ARIADNA

Awareness Raising and capacity building
Increasing ADoption of GALILEO in urbaN mobility
Applications and services

White Paper: EGNSS technology in Urban Mobility and Public Transport

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Glossary

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DRT	Demand-Responsive Transit
EGNOS	European Geostationary Navigation Overlay Service
EU SPA	EU Agency for the Space Programme
ETA	Estimated Time of Arrival
GAGAN	GPS-aided GEO augmented navigation
GCC	Galileo Control Centres
GCS	Ground Control Segment
GLONASS	Global Navigation Satellite System [Russia]
GMS	Ground Mission Segment
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSA	European GNSS Agency
GSS	Galileo Sensor Stations
HAS	High Accuracy Service
IoT	Internet of Things
IRNSS	Indian Regional Navigation Satellite System
MaaS	Mobility as a Service
MSAS	Multi-functional Satellite Augmentation System
OBU	On-Board Unit
OS	Open Service
PA	Public Administrations
PRS	Public Regulated Service
PT	Public Transport
PTA	Public Transport Authority
QZSS	Quasi-Zenith Satellite System
SAEI	Exploitation and Information Aiding System
SAR	Search And Rescue
SBAS	Satellite-Based Augmentation System
SDCM	System for Differential Corrections and Monitoring
SNAS	Satellite Navigation Augmentation System
TMB	Transports Metropolitans de Barcelona
TTC	Telemetry, Tracking & Control
TTFF	Time To First Fix
ULS	Uplink Stations
WAAS	Wide Area Augmentation System
WP	Work Package

Executive Summary

With the advent of smartphone applications and IoT technology, mobility in urban areas has experienced a bigger leap in the past few years than it has in decades. There has never been as much choice for getting around the city and as much information about public transport services available on real time. But there is one technology which all mobility services share, has been around for a long time, and is usually taken for granted: the positioning technology.

From riding a shared kick-scooter to checking the minutes left for the bus to reach our stop, none of it would be possible if we didn't have the infrastructure and technology to obtain and share reliable positioning information. This infrastructure is the Global Navigation Satellite System (GNSS), and it allows users with a compatible device to determine their position, velocity and time by processing signals from satellites.

In urban mobility, the device which picks up satellite signals changes depending on the nature of the service: public transport and shared mobility operators equip their vehicles with dedicated positioning technology, while services like ride-hailing and taxi rely on the positioning technology of the drivers' smartphones.

Whichever the case, when you order a taxi from an app and are able to see its position on real time, you are benefitting from satellite technology; when you locate and book the closest shared car on the street, you are benefitting from satellite technology; and even when you receive real-time information about the next buses at your nearest stop, you might be benefitting from satellite technology.

The incorporation of Galileo, Europe's Global Navigation Satellite System, positively impacts all existing applications of GNSS in urban mobility services, and even enables new ones. This is mostly done through better signal accuracy because there are more satellites in view, allowing for better geometry and availability especially in challenging environments for GNSS, such as urban canyons, where satellite signals from one constellation can get completely blocked by tall buildings. There is another key benefit which the Galileo system, and no other GNSS at the moment, offers: the authentication of the satellite signal. According to experts in the field, this is the most differentiative, added-value feature of Galileo, and it will enable a whole range of applications that are not possible today.

The Galileo system authenticates its satellite signals by incorporating a digital signature to the navigation data that certifies its source. This allows EGNSS users to assess the trustworthiness of the signals, making them more robust against spoofing attacks. Spoofing attacks send fake GNSS signals to make receivers transmit a false location and create the impression that a person or a vehicle is in another place. The implications of this for GNSS applications in urban mobility are worth-noting. Imagine, for example, if some individuals used this vulnerability to take control over free-floating shared vehicles and deprived others from being able to find them and use them. Some new applications are even hard to picture becoming a reality without authenticated signals. Think of a seamless public transport system where users don't need to purchase tickets or top up any credit, because it relies completely on the positioning data from their smartphones to charge them for their trips. Tricking the system into believing that you've travelled much less than you've actually done sounds like a big risk that can't be taken by public transport authorities.

1. Context

With the advent of smartphone applications and IoT technology, mobility in urban areas has experienced a bigger leap in the past few years than it has in decades. IoT, or Internet of Things, is the term used for describing the increasing number of objects or devices enabled with connectivity capabilities. In urban mobility, such “objects” are the vehicles used in transportation services. By equipping them with connectivity capabilities, we can obtain information about them remotely and interact with them on real time. This technological trend combined with the vast possibilities of smartphone applications create the perfect cocktail for a revolution in urban environments.

There has never been as much choice for getting around the city and as much information about public transport services available on real time. It is increasingly common to find the streets of any city populated by all sorts of vehicles —cars, scooters, bicycles, kick-scooters and other types of personal mobility vehicles— ready to be booked through different apps. Public transport is also exploiting the benefits of mobile apps, offering its users real-time updates about schedules and service incidences, among other functionalities.

As mobility offer increases —along with the number of apps in our smartphones—, the opportunity for including all the available mobility services under a shared ecosystem becomes clearer. The goal would be to offer a seamless mobility experience for the user from one single app, eliminating the need to install an app for every service. This phenomenon is being referred to as “Mobility as a Service” (MaaS), and is being developed in different cities across the globe.

Regardless of the development of MaaS, there is one technology which all mobility services share, has been around for a long time, and is usually taken for granted: the positioning technology. From riding a shared kick-scooter to checking the minutes left for the bus to reach our stop, none of it would be possible if we didn’t have the infrastructure and technology to obtain and share reliable positioning information. In addition, this will surely be an important piece of the puzzle for a seamless experience when switching from a mobility service to another.

2. GNSS applications for urban mobility services

GNSS stands for Global Navigation Satellite System, and 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 (Russia), Galileo (EU), BeiDou (China).
- Regional constellations: QZSS (Japan), IRNSS (India), and BeiDou regional component.
- Satellite-Based Augmentation Systems (SBAS): WAAS (USA), EGNOS (EU), MSAS (Japan), GAGAN (India), SDCM (Russia) and SNAS (China).

In order to assess the quality of GNSS signals, the following requirements are used:

- Availability: the percentage of time that the position or timing solution can be computed by the user.
- Accuracy: the difference between the real and computed position or time.
- Continuity: the ability to function without interruption once the operation has started.

