GNSS in Cadastral Surveying: State of the Art and future perspectives in the framework of Galileo

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Key words: Cadastre, Galileo, GNSS, RTK, PPP

SUMMARY

High Accuracy GNSS (Global Navigation Satellite System) is today commonly used in Cadastral Application and Mapping. Current techniques (e.g. Network-RTK) are based on Local and Regional Network of GNSS Reference Receivers, with inter-distances in the order of 70 Km. Such Networks are commonly managed by Land Administration or Geodetic Authorities.

Relevant implementation and maintenance costs of such Networks are a blocking factor for the development of High Precision techniques. New techniques (e.g. PPP-RTK, Precise Point Positioning RTK) are promising global and regional solutions at affordable costs. Very sparse Network of GNSS receivers are implied in this case.

Furthermore, multiple constellations and frequencies will allow an higher availability in urban areas and a reduction of the initial time to convergence to cm level position (Time To Fix Carrier Phase ambiguities). Instantaneous centimeter level positioning is the final target of future techniques, as many studies revealed.

Within such framework, Galileo is introducing Commercial Services, that can be an enabler for the affordable development of such techniques.

Out of Surveying and Mapping, most of the applications with a relevant spatial and geographical content are today requiring more and more High Precision positioning and reliability. Automatic driving is one of the most relevant. High resolution and high precision cartography are therefore needed. In this case, economy of scale can be activated.

Through multiple constellations and frequencies, different High Accuracy Service Level can be defined.

The use of Galileo Commercial Services is the starting point for the present analysis.

A profitability and Cost Benefits Analysis has been carried out. At this aim, the presence of a Global Operator offering a first level of Augmentation for High Accuracy (e.g. 10 cm) has been assumed. A densification with local network or Cooperative approaches among users for sharing Local Ionospheric Estimation has been defined for Higher Accuracy levels (at the level of current RTK performances).

The performed analysis showed that a Commodity scenario, where automotive introduces the needed Economy of Scale, offer a better profitability and more positive results in terms of Cost Benefits Analysis than a Conservative Scenario.

Therefore, an initial technical and Cost Benefit Analysis will be carried out in order to define a suitable model for the application of innovative High Precision techniques in GNSS Cadastral Surveying in the view of Galileo.

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1. THE CADASTRAL SECTOR NOWADAYS

The term “Cadastre” refers to a land ownership information register.
The origin of the Cadastre belongs to the Egypt, where it was necessary to redefine land properties after the Nyle flooding.
The Cadastre can be classified in different ways: urban or rural, probative or not probative (if relevant acts have or mnot a juridical value), descriptive (describing land information) or geometrical (planar representation).
Main functions of the Cadastre are:

- Topographical and Mapping: recording of land boundaries
- Title registration: recording of the ownership and relevant legal rights
- Property Valuation: defining land taxes and property type based on land property

In many countries, Cadastre, Mapping and Land Registry functions are separated. Surveying is carried out by surveyors, while title registration is performed by Notaries.
A Great part of the Countries developed a complete digitalization of the Cadastral mapping system, starting from the existing paper maps. In many countries the Cadastral Maps are published on the Web by relevant Authorities.

Cadastral Authorities at national level are under the responsibility of different Ministries (e.g. Ministry of Interior, Justice or Economy and Finance).

Cadastral parcels boundaries are recorded through the establishment of a relationship between maps and survey control points taken on the field. Points and relevant baseline measurements are taken nowadays through the Hybridisation of EDM (Electronic Distance Measurements), Total Stations and GNSS professional measurements. Needed measurements accuracy is in the order of 0.1-0.3 m. In the past, dual GNSS receivers where needed by a surveyors for achieving such accuracies. Today the diffusion of Local Augmentation Network for RTK and Network RTK methodologies, as well as emerging Global Systems, allows implementing a high accuracy surveying with a reduced effort.

A Network of control points is maintained by Mapping and Cadastral National Agencies for linking the performed surveys to National Coordinate Systems.

Surveying activity is performed by different actors in any Country, depending on relevant Land Administration Authority organization and regulation.

Standardisation of Cadastral Data Models and relevant representation involves many disciplines and bodies working in the GIS and SDI (Spatial Data Infrastructure) development.
Among the others, is has to be remembered the role of FIG (International Federation of Surveyors), ISO (e.g. TC 211) and EUROGI.

For Europe, the INSPIRE European Commission initiative was created for standardising spatial data information and providing implementation rules for the European Union Policy.

The Directive 2007/2/EC of the European Parliament establishes the basis for Spatial Information systems in the European Community. The use of a common European Reference Coordinate Realization (ETRF2000) is there recommended for Public Administrations.

2. STATE OF THE ART OF HIGH ACCURACY GNSS

The traditional High Accuracy techniques are based on differenced measurements between the rover receiver and a single GNSS Reference Station, leading to RTK (Real-Time Kinematics) techniques. The evolution of such a concept is NRTK (Network-RTK).

The first is based on double differences between a rover and a single Reference Receiver for eliminating common mode errors and fixing Carrier Phase ambiguities. Such an approach is limited in particular by the spatial decorrelation of ionospheric errors. It leads to the need for the rover to be no more than 30 km far from the closest Reference Station (current algorithms allows to extend such limit). For implementing a homogeneous service over a continental area, thousands of such Reference Stations are needed.

On the other hand, Network-RTK approach is based on a sparser network, divided by clusters of 4-5 Reference Stations, with maximum Reference Station interdistance in the order of 70 km. In this case, corrections within the coverage area are calculated through statistical interpolation of the errors (e.g. Collocation method or Kriging Interpolation, A. Al-Shaery, 2011) or through single error estimation (e.g. Ionospheric and Tropospheric estimations through a Kalman filtering) in the so called SSR (State Space Representation) approach, developed by the RTCM-SC 104 (G. Wübbena, 2001). The concept of VRS (Virtual Reference Station) has been originally introduced for transmitting to the user GNSS measurements from a “Virtual” reference receiver generated, through Reference Stations measurements interpolation, close to the user. This reduces the intricacy due to spatial decorrelation as perceived by the rover receiver.

Such Augmentation networks are managed by GNSS High Accuracy Service Providers.
Furthermore, through Network-RTK, the number of Reference Stations needed for a continental service is quite high. The cost to be supported is proportional to the number of Reference Stations, both in terms of hardware overhead and software computational load.
Concerning the implementation, maintenance and recovery costs are also relevant recurrent costs for High Accuracy Service Providers.

Due to possible different network adjustment procedures among overlapping networks, relevant positioning results can be not homogeneous among different services.
Starting from the above considerations, the PPP (Precise Point Positioning) concept has been developed (J. F. Zumberge, 1997). It is a based on the calculation of correction for the user calculated through a Network of sparse Reference Stations (400-1000 km interdistances) covering a wide area. Through such networks, it is possible to estimate precise satellite orbits and clock corrections and to provide them to the rover receiver. If Ionospheric error can be reduced (e.g. through Ionospheric-Free raw measurements combination), such correction allows a user to achieve 10 cm accuracy (not fixed ambiguities) in 15-40 min without the need of a close Reference Station. Basic formulation is the following:

$$P_{fk}^{i} = \rho_k^i + c(dt_k - dt^i) + T_k + \frac{f_1^2}{f_f^2} I_1 + b_{Pfk}^i + \varepsilon_{Pi}$$

$$L_{fk}^{i} = \rho_k^i + c(dt_k - dt^i) + T_k - \frac{f_1^2}{f_f^2} I_1 + \lambda_f N_{fk}^i + b_{Lfk}^i + \varepsilon_{Li} \qquad (1)$$

$$b_{Pfk}^i = b_{Pfk} - b_{Pf}^i$$

$$b_{Lfk}^i = b_{Lfk} - b_{Lf}^i$$

where ρ_k^i are the geometric differences, d_{tk} and d_{ti} are the receiver and satellite clock offsets, T_k is the tropospheric error, I_1 is the ionospheric error, b_{Pfk}^i and b_{Lfk}^i are the differences between receiver and satellite biases for Pseudorange and Carrier Phase and f, k and i are the frequency, receiver and satellite indexes. N are the Carrier Phase Ambiguities to be solved for achieving high accuracy at a few centimeter level.

