A Soft Touch

Sogei's GPS/Galileo Software Receiver and Institutional GNSS Applications in Italy

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Hardware GNSS receivers can sometimes be hard on users — especially those faced with demanding commercial and institutional applications, such as customs enforcement. Evolving requirements and the need for special features and functionality — such things as high configurability, reliability, precision, service guarantees, authentication, security, and anti-jamming — can make proprietary solutions expensive and short-lived. That situation led Sogei, a government-owned Italian company, to come up with a software-based solution of its own.

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During last 10 years, the GNSS panorama has changed rapidly, bringing new pressure on product designers and system developers to adopt new approaches to their efforts. Let's take a look at some of these changes.

In the consumer mass market, low-cost GPS terminals and car navigation systems are widely available, and their integration on "smart-phones" is mature.

For commercial and institutional applications, however, some issues are still on the table. In particular, institutional users are asking for GNSS solutions that offer high configurability, reliability, precision, service guarantees, authentication, security, and anti-jamming — and, by definition, the availability of open and standard solutions.

High-accuracy terminals or other GNSS equipment with demanding requirements are often based on pro-

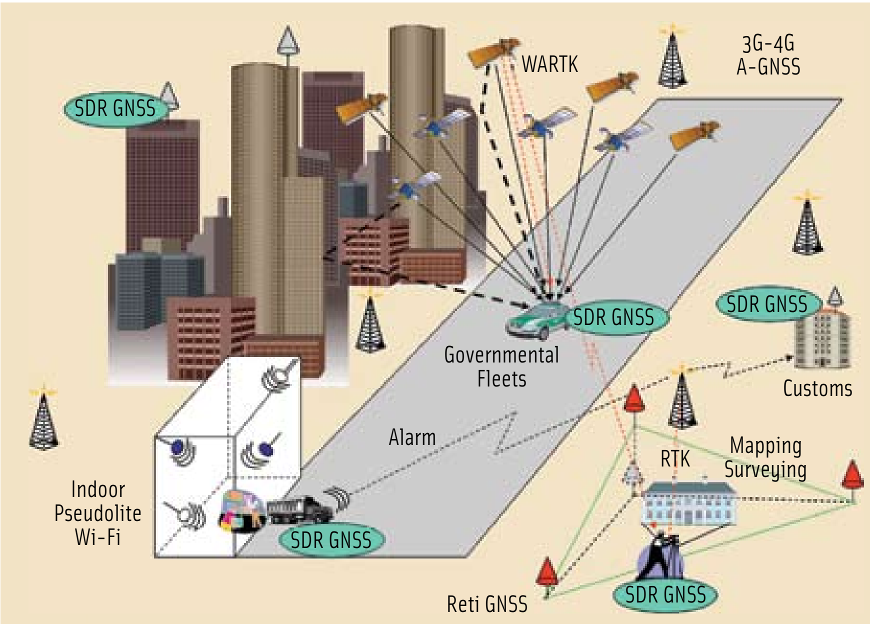


FIGURE 1 **Future GNSS Applications Scenario**

prietary and expensive solutions. At the same time, in some countries high-accuracy GNSS augmentation services are the exclusive initiatives of a single private provider or local public agency.

Meanwhile, standards and regulations are changing for almost every application. Therefore, in the near future a user terminal should be expected to support numerous standards and protocols. Furthermore, today's technologically skilled GNSS user is always asking for more advanced solutions in terms of accuracy — just as evolving demands for mobile communications required ever more bandwidth.

Systems and services are converging. Information and communication technologies (ICT) are ever more frequently providing integrated hardware/software solutions for navigation and communications. Integration of GNSS with inertial sensors, communication systems (e.g., WiFi) and assisted (AGNSS) solutions are, of course, essential for providing higher continuity of service in a range of indoor situations.

In the near future, guaranteed and augmented solutions (in terms of precision and integrity) will be necessary not only for geodetic and surveying applications, but also for mass market applications such as advanced driver assistance systems (e.g., automatic lane keeping). **Figure 1** illustrates some of these near-term applications.

