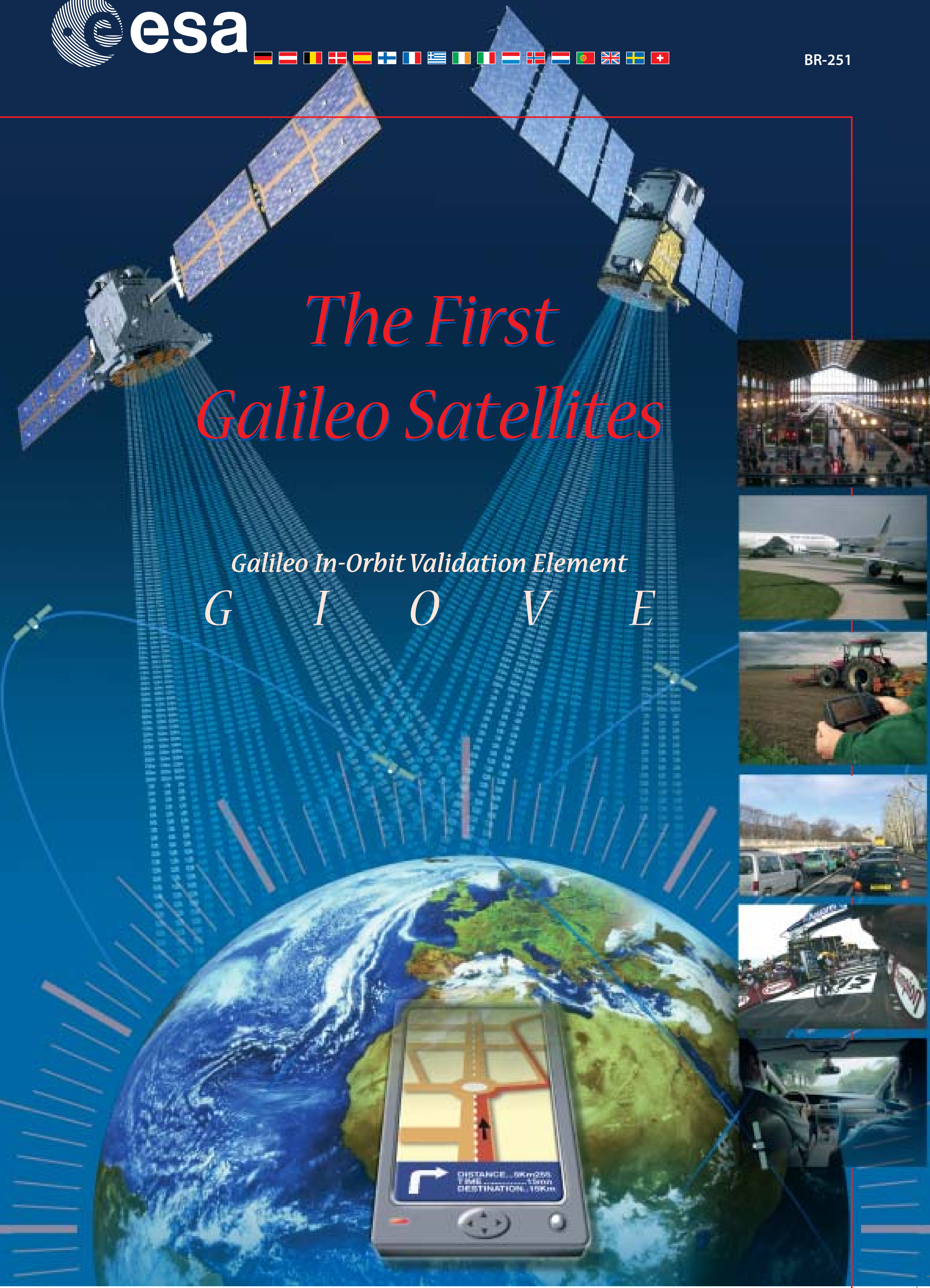
esa

BR-251

The First Galileo Satellites

Galileo In-Orbit Validation Element

G I O V E



BR-251 (2nd imprint, August 2006)
Published by: ESA Publications Division
ESTEC, PO Box 299
2200 AG Noordwijk
The Netherlands
Editor: Andrew Wilson
Design/Layout: Eva Ekstrand

Text coordination: Dominique Detain

ISSN: 0250-1589
ISBN: 92-9092-497-7
Price: 10 Euros

Printed in The Netherlands

BR-251
August 2006

The First Galileo Satellites

Galileo In-Orbit Validation Element

What is Galileo?

The first Galileo satellite was launched on top of a Soyuz rocket from Baikonur Cosmodrome in Kazakhstan on 28 December 2005.

Galileo, the first satellite positioning, navigation and timing system specifically designed for civil use, will offer state-of-the-art services with outstanding accuracy, availability, integrity and guarantee. It is a joint initiative of the European Commission (EC) and ESA.

