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Enhancing SBAS performance: the EGNOS pseudolite concept

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1. Abstract

The paper is aiming at introducing the concept of ***"EGNOS pseudolites***": a new system based on the combination of GPS pseudolites technology and SBAS standards. The EGNOS pseudolite is a system conceived to access the SBAS messages generated by the EGNOS system computing platform and, process them in a way to allow their broadcast through one or more pseudolite units using typical GPS/SBAS PRN codes on the L1 frequency. In the frame of the European Space Agency plan for the development of the EGNOS pseudolite system, the paper includes a description of the system mission and applications, the high level architecture, the work logic, the implementation issues and some indications of the expected navigation performance derived through simulations.

2. Introduction

Following the excellent results obtained after the implementation of the EGNOS system, a large number of civil applications will require more and more reliable positioning and timing information based on satellite navigation and, specifically, on GPS augmented by EGNOS. For some applications and specific operational conditions (e.g. navigation in urban environments), it would be of interest to further improve the access to the EGNOS augmentation and ranging signals.

In this context, a lot of techniques, most of them enabled by the ESA SISNeT technology, have been proposed at experimental level for the broadcast of EGNOS messages with means other than the geostationary satellites to improve the access to the EGNOS augmentation signals. Typical examples are: Internet, GSM/GPRS, DAB, RDS, etc. Despite these techniques have demonstrated their feasibility and the good navigation performance obtainable, they present two shortcomings: the relative complexity of the user terminal (e.g. GPS/SBAS receivers with GSM/GPRS or DAB module) and the inability to provide any extra ranging measurement to be included in the navigation solution computed by the GPS/SBAS receiver.

On the other side, a lot of studies/experiments have demonstrated the enhancements brought by GPS pseudolites in terms of ranging availability and accuracy when operated in combination with GPS satellites.

The further natural step is therefore the use of pseudolite for the broadcast of SBAS messages through GPS-like signals in a way similar to the EGNOS geostationary satellites.

Key added values of EGNOS pseudolites in existing GNSS scenario are:

- Enhanced availability of EGNOS augmentation where the geostationary satellites are not fully accessible;
- Improvement of measurement geometry (lower DOP factor compared to GPS/EGNOS);
- Easy synchronization with GPS/SBAS time reference and, therefore, low residual ranging errors;
- Low implementation and maintenance costs compared to any other navigation system providing the same navigation performance;
- With minor modifications to typical GPS/SBAS receivers, the signals broadcast by an EGNOS pseudolite can be processed as if they were broadcast by an ordinary EGNOS geostationary satellite, but placed somewhere on the Earth (where augmentation and ranging signals are needed).

3. Mission and applications

Main motivations leading to the development of a system that broadcasts an EGNOS-like signal through pseudolites are therefore the following: overcome the typical limitations occurring in the broadcast of EGNOS messages through the geostationary satellites, provision of additional ranging sources where it is needed and, access to EGNOS augmentation messages and to additional ranging sources using the same terminal GPS/SBAS terminal.

The EGNOS pseudolite system shall fulfill the following mission requirements:

- Broadcast of the EGNOS augmentation messages in areas where the visibility of EGNOS geostationary satellites is limited or it is blocked (Figure 1 – Signal Blocking);
- Broadcast of EGNOS-like ranging signals to increase the number of the ranging sources available (Figure 2 – Increased ranging availability);
- The augmentation and ranging signals broadcast by the EGNOS pseudolite system shall be compliant with the existing GPS/SBAS standards and shall be exploitable, with minor modifications, by means of existing GPS/SBAS receivers.

Any user operating within the coverage area of an EGNOS pseudolite system will therefore be able to compute position and integrity using SBAS augmentation and additional ranging measurements.

Further concepts on the system requirements are presented in the section dealing with the system implementation issues.

Examples of applications that may benefit from the implementation of an EGNOS pseudolites system are the following:

- aircraft landing and take-off operations (Figure 3 – Aviation applications) ;
- harbor operations;
- navigation in high latitudes and in valleys;
- positioning of trains along railroads;
- machine control at mining sites;
- positioning of goods and vehicles in industrial sites;
- improvement of signal coverage in urban environments (Figure 4 – Navigation in urban environments).