PPP is based on undifferenced measurement. Therefore, all common errors and biases that are eliminated through Reference to rover receiver differencing, have to be properly estimated or modelled. The following are of relevance: Phase windup, due to the attitude of satellite and rover antennas, Tropospheric wet component, depending on Pressure and Temperature, Site displacements due to Earth Tides and Ocean Loading effects, as well as antennas Phase Center Variation (estimated by international organizations) and IFB (Inter Frequency Biases).
Usually, Ionospheric-Free combination is used for cancelling first order Ionospheric delay. Such combination is characterized by a wavelength off about 6 mm, therefore relevant ambiguities are difficult to solve.

For overcoming such point, a cascade approach is adopted and Widelane (through the Melbourne-Wübbena combination) and Narrowlane combinations ambiguities are solved in sequence.

If we were able to fix Carrier Phase ambiguities, convergence time can be reduced and classical RTK accuracy can be achieved. Such PPP-AR (PPP- Ambiguity Resolution) techniques have been studied by the scientific community and different approaches have been derived. Satellite biases estimations have to be provided to the user for performing PPP-AR.
Within such an approach, Continental/Global Network Control Centres (e.g. CNES, 2010) are in charge of estimating Widelane and Narrowlane satellite biases and to provide them to the user. Such biases are eliminated through differencing raw measurements in the RTK and Network-RTK approach, but are needed for high accuracy undifferenced measurements processing. Through such biases, Precise Ephemeris and Clock corrections, the rover receiver is able to fix ambiguities and achieve RTK accuracy level in less than 15 min. Many studies have been developed on such matter (D. Laurichesse, 2009, P. Collins, 2010, J. Geng, 2010).
Furthermore, it has been showed that the availability of precise ionospheric error estimation (below 0.1 TECU accuracy) from an external source allows to constraint the Ionospheric delay I_1 in (1). This leads to achieve the target of instantaneous 10 cm accuracy though Reference Stations located at interdistances of 150 km (S. Banville, 2014).

Rapid Fixing can be obtained with closer network of receivers and PPP-AR. Such Ionospheric corrections can be provided by existing Reference Stations in the neighbour of the rover or through Cooperative approaches. The height accuracy is limited by tropospheric error. The use of the third frequency can be furthermore beneficial for that (D. Laurichesse, 2016).

It has to be emphasized that using PPP corrections, the solution is expressed in the Standard Reference Frame where corrections are calculated (e.g. following IERS standards). It is, therefore, in charge of NMAs (National Mapping Authorities) to calculate the necessary Coordinate Transformation for being compliant with relevant national or regional regulations (e.g. INSPIRE Directive, dictating the reference to ETRF2000 Reference Frame for Europe).
Concerning the current distribution of Local Augmentation Networks, it has to be emphasized that the current density of Reference Stations in the world is different. While CORS (Continuously Operating Reference Station) are quite well dense in Europe and US, CORS Networks in the rest of the world of variable density. The availability of Reference Station Networks impacts on professional user willingness to pay and perceived benefits.

3. GNSS HIGH ACCURACY SYSTEMS INNOVATIONS

If a Real-Time PPP-AR can be implemented, such system will allow the deployment of a reduced cost, Regional Augmentation network for a plethora of users categories.

Furthermore, the emerging development of Connected Cars and Automatic Driving, as well as Rail TCS (Train Control Systems) based on GNSS, imposes the need for the development of highly reliable systems for Safety applications. GNSS Integrity is therefore a need to be associated to High Accuracy. Regulation and standards have to be built based on High Accuracy and High Integrity services for allowing a penetration of GNSS in those sectors.

Integrity concept was born in the aviation sector in order to define Wide Area (RTCA, Minimum Operational Performance Standards for Global Positionnig System/Satellite-Based Augmentationn System Airborne Equipment-RTCA DO-229D, 2013) or Regional Systems (RTCA, Minimum Aviation System Performance Standards for the Local Augmentation System (LAAS), 2004) able to meet a requirements in terms of acceptable Probability of a not detected failure in the positioning system. For the aviation sector such Integrity Risk Requirement is $2x10^{-7}$/150s. In the case of Rail, adopting SIL-4 Safety Requirements, the THR (Tolerable Hazard Rate) parameter is adopted, with a value of 10^{-9}/h. For the automotive sector, such value can also be more stringent. The Integrity Requirement has to be met for the whole Navigation System, including Reference Stations and Control Centre, in case of Local Augmentation.

Some studies have been developed for the extension of the Integrity concept to PPP. CRAIM (Carrier Phase Receiver Autonomous Integrity) is a mean for dealing with PPP Integrity through a specific Protection Level calculation (S. Feng, 2014). In case of Ambiguity Fixing, the incorrect Ambiguity Fix raises as further case of Faults to be monitored.

From what above, it is clear how PPP is a very promising High Precision Technology, but there are some gaps to be filled between the theory and a real operational implementation of a Wide Area High Precision System based on PPP.

RTCM-SC 104 is a de facto the standardization body for terrestrial Augmentation messages definition. It is currently working on the implementation of SSR messages. Such messages includes the estimation of single errors from a control centre. Corrections relevant for PPP services delivery (e.g. satellite biases) are foreseen within the Standardization Group. Furthermore, a Working Group on Integrity Monitoring (Integrity Monitoring for High Precision Application) has been recently setup with the aim of defining the definition of Integrity messages for Local Augmentation Systems.

An experimental Real-Time Global Augmentation Service is provided by the IGS RTS (International GNSS Service Real Time Service, http://www.igs.org/rts). They are providing in an experimental way most of the RTCM SSR messages for PP implementation to the rover, from precise ephemeris and satellite clock corrections, to satellite biases estimation, as generated by main centres currently working on PPP-AR.

Looking at future evolutions, it is expected that most of transport applications, out of classical geodetic, surveying and mapping ones, will require High Accuracy and High Integrity Services. Different levels of services can be established, depending on the availability of local and global augmentation infrastructures.

In Figure 1 a possible development scenario is showed (Capua, 2017). A first Level of Augmentation can be setup based on a sparse backbone regional network able to monitor in Real-Time GNSS satellites status and to derive relevant parameters (precise ephemeris, clock corrections and satellite biases). Such First Level of Augmentation can provide the needed corrections for 10 cm level accuracy with long convergence times (e.g. 20-40 min). Typical applications are terrestrial, offshore surveying and low cost geodetic networks densification.
Through the densification of such network, based on existing Reference Stations of Cooperative approaches among users, precise estimation of Ionospheric error can be obtained. It is therefore possible to extend the service to a second level, where classical RTK cm level accuracy can be obtained and transport applications can be served.

