A Totally SDR Single-Frequency Augmentation Infrastructure for RTK Land Surveying: Development and Test

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BIOGRAPHIES

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Roberto Capua received his MSc in Electronic Engineering in 1996 from the University of Rome “La Sapienza”. He has 20 years of experience in GNSS systems development. He worked on GNSS R&D and European Galileo Projects for Aereospace and Satellite Service Providers companies, where he was satellite navigation Program Manager. He is a delegate of the Galileo Services Association. Since 2002 he is working for Sogei, where he is responsible for GNSS R&D within the Research and Digital Laboratory Department. Relevant specializations are: GNSS Surveying, SDR and Advanced Augmentation systems.

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Alessandro Caporale received a MSc Degree in Electronic Engineering with specialization on Applied Electromagnetics from the University of Roma Tre in 2009 and a Master in Advanced Communication and Navigation Satellite Systems from the University of “Tor Vergata” in 2012. He worked for Aerospace and System Engineering companies. In 2012 he joined the R&D GNSS Team in Sogei SpA, where he worked till August 19, 2016. Main areas of work are GNSS SDR, high accuracy GNSS, Spoofing detection and Antennas design.

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Marco Giangolini

Marco Giangolini received the bachelor degree in Aerospace Engineering in 2007 from University of Rome “La Sapienza” and the MSc degree in Astronautical Engineering in 2012 from Scuola di Ingegneria Aerospaziale in Rome. He worked for his thesis in the field of space robotics and he received a Master in Advanced Communication and Navigation Satellite Systems by the University of Rome "Tor Vergata". In 2013 he joined the Research and Digital Laboratory group in Sogei S.p.A. working on multicore and GPU programming for the GNSS SDR development.

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He is a Senior Civil Engineer. He received a MSc Degree in Civil Engineering from University of Rome “La Sapienza in 1987”. He is currently the Head of the Pregeo project within Sogei. He is a Senior Professional Surveyor with more than 30 years of experience in Cadastral Surveying through topographic and GNSS sensors.

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He received a bachelor of Science in Computer Engineering from the University of Rome “La Sapienza” in 2007. He is specialized in Human-centered design, Java and Web Programming. He is currently working within the Sogei’s Research and Digital Laboratory Department on Graphical interfaces and mobiles programming.

Camillo D’Amico

Camillo D’Amico is an expert Electronic technician, with a specialization on RF devices. He worked for years in the field of HF radio transmissions. He is currently involved in the development of PCB and RF circuits within the Sogei’s Research and Digital Laboratory Department.

Antonio Bottaro

Antonio Bottaro received a MSc in Electronic Engineering in 1977 from the University of Rome “La Sapienza”. He is the Head of the Research and Digital Laboratory Department within Sogei S.p.A and the CEO of Geoweb, a company owned by Sogei and the National Council of Italian Surveyors. His main area of activity concerns Advanced GIS and GNSS platforms Design

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He received a MSc Degree in Civil Construction Engineering in 1984. He worked for several years in aereophotogrammetry and cartography. In 1987 he joined the Italian National Cadastre. After the incorporation of the Italian Revenue Agency, since 2007 he is the Head of the Cadastral Cartographic Services.

ABSTRACT

Nowadays, high accuracy services for Land Surveying are limited by the need of costly Reference Stations infrastructures and rover receivers.

SDR technology is rapidly developing and allows several advantages in terms of costs and flexibility. This paper, moves from an implementation of a GNSS single-frequency SDR receiver, code and phase, able to process code and phase and to perform RTK. It is totally based on COTS and runs on Notebooks and Tablet. It describes the development of an augmentation infrastructure (Reference Stations and rover receivers) totally based on SDR technology.

An extensive test campaign has been carried out in Italy involving Professional Land Surveyors and Institutional actors (e.g. Italian Revenue Agency) for evaluating the new solution for real Land Registry (named “Cadastre” in Italy) update GNSS RTK surveying.

Traditional topographic instruments and GNSS have been used for demonstrating the suitability of the proposed solution for the institutional Land Surveying sector. A performance analysis has been carried in order to identify the weakness and strength of such solution for future development. The impact of baseline lengths and number of visible satellites has been analyzed, as well as communication network impacts, feeding in parallel the SDR receiver and the Hardware one to the same antenna through a splitter.

The analysis demonstrated that the convergence time and the expected performances in terms of correct fixes and achievable accuracy are in line with hardware GNSS single frequency receivers. Major factors impacting on the convergence time and correct fixes percentage are the baseline length, the number of visible satellites and the presence of multipath. Communication losses between the Network Control Centre and the rover have also a relevant impact on performances. The achieved results are very promising for a full implementation of the system.

INTRODUCTION

Land Surveying and Geodesy have been some of the key applications at the beginning of the GNSS era. The possibility to calculate baselines with centimeter level accuracy was the main driver of such applications.

The Italian Land Registry (named “Catasto” in Italy, known as Cadastre in several Countries) is currently managed by a branch (formerly Italian Land Agency) of the Italian Revenue Agency.

The Italian Land Registry update system is based on an innovative workflow, able to integrate traditional topographic measurements (e.g. EDM, Electronic Distance Measurements and Total Stations) and GNSS Land Surveying measurements.