All the listed applications, depending on the operational requirements and constraints, may need additional ranging measurements and/or access to EGNOS augmentation with means other than the geostationary satellite and, possibly using the same GPS/SBAS navigation terminal.

4. High level system architecture

The EGNOS pseudolite is basically envisaged as a system which access, process and broadcast through pseudolites - operating on the L1 frequency and using typical GPS/SBAS PRN codes - the augmentation messages generated by the EGNOS system computing platform.

The system can be therefore implemented with the following high level architecture: a master or central unit, one or more transmitting units and a monitoring unit (Figure 5 – High level architecture; Figure 6 – Functional architecture).

The master or central unit contains the following modules:

- a central control unit (it is the heart of the EGNOS pseudolite system, it allows the system configuration and automatic control);
- a module to access the EGNOS messages (it allows the connection to the EGNOS Data Access Server);
- a module for the processing of the EGNOS messages (it substitutes the data on geostationary satellites with the pseudolites corresponding data);
- a time reference module (typically a GPS/SBAS time receiver) to keep synchronization with EGNOS and to steer the entire system;
- a pulsing synchronizer (to steer the RF carrier pulsing);
- a signal-in-space monitoring and RF calibration modules (to ensure that the transmitting units broadcast correct data and with proper signal levels).

The transmitting unit is composed by:

- a module for the generation of the RF carrier (centered on the L1 frequency) and of the pseudolite PRN code (in the prototype system it is chosen among the 210 foreseen by SBAS standards);
- a pulsing switch (to enable the pulsed transmission)
- a transmitting antenna (typically a helical antenna)

The monitoring unit is composed by:

- a receiving antenna (typically omni-directional to receive both GPS satellites and pseudolites signals);
- a pre-amplifier unit (to feed the SIS monitoring module, the RF calibration module and the EGNOS time receiver).

However, it shall be noted that, without changing the functionality of each of the component modules, in the development of the EGNOS pseudolite prototype some architectural sub-systems might be combined to achieve an efficient system design.

5. System work logic

The system input data is represented by the EGNOS augmentation messages provided by the EGNOS Data Access Server. Main configuration parameters for the transmitting units are the PRN codes, the geographical coordinates, the power setting and the pulsing rate.

It shall be noted that the augmentation messages received through the EGNOS Data Access Server are received slightly before the ones received from the EGNOS geostationary satellites (there is no delay due to the up-link process). This allows more flexibility in the processing time.

The EGNOS pseudolite system then, in tight synchronization with EGNOS broadcasts, replicates all augmentation messages except those containing data on the geostationary satellites.

In these messages (MT 1, 2, 3, 4, 5, 6, 7, 9, 10, 17, 24, 25) all data concerning the geostationary satellites (SBAS service identification, PRN number, ranging source coordinates, differential corrections and integrity information) is systematically replaced with the corresponding data of the pseudolites. The message format remains unchanged and compliant with SBAS standards (Figure 7 – Signal in space).

This substitution is operated in the module dedicated to the processing of the incoming SBAS messages and has the following purposes: to enable the identification of any transmitting unit with a specific PRN code and to allow the activation of the pseudolite ranging function.

It shall be noted that most of the data to be replaced is represented by constant data or configuration parameters. In this way, any transmitting unit of the EGNOS pseudolite system behaves exactly as a typical SBAS geostationary satellite with its specific PRN code. The user equipped with a GPS/SBAS receiver (with minor modifications as it will explained later on) may then access the EGNOS augmentation and ranging signals from one or more transmitting units of the EGNOS pseudolite system as if it were accessed from the EGNOS system geostationary satellites.

The implementation of a GPS/SBAS time receiver in the system design provides the time reference for the synchronization of the entire system. The RF carrier generation, PRN code generation, pulsing broadcast and message broadcast rely on this module. It has been proved at experimental level that, once the system is synchronized and stabilized, the accuracy of the pseudo-range measurements taken from the pseudolite is well below 1 meter.

