GALILEO :

Satellite System Design and Technology Developments

J. Benedicto, S.E.Dinwiddy, G. Gatti, R. Lucas, M. Lugert

European Space Agency

November 2000

Abstract

During 1999/2000 the GALILEO system has been defined by a number of studies let by the European Commission and the European Space Agency. The architecture for the GALILEO space segment and related ground segment has been studied in detail, arriving at a constellation of thirty satellites that will be able to meet the European service requirements. ESA has also initiated associated technology developments for a complete range of critical satellite hardware equipment.

Introduction

Navigation satellites already guide ships, planes and spacecraft. They provide the surveying reference for roads, bridges and cities and the time reference for power and telecommunications networks. They help cars, buses, taxis and ambulances to find their way along roads and help walkers, climbers, pleasure boats and golf buggies to find their way off the road. Quite soon, mobile phones will be equipped with navigation receivers, opening the way for a wide range of new services.

The popularity of GPS, despite its origin as a military system, and the fragility of the Russian GLONASS System, currently comprising too few satellites to offer a reliable service, together underline the strategic importance of navigation satellites to modern society. Accordingly, the European Transport Council decided in June 1999 to engage in the GALILEO Definition Phase and to take a decision on the implementation of GALILEO by the end of 2000. The member states of ESA decided in parallel on the complementary GALILEOSAT Programme, which is to cover part of the definition studies and the development of the GALILEO space and related ground segments, including the in-orbit validation of GALILEO.

The GALILEO initiative comprises the independent global GALILEO satellite constellation and associated augmentations and systems and also the integration of the EGNOS service. This paper describes the main technical features of the GALILEO space and related ground segments as they emerge from the current definition studies and also introduces the key technology developments that are sponsored by ESA.

Service Requirements

GALILEO is specified to be usable as a stand-alone, global system, yet it will be inter-operable with other services, such as GPS, and it has been declared as open to international co-operation. It is to provide state-of-the-art positioning and timing services with adequate guarantees and availability. Service guarantees are also to be offered by the independent GALILEO Integrity service. In addition, revenue-generating services, either in combination with other systems or as an integral part of the GALILEO infrastructure, are being studied. At the present time a Search and Rescue service according to COSPAS SARSAT standard forms integral part of the baseline.

Two basic accuracy requirements were identified as the objective for the Definition Phase, as shown in Table 1.

Primary Application	**Mass Market**	**Safety Related**
User Masking Angle	25°	5°
Accuracy (95 % confidence)	10 metres horizontal	4 metres vertical
Coverage	Global	
Availability	Better than 70%	Better than 99%
Integrity	Not generally required	Mandatory

Table 1: Navigation Service Requirements

The "Mass Market" requirement, applicable with limited view of the sky as seen by vehicles or mobile receivers in towns, encompasses most of the road and communication-related applications. The moderate-availability target for the GALILEO signal takes into account that mass-market users normally do not require the signal at all times as they will be able to receive signals also from other systems or sensors.

The "Safety-Related" requirement, applicable with good visibility of the sky as seen by ships at sea or aircraft in flight, is aimed primarily at safety-of-life applications. 4 metres is the vertical accuracy requirement for civil aviation CAT-I precision approach and landing.

GALILEO is required to provide navigation signals comprising ranging codes and data messages. The data messages will be up-linked to GALILEO satellites from the ground, stored on board and transmitted continuously using a packet data structure that will allow urgent messages to be relayed without delay and will allow the repetition frequency of all the various messages to be optimised.

The data messages are foreseen to include not only the measured satellite clock epoch, relative to GALILEO System Time (GST) and the measured satellite ephemeris which, together with the satellite identity and status flag, are the essential elements to allow the user receiver to calculate its position, but also a constellation almanac, which will allow the user receiver to search quickly for new satellites, and a Signal-In-Space-

Accuracy (SISA) signal. This SISA will give the user a prediction of the satellite clock and ephemeris accuracy over time from its last up-date, which will allow the receiver to weight the measurements of each satellite and improve its navigation accuracy.

Provision is made for the broadcast of Integrity messages, determined by independent global or regional integrity networks, monitoring the GALILEO constellation and possibly also other navigation-satellite constellations.

For revenue-generating services data broadcast services by means of some navigation signals could be an important element, so industry has been requested to study the feasibility of providing extra data broadcasting capacity without compromising navigation accuracy.

Distress signals from standard 406 MHz Search and Rescue distress beacons are relayed to the COSPAS-SARSAT service centres trough a transparent payload on each GALILEO satellite. The GALILEO Search and Rescue service will allow reduction of the alarm detection time and will also reduce the incidence of false alarms. The GALILEO Search and Rescue service could also relay responses, such as distress acknowledgements or co-ordination messages generated by the COSPAS-SARSAT service, back to the user by integrating such messages into the navigation data message stream so that they could be received by any Search and Rescue user equipped with a suitable GALILEO navigation receiver.

Constellation Optimization

The key to the overall system design is the constellation. Based on earlier studies, the Definition Study has concentrated on two options, one using satellites in MEO (medium Earth orbit) and the other using a mix of MEO + GEO (geostationary Earth orbit) satellites. Emphasis has been put on providing high quality services globally and in particular over all of Europe including the Northern latitude regions.

In order to be able to guarantee services for commercial and safety-of-life applications, the constellation is designed to be very robust to satellite failures while still being economically viable. The constellation optimisation exercise used the two target performance specifications shown in Table 1.

A novel aspect in the optimisation process has been the interpretation of the availability requirement. In the past, satellite navigation availability has been measured in terms of mean values, obtained by multiplying the availability achieved by each state of the constellation (full constellation, full constellation with one satellite failure, with two failures, etc.) with the probability of the constellation being in this state. With this computation, all information on how performance outages evolve over time is lost and two constellations may present similar mean availability results with different distribution of outages. Industry instead proposed that the outage information be retained by specifying availability for each state. This will allow recognition that, in the “no-failure” case, the performance is met at all locations for all the time and that failures will lead to “holes” in the performance which can be predicted and notified. It will also allow performance to be expressed in typical “Quality-of-Service” (QoS) terms of availability over defined periods of time (1 day, 1 month or 1 year).

Often, performance of satellite navigation systems is only assessed for low masking angles, perhaps due to civil aviation heritage. It is therefore interesting to note that, in the first round of analyses, the “MEO-only” and “MEO + GEO” constellations were found to be very similar for the “Safety-Related” specification while the “Mass-Market” specification showed noticeable differences, especially when considering the different failure states. This is seen in comparing the “two-failure” availability curve for the MEO-only constellation, shown in Figure 1, with the much lower “one-failure” availability curve for the MEO + GEO constellation, assuming one GEO already failed, so that there are two failures altogether, shown in Figure 2. These results, together with the recognition that the “holes” caused by MEO failures tend to move around so that no place is affected for long while the “holes” caused by GEO failures stay over one region led to the preference for the MEO-only constellation.

