Overview of Galileo Receivers

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Abstract. After the successful launch of the first experimental Galileo satellite, i.e. GIOVE-A, and after the signature of the Galileo-IOV-CDE1 contract, the constituted European enterprise consortium is working hard in order to achieve the Galileo In-Orbit-Validation by 2009. During this IOV phase, the first four operational satellites will be launched and the ground segment will be set up and validated, including the development of the first test user receivers.

After an introduction on the Galileo overall system, this paper will describe the Galileo receivers under development in the frame of the IOV contract, focusing on the impacts of the Galileo system requirements towards the receivers design.

1 Galileo System High Level Overview

Figure 1 outlines the Galileo Overall Architecture, including the following segments:

- the **Galileo Space Segment** including a constellation of 30 satellites placed at an altitude of in Medium Earth Orbit (MEO) altitude km
- the **Ground Mission Segment** (GMS) providing the determination and uplink of the navigation data messages and integrity data messages needed for the provision of navigation services and UTC time transfer service. The GMS includes a worldwide network of Galileo Sensor Stations (GSS network) providing the collection of the input observable data, which are subsequently processed at Galileo Control Center (GCC) to determination the Galileo navigation data messages and integrity data messages.
- the **Ground Control Segment** (GCS) providing the telemetry, telecommand and control function for the whole Galileo satellite constellation.
- the **Test User Segment** (TUS) including a number of Test User Receiver (TUR) Configurations.

Figure 1 highlights the two different types of receivers are under development in the frame of the Galileo IOV contract, namely:

- The Test User Receiver (TUR): used to perform Galileo IOV system tests and hence demonstrating the capability of the Galileo System to meet the Galileo performance requirements.
- The Galileo Reference Chain (GRC) installed in each GSS. The GRC provides code phase and carrier measurements of the Galileo L-band navigation signals, as

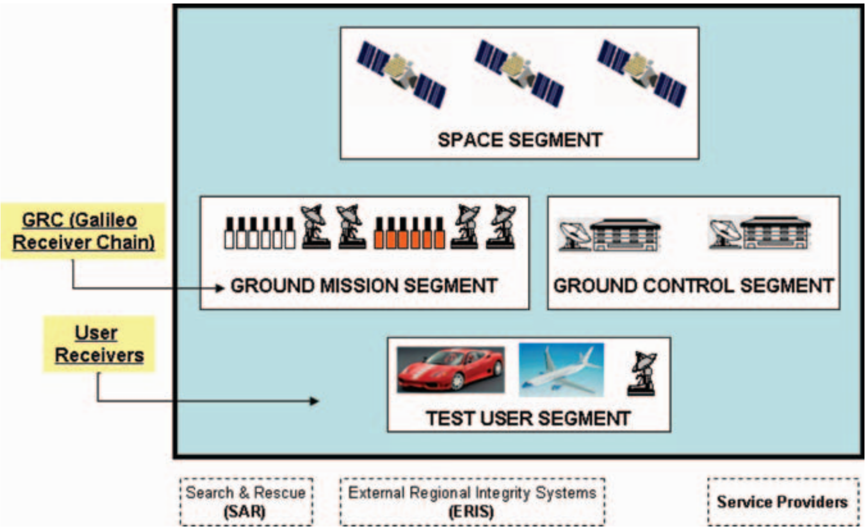

Fig. 1. Simplified Galileo system overview.

required to derive the navigation data and integrity data broadcast to user through the Galileo signals.

2 System Design Drivers

The design of the navigation satellite systems (including Galileo) is usually done taking into account a lot of system requirements. Among them, a subset could heavily impact the design and performance of the system: they are usually called "design drivers". Tables 1–3 summarise the main ones for Galileo. Three main groups can be identified:

- The frequency bands
- The services
- The navigation performance requirements

Table 1. Galileo frequencies.

Navigation signal in space	
Design aspect	Value
Carrier Frequency/Bandwidth	E5: 1191.795MHz / 92.07MHz E6: 1278.750MHz / 40.92MHz L1: 1575.420MHz / 40.92MHz
Min Receiver Power Level	–152.2 dBW (at 10° elev. angle)

Table 2. Galileo services.

Galileo services	
Acronym	**Meaning**
OS	Open Service
CS	Commercial Service
SoL	Safety of Life
PRS	Public Regulated Service

Table 3. Galileo navigation performance requirements.