The EGNOS pseudolite system broadcast its augmentation and ranging signals though one or more transmitting units. Their RF carrier generator and PRN code generator are steered by the system time reference. The signal is broadcast through a helical antenna.

The power and spectral characteristics of the signal received by a GPS/SBAS receiver operating in the service area of an EGNOS pseudolite system are made similar to those of EGNOS geostationary satellites (L1 centre frequency, 2.2 MHz bandwidth, 250 bit per second data rate). In order to cope with the near-far problem and avoid any interference to GPS signals and receiver jamming, the transmitting units are operated in a pulsing mode (Figure 8 – Pulsing signal).

It has been found at experimental level that with a reduction to 5-10 % of the carrier duty cycle it is possible to reduce the average power received within the service area to approximately 155-160 dBW: values in line with GPS/SBAS standards.

Signal and data broadcast by the EGNOS pseudolite system are checked through a dedicated module (essentially an independent receiver with data processing capability) fed by an omni-directional antenna. If the signal and data broadcast are out of tolerance or contain misleading information the system reacts with a recalibration of the transmitted signal (through the RF calibration module) or an interruption of the signal broadcast.

6. Implementation issues

Despite the signal broadcast by the EGNOS pseudolite system presents the same characteristics of EGNOS signals (the format is SBAS standard compliant), some minor modifications are required at receiver level to process the pseudo-range measurement taken from the EGNOS pseudolites. An ordinary GPS/SBAS receiver would consider the measurement taken from the pseudolite as "out of range" because too short compared to user-satellite ordinary distances. In addition, the receiver would correct for the ionospheric propagation delay any pseudolite range measurements. It would not be a problem the application of "clock" and "ephemeris" corrections because all transmitting units have a fixed location on the earth (coordinates of geostationary satellites are expressed in ECEF coordinates) and their clock is quite stable and highly synchronised with the system time.

Software modifications like: regulation of the range of acceptable pseudo-range measurements and, avoiding the application of corrections for the ionospheric propagation delay to the measurement taken from the pseudolites, represent for the majority of the receiver manufacturers a minor effort and a strategic upgrade for existing GPS/SBAS receivers to meet the needs of future EGNOS pseudolite users.

These mentioned modifications, together with the definition of new service identifiers (in the MT 17) that clearly indicate that the SBAS message being used is coming from an EGNOS pseudolite system, should be considered in the future versions of SBAS standards.

Since the EGNOS pseudolite system is de facto a navigation system operating on the L1 frequency, the installation, calibration, maintenance and operation should follow the applicable international and national regulations to avoid any misuse.

Installation of EGNOS pseudolite systems should take place in a coordinate manner in order to provide adequate geographical separation between systems using the same PRN codes and the same pulsing scheme.

In addition, the use of EGNOS pseudolite systems in safety critical applications (e.g.: aeronautical and maritime operations) might require specific certifications for the equipments (ground system and receiver) used and on the type of operation performed.

7. Expected navigation performance

In order to make a preliminary assessment on the impact of the EGNOS pseudolite system if implemented in scenarios where the access to EGNOS augmentation through the geostationary satellites is quite limited, two different types of simulations have been performed.
The first type of simulations had the objective of assessing the added value of an additional ranging source in terms of positioning availability for a number of simulated urban scenarios (streets surrounded by buildings presenting masking angles up to 60°).

The second type of simulations had the objective of assessing the number of visible ranging sources and the resulting positioning accuracy for a user navigating in the streets of a real city.

The simulations of the first type were performed using the service volume simulator ESPADA (developed by ESA) in combination with a specific tool dedicated to the modelling of obstacles/buildings placed in the simulation scenario. It was then computed the positioning availability of the GPS system "stand alone" (availability of 4 or more satellites in view) with the one provided by the GPS system (availability of 3 or more satellites in view) augmented through an EGNOS pseudolite system. The ranging measurements provided by the EGNOS pseudolite system is supposed to be always available.

