Architecture, mission and signal processing aspects of the EGNOS System: the first European implementation of GNSS

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INTRODUCTION

The European Tripartite Group (ETG), (ESA – EC – EUROCONTROL) is implementing, via the EGNOS project, the European contribution to the Global Navigation Satellite System (GNSS-1) which will provide and guarantee navigation signals for aeronautical, maritime and land mobile Trans-European network applications. On behalf of this tripartite group, the European Space Agency is responsible for the system design, development and technical validation of an Advanced Operational Capability (AOC) of the EGNOS system. The Technical validation is to be completed in early 2004, to enable operational use of the EGNOS Signal in 2004.

EGNOS will significantly improve the GPS services, in term of accuracy (from 20 meters to 3-5 meters), service guarantee (via Integrity signal) and availability (via additional ranging signals). It will operate on the GPS L1 frequency, and will thus be receivable with standard GPS front-ends. EGNOS is one of three Satellite-Based Augmentation Services (SBAS), the two others being the United States WAAS and the Japanese MSAS. The EGNOS coverage will first be the ECAC (European Civil Aviation Conference) area, and could be later extended to include other regions such as Africa, Eastern countries, and Russia. EGNOS will meet, in combination with GPS and GLONASS, many of the current positioning, velocity and timing requirements of the land, maritime and aeronautical modes of transport in the European Region. EGNOS is the first step of the European Satellite Navigation strategy and a major stepping stone towards GALILEO, future European satellite navigation constellation.

This paper describes the EGNOS System requirements, the overall System design, some of the key signal processing techniques, as well as the current status of the on-going development activities, including the EGNOS system test bed.

DESCRIPTION OF THE EGNOS MISSION REQUIREMENTS

The current capabilities of GPS and GLONASS, although very adequate for some user communities, present some shortfalls. First, the lack of civil international control presents a serious problem from the institutional point of view. Second, GPS or GLONASS cannot meet all civil aviation requirements for precision and non-precision approach phases of flight. Marine and land users will also require some sort of augmentation for improving GPS / GLONASS performances.
The first generation Global Navigation Satellite System, GNSS-1, as defined by the experts of the ICAO/GNSS Panel, plan for some system augmentations in addition to the basic GPS and GLONASS constellations to achieve the level of performance suitable for civil aviation applications.

The purpose of EGNOS program is to implement such a system, that fulfils a range of user service requirements by means of an augmentation to GPS and GLONASS, based on the broadcasting through GEO satellites of GPS-like navigation signals containing integrity and differential correction information. EGNOS will address the needs of all modes of transport, including Civil Aviation, Maritime and Land users.

Aeronautical Applications

The performance objectives for aeronautical applications are usually characterised by four main parameters: accuracy, integrity, availability and continuity of service. The values for these parameters are highly dependent on the phases of flight. For typical phases of flight, typical requirements are those included in Table 1. Neither GPS nor GLONASS can meet the above integrity, availability and continuity of service objectives without a system augmentation, although their performance in terms of accuracy alone could meet the requirements of en-route, terminal area navigation and non-precision approaches.

These requirements have been recently finalised by the International Civil Aviation Organisation (ICAO) under the form of SARPS (Standards and Recommended Practices), as a part of Amendment 76 to Annex 10 of Chicago Convention. The SARPs will be published later in 2001 with the applicability date of the 1st of November 2001.

Table 1: Aviation GNSS Signal-in-space performance requirements

<table>
<tr><th>Typical operation(s)</th><th>Accuracy lateral /vertical 95%</th><th>Alert limit lateral /vertical</th><th>Integrity</th><th>Time to alert</th><th>Continuity</th><th>Availability</th><th>Associated RNP type(s)</th></tr>
<tr><td>En-route</td><td>2.0 NM
/ N/A</td><td>4 NM
/ N/A</td><td rowspan="4">10^{-7}/h</td><td>5 min.</td><td rowspan="4">$1-10^{-4}$/h to $1-10^{-8}$/h</td><td>0.99 to 0.99999</td><td>20 to 10</td></tr>
<tr><td>En-route</td><td>0.4 NM
/ N/A</td><td>2 NM
/ N/A</td><td rowspan="2">15 s</td><td rowspan="2">0.999 to 0.99999</td><td>5 to 2</td></tr>
<tr><td>En-route, Terminal</td><td>0.4 NM
/ N/A</td><td>1 NM
/ N/A</td><td>1</td></tr>
<tr><td>Initial approach, NPA, Departure</td><td>220 m
/ N/A</td><td>0.3 NM
/ N/A</td><td rowspan="2">10 s</td><td rowspan="4">0.99 to 0.99999</td><td>0.5 to 0.3</td></tr>
<tr><td>APV-I</td><td>220 m
/ 20 m</td><td>0.3 NM
/ 50 m</td><td rowspan="3">$2x10^{-7}$ per approach</td><td rowspan="3">$1-8x10^{-6}$ in any 15 s</td><td>0.3/125</td></tr>
<tr><td>APV-II</td><td>16 m
/ 8 m</td><td>40 m
/ 20 m</td><td rowspan="2">6 s</td><td>0.03/50</td></tr>
<tr><td>Category I</td><td>16.0 m
/ 4-6 m</td><td>40 m
/ 10-15 m</td><td>0.02/40</td></tr>
</table>