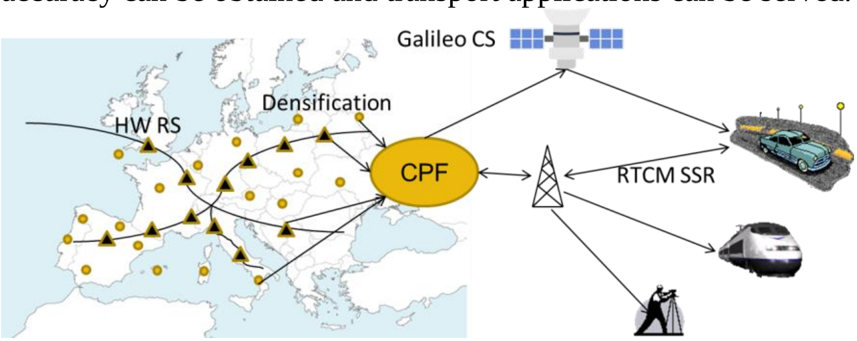

Figure 1 - A domain shared Augmentation Infrastructure

Another important field of development concerns GNSS surveying through Smartphones. Recently, smartphone chip manufacturers are beginning to produce multifrequency GNSS, chipset for smartphones (Broadcomm, 2017), including Galileo. Intersting enough, the system is based on the L1/E1 and L5/E5 frequencies, leading to better performances with respect to the classical GPS L1/L2 receivers in terms of Ionospheric and Multipath error reduction.

Currently, smartphones do not allow achieving high accuracy due to the technical limitations. Concerning antennas, they are linearly polarized and highly affected by multipath. On the other hand, power duty-cycle, for saving reasons, interrupts GNSS operations, leading to

Carrier Phase measurement Loss of Lock. This does not allow implementing a real-time RTK. Research is anyway going on for integrating basic PPP functionalities on the smartphone.

Receiver Manufacturers are also starting to provide solutions for High Accuracy Surveying based on reduced cost terminal or a Central Processing of raw measurements sent by the user.
Furthermore, SDR (Software Defined Radio) technology is rapidly developing. This solution is based on a minimal Hardware component (a signal sampler) connected to a processing unit (e.g. a General Purpose PC or an FPGA) able to perform GNSS Signal Processing via Software. This allows a complete flexibility and the possibility to easily upgrade the receiver in case of new coming constellations or frequencies. SDR can also play a relevant role in Cyber Security and anti-spoofing. A first use of SDR technology for the development of GNSS High Accuracy Systems for Cadastral surveying has been studied (Capua, et al., 2016).
A possible view of technological trends of High Accuracy systems are reported in Figure 2. Local RTK/NRTK Augmentation Infrastructure are costly and Global systems are envisaged to be implemented in a range of 10 years.

On the other hand, high accuracy receivers are moving from costly high end terminals, to lower cost, mass market products.

This process, accelerated by the economy of scale introduced by the transport sector, is expected to pave the way for the development of a low cost High Accuracy services for Mass Market in the medium term (e.g. ten years).

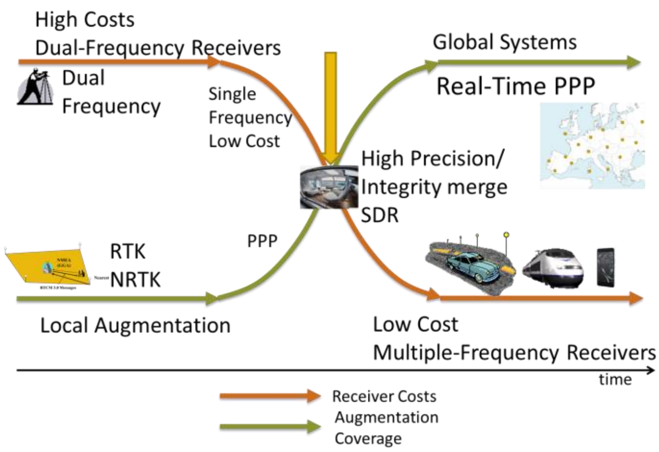

Figure 2 – The technological trends of High Accuracy applications

3.1 The Galileo Commercial Services

Galileo Commercial Services are going to provide basic High Accuracy Services and Message Authentication. The implementation of such services is described in the European in the Commission implementing Decision (EU, 2017). Other amendments are under discussion about the level of Services and the Service Provisioning models.

Concerning High Accuracy Services, Augmentation data will be transmitted within the navigation message in order to allow users to achieve an accuracy level comparable with classical PPP without Ambiguity Fixing.

The above EU Decision states that Commercial Services will be supplied by one or more service providers through the GSC (GNSS Service Centre), the Ground Segment and transmission of augmentation messages by Navigation satellites to the rover.

Galileo only Network RTK can be tested with the available satellites in the Sky. In Figure 3 it is reported a Network-RTK solution developed through five Reference Stations in Italy, with interdistances in the order of 20-50 km. The Central Reference Station is used as a rover.

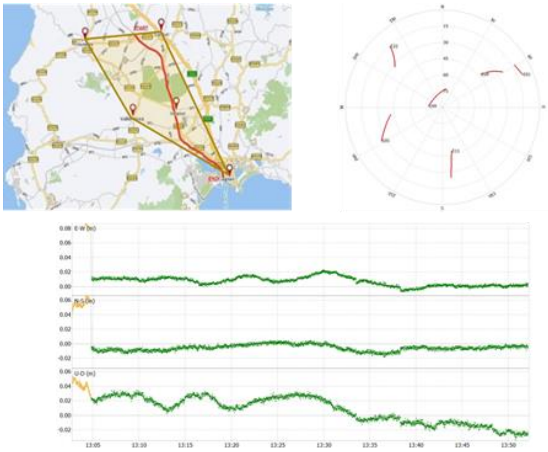

Figure 3 – Galileo only Network-RTK results

Testing and validation phase of the Commercial Services is foreseen between 2018 and 2020. The Full Commercial operating phase is foreseen from 2020.

Relevant satellite visibility and accuracy are reported, showing usual RTK performances.

3.2 Advantages for On-Field Surveying

The availability of described innovate High Accuracy service will lead to several practical advantages or GNSS surveying, compared to classical RTK/NRTK surveying procedures.
First of all, the configuration of the rover receiver will be independent from the location. Due to the fact that a material or Virtual Reference Station in the proximity of the surveying area is no more needed, the configuration for the access to global corrections messages can be performed once for all.

The increased satellite availability, due to multiple interoperable constellations (e.g. GPS and Galileo), leads to several advantages on the field. New available signals (e.g. Galileo E5a and E5b) allow a reduction of multipath effect and less noisy raw measurements.

An improved availability of satellites, as well as the availability of the third frequency, will allow the reduction of TTFA (Time To fix Ambiguities) and therefore more efficiency on the field (Odjik, 2002). Furthermore, the improved satellite visibility will allow to reduce the need for more time consuming Hidden Points surveying.

The availability of the new Global High Accuracy services is expected to eliminate the need of a second receiver to be setup by the surveyors due to the unavailability of Reference

Stations close to the surveying point. Access to local area precise ionospheric corrections can be performed through broadcasting services and relevant messages attached to the global one by the local NTRIP broadcaster.
As last effect of the availability of a Global High Accuracy System, it has to be remembered that PPP solutions are referenced to the Global Reference Frame and conventions used for PPP correction calculations. If transformation from Global to Local and Regional Coordinate Framework (e.g. ETRF2000 for Europe) are properly defined, this can lead to a harmonisation of Coordinate Systems for Cadastral applications.