Backward compatibility with respect to legacy systems also has to be assured for a real exploitation of institutional market. An example of such an application is introduction of GNSS/RFID technology for implementing well-consolidated customs operational procedures and regulations. However, that application will require a complete and *transparent* integration of new freight "location" reporting systems within existing tracking systems.

Introducing a new "black box" system for this purpose (despite its efficiency), leading to a complete revolution for institutional freight tracking, will not be accepted by the institutional customer. Similar considerations appear in considering the application of innovative high-accuracy technologies in cadastral surveying operations.

The availability of new GNSS constellations and multi-frequency solutions (e.g., TCAR, three carrier ambiguity resolution) will change the scenario within a few years, leading to the need for quick front-end and firmware upgrades in GNSS receivers. New long-range real-time kinematic (RTK) solutions are also coming, based on innovative ionospheric modelling.

In this technological and business environment, embedded systems offer a near-future path to providing tightly integrated navigation and communication solutions with low-cost, accurate, portable, and highly reconfigurable receivers.

A concurrent technological advance, GNSS software receivers (referred to hereinafter as SDR, for software defined radio), will allow developers to provide code/phase solutions and the processing of signals from satellite-based augmentation systems (SBAS) and regional GNSS reference networks in an open environment.

Furthermore, through a suitably flexible front-end, adapting SDR solutions to emerging navigation constellations will be easily implemented. This approach seems like an ideal solution for institutional applications.

A side effect of the development of such solutions may be the ability to implement low-cost GNSS SDR-based augmentation networks, overcoming the usual problems related to high installation costs and the need for continual firmware upgrades.

This article will describe the activities of Sogei, in cooperation with the University of Tor Vergata in Rome, to develop an open SDR GNSS receiver for such applications.

Sogei R&D activities

Sogei is an Italian company owned by the Ministry of Economy and Finance of Italy charged with developing ICT solutions for national institutions. Among other responsibilities, Sogei manages the Italian system for updating cadastral maps as well as the information system of for Italian Customs.

To support such missions, Sogei is continuously carrying out extensive R&D activities on GNSS state-of-the-art solutions. In 2007, Sogei signed a collaboration agreement with the University of Tor Vergata, as part of its Master of Science degree program in "Advanced Communications and Navigation Satellite Systems" (MasterSpazio). The main topic of this agreement is the R&D on innovative GNSS SDR and Augmentation solutions.

R&D activities are focusing on two reference applications: cadastral surveying and mapping that requires high accuracy (< 10 centimeters), reliable RTK and static GNSS solutions, and integration with topographic sensors (see the sidebar article, "Building a GNSS Reference Network."); and customs operations such as freight tracing and tracking, anti-fraud, and risk management, that require medium accuracy (two-three meters), high reliability, service guarantees, and anti-jamming capability.

Platform Architecture and Results

Development of Sogei's GNSS SDR platform has been carried out using a popular simulation, modelling, and design software suite for rapid prototyping. Furthermore, we avoided any reliance on proprietary libraries and integrated our own C-code modules within the platform. Following this approach, our development platform is based on a bi-processor workstation, equipped with Windows OS, commercial software packages as well as free C compilers. Concerning hardware implementation and high performances, we are testing our code on an advanced DSP/FPGA SDR development platform.

The architecture is based on the following components:

- An RF signal GNSS simulator able to generate RF GPS signal (C/A and P codes) and Galileo E1 BOC(1,1); the simulator is used only to validate and test algorithms (see **Figure 2**)
- A GNSS data sampler: a simple, commercial superetherodyne front-end with a receive bandwidth of 2.2 MHz and an IF output of 4.13 MHz that allows us to acquire signals from GPS, GIOVE-A, the European Geostationary Navigation Overlay Service (EGNOS), and the U.S. Wide Area Augmentation System (WAAS). For this purpose, we used one of the first developed commercial GNSS front-ends and are now acquiring new hardware for such purposes.
- a signal acquisition software component that acquires GNSS signals at IF through parallel search and roughly estimates C/A-code beginning and Doppler shift
- another software component that performs GNSS signal tracking with classical delay-locked loops and phase-locked loops developed via software for code and carrier tracking and a frequency-locked loop implemented for calculating the Doppler shift
- Positioning software that calculates pseudoranges through the most advanced algorithms suitable for SDR implementation: no absolute time reference available in digitized data, only relative measurements among satellites, and finally position calculation. (For further discussion of these topics, see the articles by J. Tsui and K. Borre et alia in the Additional Resources section near the end of this article.)