Maritime Applications

The performance objectives for maritime applications are generally broken down into ocean, coastal, in-land waters and harbour navigation. Minimum performance requirements for these four generic cases have been quantified by the European Maritime Radionavigation Forum (See Table 2):

Table 2: Maritime GNSS typical performances

	GNSS System level parameters			
	Accuracy Horizontal	***Integrity Alert limit***	***Integrity Time to alarm***	***Integrity risk*** (per 3 hours)
Ocean	*10 m*	*25 m*	*10 sec*	10^{-5}
Coastal	*10 m*	*25 m*	*10 sec*	10^{-5}
Port approach and restricted waters	*10 m*	*25 m*	*10 sec*	10^{-5}
Port	*1 m*	*2.5 m*	*10 sec*	10^{-5}
Inland waterways	*10 m*	*25 m*	*10 sec*	10^{-5}

Land Applications

There are a large number of applications under development world-wide related to the use of satellite navigation and land mobile applications. These include: vehicle positioning, fleet management, position tracking, emergency services, theft protection, passenger information, control road, etc.
Depending on the application, the accuracy required for the various systems ranges from hundreds of meters to a few meters, requiring the use of differential corrections. Integrity is also required for some of these applications.

Other applications

Another important benefit of satellite navigation is the provision of a global time reference. EGNOS will provide a stable time reference within few ns of the Universal UTC time. Related applications include, time synchronisation of cellular phone networks, VSAT synchronisation, electric power synchronisation networks, Internet nodes synchronisation, etc.
In addition, the combination of satellite navigation and mobile services will provide a wide-range of new services.

EGNOS SERVICE AND PERFORMANCE REQUIREMENTS

Of the three user communities, civil aviation requirements are the most stringent (in terms of integrity and continuity) and hence the EGNOS performance objectives are mostly driven by the needs of civil aviation, covering then, the needs of land and maritime user communities.
The coverage area serviced by EGNOS will be the European Civil Aviation Conference (ECAC) service area comprising the Flight Instrument Regions (FIR) under the responsibility of ECAC member states (most of European countries, Turkey, the north sea and the eastern part of the Atlantic ocean). ECAC is defined in Fig.1.
The EGNOS AOC perfomance objectives are to provide a primary means service of navigation for all phases of flight from en-route through precision approach within this ECAC area. In addition, EGNOS has the capability to extend services beyond the ECAC region, within the Geostationary broadcast area, and actions are being pursued with international partners to exploit this capability, towards a full seamless service over wider areas.

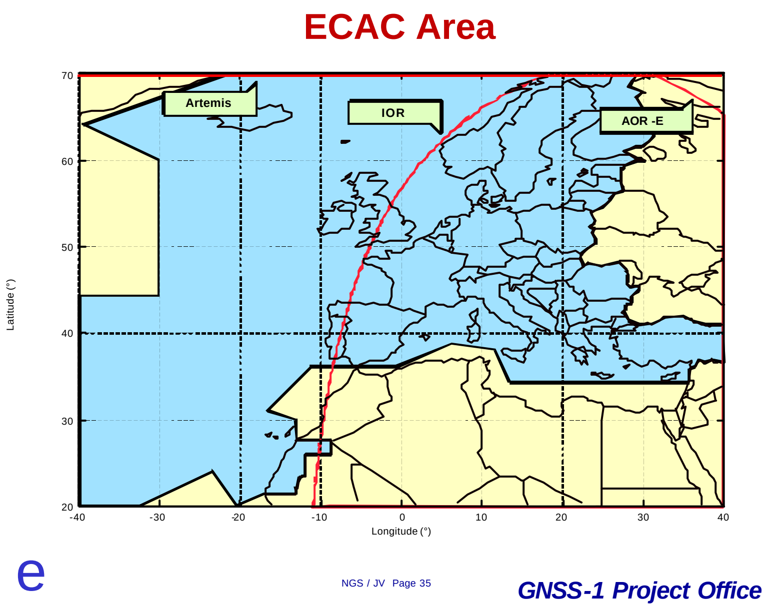


Figure 1 European Civil Aviation Conference (ECAC) approximate area coverage

The EGNOS system will provide the following services:

GEO Ranging (R-GEO): Transmission of GPS-like signals from 3 GEO satellites (INMARSAT-3 AOR-E, INMARSAT-3 IOR and the ESA ARTEMIS satellite for the AOC phase. This will augment the number of navigation satellites available to the users.

GNSS Integrity Channel (GIC): Broadcasting of integrity information. This will increase the availability of GPS / GLONASS / EGNOS safe navigation service up to the level required for civil aviation non-precision.

