

PROJECT GALILEO, AN OVERVIEW

Sigfrido Leschiutta*° - Patrizia Tavella°

*Politecnico di Torino, Dip. Elettronica
Corso Duca degli Abruzzi 24, Torino, Italy

°Istituto Elettrotecnico Nazionale "Galileo Ferraris"

Strada delle Cacce, 91 – 10135 Torino, Italy

Tel. +39 011 39191, Fax +39 011 346384, E-mail: pres@amm.iien.it

Abstract

Some years ago decision was taken by EC – the European Community Commission – to study the feasibility of a global satellite navigation system; the main requirements were to design a full system, complementary but independent from GPS. An additional requirement was the integrity service. The aim of this paper is to present an overview on the activities performed in the years since 1999 and the major issues insofar agreed.

For this purpose, four points are covered:

- *the main lines of the project, as stands at the end of 2001, pointing out similarities and differences with respect to GPS,*
- *the organization of the research effort mounted in 1999-2001 by EC and ESA (European Space Agency),*
- *the relations with EGNOS (European Global Navigation Overlay System), the counterpart of the American WAAS, and finally,*
- *the developments foreseen at the moment.*

Also the financial envelope will be presented. The aspects related to precise time and timekeeping will be examined, covering the current European projects of clock development, clock synchronization, time scale formation, and the relationship with the UTC community.

INTRODUCTION

For the past few years Europe has been involved in the development of GNSS systems either in the GPS and GLONASS augmentation with the EGNOS project, or in the challenge of building a new, independent, European Global Navigation Satellite System II, called Galileo.

The aim of this paper is to present an overview of the current projects, pointing out the PTTI aspects and the possible future development. Most of the material presented in this paper comes from official documents or Web sites of the ESA or EC [1-10].

GALILEO SYSTEM

Galileo is a joint initiative of the European Commission (EC) and the European Space Agency (ESA). The EC is responsible for the political dimension: it is undertaking studies into the overall system architecture, the economic benefits, and the needs of users. During the current definition phase, ESA is defining the Galileo space and ground segments under an ESA program called GalileoSat. ESA has placed a number of contracts with European industry to develop critical technologies, such as navigation signal generators and highly accurate atomic clocks, and to provide tools to simulate the performance of the whole constellation. The studies supported by the EC will feed into the design of the Galileo constellation and ground segment as well as the political decision-making process [7].

The stages of the Galileo program are as follows [1]:

- *Definition phase (1999-2000)*
- *Development phase (2001- 2005)*
 - ✓ Detailed definition of the segments as a whole (space, ground-based users)
 - ✓ Development of the satellites, ground-based components
 - ✓ In-orbit validation of the system
- *Deployment phase (2006-2007)*
 - ✓ Satellite development and launching
 - ✓ Installation of the complete ground-based component
- *Operating phase*
 - ✓ Satellite renewal, operation of the Centers, maintenance

CURRENT SYSTEM BASELINE

Galileo will be Europe's own global satellite navigation system, providing a highly accurate, guaranteed global positioning service under civilian control. It will be interoperable with GPS and GLONASS, the two other global satellite navigation systems. By offering dual frequencies as standard, Galileo will deliver positioning accuracy down to 4 m. It will also guarantee availability of the service under all but the most extreme circumstances and will inform users within 6 seconds of a failure of any satellite. This will make it suitable for applications where safety is crucial, such as aircraft landing. The full-fledged service will be operating by 2008; 30 Galileo satellites will be in position in be launched in 2004 and by 2006 sufficient should be in place to begin an initial user service. The orbits (medium Earth orbits or MEOs) will be inclined at an angle of 55-60° to the equatorial plane, giving very good coverage of latitudes up to 75° north, that is, up to the North Cape and beyond. Twenty-seven of the Galileo satellites will be operational and three will be active spares. The large number of satellites and the availability of the spares will ensure that the loss of one satellite has no discernible effect on the user. The MEO Galileo satellites may be complemented by a few geostationary satellites. About 14 ground stations positioned over the globe will monitor the satellites' positions and the accuracy of their on-board clocks. The ground stations will be connected to central control facilities in Europe via a dedicated communications network. The control facilities will compute the corrections that need to be sent back up to the satellites via the ground stations. The control facilities will also keep service providers, such as providers of traffic management services, informed about the operating status of the satellites [7]. The current project foresees [5]:

a *Global Component* composed of:

