EGNOS: The First Step in Europe's Contribution to the Global Navigation Satellite System

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The European Tripartite Group* - consisting of ESA, the European Commission and Eurocontrol - is implementing, via the EGNOS project, the European contribution to the Global Navigation Satellite System (GNSS-1), which will provide and guarantee the availability of navigation signals for aeronautical, maritime and land mobile trans-European network applications. On behalf of this Tripartite Group, ESA is responsible for the system design, development and qualification of an Advanced Operational Capability (AOC) of the EGNOS system.

EGNOS will significantly improve the accuracy of GPS, typically from 20 m to better than 5 m, will offer a service guarantee by means of the 'Integrity Signal', and will also provide 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 inter-regional Satellite-Based Augmentation Services (SBAS) that complement GPS and GLONASS. The other two are the United States WAAS and the Japanese MSAS. The EGNOS coverage area will be the European Civil Aviation Conference area, but could be readily extended to include other regions within the broadcast area of the geostationary satellites, 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. It is the first element of the European satellite-navigation strategy and a major stepping stone towards Galileo, Europe's own global satellite navigation system for the future.

This article summarises the EGNOS system requirements, the overall system design, as well as the current status of the on-going development activities, including the EGNOS System Test Bed (ESTB).

* A formal agreement based on Article 228 of the EC Treaty was concluded on 18 June 1996 between the European Community, Eurocontrol and ESA, for the development of the European Contribution to the first-generation Global Navigation Satellite System (GNSS-1).

Introduction

The current capabilities of GPS and GLONASS, although very adequate for some user communities, present some shortfalls. The lack of civil international control represents a serious problem from the institutional point of view. In addition, there is a need for enhanced performance. In particular, the civil-aviation requirements for the precision and non-precision approach phases of flight cannot be met by GPS or GLONASS only. Marine and land users may also require some sort of augmentation for improving GPS/GLONASS performance.

The first-generation Global Navigation Satellite System, GNSS-1, as defined by the experts of the ICAO/GNSS Panel, includes the basic GPS and GLONASS constellations and any system augmentation needed to achieve the level of performance suitable for civil-aviation applications. EGNOS, which is a regional satellite-based augmentation equivalent to the American Wide-Area Augmentation System (WAAS) or the Japanese Multi-transport Satellite-based Augmentation System (MSAS), is the first European implementation for GNSS. EGNOS will become operational during early 2004. From 2006/2008 onwards, Europe should also have available the independent Galileo system, which will be compatible and interoperable with GPS/GLONASS/EGNOS.

The EGNOS mission

General objectives

The purpose of EGNOS is to implement a system that fulfils a range of user service requirements by means of an overlay augmentation to GPS and GLONASS, based on the broadcasting through geostationary satellites of GPS-like navigation signals containing integrity and differential-correction information applicable to the navigation signals of the GPS satellites, the GLONASS satellites, EGNOS's own GEO Overlay satellites and the signals of other GEO Overlay systems (provided they can be received by a GNSS-1 user located within the defined EGNOS service area). EGNOS will address the needs of all modes of transport, including civil aviation, maritime and land users.

Table 1. Aviation GNSS signal-in-space performance requirements

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

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, typical requirements for which are included in Table 1. Neither GPS nor GLONASS can meet the required 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 and terminal-area navigation and non-precision approaches. The actual requirements for Europe are currently being finalised by the International Civil Aviation Organisation (ICAO) in the form of SARPs (Standards and Recommended Practices).

Maritime applications
The performance objectives for maritime applications are generally broken down into ocean, coastal, inland-water and harbour navigation. Minimum performance requirements for these four generic cases have been quantified by the European Maritime Radio-Navigation Forum (see Table 2).

Table 2. Maritime GNSS typical performances

	System-level Parameters			
	Predictable Accuracy	Integrity		
	Horizontal (m)	Alert limit (m)	Time to alarm (s)	Integrity risk (/h)
Ocean	10	25	10	10^{-7}
Coastal	10	25	10	10^{-7}
Port approach and restricted waters	10	25	10	10^{-7}
Port	1	2.5	10	10^{-7}
Inland waterways	10	25	10	10^{-7}

Land applications
There are a large number of applications under development worldwide 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, road control, etc. Depending on the application, the accuracy needed for the various systems ranges from hundreds of metres to a few metres, 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 to within a few nanoseconds of Universal Time

(UTC). Related applications include time synchronisation for cellular-phone networks, VSAT synchronisation, electric power synchronisation networks, Internet node synchronisation, etc. In addition, the combination of satellite navigation and mobile services will provide a wide range of new services.

Performance objectives for the EGNOS system

Of the three user communities, the civil-aviation requirements are the most stringent (in terms of integrity and continuity) and hence the EGNOS performance objectives are driven by those needs, whilst still covering the needs of the land and maritime user communities.

The coverage area serviced by EGNOS will be the European Civil Aviation Conference (ECAC) service Area (Fig. 1), comprising the Flight Instrument Regions (FIR) under the responsibility of ECAC member states (most European countries, Turkey, the North Sea, and the eastern part of the Atlantic Ocean).