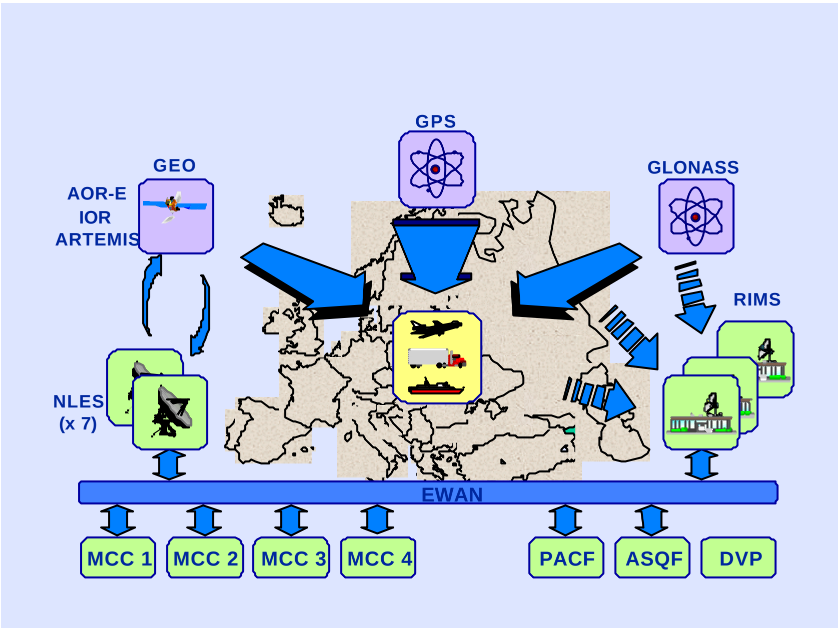
Wide Area Differential (WAD): Broadcasting of differential corrections. This will increase the GPS / GLONASS / EGNOS navigation service performance, mainly its accuracy, up to the level required for precision approaches.

EGNOS ARCHITECTURE AND SYSTEM DESCRIPTION

The EGNOS Reference architecture is illustrated in Fig. 2. It is composed of four segments: ground segment, space segment, user segment and support facilities.

The *EGNOS Ground Segment* consists of GNSS (GPS, GLONASS, GEO) Ranging and Integrity monitoring Stations (called RIMS) which are connected to a set of redundant control and processing facilities called Mission Control Centre (MCC). The system will deploy 34 RIMS located in mainly in Europe and 4 MCCs located in Torrejon (E), Gatwick (UK), Langen (D) and Ciampino (I). The MCC determines the integrity, differential corrections for each monitored satellite, ionospheric delays and generates GEO satellite ephemeris. This information is sent in a message to the Navigation Land Earth Station (NLES), to be uplinked along with the GEO Ranging Signal to GEO satellites. These GEO satellites broadcast this data on the GPS Link 1 (L1) frequency with a modulation and coding scheme similar to the GPS one. All ground Segment components are interconnected by the EGNOS Wide Area Communications Network (EWAN). The system will deploy 2 NLESs (one primary and one back-up) per GEO navigation transponder and an NLES for Test and Validation purposes, located in Torrejon (E), Fucino (I), Aussaguel (F), Raisting (D), Goonhilly (UK), and Sintra (P) respectively. Planned sites for the different EGNOS G/S elements are illustrated in Fig. 3.

Figure 2: EGNOS AOC Architecture



The *EGNOS Space Segment* is composed of Geostationary transponders with global Earth coverage. The EGNOS AOC system is based on the use of the INMARSAT-3 AOR-E and IOR, and the ESA ARTEMIS navigation transponders, with the Broadcast Areas illustrated in Fig. 4.

The *EGNOS User Segment* consists of an EGNOS Standard receiver, to verify the Signal-In-Space (SIS) performance, and a set of prototype User equipment for civil aviation, land and maritime applications. Those prototype equipment will be used to validate and eventually certify EGNOS for the different applications being considered.

Finally, the EGNOS support facilities include the Development Verification Platform (DVP), the Application Specific Qualification Facility (ASQF) located in Torrejon (Spain) and the Performance Assessment and System Checkout Facility (PACF) located in Toulouse (France). Those are facilities needed to support System Operations and future Qualifications.