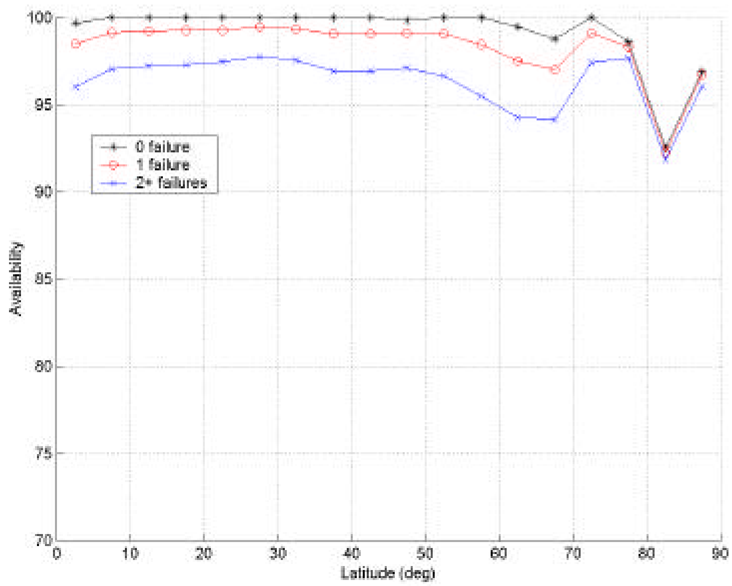

Figure 1: Availability of “Mass-Market” performance with a 30-MEO constellation

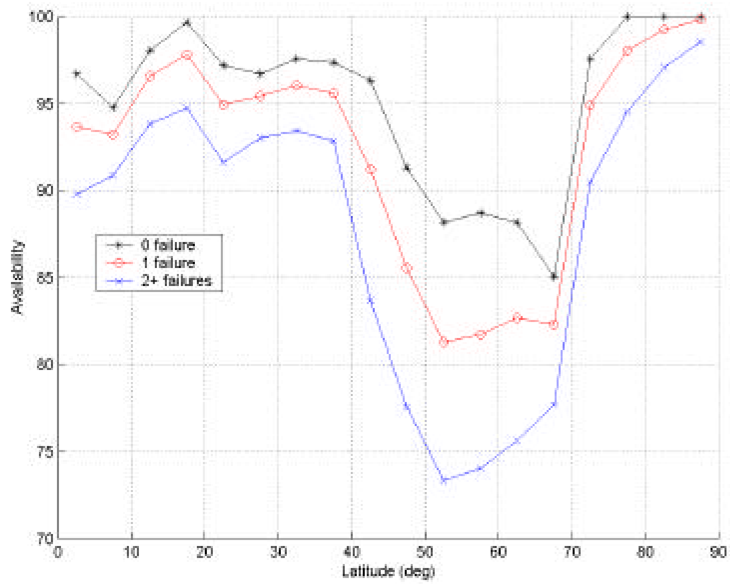

Figure 2: Availability of "Mass-Market" performance with a 24 MEO + 8 GEO constellation assuming one GEO failure

The second stage of analysis involved examination of the strategy for replacement of failed satellites, in which concepts of spares-on-ground and spares-in-orbit were compared. A single spare satellite on the ground can be used to replace any failed satellite in the constellation but about five months has to be allowed to launch a spare from the ground. A spare satellite in orbit can only be used to replace a failed satellite in the same orbit plane (unless it carries a very large fuel reserve), so one spare in orbit is needed for each orbit plane. However, only about five days are needed to move a spare in orbit around the orbit plane to replace a failure. The analysis compared a MEO constellation with 30 operational satellites, launching a new satellite to replace each failed satellite, with a similar constellation with 27 operational satellites plus 3 in-orbit spares, using the spare to replace a failed satellite and launching a new satellite to replace the spare. Both constellations met the "Safety-Related" performance when all satellites are working, but the mean probability over 20 years of all satellites working is over 90 % for the "27 + 3" constellation but less than 70 % for the "30 + 0" constellation. In the event of a satellite failure, the availability with the "27 + 3" constellation is lower than that with the "30 + 0" constellation. However, the failure can be repaired so much more quickly that the overall probability of occurrence of a failure case is much lower with the "27 + 3" constellation. The position accuracy obtained against the "Safety-Related" requirement is illustrated with Figure 3.

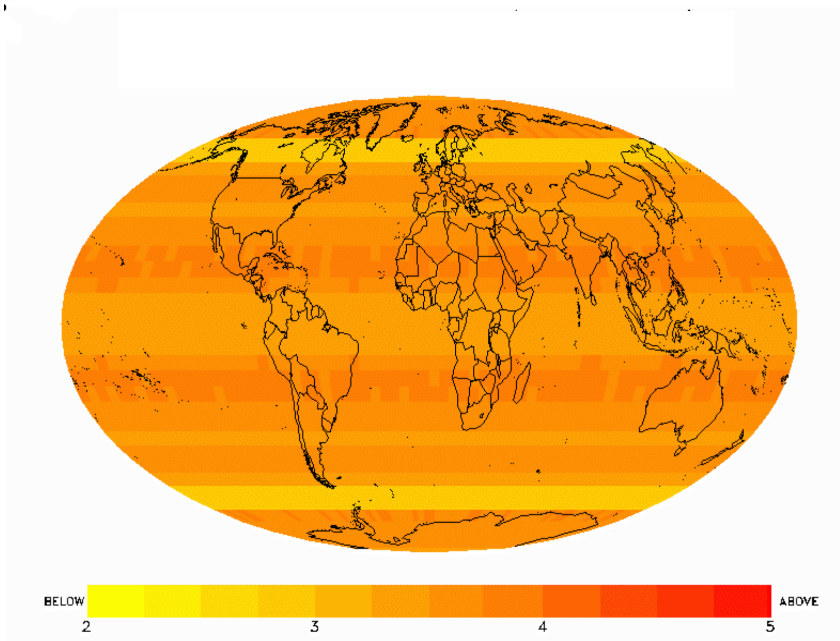

Figure 3: Vertical accuracy obtainable with MEO constellation
(Range: 2 to 5 metres)

The MEO constellation has three planes, all with an inclination of 56 degrees, with equally-spaced operational satellites, all at an altitude of 23222 km, in each plane. The orbital parameters of each satellite (altitude, mean anomaly etc.) have been finely tuned in order to reduce the number of satellite manoeuvres required to maintain the constellation throughout the life-time of the satellites. This factor increases availability of service as well as allowing fuel savings that contribute to the reduction of deployment costs. The constellation is illustrated in Figure 4.