Design, Developments Hints

Developing a GNSS SDR platform implies continuous design choices in order to find the best trade-off between performance and computational efficiency.

Concerning the acquisition phase, the bottleneck is, of course, the fast Fourier transform (FFT) calculation for implementing the parallel search. To achieve this goal, we developed and integrated an efficient FFT and inverse FFT algorithm into the platform.

Synchronization of data between the acquisition phase and the tracking phase is also a relevant issue, in particular for real-time implementations. In our platform, the tracking phase is the most important aspect in regards to the computational load. We made a particular effort to achieve the maximum reduction of wasted processing time in order to start the tracking of each satellite quickly after the corresponding signal acquisition is completed and data are passed to the tracking phase.

Selection of the delay locked loop (DLL) discriminator curve also affects tracking efficiency. Here, developers need to evaluate the trade-off between performance and computational load in detail. For Galileo tracking, we followed a dedicated procedure to overcome the well-known problem of convergence of the DLL to unstable points, due to the discriminator curve behavior for BOC(1,1).

The basic driver is to exploit as much as possible the similarity between the classic autocorrelation function (ACF) of the GPS C/A code and the one related to BOC(1,1) and to reduce at minimum the discriminator computational load. Other efficient procedure algorithms are under study.

Of course, the use as much as possible of the precalculated tabled data

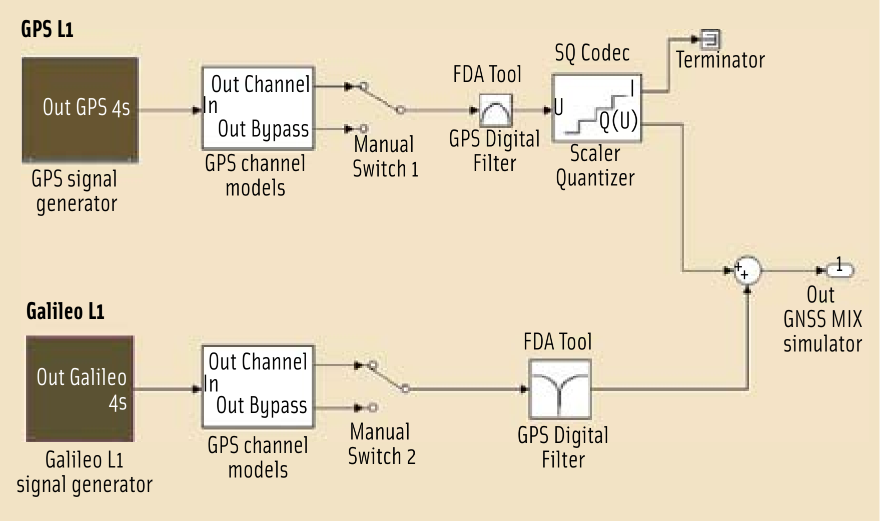
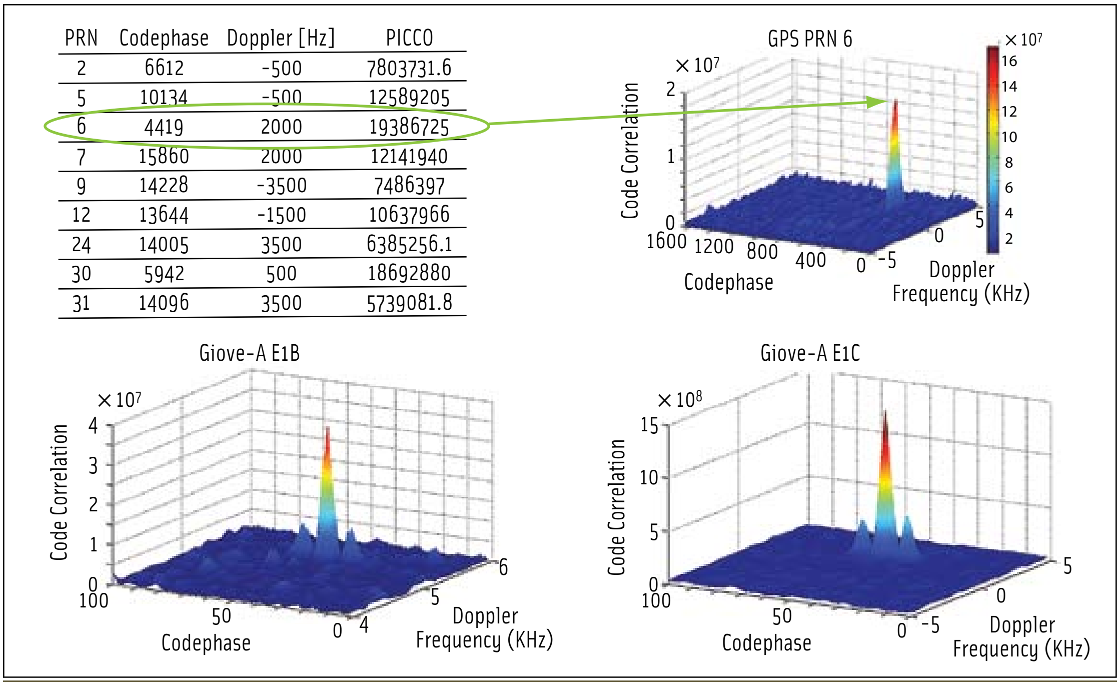


