On-board Applications of Active Microwave Technologies to GALILEO and other European Space Programs

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***Abstract* — Space programs are highly dependant on active microwave technologies. This paper will highlight the applications where these technologies play a fundamental role, pointing our strength and weakness. Special focus will be made on the European Satellite Navigation Program GALILEO.**

I. Introduction

Satellite applications are significantly demanding for equipment based on semiconductor technologies. The harsh space environment (radiations, mechanical and thermal environment) and the limited resources on-board (power availability, mass and size) call for robust and efficient technologies.

II. TECHNOLOGIES, TRENDS AND APPLICATIONS

II.1 Semiconductors

The development of most micro/millimetre-wave systems has, for long, been closely related to the progress made in the field of semiconductors. The performance development is primarily dependent on the advancement in material technology as well as innovations in the operating principles of the devices.

At frequencies below several tens to roughly 100 GHz, depending on the application, the three-terminal devices (i.e. transistors like HEMTs, HBTs,…) are predominant while at higher millimetre and sub-millimetre-wave frequencies two-terminal devices (hetero-junction barrier varactors, Schottky diodes,…) become more important.

Semiconductor applications can be classified in three categories. The first two, namely power generation and low noise amplification, are mostly covered by III-V technologies. The last one, which can be labelled as "general purpose" (gain block, switch, mixed function,…), is more open to "new comers", originating from the silicon IC industry, such as SiGe or SOI.

II.2 Power amplification

Gallium nitride (GaN) technology is becoming an increasingly interesting candidate for microwave solid-state power amplifiers (SSPA) in the near to medium term. Since GaN is a wide band gap material, devices realised on this compound semiconductor will have inherent high breakdown voltage capability. GaN components can operate at higher bias voltage (typically 40 V, which is almost coinciding with current satellite platform bus voltages, leading to a simplified and cheaper power supplies, with better overall efficiency), with very large associated output power per unit gate width (up to 10 times GaAs capabilities).

Therefore, very high RF power levels (i.e.100 W at C-band, 40 to 50 W at Ku-band or 20 to 30 W at Ka-band) on a single chip should be possible. Also, due to the relatively high voltage–current ratio of the transistor channel, the devices have higher output impedance, with significant reduction of output matching loss and thus better efficiency.

Another advantage of GaN is related to the better thermal resistance as compared to GaAs (1.3 vs. 0.54 W/K.cm), although this improvement may be altered by the properties of the substrate material used to grow the GaN (SiC, Sapphire or Silicon).

Finally, GaN is able to withstand much higher junction temperatures than GaAs (500°C vs. 175°C), which should imply good reliability and high power handling capability, especially when grown on SiC.

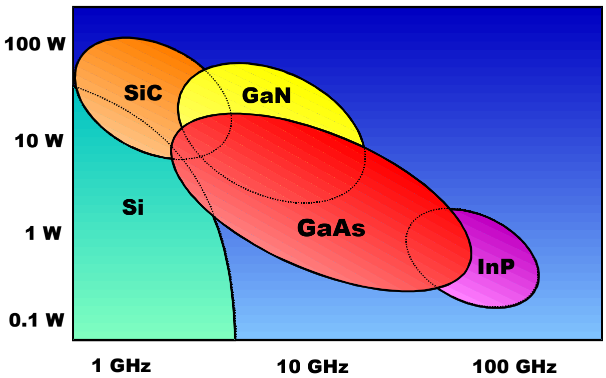

Figure II.1: Current capabilities of RF power solid-state technologies for a single device.

It is anticipated that GaN will represent a breakthrough on active transmit antennas (multiport amplifier based or phased array concepts) for next generation telecommunication satellite payloads implementing a very high (>100) number of beams.