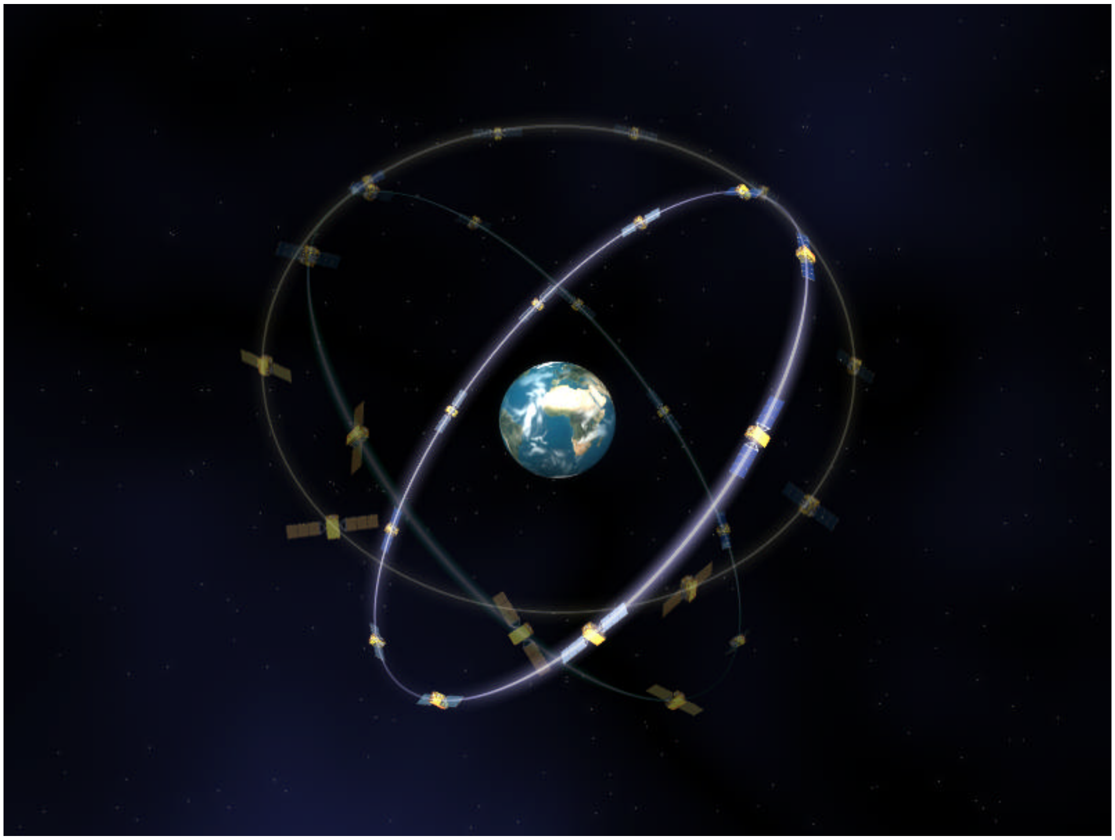

Figure 4: Illustration of MEO constellation

Frequencies and Signals

The GALILEO satellite is being designed to support the transmission of up to four carriers in L-band making maximum use of RNSS allocations, including the new allocations made by WRC-2000.

The baseline frequency plan is still subject to finalisation, pending the results of studies within Europe and negotiations with other countries. A previous paper in this Journal [1] has discussed this aspect in more depth.

The use of pilot components (a ranging code with no data message) is expected to be incorporated in several of the carriers. The use of pilot signals improves the performance for very low received power levels. Studies by Industry have shown that the mean-time-to-loss-of-lock for carrier tracking is significantly reduced. The pilot is also good for coping with multipath errors in dynamic environments, such as are encountered during aircraft landing. In this case it has been found that, by tracking the pilot signal with a narrow pre-detection filter (which is possible because the pilot signal has no modulating data), the multipath error can be reduced to about one third of that of a signal modulated with data.

A wide range of data message rates, from 250 bit/s to 1500 bit/s, is being considered. Low data rates cause minimum disturbance to the navigation signal. High data rates maximise the potential for adding ancillary messages, for which a wide range of applications can be imagined (as shown in Table 2).

Ancillary Messages for Safety Applications	Ancillary Messages for Commercial Use
Integrity Messages; Search and Rescue Messages: Distress Acknowledgements, Co-ordination Messages; Weather Alerts: Storm Warnings, Flood Warnings etc.; Accident Warnings etc.	Map Updates; Temporary Map Changes: Diversions, Traffic Jams etc.; Extra Map Information: Petrol Stations, Restaurants, Hotels etc.

Table 2: Potential Ancillary Data Messages

The use of diversity reception techniques is also being analysed. With this technique, signals from different satellites are combined at signal sample level before data demodulation. This can improve data reception under extreme fading, for example due to interference, or poor visibility conditions, for example in an urban environment. Diversity reception requires synchronisation of the data broadcast from different satellites and some means to inform the user of which satellites are transmitting synchronised data that can be used for diversity reception.

Navigation Accuracy

There are several contributors to the accuracy of a satellite navigation system. These are conveniently grouped into DOP, signal effects and UERE.

DOP is dilution of precision, which measures the effectiveness with which a satellite constellation provides the ideal geometry of at least four satellites at widely spaced angles across the sky. DOP is already included the accuracy predictions of Figure 3.

Signal effects, arising from the ability to derive precise timing from the incident radio waves, are dependent on the modulation type, the chip rate, the available bandwidth and the effectiveness of the ranging code, discussed above.

UERE is User Equivalent Range Error arising from imperfect prediction of the satellite orbit determination and time synchronization (OD&TS), imperfect correction of ionospheric and tropospheric delay and distortion of the signal due to multipath reflections in the vicinity of the receiver (for example, from buildings near a vehicle or from the vehicle itself, as the wings of an aircraft parts or the superstructure of a ship).

Studies show that the OD&TS error can be maintained to within 65 centimetres, by using a world-wide network of orbitography and synchronisation stations (OSS) performing continuous measurements of all satellites.

Ionospheric delays, which vary with frequency, can be corrected by receiving two signal frequencies (one in the upper band and one in the lower, for example “E1” and “E5”). The residual error is not easy to predict. One of the main problems is how to deal with multipath effects on the dual frequency measurements and how to avoid being either too pessimistic or too optimistic. The pessimistic case is to consider that all the multipath error in each of the frequencies will be de-correlated so that the amplification factor due to the dual frequency measurement applies to all the multipath error. The optimistic case is to consider that multipath will not be amplified by the dual frequency measurement at all. As the analyses are not yet concluded, we consider here the UERE without the multipath contribution.

It is not possible for the receiver to correct for tropospheric delay, so correction will require the broadcast of a model.