The Italian Registry Update System is divided by more than 100 Provincial Offices. They are in charge of a continuous Land Registry update in their area of competence. On-the-field Land Surveying activities for map updates are performed day by day by private Professionals. The proposal for a map update can be due, for instance, to a parcel subdivision, to an insertion of a new building into the map or to a border reconstruction.

Professional Surveyors are in charge of performing the relevant survey and to submit the map update proposal to the competent Provincial Office for approval.

Each map (identified by sheet and parcel IDs) can be geolocated through the surveying of Ground Truth Points, named *Fiducial Points*. Italy is covered by about three millions of such points. Each Professional has to locate such Fiducial Points (indeed, baselines from Reference Stations to the rover measured through RTK), as well as relevant points needed for performing the map update proposal, through GNSS. The measurements have to be performed through RTK or post-processing.

It has to be pointed out that, due to the fact that the taken measurements are essentially baseline measurements and that maps are referring to such Fiducial Points, the whole Land Registry Mapping system is independent from a particular Reference Systems. Changing the Fiducial Points coordinates implies changing the whole reference system of the Land Registry.

The taken measurements have to be elaborated through the institutional software Pregeo (it can be freely downloaded by the Italian Revenue Agency website).

Such Software performs a network adjustment of the measurements taken by the professional (basically baselines measurements), excludes outliers through relevant statistics and validates the Map Update Proposal.

GNSS is furthermore used by the Italian Revenue Agency Professionals for performing some of their institutional tasks:

- On-the field Validation of Map Proposals
- Small Reference Systems Update (many parcels and sheets are historically referred to old local reference systems)

- Redefinition of parcels borders due to a submitted proposal

Measurements for a Land Registry update proposal, defined by an official Technical Note of the Italian Land Agency, have to be taken with an accuracy of at least 30 cm.

Within the adjustment procedure performed by the institutional Software Pregeo, measurements are opportunely weighted by covariance matrixes values.

Land Registry update surveying are a good benchmark for a satellite positioning system. Parcels are in fact located in areas characterized by different environmental conditions, from suburban areas, subject to foliage attenuation and natural obstacles, to pure urban areas, characterized by urban canyons, low visibility, high multipath conditions and frequent losses of lock. In several situations, points to be surveyed are heavily affected by shadowing (e.g. corners of a building in an urban canyon). Such points are commonly identified with the term *Hidden Points*. In such a case, the hybridization with EDM (Electronic Distance Measurement) observables taken from external points surveyed through GNSS can allow to determine Hidden Points through classical topographic methods.

Public Administrations, wishing to adopt a new technology for their activity, are commonly subject to some limitations:

- High volumes of equipment to be acquired
- Quick obsolescence (e.g. due to new incoming constellations and frequencies)
- Need to maintain legacy systems and procedures
- Flexibility and reconfigurability, in order to follow regulation changes

For Land Surveying applications, the other relevant constraint is the availability in the area to be surveyed of a GNSS Network for performing High Accuracy RTK Surveying.

Concerning GNSS, an ideal system aiming at satisfying such requirements is SDR (Software Defined Radio).

Sogei, within the framework of its institutional R&D activities, designed and developed a Single Frequency GPS and SBAS SDR receiver, able to run in Real-Time on PCs or Tablets.

High accuracy applications require the installation and maintenance of extensive GNSS Reference Stations Networks at national or regional level. Such Reference Stations are costly in terms of upgrade and maintenance.

On the other hand, Freights management for institutional applications is requiring a high level of reliability, data security and data messages customizability.

For such kind of applications, GNSS SDR is one of the most suitable cutting-edge technologies, due to its intrinsic flexibility, scalability and openness to the integration of new signal waveforms.

By the way, it has to be considered that Reference Stations by themselves can be implemented through SDR receivers. At this aim, a total SDR infrastructure has been developed (Reference Stations and Rovers) and tested though extensive on-field surveys. This paves the way for the implementation of extremely flexible and cost effective high accuracy infrastructures and services.

In order to evaluate the suitability of such SDR for institutional Land Registry Update operations, real complete on-the field map update proposals have been performed through GNSS RTK Surveying. At this aim, Geoweb, a company owned by Sogei and the National Council of Italian Surveyors, supported the surveys organization. Performance Analysis has been carried out in order to depict Accuracy and Availability measures and evaluate the suitability of a totally SDR infrastructure for Land Registry Surveying and Update.

Results of such totally SDR infrastructure and relevant performance analysis results are reported in the following.

THE ITALIAN CADASTRAL UPDATE SYSTEM

The current Land branch of the Italian Revenue Agency, is working since 1987 for the introduction of new technologies and procedures for the implementation of an efficient Map Updates system.

The introduction of GNSS in the Surveying operations has been an important milestone for such objective.

A Web Based GIS system has been carried out, able to publish online existing maps for professional use and to perform an automatic update, having as input their surveying results in a standard format. Such results are obtained through the processing of on-field measurements performed by professionals through the freely downloadable Pregeo Software Package.

The Inland Revenue Provincial Office, equipped with the Wegis Software package, gathers such map proposal, processes it and, if relevant Quality Indicators are met, the maps update is automatically inserted into the Land Registry Cartographic DB. Such process is reported in Figure 1, where a classical surveying operation is performed by professionals through the described workflow.