FIGURE 2 GNSS Signal Simulator



PRN	Codephase	Doppler [Hz]	PICCO
2	6612	-500	7803731.6
5	10134	-500	12589205
6	4419	2000	19386725
7	15860	2000	12141940
9	14228	-3500	7486397
12	13644	-1500	10637966
24	14005	3500	6385256.1
30	5942	500	18692880
31	14096	3500	5739081.8

FIGURE 3 GNSS Signal Acquisition

instead of running software procedures (having a high computational processing load) is mandatory for real-time achievements. Tabled data are, apart from sine and cosine functions, C/A code samples and relevant "early" and "late" samples to be used respectively in the acquisition phase for code generation and in the tracking phase for DLL implementation.

Sogei's SDR platform is currently running for testing purposes on portable PCs and desktop computers equipped with the needed suitable RAM and HD sizing, on which the GNSS data sampler, its patch antenna, and the SDR software are installed. We are working on implementations for digital signal processors (DSPs) and field programmable gate arrays (FPGAs).

The use of computer-aided tools allows fast design and prototyping, but in moving from the design to the implementation phase, classical development problems rise. This is particularly true if commercial SDR development environments are used.

The most relevant considerations for open GNSS developers are:

- Availability of low-cost processors with real-time operation systems (RTOSs) equipped with all relevant hardware application programming interfaces (APIs) and drivers. All such costs together amount to about three or four time the cost of the needed hardware for SDR implementation.
- Availability of FPGA/DSP drivers
- Dependence on proprietary libraries implementing the interface between the prototyping environment and the hardware to be used. Toward this goal, Sogei used as much as possible open RTOS and developments independent from external libraries.

GNSS SDR results

The SDR platform performs nominally during the signal acquisition phase. After GNSS signal-in-space data acquisition and proce ssing, the platform is able to carry out track signals from GPS, EGNOS, WAAS, and GIOVE-A, as shown in **Figure 3**. In the bottom graphs of the figure, note the two lateral autocorrelation peaks for GIOVE-A, as foreseen by the theoretical signal specifications for the binary offset carrier (BOC) signal modulation. Recently, we also performed GIOVE-B acquisition using our platform.

Our SDR receiver was able to track GPS and GIOVE-A and to decode the relevant navigation data. The following discussion elaborates on results from a test campaign with our receiver.