- Integrity: the measure of trust that can be placed in the correctness of the position or time estimate provided by the receiver.
- 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.
- Robustness to spoofing and jamming: a qualitative parameter that looks at the type of attack or interference which the receiver is capable of mitigating. Spoofing is the transmission of counterfeit GNSS signals that may force a receiver to compute an erroneous position and lead the user to believe they are in a different location from where they effectively are. Jamming is the intentional transmission of radio frequency signals that can interfere with GNSS signals leading to a degradation or blocking of GNSS navigation and timing services. [1]
- Authentication: the ability of the system to assure users that they are utilising signals and/or data from a trustworthy source, and therefore that they are protected from spoofing threats. [2]

[1] GSA. (2018). *PRS. Luxembourg: European Union https://www.gsa.europa.eu/security/prs*

[2] GSA. (2019). *GNSS Market Report. Issue 6. Luxembourg: Publications Office of the European Union*

SERVICE	GNSS APPLICATION	RELEVANT STAKEHOLDER/S	CRITICAL GNSS PARAMETER/S
BUS	**Fleet management**		
	Track vehicles Buses transmit their position on real time, which allows the fleet operator to track where each of them is at all times. This information is often required by the authorities responsible for public bus services.	Fleet operator, PTA	Availability Accuracy
	Monitor incidences With the real-time positioning of buses, the fleet operator can detect incidences such as important delays, detours, and breakdowns as soon as they happen. This is important in order to also raise an alarm for the authority responsible for the service.	Fleet operator, PTA	Availability Accuracy Integrity
	Sharing information with users		
	Proximity of buses The GNSS data computed by every bus can be used to display its live geographical position through the user app. That way, users can visualize on a map where the closest buses are and where they are headed.	Final user	Accuracy Availability Integrity

SERVICE	GNSS APPLICATION	RELEVANT STAKEHOLDER/S	CRITICAL GNSS PARAMETER/S
	Estimated time of arrival Fleet operators use the real-time positioning of buses and the location of stops to calculate and communicate an estimated time of arrival for the following stops in the route. This information is displayed on digital panels at the stops and on the app.	Final user	Accuracy Integrity
	Current and next stop The real-time position information computed by every bus is also used to show passengers on board the current stop and the next ones in the line.	Final user	Accuracy Integrity
	Communicate incidences When incidences such as important delays or detours are detected by the fleet operator thanks to the real-time positioning information from the buses, it is immediately communicated to users and the PTA responsible for the service.	Final user, PTA	Availability Accuracy Integrity
	Service quality control		
	Overview of the operations A very insightful way of overviewing operations for fleet operators and PTAs is visualizing the “service position” of every bus, that is, its relative position to the last and next stop, and to other buses in the same line. This representation of information uses real-time GNSS data from buses and the location of the stops	Fleet operator	Accuracy Availability Continuity

SERVICE	GNSS APPLICATION	RELEVANT STAKEHOLDER/S	CRITICAL GNSS PARAMETER/S
	Regularity To ensure that the service regularity is maintained at a specific time value (e.g. one bus on line V29 every 10 minutes), the fleet operator needs to continuously track the distance between two buses in the same line and adjust their speed if the target regularity value is at risk. Keeping track of this performance indicator is essential, since it is controlled by PTAs to measure the quality of the service.	Fleet operator, PTA	Accuracy Availability Continuity Integrity
	Improve estimated time of arrival Comparing historic data about the ETA provided to users at a certain stop and the real time of arrival of the bus can help fleet operators design more accurate schedules and time estimates.	Fleet operator	Accuracy Availability
	Understand the cause of incidences External traffic data can be used to identify the reason behind some service incidences, such as a detour caused by an accident, if coupled with position fixes from the bus at the time of the traffic event	Fleet operator, PTA	Accuracy Availability
	Optimize service performance By analysing historic positioning data and the time stamps associated with every position fix, the fleet operator can identify if any segments of the route or the schedules must be modified in order to optimize the speed of the service.	Fleet operator, PTA	Accuracy Availability Integrity

SERVICE	GNSS APPLICATION	RELEVANT STAKEHOLDER/S	CRITICAL GNSS PARAMETER/S
	Impact on urban environment		
	Analyse impact on traffic patterns Looking at aggregate positioning data from bus services can help understand their impact on congestion in certain areas of the city. The conclusions of such analysis can be then shared with mobility and urban planners to make important decisions for the quality of life of citizens.	PTA	Accuracy Availability Integrity
DRT	**Fleet management**		
	Track vehicles Vehicles transmit their position on real time, which allows the fleet operator to track where each of them is at all times. If the service is operating under a public contract, this information is often required by the responsible authority.	Fleet operator	Availability Accuracy
	Service provision		
	Pick-up process In DRT services, pick-up locations are usually not physically signalled: they are either virtual stops previously set up by the service provider, or a location provided by the user. In this last case, GNSS is used by the user's mobile device to compute its position and then share it with the service provider.	Fleet operator, final user	Accuracy
	Sharing information with users		

SERVICE	GNSS APPLICATION	RELEVANT STAKEHOLDER/S	CRITICAL GNSS PARAMETER/S
	Position of vehicles The GNSS data computed by every vehicle can be used to display its live geographical position through the user app. That way, users can visualize on a map where the closest vehicles are, as well as see their assigned vehicle approaching once they have booked a trip and are waiting to be picked up.	Final user	Accuracy Availability Integrity
	Estimated time of arrival Fleet operators use the real-time positioning of vehicles and the location of stops or users to calculate and communicate an estimated time of arrival through the user app	Final user	Accuracy Integrity
	Service quality control		
	Optimize service performance Since the routes performed by the service are dynamic, it is crucial to have access to data such as kilometres travelled with passengers on board, most recurrent routes, and most demanded locations or areas in the city. This information can help the operator identify demand patterns and redesign the service to better satisfy them.	Fleet operator	Accuracy Availability
	Impact on urban environment		
	Analyse impact on traffic patterns Looking at aggregate positioning data from DRT services can help understand their impact on congestion in certain areas of the city. The conclusions of such analysis can be then shared with mobility and urban planners to make important decisions for the quality of life of citizens.	PA	Accuracy Availability Integrity

SERVICE	GNSS APPLICATION	RELEVANT STAKEHOLDER/S	CRITICAL GNSS PARAMETER/S
Ride-hailing / Taxi	**Fleet management**		
	Track vehicles The positioning data coming from vehicles allows ride-hailing operators to monitor how many of their drivers and in what areas are giving service.	Service provider	Availability Accuracy
	Sharing information with users		
	Position of vehicles The GNSS data computed by every vehicle can be used to display its live geographical position through the user app. That way, users can visualize on a map where the closest vehicles are, as well as see their assigned vehicle approaching once they have booked a trip and are waiting to be picked up.	Final user	Accuracy Availability Integrity
	Service provision		
	Pick-up process To order a ride, the user must provide a location for pick-up. The user's mobile device uses GNSS to compute its position and then share it with the service provider.	Service provider, final user	Accuracy
	Compliance of service restrictions In some parts of the world, ride-hailing operators have been imposed legal restrictions which affect whether their drivers can pick up users on the go or wait for them from strategic locations such as airports or stations, or need to stay at the operational base until they receive a request. Positioning data from drivers can be used to detect when these restrictions are not being respected, task which might be required, or directly executed, by the public administrations imposing such restrictions. Taxi app operators are also imposed legal restrictions, but concerning other matters such as working schedules of taxi drivers. Having access to historic positioning data from their service hours allows public administrations to have control over their work conditions.	Service provider, PA	Availability
	Service quality control		
	Optimize service performance Indicators such as kilometres travelled while carrying passengers, most demanded locations or areas in the city, and evolution of demand during the day, all of which make use of GNSS signals, can be used by the operator to identify demand patterns and reinforce the service where or when offer doesn't meet demand.	Service provider	Accuracy Availability
	Impact on urban environment		
	Analyse impact on traffic patterns Looking at aggregate positioning data from these services can help understand their impact on congestion in certain areas of the city. The conclusions of such analyses can be then shared with mobility and urban planners to make important decisions for the quality of life of citizens.	PA	Accuracy Availability Integrity