Power amplifiers used in these active transmit antennas will work under multi-carrier conditions, with the associated low efficiency and high heat dissipation. As a consequence a complex and heavy thermal subsystem is required, with large mass and cost increase. GaN, with its excellent power and thermal capabilities will allow very compact and low mass RF front ends from mobile applications (L/S-bands) up to broadband multimedia (Ku/Ka- bands)

GaN technology will certainly play a role in SSPAs for future Ka-band user terminals. GaN, with its very high power density will lead to a ten fold increase of the user terminal EIRP, using similar area chips as currently feasible with GaAs. Alternatively, similar EIRP values as feasible today using GaAs technology could be obtained with a very significant cost reduction on the outdoor unit, due to a drastic reduction on MMIC chip size.

Another possible application of GaN technology is in the domain of T/R Modules on active arrays for SAR applications. Significant power, thermal and cost improvements will also be induced by the use of GaN on the SSPAs.

Furthermore, GaN devices have shown very good low RF noise properties, comparable to GaAs devices. This feature, together with the very high breakdown voltage and high RF overdrive capabilities can allow the suppression of limiters in front of the LNA in T/R modules, with the associated reduction on complexity, cost and noise figure (NF).

GaN technology developments are ongoing in Europe. In the coming years, GaN processes will be available to start breadboarding and development activities on satellite SAR, telecommunication payload and user terminals.

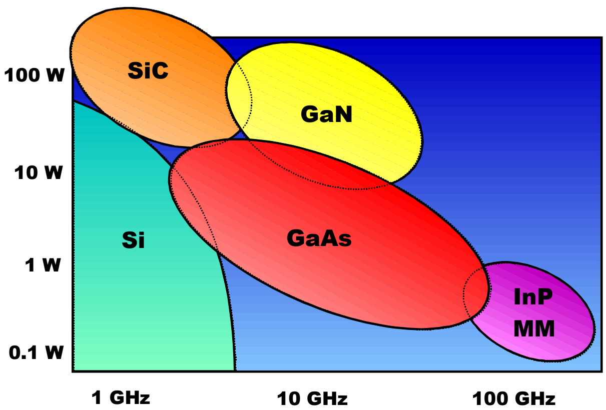

Figure II.2: Foreseen capabilities of RF power solid-state technologies for a single device in medium term.

Silicon carbide (SiC) has even better RF power and thermal properties than GaN up to C-band due to its very high breakdown electric field, high saturated electron velocity and high thermal conductivity. The high thermal conductivity and high allowed junction temperature of SiC together enable power levels that cannot be achieved with any other semiconductor technology. But the commercialisation of the technology is dependent on the wafer quality development, which however, has evolved significantly over the last years. Compared to a GaAs MESFET, a 30-fold power density improvement is foreseen. However, the high operating temperature probably requires new methodologies to be used for proper packaging and for the reliability and quality assessment.

For the same reasons given for GaN technology, SiC will improve the performance, compactness and cost of transmit active antennas for mobile service applications at L and S-band. Also, SiC will allow very high power RF levels (>100 W) for L/S-band HPAs, to be used in mobile payloads supporting contoured beam generation or in navigation applications.

Several players in Europe are involved in SiC technology. Two inch SiC wafers are already available and it is believed that in a few years SiC technology will be mature to start breadboarding and hardware development activities. However, since most of the RF potential applications for SiC, can also be covered by GaN (which can also handle higher frequencies) and/or by low frequency (LF) high power GaAs HBTs, it is not clear that SiC will emerge as a standard process for RF devices.

One of the basic building blocks of the SSPA technology is the GaAs MESFET, which has traditionally been used in a discrete packaged form, from L to C and also X-band today. However, when going to higher frequencies and/or more compact footprint, the trend is to use MESFETs in die format. Although the technology of the discretes is well established, the selection of space qualified European devices is limited. HBT GaAs technology is currently the only technology available in Europe, which has been primarily developed to cover RF high power amplification. However, it was mostly optimised to cover X and Ku-band applications. By optimising the process for lower frequency such as L or S-band, this technology could prove an alternative European solution to current high power GaAs MESFETs.

Due to the fact that the InP technology provides the fastest transistors, the InP HEMT is very well suited for power amplification at frequencies around 100 GHz and above, the GaAs P-HEMT being a better or equal competitor at approximately up to 100 GHz. Power levels of several hundreds of milliwatts are feasible from a single device at W-band today.