The EGNOS AOC performance objectives are to provide a primary navigation service for all phases of flight, from en-route flying through to precision approaches within the ECAC area. In addition, EGNOS has the potential to also offer services over the full geostationary broadcast area, and discussions are being pursued with international partners to provide this capability in order to offer users a seamless global service.

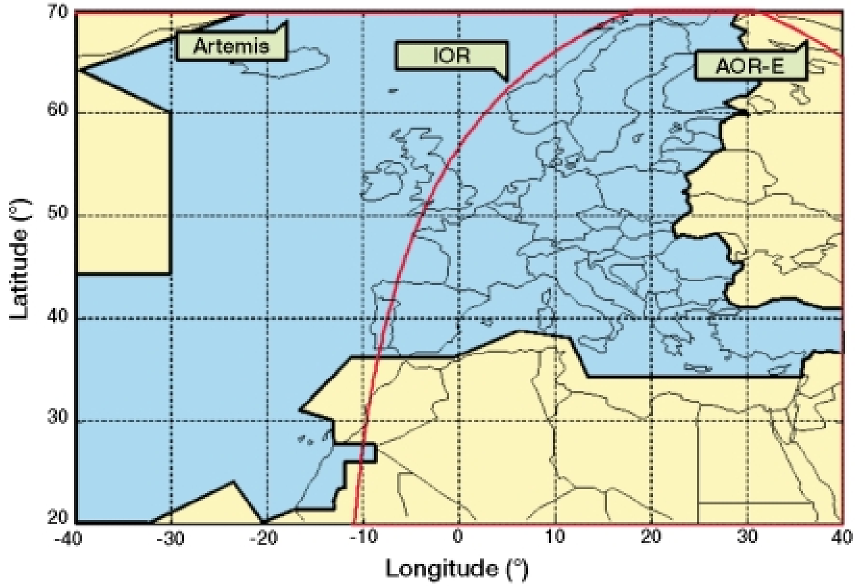


Figure 1. European Civil Aviation Conference (ECAC) approximate area coverage

The Main EGNOS Functionalities

- *GEO Ranging (R-GEO): Transmission of GPS-like signals from three GEO satellites (Inmarsat-3 AOR-E, Inmarsat-3 IOR, and ESA's Artemis satellite (Fig. 2) for the AOC phase), will augment the number of navigation satellites available to users.*
- *GNSS Integrity Channel (GIC): Broadcasting of integrity information will increase the availability of the GPS/GLONASS/EGNOS safe-navigation service to the level required for civil-aviation non-precision.*
- *Wide-Area Differential (WAD): Broadcasting of differential corrections will increase the GPS/GLONASS/EGNOS navigation service performance - mainly its accuracy - to the level required for precision approaches down to CAT-I landings.*