In order to replicate the operational conditions experienced by the GPS/SBAS users operating in urban environments, a group of three different obstacle/building configurations (Figure 9 – Urban artificial scenarios) limiting the satellites visibility (masking angles up to 60°) were placed in the simulation scenario:

1. buildings surrounding a street oriented in the North-South direction;
2. buildings surrounding a street oriented in the North East-South West direction;
3. four buildings placed at the corners of a crossroad oriented along the local meridian and the local parallel.

The simulations were performed with the same scenarios in two different locations: Toulouse (France) and Lappenranta (Finland). The position of the EGNOS pseudolite is not specified, it is assumed that the augmentation and ranging signals are always provided through the EGNOS pseudolite and not through the geostationary satellites. The number of GPS satellites considered is 24. No satellite failure model has been applied.

It was expected that, in presence of obstacle blocking the satellites visibility, the availability of 3 GPS satellites plus one or more pseudolites is greater than the availability of 4 satellites.

The tables reported hereafter confirm the expectations for both locations and indicate the figures for the improvement obtainable in terms of positioning availability when the GPS system is augmented through the EGNOS pseudolite system.

Scenario number and description		Availability of position without EGNOS pseudolite	Availability of position with EGNOS pseudolite
1	(N-S street)	16.3%	52.9%
2	(NE-SW street)	25.7%	67.1%
3	(crossroads)	56.4%	81.4%

Results obtained in Toulouse (France)

Scenario number and description		Availability of position without EGNOS pseudolite	Availability of position with EGNOS pseudolite
1	12 (N-S street)	17.4%	57.1%
2	14 (NE-SW street)	10.6%	51.0%
3	15 (crossroads)	76.5%	97.7%

Results obtained in Lappenranta (Finland)

The simulations of the second type were performed using the service simulator Polaris (developed by GMV). The simulation scenario (Figure 10 – EGNOS Pseudolite simulation scenario) considered was a rectangular area of 2.0 by 1.7 km taken within the city centre of Madrid (Spain) where the buildings have an average height comprised between 25 and 30 meters.

Then 6 pseudolites, having the capability to broadcast the EGNOS augmentation and ranging signal within a radius of 1 km, were placed in the simulation scenario to cover the maximum number of streets possible. The height of each pseudolite were set to the value of 29 meters to overcome some limitations found in the 3D model representing the obstacles/buildings when used with the pseudolites.

The residual error of the EGNOS pseudolite used in the simulations, according to data provided by industry, was set to 2 centimetres.

Then for the following system configurations:

- GPS/EGNOS
- GPS/EGNOS plus 6 EGNOS Pseudolites

the number of visible ranging sources and the accuracy in the horizontal plane was computed and compared.

Simulation results indicate a clear improvement of the number of ranging sources available in the area analysed: from 3-4 in the system configuration GPS/EGNOS (Figure 11 – Nr. of visible SV for GPS/EGNOS) to 6-7 in the system configuration GPS/EGNOS plus 6 EGNOS Pseudolites (Figure 12 – Nr. of visible SV for GPS/EGNOS plus 6 EGNOS PL).

For what concern the accuracy in the horizontal plane the results are quite surprising: while the GPS/EGNOS horizontal accuracy and positioning availability is generally limited by the signal blocking operated by the obstacles/buildings (Figure 13 – Horizontal accuracy for GPS/EGNOS), a very good positioning availability and an accuracy value below 1 meter can be obtained almost everywhere when the GPS/EGNOS system is augmented by the signals broadcast by the EGNOS Pseudolite system (Figure 14 – Horizontal accuracy for GPS/EGNOS plus 6 EGNOS pseudolites).

8. Summary

The combination of accurate pseudolite ranging measurements with the SBAS messages is expected to be very effective for those application in which the EGNOS geostationary satellites are partially or completely not accessible by the users (e.g. urban areas) and, where additional ranging sources are required to improve the measurement geometry and the ranging source availability in specific locations, or to perform specific navigation operations.

Access to EGNOS augmentation and ranging signals may therefore be obtained with the implementation of the EGNOS pseudolite system.

The EGNOS pseudolite system behaves exactly as a typical SBAS geostationary satellite with its specific PRN code. The user equipped with a GPS/SBAS receiver (with minor modifications as explained through this article) may then access the EGNOS augmentation and ranging signals from one or more transmitting units of the EGNOS pseudolite system as if it were accessed from the EGNOS system geostationary satellites.