II.3 Low noise amplification

The InP HEMT provides the lowest NF and the highest operating frequency of any three-terminal semiconductor device. Consequently, the InP HEMT technology provides the means for millimetre wave low noise (and also power amplification) at frequencies up to around 100 GHz, and well above in the future.

Today, the InP transistors are implemented on bulk InP substrate, which results in relatively high material and processing costs because of the brittleness of InP substrates combined with the limited wafer size. Potential applications are thus limited to those requiring ultimate low noise performance and where the cost is not an issue.

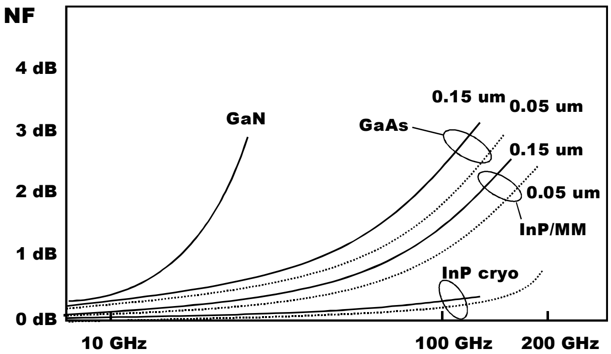

Figure II.3: Capabilities of RF low noise solid-state technologies (solid lines) and expected.

Recent development in epitaxy has lead to the implementation of InGaAs with high In content on a GaAs substrate. This new type of semiconductor substrate is called metamorphic while the HEMT implemented on it, is an M-HEMT. This new approach could result in large savings in substrate and processing costs while still showing potential for equal or nearly equal performance to the InP substrate based HEMT . Transition frequencies of 200 GHz have already been demonstrated.

In addition to the use of a less expensive substrate, the MMIC fabrication can take the advantage of the established GaAs MMIC wafer processing. It is expected that the M-HEMT will become a cost-effective replacement for InP at very high frequencies and a performance boosting alternative for GaAs P-HEMT at lower millimetre-wave frequencies. The InP technology still dominates in applications at W-band and above in short to medium term but the M-HEMT technology is foreseen to take its place in the medium to long term.

The InP HEMT applications are found in W-band LNA while usable gain is available at frequencies above 200 GHz. In addition, InP based circuits facilitate lower power operation than equivalent GaAs based circuit while still maintaining similar or slightly better noise performance. This is an advantage in cryogenic applications (the low noise and low-power InP technology is the core of the ESA Planck mission, where the cooled receivers of the Low Frequency Instrument (LFI) exploit it up to 110 GHz).

At lower frequencies, low NF is requested in IF amplifiers of sensitive super-heterodyne millimetre-wave receivers. In sub-millimetre-wave super-heterodyne SSB receivers, reasonable side band filtering recalls the use of very high IF frequency (several tens to few hundreds of GHz). InP HEMT and M-HEMT have potential for the lowest NF in these applications, too.

The trend towards shorter HEMT gate-lengths, below 0.1 um, will further improve the performance of both the InP HEMT and M-HEMT technology in the near future (50 nm devices are expected around year 2004). Applications at 200 GHz, and even above, should then be feasible. Several European players are working on the development of the MHEMT and/or InP technology. Important boosters for the industry are the increasing demand on millimetre-wave systems or equivalent such as local to multipoint distribution, wireless LANs, and very high speed digital circuits for terrestrial communications.

Potential space applications in the medium to long term are LNAs up to 200 GHz (a robust replacement of Schottky mixers), very low noise cryogenic amplifiers for science missions, wideband very low noise IF amplifiers in sub-millimetre-wave receivers used for Earth Observation, and state of the art communications systems for deep-space.

Following the industrial orientation towards M-HEMT, it is likely that the M-HEMT technology will be mature before InP, which will remain at laboratory level in Europe. Still, many technological aspects related to M-HEMT need investigations. Attempts shall be made to promote the European M-HEMT MMIC technology for the needs of the future Earth Observation and Science missions in the medium to long term. Although an established European InP HEMT source would be also a very welcome facility for the very top-performing Space Science instruments, it is likely that there is not enough market pull for supporting such an attempt.