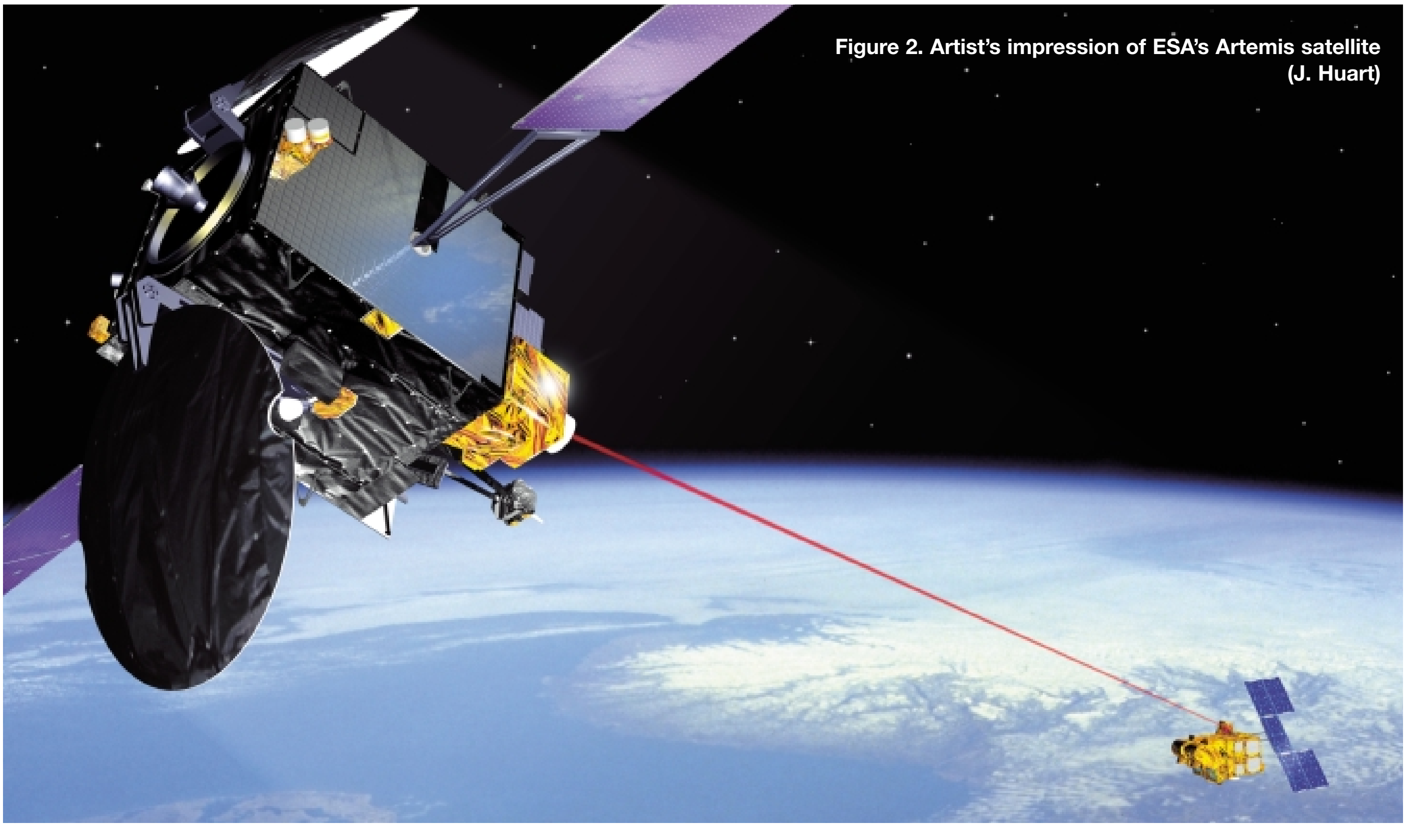


Figure 2. Artist's impression of ESA's Artemis satellite (J. Huart)