Simulations have shown quite promising results in terms of service availability and accuracy (below 1 meter in the horizontal plane) obtainable with the implementation of an EGNOS pseudolites system in a typical European downtown area (Madrid centre).

The concept of EGNOS pseudolite has recently been proposed by the European Space Agency for a professional development activity which shall be concluded during 2006. This development activity will deliver a full professional demonstrator, where an EGNOS pseudolite will connect to the EGNOS Data Access Server (EDAS) (which is developed in parallel), and will provide in real time and in the local area both the EGNOS augmentation messages (corrections and integrity data) and additional EGNOS-like ranging signals.

An extensive testing campaign on the EGNOS pseudolite system delivered by industry should confirm the expectations on the system navigation performance and promote the development of applications based on the EGNOS pseudolite system.

9. Acronyms

DAB – Digital Audio Broadcast
ECEF – Earth Centred Earth Fixed
EDAS – EGNOS Data Access System
EGNOS – European Geostationary Navigation Overlay Service
GPRS – General Packet Radio Service
GPS – Global Positioning System
GSM – Global System for Mobile Communications
PRN – Pseudo Random Noise
RDS – Radio Data System
RF – Radio Frequency
SBAS – Satellite Based Augmentation System

10. Reference documentation

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[RD 03] – M. Strom, "GNSS pseudolites", ECC 40th WG SE Meeting, Helsinki-Finland, 26/01/2005

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[RD 14] – Radio Technical Committee for Aviation (RTCA) DO-245, Minimum Aviation System Performance Standards for Local Area Augmentation System (LAAS) - Issued 9-28-98

11. Figures

Figure 1 – Signal Blocking
Figure 2 – Increased ranging availability
Figure 3 – Aviation applications
Figure 4 – Navigation in urban environments
Figure 5 – High level architecture
Figure 6 – Functional architecture
Figure 7 – Signal in space
Figure 8 – Pulsing signal
Figure 9 – Urban artificial scenarios
Figure 10 – EGNOS Pseudolite simulation scenario
Figure 11 – Nr. of visible SV for GPS/EGNOS
Figure 12 – Nr. of visible SV for GPS/EGNOS plus 6 EGNOS PL
Figure 13 – Horizontal accuracy for GPS/EGNOS
Figure 14 – Horizontal accuracy for GPS/EGNOS plus 6 EGNOS pseudolites