- A constellation of up to 30 satellites in Medium-Earth Orbit (MEO) providing adequate coverage for the provision of the GALILEO services on a worldwide basis. Each satellite will contain a navigation payload and a search and rescue transponder.
- A ground segment in charge of managing the constellation of navigation satellites, controlling core functions of the navigation mission (orbit determination of satellites, clock synchronization) and determining and disseminating (via the MEO satellites) the integrity information (warning alerts within time-to-alarm requirements) at the global level. Implementation aspects of global integrity concept are under evaluation. The Global ground segment will also provide interfaces with service centers, providing value-added commercial services and with the COSPAS-SARSAT Ground Segment for the provision of search and rescue services.

Regional Components including:

- Non-European GALILEO Regional Components, made of ground segments dedicated to GALILEO integrity determination over their specific area if regions choose not to adopt GALILEO's global integrity.
- Regional integrity data can be up-linked directly from each region or, alternatively, routed to the Ground Segment of the Global Component for up-linking to the satellites, together with the Search and Rescue and service provider's data.
- EGNOS, providing integrity and differential correction for GPS and GLONASS through geostationary satellites.

LOCAL COMPONENTS

Some classes of user have local area requirements more demanding than those that will be available from the global system (accuracy, integrity time-to-alarm, signal acquisition/reacquisition, etc.). These special services will be met through the use of augmentation provided by local components.

In addition to providing differential levels of accuracy and stringent integrity time-to-alarm requirements (within 1 second), Local Components can provide services such as:

- Commercial data (corrections, maps, databases)
- Additional navigation signals (pseudolites)
- Enhanced positioning data in areas of poor signal reception (e.g. underground car parks) from GSM/UMTS station-based assisted position calculations
- Mobile communication channels

The design of the GALILEO signal is conditioned to support the operation of local components. An optimum use of those features and capabilities, together with the deployment of complementary local components under the responsibility of the respective service providers, will provide for the commercial exploitation of the GALILEO signals.

User Segment

Consisting of different types of user receivers, with different capabilities related to the different GALILEO signals in order to fulfill the various GALILEO services.

Service Centers

The GALILEO system provides an interface to users and value-added service providers (including local component value added services) through Service Centers. Where appropriate for the different positioning, timing and navigation service categories, these centers perform functions such as providing:

- Information and warranty on performances and data archiving;
- Subscription and access key management;
- Insurance, liability; legal, and litigation management;
- Certification and license information management;
- Commercial interfaces; and
- Support to application development and possible elaboration of R&D approaches.

The precise functions depend on the nature of services provided, where appropriate, Service Centers can also play a role in collecting fees. GALILEO will also provide interfaces with External Complementary System (GPS, GLONASS, LORAN-C, etc.) for the provision of combined services.