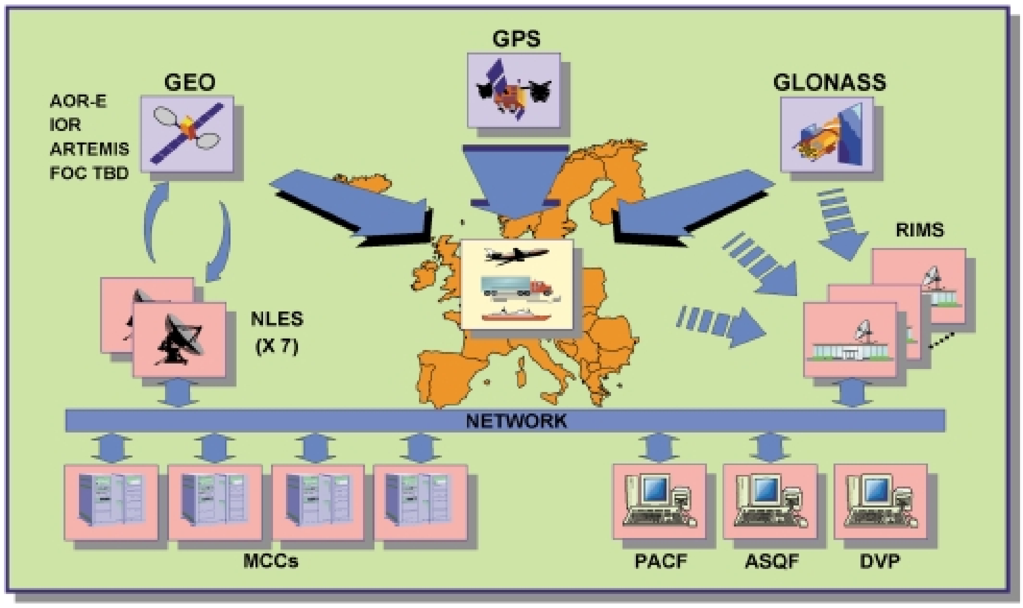


Figure 3. The EGNOS system architecture

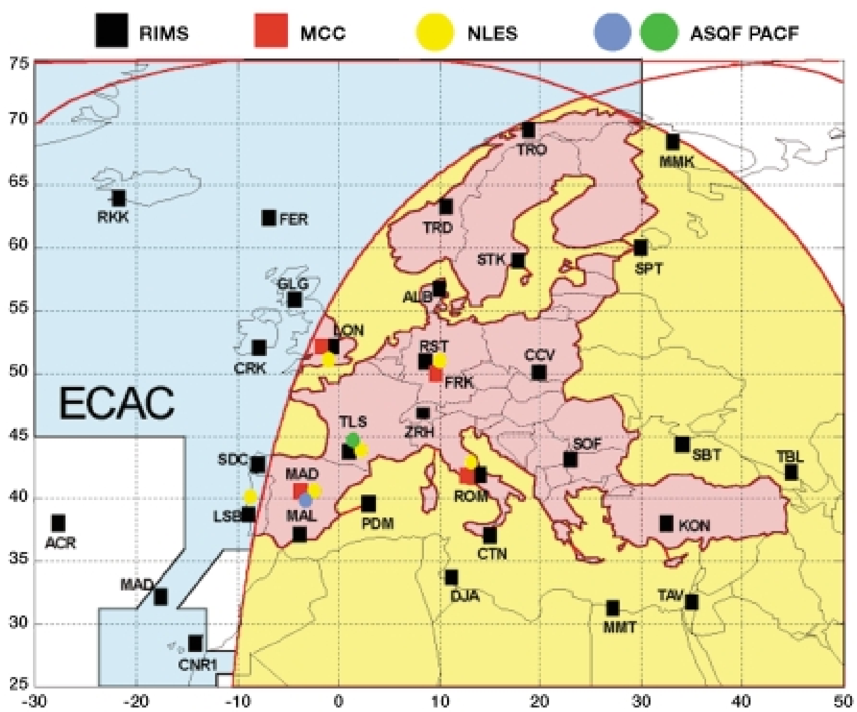


Figure 4. Planned sites for the various EGNOS Ground Segment elements

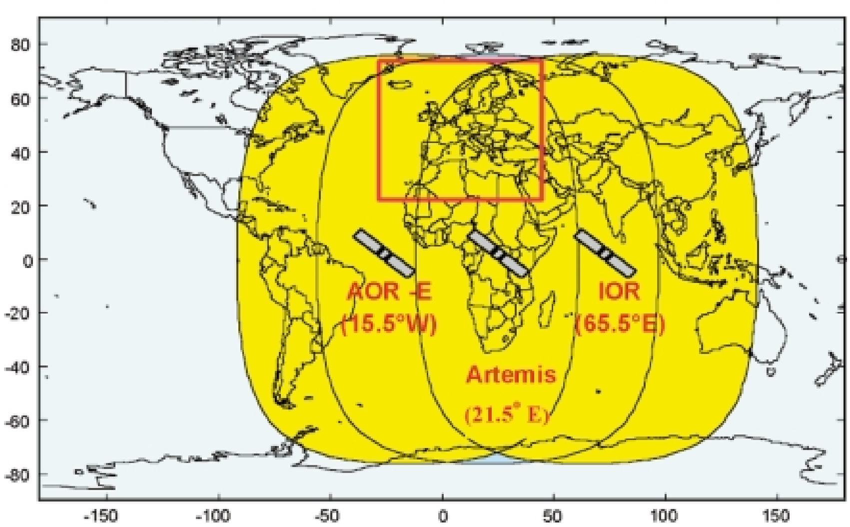


Figure 5. Inmarsat and Artemis EGNOS geostationary-satellite broadcast areas

The EGNOS architecture and system

The EGNOS reference architecture, depicted in Figure 3, is composed of four segments:

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 Centres (MCCs). The system will deploy 34 RIMS located mainly in Europe, and four MCCs located at Torrejon (E), Gatwick (UK), Langen (D) and Ciampino (I). The MCC determines the integrity, pseudo-range differential corrections for each monitored satellite, and ionospheric delays and generates the 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. The latter downlink 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 two NLESs (one primary and one back-up) per GEO navigation transponder and an NLES for test and validation purposes, located at Torrejon (E), Fucino (I), Aussaguel (F), Raisting (D), Goonhilly (UK), and Sintra (P), respectively. Figure 4 shows the planned sites for the various EGNOS ground-segment elements.

The *EGNOS Space Segment* is composed of geostationary transponders with global Earth coverage. The EGNOS AOC system is based on Inmarsat-3 AOR-E and IOR and the ESA Artemis navigation transponders (Fig. 5).

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. This prototype equipment will be used to validate and eventually certify EGNOS for the different applications being considered.

Last but not least, the *EGNOS Support Facilities* include the Development Verification Platform (DVP), the Application Specific Qualification Facility (ASQF) located in Torrejon (E), and the Performance Assessment and System Checkout Facility (PACF) located in Toulouse (F). These facilities are needed to support system development, operations and qualification.

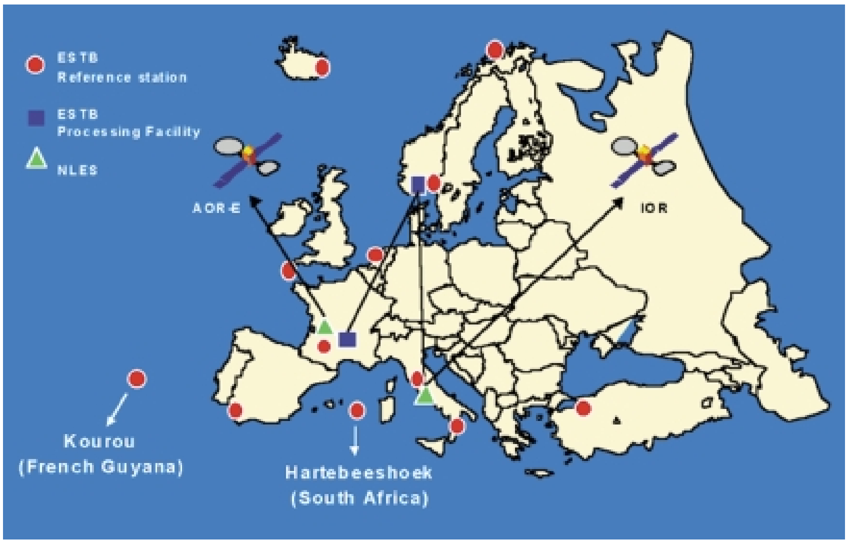
The EGNOS AOC Pre-Operational Implementation involves the detailed design, development, deployment and verification of three elements:
– the EGNOS System Test Bed (ESTB)
– the EGNOS Advanced Operational Capability (AOC) System
– the AOC Complementary Activities.