4. ECONOMIC SCENARIO ANALYSIS

In the following, the Economic Scenario Analysis for the application of the innovative GNSS High Accuracy Augmentation systems is analysed. The analysis will be carried out starting from the assumed availability of Galileo Commercial Services.

A preliminary Value Chain Analysis is carried out and a relevant Business Model defined for identifying revenue and cost sharing mechanisms.
Therefore, the available and Addressable Market is estimated in terms of number of Surveyors in the World willing to pay for such GNSS Augmentation services.
Two Economic Scenarios for the analysis are defined (Commodity and Conservative) and relevant parameters defined. Based on that, a price law is derived for the following Market and Cost Benefits Analysis.

4.1 Value Chain and Business Model Analysis

Cadastral Surveying Value chain is currently composed by the following actors:

- **Cadastre Authority**: it can be a dedicated Agency (e.g. an NMA) or an organisation being part of a larger institution (e.g. a Ministry); some Countries does not have a Cadastral Authority and relevant Land Registry is maintained by a dedicated board (e.g. Bureau of Land Management in US)
- **Local Augmentation Service Providers**: they are provide augmentation messages for RTK/NRTK surveying; relevant services can be for free or subject to the payment of a fee; in some countries, relevant they are managed by Cadastral Authorities, other institutions (e.g. SWEPOS, Sweden) or by Council of Surveyors
- **Council and Surveyors**: at national or international level, they represent Professional Surveyors and develop Working Groups and recommendations for the use of innovative technologies, as well as Surveyors Training
- **Aereophotogrammetry Companies**: with reference to particular survey needs or for the establishment of a mapping base in developing Countries, Aerophotogrammetry companies are involved
- **GNSS and Topographic Instruments manufacturers**: they provide GNSS Reference Stations for Local Augmentation systems development and surveying instrumentation (GNSS rover receiver, Total Stations, EDM), as well as RTK/NRTK Local Augmentation Sofware; they are also Local Augmentation Service Providers in some Countries
- **Mobile Communication Operators**: they are in charge of transmitting augmentation messages to the user; relevant communication fee is in charge of the user

A graphical representation of the Current Value Chain is reported in Figure 4.

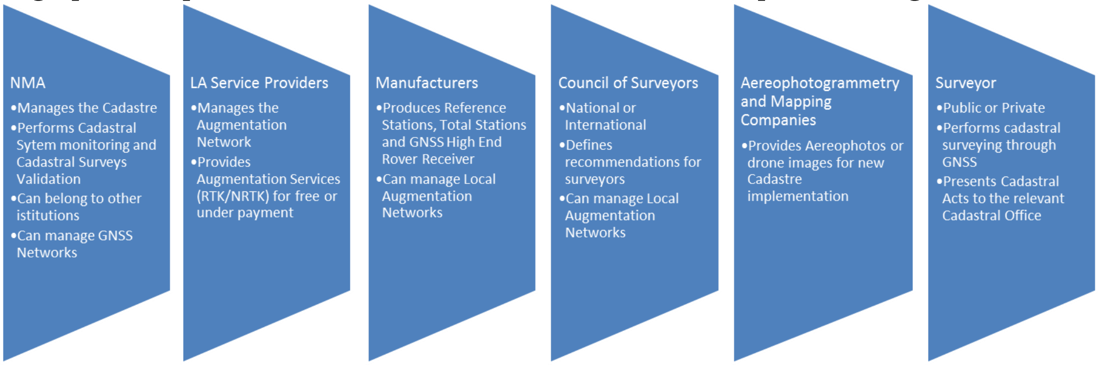

Figure 4 – High Accuracy Cadastre Value Chain

The future High Accuracy systems development scenario depends in a relevant way on the penetration of High Accuracy services in the automotive Sector.
Value Chain actors trends can be summed up as in the following:

- **Basic Global Augmentation Services**: provision of basic augmentation messages for PPP implementation (e.g. precise Ephemeris and Clock Corrections) from International Organizations; such services are currently for free and it is expected that future GNSS System Operator are going to provide for free such basic augmentation data, following the IGS RTS case. Satellite biases, as the first step needed for RTK-level services, are expected to be provided for free in the long term. This will allow the provisioning of a Basic PPP service, with decimetre level accuracy and tenths of minutes convergence time; this service can address Geodetic community and Surveying communities
- **Local Enhanced Augmentation Services**: Basic Augmentation Services cannot be used for large scale applications requiring High Accuracy in Real-Time in Real-Time, as in the automotive case; here, as the estimation of local effects (e.g. at least Precise Ionospheric error estimation) is needed; it is expected that such services will be provided by Service Operators with the payment of a fee; possibly, ionospheric corrections can be also left to Cooperative approaches
- **National Mapping Agencies**: they are in charge of defining and maintaining National Reference Systems, aligned with Regional/Continental recommendations (e.g. INSPIRE and the ETRF2000 Realization of the ETRS89 for Europe); in the future, they can monitor the provided Global and Local Services for certifying the use for surveyors activity; it is relevant to note that PPP can be used for the densification of Geodetic network at low cost
- **Manufactures**: it is expected that, due to the future penetration of low cost GNSS multi-frequency chipsets, the high-end receiver price will decrease

For the sake of the Market analysis, the following assumptions are considered.
Concerning Galileo, the main assumption is that Commercial Services will be provided for free for a basic decimeter level accuracy. With this scope, it is assumed that Galileo will broadcast basic Augmentation data (precise ephemeris, clock corrections and satellite biases). Relevant Services are assumed to be provided for free.

The further level of Augmentation needed for achieving reduced Time for Convergence is expected to be shared between external Operators and Cooperative approaches.

It is assumed that the needed Sparse Network implementation and relevant operation will be assigned to a Global Augmentation Service Operator (GASOp) by European Commission.
The broadcasting capability and the provisioning of any kind of Augmentation is open to any Private Service provider in any Scenario.

The reference period for the analysis is 2020-2035.
Table 1 summarizes the assumptions for the Value Chain in the Analysis to be carried out.
Two Scenarios can be defined for the Analysis as follows:

- **Commodity Scenario**: High accuracy is required by the Automotive Sector; in this case, economy of scale for receivers is activated and other transport sectors (e.g. Maritime and Aviation) are sharing costs for implementing a shared Local Augmentation Networks for Local Ionospheric Estimation for free for any application; Cooperative approaches are implemented among users; National/Global Augmentation systems are implemented; penetration of High Accuracy Services for surveyors and other sectors reaches 100% on 2030; Smartphone manufacturers and Professional Receiver manufacturers develop low cost multi-constellation/multi-frequency terminals; 90% of new cars are fully autonomous; Regulation supports the introduction of High Precision GNSS in the Automotive sector
- **Conservative Scenario**: the current situation of High Accuracy Services implemented by Local Augmentation Service Providers through NRTK techniques is considered, with relevant Service, Operation and Maintenance costs applied; Rail, Aviation and Maritime, needing High Accuracy and High Integrity, are developing their own Augmentation Services; Regulation does not explicitly support the introduction of High Accuracy, only a small percentage of new cars are fully autonomous

A General Case Business Model is reported in Figure 5.
The GASOp is the Global Augmentation Service Operator in charge of Basic Augmentation messages and to transfer them to the GNSS Service Operator for the final broadcasting through Galileo satellites navigation message. This service is provided for free to the user.
LASOp (Local Augmentation Service Operator) are in charge of providing to the user the needed Local Augmentation data (e.g. Precise Local Ionospheric error) for achieving High Accuracy near Real-Time Services.