SERVICE	GNSS APPLICATION	RELEVANT STAKEHOLDER/S	CRITICAL GNSS PARAMETER/S
Shared mobility (Car- / scooter- / bike- / kick scooter-sharing)	**Fleet management**		
	Maintenance For vehicles without a built-in odometer, like some bike and kick-scooter models, historic GNSS data can be used to schedule maintenance operations after they've travelled a certain number of kilometres.	Fleet operator	Availability
	Charging operations Since most of the vehicles used in these kinds of services are electric, it is critical to recharge them when their batteries go below a certain percentage of charge that compromises their availability for the service. For cars and kick-scooters, this implies driving the vehicles to a charging hub, where they will stay until they've replenished their batteries and are ready to be put back onto the streets. For scooters, since they are usually equipped with swappable batteries, the procedure consists of reaching those vehicles with low charge and replacing their batteries on site. In both cases, knowing the vehicles' position when they need to be recharged is an essential part of these services' fleet management. It's not, logically, in those services where vehicles are parked at a dedicated location with an associated charger or at a docking station with charging capabilities.	Fleet operator	Accuracy Availability
	Rebalancing Whether due to demand patterns causing part of the fleet to concentrate in certain areas of the city, or due to city regulations imposing a specific fleet distribution per area, operators of free-floating services must relocate a great number of their vehicles daily. This operation is known as rebalancing, and it requires accessing the real-time position of every single vehicle in the fleet, in order to find it and transport it where needed.	Fleet operator	Accuracy Availability
	Theft alert and vehicle retrieval Permanently tracking GNSS signals can raise alarms in situations such as the non-restitution of the vehicle after the end of a reservation or the vehicle being moved without an associated reservation. In case of theft, the fleet operator can use its last position fix to find the vehicle and retrieve it.	Fleet operator	Accuracy Availability
	Service provision		
	Location of vehicles In free-floating services, the position of every vehicle is shared with users on real time, most commonly by displaying it on a map on the service's app. Users then are able to locate and book their nearest available vehicle.	Final user	Accuracy
	Billing Many of these services are charged by the minute, which means that the service provider must have reliable time stamps, provided by GNSS signals, for the start of the trip and the end of it. This information is then used for automatic billing of the trip on the user's account. In station-based solutions, such as some carsharing services, the trip cannot be ended until the car is not back in its designated spot. In this case, both positioning data and time stamps are used for billing.	Fleet operator, final user	Accuracy Availability Continuity

SERVICE	GNSS APPLICATION	RELEVANT STAKEHOLDER/S	CRITICAL GNSS PARAMETER/S
	Geofencing This term is used to describe the enforcement of a set of rules tied to a specific geographical boundary. When the vehicle's receiver starts computing position fixes within the affected geographical area, certain rules are automatically triggered. Geofencing is most commonly used in micromobility services. Fleet operators can, for instance, disable the vehicle's power or limit its speed within restricted areas (e.g. parks), or forbid ending a trip out of the operational limits defined by the service provider.	Fleet operator, final user	Accuracy Availability Integrity
	Service quality control		
	Optimize service performance By analysing historic aggregate positioning data from the trips, the fleet operator can identify demand patterns and reinforce the service where needed.	Fleet operator	Accuracy Availability
	Impact on urban environment		
	Analyse impact on traffic patterns Looking at aggregate positioning data from these services can help understand their use of the infrastructure and their impact on congestion in certain areas of the city. The conclusions of such analyses can be then shared with mobility and urban planners to make important decisions for the quality of life of citizens.	PA	Accuracy Availability Integrity

Table 1: *GNSS applications in urban mobility, by type of service*

3. Getting to know Galileo

In the previous section, we briefly mentioned Galileo as one of the global constellations providing GNSS signals. Precisely, Galileo is Europe's Global Navigation Satellite System, and along with the Satellite-Based Augmentation System EGNOS, constitutes Europe's satellite navigation programme. Together, they provide positioning and timing information with significant positive implications for many European services and users.

a. Overview

The Galileo system is composed of three segments: [3]

- **Space segment.** The Galileo constellation in space will comprise 30 satellites in total. There will be 24 operational satellites, plus 6 spare satellites, circulating in medium Earth orbit on three orbital planes (24/3/1 Walker constellation configuration).
- **Ground segment.** The Galileo ground segment is in place to essentially monitor the satellites, checking that they are functioning correctly and generating the navigation data to be sent to end users. It includes both the Ground Control Segment (GCS) and the Ground Mission Segment (GMS), and it encompasses the following infrastructures:
  - Two Galileo Control Centres (GCC), computing information and synchronising the time signal of the satellites.
  - A worldwide network of Galileo Sensor Stations (GSS), receiving and monitoring the navigation signal from the constellation.
  - A worldwide network of Galileo Uplink Stations (ULS), transmitting navigation signals.
  - A worldwide network of Telemetry, Tracking & Control stations (TTC stations), monitoring and controlling satellites in orbit.

[3] GSA. (2017). *Galileo & EGNOS; The EU satellite navigation programmes explained. Luxembourg: Publications Office of the European Union*

- **User segment.** With the constellation of satellites transmitting navigation signals and GNSS receivers receiving and transforming the signals into coordinates and accurate time, users can benefit from a wide range of services, some of which have been already explored in this document.

Until recently, GNSS users had depended on non-civilian American GPS and Russian GLONASS signals. Galileo programme stands alone as the world's unique option for GNSS under civilian control. This is especially relevant when considering the world's increasing dependence on GNSS.

Satellite positioning has become an essential service not only for mobility. If GNSS signals were suddenly switched off, financial and communication activities, public utilities, security and humanitarian operations, and emergency services would all come to a standstill. In other words, as the use of satellite-based navigation systems continues to expand, the implications of a potential signal failure become even greater. With the addition of Galileo to the global GNSS constellation, this risk is minimised.