The EGNOS System Test Bed (ESTB)
The ESTB, which became operational in January 2000, is a real-time prototype of EGNOS, providing the first continuous GPS augmentation service within Europe. It has been developed under ESA contract by an industrial consortium involving key European satellite-navigation companies such as Alcatel Space Industries, Astrium, GMV, Racal, Seatex and DLR. To optimise the overall ESTB effort, existing assets have been taken into account in building up the ESTB. These include the SATREF™ system from NMA (Norwegian Mapping Authority) and the EURIDIS ranging system from CNES. In early 2001, the ESTB will also be fully connected with the Italian Mediterranean Test Bed (MTB) being provided by ENAV (Italian Civil Aviation Authority).

The ESTB therefore constitutes a great step forward in terms of the European strategy for developing the future European EGNOS and Galileo satellite-navigation systems. The driving objectives in its development include:
– The support to EGNOS design: In particular, algorithm design benefits from the ESTB experience in both design and usage.
– The demonstration of the capabilities of the system to users: The ESTB constitutes a strategic tool for the European Tripartite Group (ETG). The ETG is promoting the use of EGNOS and analysing its capabilities for different applications. In particular, ESTB availability will allow Civil Aviation Authorities to adapt their infrastructure and operational procedures for future EGNOS use when it becomes operational. An ETG-sponsored workshop aimed at fostering the use of ESTB and analysing the needs of potential users was organised on 6/7 July 2000. The very large number of participants represented a wide variety of different users and countries worldwide.
– The analysis of future EGNOS upgrades.

The ESTB architecture (Fig. 6) is made up of a space segment comprising nominally two transponders onboard the Inmarsat-III Atlantic Ocean East and the Indian Ocean satellites, a ground segment comprising a number of reference stations spread across Europe and beyond, a processing centre and the Inmarsat uplink stations. Communication lines interconnect all stations. During the ESTB's development, the contributions from various providers have been integrated with the existing assets:
– a network of RIMS, consisting of eight in a first step, to be expandable in the near future, and which are permanently collecting GPS/GEO/GLONASS data
– a Central Processing Facility (CPF), generating the WAD (Wide Area Differential) user messages. The CPF is located in Hønefoss (N), and hosted by the SATREF™ platform
– one Navigation Land Earth Station (NLES), forming part of the EURIDIS ranging system, located at Aussaguel (F) and allowing access to the Inmarsat-III AOR-E satellite
– three EURIDIS RIMS for GEO ranging purposes. These RIMS are distributed on an intercontinental basis to provide a wide observation base for the geostationary orbit; they also collect GPS/GEO data
– a Processing Centre sited in Toulouse (France), devoted to the generation of the GEO ranging data, and which also acts as a node for the transmission of user messages
– a real-time communication network, allowing the transfer of the RIMS data to the CPF, and navigation messages from Hønefoss to the NLES.