Table 1 – GNSS High Accuracy Value Chain actor role and assumption for the Analysis

Actor	**Service Provision**	**Service Delivering modality**
GNSS Service Centre (e.g. Galileo GSC or IGS)	Precise Ephemeris, clock Corrections for non Real-Time, 10 cm accuracy positioning	Free
Global Augmentation Service Providers	Satellite Biases and any other relevant augmentation data needed for reducing convergence time to 1-20 min	Payment of a service fee
Local Augmentation Service Providers	Local Ionospheric Errors estimation for istantaneous Real-Time Services	Payment of a service fee
User Communities	Cooperative approach for sharing Ionospheric and local information (e.g. automotive)	Free (not guaranteed)
National Mapping Agencies	National Reference System and GTRF Coordinates Transformation	Free or for payment

	Parameters; Global and Local Augmentation Services Certification	

A service fee is paid by the users for that. In the figure, the payment of the fee is identified by the dashed lines. The Surveyor fee is identified by f_s, the Road by f_A, the Rail by $f_{R,}$ and other sectors fee (e.g. Rail) by f_O.

National Mapping Authorities can assume a double role. They can monitor GASOp and LASOp Quality of Services and become High Accuracy Services Certifiers for mapping purposes. On the other hand, they can be GNSS High Accuracy users, where their role in role is to validate external Cadastral Map Updates performed by private Surveyors.

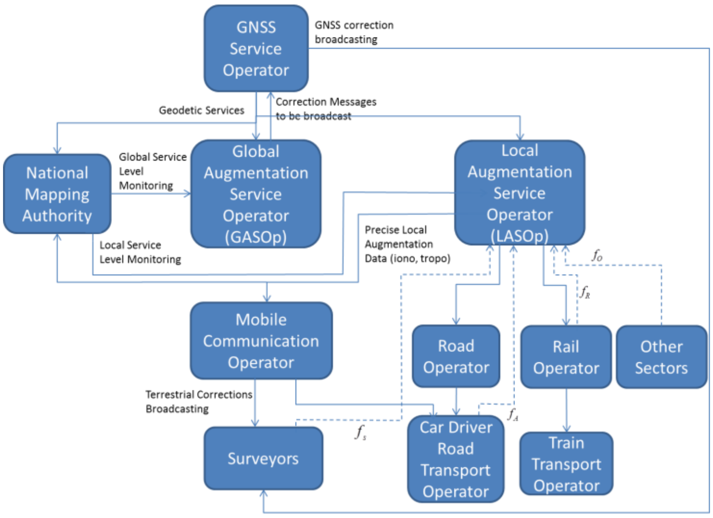

Figure 5 – High Accuracy Business Model

Concerning High Accuracy Services, Several Service Levels can be defined based on different Augmentation infrastructures. A hypothesis is reported in Table 2.

For Rail and Automotive applications, SLA3 and SLA4 can be applied. Applicable levels for Cadastral Surveying are SLA 1 (if occupation time is not critical) and SLA 2.

Table 2 – High Accuracy Service Level Definition

Service Level	Accuracy	Integrity	Mode
SLA 1	10 cm	-	Long convergence Post-Processing Global Augmentation
SLA 2	< 5 cm	-	Post-Processing and Real-Time: supported by Local Augmentation for precise atmospheric errors estimation to be used as complement to the Global Augmentation service
SLA 3	< 5 cm	SIL-4	Real-Time: supported by Certified Local Augmentation Service Providers through atmospheric errors estimation and Integrity Monitoring
SLA 4	< 5cm	Greater than SIL-4	Real-Time: supported by Certified Local Augmentation Service Providers through atmospheric estimation and Integrity Monitoring

4.2 GNSS Receiver Prices

In order to define possible Market Scenarios, an estimation of GNSS receiver prices has been carried out in a qualitative way, starting from current price trends and technological trends.

- **Commodity Scenario**: multi-constellation and multi-frequency devices have achieved the economy of scale and professional equipment manufacturer have developed low cost products with advanced Low cost Antennas for High Accuracy Surveying. Reference Station and Total Station prices are also impacted by the economy of scale in a great extent.
  On 2020, a peak due to the operational capability of Galileo and relevant firmware upgrades or new brand receiver is showed
  Relevant Rover receiver, Reference Station and Total Station price trends are reported in Price trends are reported
- **Conservative Scenario**: the same kind of Analysis is reported if the economy of scale is not activated by the Automotive sector. In this case the price decrease is less sensible. Such price law is reasonable, taking into account the Reference Station price decrease from 2005 to the present.

Relevant results are reported in Figure 6.

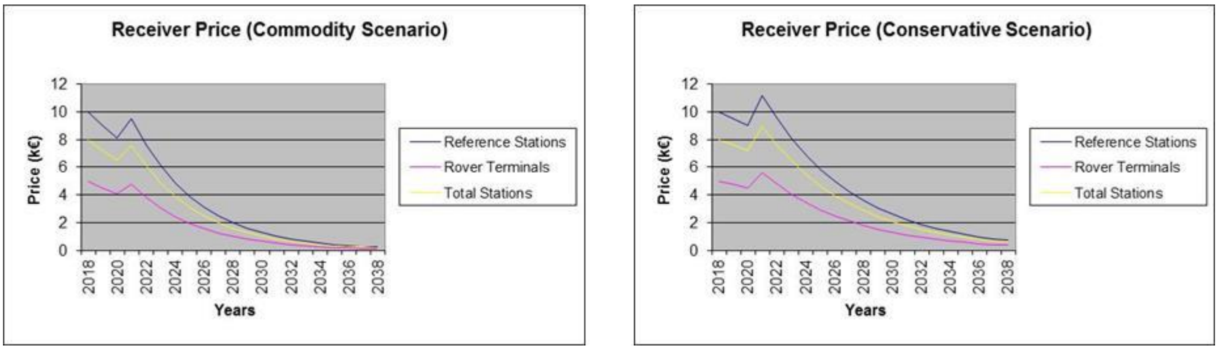

Figure 6 – GNSS Receiver Price

5. MARKET ANALYSIS

The aim of the chapter is to perform a Preliminary Market Analysis for the development of a High Accuracy Service based on Basic Global Augmentation Services (as provided by Galileo Commercial Services) and relevant Local Enhancement Augmentation Services.
CAPEX (CAPital EXpenditure) and OPEX (OPerating EXpenditure) are calculated for the two Scenarios defined above.

A Service Price is defined in order to derive revenues for the downstream Value Chain actors involved in the Service Provisioning.

A Cost/Benefits Analysis is performed for the European Region for identifying benefits for Professionals and Citizens.

The Analysis will be updated in the future, taking into account Services and Business Scenarios developments.

5.1 Available and Addressable Market

The Available and Addressable Market for the Cadastral Sector can be expressed in terms of number of Surveyors and number of Surveying acts performed per nation or continental area.
The sources for the present analysis are: the reports of Commission 7 "Cadastre and Land Management" of the FIG (International Federation of Surveyors), the "Cadastral Template 2.0", developed by the FIG, PCGIAP (Permanent Committee on GIS Infrastructure for Asia & the Pacific), the official "Inventory of Land Administration Systems in Europe and North America" available from WPLA (UNECE Working Party on Land Administration), European requirements for cadastral surveyor activities (CLGE, 2008).

Furthermore, data have been integrated, where necessary, by single National Cadastral Authorities and Organisation statistics.

Starting from FIG (Steudler, 2003), UNECE (UNECE, 2014), GSA Market Report (GSA, 2017), as well as National Mapping Agencies and CLGE (Council of European Geodetic Surveyors) data, an estimation of the number of Surveyors has been performed.