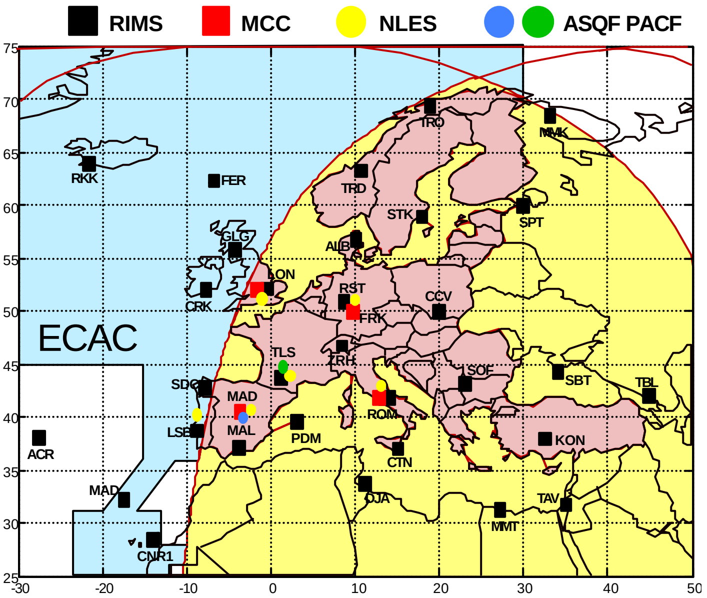


Figure 3: Planned sites for the different EGNOS Ground Segment elements

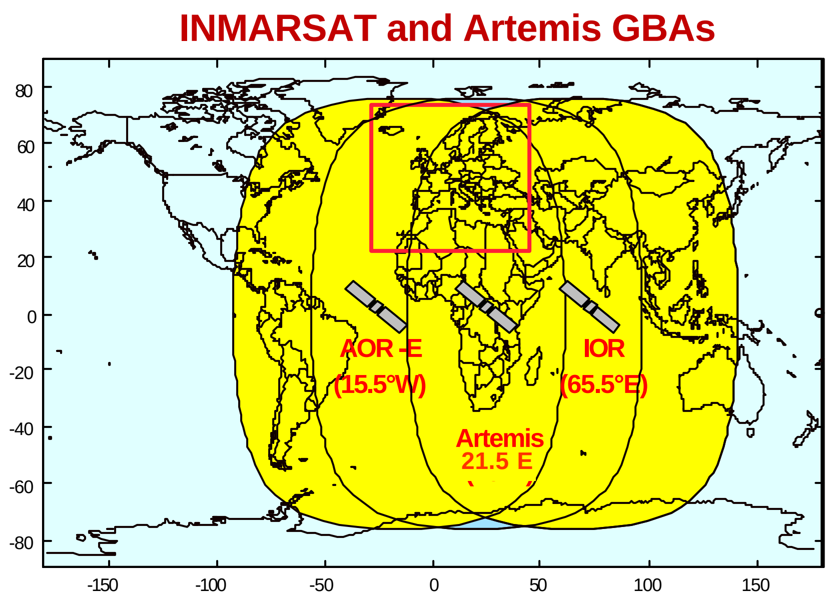


Figure 4: Inmarsat and Artemis EGNOS Geostationary Satellite Broadcast Areas

SIGNAL PROCESSING TECHNIQUES USED IN EGNOS

Digital Signal Processing techniques are extensively used in EGNOS. We would like here to list some of the *key signal processing functions* that are implementing in each one of the EGNOS sub-systems.

1. The *RIMS A and B* include the following signal processing functions:

- Perform pseudorange code / phase measurements towards monitored satellites (GPS L1 and L2 + GEO/GLONASS L1);
- Demodulate/ decode (Viterbi decoding) SIS messages;
- Built-in in software to mitigate local multipath and interferences;
- Messages formatting and transmission towards EGNOS CPF;

- A specific RIMS also includes a processing function to measure the *time offset* between a reference UTC clock (located at Paris) and the EGNOS Network time (ENT).

The RIMS S/S also performs support functions in order to allow remote monitoring and control from the EGNOS Central Control Facility (CCF). Such functions are for instance built-in-tests actionable either automatically at RIMS or upon remote request from CCF, elaboration of failure diagnostics, mechanisms allowing to accept software downloading from CCF via the EGNOS network. It is important to indicate that, for safety considerations, RIMS A and RIMS B processing are diversified, i.e. despite they are built against the same specifications, they are designed by independent teams with independent algorithms considerations.

2. The *RIMS C* includes sophisticated signal processing techniques to detect GPS signal anomalies, known as *"evil waveforms"*. Diagnostics are performed on the shape of the measured satellite signal correlation function. RIMS channel C settle flags towards CPF upon detection of a satellite signal failure.

3. The EGNOS *Central Processing Facility* is the *"brain"* of EGNOS and the subsystem where signal processing techniques are more intensively used. It includes a *processing-set* and *two check-set* units.

   The Processing Set is a data processing facility where data coming from the different receivers located at the RIMS are processed to generate the EGNOS navigation message. Processing is mainly addressed to the estimation of the following parameters:

- Pre-process and validate RIMS A minimising the systematic errors present in the data by removing ionospheric and tropospheric delays. This function removes carrier phase cycle slips and smoothes the input data to reduce the random noise and filter out residual multipath components;
- Estimate the *clock corrections* to be applied to GPS and GLONASS satellites (which includes the estimation of RIMS clock biases);
- Estimate the *Orbit errors* linked to GPS, GLONASS and GEO satellites;
- Provide *ionospheric corrections* for the European Service area;
- Determine a *confidence bound* for both *orbit/clock* (UDRE) and *ionospheric* remaining errors (GIVE) after corrections;
- Specific algorithms for *message selection* respecting message time-outs and alarms. This function determines the actual message to be broadcast in the current cycle and formats the message according to the standards set for the user receiver (MOPS RTCA DO-229);
- Generate a meaningful processing set performance figure known as Quality of service.