II. 3 General purpose

SiGe technology is becoming commercially an attractive alternative for GaAs at least up to X-band and possibly up to Ku-band in highly integrated low-cost volume products.

The SiGe technology facilitates the implementation of CMOS and HBT devices on a single chip by standard silicon techniques, which in turn, results in a cost reduction by a factor of up to 10 (depending on the volume), compared to a GaAs based equivalent function.

A potential application for SiGe could be highly integrated multi-function chip (i.e. variable attenuator + variable phase shifter + gain blocks …) for active array antennas up to at least X-band. SiGe is also an excellent candidate for high performance frequency generation (VCO, PLLs) as described later in this document. However, the rather low volume generally associated with space systems may hinder the access to this technology, which is available mostly from major industrial silicon foundries..

The silicon on insulator (SOI) technology is continuation to the bulk MOSFET technology with improved performance. The key is to fabricate the transistors on top of an insulating SiO_2 layer, which results in lowered parasitics and higher operating frequency, and inherent radiation tolerance. Furthermore, the passive elements can be implemented on high resistivity silicon facilitating low-loss embedding RF circuitry on the chip. The SOI technology facilitates the implementation and low-cost mass production of LNAs, mixers, VCOs, PLLs, and other low-power functions using the standard CMOS processing. As for SiGe, the access to the technology may be difficult given the fairly low volume usually required in space applications..

Main areas of applications are detected in receiving antenna arrays up to Ka-band and in very low-power navigation receivers. As standard silicon production lines can be exploited in the MMIC fabrication, the technology has potential for low-cost and high volumes. Activities shall be started to assess the performance of the technology for integrated RF receiver front-ends by demonstrators.

II.4 Prospective semiconductor technologies

The technologies described in this section are at the very early stage of development. Up to now, the microwave technologies have been based on Si, GaAs and InP. However, the development in the semiconductor technology has been very fast and new degrees of freedom in implementing material systems, bandgap engineering and epitaxy have been continuously observed. Further developments in these areas could facilitate very high integration degrees with very high performance over the whole range of current applications as well as facilitate many new ones.

GaAs technology has become the workhorse in solid-state microwave circuits to date. However, the main drawbacks of GaAs are the expensive substrate material and manufacturing processes. In order to improve the cost effectiveness of the established GaAs MMIC processes, it would be advantageous to reduce the GaAs chip area by moving the passive functions onto cheaper substrate materials.

The use of multilayer (or three-dimensional) structures would allow the passive circuits to be implemented on upper layers and connected using via-holes thus ultimately assigning the GaAs area solely for the active function. Important application field of highly integrated cost-effective GaAs technology is seen in electronically steered low-cost arrays.

InSb (indium antimonide) is a very promising material which has potential for very fast, low-noise, and low-power operation. Based on experiments and theory, it is realistic to expect that InSb could lead to HEMT and HBT devices twice as fast as their InP counterparts.

Solving the problems in the diamond epitaxy would mean a new breakthrough in solid-state power density by an additional factor of 10, when compared to GaN. Development of the ballistic transistor may lead to very fast devices at the terahertz range.

II.5 Micro-machining and MEMS

Micro-machining is used to realise micro electro-mechanical systems (MEMS). At this moment the main focus in research and development is on the realisation of reliable MEMS switches which are attractive for space use e.g. in switch matrices and redundancy switches. As matter of fact their offer many advantages compared to their semiconductor equivalent (based on PIN diodes or GaAs transistors): very low losses (specially at higher frequencies), negligible consumption, and very good linearity.

However, the reliability is still an issue (one of the difficulty is to get rid of the “stiction” by which the switch becomes inoperable because the contacts stick together) while the packaging remains expensive since it has to be hermetic to protect the devices form contaminants which enhance the stiction problem.

Next generation telecommunication satellite payloads with a very high number of beams (more than 100) will need the implementation of high order switch matrices for on board channel to beam reconfiguration. In the case of analogue payloads implemented using IF processors, very high order IF switch matrices will be required.