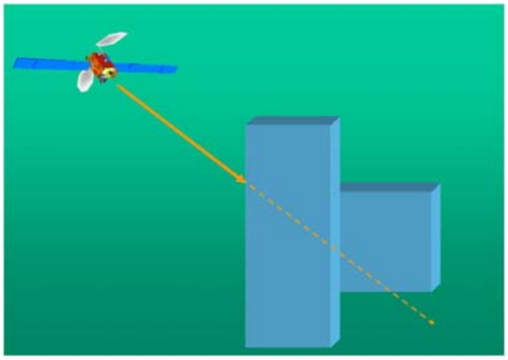

Figure 1 – Signal Blocking

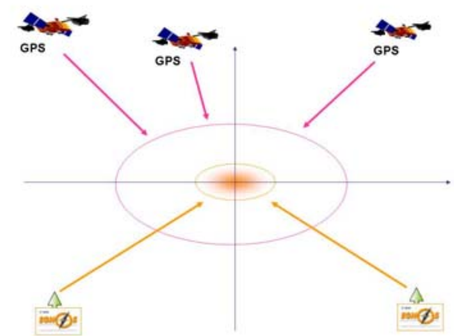

Figure 2 – Increased ranging availability

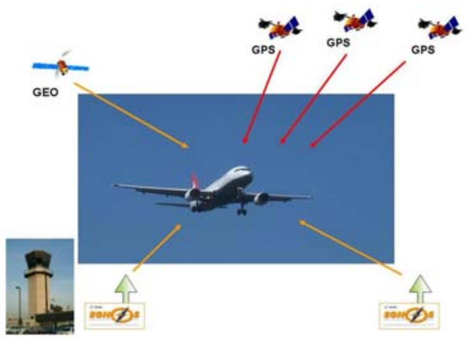

Figure 3 – Aviation applications

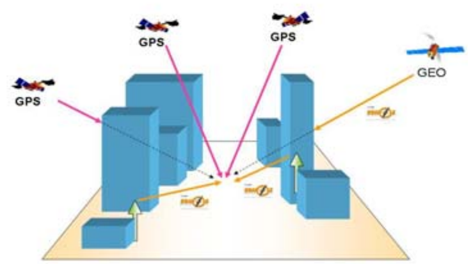

Figure 4 – Navigation in urban environments

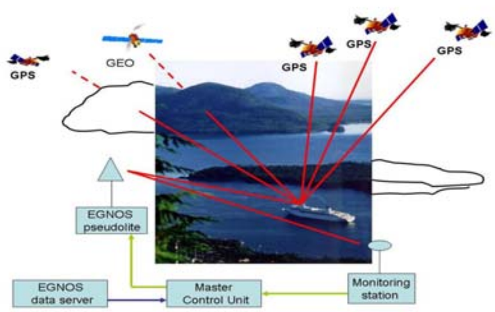

Figure 5 – High level architecture

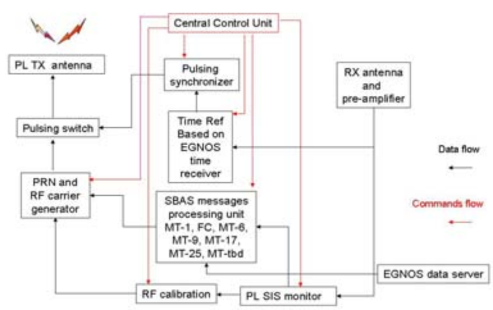

Figure 6 – Functional architecture

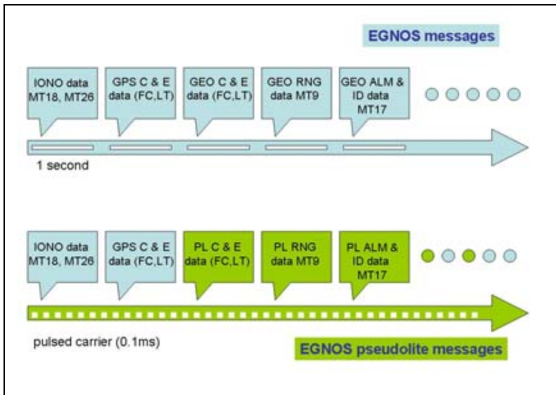

Figure 7 – Signal in space

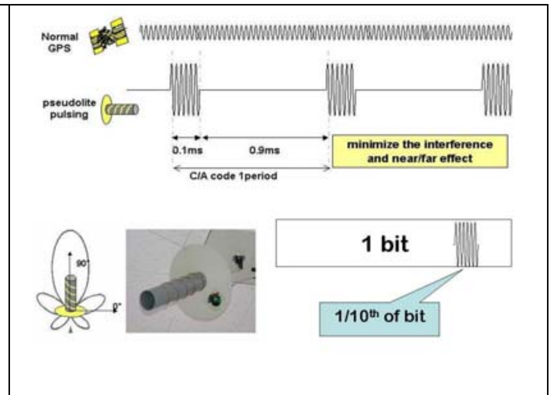