A professional surveyor intended to present a map update, takes existing map from the relevant provincial office on-line services. He identifies three Fiducial Points containing the area to be surveyed and performs the surveying through GNSS RTK and traditional topographic measurements. In Figure 2, the performed measurements in a typical case are reported. In red, GNSS baseline measurements from the Reference Station to the Fiducial Points (PFs) are reported.

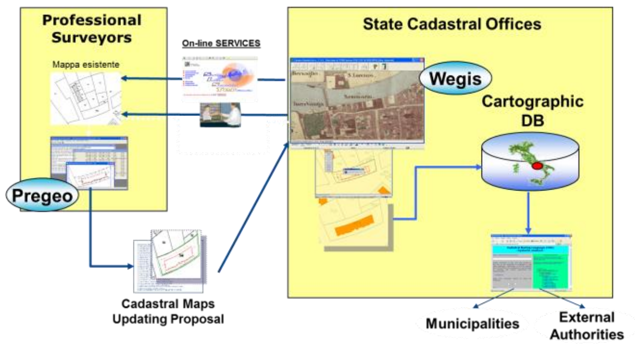

Figure 1 - Land Registry Update Workflow in Italy

An example of Hidden Point (e.g. the corner of a building, where a great part of visible satellites are shadowed) is also showed. In order to perform such measurement, the surveyor has to apply one of the available topographic methods. In the reported case, two external points are taken through RTK GNSS and a forward intersection is performed through EDM measurements. In the example, the Fiducial Point (PF) is on the corner of a building and is surveyed through forward intersection: d_1, d_2 and d_3 are distance measurement taken through an Electronic Distance Measurements device (e.g. Laser or Total Station), while points 601 and 602 are surveyed by classical GNSS RTK.

Such measurements are therefore processed and compared to the historical database of Fiducial Points measurements taken in the past by other surveyors. Such historical Database collects measurements and relevant covariance matrices. It is a statistical source for surveying activities quality checking. Such database has been used for validating the Performance Analysis results.

The taken measurements are therefore processed and compared to the Fiducial Points distance statistics present in the Historical database storing map updates performed by other surveyors in the past.

Such historical Database collects measurements and relevant covariance matrices and is a strong statistical source for surveying activities quality checking. Such database has been used for validating the Performance Analysis results.

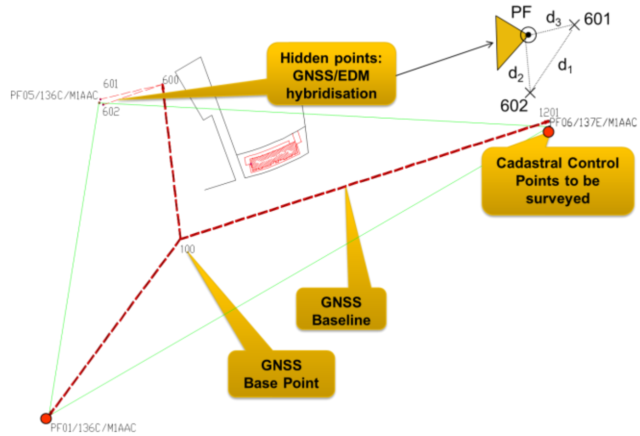

Figure 2 - A Typical Land Surveying for Maps Update

The relevance of GNSS surveying for Land Registry update purposes can be showed by the following numbers.

Italian Professional Surveyors are about 80,000. About 300,000 map update proposals are presented every year. In 2015, almost 50% of such proposals were performed trough GNSS surveying. The Growth Rate for the use of GNSS is about 7% per year.

Based on such numbers, there is a real interest in trying to find a cost effective and flexible solution for allowing Land Administration to use GNSS RTK as a very efficient surveying mean.

THE SOGEI GNSS SDR

Sogei, the ICT Company of the Ministry of Economy and Finance of Italy, started in 2008 a Project intended to develop a flexible GNSS SDR receiver for high demanding applications ([R7] and [R8]).

Sogei GNSS SDR platform is able to perform Real Time GPS and SBAS Acquisition, Tracking and PVT. It applies SBAS Augmentation messages and performs RTK positioning through Code and Phase measurements processing.

The architectural components of the system are:

- *GNSS IF Front-End*: internally designed and totally based on COTS ADCs and sampler, outputs IF samples on a USB (Figure 3)
- *Acquisition, Tracking and PVT software modules*: implemented in C/C++, they are multi-threaded and communicating through TCP/IP sockets

- *Notebook and Tablets*: running the GNSS SDR Software
- *GUIs*: implemented using OpenSource tools and RTKLIB

Multi-Core programming is implemented using the Cross-Platform OpenMP Parallel Programming API, while high computational tasks like FFT and multiplications are performed using SIMD (MMX and SSE) instructions. GPU processing and parallel programming are used in the Acquisition phase for improving relevant performances. Further studies are going on for partitioning tasks between CPU and GPU, taking into account the inherent I/O constraints.

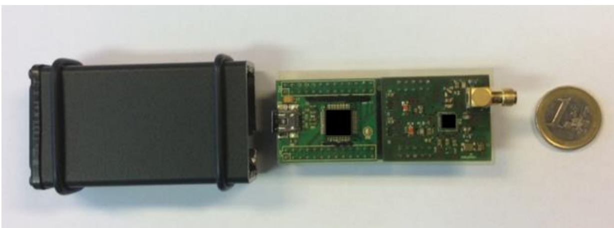

Figure 3 - A Typical Land Surveying for Maps Update

In Figure 4, the Sogei GNSS platform Architecture is represented.