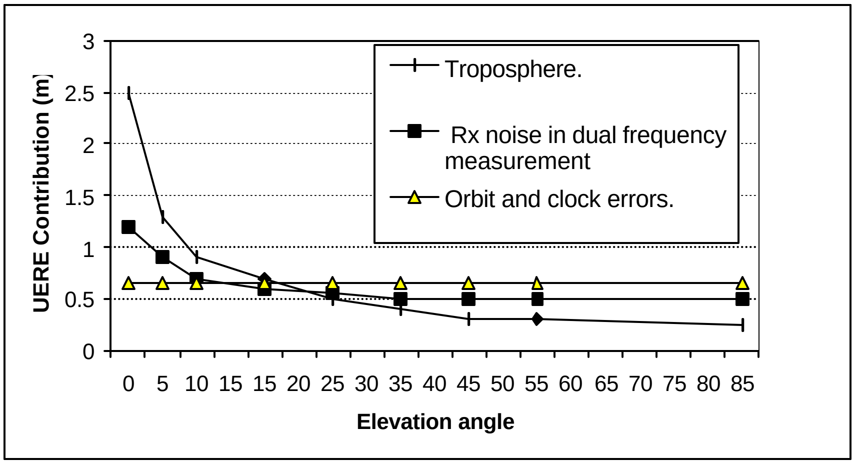

Figure 5: Contributions to UERE with dual-frequency (“E1”/ “E5”) reception

For low elevation angles, the main sources of error (apart from multipath) are the tropospheric residual and the receiver noise, as shown in Figure 5. The orbit determination and time synchronization error is similar to the combined error introduced by the residual tropospheric delay and the receiver noise above 30 degrees.

GALILEO Satellites

The GALILEO satellites are of the medium-size class, weighing some 650 kg in final orbit and generating some 1500 Watt of electrical power. The satellite geometry, as illustrated with Figure 6, has been designed for launch of multiple satellites with ARIANE or similar launcher, as illustrated with Figure 7. Smaller launchers are envisaged for replacement of failed satellites and for the initial in-orbit validation tests. The satellite body rotates around its Earth-pointing (yaw) axis to allow the solar arrays to rotate and point directly towards the sun. Figure 8 shows the block diagram of the navigation payload.