At the beginning of 2007, after checking for GIOVE-A visibility at our latitudes, several minutes of signal data were acquired, recording different sessions through the SDR testing environment in open-sky conditions. **Figure 4** shows the data recorded from a GPS satellite for carrier phase (left-side graphs) and code. It shows regime behaviors of the tracking phase, after pull-in.

Concerning the correlation output, the data showed how the energy is concentrated on the in-phase component, while in-quadrature components are going to 0 (top graphs in the figure), as expected by the theory. Furthermore, frequency, phase and code are correctly estimated (errors going to the classical noise level), while the navigation bits are correctly extracted from the in-phase components (right graph in the middle). Such results demonstrate the nominal behavior of the SDR, compared with conventional hardware.

Figure 5 presents sample data decoded from navigation message of GIOVE-A transmissions. Here it is possible to recognize the sub-frame structure of the GIOVE-A navigation message.

Sogei and the University of Rome "Tor Vergata" had accumulated and evaluated positioning results from several campaigns using Sogei's SDR GNSS receiver.

Figure 6 graphically presents data showing the achievable accuracy under high masking conditions (e.g., building shadowing), comparable to a commercial receiver. Points have been reported on a mapping framework developed by Sogei. Data analysis showed an RMS in

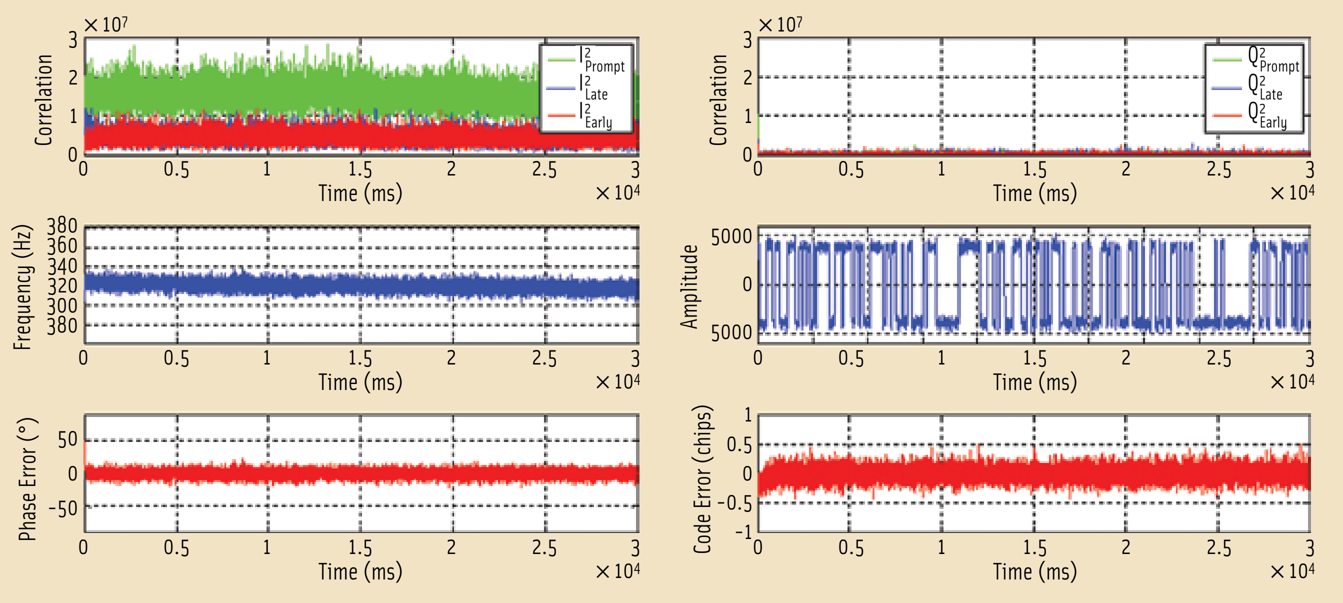


FIGURE 4 GPS Tracking Performances (SV 6)