Figure 6. The EGNOS System Test Bed (ESTB) architecture



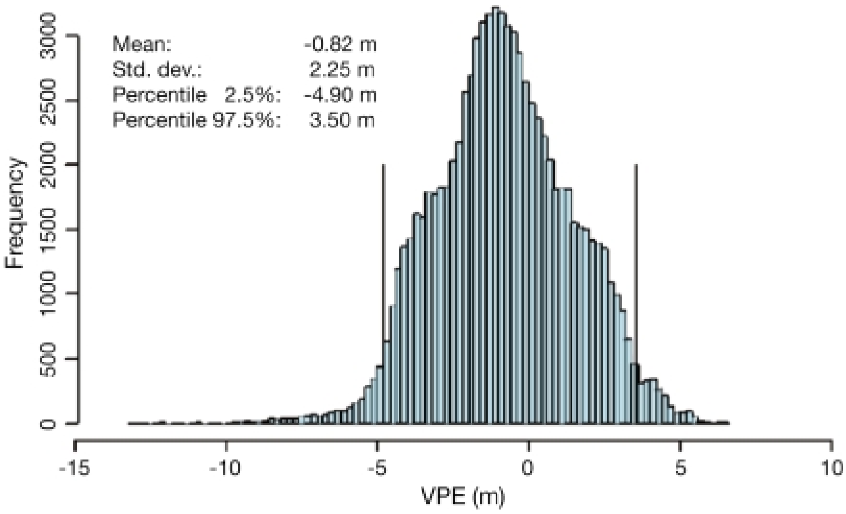


Figure 7. Typical ESTB vertical-error histogram

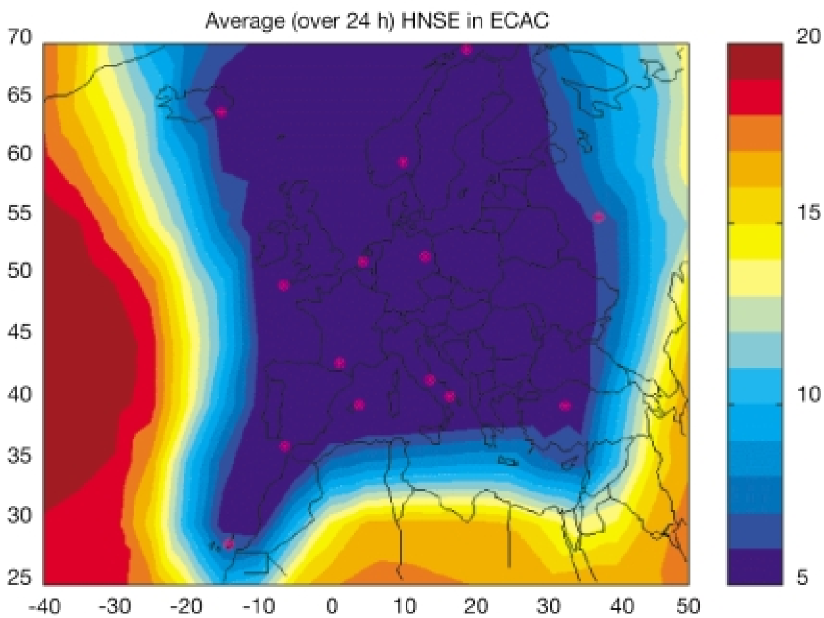


Figure 8. Estimated ESTB accuracy (2-sigma value) performances (including MTB)

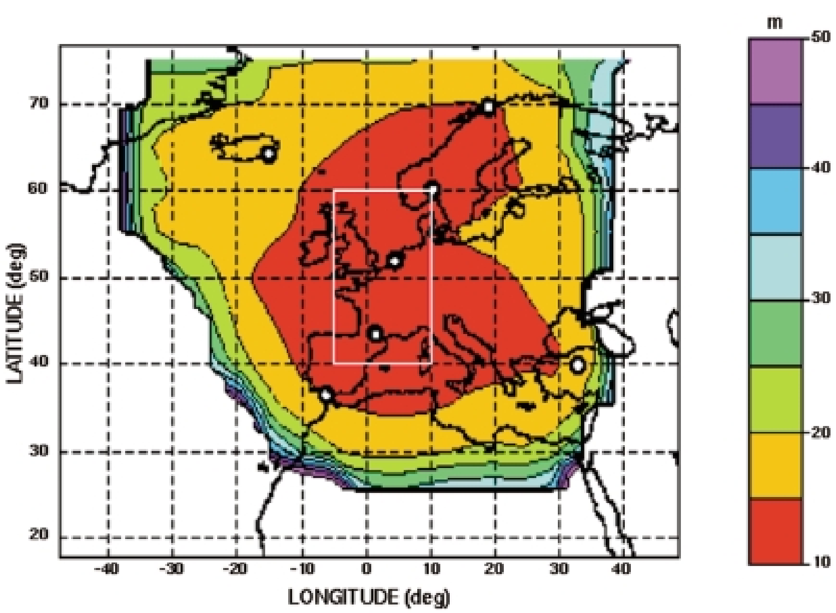


Figure 9. Typical vertical protection levels achieved by the ESTB

By using GPS and the ESTB Signal-In-Space, users within Europe can nowadays determine their positions with an error of less than 3 m horizontally and 5 m vertically, for 95% of the time. A typical ESTB vertical error distribution is represented in Figure 7, where the histogram of the errors is shown together with the associated statistical values (mean, standard deviation and 95th percentile). The area within which the test signal can be exploited is determined primarily by the locations of the reference stations. The present accuracy performances are illustrated in Figure 8.

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 with a particular operation. Figure 9 shows typical vertical protection levels (reflecting the guaranteed maximum error provided by the system ensuring the required level of safety) achieved throughout Europe through the ESTB. The values required for aircraft precision-approach landing are ensured across most of Europe. These results provide additional confidence in the current EGNOS design, especially given the reduced number of reference stations available and the current high solar activity.

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

The ESTB is still evolving to include the latest ICAO standards. Moreover, early in 2001 it will be operational 24 hours/day, 7 days/week, and will embrace capabilities for service expansion (outside Europe) and interoperability analysis (with other augmentation systems such as WAAS). In addition, the ESTB will be fully connected with the Italian Mediterranean Test Bed (MTB) being provided 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 via the E-mail address ESTB@esa.int. General information on ESTB scheduling, signal standards and the like can be found at: http://www.esa.int /navigation.

Interoperability of SBAS systems

In addition to EGNOS, there are currently two other Satellite-Based Augmentation Systems (SBASs) under development: the Wide-Area Augmentation System (WAAS) in the USA, and the multi-functional MTSAT-based augmentation system (MSAS) in Japan. Although all SBASs are currently defined as regional systems, it is commonly recognised that there is a need to establish adequate co-operation/co-ordination between the different systems so that their implementation becomes more effective and part of a seamless worldwide navigation system.