   The Processing set needs to process every second data from up to 60 RIMS, observing about 20 satellites each (including, GPS, GLONASS and GEO satellites). All this data must be processed in real-time.

   The *Check set of the CPF* implements specific signal Processing algorithms to:

- Pre-process and validate RIMS B data eliminating noises, hardware biases and detecting possible satellite anomalies;
- Statistical tests on EGNOS products integrity before the EGNOS message is broadcast (CHECK Before);
- Perform statistical tests, after transmission, to verify the correct transmitted bounding levels for the satellite corrections (UDRE) and ionospheric corrections (GIVE) (CHECK after);
- Process RIMS C information on GPS evil waveform presence;
- Generate a meaningful check set performance figure known as *Quality of service*.

4. The *Central Control Facility* includes specific Processing software to monitor and control the EGNOS ground segment; monitor the EGNOS mission performances and interface with Air Traffic Control.

5. The *NLES* is the responsible of generating a GPS-like signal and transmit it to a GEO transponder. NLES processing includes the control of a specific Long-loop to synchronise the up-link signal to the EGNOS time (ENT) at the output of the GEO L1-band antenna. In addition, a specific processing function is built to control of the code/carrier coherency of the transmitted signal and to check in the down-link the format/content of the messages sent (integrity box).

6. The *EGNOS receiver* includes the following processing functions:

- Geo satellite signal processing (L1C/A, code + phase), Viterbi decoding and data demodulation (Geo navigation data + GPS/Glonass correction data)
- processing of GLONASS signals (option used for Cat 1 landing operations which enhances accuracy compared to GPS/Geo processing only)
- processing of algorithm for ionospheric corrections computation using the data contained in the Geo message plus a spatial interpolation algorithm at the user location
- application of differential clock, ephemeris and ionospheric corrections to the pseudo-ranges measurements from GPS, Geo and optionally GLONASS satellites
- processing of a weighted least square algorithm to compute the user position
- processing of the GIC integrity algorithms (or "XPL") based on the Geo satellite data

Probably, the single most important consideration on the EGNOS system is that it needs to be designed for a *safety-of-life* mission, with extremely demanding integrity and a real-time safety requirements. The very demanding EGNOS performances calls for optimised algorithms, bringing them in the boundary of the state-of-the-art technology. It is not just the processing theory behind algorithms what is at stake here: simplicity (e.g. allowing reduced CPU consumption at CPF), reliability, failure tolerance are major drivers for the algorithm design. The signal processing algorithms listed above need to be considered within this perspective, which makes the whole EGNOS project a major challenge.

THE EGNOS SYSTEM TEST BED (ESTB)

To support the development of the EGNOS system, an EGNOS System Test Bed (ESTB) has been developed and is now operational. The ESTB is a real-time full-scale prototype of EGNOS (European Geostationary Navigation Overlay Service). It provides the first continuous GPS augmentation service within Europe. The ESTB has been developed under European Space Agency (ESA) contract by an industrial consortium, involving key European Satellite Navigation industries such as Alcatel Space Industries, Astrium, GMV, Racal, Seatex and DLR. This development was based on a number of pre-existing assets: These include the SATREF™ system from NMA (Norwegian Mapping Authority) and the EURIDIS ranging system from CNES. Since early 2001, the ESTB is also fully inter-connected with the Italian Mediterranean Test Bed (MTB), operated by ENAV (–Italian Civil Aviation Authority--).

The ESTB, operational since February 2000, constitutes a great step forward for the European strategy to develop the future European Satellite Navigation Systems, EGNOS and GALILEO.

The ESTB architecture is presented in Fig. 5. The ESTB is made up of the following elements:

- a space segment comprising two transponders on board the Inmarsat-III Atlantic Ocean East and the Indian Ocean satellites,
- a network of RIMS, sized to a number of 8 in a first step, to be expandable in the near future, and which are permanently collecting GPS/GEO/GLONASS data;
- Central Processing Facility (CPF), generating the WAD (Wide Area Differential) user messages. The CPF is located in Hønefoss (Norway), and hosted in SATREF™ platform;
- one Navigation Land Earth Station (NLES) part of the EURIDIS Ranging system, located at Aussaguel (France), allowing the access to the INMARSAT III AOR-E satellite;
- three EURIDIS RIMS for the purpose of the GEO Ranging function, located on an intercontinental basis in order to provide a wide observation base for the GEO. They are also collecting GPS/GEO data;
- an Operation control and processing centre located at Toulouse (France), devoted to the generation of the GEO ranging data, and which also acts as a node for the transmission of the user message;
- a real-time communication network, allowing the transfer of the RIMS data to the CPF, and of the navigation messages from Honefoss to the NLES.