The feasibility of such matrices is not obvious using current technologies (i.e. GaAs switches on multi-layer substrates). MEMS technology, together with multilayer substrates and advanced packaging technologies will allow the implementation of very compact and low cost high order switch matrices.

In the same way, large switch matrices are currently required for the implementation of input TWTA redundancy rings. Coaxial technology is currently used. MEMS based switch matrix would allow a extremely compact, reliable and low cost implementation of these input low power redundancy switches.

Micro-machining techniques also offer a solution for manufacturing filters and other waveguide components and housings for high frequencies. Very promising results have been achieved in realising sub-millimetre-wave receivers, especially regarding the ease and cost of manufacturing, and the excellent mechanical tolerances. These efforts are planned to be continued, together with the development of techniques to integrate semiconductor devices to such structures, e.g. by using membranes.

Providing that reliability can be achieved, it is expected that in a few years from now, MEMS devices (inductors, varactors, resonators, filters, …) will find their way to many applications, for microwave functions such as:

- low phase noise voltage controlled oscillators (VCO) with very wide tuning range
- miniaturised high-Q switchable filter/filterbanks for microwave and below,
- tunable high-Q filters with very high linearity (IP3),

- tunable amplifiers with high linearity,
- resonator based filter and oscillator designs,
- phase shifters.

However, it is the integration potential of MEMS with semiconductor devices like Si and GaAs which may revolutionise the way microwave systems are built, as the integration of entire subsystems on one chip becomes feasible.

The integration of above components together with high-speed A/D and D/A converters based on SiGe leads to complete new mixed signal systems on chip (SoC) with unparalleled performance.

III. THE GALILEO PROGRAM

The GALILEO Program was created by the European Commission and the European Space Agency in 1999 and it has been structured in phases. Both the Definition Phase dealing with services definition and the System Design and the Critical Technology Development Phase have been successfully completed.

The Development and In-Orbit Validation Phase (IOV) has already started in December 2003 and industrial contracts have been initiated.

In preparation of the IOV phase, two experimental satellites (GSTB-V2 satellites) are under production (one by Surrey Space Technology Limited and one by Galileo Industries) with the main objectives of securing the frequency filings for the GALILEO program, characterizing the orbit radiation environment, evaluating critical payload technologies and of enabling early signal experimentation.

III.1 *GALILEO Services*

The GALILEO system will meet a variety of user needs through a number of services provided by the GALILEO satellites:

- Open Service: it will provide positioning, velocity and timing information that can be accessed free of charge. This service is suitable for mass-market applications such as in-car navigation and mobile telephones location services. An accuracy of about 4 m horizontal and 8 m vertical is specified for dual-frequency receivers.
- Commercial service: it will allow developing professional applications by supporting the dissemination of added-value- data through dedicated signals, with controlled access.
- Safety of Life Service: it is intended for safety critical users that require stringent performance and adequate safety levels. This service will include integrity information: timely warning will be issued to users when the service cannot be guaranteed within the specifications. A time to alarm of 6 second is presently specified.
- Public Regulated Service: it will be offered only to government authorized users requiring a higher level of protection, e.g. against interference. The service will be based on encrypted signals and the access will be controlled by a government approved secure key distribution mechanism.
- Search and Rescue Service: it will allow relay of alarms from distress beacons to Search and Rescue organizations, through transponders on the GALILEO satellites, providing a significant improvement to existing services.

III.2 *GALILEO System*

The GALILEO System is decomposed in a number of segments:

- The space segment, composed of a constellation of 30 satellites distributed over 3 orbital planes
- The ground segment, composed of a network of sensor stations, the control centers, up-link stations and telecommand/telemetry stations.
- The user segment, composed by a variety of navigation receivers, exploiting the different types of GALILEO services.

III.3 *The GALILEO Satellite*

The GALILEO satellites will be a Medium Earth Orbit (MEO) with an altitude of approximately 24,000 Km, and will have a mass of about 700 Kg and a end-of-life power capability of around 1.6 KW.