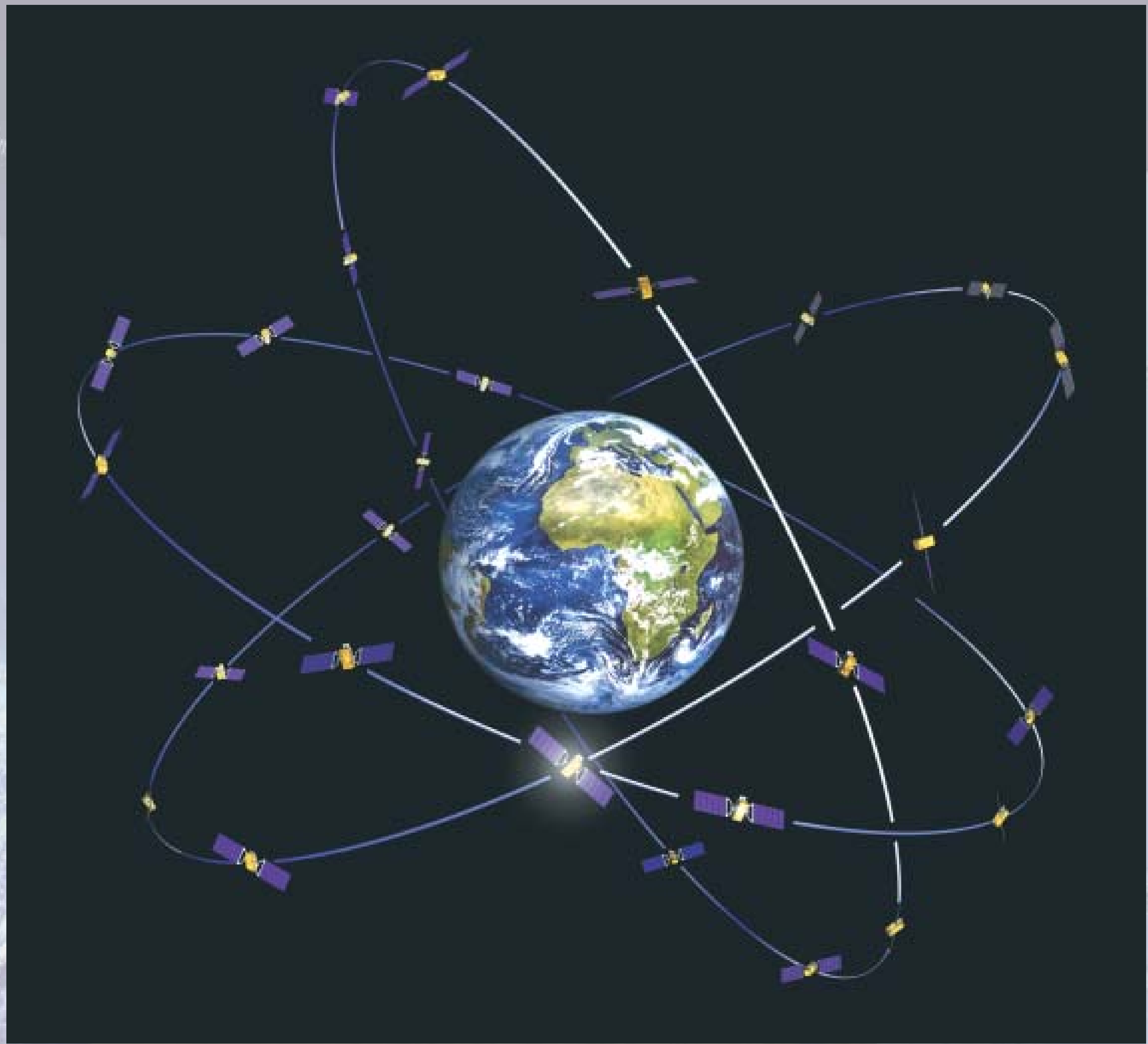
The Galileo Programme has three phases:

— definition;
— development and in-orbit validation;
— full deployment and operations.

Definition, completed in 2003, produced the basic specifications for the system. It will be validated by deploying four satellites of the overall constellation together with the ground stations and control centre. Four satellites are the minimum to guarantee precise positioning and time services at specific locations.

Early in this phase, the GIOVE (Galileo In-Orbit Validation Element) mission will employ two satellites, GIOVE-A and -B, and their mission- and ground-control segments. GIOVE is securing access to the Galileo frequencies allocated by the International Telecommunications Union (ITU), characterising the radiation environment of the Medium Earth Orbits (MEOs) planned for the Galileo satellites, testing the most critical technologies (such as the on-board atomic clocks, signal generator and user receivers), and characterising the novel features of the Galileo signal design.

Following completion of the IOV phase, Galileo will begin full deployment, covering the entire ground network and launching the remaining 26 satellites to complete the constellation.



GIOVE: Galileo In-Orbit Validation Element

In preparation for developing the Galileo system, in 2002 ESA began the development of a system consisting of a ground segment and two satellites.

GIOVE represents several major achievements for Europe:

- the first European navigation satellite;
- the first European satellite in MEO;
- the best clock ever flown in space;
- Europe will secure access to new Galileo frequency spectrum;
- Europe will demonstrate in-orbit new types of navigation signals;
- Europe will test the new generation of satellite navigation.

Operating the ground testbed at ESTEC.

For GIOVE, a ground segment has been deployed consisting of a worldwide network of sensor stations collecting high-quality Galileo data at 1 Hz, an Experimental Precision Timing Station providing the reference time scale using Universal Time and International Atomic Time (UTC/TAI), and a Processing Centre at ESA-ESTEC in The Netherlands. The latter features orbit-determination, integrity and time-synchronisation algorithms, and generates navigation and integrity core products based on Galileo-like algorithms.

GIOVE is proving that it is possible to 'broadcast' near-real-time orbit-determination and time-synchronisation data with high accuracy (< 50 cm) and low update rate (2 h), as envisaged for Galileo.

GIOVE's two satellites are the first step in the in-orbit validation of the Galileo system. Surrey Satellite Technology Limited (SSTL, UK) built one of these satellites, GIOVE-A; GIOVE-B was built by Galileo Industries, a European consortium of Alcatel Space Industries (F), Alenia Spazio (I), Astrium GmbH (D), Astrium Ltd (UK) and Galileo Sistemas y Servicios (E).

GIOVE-A and -B were built in parallel to provide in-orbit redundancy; their capabilities are complementary. The smaller Surrey Space Technology satellite carries a rubidium atomic clock and transmits a signal through two separate channels at a time. The larger Galileo Industries satellite adds a hydrogen-maser clock and will transmit a signal through three separate channels. Launch will be by a Soyuz rocket from the Baikonur Cosmodrome.