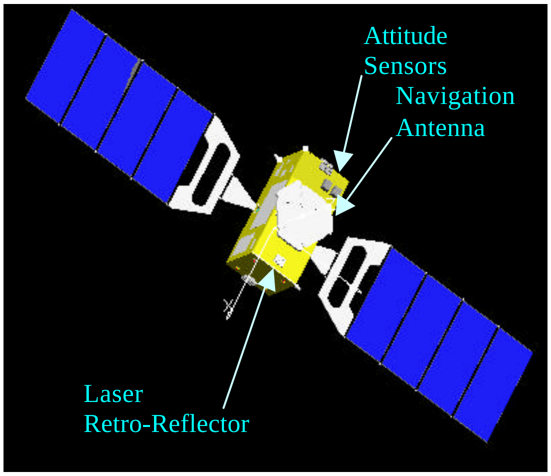

Figure 6: Artist's Impression of GALILEO Satellite

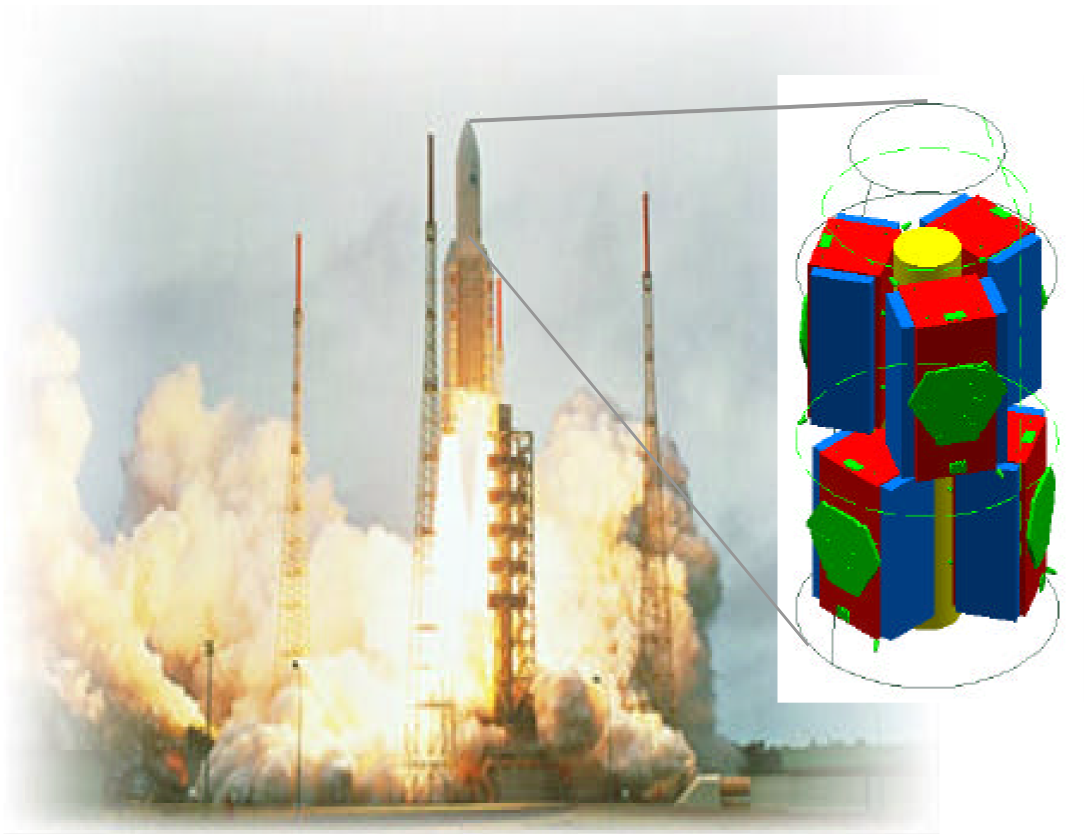

Figure 7: Illustration of Multiple Satellites Launch

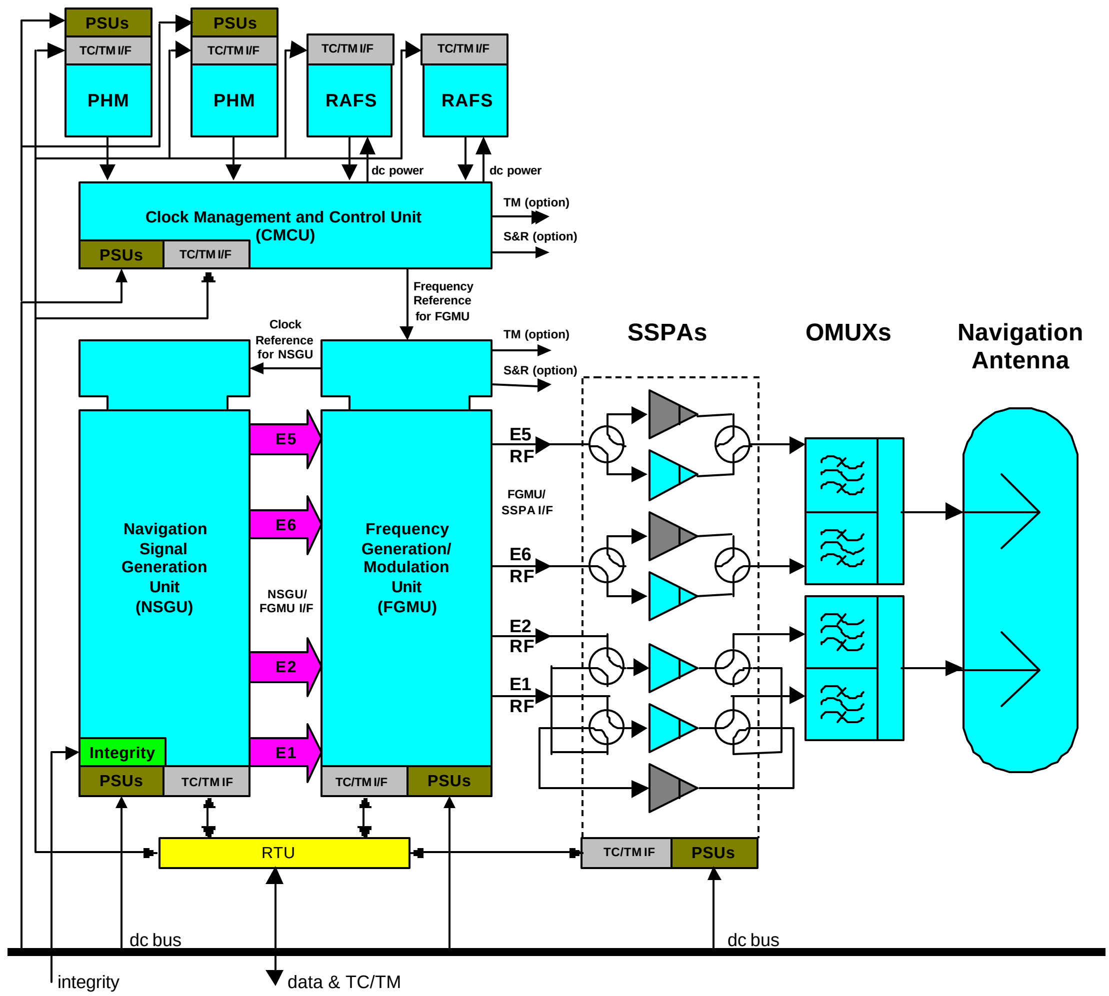

Figure 8: GALILEO Navigation Payload Block Diagram

GALILEO Ground Control System

After detailed analysis of the functions and operation of the GALILEO Ground Control System, a baseline architecture has been defined comprising a Navigation System Control Centre (NSCC), a global network of unmanned Orbitography and Synchronisation Stations (OSS) and a number of remote-controlled Tracking, Telemetry and Command (TT&C) Stations, as shown in Figure 9. The ground segment required for integrity determination and dissemination is treated as a complementary function though many of the stations and other facilities will be co-located with the main ground control system.

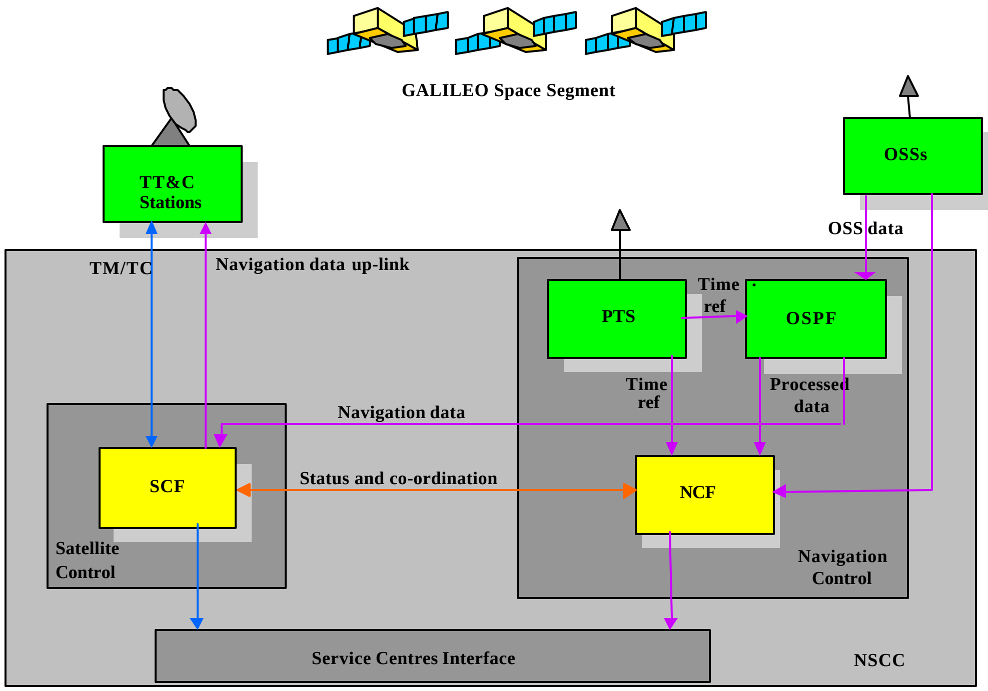

Figure 9: The GALILEO Ground Control System

Each OSS collects one-way pseudo-range raw measurements, referenced to a local atomic reference clock, together with navigation messages received from all GALILEO satellites within visibility and submits all this, together with local meteorological and other data, to the NSCC.

Within the NSCC, the Satellite Control Facility (SCF) provides satellite housekeeping and orbit control and provides telemetry, telecommand and two-way ranging links via the TT&C Stations, both during nominal satellite operations and during the launch and early orbit phase (LEOP) and contingency operations.

The navigation facilities in the NSCC comprise:

- the Orbitography and Synchronisation Processing Facility (OSPF),
- the Precision Timing Station (PTS),
- the Navigation Control Facility (NCF).

The OSPF periodically processes the signals from the OSSs to compute the ephemeris data for each satellite, the on-board clock offset data for each on-board clock and to predict the evolution of these parameters in order to generate the SISA (signal-in-space accuracy) for each satellite as a function of time.

The data sets generated by the OSPF are routed via the SCF and the TT&C station network to the relevant satellite, for incorporation into its Navigation Data Message.

The Precision Timing Station (PTS) comprises an ensemble of high performance atomic clocks, which generates GALILEO System Time (GST), which is also the time reference for an OSS located in the NSCC.

A special-purpose OSS will be installed at selected timing laboratories to determine the off-set of GST relative to UTC (Coordinated Universal Time) and to permit steering of GST to TAI (International Atomic Time).