GSA reports the number of GNSS devices shipped in 2015 in the Cadastral sector in the order of 100000, while the forecast for 2025 is about 250000, with Asia and North America Driving the Market Growth. A Growth Rate in the order of 6%/year is therefore expected. This is in line with recent estimations for the use of GNSS in the Cadastral sector for Countries operating with advanced systems (Capua, 2017).

The total number of licensed Professional Surveyors operating in the Cadastre field in the European area can be estimated in the order of 118000. Concerning USA, updated statistics (2016) refers a number of surveyors in the order of 105000.

In Figure 7 a possible estimation of the Available Market for the Cadastral sector is reported.
The total number of surveyors can be estimated in the order of 573000 for the whole world.
Taking into account innovations in the field of surveying (e.g. Drones) and the number of subscriptions to the Geodetic and Surveying University faculties, it is assumed that such number will remain constant or increase with a small rate in the following years.

For the Cadastral sector, another relevant statistic is the number of Cadastral Parcels in the world. Starting from the available numbers from FIG, UNO, National Authority sources and the FIG Cadastral Template, it can be derived that about 1820 million parcels are registered in the world. For Europe, the number of parcels is about 593 millions.

Comparing such estimations with similar studies carried out in the past (e.g. GSA, MONITOR: Land surveying and civil engineering monitoring), it can be argued that such number is expected to remain at the same level in the future.

Such number is the base for calculating the number of available Map Update Acts to be carried through GNSS.

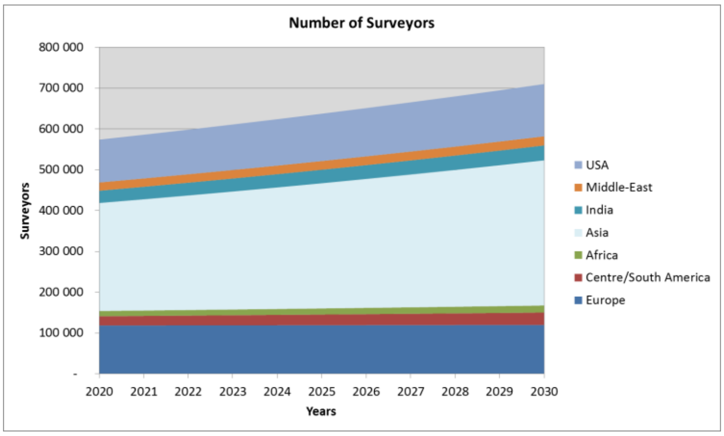

Figure 7 – Number of Surveyors (Available Market)

5.2 Revenues Mechanism

Currently, Local Area Augmentation Service Providers are applying an annual service fee in the range of 200-400 €/year. In some countries, such services are provided for free for institutional purposes.
Due to the fact that Local Augmentation Services will be reduced to precise Local Ionospheric and Tropospheric estimation (when not covered by Cooperative approaches), a fee of 200 €/year (50% of current annual fees) can be applied in the Commodity Scenario.
Concerning the NMA service monitoring, for each map update, a fee can be applied for NMA GNSS service monitoring and certification processes for Cadastral applications. Through such fee, NMA can return on service monitoring and certification investments. This fee is not applied in the present analysis.

5.3 CAPEX and OPEX

Main costs involved into the development of the High Accuracy Augmentation Systems are the following:

- **Global Augmentation Services**: Network and Infrastructures for Basic Global Augmentation Services; relevant costs are in charge of a GASOp for basic PPP correction messages (e.g. precise ephemeris and clock corrections); they are considered as provided for free in the present analysis; they are only taken into account in the Commodity Scenario
- **Local Enhanced Augmentation Services**: Reference Stations Network densifications and service infrastructures for Local Enhanced Augmentation Services (precise local Ionospheric delay estimation)
- **Rover Receiver Costs**: derived considering the receiver price law defined in par. 4.2

Concerning Local Enhanced Augmentation Services, relevant CAPEX and OPEX are different, depending on the implemented Scenario. It is assumed that in the Commodity Scenario, the costs associated to the Surveyor Market Segment for the development of the Augmentation System are 1/3 of the total Cost (Cost Sharing among three main applications: Survey, Rail, Road).

For calculating the number of Reference Stations needed for the implementation of Local Enhanced Augmentation Services, Land Use statistics are considered. Concerning Europe, available Statistics (EUROSTAT, 2017) shows that the percentage of land densely occupied and used for services, residential and heavy transport applications are to 10 % of the total. Following the technical discussion about Global Augmentation Services (Par. 2), Reference Station interdistance are set to 150 km for remote areas and 30 km for densely populated and transport intensive ones. In this way, it is estimated that about 1100 receivers are needed for covering the whole Europe in the Commodity Scenario. In the Conservative Scenario, the classical NRTK coverage (maximum interdistance of 70 Km) is applied. The number of needed Reference Stations is in the order of 2100 in this case.
The following cost voices are taken into account for the calculation of CAPEX and OPEX: Software Design and Development, Reference Stations installation and replacement after ten years, Reference Frame establishment and monitoring, High QoS Communication Costs, Validation, Maintenance and Operation. The Reference Station installation and Augmentation System Development plan is allocated in three years: 60% in 2020, 20% in 2021, 20% in 2022. Reference Station renewal is foreseen starting from 2031.

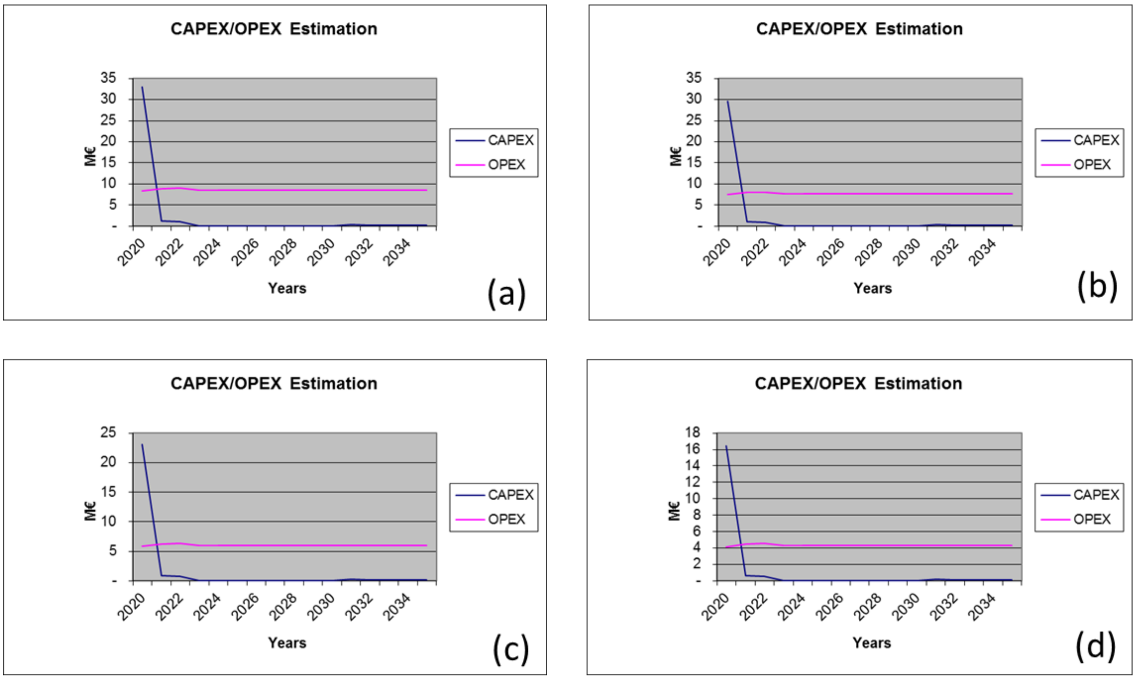

Figure 8 – CAPEX and OPEX for the Commodity Scenario for different Cooperative Factors: (a)=0%, (b)=10%, (c)=30%, (d)=50%