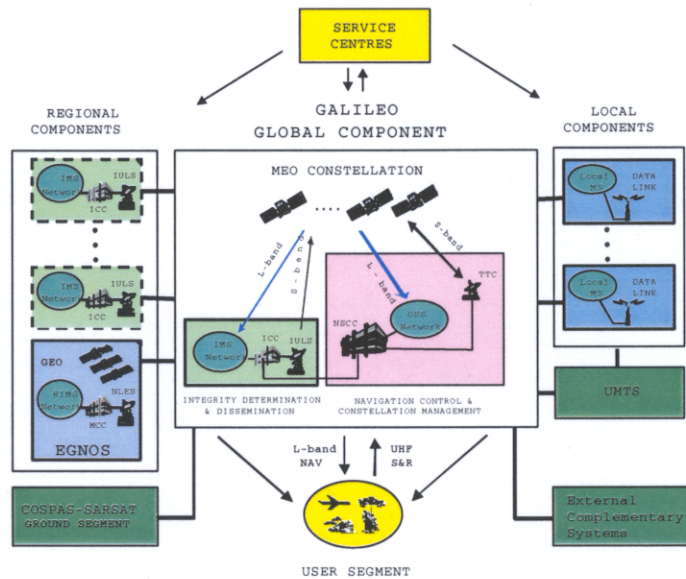


Fig 1. Galileo System Architecture

GALILEO SERVICES

The services that Galileo offers may be listed as follows [6]:

Open Services

- Positioning, navigation, and timing signals provided to users free of charge
- With an horizontal accuracy of 4 meters and a service availability close to 99%
- A precise timing service with an accuracy of 30 to 50 ns (dual frequency) with respect to UTC/TAI
- Performance similar to future GPS, but better performances could be easily obtained by dual constellation usage

Commercial Services (Open Service + Commercial Data)

- Encrypted data available within the Open Service signals to provide a Commercial Service
- This Commercial Service will offer added value with respect to the Open Service
- Performance defined by the service providers based the quality of the commercial data broadcast and by the performance provided by the local components
- Service centers are intended to be deployed to provide a direct interface to end users

Safety of Life Service (Open Service + Integrity Data)

- Warning for loss of integrity within a defined time to alarm limit
- Service availability above 99.9% would make it usable for primary means

- Combination of this service either with the current GPS as augmented by EGNOS corrections, or the future improved GPS and EGNOS integrity-only, will support CAT-1 performance and offer the prospect of sole means availability

Public Regulated Service

- Robust and resistant to interference, jamming, and other accidental or malicious aggressions
- Position and timing information on dedicated protected frequencies
- The signals will include encrypted ranging codes and data
- Access controlled by the EU Member States, restricted to EU users and users from other participant States authorized by the EU Member States

Search and Rescue (SAR) Service

GALILEO will extend the current COSPAS-SARSAT SAR mission in providing benefits such as:

- improvement of the time-to-detection and the accuracy of location of distress beacons
- provision of an acknowledgment of receipt of the distress message

Navigation-Related Communication Service

- The baseline for this service is the combined use of GALILEO with an existing wireless, terrestrial (e.g. GSM/UMTS), or satellite network
- A communication transponder onboard GALILEO is currently under evaluation
- This service would be appropriate for regulated applications requiring global and high availability and reliable position reporting

Satellite-based Augmentation Related Services

- Including EGNOS, satellite-based augmentation services are also part of the detailed definition phase
- The European GALILEO Regional Components, made of ground segments, dedicated to GALILEO integrity determination over their specific area

WORK IN THE YEARS 1999-2000

From [2], these are the main projects pursued in the past 2 years:

- GEMINUS, which defines the services which need to be provided by Galileo, based on critical review of user requirements and analysis of business, institutional, and market structures;
- GALA, which specifies the Galileo overall architecture necessary to meet the user requirements, trades off the various options for delivering the service and apportions the resulting requirements amongst functional elements. Schedule and cost data can then be assessed and traded off against potential revenue streams;
- INTEG, which provides the optimum method for integrating EGNOS (the European Navigation overlay service) with Galileo, to maximize infrastructure reuse whilst ensuring service continuity;
- SAGA, which develops the standards upon which Galileo data will be utilized for a range of services; it also aims at supporting the international standardization groups dealing directly or indirectly with navigation, positioning, and timing
- GalileoSAT, under the auspices of ESA, which defines the Space segment and related ground

segment needed to fulfil the space segment requirements specified within GALA

Some other specific programs were also added as:

- Search and Rescue on Galileo SARGAL
- Certification of Galileo receivers GUST

ESA are also conducting, or planning, a range of other studies, concerning technologies related to Galileo. These include:

- GalileoSat System Simulation Facility (GSSF),
- Hardware developments (rubidium & H-maser clocks, solid state power amplifier and multiplexer, onboard wideband antenna)
- A number of studies are in preparation, including Galileo System Test Bed (GSTB), TT&C transponder, and onboard signal processor.