The Navigation Control Facility (NCF) provides the overall monitoring, control and management of the OSPF, OSS, PTS and NCF.

The Service Centres Interface provides the point of contact with external entities and service providers as shown in Figure 10.

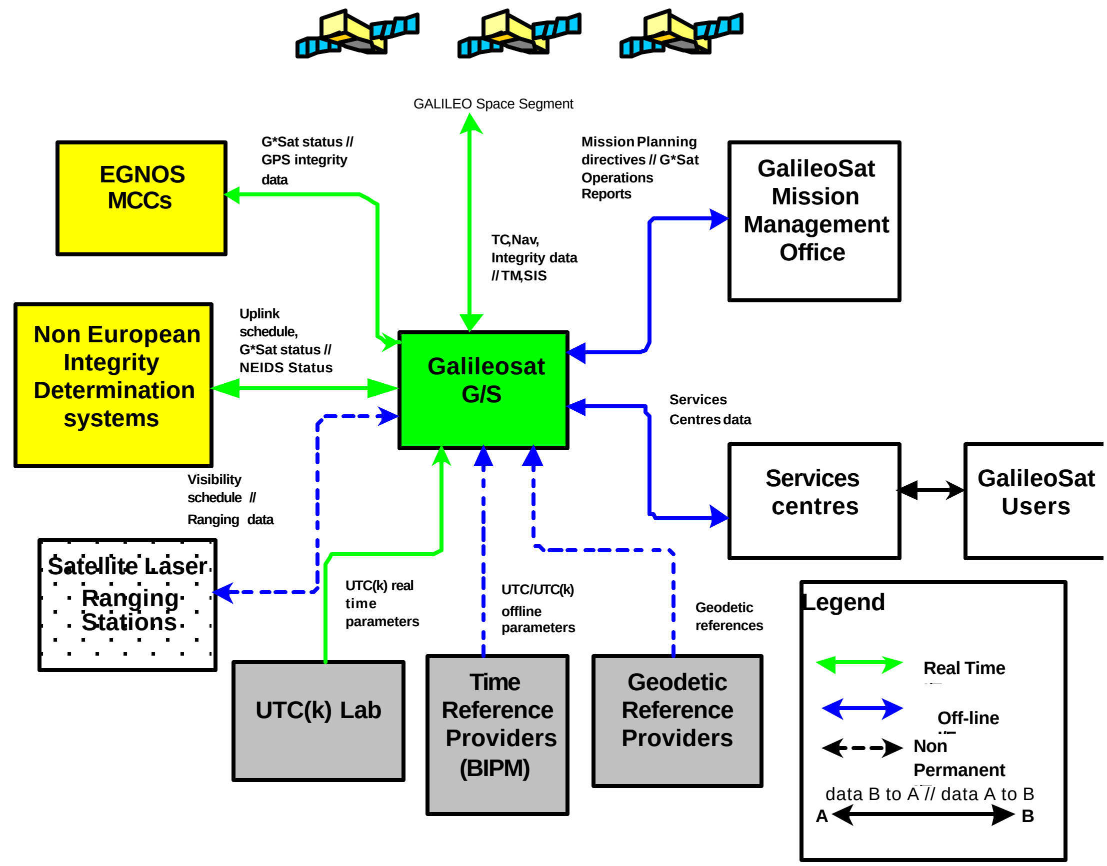

Figure 10: GALILEO Ground Segment External Interfaces

Integrity

A key asset of GALILEO will be its ability to offer the integrity required for the provision of service guarantees and for the support of safety-of-life applications. It is planned to provide integrity by broadcasting integrity alerts to the users. These alerts will indicate when the GALILEO signals are outside specification. The user receiver can then reject signals from satellites to which an alert refers or, using the outputs of the receiver signal processing in conjunction with other receiver techniques, such as RAIM (Receiver Autonomous Integrity Monitoring), reduce the influence that these signals have on the final computed position.

The Integrity Determination System will produce the integrity flags on the basis of measurements taken by a network of Integrity Monitoring Stations distributed over the coverage area.

The Integrity Dissemination System will use the satellites of the GALILEO constellation to broadcast the integrity flags to users. Integrity flags will be up-linked from the Integrity Ground Segment directly to the satellites, for incorporation in the navigation signal-in-space. A time-to-alert of 6 seconds is the current design requirement. The service is designed to guarantee that a user will always be able to receive integrity data through at least two satellites with a minimum elevation angle of 25°.

The measurements made by the Integrity Monitoring Stations are sent, together with local meteorological and other data, to the Integrity Centre, as shown in Figure 11. Here, an Integrity Processing Facility determines integrity using statistical methods and checks against well-defined integrity barriers, under supervision from the Integrity Control Facility.

The Integrity Messages are then sent via the Integrity Up-Link Stations to selected satellites which incorporate them into the navigation data message streams broadcast to all users.

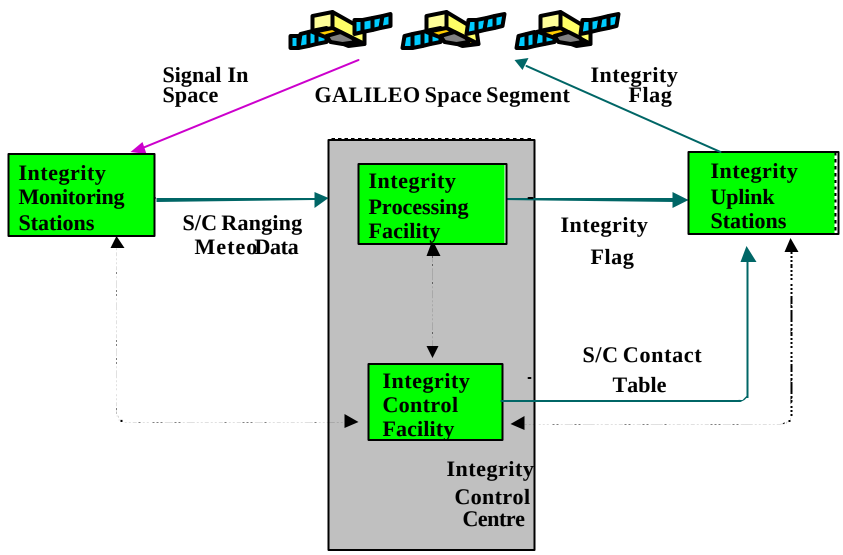

Figure 11: Integrity Determination System Architecture

Satellite Technology Developments

ESA has initiated, through competitive tender actions, a number of technology development activities to guarantee availability of critical on-board equipment for GALILEO in Europe. This equipment includes the main elements of the GALILEO satellite navigation payload.

In addition to the two satellite clocks, the Rubidium Atomic Frequency Standard (RAFS) and the Passive Hydrogen Maser (PHM), the Solid-State Power Amplifier (SSPA), the Output Multiplexer (OMUX) and the Navigation Antenna, which are described below, ESA intends to place contracts for the development of:

- Clock Monitoring and Control Unit (CMCU),
- Navigation Signal Generation Unit (NGSU),
- Frequency Generation and Modulation Unit (FGMU),
- Telemetry, Tracking and Command (TT&C) Transponder.