While European independence is a principal objective of the programme, Galileo also gives Europe a seat at the rapidly expanding GNSS global table. The programme is designed to be interoperable with other Global Navigation Satellite Systems (GNSS) such as GPS, Russia's GLONASS and China's BeiDou. Receivers with multi-constellation capacity are able to combine signals from different constellations to provide greater positioning accuracy. In this sense, Galileo is positioned to enhance the coverage currently available, providing a more seamless and accurate experience for multi-constellation users around the world.

To further increase the level of Galileo integration, EUSPA works directly with chipset and receiver manufacturers through technology workshops, sharing Galileo updates, co-marketing efforts, and dedicated funding for receiver development projects and studies.

As a precursor to the Galileo programme, and working side by side with it, the European Geostationary Navigation Overlay Service (EGNOS) is Europe's regional satellite-based augmentation system (SBAS). EGNOS can improve the information received from GPS, Galileo or other GNSS by correcting errors such as those linked to ionospheric disturbances. Although currently available in Europe, its services will be progressively extended to European neighbouring countries.

EGNOS uses GNSS measurements taken by accurately located reference stations deployed across Europe. All measured GNSS errors are transferred to a central computing centre, where differential corrections and integrity messages are calculated. These calculations are then broadcast over the covered area using geostationary satellites that serve as an augmentation, or overlay, to the original GNSS message. As a result, EGNOS improves the accuracy and reliability of GNSS positioning information, while also providing a crucial integrity message regarding the continuity and availability of a signal. In addition, EGNOS also transmits an extremely accurate universal time signal.

b. Service

The Galileo system, once fully operational, will offer four high-performance services worldwide:

- **Open Service (OS):** Galileo's open and free of charge service set up for positioning and timing services. In the future, the Galileo Open Service will also provide Navigation Message Authentication, which will allow the computation of the user position using authenticated data extracted from the navigation message.
- **High Accuracy Service (HAS):** a service complementing the OS by providing an additional navigation signal and added-value services in a different frequency band. The HAS signal can be encrypted in order to control the access to the Galileo HAS services.
- **Public Regulated Service (PRS):** The Public Regulated Service is for government authorised users, such as civil protection, fire brigades, customs officers and the police. It is particularly robust and fully encrypted to provide service continuity in national emergencies or crisis situations, such as terrorist attacks.
- **Search and Rescue Service (SAR):** The Galileo Search and Rescue (SAR) service is Europe's contribution to an international emergency beacon locating system called "Cospas-Sarsat". Galileo is the first satellite constellation to offer global SAR capability and significantly reduces the time needed to accurately locate a distress beacon. Galileo SAR also contains a unique return link that lets users know that their distress signal has been received and that help is on the way.

Moreover, the Galileo Programme is fully engaged in the process of developing Galileo 2nd Generation (G2G). Procurement activities for system, satellite and ground segment have been initiated in 2020 with the ambitious goal of starting deployment of the new infrastructure in 2024. With them, more services are announced to be operative such as eCall – the EU emergency-call system.

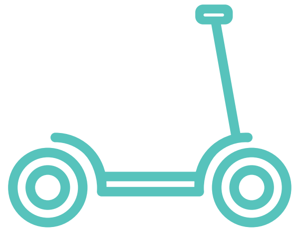
c. Benefits

In addition to gaining independence and control over continuity of service, with Galileo's constellation available there are more GNSS satellites in view, which means more accurate and reliable positioning and timing synchronization for the end users globally. This is especially relevant in higher latitudes, where Galileo offers better coverage than other GNSS systems.

A summary of the main benefits that Galileo brings for users —which will be explored in more detail in the next section—, including important added-value features, is presented below:

- Positioning accuracy down to decimetre level at full open sky.
- Robust positioning through the authentication of the navigation data.
- Resistance to interference (jamming and spoofing) and high resilience.
- Introduction of a return link for Search and Rescue operations, which informs the sender that their distress alert has been received.

4. EGNSS in urban mobility and PT



Having presented applications of GNSS in urban mobility services and having explained the Galileo system and its benefits, this section's goal is to explore how Galileo can improve the performance of current GNSS applications, and what new ones it can enable.

For this purpose, we have conducted desk research and in-depth interviews with positioning experts and urban mobility stakeholders, such as public transport operators. Thanks to these interviews, we have gathered three valuable experiences using EGNSS, which we are presenting next.

The first experience is shared by TMB, the publicly-owned company operating metro, regular bus, and tourist bus services in Barcelona.

In 2016, some of its 1,170 buses underwent a process of renovation of their on-board technology for aiding service exploitation —called SAEI, which stands for Exploitation and Information Aiding System in Catalan—. The operator seized this opportunity to replace the positioning unit embedded in the SAEI for one with the latest technological advances.

The new receiver is a mass-market solution which integrates multi-constellation and dead reckoning capabilities. The former allows the receiver to pick up signals from all existing GNSS constellations, including Galileo. The latter is a technique which complements GNNS signals with information coming from the sensors embedded in the receiver, such as accelerometer and gyroscope, to predict the trajectory in challenging situations for GNSS technology, where GNSS signals are missing or unreliable (e.g. driving through a tunnel).

Some tests were run by the operator before and after replacing the positioning unit, to compare the changes in performance. The tests were conducted while the bus was providing service in one of the city's bus lines, which makes their results a faithful reproduction of the situations faced by the positioning technology during operations. These different situations are shown in the images below, which were extracted from recordings made with both receivers.

The first set of images is from a segment of the route which takes place in one of the city's main roads, with many lanes and tall buildings on both sides. Figure 1 shows position fixes from the old, GPS-only, receiver. It is clear how the GNSS signals computed by the receiver were many times off the limits of the road. Figure 2 shows position fixes from the new receiver in the same segment of the route. The improvement is outstanding, with the receiver returning much more accurate position fixes.

According to TMB, the bus operator, the positioning error in the most challenging sections of this road went from between 40 and 60 metres to between 2 and 5 metres. The reference that TMB takes to calculate the error is the distance from the position fix to the lane most to the right, since that is where the bus lane is located in this specific road.

Figure 1: TMB, *Position fixes from a bus equipped with an obsolete receiver in urban environment*

Figure 2: TMB, *Position fixes from a bus equipped with a last-generation receiver in urban environment*

The second set of images is from the bus depot, which has both ground-level and underground parking. The recordings capture the following sequence: the bus arrives to the depot from finishing the service, goes underground to find its parking spot, spends the night at the depot, and leaves the next day to start the service again.

Figure 3: TMB, *Position fixes from a bus equipped with an obsolete receiver in an underground depot*

Figure 4: TMB, *Position fixes from a bus equipped with a last-generation receiver in an underground depot*

Figure 3 shows the behaviour of the old receiver, which is unable to keep track of the bus once it goes underground, since it only relies on GNSS signals. Figure 4 shows the performance of the new receiver, which was able to accurately locate the bus at all times. In this situation the improvement comes mostly from the dead reckoning technique used by the receiver, although it's true that an accurate positioning of the bus right before entering the underground parking area contributes to a more accurate estimate of the position overall.