In order to take into account the percentage of solutions derived through a Cooperative approach, a Cooperative Factor is introduced, for coherently reducing the number of needed Reference Stations.
In Figure 8 CAPEX and OPEX estimation for the deployment of Local Enhanced Augmentation Services all over Europe is showed for the Commodity Scenario for European Commission, with different Cooperative Factors applied. A Cost Sharing factor of 33% has been applied (1/3 of the costs allocated to the Surveying sector).
It can be noted that, thanks to the assumption on Global Augmentation Services and the possible implementation of Cooperative approaches, the level of initial and recurrent costs to

be supported is quite limited. This can lead to a suitable return on investments, as can be seen in the following profitability and Cost Benefits Analysis.
In Figure 9 it is reported the CAPEX/OPEX Analysis for Europe (Conservative Scenario).

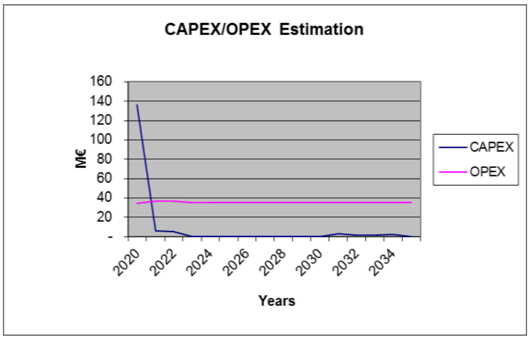

Figure 9 – CAPEX and OPEX (EU), Conservative Scenario

An analysis for the whole world has been carried out. In this case, the number of assumed Reference Stations is in the order of 15600 for the Commodity Scenario and 30200 for the Conservative Scenario. Relevant results are reported in Figure 10.

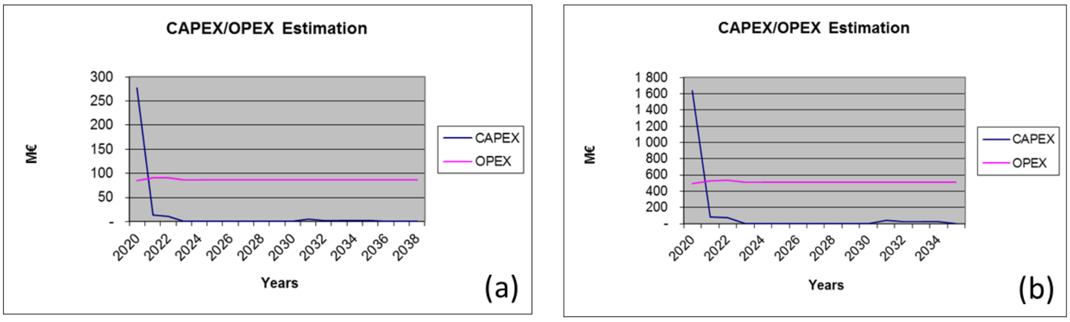

Figure 10 – CAPEX and OPEX (Whole World), Commodity Scenario (a), Conservative Scenario (b)

5.3.1 Profitability Analysis

A preliminary profitability Analysis for the development of the Augmentation System has been carried out for the Commodity and Conservative Scenario.
For this purpose, the NPV (Net Present Value) has been calculated for the European area.
The following hypotheses have been assumed.
For the Commodity Scenario, a Cost Sharing Factor of 33% and a Cooperative Factor of 30% have been applied.
The Total Number of Reference Stations to be installed in the EU area (in the conservative assumption of no Reference Station reuse from existing networks) is in the order of 1076 and 2077 for the Commodity and Conservative Scenario, respectively. Concerning the Service Price, a flat fee of 200 €/year is applied.
A Growth Rate of 8% has been assumed for the addressable Market starting from 2020, while a Service Price decrease has been assumed in the order of 1%/year in the period 2020-2035,starting with a 200 €/year.
An initial penetration of 60 % and 55 % for the number of Surveyors is assumed for the Commodity Scenario and for the Conservative Scenario.
The Local Augmentation Service Price for the Commodity Scenario is set to 390 €/year
For the NPV calculation, a discount rate of 4% has been applied.

In Figure 11 Cost and Revenues are reported for the Commodity Scenario and Cooperative Scenario, respectively.
As can be seen, saturation is achieved in 2027 for the Commodity Scenario, while the Conservative Scenario shows not highly profitable situation.

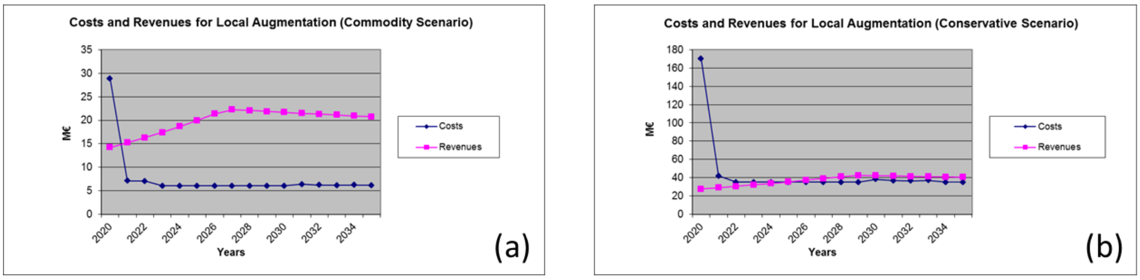

Figure 11 – Cost and Revenues (EU), for (a) Commodity Scenario (Cooperative Factor 30%), (b) Conservative Scenario

5.3.2 Cost/Benefits Analysis

A Cost/Benefits Analysis has been carried out for evaluating the impact of the introduction of the new Augmentation system for Cadastral Surveying operations.
Concerning Costs, an overall estimate of the GASOp costs for the society have been added to the Commodity Scenario in addition to the LASOp costs reported in the previous paragraphs.
For this scope, it has been assumed a sparse network of 63 Reference Station to be developed in the EU area, while a permanent staff of about 20 employees is working for this service. Relevant Costs for designed, development and operations have been added.
Benefits for the Surveyors, Citizens and NMA derived by the innovative GNSS Augmentation and constellations, can be summarized as in Table 3.
In order to monetize the benefit for single surveyor, the following assumptions can be done:

- Number of Cadastral Surveys/month: 8
- Saved time for planning and Receiver configuration update (e.g. mountpoint change for network or Reference Station change) on the field: 15 min/survey
- Percentage of Hidden Points/Survey: saved time of 30 min/survey, due to avoided hidden points surveying with EDM integration
- Augmentation Service annual fee saving: 200 €

A reduction of 45 min per transaction for NMA has been assumed, as well as a reduction of Cadastral transaction costs of 5%.
Furthermore, it is assumed that 70% of the surveyors willing to pay for the new service being already equipped with a GNSS receiver the first year. Assuming a Service Price of 200€ and current Service Prices, this leads to a net cost savings of about 200€/year per surveyor.
For receiver renewal and obsolescence, it has been assumed that 70% of surveyors are still equipped with a Galileo enabled GNSS receiver at the start of the service.
Assuming a Growth Rate of 8% per year and a receiver price decrease law as indicated in Par. 5.1.1, the relevant Costs and Benefits for surveyors in Europe are reported in Figure 12. It can be noted that benefits for surveyors are huge, due for a great extent to improved efficiency.

