.e. the time taken to process a solution). Latency is usually not considered in positioning, as many applications operate in, effectively, real time. However, it is an important driver in the development of receivers. This is typically accounted for in a receiver, but is a potential problem for integration (fusion) of multiple positioning solutions or for high dynamics mobiles.

Power consumption: the amount of power a device uses to provide a position. The power consumption of the positioning technology will vary depending on the available signals and data. For example, GPS chips will use more power when scanning to identify signals (cold start) than when computing position. Typical values are in the order of tens of mW (for smartphone chipsets).

It is important to note that applications often trade off parameters against each other depending on their requirements. For example, in aviation an application's integrity is prioritised over accuracy, whilst in mass market applications low power consumption and TTFF are prioritised over integrity.

Important Notice: The above definitions are applicable to this report only, and are not meant to be used for any other purpose.

List of Acronyms

3D Three Dimensional
ADAS Advanced Driver Assistance System
ADC Analogue-to-Digital Converter. See DAC
A-GNSS Assisted GNSS
AltBOC Alternative BOC modulation
ARINC Aeronautical Radio, Incorporated
ARNS Aeronautical Radio Navigation Service
ARAIM Advanced RAIM
ASIC Application Specific Integrated Circuit
B2B Business to Business
BDS BeiDou Navigation Satellite System. See BeiDou
BeiDou Chinese GNSS, formerly known as Compass
BOC Binary Offset Carrier modulation
BPSK Binary Phase Shift Keying modulation
C-ITS Cooperative Intelligent Transport System
CAT I, II, III ILS Categories for precision instrument approach and landing
CDMA Code Division Multiple Access
CDU Control and Display Unit
CEP Circular Error Probable (50% percentile of horizontal position error)
CMOS Complementary Metal Oxide Semiconductor
COMPASS See BeiDou
COSPAS-SARSAT Russian Cosmicheskaya Sistyema Poiska Avariynich Sudow - Search and Rescue Satellite-Aided Tracking
C/N0 Carrier to Noise Ratio
CS (Galileo) Commercial Service
CS-HA (Galileo) Commercial Service High Accuracy
CSAC Chip-Scale Atomic Clock
CW Continuous Wave
DAC Digital-to-Analogue Converter. See ADC
DGNSS Differential Global Navigation Satellite System
DGPS Differential Global Positioning System
DoA Direction of Arrival
DoI Direction of Interference
DSP Digital Signal Processor
DSSS Direct Sequence Spread Spectrum
DT Smart Tachograph
DTM Digital Terrain Model
EC European Commission
EDAS EGNOS Data Access Service
EDGE Enhanced Data Rates for GSM Evolution
EGNOS European Geostationary Navigation Overlay Service
E-GNSS European GNSS
ELT Emergency Locator Transmitter
ENIAC European Nanoelectronics Initiative Advisory Council
EPIRB Emergency Positioning Indication Radio Beacon
ES Enhanced Services
ESA European Space Agency
(E)TSO (European) Technical Standard Order
EU European Union
EU28 European Union (28 Member States)
FDMA Frequency Division Multiple Access
FLS Forward Link Service
FOC Full Operational Capabilities
FP7 7th Framework Programme for Research and Technological Development
GA General Aviation
GAGAN GPS Aided Geo Augmented Navigation
GBAS Ground Based Augmentation System
GDOP Geometric dilution of precision
GLONASS Russian GLObalnaya NAvigatsionnaya Sputnikovaya Sistema (Global Navigation Satellite System)
GNSS Global Navigation Satellite System
GPS Global Positioning System
GSA European GNSS Agency
GSM Global System for Mobile Communications
H2020 Horizon 2020
IALA International Association of Marine Aids to Navigation and Lighthouse Authorities