- ➢ a ground segment comprising a number of reference stations spread over Europe and beyond, a processing centre and the Inmarsat uplink stations. Communication lines interconnect all stations.

By using GPS and ESTB Signal-In-Space, users within Europe can nowadays determine their position with an error less than 3 meters (horizontal) and 5 meters (vertical), 95 percent of the time. A typical ESTB Vertical error distribution is represented in Fig. 6, where the histogram of the errors is shown together with the associated statistics values (mean, std. deviation and 95th percentile). The area within which the test signal can be exploited, is determined primarily by the location of the reference stations. At the present time the accuracy performances are as illustrated in Fig. 7.

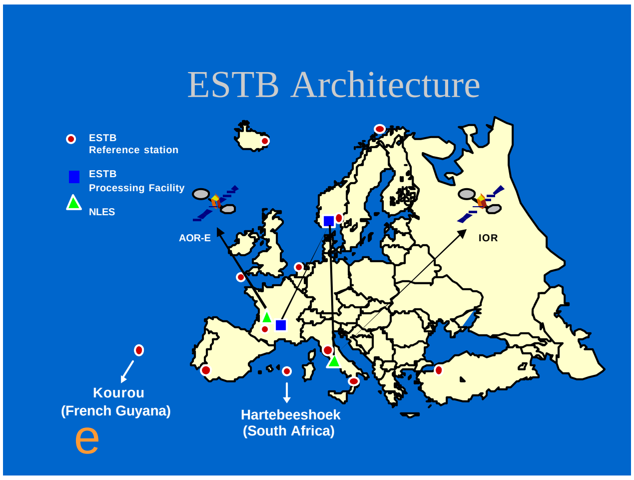


Figure 5: EGNOS System Test Bed (ESTB) architecture

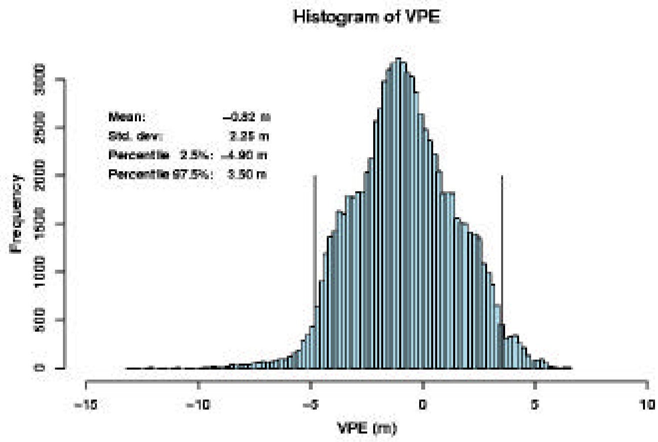


Figure 6: Typical ESTB Vertical error histogram

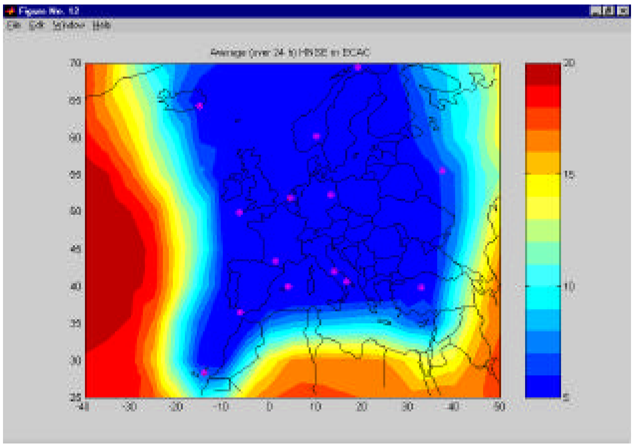


Figure 7: ESTB accuracy (2 -sigma value) performances (includi ng MTB)

The ESTB is also providing an integrity service, represented by the Vertical and Horizontal protection levels computed by the User with the ESTB information data, which are to bound with a probability of 2x10-7/150 sec the Alert limits associated to a particular operation. Fig. 8 depicts typical Vertical Protection Level achieved throughout Europe through the ESTB. Values required for aircraft precision approach landing are ensured at that time in most of Europe. Results provide additional confidence in the current EGNOS design specially considering the reduced number of reference stations available in the ESTB and the current high solar activity.