Table 3 – Benefits derived by the introduced Innovation

Innovation Impact	Surveyors	Citizens	NMA

Improved Survey Efficiency	Reduction of Surveying costs, fixed receiver setup	Reduction of Cadastral Transaction time	Improved Map Update Rate
Reduced Augmentation Service Fee	Reduction of Surveying Costs	Reduction of Cadastral Transaction Costs	Reduction of NMA Cadastral Surveying activities or Map Update Validation costs Reduced costs for institutional Surveying
Improved satellite visibility and availability	Reduction of Surveying Costs (reduced need for Hidden Point Sureying)	-	Reduction of Surveying Costs (reduced need for Hidden Point Surveying)
Local Augmentation Implementation Cost Sharing	Reduction of Annual Fee	Reduction of Transaction Costs	Reduction of costs for Institutional surveying

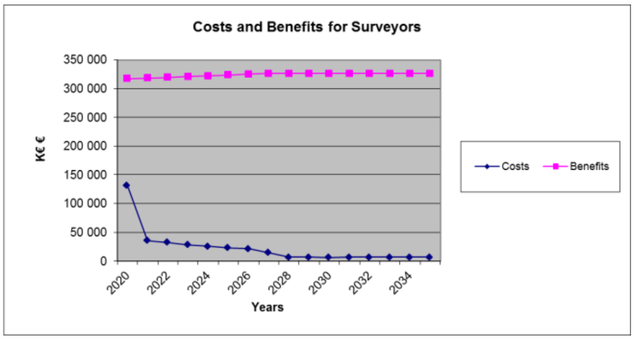

Figure 12 – Cost and Benefits Analysis for Surveyors - Commodity Scenario (Europe)

The expected NPV for the Cost/Benefits Analysis is in the order of 2.5 billion €.
Furthermore, the introduction of large scale High Accuracy will lead to a relevant impact on transport efficiency. Previous studies (Goldman Sachs, 2015) reported that the expected savings due to the introduction of autonomous cars (at different levels of development) will imply annual fuel savings of 12.8 billion $/year for Europe and 21.09 billion $/year. A reduction of 90% of car accidents and increased lane capacity is also expected worldwide. Concerning CO_2 emission, a reduction of 19.14 billion kg/year is foreseen.
Such externality (e.g. 10% linked to surveying investments in Augmentation systems) leads to an NPV increase by one order of magnitude.

6. CONCLUSIONS

GNSS High Accuracy positioning has been used for years in geodetic, surveying and mapping applications. Innovative applications are starting to require higher accuracy (e.g. automatic driving).

High Accuracy Augmentation Systems are currently based on costly infrastructures (dense networks of GNSS Reference Stations).
The availability of new GNSS systems and relevant services (e.g. Galileo) leads to new opportunities for the development of such services. Global services based on PPP can lead to a reduction of the needed infrastructures and to the development of different level of services.
A preliminary Cost Benefit Analysis has been carried out for the introduction of the new technologies in the Cadastral Surveying Sector. The availability of a Global Augmentation Service developed by a GASOp (Galileo Augmentation service Operator), based on a sparse Reference Station Network, has been assumed. It is able to provide basic corrections (through a PPP approach) for a first level of accuracy at 10 cm with a long convergence time (20-40 min). For achieving the classical RTK performances, local services have to be provided, able to provide precise ionospheric corrections. National LASOp, able to perform such services, have been added. Furthermore, a Cooperative approach (with users sharing ionospheric estimations) has been showed to be of relevance for cost sharing purposes.
Two Scenarios for a Cost Benefits Analysis due to the introduction of Global Augmentation Services have been defined. In the Commodity Scenario, automotive sector highly adopt the new system and economy of scale significantly reduces high-end receiver costs needed for high accuracy. In the Conservative Scenario, Local Augmentation is needed for providing High Accuracy services. In the Commodity Scenario, a Global Service provided under the framework of Galileo Commercial Services has been assumed. The commodity scenario requires Regulation to support the development of Augmentation services. For that purpose, GNSS High Integrity systems have to be coupled with High Accuracy.
A CAPEX/OPEX analysis has been carried out in the period 2020-2035 for the EU area. Starting from the assumption of a GASOp (Global Augmentation Service Operator), able to provide a Basic Global Augmentation for free, relevant Capital and Operational costs have been defined. GNSS receiver COTS have been considered for the deployment of the system. The results for Europe showed a limited amount of needed investments (in the order of 4 to 10 M€ for the Commodity case and 20 to 45 M€ for the Conservative Scenario for developing the needed Reference Stations Network). Relevant Analysis for the whole World showed values in the order of 100 to 500 M€ for the Commodity and Conservative Scenarios. The analysis has been anyway focused on the EU area.
A Cost/Benefits Analysis has been carried out for evaluating the impacts of such a new system on the society. At this aim, benefits for the Land Surveyors have been evaluated in terms of improved surveying efficiency and reduction of Augmentation Service fees. Benefits for the society have been evaluated in terms of reduced Cadastral transaction costs and reduction of time for Cadastral transaction completion. Overall NPV value has resulted in about 2.5 billion €.
Concerning strength and weakness of the two approaches and relevant Scenarios, a Global Service offering PPP undifferenced solutions need local elements for a Real-Time application. On the other hand, such implementation do not implies Control Centres on the field and each receiver can in principle act as a ionospheric corrections probe. Furthermore, Cost and Benefits are greater than the Network-RTK approach. On the contrary, NRTK has the strength to be independent from a wide area system estimating biases and precise ephemeris and clocks. This is anyway achieved at a too high cost for being implementable at a large scale, taking into account the high installation and maintenance costs and the number or needed receivers, as the CBA showed.

It is concluded that the availability of Global Services through the PPP approach, and Local densification through Local Augmentation, leads to improved benefits for both the Citizen and the Cadastral surveying sector.
Furthermore, if the external benefits for the automotive sector are taken into account, the estimated NPV improves by one order of magnitude. Therefore, Cost sharing in the development of the GASOp and LASOp infrastructure establishment is justified, due to huge improvement in societal benefit (e.g. reduced fuel consumption and pollution for the automotive sector).
It is therefore concluded that Galileo Commercial Services, through the provisioning of Basic Augmentation Services, can provide a significant improvement to Professional Surveyors operations.
This work paves the way for further technical and economic analysis for the development of GNSS High Accuracy services.

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BIOGRAPHICAL NOTES

Roberto CAPUA received a Master Degree in Electronic Engineer. He has a consolidated background in the field of GNSS applications Research and Development for Public and Private Organisations. He worked on most important European Commission Programmes on Galileo design and applications. He was a Program Manager on satellite navigation applications for an important European Satellite Service Provider. His areas of activity include advanced high precision GNSS and Augmentation Systems, GNSS Software Receiver and GNSS surveying for cadastral and mapping applications. He worked on the development of hardware and software navigation and communication technologies for Road, Inland waterway, Aerospace and Surveying. He is currently responsible for GNSS R&D for Sogei, where he is managing a GNSS Network for Cadastral Purposes and the GNSS SDR development project. He is furthermore delegate for his company in the Galileo Services Association and RTCM SC-104 Committee, where he chairs the Integrity Monitoring for High Precision Application WG.

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