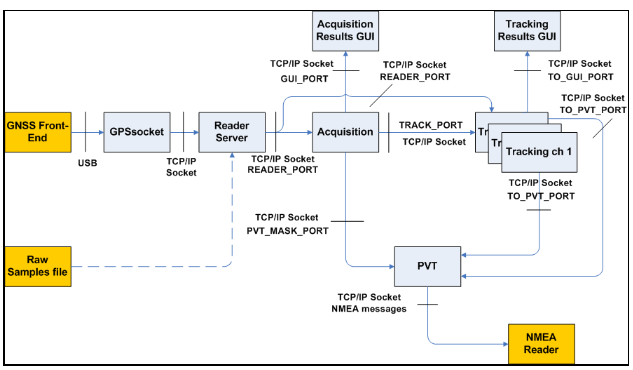

Figure 4 - Sogei GNSS Platform System Architecture

IF is set by default to 1.023 MHZ with a sampling frequency of 4.092 MHz for GPS and a 2-bits (1-bit Sign and 1-bit Magnitude) quantization. The integration of Galileo can be achieved, using an IF of 2.046 MHz and a sampling frequency of 8.184 MHz is now commonly used.

The Sogei GNSS SDR can operate also at IF equal to zero, through the processing of both I and Q samples coming from GNSS Front-End. This allows an optimal use of the bandwidth and a reduction of the sampling rate.

The Sogei GNSS SDR is able to run on the general purpose PC, Notebooks and tablets (see Figure 5).

Acquisition is implemented though a Parallel Code Phase Search. Sine and cosine Look-Up Tables and FFT code replicas are generated off-line and loaded into the cache memory at start-up. Acquisition is performed in two steps (Coarse and Fine), in order to provide a finer Doppler estimate. Warm and Hot start modes are available.

Tracking Loop is implemented by default through a second order PLL and a first order FLL. A third-order PLL can be activated on request. The FLL is selectively activated at start-up or after a loss of lock and switched off after a positive test on phase error variances. Raw samples are packed in two words of 32 Sign and 32 Magnitude bits, respectively. Code correlation and Carrier mixing is therefore implemented through very efficient logical operators.

In order to minimize the number of needed correlators, the normalized Dot product DLL discriminator is used ([R2] and [R3]) for Code tracking.

Prompt and Early-Minus-Late Code Look-Up tables are generated off-line for 32 Code phase steps. Such tables are oversampled, due to the fact that the sampling frequency is higher than the chip rate. Code Doppler is assumed to be zero in the Code-Look-Up table.

Sine and Cosine Intermediate Frequency Look-Up tables for carrier wipe-off are generated with $\pi/8$ phase steps and 175 Hz frequency steps. Carrier levels are represented by 2 bits (Sign and Magnitude).

Costas loop discriminator is implemented through the classical $\operatorname{atan}(Q_P/I_P)$, while FLL uses the atan2 function.

Carrier Phases Measurements has been extracted from the PLL through a fine clock steering process.

The initial PVT was originally based on an Extended Kalman Filter (EKF). In order to better cope with non linearities, an Unscented Kalman Filter (UKF) ([R4] and [R5]) has been implemented and is currently working on the Sogei GNSS SDR. It is able to calculate navigation solution into NMEA GGA message with 500 ms update rate.

The measurement vector is:

$$z = h(x) = \begin{bmatrix} PR \\ D \end{bmatrix}$$

where PR and D are the vectors of relative pseudorange and Doppler measurements for the observed satellites.

The relative pseudorange between satellites, usually needed for SDR computation ([R1] and [R2]), for satellite i can be expressed in the following way:

$$PR^i = c(t_{off} + t_{ti} - t_{s\min})$$

where c is the velocity of light, t_{off} is a bias of 68 ms (taking into account that the travel time between a GPS satellite and the Earth ranges is in the 67-86 ms range), able to assure that all relative pseudoranges calculated in this way are positive, t_{ti} is the travel time derived by the number of samples elapsed till Subframe starts and $t_{s\min}$ represents the travel time of the reference satellite.

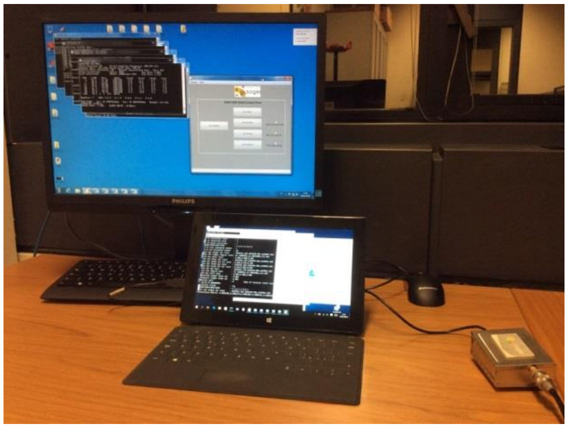

Figure 5 - The Sogei GNSS SDR

Classical nonlinear measurement model is used for pseudorange estimation:

$$PR^i = \sqrt{(x^i - x_u)^2 + (y^i - y_u)^2 + (z^i - z_u)^2} + d\rho^i +$$
$$+ c(dt^i - dT) + d_{ion_i} + d_{trop_i} + \varepsilon$$

where $d\rho^i$ are the orbital errors, dt^i is the satellite clock error, dT is the receiver clock error, d_{ion_i} and d_{trop_i} are the ionospheric and tropospheric delay for satellite i and ε is the measurement noise. Using UKF, relevant Jacobians for Gain and Covariance prediction, are no more calculated, while the nonlinear measurement function is used without linearization and calculated by points.