IC Integrated Circuit
ICAO International Civil Aviation Organisation
IF Intermediate Frequency
ILS Instrument Landing System
IMO International Maritime Organisation
IMU Inertial Measurement Unit
INS Inertial Navigation System
I/O Input / Output
IOC Initial Operational Capabilities
IoT Internet of Things
IOV In-Orbit Validation
IRNSS Indian Regional Navigational Satellite System
IS Initial Services
IT Information Technologies
ITS Intelligent Transport System
ITU International Telecommunication Union
JRC (EC's) Joint Research Centre
LBS Location Based Service
LED Light Emitting Diode
LEO Low Earth Orbit
LEOSAR Low Earth Orbit Search And Rescue satellites
LHCP Left Hand Circular Polarisation
LNA Low Noise Amplifier
LP Location Protocol
LPV Localizer Performance with Vertical guidance
LPWAN Low Power Wide Area Network
LTE Long-Term Evolution, commonly known as 4G LTE
LUT Local User Terminal
MCC Mission Control Centre
MCU Modular Concept Unit
MEDLL Multipath Estimating Delay Lock Loop
MEMS Micro-Electro-Mechanical Systems
MEO Medium Earth Orbit
MEOSAR Medium Earth Orbit Search and Rescue satellites
MF Medium Frequency
MSAS Multi-functional Satellite Augmentation System
MSS Mobile Satellite Services
MtM More than Moore
NLOS Non Line of Sight
NMA Navigation Message Authentication
NMEA National Marine Electronics Association
N-RTK Network RTK
NTP Network Time Protocol
OBU On-Board Unit
OICA Organisation Internationale des Constructeurs d'Automobiles (International Organization of Motor Vehicle Manufacturers)
OS (Galileo) Open Service
OTA Over The Air
PBN Performance Based Navigation
PLB Personal Location Beacon
PND Portable Navigation Device
PNT Positioning, Navigation, and Timing
PPP Precise Point Positioning
PPS (GPS) Precise Positioning Service
PRS (Galileo) Public Regulated Service
PTP Precise Time Protocol
PVT Position, Velocity, Timing
QZSS Quasi-Zenith Satellite System
RAIM Receiver Autonomous Integrity Monitoring
RF Radio-Frequency
RFID Radio-Frequency Identification
RHCP Right Hand Circular Polarisation
RLS Return Link Service
RNSS Regional Navigation Satellite System
RTCA Radio Technical Commission for Aeronautics
RTCM Radio Technical Commission for Maritime Services
RTK Real Time Kinematic
RPAS Remotely Piloted Aircraft Systems
RUC Road User Charging
R&D Research and Development
SAR Search and Rescue
SBAS Space Based Augmentation System
SDCM System for Differential Corrections and Monitoring
SDR Software Defined Radio
SiS Signal In Space
SiP System in Package
SLAM Simultaneous Location And Mapping
SME Small and Medium-sized Enterprises
SNAS Satellite Navigation Augmentation System
SoC System on Chip
SoL Safety of Life
SOOP or **SoOp** Signal of Opportunity
SPS (GPS) Standard Positioning Service
TAI Temps Atomique International or International Atomic Time
TCAR Three Carrier Ambiguity Resolution
TTFF Time To First Fix
UAV Unmanned Aerial Vehicle
UHF Ultra High Frequency
UMTS Universal Mobile Telecommunications System
USCG United Stares Coast Guards
UTC Coordinated Universal Time
UTC (NTSC) Local representation of UTC at the National Time Service Centre, Chinese Academy of Sciences
UTC (SU) Local representation of UTC generated by the State Time/Frequency Reference of the Russian Federation
UTC (USNO) Local representation of UTC at the US Naval Observatory (USNO)
V2I Vehicle to Infrastructure
V2V Vehicle to Vehicle
V2X V2I + V2V
VBS or VRS Virtual Base Station or Virtual Reference Station
VFR Visual Flight Rules
WAAS Wide Area Augmentation System
WACS Wide Area Control System
WAMS Wide Area Measurement Systems
Wi-Fi Wireless Fidelity. Wireless communication protocols standardised by IEEE 802.11 (ISO/CEI 8802-11)
WWRNS World-Wide Radio Navigation System