Service required navigation performance			
Galileo required navigation performance	Open service	Commercial service	Safety of life service
Coverage	Global	Global	Global
Position Accuracy (95% confidence level)	4 m H - 8 m V (dual frequency)	NA	4 m H - 8 m V (dual frequency)
UTC Time Transfer Accuracy (only for dual frequency)	Accuracy: 30 nsec (95% confidence level)	NA	NA
Availability	99.5%	NA	99.5%
Integrity		NA	Required
Alert Limit		NA	12 m H - 20 m V
Time to Alert	NA	NA	6 seconds
Non-Integrity Risk		NA	2.0×10^{-7} / 150 sec (Excluding user receiver contribution)
Discontinuity Risk		NA	8.0×10^{-6} / 15 sec (Excluding user receiver contribution)
Access Control	Free Open Access	Controlled Access of Ranging Code and Nav Data Message	Controlled Access of Nav Data Message

3 Test User Segment (TUS)

The TUS under development in the frame of the Galileo IOV contract will be used during IOV system test campaign to demonstrate the capability of the Galileo System to meet the performance requirements specified in [1] for the following Galileo Satellite-only services:

- Single-Frequency Open Services (SF-OS)
- Dual-Frequency Open Services (DF-OS), including dual frequency navigation service without integrity and UTC dissemination service

- Safety of Life Services (SOL), including integrity
- Dual-Frequency Public Regulated Services (DF-PRS), including integrity
- Single-Frequency Public Regulated Services (SF-PRS), without integrity
- Commercial Services

The different Galileo Services are to be provided in a number of environments. The mapping og Galileo services on the specified environments is summarized in Table 4.

These environments are characterized by various parameters including satellite masking angle (10°), user dynamics environment, tropospheric environment, ionospheric environment, multipath environment, and external interference (see Table 5).

Table 4. Mapping of Galileo service on environments.

Environment	Environment ID	Service
Rural Pedestrian	RP	OS, SF-PRS
Rural Vehicle	RV	OS, CS, SOL
Aeronautical	AR	OS, CS, SOL, DF-PRS
Fixed	FX	OS, CS

Table 5. Definition of environment conditions applicable to test user receiver.

Env. ID	Dynamics	Troposphere	Ionosphere	Multipath	Interference
RV	Vel: 100m/s Acc: 10m/s^2 Jerk: 20m/s^3	Vertical delay: 2.7 mt	-S4 Scintillation: 0.2 -Vertical TEC: 50 TECU (single freq) 250 TECU (dual freq)	-Average delay 50 ns; -Linear decay slope 10 dB/µs; -Doppler bandwidth 140 Hz; -relative power –7.2 dB	–141.3 dBW/ MHz
RP	Vel: 10m/sec	As above	As above	As above, except Doppler bandwidth 4 Hz;	As above
FX	None	As above	As above	As above, except Doppler bandwidth: 2.5 mHz	As above
AR	Vel: 128.6m/s Acc: 20m/s^2 H 15m/s^2 V Jerk: 7.4 m/s^3 -Banking angle: 0°	As above	As above	-Diffuse Component: Delay: 0s; Relative Power: 14.2 dB -Fuselage Reflective Compon.: Delay: 1.5 ns Relative Power: 14.2 dB -Ground Reflective Compon.: Delay: 10 ns Relative Power: 14.2 dB	–141.3 dBW/ MHz plus ICAO DME

3.1 TUS Development Concept

In order to cope with the different Galileo Services and environments. the Test User Segment is conceived to provide the emulation of different Test User Receiver (TUR) classes.

Several types (i.e. aeronautical, pedestrian, vehicle, fixed) of TUR are envisaged with different configurations, namely:

1. Single or Dual Frequency Band
2. With or Without Integrity
3. Position/Velocity/Time or Precise Timing/Frequency Calibration
4. Service: PRS or SoL or OS or CS.