To guarantee a seamless worldwide service, it is essential that the three systems meet some common interoperability requirements. The service providers of those SBAS systems meet regularly in so-called 'Interoperability Working Group (IWG)' meetings to arrive at a precise understanding of the term interoperability, and to identify the necessary interfaces between SBASs. The EGNOS system includes specific requirements so that interoperability may indeed be achieved. In parallel, several initiatives are in progress for performing testbed interoperability demonstrations and flight trials in the near future.

In addition to interoperability, EGNOS has a built-in expansion capability to enable extension of the services over regions within the Geostationary Broadcast Areas of the GEO satellites used, such as Africa, Eastern countries, and Russia (Fig. 10). This combination of SBAS interoperability and expansion possibilities should allow the provision of a truly global and seamless worldwide navigation service (Fig. 11).

Current EGNOS programme status

The EGNOS programme comprises two different phases: the Initial Phase and the AOC Implementation Phase. The EGNOS Initial Phase was successfully concluded in November 1998 with the System Preliminary Design Review (PDR). The relevant ESA Programme Board approved full implementation of the EGNOS AOC System in December 1998, and the prime contract was signed with Alcatel Space Industries (F) on 16 June 1999 (Fig. 12).

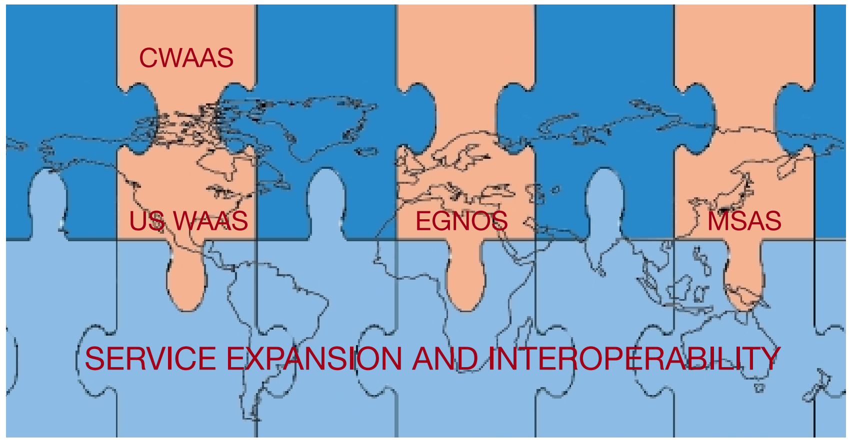


Figure 10. SBAS global interoperability and potential service expansion

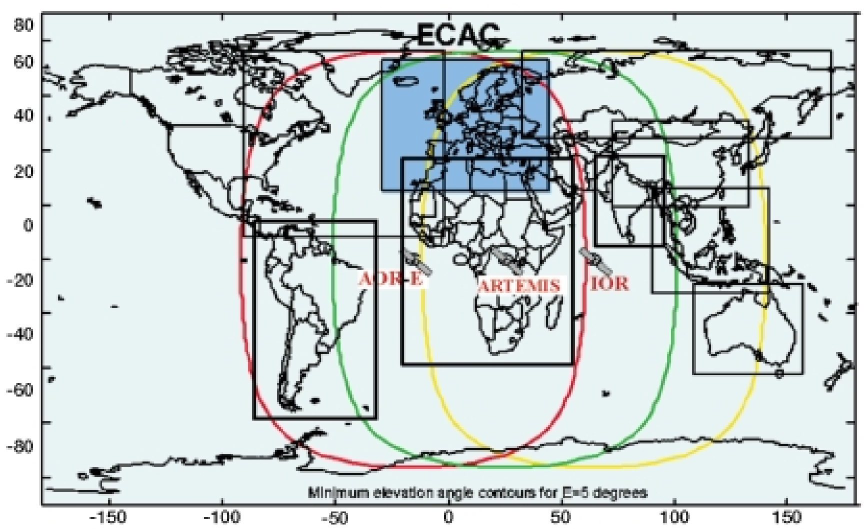


Figure 11. EGNOS AOC service broadcast areas

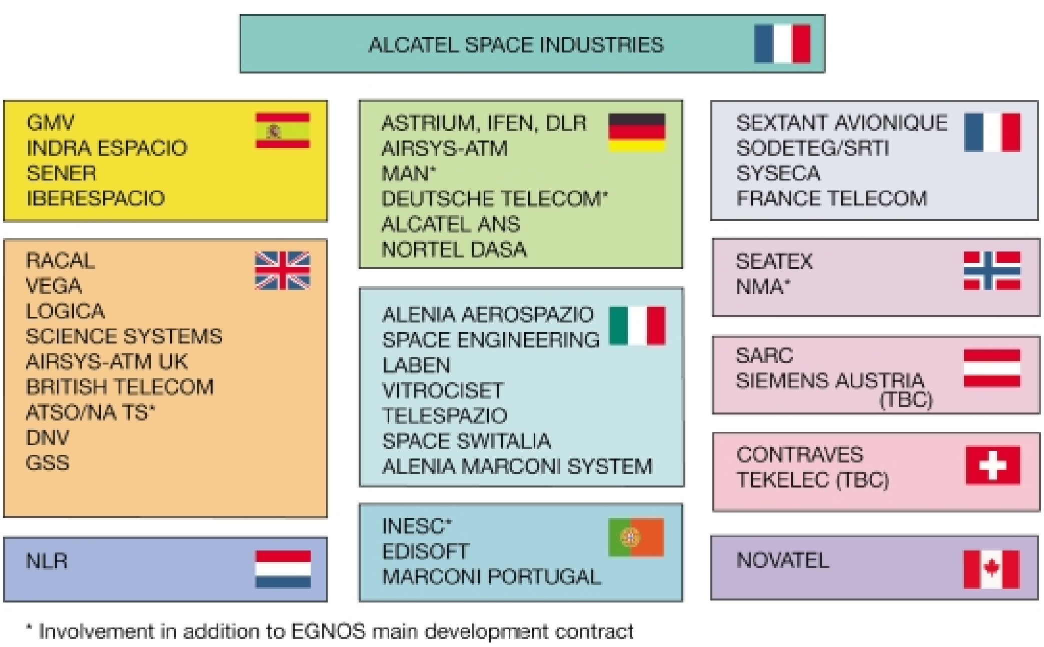


Figure 12. The industrial team in charge of EGNOS AOC

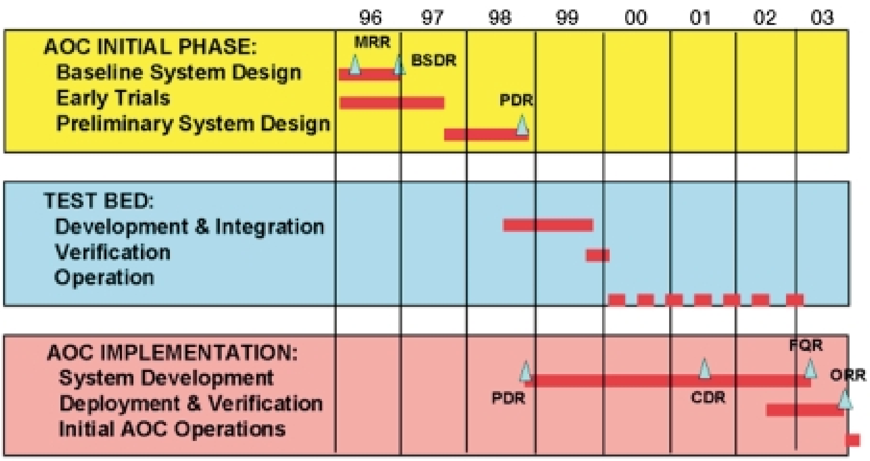


Figure 13. EGNOS AOC implementation schedule

Since then, all subsystem activities have been kicked-off and detailed design of those subsystems is currently in progress, after progressive completion of all subsystem PDRs during the course of 2000. The Operational Readiness Review is scheduled for December 2003.