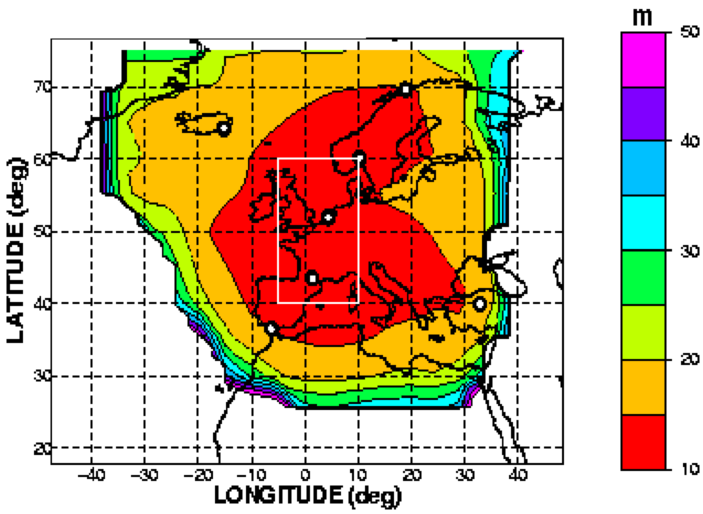


Figure 8: Typical Vertical Protection levels achieved by the ESTB

During the year 2000, the ESTB supported already a number of application demonstrations. They included landing planes at several airports, guiding ships into harbours but also navigating cars. The European Commission, national agencies and ESA are supporting the demonstration initiatives of European industry and operators in a number of ways.

During year 2001, thanks to additional supports from the European Commission, the ESTB will become 24 hours / 7 days a week operational, and will embrace capabilities for service expansion (outside of Europe) and interoperability analysis (with other augmentation systems such as WAAS). In addition, the ESTB will be used in connection with the Italian Mediterranean Test Bed (MTB), operated by ENAV (Italian CAA) and will incorporate additional reference stations provided in co-operation with AENA (Spanish CAA).

The ESTB Help Desk service can be reached through the Email address ESTB@esa.int. General information on ESTB scheduling, signal standards and the like can be found on http://www.esa.int /navigation.

INTEROPERABILITY OF SBAS SYSTEMS

Two other Satellite Based Augmentation Systems (SBAS) are under development, namely the Wide Area Augmentation System (WAAS) in USA, and the Multi-functional transport satellite (MTSAT) satellite-based augmentation system (MSAS), in Japan (see Fig. 9). Those SBAS are primarily defined as regional systems, and co-operation/co-ordination among the different systems will enable to provide a seamless world-wide navigation system. To this aim, the three systems have set up some common interoperability requirements and will provide adequate system compatibility. The Development teams of those SBAS systems are regularly meeting through so called "Interoperability Working Group (IWG)" meetings to develop and maintain common understanding of interoperability requirements and capabilities, and on the identification of the necessary interfaces among SBAS that each conceivable interoperability scenarios may imply. As a result of those works, the EGNOS system includes specific requirements so that interoperability may be achieved. In parallel, interoperability demonstrations have been performed, based on the available Test Beds.

In addition to interoperability, EGNOS has built-in expansion capability to enable extension of the services over regions within the Geostationary Broadcast Area of GEO satellites used, such as Africa, Eastern countries, and Russia . The combination of SBAS Interoperability and expansion concepts should allow to provide a true global world-wide navigation seamless service.

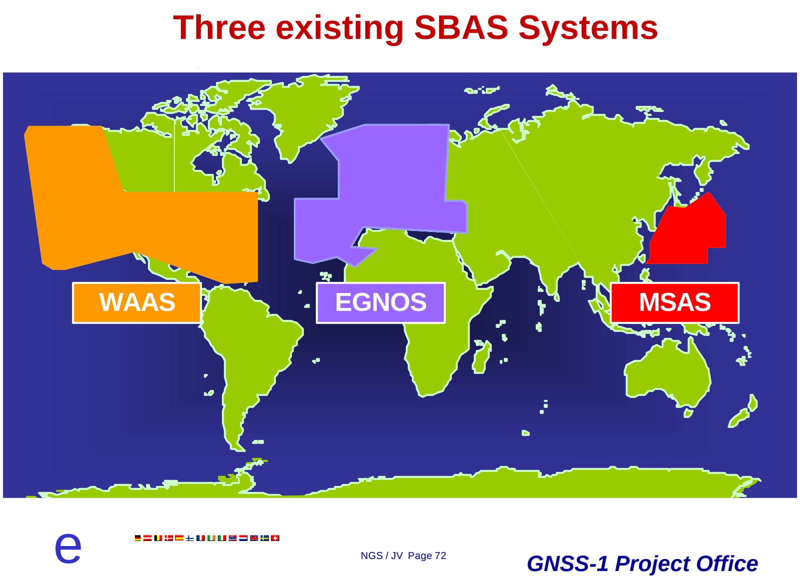


Figure 9: WAAS, EGNOS and MSAS nominal service volumes

EGNOS PROGRAMME STATUS OVERVIEW

The EGNOS programme was made of two different phases: Initial phase and AOC Implementation phase; The EGNOS Initial Phase was successfully concluded in November 1998 with the System Preliminary Design Review (PDR), and has enabled the effective start of the Implementation phase by the end of 1998. The industrial team in charge of EGNOS AOC development is led by Alcatel Space Industries (France) with the participation of companies from all participating States, as illustrated in Fig. 10. The prime contract was signed with Alcatel on 16 June 1999. In December 1999, an important change was implemented to reflect latest versions of international standards. This change has brought the main development contract to an amount of 214 M€. The EGNOS AOC Implementation Phase schedule is illustrated in Fig. 11. Current major project milestones are the subsystems Critical Design Reviews, in the first half of year 2001, and the System Critical Design Review (CDR), planned early 2002. The System Factory Qualification Review (FQR) is planned in early 2003, and the EGNOS AOC Operational Readiness Review (ORR), which concludes the Technical Validation Phase, in February 2004.