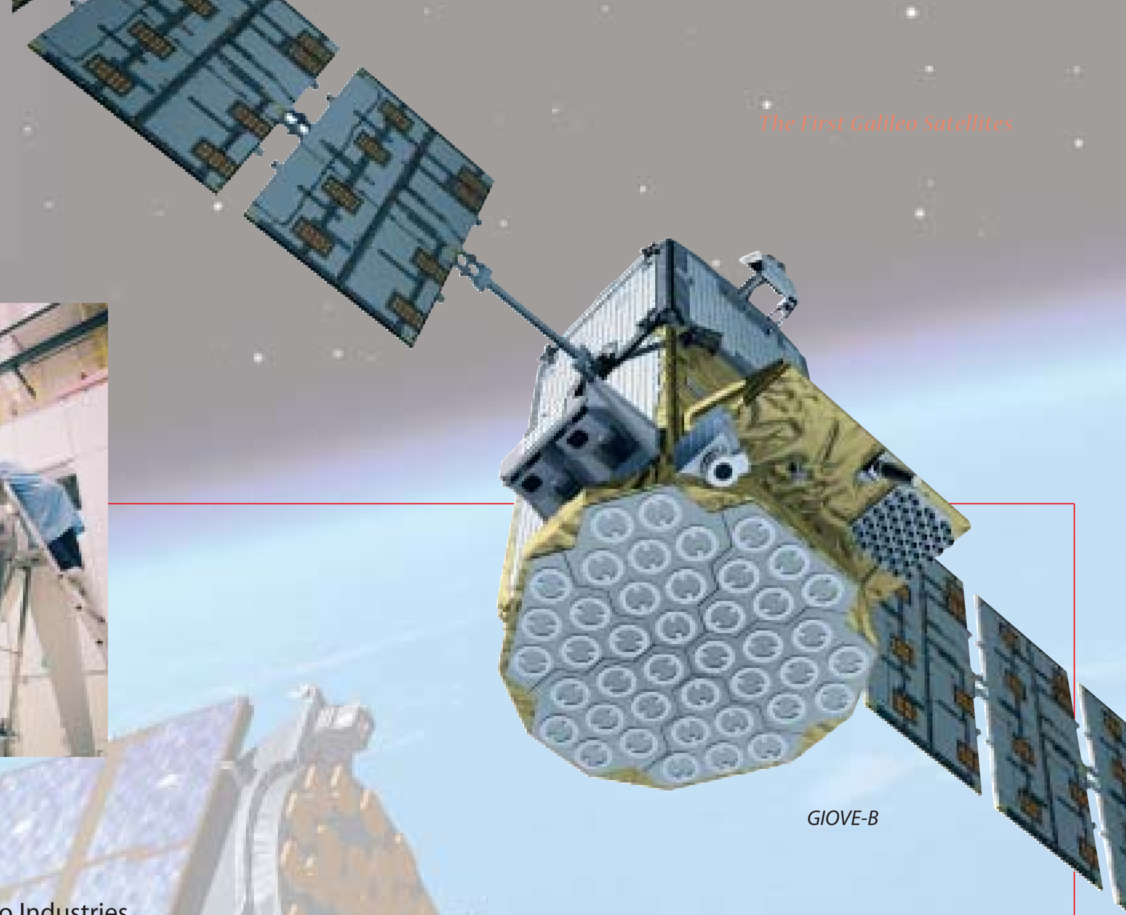
Experience from GIOVE is supporting the development of the IOV system, thereby reducing risk and helping to guarantee the success of the Galileo mission.

GIOVE-A is providing Galileo's first space demonstration.

GIOVE-B will extend the first Galileo demonstration.




GIOVE-A testing in ESTEC.



GIOVE-B

GIOVE-A

GIOVE-A

GIOVE-A was built by SSTL. This 3-axis-stabilised satellite has a cube-shaped body of 1.3 x 1.8 x 1.65 m, a launch mass of 600 kg and a power demand of 700 W satisfied by two wings of Sun-tracking arrays, each 4.54 m long. The satellite has a butane propulsion system with two tanks each holding 25 kg.

The triply-redundant payload transmits a Galileo signal in two separate frequency channels. The payload's main elements are:

- the antenna: a phased array of individual L-band elements, illuminating the whole visible Earth below;
- the signal-generation units to create two representative Galileo signals;
- the clocks: two redundant, compact rubidium atomic clocks with a stability of 10 ns per day;
- two radiation monitors to characterise the MEO environment;
- the navigation receiver to experiment with autonomous localisation in the MEO orbit.

GIOVE-B

GIOVE-B was built by the Galileo Industries consortium. This 3-axis-stabilised satellite has stowed dimensions of 0.95 x 0.95 x 2.4 m and a launch mass of 530 kg. Its two solar wings, each 4.34 m long, will supply up to 1100 W. The propulsion system has a single tank carrying 28 kg of hydrazine.

The doubly-redundant payload will transmit a Galileo signal on three separate frequency channels. The main payload elements are:

- the antenna: a phased array of individual L-band elements, illuminating the whole visible Earth below;
- a signal-generation unit able to provide different types of signals;
- the clocks: a passive hydrogen-maser (PHM; stability 1 ns per day) that will be the most accurate clock ever flown in space, and two compact rubidium atomic clocks (stability 10 ns per day), one of which will be in hot redundancy for the PHM, and the other in cold redundancy;
- a radiation monitor to characterise the MEO environment.

For both satellites, the expected lifetime is 2 years.

GIOVE-B preparations at Galileo Industries.

IOV: The First Four Satellites of the Constellation

As part of the Development and IOV phase, the first four Galileo satellites to be launched will be fully representative of the 30 satellites of the Galileo constellation. Each will broadcast precise time signals, ephemeris and other navigation and commercial data. The Galileo constellation is optimised to:

- circular orbits at 23 222 km altitude;
- orbital inclination of 56°;
- three equally spaced orbital planes
- nine operational satellites, equally spaced around each plane;
- one spare satellite (also transmitting) in each plane.

Following the IOV phase, the Full Deployment phase will cover the manufacture and launch of 26 satellites and the completion of the ground segment, an extensive network of stations and local and regional service centres.

The future Galileo Operating Company, selected by the Galileo Joint Undertaking, will take charge of the final deployment and then the operations.

GalileoSat (1-30) facts and figures	
Bus dimensions	2.7 x 1.1 x 1.2 m
Solar array span	13 m
Peak power	1600 W
Launch mass	700 kg
Navigation signals	10 signals transmitted in 1200-1600 MHz range

The Galileo Payloads

Galileo's master passive maser clock is accurate to 1 ns over 24 h; the rubidium clock is accurate to 10 ns over 24 h. The satellite carries two clocks of each type, but only one of each operates at any given time. Under normal conditions, the operating maser clock produces the reference frequency from which the navigation signal is generated. Should this clock fail, the operating rubidium clock would take over instantaneously and the two reserve clocks start up. With four clocks, the satellite is guaranteed to be generating a navigation signal at all times.