Rubidium Atomic Frequency Standard

Following initial developments carried out in the frame of other scientific missions, ESA has for a number of years been supporting the development of a Rubidium Atomic Frequency Standard (RAFS) for navigation applications. The first stage of this development activity was completed in May 2000 with the delivery of an Electrical Qualification Model (EQM) clock. The main characteristics of this unit are:

- Short term Stability ≤ $5x10^{-13}$ over 100 s
- Mass ≤ 1.4 Kg
- Volume ≤ 1.3 litres
- Power consumption 20 W

A picture of the EQM is shown in Figure 12.

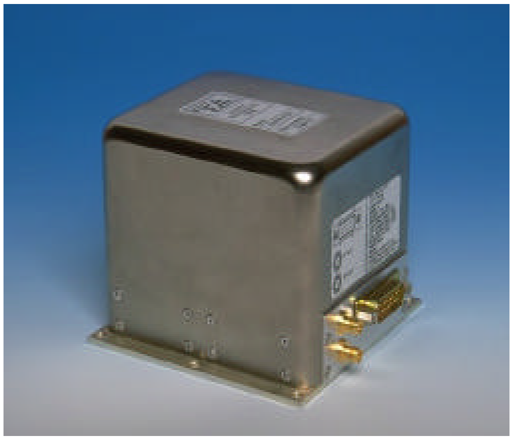

Figure 12: Rubidium Atomic Frequency Standard (RAFS) Electrical Qualification Model (EQM)

Currently these units are entering a qualification phase. Initially in this phase a design consolidation will be performed, including the integration of an autonomous thermal regulation system within the clock structure.

The manufacturing and test of a RAFS Qualification Model, which will follow the design consolidation, is due for completion by July 2001. After this, the qualification activity will continue with a lifetime test of five RAFS units in flight configuration over a period of three years.

Passive Hydrogen Maser

In 1998, ESA started a development activity for a space qualified Active Hydrogen Maser. Using the background acquired from this activity, ESA has now initiated the development of a passive version of this maser.

A Passive Hydrogen Maser (PHM) is smaller than an active maser and can be more easily accommodated on the spacecraft. A first layout of the PHM under development is shown in the Figure 13. The main specifications are:

- Long term stability ≤ $1x10^{-14}$ over 10 000 s
- Mass ≤15 kg
- Volume ≤ 25 litres

- Power Consumption ≤ 60 W

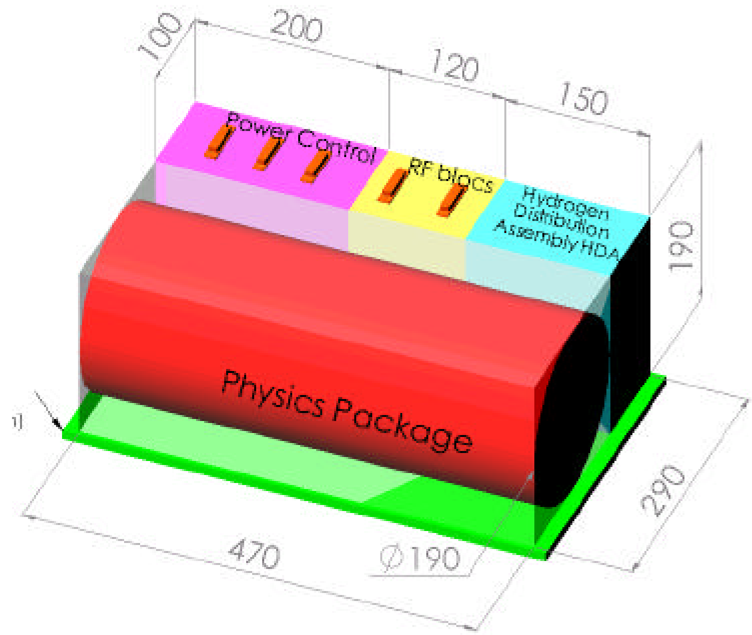

Figure 13: Passive Hydrogen Maser preliminary layout

Solid State Power Amplifier

The pre-development activity for a highly efficient and linear solid state power amplifier (SSPA) was initiated by ESA at the end of 1999. The amplifier incorporates a pre-distortion lineariser to minimise spectral re-growth due to non-linearity and autonomous compensation circuits to minimise the variation of delay and of output-power over the operating temperature range.

The amplifier utilises a compact structure with the power supply section on top of the RF section, as shown in Figure 14. Advanced GaAs MESFETs are used for high power delivery and low power consumption combined with high reliability. Specific design features are included in order to avoid multipactor discharge phenomena.

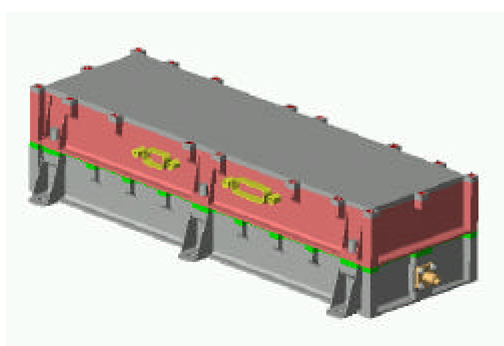

Figure 14 Solid state power amplifier preliminary layout

The main specifications of the SSPA are:

- Output power 50 W
- Output power stability 0.2 dB p-p

- Absolute delay stability 0.05 ns
- Gain 60 dB
- Mass 0.8 kg
- Size 250 x 80 x 60 mm
- Power consumption 120 W

The amplifier is designed to operate from a stabilised main bus of 50 V.

Engineering Models of this SSPA are scheduled for completion in the first quarter of 2001, with Electrical Qualification Models (EQM) available by the end of 2001.

Output Multiplexer

Each GALILEO Output Multiplexer (OMUX) is required to combine the output signals from two SSPAs, each at close-spaced frequencies, with low loss and high group delay stability. The OMUX must have excellent electrical characteristics, low mass and size, high reliability and low manufacturing cost for large production quantities.

The stringent requirement for stability requires the use of advanced compensation techniques. Two different technologies will be used for the development of the multiplexers, both based on the use of dielectric loading. The first is the standard technology based on “mushroom” type resonators, the second is essentially similar to the “re-entrant coaxial” technology, but with the centre rod of the resonator changed from metal to dielectric material. This choice has been dictated by the fact that with dielectric loading one can achieve very high unloaded Q-factors and, at the same time, both very high temperature stability and reduced volume. Figure 15 shows the baseline concept for the filters of one of the multiplexers.