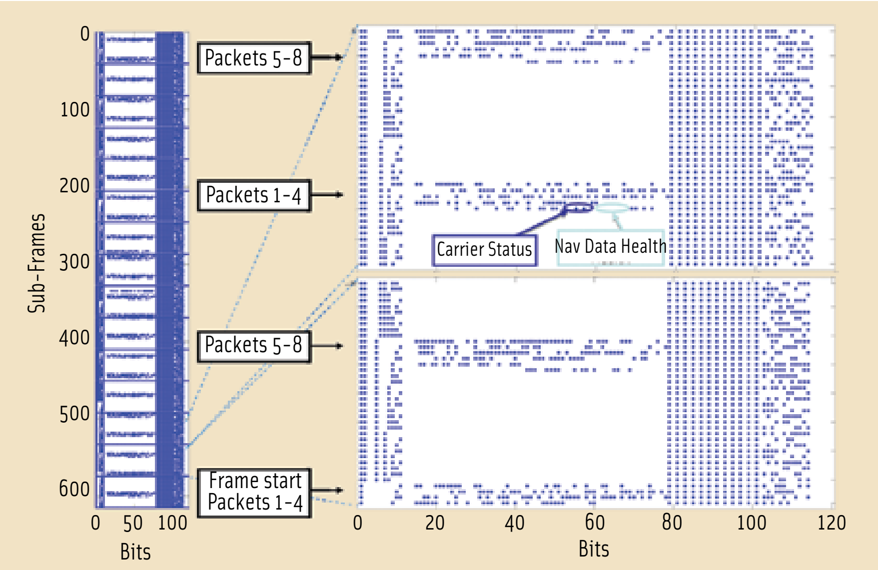


FIGURE 5 GIOVE A navigation data (January 18, 2008)

FIGURE 6 GNSS Positioning (high masking environment)

the order of 7–8 meters in latitude and longitude and 15 meters in height.

Future Perspectives

Worldwide, the implementation of a real-time GNSS SDR receiver is typically based on the integration of the code in a FPGA or DSP platform, and the subsequent implementation in dedicated chips (ASICs). Creating a truly open and reconfigurable solution for institutional applications, however, depends in such case on the use of such kind of devices. The integration of SDR within a commercial PDA or laptop is currently limited by the usual problems of power consumption and computational load problems.

Computational Load limitations (especially for the tracking phase) could be overcome in a few years by the continuous progress in commercial processor implementations (increasing MIPS, transistor size reduction, cost reduction, multiple-core implementations, in accordance with Moore's Law).

Power consumption could remain a burden for a while, but the use of AGNSS techniques and technological progress may allow these limitations to be overcome in the future.

Given this state of our GNSS SDR development, Sogei's R&D activities are currently focused in the following areas:

- Integration of the SDR code on a DSP/FPGA platform without relying on external libraries introduced by the development platforms,
- Integration of the SDR code within advanced commercial laptops for customs tracing and tracking applications,
  - Implementation of SBAS capabilities

Building a GNSS Network

In 2003, Sogei developed a reference GNSS network in central Italy (see Figure 7), within the framework of the institutional R&D program for public administration and in collaboration with the Italian Land Agency. We named this Network GRDNET (GNSS Research and Development Net).

Using multi-reference station/virtual reference station (MRS/VRS) technology, the network architecture is based on the following components:

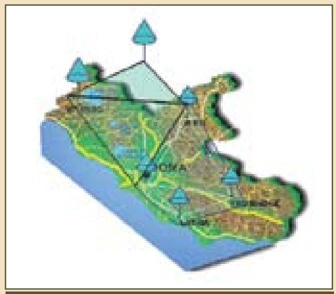


FIGURE 7 Sogei GNSS Network

- **Reference Stations (RS):** currently six geodetic GNSS stations with an inter-distance of 40-80 kilometers installed on the roofs of land agency offices in the region and connected to a reference network control center through a high quality of service, public administration wide area network;
- **Network Control Center (NCC):** located in Sogei, it calculates geodetic solutions (ITRF05, IGb00, IGS05), provides real-time kinematic (RTK) services and generates VRS RINEX files through an MRS approach
- **User:** must be equipped with a commercial surveying GNSS receiver, with integrated TCP/IP connection capability (e.g., GPRS/UMTS) for accessing RTK services.
- **Network Website:** a dedicated website, accessible by authenticated users, allows them to obtain a VRS RINEX file for a point position within the network, to acquire reference stations coordinates and ancillary data, and to perform quality checks.