From the results of the EC studies [2], particularly interesting is the change foreseen in the European GNSS market from 1999 to 2005 as reported in [6] and depicted in Fig. 2.

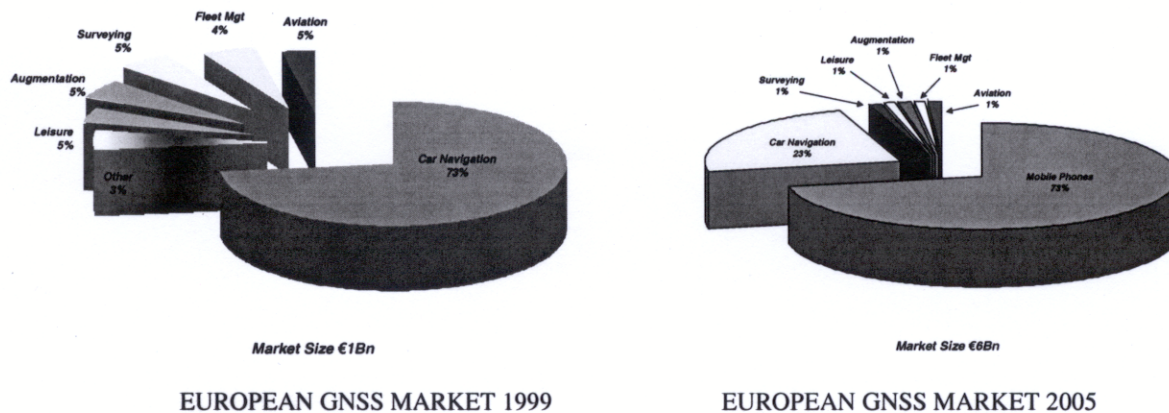


FIG. 2.

CURRENT ACTIVITIES

The current activities in the frame of the EC concern a large study called *GALILEI*, whose tasks include [6]:

- local *Element Definition*
- impact of *Interoperability* on the system definition
- *frequency* allocation and protection, certification, and standardization
- detailed *Service Analysis*
- legal, institutional, and *regulatory* framework for GALILEO

In addition, some activities initiated during the Definition Phase are still in course:

- GENESIS Thematic Network

- SAGA

Inside ESA, the main project is called “*Galileo Phase B2*,” whose main tasks are:

- a mission and system requirements consolidation
- preliminary system design iterations, and production of associated Design Justification Files and performance budgets
- consolidation of development, deployment, verification, and in-orbit validation plans
- program schedule and cost assessment, in order to ensure a design-to-cost implementation approach
- finalization of the technical documentation to be used to start the next phase

Other projects concern:

- development of pilot projects and user tools
- Development of a business plan for GALILEO to be used also as a basis for defining conditions for private sector participation
- Setting-up of the GALILEAN Thematic Network to promote and foster the development of satellite navigation applications

GALILEO ORGANIZATION

The European Commission, ESA, and private industry are expected to meet the 2,900 million Euro estimated cost of Galileo through a public/private partnership (PPP). The nature of the PPP has yet to be worked out and will depend partly on the outcome of studies and trials to determine the nature and size of the revenue stream that Galileo is expected to deliver to industry. An early study by consultants, however, suggested that Galileo will repay its initial investment handsomely. The study estimated that equipment sales and value-added services will earn an extra 90 billion Euros over 20 years, a substantial proportion of which will return to government exchequers through taxation. Other, more recent studies have arrived at even higher estimates by considering potential earnings from value-added services that combine Galileo positioning with other services provided by the new generation of mobile phones (GSM/UMTS), such as Internet services. So far, the EC and ESA have agreed a common action plan, but have financed the industrial definition studies and critical technology developments separately. Funding on the EC side has come from the European Union’s 5th Framework program of research and development and on the ESA side from the Agency’s GalileoSat definition program. Different arrangements, however, will be put in place for the development phase, which is due to start early in 2001. The development phase can be divided into three, each of which could operate under different financial arrangements. Stage one is known as initial validation. This stage will be financed from EU infrastructure and development funds and through the ESA GalileoSat development and validation program. It involves a number of critical checks on technologies and will probably include building and launching three or four satellites and the associated ground segment for testing before embarking on the rest of the project. Stage one is estimated to cost 1,000 million Euros. Stage two, which would bring the Galileo system to initial operational capability, involves adding a further dozen or more satellites at a cost of about an extra 1,000 million Euros. This initial operational capability is sufficient to demonstrate a limited, but effective, service to users from which future commercial benefits can be accurately judged. Stage three involves completing the constellation by adding 15 more satellites at a further cost of 0.9 billion Euros. This full constellation will meet the ultimate targets on service availability and guarantees [1].