TMB declares that being able to accurately locate buses in its depot, which can store up to 440 of them, had always been a problem they hadn't been able to solve. That is why the operator is very satisfied with how the current solution performs in this situation. The reasons why this improvement is relevant for the operations is because it makes it easier to find a specific bus when it has to undergo maintenance tasks, such as cleaning and refuelling. It also helps drivers find the bus which they were assigned quicker, at the beginning of the day.

The last image shared by the operator (figure 5) corresponds to a recording which includes moments when the bus was driving through some tunnels and partially enclosed roads in the city (section of the yellow line which is closest to the mountains). The position fixes were still able to follow the road in such situations, especially helped by dead reckoning in the first case, and also by multi-constellation in the second.

Figure 5: TMB, *Position fixes from a bus equipped with a last-generation receiver driving through tunnels*

Overall, TMB reports a 7% improvement of the indicator that it uses to measure the amount of time that a bus is correctly positioned while in service, which is currently at 97% for the buses with the new receiver. The operator also declares being able to provide more reliable real-time information to users and a more accurate ETA.

In conclusion, looking at the results of the tests carried out by the operator, it is only possible to affirm that multi-constellation acquiring signals from Galileo and other GNSS constellations and other technologies embedded in the receiver making use of techniques such as dead reckoning work in a complementary way that maximizes the value that each of them brings individually.

The second experience we are presenting comes from a scooter-sharing operator in Spain. In 2016, the company tested a new on-board unit (OBU) which integrated a multi-constellation receiver that also made use of EGNOS, Europe's satellite-based augmentation system.

The main reason for testing a new receiver was the fact that some friction along the reservation process had been detected: in deep urban environments, sometimes users would have problems finding the scooter they had booked because the positioning information wasn't reliable, meaning that the scooter was showing a location on the app different from the real position. This can be seen very clearly in Figure 6, which illustrates the behaviour of both receivers when the scooter is parked in a narrow street, with high buildings on both sides. The position fixes from the new OBU are represented in red, and the ones from the old OBU are represented in purple. While the former show acceptable values for accuracy and integrity, the latter are so erratic and inaccurate in such scenario that can sometimes lead the user to the wrong street.

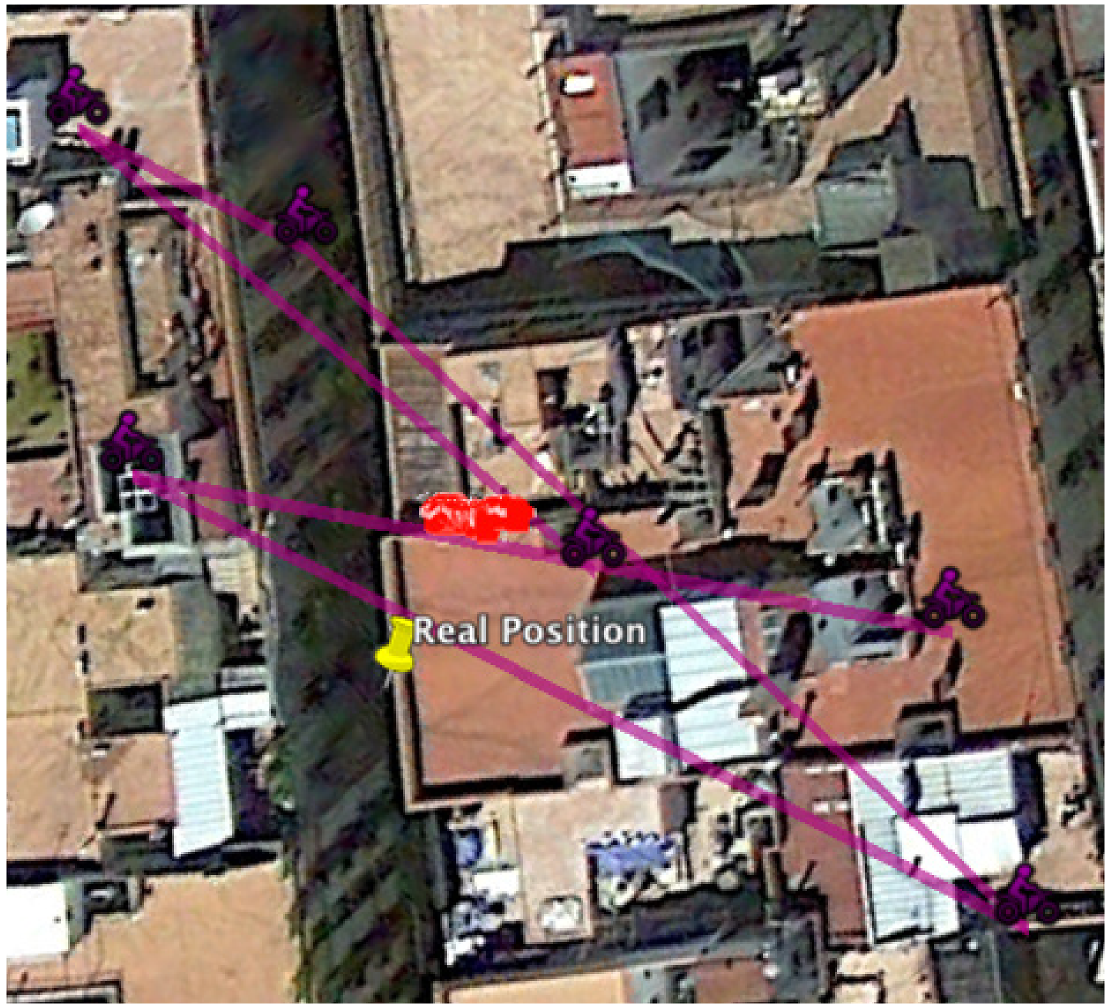


Figure 6: G-MOTIT, *Static positioning from a GPS-only receiver (purple) and a multi-constellation receiver (red) equipped on a shared scooter parked at a street in deep urban environment*

The test also included recordings from the scooter in motion, in a semi-urban environment (Figure 7). The new OBU's position fixes are always closer to the road than the old OBU's. There are also many more of them, showing not only a great improvement in accuracy, but in availability as well. One important factor that contributed to the accuracy improvement was the use of EGNOS, which reduced in a couple of meters the bias introduced by the system.