The satellite has been designed to be launched in a single or multiple launch configuration (up to 8 satellites)by a variety of launchers (Soyuz, Zenit, Ariane and Proton) with a direct injection into the operating orbit altitude, with.

In addition the satellite design is modular to allow for a short production turn-around, necessary for a fast constellation deployment.

A drawing of the satellite in stowed configuration is shown in figure III.1 (courtesy Astrium-GmbH).

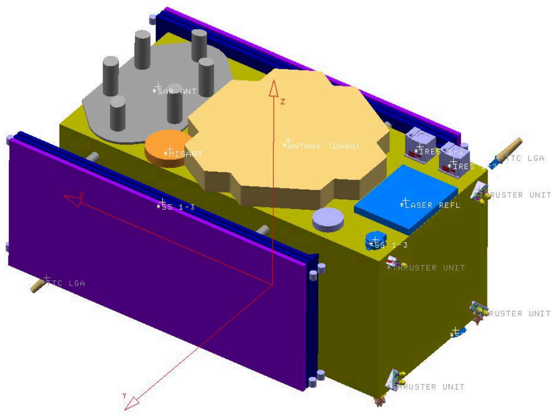

Fig. III.1 – GALILEO satellite.

III.4 *The GALILEO Satellite Payload*

The payload broadcasts navigation data on 3 carrier frequencies in L-band, each carrier being modulated with the navigation data for the services indicated in section III.1.

The navigation data are uploaded to the GALILEO satellite by means of a dedicated C-band up-link based on spread spectrum modulated signals, which allow separation of simultaneous uplink signals coming from different regions of the Earth.

The payload includes also a transparent Search and Rescue transponder to re-transmit to ground (at L-band) the signals sent by the distress beacons (at UHF frequencies).

A block diagram of the payload and of its interface to the satellite main sub-systems is shown in figure III.2.

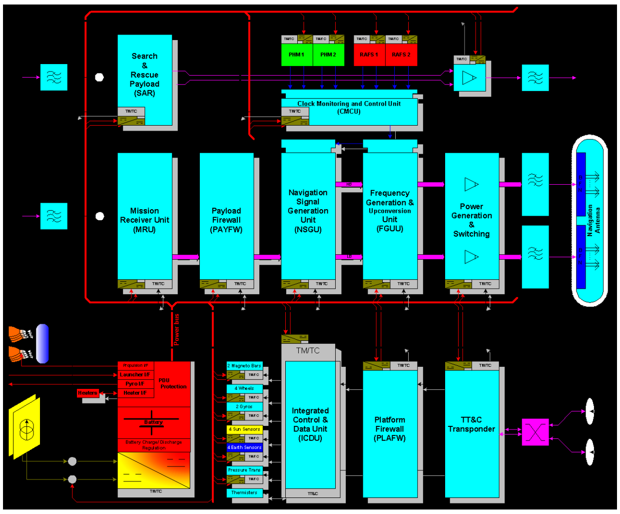

Fig.III.2 – Block diagram of the GALILEO satellite payload

The payload consists of the following main units:

a. Rubidium Atomic Frequency Standards (RAFS). This unit is currently being qualified for the Galileo experimental satellites. Six flight models are due for delivery by end of the year and beginning of 2005. The RAFS developed by Temex Neuchatel Time and Astrium Germany has shown excellent stability performance with a flicker floor of $3*10^{-14}$ A picture of the RAFS Engineering Qualification Model is shown in figure III.3 (courtesy TNT, Switzerland, and Astrium-GmbH, Germany).

b. Passive Hydrogen Maser (PHM). Following an initial development phase that led to the delivery of an EM model in 2002, the development is now being completed with the delivery of a qualification model in August and a flight unit by end of the year. With its extraordinary stability performance (flicker floor less than $1*10^{-14}$), the Maser will ensure a high level of autonomy to Galileo by keeping the system performance within the specified limits for an upload time of 8 hours. A picture of the PHM Structural and Thermal Model is shown in fig. III.4 (Courtesy Galileo Avionica, Italy, and TNT, Switzerland).