GALILEO PROGRAM COST [1] (INCLUDING EGNOS), IN MILLIONS OF EUROS

220 PER YEAR	OPERATING PHASE (2008-)
2.150	DEPLOYMENT PHASE (2006-2007)
1.000	DEVELOPMENT AND VALIDATION PHASE (2001-2005)
80	DEFINITION PHASE (1999-2000)

As a latest decision, two new bodies should be established before the creation of the GALILEO Agency and the Operational Company [6]:

1. *The GALILEO Interim Support Structure (GISS) Just Established*

Twenty-five experts based in Brussels to assist the European Institutions before the establishment of the GALILEO Joint Undertaking. The team reports functionally to the GALILEO Programme Board (PMB). In charge of the harmonization, it is under the authority of the GALILEO PMB of the proposals submitted to ESA PB-NAV and to the GALILEO Steering Committee. GISS Tasks include:

- Definition of infrastructure, services, and mission requirements,
- Assessment and proposals for a Public Private Partnership,
- Standardization,
- Support for international negotiations, integration, and promotion of EGNOS, and
- Consolidation and maintenance of the overall GALILEO program work-plan

2. *The Joint Undertaking (JU)*

Statutes prepared in close cooperation with industry and to be discussed in the next Transport Council meeting. The GALILEO Joint Undertaking will be:

- A single legal entity based in Brussels,
- Composed of EC, ESA, EIB, and companies subscribing to the JU capital,
- In charge of the overall management of GALILEO from 2002 onwards (initial duration: 4 years),
- Responsible for the implementation of the development of the constellation and the related ground infrastructure as well as the exploitation phase

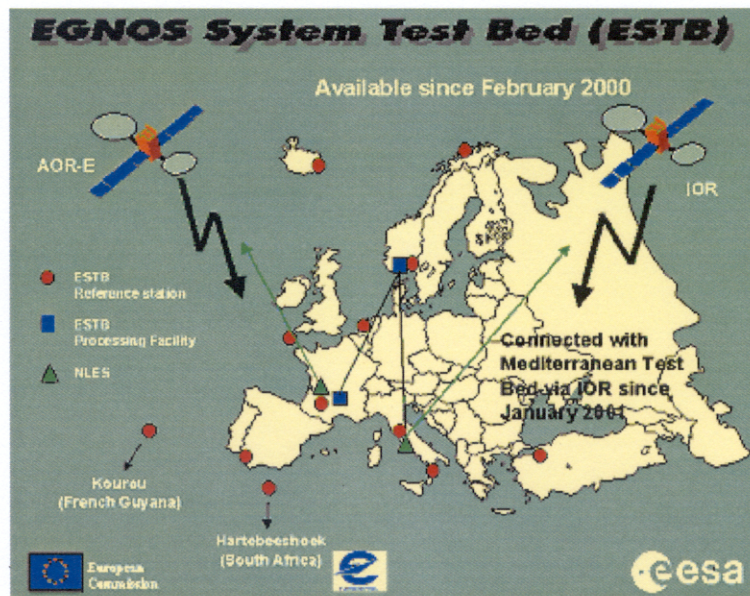
NEXT POLITICAL STEPS [6]