The key technical specifications of the multiplexer are:

- Insertion loss 0.4 dB
- Absolute group delay variation 0.05 ns
- Channel isolation 40 dB
- Mass 0.5 kg

The development activity is divided into two phases. The first phase started in July 2000 and will end in the third quarter of 2001 with the development of two EM models. The second phase will end in the second quarter of 2002 with the manufacture of two EQM models.

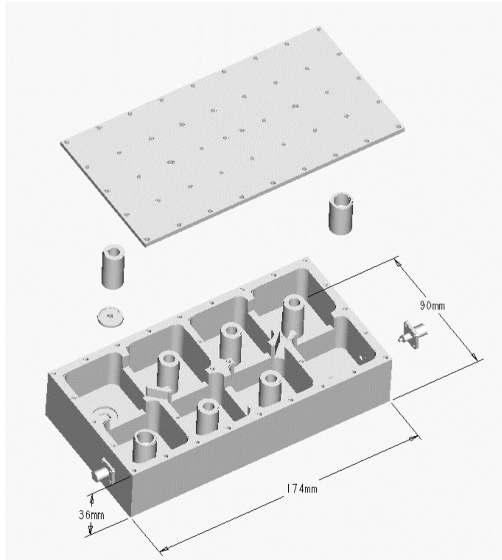

Figure 15: Output Multiplexer

Navigation Antenna

The GALILEO navigation antenna is designed to radiate the navigation signals towards the ground and to provide coverage of the entire visible surface of the Earth.

Its main performance specifications are as follows:

- Gain 15 dBi at edge of coverage
- Gain ripple < 2 dB across the coverage
- Axial Ratio < 1 dB across the coverage
- Mass 8 - 10 kg
- Maximum size 1.4 x 1.6 x 0.2 m

The need to produce the antenna in a small series at minimum cost has led to the adoption of a modular approach whereby each antenna is made of 4 or 6 identical elements.

Given the important technological issues involved in the antenna development, two parallel and independent activities were launched in 1999 to investigate different solutions.

Both developments are based on the use of multi-layer planar antenna technologies. One solution, shown in Figure 16 uses cavity-backed patch elements while the other uses 4-level stacked patches. In both cases, independent beam forming networks are used for the two frequency bands (1.2 GHz and 1.5 GHz). These beam forming networks are embedded in the antenna backing structure to reduce mass and volume.

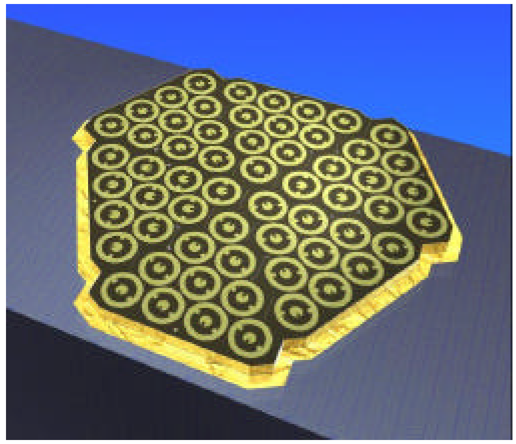

Figure 16 Navigation Antenna

For both developments, initial test structures have already been developed and EQM units are expected to be available during middle 2001.

GALILEO Programme Schedule

The indicative master schedule for the implementation of GALILEO system is shown in Figure 17 The current Definition Phase will be completed at the end of this year. This will be followed, subject to the approval of the GALILEO Programme later this year, by the Design, Development and In-Orbit Validation (IOV) phase of the system. The IOV Phase will include deployment of a small constellation of satellites, planned for launched in 2004. Prior to the IOV launch, a comprehensive GALILEO Test-Bed is foreseen to be deployed as piggyback payload embarked on a GLONASS satellite of the next generation. Thereafter, an initial operational capability, comprising some twelve satellites, is planned to be ready in 2006. The full system deployment is foreseen to be completed by the end of 2007.

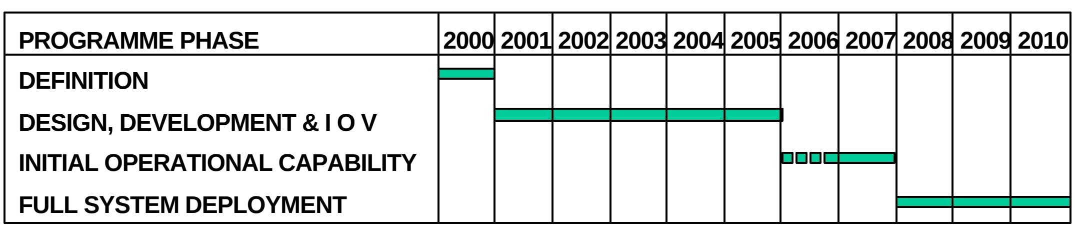

Figure 17 "Indicative GALILEO Master Schedule"

Acknowledgements

The authors acknowledge the initiatives and contributions of the European Commission, national agencies and their support staff and of the many different companies working on the Galileo definition, in particular of the system team led by Alenia Spazio, with Alcatel Space Industries and Astrium.

Conclusions

Studies carried out over the past year have demonstrated the feasibility of GALILEO to provide, from 2006/2008 onwards, global navigation services with guaranteed performance for mass-market, commercial, safety-of-life and public sector applications.

The preferred constellation for GALILEO, comprising thirty satellites in three circular orbit planes at 23 222 km altitude, will be able to offer navigation accuracy well within the 5 meters range without any need of external augmentations.

Further Information

For further information on the paper or any of the underlying studies, readers are invited to contact the GALILEO Project Office at the European Space Agency:

ESA –ESTEC

APP-NS
P. O . Box 299,
2200 AG Noordwijk,
The Netherlands.

Phone: +31 71 565 3193

Fax: +31 71 565 4369

e-mail: acasado@esa.int

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Biographies:

Javier Benedicto is the Head of the GALILEO Project Division in the Navigation Department of the European Space Agency. Before taking over that responsibility he has been leading the EGNOS project from the ESA Toulouse office. His previous positions concerned mobile satellite systems and the development of advance radio-frequency technologies.

Simon Dinwiddy is a member of the GALILEO Project Division and is responsible for system specification matters. Before engaging into satellite navigation he had held a number of system engineering positions concerned with the development of satellite communication and data relay techniques.

Giluliano Gatti is the Space Segment Manager within the GALILEO Project Division. Before that he had been leading a section in the Technical Directorate of the European Space Agency dealing with advanced microwave equipment. His previous experience involves a number of positions in microwave developments.

Rafael Lucas is the Systems Manager within the GALILEO Project Division. Before that he had been instrumental in leading the GALILEO system design from early conception into the definition of today. His previous positions dealt with the development of navigation applications for satellite control.

Manfred Lugert is the Ground Segment Manager within the GALILEO Project Division. Before that he had been leading the development of a VSAT communications service. His previous positions concerned a number of developments in ISDN and satellite networking.