Tropospheric corrections are applied to pseudoranges using a standard refraction model (Goad and Goodman model). Ionosphere propagation error is mitigated through classical Klobuchar method or SBAS corrections.

For Doppler measurements, the following model is used:

$$-\frac{c}{f_{L1}} \cdot D^i = H^i(v^i - v_u) + c \cdot \dot{b} + \varepsilon$$

where D^i is the Doppler measurement for satellite i, obtained from the Carrier Tracking Loop, v^i is the i satellite velocity, H^i is the cosine directional vector from the receiver to the satellite i, v_u is the user receiver velocity and ε is the measurement error.

Filter initialization is performed through Bancroft algorithm.

Single satellite measurements are assumed to be uncorrelated. Using such assumption, each measurement can be sequentially processed in a scalar way, leading to a very significant computational load reduction.

The GNSS SDR implements RTCM version 3 messages format and NTRIP RTCM 3 for gathering corrections from GNSS Networks.

Carrier Phase ambiguity fixing is performed through LAMBDA decorrelation method.

THE TOTAL SDR HIGH ACCURACY AUGMENTATION INFRASTRUCTURE CONCEPT

Sogei is operating a GNSS Augmentation Network in the Centre of Italy named GRDNet (GNSS R&D Network). It is based on COTS Hardware GNSS Reference Stations.

The interfacing between Reference Stations and the Control Centre (located in the high security Sogei's Fiscal Data Center in Rome) is performed through strictly standard RTCM 3.2 messages format ([R8]), while communication between Control Centre and users is based on the standard NTRIP ([R9]).

Such architecture is completely open and can integrate any kind of Reference Station receiver able to output raw data through standard RTCM messages.

Reference Stations are located in Public Administration offices and connected to the Control Centre through a High QoS communications network.

The operation of such Networks implies high costs in terms of firmware upgrade licensing and recovery in case of equipment failures. Furthermore, due to the obsolescence of receivers and in view of incoming constellations and frequencies, the hardware obsolescence is expected to increase.

Such limitations can be reduced if a totally or Quasi totally GNSS SDR infrastructure can be implemented. Using SDR Reference Receivers, a Reference Station is constituted by a simple PC and a small Front-End (apart from the classical Geodetic Antenna). Any kind of upgrade (e.g. new frequencies or processing capabilities) can be implemented by the Control Centre through a simple GNSS SDR Software upload.

The idea of a Total SDR Augmentation infrastructure is reported in Figure 6.

Taking into account current developments and perspectives of PPP (Precise Point Positioning), based on a sparse array of Reference Stations at Regional level, and relevant needs for PPP-RTK implementations, SDR receivers can also be used as low cost densification of Sparse Regional Networks at local level.

In the Totally SDR Augmentation architecture, both the Reference Station and the rover are implemented through a GNSS SDR Receiver.

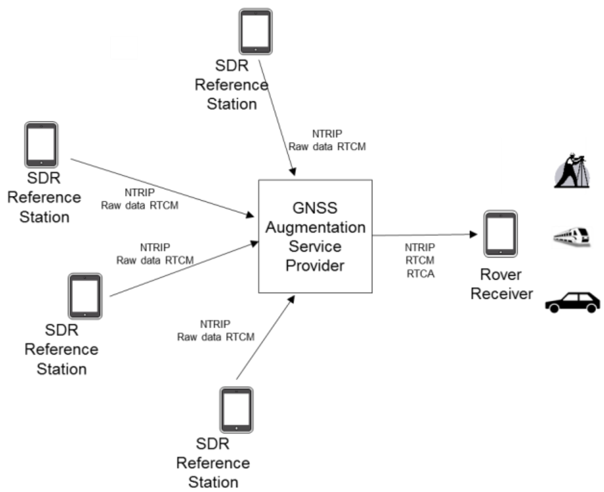

Figure 6 - The Total SDR High Accuracy Positioning Infrastructure

Such an infrastructure follows ICT future development perspectives, dealing with universal terminals with medium/high processing power, able to perform any kind of tasks through installable APIs.

TESTING CAMPAIGN ARCHITECTURE

In order to implement the total SDR Augmentation infrastructure Performance Test, the GRDNet Reference Station Antenna in Rome has been connected through an antenna splitter to a GNSS SDR (constituted by a Front-End and a PC running the SDR software).

The GNSS SDR Reference Station has been connected to the GRDNet Network Control Centre through TCP connection on a High QoS Public Administration Communication Network. Raw measurements have been packed in an RTCM 1002 message and relevant Antennas information in a 1006 message. An SDR relevant mountpoint has been created, inserted into the published NTRIP Caster sourcetable and made available to any user. Such GNSS SDR Reference Station has been used for any test of the present work.

For the rover side, the GNSS SDR software has been installed on a tablet and connected to the Front-End.

The Test Campaign has been carried out through the following testing GNSS RTK Surveying scenarios.