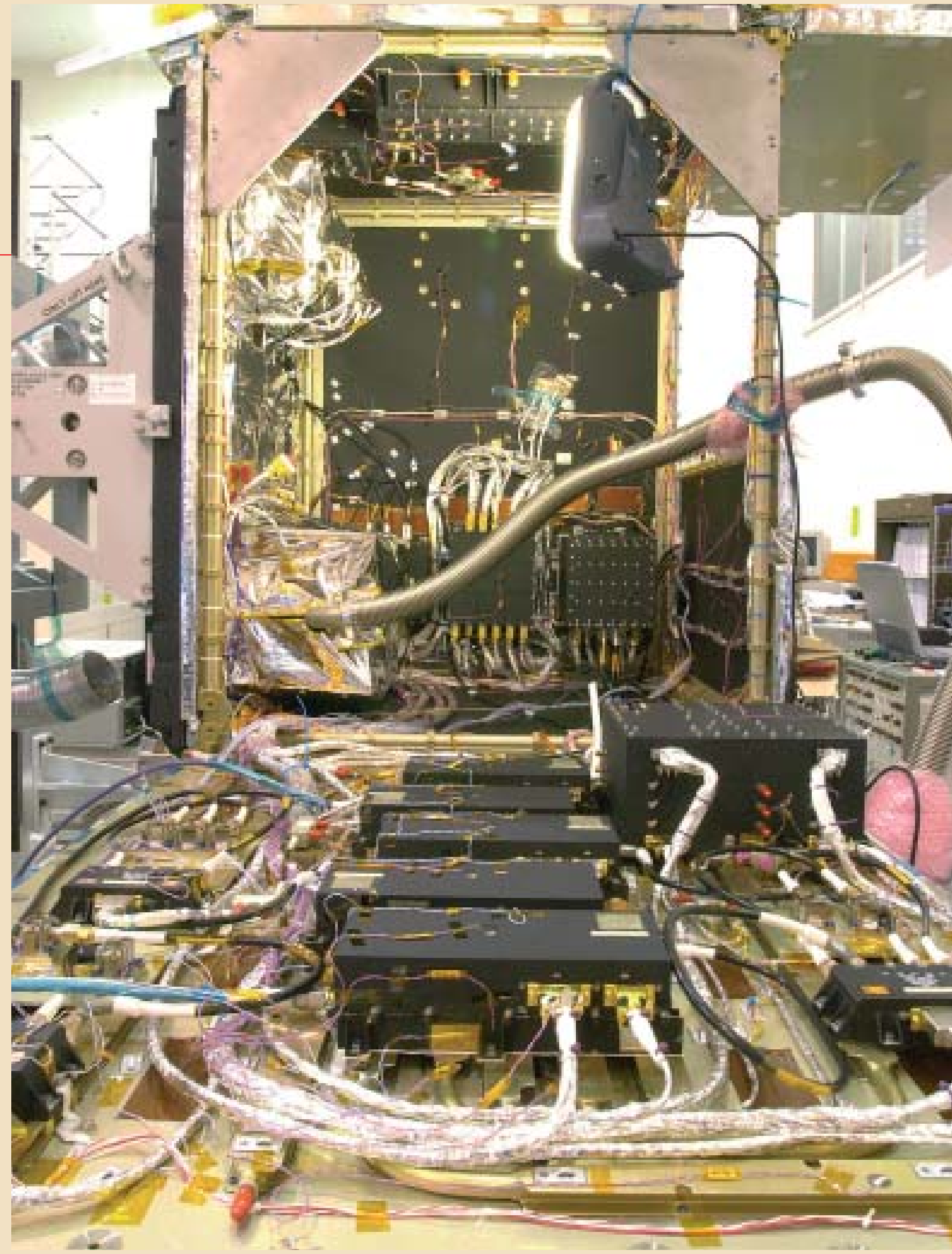
The L-band antenna array on GIOVE-A.

The clock monitoring and control unit is the interface between the four clocks and the navigation signal-generator unit (NSGU). The NSGU and the frequency-generator and up-conversion units generate the navigation signals using input from the clock monitoring unit and the up-linked navigation and integrity data from the C-band antenna. The navigation signals are converted to the L-band for broadcast to users. The remote terminal unit is the interface between all of the payload units and the onboard computer.

Galileo Onboard Clocks

Rubidium clock

The rubidium clock consists of an atomic resonator and control electronics. In the resonator's rubidium vapour cell, the atoms are kept in a gaseous state at high temperature. In order to trigger resonance, the atoms are excited to a higher state by the light of a rubidium discharge lamp at one end of the resonator. At the other end, a photodiode detects the amount of light passing through the cell. Following the excitation, the atoms decay to a lower state level. From this state, they are excited back to an intermediate level by injecting microwave energy into the resonator at a given frequency. Transition to the intermediate level occurs only if the frequency corresponds exactly to the one associated with that transition. When the atoms are in the intermediate state, the absorption of light is at a maximum. The output of the photodiode is connected to control circuitry that adjusts the microwave frequency. The correct frequency is maintained by tuning the microwave source to obtain maximum light absorption. The resonance is maintained by the energy from the rubidium lamp, since the atoms in the intermediate state are again excited to the higher state and then decay to the lower state, from where the whole process starts again.



Far left: the GIOVE-A payloads. Left: the GIOVE-B payloads.

Hydrogen maser clock

The hydrogen maser clock comprises an atomic resonator and control electronics. A small storage bottle supplies molecular hydrogen to a gas-discharge bulb, where the molecules are dissociated into atomic hydrogen. The atoms then enter a resonance cavity through a collimator and a magnetic-state selector. This selector allows in only atoms of the desired energy level. In the cavity, the atoms are confined to a quartz storage bulb, where they tend to return to their fundamental energy state, emitting a microwave frequency as they do so. This frequency is detected by an interrogation circuit, which locks an external signal to the natural transition of the hydrogen atoms. Locking occurs when the injected frequency is the same as the resonant frequency of the atoms; this corresponds to an amplification of the microwave signal.