Fig. III. 3 – Rubidium Atomic Frequency Standard

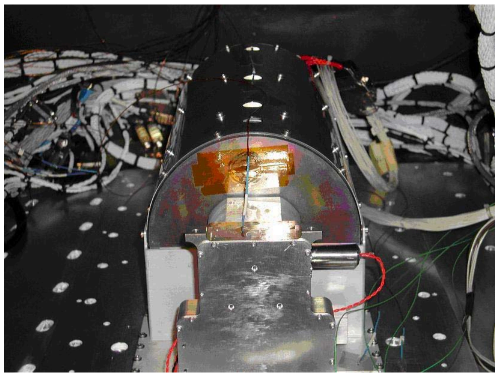

Fig. III. 4 – Passive Hydrogen Maser

c. Clock Monitoring and Control Unit (CMCU) . This unit interfaces the four atomic clocks of the Galileo Navigation Payload being in charge of deriving the appropriate reference frequency for the modulation and up-conversion chain.. Besides this task the CMCU has also embedded a phase comparison system comparing constantly the hot redundant Rubidium clock with the payload master clock (PHM). This phase information is regularly sent to ground for post processing and to allow early modeling of the RAFS behavior in oreder to reduce satellite outages in case of need to switch to the redundant clock. A picture of the CMCU Engineering Model is shown in figure III.5 (courtesy Alcatel Espacio, Spain).

d. C-band mission receiver unit (MRU) . This unit receives up to six up-link streams from different GALILEO up-link stations and forward them to the Payload Firewall.

e. C-band receiver antenna. This unit receives the C-band up-link signals.

f. Navigation Signal Generator (NSGU) . This unit is generating the four Galileo Signals. Main tasks performed by this unit are: reception of navigation message information, generation of navigation message modulating a set of PRN codes, multiplexing of the various signal components for base-band/IF interface with the up-conversion unit.. Two parallel developments are ongoing led respectively by Saab Ericsson (S) and Laben (I) leading to the delivery of flight units for the GSTBV2 satellites in January 2005

Fig. III.5 – Clock Monitoring and Control Unit

g. Frequency Generation and Up-converter Unit (FGUU) . The main function of this unit are: receiving signals from NSGU, generate LO signals for frequency translation, conditioning and filtering of signals to meet system requirements, generation of the NSGU reference clock signal. The FGUU is being developed by AME (N), a flight model is due for delivery by end of the year.

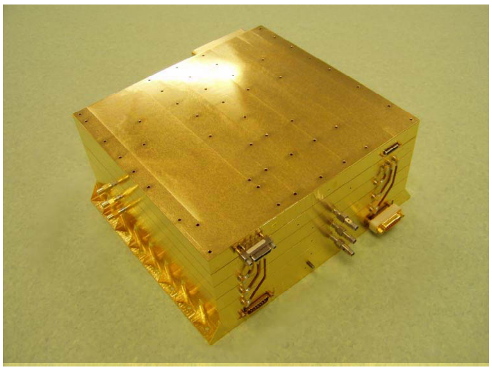

Fig. III.6 – Frequency Generation and Up-converter Unit

h. Solid State Power Amplifiers (SSPAs) . This unit is amplifying the output RF carriers of the Navigation Signals to a power level of approximately 50W. Three different SSPAs are being developed for Galileo covering all the assigned frequency bands. Flight models for the GSTBV2 payload will be delivered by end of 2004. A picture of a prototype of this unit is shown in figure III.7 (courtesy Galileo Avionica, Italy and Astrium-Ltd, UK).

Fig. III.7 - SSPA prototype

i. Navigation antenna (NAV-ANT). This unit is based on array technologies, with integrated beam forming network. Two parallel developments are ongoing led respectively by CASA (E) and Alenia (I). A picture of the antenna is shown in figure III.8 (courtesy EADS-CASA, Spain).