Figure 7: G-MOTIT, *Position fixes from a test done with a scooter equipped with a GPS-only receiver (purple) and a multi-constellation receiver (red) in a semi-urban environment*

The third and last experience we are sharing comes from a DRT service in a small town of the metropolitan area of Barcelona. The operator tested two different tablets for the driver, in order to compare the positioning performance of each. The tablet is used to navigate the driver through the route —which changes according to demand— and to show users the bus's position and ETA in real time. The test, which took place at the beginning of the year, was split in two phases: a first one using a Galileo-enabled tablet, and a second one using a GPS-only tablet. The analysis was made on a route (figure 8, left) which was repeated many times by the DRT service during lockdown, when there were very few regular users and the stops requested were always the same.

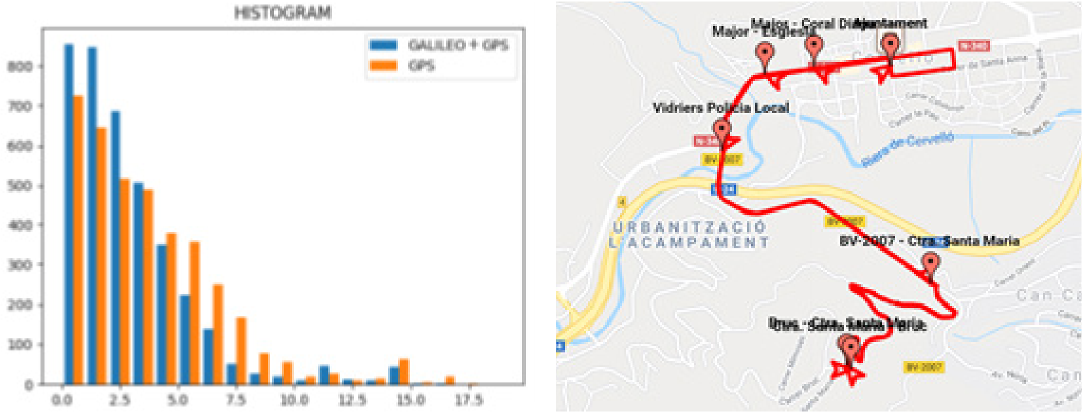


Figure 8: Galileo for Mobility, *Error samples from a GPS-only receiver and a multi-constellation receiver (histogram) equipped on a DRT bus performing the same route (image)*

In order to assess the accuracy of the receiver in each tablet, every computed position was matched to the nearest road and its error (distance to the road) was calculated. The histogram on the right side of figure 8 groups the number of error samples (Y axle) by distance in metres (X axle). Since the error samples from the Galileo-enabled tablet outnumber the ones from the GPS-only receiver as the error becomes smaller, it can be concluded that the receiver benefitting from multi-constellation is able to provide a more accurate GNSS signal.

In order to provide an overview of which new GNSS applications Galileo can enable, and which of the existing ones it can significantly improve, we have created a table following the structure of Table 1. Please note that this table doesn't include all the applications presented in Table 1, but only those where EGNSS can solve important pain points or trigger a greater impact.

In addition to the types of services covered in Table 1, Table 2 includes some applications of EGNSS in train and tram services. The railway sector is just starting to exploit the benefits of satellite technology to complement their beacons' control systems, as shown by the recent historical introduction by the Italian Railway Network (RFI) on a regional train line of a traffic control and management system that uses satellite technologies, including Galileo. [4]

[4] European GNSS Service Centre. (2020). *Satellite navigation: the new frontiers in railway traffic management. https://www.gsc-europa.eu/news/satellite-navigation-the-new-frontiers-in-railway-traffic-management*

SERVICE	EGNSS APPLICATION	RELEVANT STAKEHOLDERS	CRITICAL GNSS PARAMETER/S
TRAIN / TRAM	**Fleet management**		
	Track vehicles Using EGNSS to build a network of virtual balises and monitoring when the vehicle reaches each of them would make physical sensor infrastructures no longer necessary, saving railway operators the resources that would be dedicated to deploying them and maintaining them.	Fleet operator, PTA	Accuracy Availability Integrity Continuity
	Maintenance [5]		
	Infrastructure maintenance By combining the use of sensors in different parts of the vehicle and the positioning information from EGNSS signals, it is possible to detect the exact location where the infrastructure needs maintenance interventions. This could be used to identify the localization of catenary wear or incorrect height and stagger, or of rail corrugation and short-wave irregularities, for example.	Fleet operator	Accuracy Availability Integrity Continuity

[5] SIA Project. (2018). System for vehicle infrastructure Interaction Assets health status monitoring. https://siaproject.eu

Service quality control

Speed and distance regulation With EGNSS, it is possible to automatically adapt the speed of vehicles to the speed limit of every section of the line, as well as to the train ahead in order to keep the distance between them under certain safety and service parameters.	Fleet operator	Accuracy Availability Continuity

Sharing information with users

Estimated time of arrival Currently, the real-time position of trains and trams is calculated by taking the last balise which communicated with the vehicle as a reference and counting the number of wheel revolutions from there. This technique brings significant errors in curves and stops/starts on wet or leaf-covered rails.[6] Using EGNSS signals would provide a more reliable position of the vehicle, which would impact on more accurate ETA information for users.	Fleet operator, final user	Accuracy Integrity Continuity

BUS

Fleet management

Depot operations Finding a bus inside a big depot can be difficult if the positioning information isn't accurate. EGNSS can help locating vehicles faster when certain maintenance tasks —such as cleaning, repairing, and refuelling— need to be undertaken. It would also make it easier for bus drivers to find their assigned bus in the morning, before starting a service.	Fleet operator	Accuracy Integrity
Track vehicles With EGNSS, it's unnecessary to implement and maintain a sensor infrastructure (e.g. beacons) to know when the bus has reached specific locations in the line.	Fleet operator	Accuracy Availability Integrity

Service quality control

Driver behaviour On one hand, EGNSS would allow the fleet operator to detect whenever the driver leaves the designated route. On the other hand, it would provide precise and real-time information about the quality of driving, allowing the operator to detect undesirable behaviours such as speeding and sudden braking and accelerating.	Fleet operator	Accuracy Availability Continuity
Work shift monitoring By providing more accurate position and time information, EGNSS can allow for automatic monitoring of work shifts. This is possible when combining EGNSS signals (position fixes and the time stamps associated with them) with information of the drivers' timesheets (start of shift, breaks and end of shift).	Fleet operator	Accuracy Availability Continuity

Service provision

Improve commercial speed There are two ways in which EGNSS can be used to improve commercial speed of bus services. One way is by exploiting the accurate positioning data that	Fleet operator, PTA	Accuracy Availability Integrity Continuity