The Galileo Services

Galileo will set the global standard for civil navigation by satellite. There will be total compatibility and interoperability between the European and US systems (an agreement between the European Union and the US was signed in June 2004 in Dublin, Ireland) and the Russian Glonass system. Cooperative agreements being negotiated by the European Commission with third countries give a truly global dimension to Galileo, the first civil navigation satellite system.

EGNOS test: sailing in the Greek islands.

The Galileo system will provide a range of services to users. The following services will be provided worldwide and independently from other systems by Galileo:

— the Open Service (OS) combines the open signals, free-of-charge to users, to provide position and timing performance competitive with other satellite systems;
— the Safety-of-Life (SoL) Service improves on the OS by providing timely warnings to the user when it fails to meet certain margins of accuracy or continuity (integrity). It is envisaged that a service guarantee will be provided;
— the Commercial Service (CS) provides access to two additional signals for faster data-throughput and increased accuracy. The signals are encrypted. It is envisaged that a service guarantee will be provided;
— the Public Regulated Service (PRS) provides position and timing to government-authorised users requiring a high continuity of service with controlled access. Two PRS navigation signals with encrypted ranging codes and data will be available;
— the Galileo support to the Search & Rescue service is Europe's contribution to the international COSPAS-SARSAT system. Galileo will play an important part in the MEO Search & Rescue system (MEOSAR). Galileo satellites will be able to pick up signals from emergency beacons carried by ships, planes and individuals, and ultimately relay them to national rescue centres. A rescue centre can thus know the precise location of an accident. At least one Galileo satellite will be in view of any point on Earth at all times, so real-time distress alerts will be possible.

EGNOS test: a blind pedestrian in Madrid.

EGNOS test: management of trains.

EGNOS test: landing in Africa.

The Galileo System

The Galileo system will comprise *global*, *regional* and *local* components.

The global component is the core of the system, consisting of the satellites, the ground control and the ground mission segments.

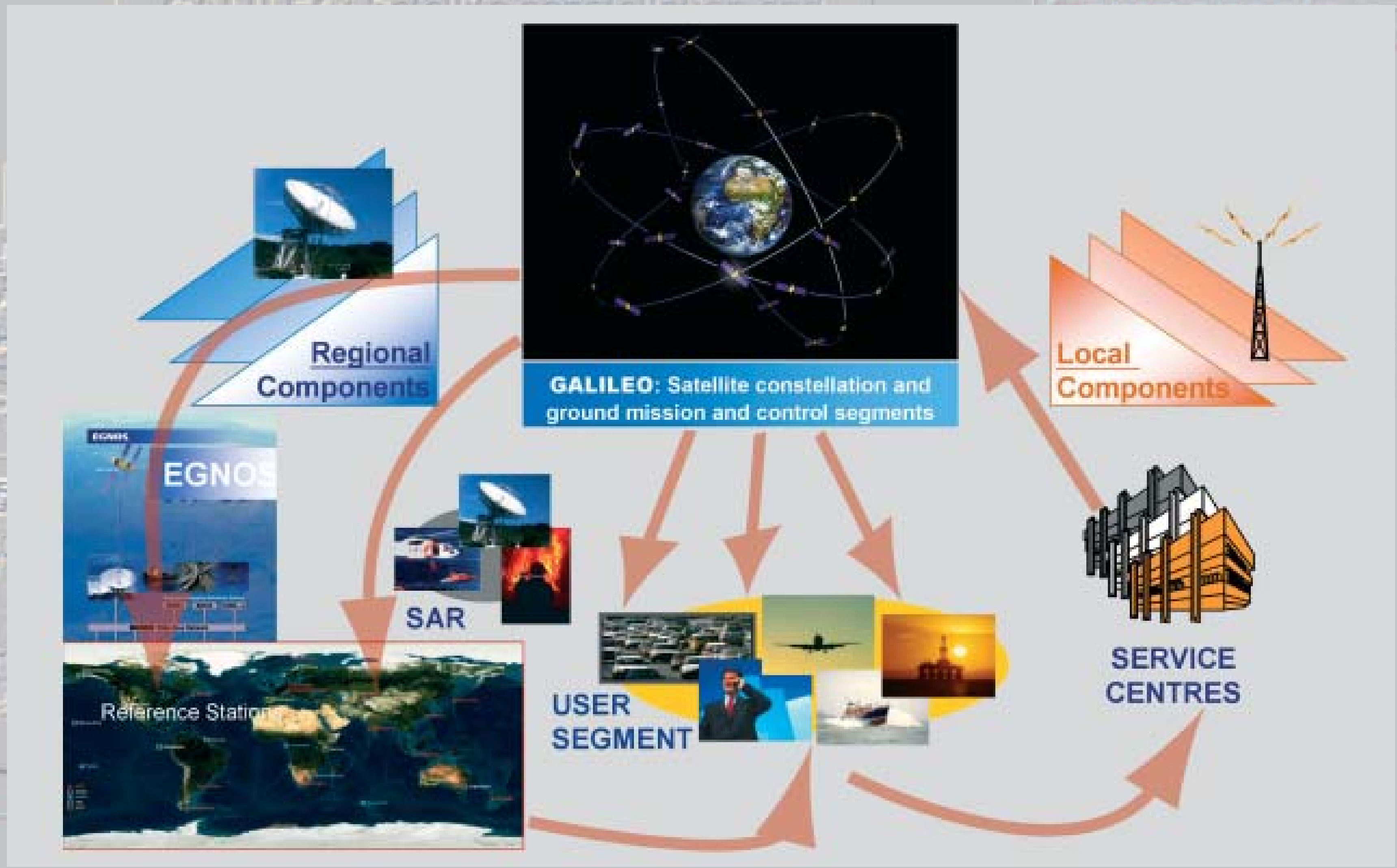
The core of the Galileo ground segment will be the two Galileo Control Centres. Each will manage 'control' functions supported by a dedicated Ground Control Segment (GCS), and 'mission' functions supported by a dedicated Ground Mission Segment (GMS). The GCS will handle satellite housekeeping and constellation maintenance, while the GMS will handle the navigation and timing system.

