Galileo Receivers - Challenges and Performance

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***Abstract* - This paper addresses the Test User Receivers (TUR) of the Galileo Satellite Navigation System.**
The paper explains the concept of TURs highlighting the difference between TUR and a commercial receiver. An outline of the high-level requirements for the TUR is provided. Functional and performance requirements are presented. The interfaces between the TUR and the Galileo System are summarized, in particular the signals in space of the Galileo System. The key differences between Galileo and GPS receivers are identified, explained, and discussed.

I. INTRODUCTION

The Galileo constellation comprises 30 identical satellites in a Walker 27/3/1 configuration, with 27 satellites equally spaced around three orbital planes plus one spare per orbital plane. All the satellites have circular orbits with an approximate orbit radius of 29600 km and nominal inclination of 56°.

The Development and Validation Phase of the Galileo system aims at qualifying the Galileo space, ground and user segments through extensive in-orbit and ground tests. This relies on operations of a core spacecraft constellation and the associated ground and test user segment (TUS), called the In Orbit Validation (IOV) System. It will consist of one experimental satellite and four operational satellites considered as the minimum number of operational satellites that is required for IOV. The experimental IOV satellite, also known as the Galileo System Test Bed Version 2 (GSTB-V2) satellite, an early version of the operational IOV satellites, will be launched in the time frame 2005-2006 and the four operational IOV satellites will be launched in the time frame 2007-2008. The Galileo TUS, consisting of the TUR, PRS-TUR, Signal/Constellation Simulator and Search and Rescue (SAR) Test Beacon is required to support system validation as well as signal experimentation.

II. GALILEO SIGNAL-IN-SPACE

This section reflects the current Galileo signal baseline, which is still subject to further consolidation in some areas. The signal description here is only a brief summary of the main parameters in order to allow better understanding of subsequent sections. For a more complete definition the reader is referred to [SIS-ICD].

A Frequency allocation and Signal description

The Galileo Navigation Signals are transmitted in the four frequency bands indicated on Fig. 1. The four frequency bands (E5a, E5b, E6 and E2-L1-E1) used provide a large bandwidth for transmission of the Galileo Signals, and allowing an efficient use of the Radio-Navigation Satellite Services (RNSS) allocations.

Most of these radio Navigation Allocations are however shared with non-radio navigation services. Receivers of Galileo Signals transmitted in E5a or E5b bands will have to tolerate DME/TACAN transmissions for aeronautical civil users, and also MIDS/JTIDS transmissions in the same frequency bands for military users. They will also have to tolerate out-of-band emissions of Radars transmitting in the L2 frequency band. Users of Galileo Signals in the E6 band will have to consider the existence of primary radar, wind profilers as well as radio-amateurs sharing the same band.

Two frequency bands, the E5a/L5 band, and the E2-L1-E1 bands, have been chosen common to the GPS current L1 band and foreseen L5 band. The use of the same respective carrier frequencies in those bands increases interoperability between the Galileo System and the GPS system.

All Galileo transmitting Satellites, making use of Code Divided Multiple Access (CDMA), will share the same frequency bands. Spread Spectrum signals will be transmitted including different Ranging Codes per signal and for each Galileo Satellites. They will be transmitted in Right-Hand Circular Polarization (RHCP).

B Spreading Codes description

The pseudo random noise (PRN) code sequences used for the Galileo Navigation Signals determine important properties of the system. Therefore an adequate selection of Galileo code design parameters is necessary. These parameters include the code length and its relation to the data rate and the auto- and cross-correlation properties of the code sequences. An important performance parameter for the Galileo codes is the cold start acquisition time. Both Spreading Codes and Navigation Message are currently undergoing final optimization.

C Coding and Interleaving

A three level error correction encoding scheme is applied to the Galileo message data, in order to strengthen the transmitted message from a Bit and Frame error rate point of view: Cyclic Redundancy Check (CRC), half rate Convolutional Forward Error Correction (FEC) Encoding and as final step Interleaving is applied.