Figure 8 – Pulsing signal

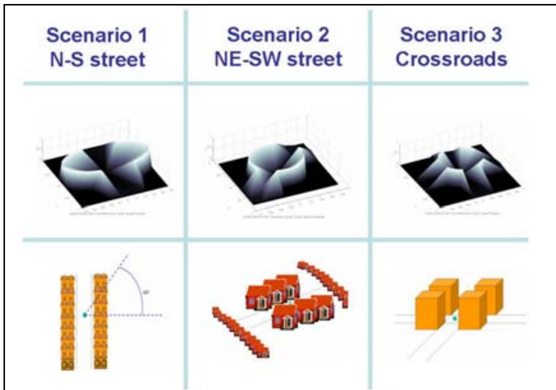

Figure 9 – Urban artificial scenarios

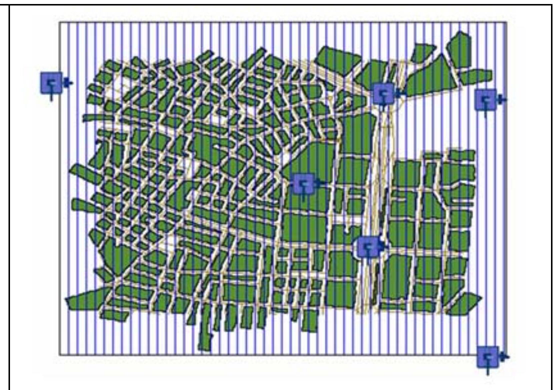

Figure 10 – EGNOS Pseudolite simulation scenario

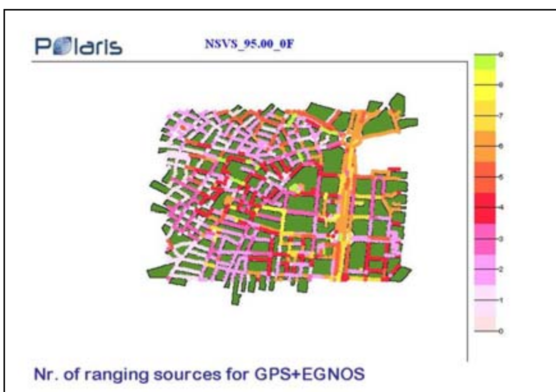

Figure 11 – Nr. of visible SV for GPS/EGNOS

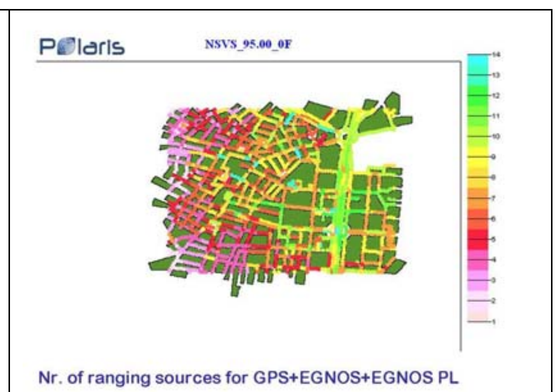

Figure 12 – Nr. of visible SV for GPS/EGNOS plus 6 EGNOS PL

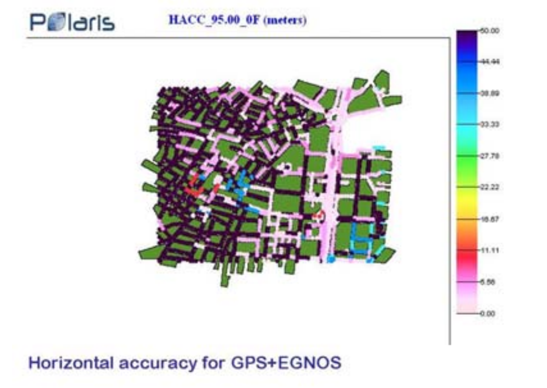	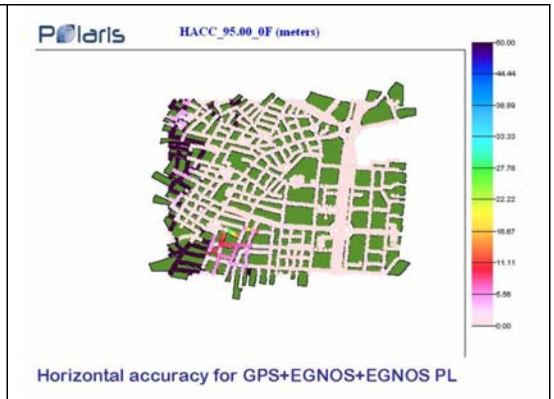
Figure 13 – Horizontal accuracy for GPS/EGNOS	Figure 14 – Horizontal accuracy for GPS/EGNOS plus 6 EGNOS pseudolites