The TUS developmental concept can be summarized as follows:

- **Modular design**: the TUS includes certain core functionalities common to all receiver classes plus certain service-specific functionalities:
  Example of service-specific functionalities are:
  - the implementation of Geographic Denial in the Galileo PRS Receivers.
  - The implementation of specific algorithms to determine the integrity and continuity of position solution for TUR with integrity

    The emulation capabilities of different receiver classes is achieved using different antennas (gain and multipath mitigation) and changing the Radiofrequency Front-end (RF FE) performance (e.g. by suitability attenuating the signals, by changing the input bandwith, by applying different quality of reference frequency (quartz, OCXO, . . .))
- **Capability for Gradual Implementation**: The TUS is designed to allow its gradual evolution for re-use during the Galileo Full Operational phase
- **Navigation Signal Flexibility**: The TUS is designed to cope with changes of the characteristics of the navigation signal (any code of the code family, data modulation,. . .).

3.2 TUS Architecture

The Test User Segment is made up with the development of two TUR products:

- Non PRS Test User Receiver (Non PRS TUR) for receiving Open Service, Commercial Service and Safety of Life Service in a reconfigurable receiver;
- PRS Test User Receiver (PRS TUR) for classified signals reception.

Figures 2 and 3 provide both the non-PRS TUS and the PRS TUS architecture overview.

The Test User Receiver non-PRS architecture is based on the following physical elements:

- The antenna and the preamplifier,
- The antenna cable (30m),
- The Core Receiver (To process the Galileo Signals),

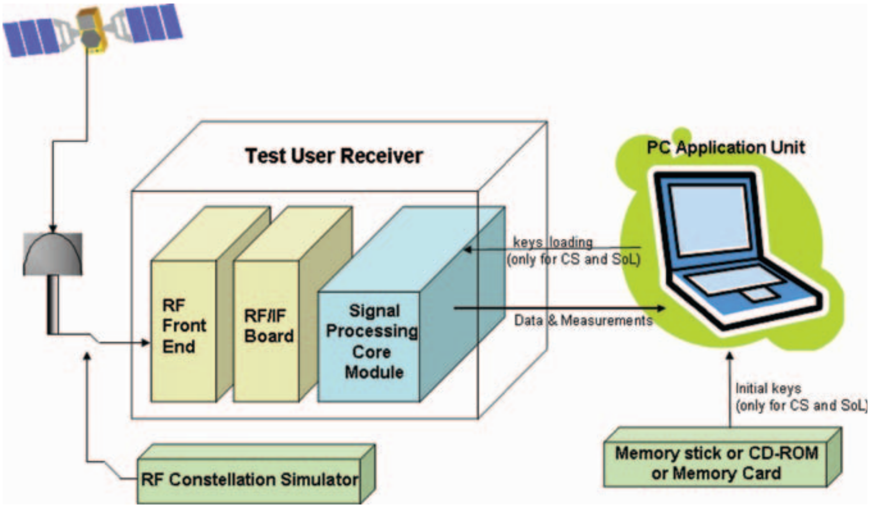

Fig. 2. Non-PRS TUR Architecture overview.

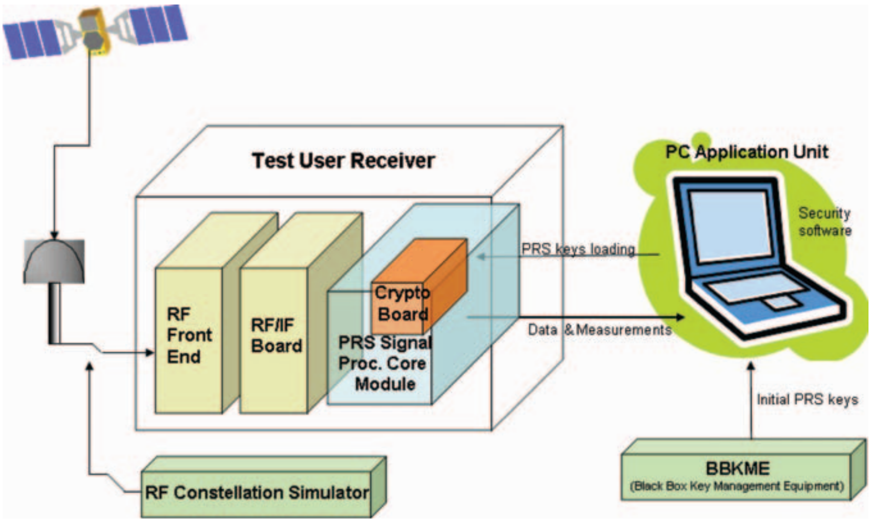

Fig. 3. PRS TUR Architecture overview.