- Autumn 2001: The signatories of the Memorandum of Understanding to confirm their commitment to the amount of 200 million Euros
- November - December 2001: ESA and EU Councils' establishment of the final management structure and release of the remaining budget provided for carrying out the development phase
- Before end of 2003: final selection of GALILEO services, decision to enter in the deployment phase

EGNOS

EGNOS is Galileo step 1 and will evolve into one of Galileo's Regional Components. EGNOS [8] is Europe's first venture into satellite navigation. It will augment the two military satellite navigation

systems now operating, the US GPS and Russian GLONASS systems, and make them suitable for safety critical applications such as flying aircraft or navigating ships through narrow channels. Consisting of three geostationary satellites and a network of ground stations, EGNOS will achieve its aim by transmitting a signal containing information on the reliability and accuracy of the positioning signals sent out by GPS and GLONASS. It will allow users in Europe and beyond to determine their position to within 5 m, compared with about 20 m at present. EGNOS is a joint project of the European Space Agency (ESA), the European Commission (EC), and Eurocontrol, the European Organisation for the Safety of Air Navigation. It is Europe's contribution to the first stage of the global navigation satellite system (GNSS) and is a precursor to Galileo, the full global satellite navigation system under development in Europe. EGNOS will become fully operational in 2004. In the meantime, a test signal, broadcast by two Inmarsat satellites, allows potential users to acquaint themselves with the facility and test its usefulness.



EGNOS design, development, and validation will cost about 300 million Euros. ESA is contributing 200 million Euros (member states and European national [civil aviation] organizations) and the European Commission 100 million Euros. Before EGNOS becomes fully operational in 2004, airline pilots and others equipped with an EGNOS receiver can tune into a test signal broadcast by one of the EGNOS satellites, Inmarsat AOR-E (Atlantic Ocean Region – East). Test signal broadcasting began in February 2000. The area over which it is available will be extended shortly when Inmarsat IOR (Indian Ocean Region) also begins broadcasting on a continuous basis later this year. The redundancy that will be built into the full-fledged service is not yet available, as only a fraction of the full complement of EGNOS ground facilities are operating. Only about 10 ranging integrity monitoring stations (RIMS), dotted about Europe, and one processing center are collecting data for modulation onto the EGNOS signal. The RIMS send the data they have collected on the GPS and GLONASS signals to a single processing center in Norway, which computes the corrections needed for each satellite and incorporates them into a signal. The processing center then sends the signal via terrestrial networks to a station in Toulouse, France for up-linking to the AOR-E satellite. It will shortly also send the signal to a station in Fucino, Italy for up-linking to the IOR satellite. EGNOS users will receive the signal from one of these two satellites on specially designed EGNOS receivers. Since the first EGNOS signal was switched on, around 10 demonstrations and one workshop for potential users have been held. Information on the EGNOS test bed is available at <http://www.esa.int/navigation>.

According to some estimates, the worldwide market for satellite navigation could be worth as much as 50,000 million Euros by the year 2005.

Although all Satellite-Based Augmentation Systems (SBAS) are regional systems, it is important to ensure that they are compatible and that SBAS providers cooperate with each other and coordinate their actions. Compatibility will make each system more effective and ensure that all the systems can be integrated into a seamless worldwide navigation system. SBAS cooperation is currently coordinated through the Interoperability Working Groups EGNOS/MSAS and EGNOS/WAAS [8].

PTTI IN GALILEO

The current GalileoSat system baseline [9] is comprised of a constellation of 30 MEO satellites. Each MEO-satellite is designed to carry two passive hydrogen masers (one is the nominal onboard reference) and two rubidium clocks (one is in hot-redundancy to the hydrogen maser). The clocks are monitored by the Orbitography and Synchronisation Stations (OSS) network globally distributed on Earth equipped with a rubidium clock with redundancy. On the ground two Precise Timing stations (PTS) are foreseen, in each of which a family of atomic clocks (12 cesium standards and two active hydrogen masers) establish the Galileo time reference and provide timing inputs to the system. From the pseudorange measurements of the OSS stations, a ground data processing center uses an Orbit Determination and Time Synchronization algorithm to estimate the orbits and the time error of each clock.