Design and Development Hints

The GNSS reference network is currently devoted to land administration tasks, such as local cadastral reference system updates, in-field tests, and training. In order to assure high configurability and adaptation to customer requests, the NCC software has been developed without using commercially available packets.

A variety of receiver models have been used for development and testing purposes. Following the open strategy described earlier, various GNSS geodetic receivers from several manufacturers are going to be installed and integrated into the GNSS Network Furthermore, coordinate transformation between the International Terrestrial Reference Frame (ITRF) and Italy's national reference system (IGM95), as well as the incoming ETRF00, have been carried out in order to guarantee the usability of field solutions in the cadastral world.

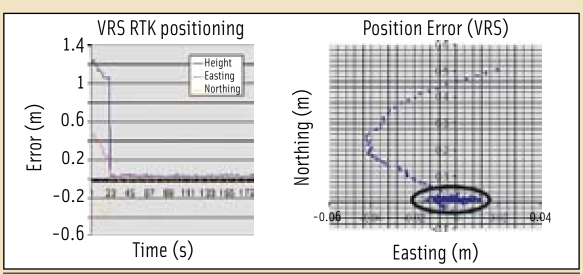


FIGURE 8 GNSS Network-RTK performance

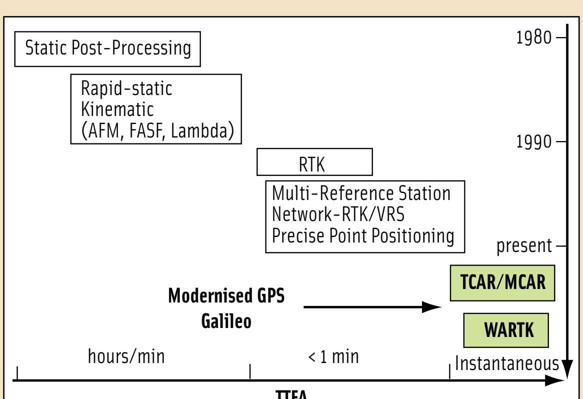


FIGURE 9 GNSS High Accuracy Solutions trend

Concerning network-RTK implementation, standard interfaces have been developed for real-time communication between the reference stations and the NCC (BINEX) and between the NCC and the user receivers (RTCM 2.x and 3.x).

In our experience, the use of BINEX also has the collateral benefit of possibly reducing use of network bandwidth by about one-fifth compared to commercial formats. Corrections broadcasts are implemented through the standard NTRIP protocol. Quality checks are performed using teqc (Translate/Edit/Quality Check) preprocessing software developed by the University Navstar Consortium.

On the postprocessing side, geodetic solutions have been carried out using traditional scientific packages (e.g., Bernese). We have implemented dedicated RINEX data downloading and storage, using an automatic integrity storage system. To date, about two terrabytes of data have been collected and processed.

GNSS Network Performance

Sogei's GNSS Network allows users to achieve accuracies of less than 10 centimeters across the entire polygon defined by reference stations and up to 10–20 kilometers outside of its borders. The average time to fix ambiguities (TTFA) is less than 30 seconds. An extensive test campaign has been carried out, comparing the achieved results with IGM95 monographic data.

Figure 8 presents, as an example, results of a campaign executed at about 50 kilometers from the closest reference station.

As for geodetic and post-processing solutions, the usual performance is obtained, leading to weekly millimeter-level solutions.

Future Perspectives

High accuracy solutions are rapidly evolving. (See Figure 9.) New regional-level techniques for estimating ionospheric errors are being implemented, such as those discussed in the article by M. Hernández-Pajares et alia, cited in Additional Resources.