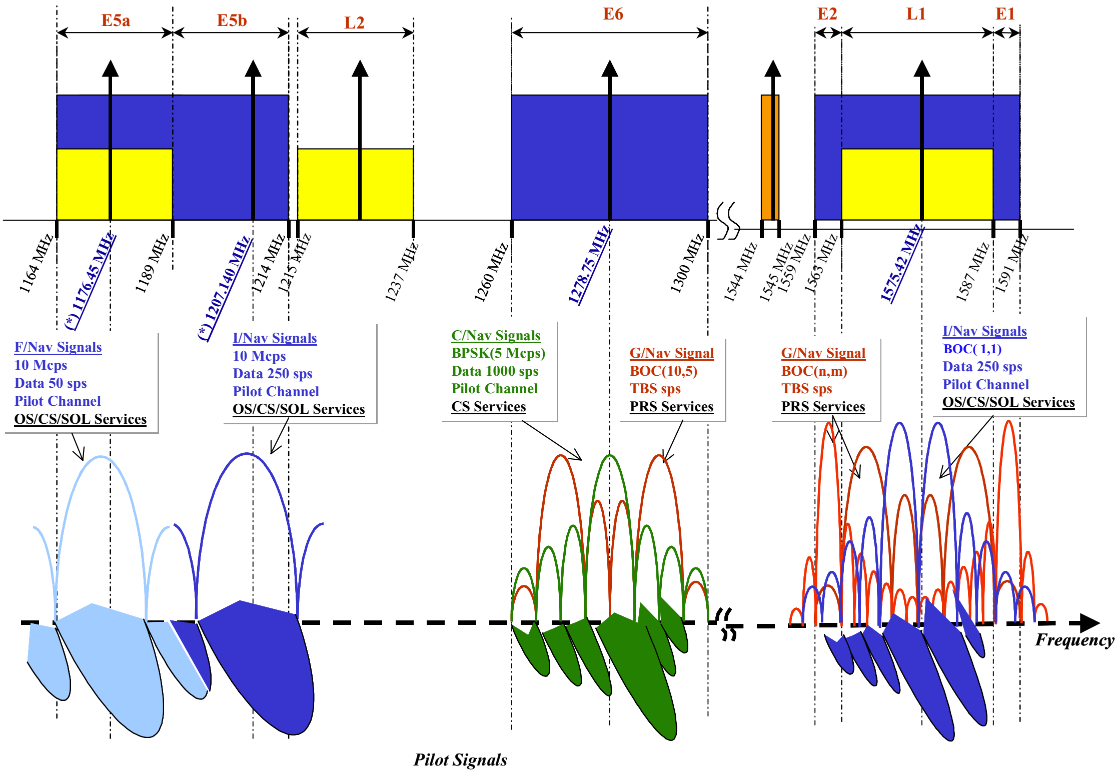

Fig. 1: Galileo Navigation Signals

III. Galileo Test User Receiver

The development of the TURs will be carried out in four phases:

- User Requirements Consolidation, High Level Performance Analyses, Receiver System Architecture Design and Detailed Specification
- Subsystem Architectural Design, Simulation, Analysis and Critical Breadboarding
- Detailed Design, Prototype Developments and Test
- Production, Procurement, Validation and Acceptance

Currently the end of the first phase has been reached and a breadboard to show feasibility of critical signal processing is already available.

The TUR will receive the SIS as transmitted by the four operational IOV satellites. It will support user receivers validation for the open, commercial and safety of life services user receivers in their standard configuration. The TUR will support field tests under static as well as dynamic conditions and will provide real time PVT solution.

The TUR will be based on a highly flexible platform supporting the 14 different receiver configurations [GALTUS]. This is achieved through a software defined receiver concept (not to be mistaken with software radio receiver concept). This will provide a flexible, configurable validation platform for critical receiver performance, in particular related to the signal processing subsystem. It will allow easy adaptation to evolving signal design. "Software defined receiver" in this context means that the functionality of the receiver can be flexibly defined by downloading different configuration files into FPGAs and operating configurable code on DSPs and CPUs.

IV. Receiver Requirements

A Structure of Requirements

The overall Receiver requirements are structured in Test User Receiver Requirements [TUSREQ] as follows:

- Generic Receiver Definition
- Signal in Space Definition
- User Environment Definition and Requirements
- TUR Common Requirements including the baseline algorithms to meet the minimum navigation end-to-end performance
- Specific Requirements for each of the 14 specific TUR Configurations
- TUR Analysis Tool
- Security Related Requirements as well as the PRS TUR configurations are specified in a classified annex.