The GMS will use a global network of nominally 30 L-band Galileo Sensor Stations (GSSs) to monitor the navigation signals of all the satellites. The prime element of the GSS is the Reference Receiver. GSS data will be disseminated to the Galileo Control Centres (GCCs) continuously through a comprehensive communications network using satellites and terrestrial connections, with each link duplicated for redundancy. The GMS processing facilities in the GCCs will process the data and produce the navigation and integrity messages up-linked to Galileo satellites via a network of Up-Link Stations (ULSs) operating at C-band. The navigation signals are generated aboard the Galileo satellites and broadcast to users in the L-band.

The satellite constellation will be controlled from the GCS facilities installed in the GCC, and supported by a worldwide network of Telemetry and Telecommand (TT&C) S-band stations.

Galileo's regional component may comprise a number of External Region Integrity Systems (ERIS), implemented and operated by organisations, countries or groups of countries outside Europe to obtain integrity services independent of the Galileo system, in order, for example, to satisfy legal constraints relating to system guarantees.

Local components may be deployed for enhancing the performance of Galileo locally. These will enable higher performance, such as the delivery of navigation signals in areas where the satellite signals cannot be received. Value-added service providers will deploy local components.



The Galileo Receivers

Galileo will benefit from many new methods and technologies to offer superior performance and reliability. Development of the advanced receivers required to exploit the system is continuing, with the first prototype now completed.

Three receiver development efforts are under way within the Galileo IOV phase, addressing the different needs of the system-development process and covering the range of signals and services that will be offered:

— receivers for the signals transmitted by the first satellites;
— test user segment, for system validation and signal broadcasting;
— Galileo sensor stations equipped with high-performance, ultra-reliable receivers.

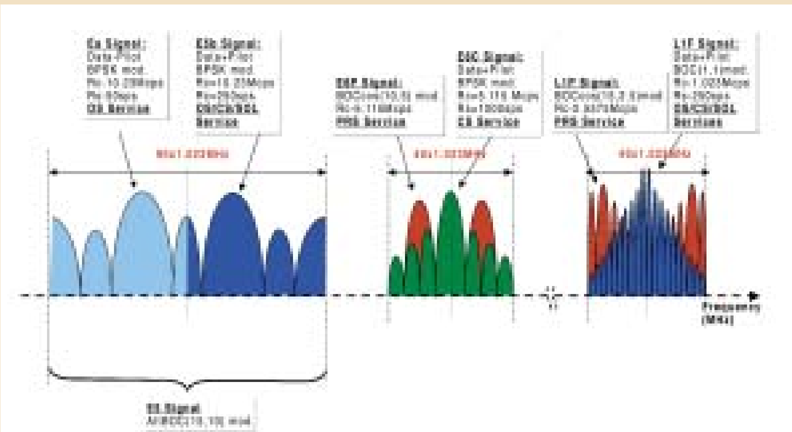
Galileo receivers process the signals broadcast by the satellites to compute position. The receivers extract

Galileo receiver: a prototype under test at ESTEC.

measurements indicating the distance from the user to each satellite. They also decode the Galileo navigation data, which contain fundamental pieces of information for computing the user position, such as the position of the satellites and the satellite clock errors as determined by the ground segment and uplinked regularly to the constellation.

The frequencies used by the satellites are within the 1.1-1.6 GHz band, a range of frequencies particularly well-suited to mobile navigation and communication services.

Each Galileo satellite will broadcast 10 different navigation signals, making it possible for Galileo to offer the open (OS), safety-of-life (SOL), commercial (CS) and public regulated (PRS) services.
Galileo will have an integrity signal to ensure the quality of the signals received. Galileo signals will offer a guaranteed accuracy down to 1 m, with value-added services achieving a real-time accuracy of 10 cm.



Each Galileo satellite will broadcast 10 different navigation signals.

EGNOS: Paving the Way for Galileo

EGNOS, the European Geostationary Navigation Overlay Service, is Europe's first venture into satellite navigation. EGNOS is a joint project of ESA, the European Commission and Eurocontrol, the European Organisation for the Safety of Air Navigation.

EGNOS is the European Satellite-Based Augmentation System (SBAS), deployed to augment services to aviation, maritime and land-based users in Europe. It is designed to augment the two satellite navigation systems now operating, the US GPS and Russian Glonass systems, making them suitable for safety-critical applications such as aircraft guidance or navigating ships through narrow channels.

EGNOS is designed to meet the extremely challenging requirements for landing aircraft, so it also meets most other users' requirements. In addition:

— availability is improved by broadcasting GPS look-alike signals from up to three geostationary satellites;
— accuracy is improved to 1-2 m horizontally and 3-5 m vertically;
— integrity (not provided by GPS) and safety are improved by alerting users within 6 s if a malfunction occurs in EGNOS or GPS.

Consisting of three geostationary satellites and a network of ground stations, EGNOS transmits a signal containing information on the reliability and accuracy of the positioning signals sent out by GPS. It will allow users in Europe and beyond to determine their position to within 1 m, compared with about 20 m at present.