Such techniques, together with multi-frequency ambiguity resolution available with modernized GPS and future GNSS constellations, will allow a real exploitation of long-range, instantaneous, and highly reliable network-RTK solutions. Furthermore, the capability of the Galileo system to broadcast short data messages could allow the implementation of wide area RTK (WARTK) corrections in the future.

GNSS networks' operational costs and installation burdens in terms of hardware and licences are currently inhibiting the implementation of open and guaranteed RTK services for institutional purposes. Integration of existing sub-networks could be a way to expand future institutional applications.

Various services could also be implemented using EGNOS/WAAS techniques for customs operations.

Sogei is going to carry out R&D on such network-RTK solutions in order to improve as much as possible their accuracy and reliability and to extend error modeling. These efforts are looking toward possible future WARTK implementations and TCAR techniques. The integration of such capabilities within the GNSS SDR platform will be carried out with the aim of implementing embedded high-accuracy solutions for the institutions.

- Implementation of phase processing and RTK capabilities — through relevant RTCM V3.x standards and Networked Transport of RTCM via Internet Protocol (NTRIP) —for surveying

Conclusions

GNSS civil and institutional applications will be of great relevance for future GNSS applications developments.

GNSS software receiver technologies offer the possibility to implement open and reconfigurable navigation and communication systems to be embedded in a PDA or Laptop. As a side benefit, low-cost terminals will be available for the user. Sogei R&D activities, in collaboration with the University of Rome “Tor Vergata”, allowed the possibility to implement an initial GNSS SDR platform able to work in a multiple constellation environment.

Meanwhile, the development of a network-RTK solution in the center of Italy, enabled users to achieve sub-decimeter accuracy with a reduced TTFA using complete standard protocols and interfaces. Modernized GPS and Galileo will allow the implementation of instantaneous and reliable high-accuracy services. RTK capabilities and TCAR processing within an open GNSS SDR environment could therefore provide a solution for future surveying and high-accuracy transport applications.

Acknowledgments

All the R&D activities described in the present paper have been developed within Sogei. A particular reference is here given to M. Torrisi and Andrea Properzi, working respectively on SDR development and GNSS network interfaces within the framework of the Masterspazio initiative of the University of Rome “Tor Vergata”.

Manufacturers

Sogei used the Matlab Simulink software from **MathWorks**, Natick, Massachusetts, United States, in its SDR development. The mapping framework used to create Figure 6 is GEOPOI (geocoding points of interest) from **Sogei, S.p.A.**, Rome, Italy. The DSP/FPGA hardware development platform for SDR is based on the Small Form Factor (SFF) Software Defined Radio (SDR) Development Platform platform and the relevant software programming interface tool, Code Composer Studio, from **Texas Instruments**, Dallas, Texas, USA. The GNSS front-end data sampler was the SE4110L from **SiGe Semiconductor**, Ottawa, Canada. The GRDNet currently incorporates the Thales Navigation Internet-Enabled Continuous Geodetic Reference Station (iCGRS) from Thales Navigation (now **Magellan GPS**, Santa Clara, California, USA, and Carquefou, France) and NetRS from **Trimble Navigation**, Sunnyvale, California, USA.

Additional Resources

[1] Borre, K., and D. M. Akos, N. Bertelsen, P. Rinder, and S. H. Jensen, *A Software-Defined GPS and Galileo Receiver: A Single-Frequency Approach,* Birkhäuser, Boston, Massachusetts, USA, 2007

[2] Hernández-Pajares, M., and J.-M. Juan, J. Sanz, R. Orús, A. García-Rodríguez, and O. Colombo, “Wide Area Real Time Kinematics with Galileo and GPS Signals,” *Proceedings ION GNSS 2004,* Long Beach, California, September 21 – 24, 2004, pp. 2541–2554

[3] Tsui, J. B-Y., *Fundamentals of Global Positioning System Receivers – A Software Approach,* Wiley InterScience, John Wiley & Sons, Hoboken, New Jersey, USA., 2004

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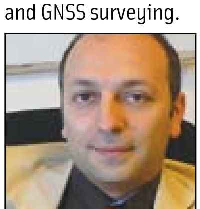

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