B High Level Receiver Requirements

Fig 2 provides a very simple block diagram of a TUR, illustrating the main functional blocks and the connectivity with the Galileo System. The main system interface is through the signals in space transmitted by the satellites. The Galileo signals are captured at the antenna and converted from radio frequency to intermediate frequency (RF/IF block). The IF is processed in the signal processor to achieve acquisition and tracking of the code and carrier and to extract the code and carrier observables as well as the message content. This then is passed to the navigation processor, which is illustrated as composed of three blocks. The role of the command/control block is to manage receiver functions.

The PVT block, including the pre-processing, is the core navigation processing functions to derive position, velocity and time. For appropriate receiver configurations, there is an Integrity pre-processor whose role is to assure the integrity of the transmissions for those configurations where it is relevant. For some receiver configurations, the PVT function is followed by the RAIM processing function, which quantifies and assures the integrity of the derived navigation solution. The man-machine (or user) interface is indicated by MMI in the figure and is running on the LapTop together with the Analysis Subsystem.

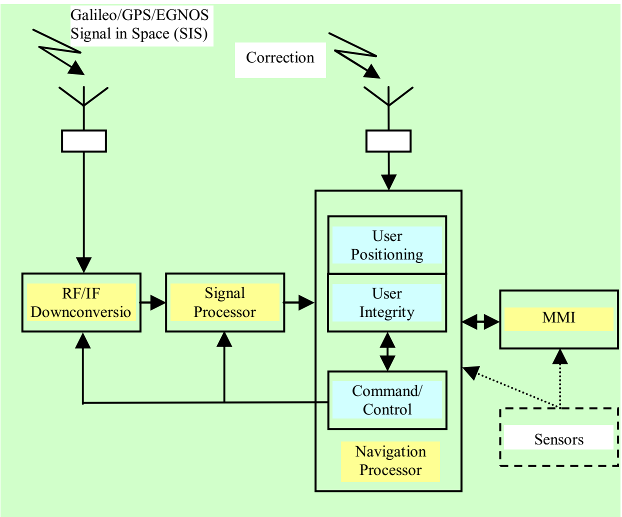

Fig 2: High-Level TUR Architecture

C Receiver Performance

Performance is specified in the range domain in terms of User Equivalent Range Error (UERE) of separate components (Ionosphere, Troposphere, Signal In Space Accuracy (SISA), Noise+Interference, Multipath (random and bias), Code-Carrier Ionospheric divergence error, Satellite Group Delay) and in the position/time domain in terms of PVT and related mean availability. For a single frequency user the horizontal accuracy is specified to 15 meters and the vertical accuracy to 35 meters with 95% confidence and with an availability of 100% of the time, in any place within the service volume, when operating in the nominal SIS constellation state and with a mean availability of 99.5%. For a dual frequency receiver the equivalent horizontal accuracy is specified to 4 meters and the vertical accuracy to 8 meters.

There are very tight requirements (sub-nano-seconds) on group delay and inter channel phase delay for Galileo Sensor Station Receivers. The requirements on Reliability, Availability and Safety on these receivers are very stringent together with the requirements on accuracy on receiver code phase and carrier phase measurements.

V. Key differences between the TUR and a commercial receiver

- As a test receiver the TUR provides access to the observables and other detailed, internal measurements and estimates. All this, including digitised input signal samples, both continuous over a programmable period and triggerable through an anomalous event, is stored on mass storage media.
- The TUR will have high performance. Lower performance receiver types can be emulated by different antenna types, different front-end noise figure, different signal bandwidth, different oscillator quality and different processing options.
- The TUR is highly flexible and configurable.
- The TUR provides an analysis subsystem for additional off-line detailed investigations on the stored data, running on a LapTop connected to the receiver. The analysis subsystem also allows processing of stored data with the relevant receiver algorithms starting either from digitised input signal samples or from the code and carrier phase measurements in an off-line manner with modified receiver algorithm tuning.
- The TUR is not optimized for mass, size, power consumption, cost and mass production.
- The TUR will not meet the requirements in terms of reliability, availability, maintainability and safety (RAMS) as a SoL receiver has to.

VI. Galileo / GPS differences

Hereafter significant differences between Galileo and GPS systems are highlighted and discussed from the TUR point of view.

The Galileo system is a civilian system. It will provide intrinsic, global integrity. It will offer better coverage for northern Europe due to the higher inclination and coverage of poles. Galileo will provide global integrity and therefore a guarantee for safety, availability, continuity and reliability all around the globe. Improved performance is achieved through a larger constellation and more advanced signal design (modulation, pilot). However the most significant performance and robustness improvement will come from the 'super constellation', which provides more than 50 satellites for the combined system and therefore increases considerable visibility. Although the typical functionality of the receiver is very similar, the detailed implementation will differ significantly in particular in the signal processing subsystem due to the BOC modulation resulting in much lower code measurement errors.