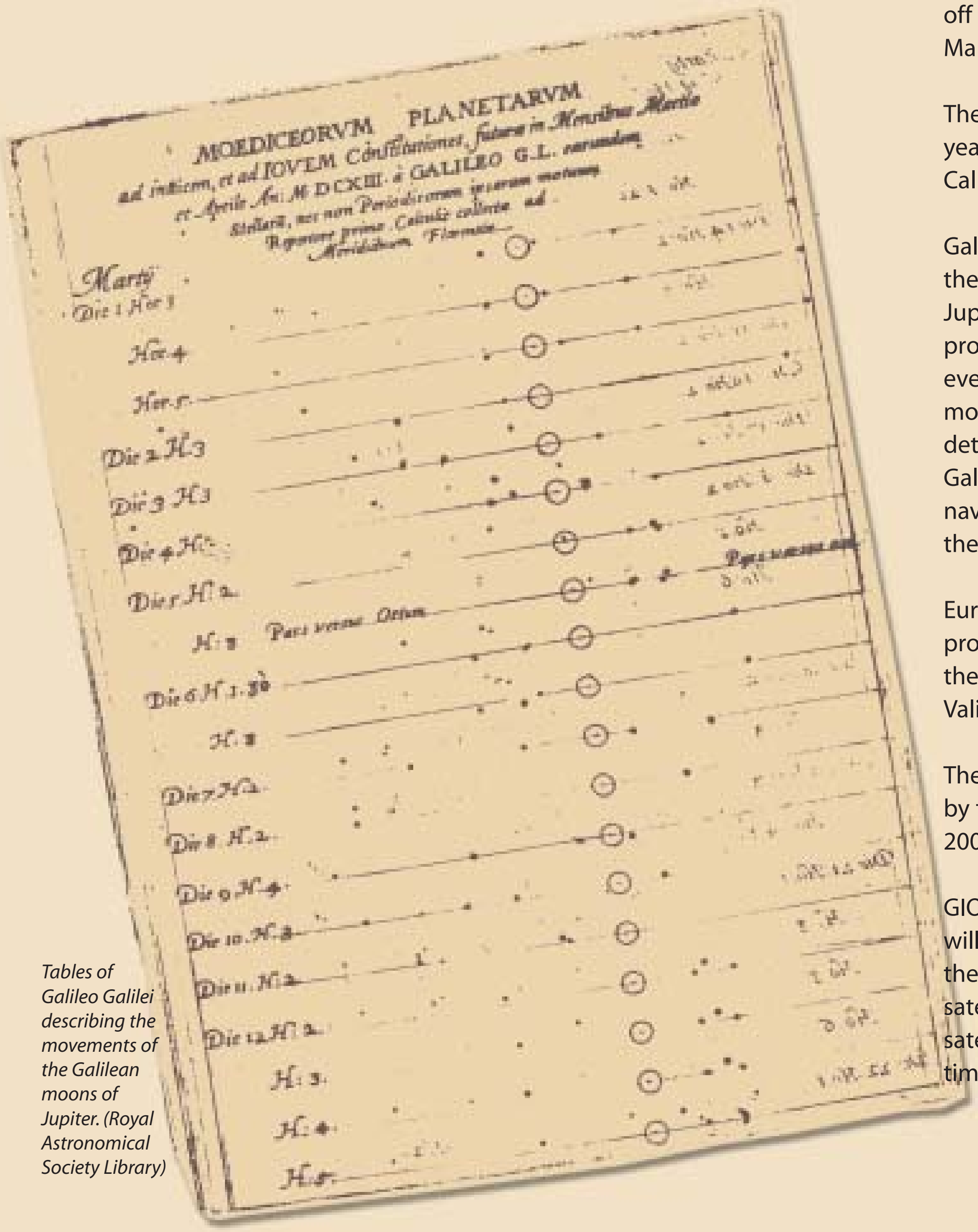
EGNOS services are already provided in Western Europe and the Mediterranean and may be extended to cover other areas, including Africa, the Middle East, Eastern Europe, South America and Asia.

EGNOS will not be the only SBAS for the current navigation satellite systems, but one of many similar systems in operation or under construction worldwide, including the USA and Canada (WAAS), Japan (MSAS) and India (GAGAN). As it is built upon common international standards, EGNOS will provide interoperability with these other systems.

For civil aviation use, EGNOS complies with International Civil Aviation Organisation (ICAO) global standards. It also covers multi-modal transport and many non-transport applications. EGNOS will be integrated into Galileo as part of the GNSS infrastructure.

EGNOS has already begun initial operations, and the EGNOS Open Service will be declared available for non-safety-critical applications in 2006. The qualification of EGNOS operations and the establishment of a service-provision structure (via the Galileo Concessionaire) will then enable the EGNOS Safety-of-Life service to be declared operational.

The Historical Perspective



Tables of Galileo Galilei describing the movements of the Galilean moons of Jupiter. (Royal Astronomical Society Library)

GIOVE
As one of the first to turn a telescope to the skies, on 7 January 1610 Galileo Galilei (1564-1642) discovered the first four moons of the planet Jupiter ('Giove' in Italian). His book, *Sidereus Nuncius*, in which his discovery was described, came off the press in Venice in the middle of March 1610 and made Galileo famous.

These four moons were named a few years later as Io, Europa, Ganymede and Callisto.

Galileo realised that the arrangement of these four satellites, whose eclipses by Jupiter are frequent and readily visible, provided a clock that could be seen from every point on Earth. Tables describing the motion of the satellites were used to determine longitude at sea and on land. Galileo's method revolutionised navigation, geodesy and cartography in the 17th and 18th centuries.

Europe's Galileo satellite navigation programme will launch its first satellite by the end of 2005 for the Galileo In-Orbit Validation Element – or GIOVE for short.

The two GIOVE satellites will be followed by the first four operational satellites in 2008.