Test Scenario 1: COTS Receiver vs GNSS SDR RTK Performances comparison

The aim of this test is to compare Accuracy and TTFA of a rover Hardware Receiver with the SDR (Reference Station and rover) ones. A Leica geodetic antenna has been connected in parallel to a GPS1200 receiver through a splitter.

Relevant tests have been performed at increasing distance from the installed GNSS SDR Reference Station (0-15 Km). Both the receivers were operating in RTK mode. Five points have been surveyed. The antenna was mounted on a stable surveying tripod on a marker on the field. For each point, in order to evaluate TTFA, several sessions has been carried out. At the end of each session, the receivers have been switched off in order to check the status and prepare the next session.

Position, number of visible satellites, covariance matrix elements and RTK validation ratios has been logged.

Test Scenario 2: Short baseline GNSS SDR RTK test

In order to test the impact of the number of visible satellites on TTFA and the absolute accuracy for short baselines (e.g. VRS), the rover GNSS SDR has been installed on a building equipped with a test geodetic Antenna mounted on the roof at 200 m from the SDR Reference Station. The testing antenna is a benchmark point, accurately georeferenced through the geodetic Bernese Post-Processing Software.

Test Scenario 3: Real RTK Land Surveying tests for a Land Registry (e.g. Cadastral) Map updates

Such a test is the operative one and is intended to demonstrate the suitability of GNSS SDR for topographic surveying for Land Registry map updates.

Three Land Surveys have been carried out in Rome and relevant map updates produced in three environmental scenarios: suburban (light presence of trees and shadowing), light urban (medium level of shadowing and multipath), deep urban (urban canyons and presence of trees in the center of Rome, close to the Colosseum). Hidden Points have been surveyed through integrated GNSS and EDM measurements. The results of the surveys have been processed through the institutional Software Package Pregeo and relevant RMS and statistics, starting from the Land Registry historical DB containing previously surveyed points, is produced. A simulated map update proposal has been submitted for approval to the relevant Provincial Office.

PERFORMANCE ANALYSIS RESULTS

Test Scenario 1

A test has been performed, making a session of parallel GNSS Receiver and SDR Surveying on six points at increasing distance from the SDR Reference Stations: 200m, 2.5 Km, 7 Km, 8 Km, 15 Km (maximum distance from the Reference Station chosen taking into account the single frequency spatial decorrelation). Relevant sites for the surveying were selected in order to be as much as possible in clear-sky conditions.

For each session (at least three for each point), the receiver and the SDR have been restarted and left running till ambiguity fixing achievement.

One of the points has been selected as an Italian Geodetic Marker (Military Geographic Institute IGM95 point).

The total amount of occupation time for this Scenario was about 10 hours.

The first performed analysis has been the comparison of position estimation of the SDR vs the hardware receiver.

Relevant results are reported in Figure 7. After the exclusion of the outliers, the comparison between SDR and hardware receiver is reported in Figure 8.

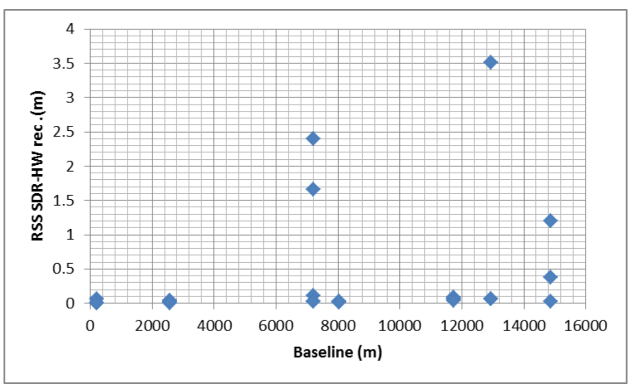

Figure 7 – Errors comparison between SDR and Hardware Receiver vs baseline

The classical dependence of performances vs. baseline length is evident. The position accuracy of the ambiguity fixed solution can be expressed as 1cm+10ppm.

Concerning the TTFA, the dependency versus the baseline is reported in Figure 9. Very high TTFA peaks are due to extended loss of mobile communication link and relevant RTCM packets between the user SDR and the Control Centre.

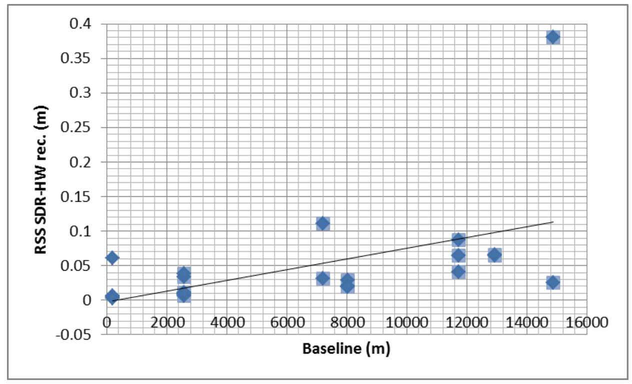

Figure 8 – Errors comparison between SDR and Hardware Receiver vs baseline (outliers removed)