Galileo provides eight open and two PRS signals per satellite while current GPS supports one open and two military signals. In particular for the reference and test receivers, which have to receive all the signals and in addition have to support a certain degree of flexibility in the signals, this leads to considerable increase of hardware and software complexity and increased CPU load as compared to currently existing navigation receivers.

The higher chip rate of the codes leads to larger bandwidth (typically an order of magnitude) and therefore higher sampling rates. The benefits of the larger bandwidth are lower code tracking error due to thermal noise and better multipath mitigation performance, achieved through narrow correlator spacing. For the AltBOC on E5 the bandwidth just including the main lobes is more than 50 MHz. This signal will provide extremely low thermal noise and very good multipath mitigation performance in the case of coherent tracking of E5a and E5b.

The longer codes (again typically an order of magnitude longer for the open signals) provide better statistical properties however they will lead to longer acquisition times if conventional techniques are used. More advanced techniques, used for fast acquisition, such as matched filters in the time domain, will be considerably more complex to implement due to the longer codes.

Multiple correlation peaks resulting from the BOC modulation (Fig 3) cause a higher false acquisition probability and difficulties during acquisition, if direct acquisition of the BOC signal is performed. New algorithms are required and a number of different techniques are being studied at the moment. Techniques such as bump jumping [GALTUS], requiring additional hardware, have been reported to ensure that the correct correlation peak is acquired and continued to be tracked. Another possibility is to acquire a SSB of the BOC spectrum and switch to BOC tracking once sufficient accuracy has been achieved in the tracking loops.

All carriers provide pilot signals without data-modulation on these pilots. Tracking performance can be improved by increasing the Pre-detection time beyond the data-bit boundary. This leads to lower noise and therefore lower tracking threshold. These pilot signals also allow usage of higher performance 4-quadrant arctan phase discriminator in the PLL.

The boundary between hardware and software has to be carefully investigated. Software radio concepts slowly being introduced for GPS C/A code receivers are certainly not feasible for the Galileo reference and test receivers due to the large number of channels, the larger bandwidth, the longer codes and the Viterbi decoding. Most likely a dedicated chip or fixed point processor has to be used just Viterbi decoding. De-interleaving will lead to high burst CPU load at the end of each frame. This in particular complicates software design in view of the requirements for load balancing schemes.

VII. Conclusions

A highlevel overview has been provided on the Galileo Test User Receiver. The implementation phase has started. Considering the tight schedule of the programme this complex receiver will be a challenging development.

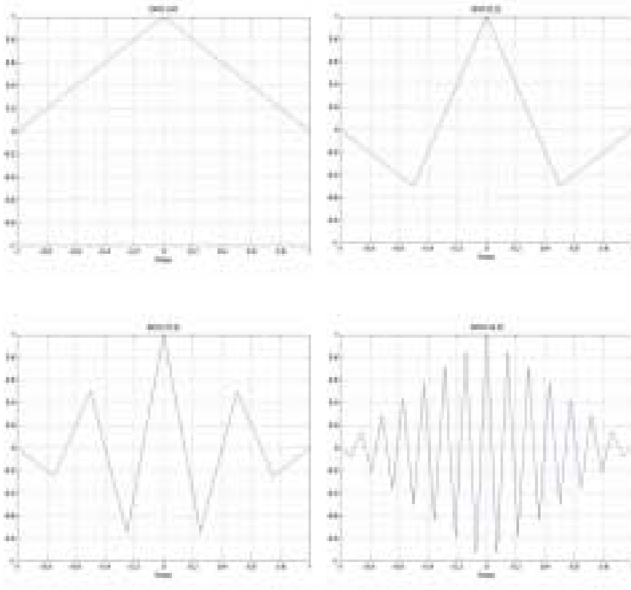

Fig 3: Many peaks within pull-in range of a classical DLL for the different BOC(n,m)

ACKNOWLEDGMENTS

The author wishes to acknowledge the support of his management and the directors of the European Space Agency, of EADS Astrium Ltd. and of Galileo Industries, for their support and permission to publish. The work and opinions presented here are, however, the work of the authors and should not be interpreted as the official policy of any of the named organisations.

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