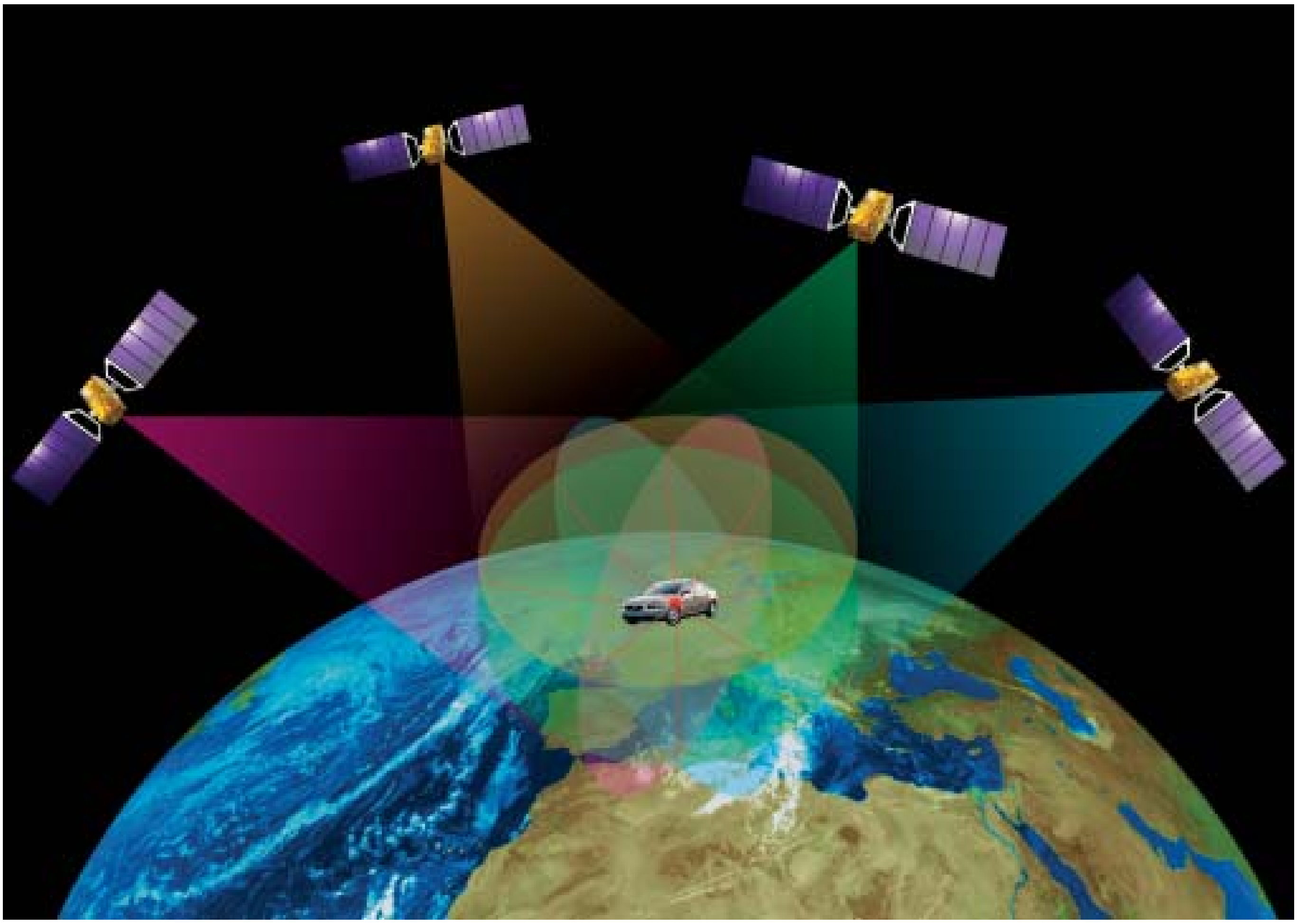
GIOVE and its four GalileoSat successors will pave the way for the deployment of the full Galileo system constellation of 30 satellites, providing for unprecedented satellite positioning, navigation and timing in the 21st century.

Galileo programme
Galileo is the fruit of a series of political decisions and technical studies starting in the early 1990s. There was even an ESA study in 1982 on a *User Segment of Navsat*.

Inside ESA, the first proposals appeared as part of the Global Navigation Satellite System (GNSS). EGNOS (GNSS-1) was proposed in 1994 by ESA, the EC and Eurocontrol, and approved by ESA Member States in October 1998. Meanwhile, in March 1998, the EC Transport Council had requested the elaboration of Europe's position on GNSS. In May 1999 the ESA Ministerial Council approved the GalileoSat programme; in June1999 the EU Transport Council endorsed a first resolution on Galileo. In November 2001 the ESA Ministerial Council approved the development of Galileo (Phase-C/D, with a budget of €550 million). In March 2002 the EU Transport Council approved this phase (€450 million). In May 2003 ESA Member States agreed on the conditions of participation in the Galileo programme.

The overall cost of the Galileo system was first estimated at €3.4 billion, with a public investment for the development and validation phase of €1.1 billion divided between the EC and ESA. This phase was re-evaluated in 2005 at €1.5 billion.

The Principle of Satellite Navigation



Satellite navigation pinpoints a location by measuring the distances between satellites and a receiver. The receiver captures time signals from the satellites and determines its position by calculating how far it is from a number of satellites. This is done by measuring the time the signals take to travel from the satellites. To pinpoint its location, the receiver needs signals from at least four navigational satellites.

The position accuracy depends on the accuracy of the time measurement. Only atomic clocks provide the required accuracy, of the order of nanoseconds . Such clocks are a major technology element aboard the Galileo satellites and contribute to the definition of international time standards. The time measurement is improved by including the signal from a fourth satellite, so special care was taken in selecting the numbers of satellites and their orbits.

Photo/image credits: Royal Astronomical Society Library (p.18), C. Beetles/Bridgeman-Giraudon (p.18), Galileo Industries (pp. 7, 11); ESA: P. Carril (front cover, pp. 4, 5, 6, 7), S. Corvaja (front cover, pp. 6, 12), D. Detain (p. 13), J. Huart (pp. 3, 8, 9), A. Le Floch (pp. 4, 10, 16), E. Pedoussaut (p. 13), P. Sebirot (front cover), Trimaran (p. 12), J. Van Haarlem (pp. 6, 7), Zig Zag (front cover, pp. 2, 3, 19)

Galileo Joint Undertaking
Rue du Luxembourg 3
B-1000 Brussels, Belgium
Tel: +32 2 507 80 00
Fax: +32 2 507 80 01
Email: info@galileoju.com
http://www.galileoju.com

European Space Agency
Directorate of European Union and Industrial Programmes
8-10 rue Mario Nikis
F-75738 Paris Cedex 15, France
Tel: +33 1 53 69 77 26
Fax: +33 1 53 69 72 86
Email: dominique.detain@esa.int
http://www.esa.int/navigation/

European Commission
Directorate General for Energy and Transport
Unit E.4 Satellite Navigation System (Galileo), Intelligent Transport, DM28 1/64
B-1049 Brussels, Belgium
Tel: +32 2 29 56040
Fax: +32 2 296 5372
Email: tren-galileo@cec.eu.int
http://europa.eu.int/comm/dgs/energy_transport/galileo/

European Space Agency
Agence spatiale européenne

Contact: ESA Publications Division
c/o ESTEC, PO Box 299, 2200 AG Noordwijk, The Netherlands
Tel. (31) 71 565 3400 - Fax (31) 71 565 5433