When all clock comparison measurements are available, the Galileo System Time (GST) is established by means of a weighted average of all the clocks used either on-ground (OSS and PTS) or on-board. The computation includes:

- ✓ Determination of the weights in the clock ensemble for each participating clock
- ✓ Prediction of the clock frequency
- ✓ Detection of clock anomaly

After the GST is generated, it is compared with the UTC (k) generated by one or a few external laboratories and, by means a suitable algorithm, GST is steered versus TAI. Therefore, GTS is the final product of a statistical average and of frequency steering. Finally, the reference H-maser is physically steered versus the GST, having in this way a physical representation of the GST itself.

The specifications of the GST accuracy and stability are quite demanding:

- ⇒ The GST time offset from TAI should be less than 50 ns (95% confidence interval on a yearly basis) with an uncertainty of 33ns (95% confidence interval).
- ⇒ The frequency stability in terms of the Allan deviation of GST shall be better than 5.5×10^{-14} over 1 day and better than 1.0×10^{-14} over 30 days.

Each of the 30 satellites in the Galileo system will have on board two rubidium atomic frequency standards and two passive hydrogen masers. The passive hydrogen maser is being built by the Observatoire de Neuchatel in cooperation with Officine Galileo of Italy, the former being responsible for the overall development and in particular for the so-called physics package, and the latter being in charge of the electronics. A similar arrangement applies for the rubidium clock, with Temex Neuchatel Time assuming overall responsibility and Astrium, Germany contributing the electronics. The rubidium clock should be ready for qualification by the end of 2001, by which time an engineering model of the hydrogen maser should be available. Both clocks will really show their capabilities in 2004, when the first Galileo satellites go on trial. ESA is considering also new technologies for longer-term application, where technology diversity and diversification in procurement policy are important factors [10]. In particular, in Europe the following projects are pursued:

- Improvement on Rubidium Atomic Frequency Standard with the objective to reduce the flicker floor to 2×10^{-14}
- Feasibility study of a Space Cs Optically Pumped (SCOP) clock by a French consortium financed by CNES
- CPT maser currently investigated at IEN in Italy
- Parallel development of an optically pumped rubidium clock

Open Issues:

- Use of TWSTFT for synchronizing the 2 PTS and the UTC(k) labs
- Experimental verification of the Orbit Determination and Time Synchronization accuracy evaluated to be at the level of 1 nanosecond
- Insertion of an external Time Provider that could offer the whole services of maintaining GST synchronized to TAI.

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QUESTIONS AND ANSWERS

SIGFRIDO LESCHIUTTA (Politecnico di Torino and Istituto Elettrotecnico Nazionale): I asked the Chairman's permission to make sort of a celebration with you. I would like to propose to you to celebrate to some extent the first common-view experiment ever performed in America. That experiment was performed not far from here, about 4 or 5 kilometers from this room, where the Los Angeles River meets the ocean. That very important experiment was performed 4 centuries and 25 years ago by the Spaniards when they tried to see how wide the earth was.

A common time reference was used, a lunar eclipse, when the moon entered on the cold shadow of the earth. You know very well that this is a common time reference for all the earth in position to see the moon at that very moment. The Spaniards made a westernmost station here. At the time, this place was called Santa Maria del Los Angeles and Portupela, but the station was installed only at the end of the river. One other station was in Mexico. A station in Spain, and another station was on the western coast of India.

The final results were very interesting. The time difference between here and Toledo was obtained with an error of 8 minutes. Please remember that no mechanical clocks were available, so they were forced to keep the time all day using sand glasses, *botellas* as they were called. And so they made an error of 2 degrees in the difference of longitude. The results from India never arrived at Spain because on that very day it was raining over there. Thank you.