The next milestones in the EGNOS AOC Implementation Phase (Fig. 13) are the System CDR in the second half of 2001, the System Factory Qualification Review (FQR) in early 2003, and the EGNOS AOC Operational Readiness Review (ORR) in December 2003.

The EGNOS project includes significant contributions from the French Space Agency (CNES), the Norwegian Mapping Authority (NMA), and the main European Air Traffic Management service providers such as AENA (E), NAV-EP (P), DFS (D), ENAV (I), DGAC (F), NATS (UK) and SwissControl (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 finalised by ESA via specific agreements with potential hosting entities. Site-survey activities started in mid-2000 and will last until mid-2001.

In parallel with those on-going development efforts, the actual integration of EGNOS into the Galileo mission is currently under detailed assessment. The results to date are very promising, and demonstrate that the EGNOS system can be used as a sound foundation on which the Galileo system architecture can capitalise.

Conclusion

EGNOS is the main European contribution to GNSS-1 to serve the needs of maritime, land transport and aeronautical applications in the European and neighbouring regions. For aviation, EGNOS AOC will be used in the ECAC Region as a primary means of navigation for all phases of flight down to CAT-I. EGNOS will be interoperable with equivalent US (WAAS) and Japanese (MSAS) SBAS systems, with the aim of contributing to a truly worldwide global navigation system.

The EGNOS Test Bed signal-in-space has been available since early 2000, and is being used to support demonstrations and trials in Europe, Africa and South America, and interoperability trials with Japan and the USA. The ESTB provides a unique opportunity for validating new application developments in a realistic environment, in preparation not only for the EGNOS operations, but also for future Galileo services.

EGNOS AOC development will be completed by the end of 2003, enabling operations to start in 2004.

Figure 14. Artist's impression of the Galileo satellite-navigation constellation (J. Huart)