[6] GUIDE-GNSS. (2019). GNSS for Railway; Tramways, regional and mainline trains, freight. https://guide-gnss.com/railway

	it provides, which enables the operator to make decisions in real-time such as sending a driver the order to detour to avoid a congested area. Another way is by combining it with Transit Signal Priority (TSP), a service that controls traffic lights along a bus route in real time to give it priority over the rest of traffic. When the bus is approaching an intersection, the OBU sends its position to a transit management centre, requesting for the traffic signal to provide a green light.		
	Improve offer In combination with a system for anonymously tracking when passengers enter and leave the bus, EGNSS can enable the operator to match them with their origin and destination stop. This information is used to build matrices which give the PTA a general perspective of the mobility flows, and help make decisions that affect the offer, such as reinforcing services with higher frequency at the stops and times of the day where buses are packed.	Fleet operator, PTA	Accuracy Availability Continuity
	Service provision		
DRT	**Pick-up process** When the pick-up occurs at a location provided by the user, the accuracy of such location has a great impact on the smoothness of the process. For example, if the user's mobile device is EGNSS-enabled, it will send a position which accurately shows on which side of a big avenue the user is waiting. This can save valuable minutes of turning around to reach the user, had the signal not been accurate enough.	Fleet operator, final user	Accuracy

	Increase service speed The duration of trips can be reduced by exploiting the accurate positioning data that EGNSS provides, which enables the operator to make decisions in real-time such as sending a driver the order to detour to avoid a congested area.	Fleet operator, PTA	Accuracy Availability Integrity Continuity
	Service quality control		
	Driver behaviour On one hand, EGNSS would allow the fleet operator to detect whenever the driver leaves the designated route. On the other hand, it would provide precise and real-time information about the quality of driving, allowing the operator to detect undesirable behaviours such as speeding and sudden braking and accelerating.	Fleet operator	Accuracy Availability Continuity
	Validation of the route In DRT services which operate under a public contract, the PTA might require the operator to have a mechanism to validate the execution of the routes provided by the DRT system, and the kilometres reported by the operator itself. This becomes critical in this type of service where the route can be different every time, and it is only possible by sharing accurate position fixes from all the routes executed, like the ones EGNSS can provide.	Fleet operator, PTA	Accuracy Availability Integrity Continuity
	Service provision		

Ride-hailing / Taxi	**Pick-up process** When the pick-up occurs at a location provided by the user, the accuracy of such location has a great impact on the smoothness of the process. For example, if the user's mobile device is EGNSS-enabled, it will send a position which accurately shows on which side of a big avenue the user is waiting. This can save valuable minutes of turning around to reach the user, had the signal not been accurate enough.	Service provider, final user	Accuracy
	Service quality control		
	Driver behaviour On one hand, EGNSS would allow the fleet operator to detect whenever the driver leaves the designated route. On the other hand, it would provide precise and real-time information about the quality of driving, allowing the operator to detect undesirable behaviours such as speeding and sudden braking and accelerating.	Service provider	Accuracy Availability Continuity
Shared mobility (Car- / scooter- / bike- / kick scooter-sharing)	**Fleet management**		
	Rebalancing and charging operations In free-floating services, when carrying out rebalancing operations (i.e. moving vehicles to change how the fleet is distributed throughout the city), finding each vehicle in the fastest possible way can have a great impact on fleet management costs. The same goes for this kind of services using electric vehicles, when operators need to find vehicles with low battery to take them to charging facilities or swap their batteries on site.	Fleet operator	Accuracy Availability
	Vehicle appropriation alert Some users of free-floating services take advantage of the fact that vehicles don't have to be returned to a station to park them in their own private facilities, such as backyards (bikes) or even their garage (cars and scooters), and have them at their disposal. The accuracy EGNSS provides makes it possible to differentiate if the vehicle is parked on a public road or if someone is trying to keep it for him/herself.	Fleet operator, final user	Accuracy Integrity
	Service provision		
	Location of vehicle and start of the trip In free-floating services, if the vehicle is parked in a deep urban environment, its receiver might provide users with misleading information about its location. Sometimes, this information can be so inaccurate that the vehicle might be displaying its location at a different street from the one where it is actually parked. In this situation, finding the vehicle can take too long, creating friction between the service and the user. With EGNSS, the chances of this happening are reduced.	Final user	Accuracy
	End of trip and billing When free-floating shared mobility operators deploy their services, they define an area within which their vehicles must be parked at the end of every trip. In semi-urban and deep urban environments, some users might have problems trying to end their trip at the edge of the delimited area, due to the	Final user	Accuracy Integrity

	receiver's inability to detect that the vehicle is still within its limits. Again, this causes friction with the user and affects the smoothness of the overall experience. Additionally, the longer the user spends trying to end the trip, the more expensive it becomes, causing him/her even more frustration. EGNSS can avoid this situation by positioning the vehicle more accurately.		
	Impact on urban environment		
	Unauthorized parking In response to the explosion of free-floating shared mobility services, many cities have implemented changes in their traffic and parking regulations. The goal of such changes is to ensure that vehicles and pedestrians coexist safely and use public space in a balanced way. In some cases, the regulation even prohibits the use of sidewalks for parking scooters, bikes and kick-scooters. The problem is that there is no efficient way to detect, fine and remove those vehicles that were parked without respecting the regulation. With EGNSS, the positioning data coming from the vehicles could be accurate enough to differentiate if they're parked on the sidewalk or not. Since many cities already require real-time access to the positioning data from operators' fleets, a system to automatically send a public agent to fine and remove the vehicle could be set up by local authorities. Some other cities have responded to the rise of free-floating services by pro-actively working with operators to enable dedicated parking spaces for shared bicycles and kick-scooters. Such spaces are usually delimited by painting a square on the ground and signalling their purpose as spaces for authorized parking of shared vehicles. With the accuracy that EGNSS provides, it is possible for operators to detect when a user hasn't parked the vehicle within one of those spaces, and hold him/her accountable for it.	Fleet operator	Accuracy Availability

Table 2: *EGNSS applications in urban mobility, by type of service*

Beyond service-specific applications, when Galileo-enabled mobile devices become the norm, public administrations will be able to access more insightful aggregated mobility data, thanks to the improvements in accuracy and availability enabled by EGNSS. For instance, it would be easier to differentiate with which means of transport users are travelling, the moment when they transfer to a different means, and how many times they transfer during the trip.

To conclude, we can affirm that EGNSS positively impacts all existing applications benefitting from satellite technologies, and even enables new ones. This is mostly done through better signal accuracy and availability, but there is another key benefit —as briefly mentioned in section 3.3— which the Galileo system, and no other GNSS at the moment, offers: the authentication of the satellite signal. According to experts in the field, this is the most differentiative, added-value feature of Galileo, and it will enable a whole range of applications that are not possible today.