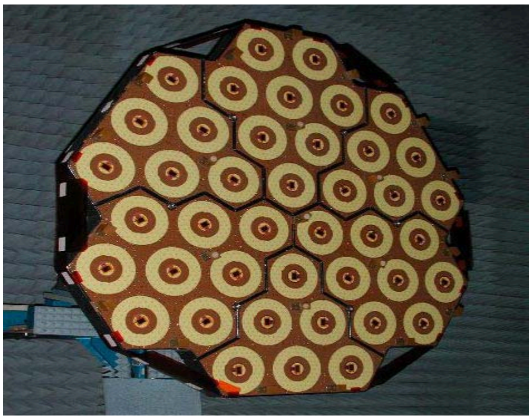

Fig. III.8 – Navigation Antenna

j. Search and Rescue Transponder. This unit includes an active repeater that receives distress signals from beacons and re-transmits them in L band to the Search and Rescue ground control centre. The transponder is constituted by a receiver-down converter unit, connected to a UHF antenna, and an up-converter and a transmitter unit, connected to a L-band transmitting antenna, integrated with the UHF receiving antenna.

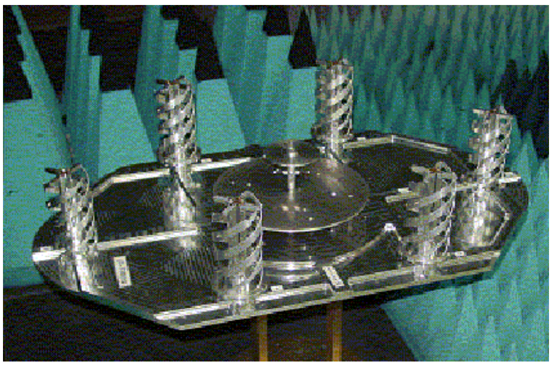

Fig. III.9 –Search and Rescue Antenna

k. Search and Rescue Dual frequency antenna. This is a receive-transmit, dual frequency antenna (UHF and L-band) and is being developed by RYMSA (E). A picture of the antenna Engineering Model is shown in figure III.9 (courtesy RYMSA, Spain).

l. Payload Firewall. This unit authenticates the data coming from the C-band uplink and generates the encrypted signal for the Public Regulated Service.

IV.5 *Critical Microwave Technologies in the GALILEO Payload*

A number of new technologies described in section III will have an impact on the next generation of equipment of the GALILEO satellite.

In the area of the navigation payload transmitter, higher power, higher efficiency SSPAs are required, compared to GSTBV2, to meet the system requirements. This means development of power amplifiers delivering 70-100W CW RF power.

Today these powers are at the limit of existing semiconductor technologies and in some cases competitive technologies might prevail (such as Traveling Wave Tubes –TWTs). GaN transistors may revolutionize the scene, by providing amplifiers operating directly at the bus voltage and requiring less demanding thermal boundary conditions.

The overall architecture of future generation satellite transmitters may also evolve toward active antennas, for achieving high antenna beam flexibility.

In this case newer technologies will also enable this evolution providing highly miniaturize components and equipment. In particular technologies that will give advantage to future Synthetic Aperture Radars for Earth Observation applications may also be needed for future navigation payloads.

For the signal generation chain further developments can be envisaged for improving the signal characteristics, and these could be based on SiGe and MEMS technologies aiming, for example, at reducing local oscillator phase noise and providing high sample rate digital to analogue converters (DAC).

The need for generation of wider band signals may also require, similarly to telecommunication future programs requiring broadband digital processors, may require advanced ASIC technologies (0.13 µm or even 90 nm technologies).

The behavior of all the new technologies described in the previous paragraphs shall however be adequately evaluated and analyzed as they have to correctly operate and survive when exposed to the high-energy radiations typical of the space environment at the Medium-Earth-Orbit (MEO) where the GALILEO satellites operate. This radiation environment is significantly harsher than for satellites operating in geostationary orbits.

V. CONCLUSIONS

Present and future active microwave technologies pave the base for advanced and more performing satellite missions, and will allow obtaining better performance, reliability, and capabilities in strategic programs such as GALILEO.

Acknowledgement

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