The EGNOS project includes significant contributions from the French Space Agency (CNES), the Norwegian Mapping Authority (NMA), and main European Air Traffic Management service providers like AENA (E), NAV-EP (P), DFS (D), ENAV (I), DGAC (F), NATS (UK) and Skyguide (CH). Those partners will in particular provide ESA with in-kind deliveries, including the infrastructure to host a number of the necessary EGNOS ground stations. Some other hosting sites are being provided via specific agreements with potential hosting entities. Site survey activities are to be performed during year 2001, to confirm adequacy of each site to host the EGNOS element, and to plan for necessary infrastructure upgrades.

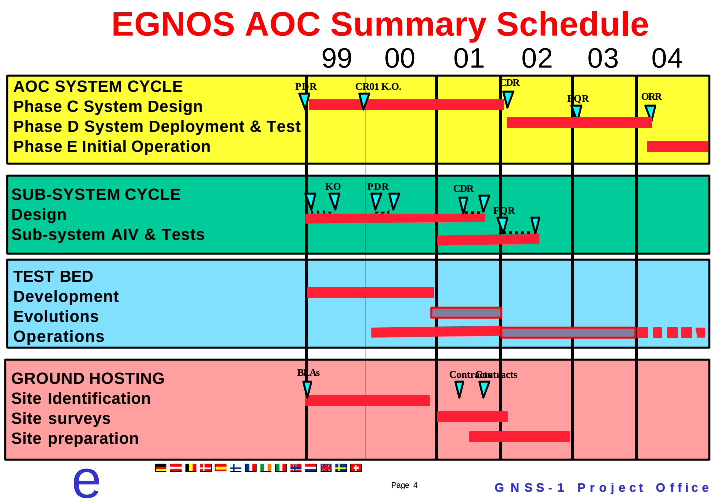


Figure 11: EGNOS AOC Planning

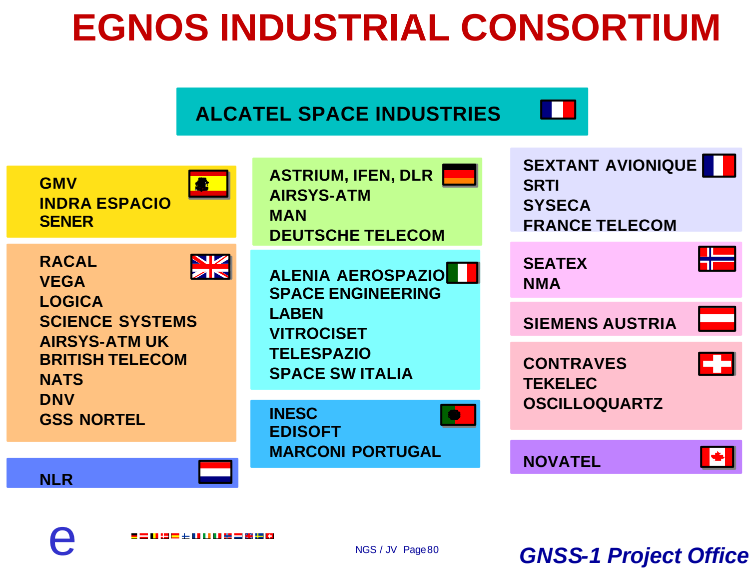


Figure 10: The industrial team in charge of EGNOS AOC

SUMMARY

EGNOS is the main European contribution to GNSS-1 to serve the needs of, maritime, land transport, time and aeronautical applications in the European and neighbouring regions. EGNOS will be interoperable with equivalent US (WAAS) and Japanese (MSAS) SBAS systems, aiming at contributing to a true world-wide global navigation system. EGNOS Test Bed signal-in-space is available since early 2000, and is used to support demonstrations and trials in Europe, Africa, South America and interoperability trials with Japan and US. EGNOS AOC Development and Technical validation will be completed by early 2004, and will be followed with initial operation and operational validation activities. EGNOS is the first step of the European Satellite Navigation strategy and a major stepping stone towards GALILEO, future Europe's own global satellite navigation system for which ESA has a major role and responsibility.

The EGNOS system needs to be designed for a *safety-of-life* mission, with extremely demanding integrity and a real-time safety requirements. The signal processing algorithms described in this paper need to be considered within this perspective, which makes the whole EGNOS project a major challenge.