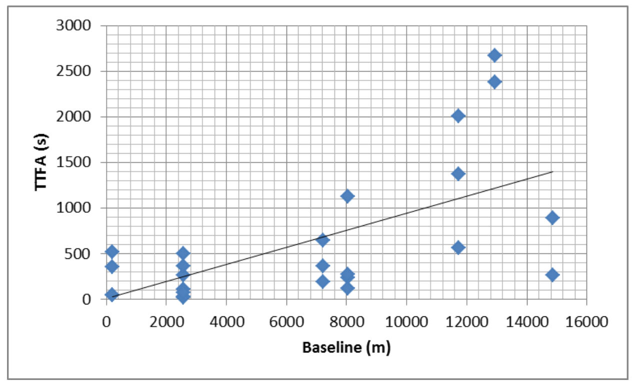

Figure 9 – TTFA vs baseline (outliers removed)

From the performed analysis, it has been derived that the achieved correct fixes percentage is in the order of 87%. Such value is correlated to the communication network availability and the possibility to rapidly recover the ambiguity fix when a satellite at the horizon reappears after a momentary lapse. It is expected that the implementation of partial fixing technique and robust OTF techniques can improve the TTFA and reliability in case of high number (e.g. >7) of visible satellites.

Test Scenario 2

For testing short baselines and VRS, the fixed receiver, located at 200 m from the SDR Reference Station, has been georeferenced and connected to the relevant mountpoint.

In Figure 10 it is reported the TTFA vs. number of used satellites.

It can be seen how in this case there is a clear dependence of the of TTFA vs the number of visible satellites.

Four RTK sessions have been planned and carried out during a day, taking into account visible satellites, in order to have a relevant change of satellite configuration.

The revealed correct fixes percentage is in the order 93%.

Such test demonstrates how, with a number of visible satellites greater than 9 and short baselines, comparable with the ones achievable with a VRS augmentation service, a TTFA of less than six minutes is expected. This leads to a real option for on-field surveying through a total SDR infrastructure and VRS modelling. Also in this case, TTFA peaks are due to loss of mobile communication links.

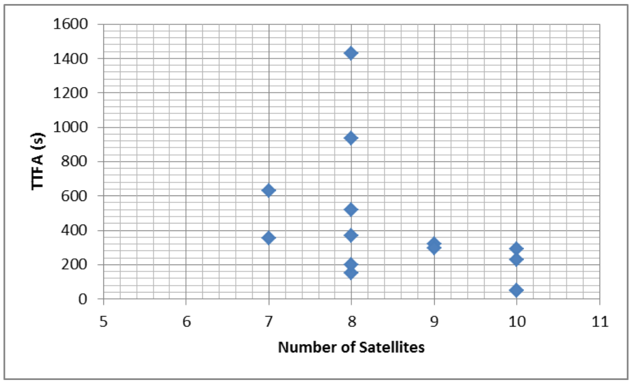

Figure 10 – Short Baseline: TTFA vs number of visible satellites

Test Scenario 3

Three surveys have been carried out. Due to the presence of high building, a telescopic pole at the maximum height extension (5 m) has been used for helping maintaining lock on the tracking channels.

The first survey has been performed in a suburban area of Rome at about 3 Km from the Reference Station. The area is characterized by the presence of moderate multipath in one point and buildings surrounding the Fiducial Point to be surveyed. The map update proposal for the insertion of a new (simulated) building has been submitted (in a simulated way) and processed along the whole institutional acceptance chain. The map proposal performed through the SDR passed all the approval steps and the new building has been inserted into the map.

For all the three Fiducial Points, a GNSS survey on two auxiliary points with forward intersection and EDM measurements was needed, due to the shadowing and the presence of trees (Hidden Point).

The first Fiducial Point is the enclosure corner of a quite low house with a tree in front of it. There was the need for a forward intersection survey through auxiliary points. The second Fiducial Point was located at the entrance of a big building located in front of another high building. The third Fiducial Point was in a corner of a medium high building, shadowing the whole south direction.

The number of visible satellite was varying from 6 to 7, with short time windows of 9. PDOP ranged from 3 to 6.7.

In the following table it is reported an extract of the network adjustment processing results performed by the Pregeo software, with the statistical comparison with historical data coming from previous surveys on the same Fiducial points.

Coppia PF	distanza	sqm	dislivello	sqm	diff.
PF21/8880/H501C-PF22/8880/H501C	306.096	+0.009	5.869	+0.037	
Tipo prot. 816357 del 2005	306.200	+0.051	-----------	------	-0.104
Tipo prot. 729373 del 2011	306.210	+0.022	-----------	------	-0.114
Tipo prot. 226731 del 2012	306.208	+0.007	-----------	------	-0.112

It is evident how the differences between currently performed surveys and previous ones (taken between 2005 and 2012) are in the order of 10 cm, therefore meeting the Italian Cadastral system tolerances.

In Figure 11, two of the fiducial points taken during the survey are showed. The first one is locate at the corner of a building, shadowed by a big tree. The second one is a corner of a building, surrounded by high trees and other buildings. It has to be underlined that loss of lock, multipath and foliage attenuation are the most critical factors impacting on TTFA and reliability of this kind of urban surveys RTK survey. TTFA was on the order of 10 minutes, while PDOP varied from 2 to 9, depending on shadowing and satellites geometrical configuration, satellites visibility was from 5 to 9. For this survey it was fundamental to perform an adequate survey planning for choosing the best satellite visibility windows.