ANNEX 3A: Sensors used in positioning systems

Sensors used in positioning system

Designation	Measured quantity	Measurement method	Environment	PVT strategy
Accelerometer	Body acceleration	Pendulous / Vibrating beam	All	Dead Reckoning: Inertial
Altimeter Barometric	Altitude (vertical range to MSL)		Air / Land	Position Fixing:Aiding or Map correlation (TRN)
Altimeter Radio	Altitude (vertical range to relief)	Timing	Air	Position Fixing:Aiding or Map correlation (TRN)
Balise / Eurobalise	Proximity detection	H Field	Land / Train	Position Fixing: Proximity
Camera (Incl. Stereo)	Angles	Optical	All	Position Fixing: Map (image) correlation, Aiding (Visual Odometry)
Cell phones – Cell Id	Proximity detection	E Field strength	Land	Position Fixing: Proximity
Csac Clocks				Position Fixing: Aiding
Doppler Log	Velocity	Acoustic Frequency shift	Marine	Dead Reckoning
Doppler Radar	Velocity	Radio Frequency shift	Land (rail)	Dead Reckoning
DSRC	Proximity detection Ranging		Terrestrial	Position Fixing: Proximity / Ranging
Gravimeter	Gravity field		Marine	Position Fixing: Map correlation
Gyroscope	Body angular rate	Mechanical / optical / vibratory	All	Dead Reckoning: Inertial
Laser Scanner & Lidar	Distance	Optical	Air / Land	Position Fixing: Map (image) correlation
LPWAN (LoRa, SigFox, Weightless - IoT networks)	Ranges		Land	Position Fixing: Ranging
Magnetometre	Magnetic field	H Field strength & direction	All	Position Fixing: Map correlation
Magnetic compass	Magnetic heading	H Field direction	All	Dead Reckoning
Odometer	Velocity		Land (automotive, rail)	Dead Reckoning
Pedometer (Step counter)	Distance travelled		Land (pedestrian)	Dead Reckoning
Pressure sensor	Depth		Marine underwater	Position Fixing: Map correlation (TRN)
Radar (Incl. Imaging - SAR)	Range & Azimuth Intensity		All	Position Fixing: Range + Bearing / Map (image) correlation
Radio beacons	Range (field strength) & Direction		All	Position Fixing: Range + Bearing
Radio & TV broadcast (incl. DAB, DVB-T)	Range		Land	Position Fixing: Ranging
RFID	Proximity detection		Terrestrial	Position Fixing: Proximity
Sonar (incl. Multibeam)	Distance to seafloor	Timing	Marine underwater	Position Fixing: Map correlation (TRN)
WLAN (Incl. Wi-Fi)	Signal strength	E Field strength	Land (urban / indoors)	Position Fixing: Map correlation
WPAN (ANT+, Bluetooth, ZigBee & derivatives)	Ranges (proximity detection)	E Field strength	Land (urban / indoors)	Position Fixing: Map correlation / Proximity / Ranging

Source GSA analysis 2016

ANNEX 3B: Data and signals used in positioning systems

Data and Signals used in positioning systems

Designation	Data / System	Measured quantity	Measurement method	Environment	PVT strategy
(Navigable) Road database	Data	Road geometry & attributes		Land	Position Fixing: Map correlation (Map matching)
DTM	Data	Terrain height		Land	Position Fixing: Aiding
DTM	Data	Terrain height		Air	Position Fixing: Map correlation (TRN)
Nautical chart	Data	Seafloor		Sea	Position Fixing: Map correlation (TRN)
Acoustic beacons	Signal	Ranges	Timing	Marine Underwater	Position Fixing: Ranging
Cell phones – Cell Id enhanced	Signal	Range (field strength / Timing advance)	E Field strength + Timing	Land	Position Fixing: Proximity + Ranging
Cell phones – E-OTD / TDOA	Signal	Ranges	Timing	Land	Position Fixing: Ranging
DME	Signal	Ranges	Timing	Air	Position Fixing: Ranging
eLoran	Signal	Ranges	Timing	All	Position Fixing: Ranging
ILS	Signal	Azimuth / Elevation		Air	Position Fixing: Ranging
LTE Direct	Signal	Ranges	Timing	Land / Indoors	Position Fixing: Ranging
Pseudolites	Signal	Ranges		All	Position Fixing: Ranging
UWB - Communications	Signal	Ranges	Timing	Land / Indoors	Position Fixing: Ranging
UWB - Dedicated positioning	Signal	Ranges	Timing	Land / Indoors	Position Fixing: Ranging
Visible Light Communication (VLC) using LEDs	Signal	Ranges	Timing	Indoors	Position Fixing: Ranging
VOR	Signal	Azimuth		Air	Position Fixing: Angular

Source GSA analysis 2016

ANNEX 4: Methodology used for creating the GNSS User Technology Report

This GNSS User Technology Report uses the GSA's internal Technology Monitoring process (TMP).