The Galileo system authenticates its satellite signals by incorporating a digital signature to the navigation data that certifies its source. This allows EGNSS users to assess the trustworthiness of the signals, making them more robust against spoofing attacks. As explained in section 2, spoofing attacks send fake GNSS signals to make receivers transmit a false location and create the impression that a person or a vehicle is in another place. The implications of this for the GNSS applications described in this document are worth-noting. Imagine, for example, if some individuals used this vulnerability to take control over free-floating shared vehicles and deprived others from being able to find them and use them. Some new applications are even hard to picture becoming a reality without authenticated signals. Think of a seamless public transport system where users don't need to purchase tickets or top up any credit, because it relies completely on the positioning data from their smartphones to charge them for their trips. Tricking the system into believing that you've travelled much less than you've actually done sounds like a big risk that can't be taken by public transport authorities.

An authenticated signal not only provides more robustness, but it can even serve as legal evidence of the correctness of the GNSS position for liability issues. An example that illustrates this very well comes from another bus operator that we have interviewed, which had a legal case opened by a citizen who had parked on a bus lane. The camera on the bus took a picture of the car and the owner was fined. The owner ended up winning the case by alleging that the bus operator had no legal evidence that the bus was there and the car was obstructing its way.

5. Exploiting EGNSS as a mobility provider

Having understood the benefits and uses of EGNSS, you might now be wondering how mobility providers can exploit them. The first important step is learning about the characteristics of the components that vehicles must equip to benefit from EGNSS signals.

One of the two critical components is the position receiver. It needs to have multi-constellation and, for better results, also dual-frequency capabilities.

Galileo-enabled mass-market receivers have become widespread and are available at very competitive costs. 76% of receivers on the market are multi-constellation (i.e. compatible with at least two different constellations), and 52% are capable of working with signals from all constellations. Multi-constellation provides increased availability especially in challenging environments for GNSS, such as urban canyons, where satellite signals from one constellation can get completely blocked by tall buildings, improved accuracy because there are more satellites in view, allowing for better geometry, and improved robustness since the position is built with data from different sources, making it less vulnerable to attacks.

Galileo transmits navigation signals in two common frequency ranges: E5 signals in the lower L Band (1164-1215 MHz) and E1 signals in the upper L Band (1559-1610 MHz). The growing number of open signals in the E5 band, coming from all four available GNNS constellations, is leading the market to increasingly adopt E5 as the second frequency in new receiver models: 20% of all available receivers have E1+E5 dual-frequency capabilities. Dual-frequency receivers can achieve better accuracy values and offer improved resistance to interferences since they work with a wider range of frequencies.

The other critical component to pay attention to is the antenna. The antenna receives, amplifies, and band-pass filters (i.e. rejects or attenuates frequencies outside a certain band) GNSS signals. No matter how good the chipset is, with a poor-quality antenna the overall performance of the positioning technology will be affected. The antenna must be multi-frequency to be able to work with the bands for which dual-frequency chipsets are prepared. [7]

Now that the characteristics of the critical components to exploit the benefits of EGNSS are clear, it is worth looking at the value chain of positioning technology and understanding the role of each stakeholder in it. For that purpose, we have taken our learnings from the interviews we have conducted with public bus operators and have illustrated the value chain of positioning technology for bus services in Figure 9.

Please note that for other kinds of mobility operators, the value chain might look quite different. For instance, a kick-scooter operator might just purchase the chipsets directly from the receiver manufacturer and integrate them by itself, and a scooter-sharing operator might ask the scooter manufacturer to include a specific receiver model in the vehicles before placing an order.

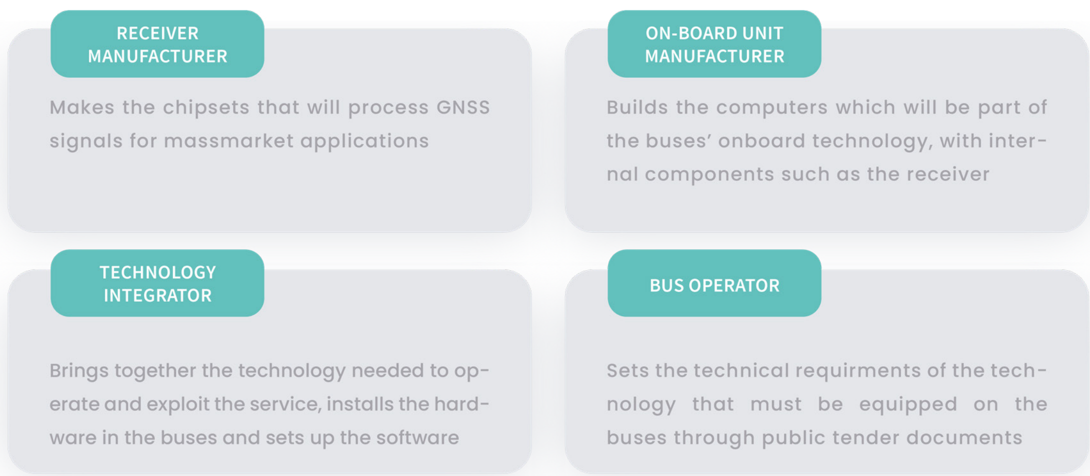


Figure 9: *Value chain of positioning technology for public bus services*

[7] GSA. (2020). GNSS User Technology Report; Editor's Special on Space Data for Europe. Issue 3. Luxembourg: Publications Office of the European Union

Some interesting insights from the interviews with public bus operators are shared below:

- When they released tenders to update the on-board technology of their fleets, one of their main motivations was to benefit from the latest advancements in positioning technology. Thus, they included multi-constellation capabilities as a requirement for the receiver in the tender documents. Compatibility with Galileo was requested only in one of the cases, but always explicitly mentioned. One of the operators is planning to also include dual frequency as another requirement for the chipset in all future tenders.

- The receiver that ends up being integrated in the buses might, or might not, come correctly configured from factory to exploit EGNSS. Some receivers even run an automatic configuration process as soon as they're installed in the vehicle, which leaves them all set for providing the best possible performance. It was not the case of one of the operators, which released a separate tender to hire a company which would carry out the operations for setting up the receivers. By doing this, the operator ended up losing control over such important step, only to find out months later that, even though its fleet was equipped with Galileo-enabled receivers, it wasn't benefitting from EGNSS because the chipsets weren't properly configured to pick up signals from Galileo.

- There are two stakeholders in the value chain which can act as advocates of Galileo-enabled positioning technology: the OBU manufacturer and the technology integrator. The OBU manufacturer offers customers the option to include a cheaper, single-constellation receiver, or a more expensive, multi-constellation receiver. If the OBU manufacturer understands well the benefits that a multi-constellation receiver can bring for the end customer, it will be able to communicate them and make recommendations. The technology integrator works with the end user of the positioning technology: the bus operator. It knows its pains and needs regarding positioning, so it is in a good position to learn and transmit how EGNSS can solve them, thus influencing the operator's choice. At the same time, it can learn from the positive experiences of the most proactive bus operators, which are already benefitting from EGNSS, and can decide to offer a Galileo-enabled technological solution to other operators.

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