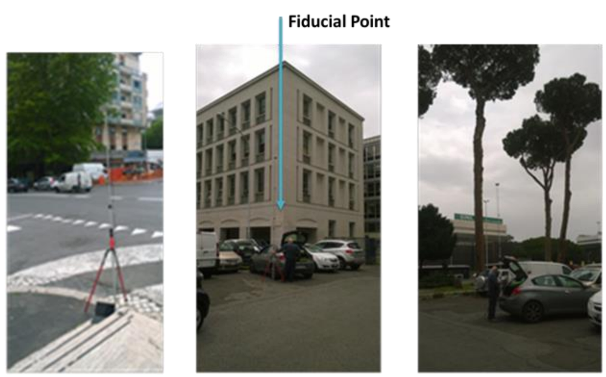

Figure 11 – EUR zone survey

Relevant comparison with Historical data is reported in the following table.

Coppia PF	distanza	sqm	dislivello	sqm	diff.
PF05/8540/H501A-PF14/8540/H501A	307.306	+0.148	4.604	+0.033	
Tipo prot. 163352 del 2006	307.463	+0.025	-----------	------	-0.157
Tipo prot. 163354 del 2006	307.463	+0.025	-----------	------	-0.157
Tipo prot. 81477 del 2006	307.463	+0.038	-----------	------	-0.157
Tipo prot. 81472 del 2006	307.463	+0.038	-----------	------	-0.157

The third survey has been carried out in the area close to the Colosseum in the center of Rome, at about 10 Km from the SDR Reference Station.

In this case, two of the three Fiducial Points are located in harsh environments. Both are surrounded by buildings and high walls. One of them is located close to a park with high trees. The average satellites visibility for those two points was 4-6 satellites, while the PDOP was in the order of 4-6. TTFA went from 6 minutes to 17 minutes.

Despite of the good visibility (for a very short time window, the visibility was 9 satellites), multipath and foliage attenuation played here a very important role. SDR receiver RINEX Post-processing was also here performed for one of the points for checking the obtained results. A fine planning was needed for choosing the right time windows for performing the survey. The continuous raising and falling of satellites above the obstacles leaded to an increase of TTFA.

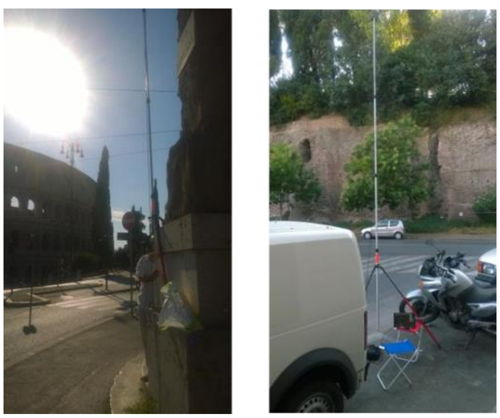

Figure 12 – Colosseum survey

CONCLUSIONS AND FUTURE WORKS

The applicability of a Total Augmentation System (Reference Stations and Rover receiver) based on GNSS SDR technology to Land Surveying for institutional purposes has been studied.

The utilized GNSS SDR Single-Frequency GPS+SBAS technology, including a very low cost Front-End, has been totally designed and developed. Relevant Real-Time processing is performed on General Purpose Processors (PC, notebook and tablets).

An extensive test campaign has been performed for validating the solution. At this aim, a GNSS SDR Reference Station has been equipped and connected to an existing GRDNet (GNS R&D Network) Network-RTK Augmentation Control Centre using standard communication messages and protocol (RTCM 1002 and 1006 messages and NTRIP). Professional surveyors have been equipped with a tablet running the SDR software and the relevant Front-End.

Three test campaign scenarios have been carried out for testing the solution.

A First scenario was intended to analyze the impact of baseline length on accuracy and TTFA. From such an analysis, nominal 1cm+10ppm accuracy is expected, while TTFA ranges between 4 minutes and 20 minute, depending on satellites availability, baseline length (the test has been carried out between 200 m and 15 Km from the SDR Reference Station) and mobile communication link availability.

The Second Scenario was concerned with a short baseline (200 m) on different time windows and satellite configurations. Such scenario identifies the possibility of overcoming limitations due to baseline lengths through VRS. The extensive analysis showed that, without loss of mobile communication link between the rover and the Network Augmentation Control Centre, a TTFA less than 6 min at average is achievable.

The Third Test Scenario was performed with real Land Registry Map Update Surveying conditions in suburban and urban areas. Such environments are characterized by urban canyons, strong shadowing, severe multipath and foliage attenuation. The analysis revealed how it is important, in such conditions, to perform a pre-survey planning for ensuring the optimal satellite availability and PDOP conditions. Furthermore, as in the previous scenario, the loss of mobile communication link leads to a few TTFA peaks. In case of severe shadowing, Hidden Points has been surveyed through classical forward intersection methods, with the integration of Electronic Distance Measurements. TTFA peaks of 17 min have been registered in such harsh environment, characterized by high PDOP.

Some lines of future developments are going to be followed. Multi-constellation positioning, due to the increase in terms of visibility and availability, is expected to improve a lot GNSS SDR RTK performance in terms of TTFA. A trade-off is anyway expected in order to balance Computational load with performances improvements. Urban Canyons, characterized by high multipath conditions and frequently raising and falling satellites, are the most critical factor. Robust Multipath rejection techniques and Partial Fixing algorithms will be studied and implemented in the GNSS SDR for mitigating such threats.

Mobile communication losses, being one of the most relevant source of service unavailability, will be analyses in detail and counteractions studied (advanced OTF techniques).

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