It complements the market monitoring and forecasting process, and its objective is the monitoring of trends and developments in the GNSS supply industry. It supports the GSA in the definition of the best strategy towards Galileo market adoption, provision of updated statistics on Galileo penetration in user terminals and chipsets, and analysing Galileo positioning among other GNSS and location technologies.

Part of the process is to keep up-to-date independent analysis, which assesses the capabilities of receivers, chipsets and modules currently available on the market. For the analysis, each device is weighted equally, regardless of whether it is a chipset or a receiver, and no matter what its sales volume is. The results should therefore be interpreted not as the split of constellations utilised by end users, but rather the split of constellations available in manufacturers' offerings.

The analysis includes all major receiver manufacturers in Europe and worldwide: Avidyne, Broadcom, CSR, Esterline, Furuno, Garmin, Hemisphere GNSS, Honeywell, Infineon, Intel, Japan Radio Co., John Deere, Kongsberg, Leica Geosystems AG, Mediatek, NavCom Technology, Nottingham Scientific Ltd, NovAtel, Omnicom, Orolia, Qualcomm, Rockwell Collins, Septentrio, SkyTraq Technology, STMicroelectronics, Texas Instruments, Thales Avionics, Topcon, Trimble, U-blox, Universal Aviation.

Search and Rescue, defence and public utilities receivers, chipsets and modules are not part of the analysis.

The information contained within this report is a compilation of in-house knowledge, scientific papers, receiver and other user technology manufacturer's websites and, if needed, verified by consultation with experts in the relevant domain.

The European Commission

The European Commission (EC) is responsible for management of the European satellite navigation programmes, Galileo and EGNOS, including:

- Management of funds allocated to the programmes;
- Supervising the implementation of all activities related to the programmes;
- Ensuring clear division of responsibilities and tasks in particular between the European GNSS Agency and European Space Agency;
- Ensuring proper reporting on the programme to the Member States of the EU, to the European Parliament and to the Council of European Union.

The Galileo and EGNOS programmes are entirely financed by the European Union.

The European GNSS Agency (GSA)

The GSA's mission is to support European Union objectives and achieve the highest return on European GNSS investment, in terms of benefits to users and economic growth and competitiveness, by:

- Designing and enabling services that fully respond to user needs, while continuously improving the European GNSS services and Infrastructure;
- Managing the provision of quality services that ensure user satisfaction in the most cost-efficient manner;
- Engaging market stakeholders to develop innovative and effective applications, value-added services and user technology that promote the achievement of full European GNSS adoption;
- Ensuring that European GNSS services and operations are thoroughly secure, safe and accessible.

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Integrated Market Development at the GSA

The **GSA GNSS User Technology Report** is a product of ongoing market development and technology monitoring activities that aim to:

- **Stay close to the user and the value chain:** involving GNSS users, downstream industry, experts and other stakeholders in key market segments by managing relationships with stakeholders, organising and participating in user and industry fora, identifying needs and assessing stakeholder satisfaction.
- **Monitor GNSS market and technology:** forecasting future developments by market segment, including regular collection, modelling and expert validation of current information, drivers and assumptions; analysis of the GNSS downstream industry market share; cost-benefit analyses of the European GNSS Programmes and future scenarios; monitoring trends in positioning technology; and tracking of E-GNSS penetration.
- **Build and implement E-GNSS market strategy with market players and institutional stakeholders:** fostering the use of EGNOS in aviation, agriculture, maritime, road, rail and surveying; preparing the market for the uptake of Galileo in all segments; promoting integration of E-GNSS inside chipsets, receivers and devices; organising workshops and testing; and supporting EU industry business development and competitiveness.
- **Manage EU-funded R&D on GNSS applications and services:** leveraging results for E-GNSS adoption and EU industry competitiveness, including 150 demonstrations of E-GNSS applications; 45 products, 80 prototypes, 13 patents/trademarks – with more results on the way.
- **Manage EU-funded R&D on GNSS chipsets, receivers and antennas:** gearing these end-products to end-users from all segments, aiming to support the EU industry with grants or tenders/procurements tailored to meet current and future user needs.

The European GNSS Agency: linking space to user needs.

European Commission

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