- The PC Platform with the Application Unit Software to compute the navigation solution and perform data processing, display, post-processing and analysis.

The PRS TUR is based on the same architecture with the same physical decomposition. The only differences result in:

- The addition inside the Core receiver of a specific "Crypto Board" to process the PRS keys and restitute the PRS secret code,
- The development of a specific software module (implementing the security functions) on the Application Unit software.

A dedicated link from the PC towards the Crypto Board is foreseen to transmit PRS-specific data.

The PRS version due to security constraints integrates a Crypto Board in the Core receiver part to process the NAVSEC function and a crypto software module in the PC Application Unit to manage the keys and process the COMSEC function.

4 TUS Sub-Systems

4.1 Antenna

Depending on the environment conditions to test, two versions of antenna will be available:

- An “Aero & Reference” antenna, based on microstrips filters and patch antenna for installation purposes, with “reasonable” LNA noise figure and weak group delay bias requirements,
- An “High-End” antenna, based on cavity filters for fix applications and cross-dipoles based antenna, with “low noise figure”.

The types of antenna are common for Non PRS and PRS TUR. No specific antennas will be dedicated to the TUR PRS.

4.2 TUS Core Receiver

The Core Receiver built with a modular concept, is broken down into the following sub-systems:

- **One RF sub-system:**
  - One Clock & **RF Front End** board to provide reference clock and to separate and distribute all the RF frequency bands. The RF Front End components is composed by the following parts:
    - The receiver RF Front End which is to recover, filter and suitably distribute the RF signal and clock reference;
    - The clock generation & interface and HW synchronization functions and resources. This specific board RF FE board is dedicated to the purpose of: LO Frequencies synthesis, Clock generation and distribution (in charge to distribute the reference frequency locally generated), 1 PPS output signal synthesis.
- Two **RF/IF boards (E5, L1/E6)** to carry out the frequency down-conversion for each RF frequency band, the filtering and amplification. It is configurable in order to be used with more than one RF frequency (not at the same time). A common RF/IF module is expected for all the environment configurations (Reference, High End, Aero).
- Two **Core Module boards (E5, L1/E6)** to amplify and digitize the IF signal, to acquire and track N satellites per frequency and provide code and carrier raw measurements as well as the navigation data. The core module performs the digital signal processing and is mainly in charge of performing pseudo-range measurements

on the SIS ranging codes and pseudo-phase measurements on the SIS carrier. 16 parallel channels allows to process all the satellite in view (Maximum visible satellite = 11 according to Galileo visibility analysis with a mask elevation angle of 10 degrees). The main functions performed are:
  - Carrier Tracking
  - Carrier phase measurement
  - Ranging code tracking
  - Ranging code measurement
  - Multipath mitigation
  - Interference mitigation
  - Cycle-slip detection and correction
  - Signal monitoring

  and also the recovering of the navigation data transmitted by the Navigation Signals (satellite parameters, integrity flags, SISA, . . .). To carry out this function the following tasks are needed:
  - Bit synchronisation
  - Frame synchronisation
  - Frame Demultiplexing
  - Symbol recovery
  - CRC check
  - Viterbi decoding
  - De-interleaving
  - Bit recovery
- One **Mainframe** sub-system including: Enclosure, Power Supply and Backplane to allow the assembly, the power supply and the interconnection of all the boards.
- One **Crypto Board** in the TUR PRS dedicated to the processing of the security code deciphering and the NAVSEC (i.e. Navigation Security) function in relation with the Core Module.

In order to combine the synergies between each Non PRS services and between Non PRS and PRS services, a common core module architecture (a generic processing board) will be developed. This board can address the Non-PRS services with its generic signal processing resource or the PRS service:

- A provision of HW resources (included in the common core module design),
- A software customization,
- The addition of a mezzanine crypto board having an external direct connexion for transmission of specific security management related to PRS.

4.3 TUS PC Application Unit

The Application Unit is decomposed in:

- A PC platform (COTS laptop PC)
- A PC SW composed of:
- The Navigation/Integrity Module which process the following main functions: Navigation Data Recovery, Raw Measurement preprocessing, Navigation Solution

Determination, SIS integrity determination, Autonomous Integrity Monitoring and HMI related Computations.

- The Performances Analysis Software Module (PAS) which analyses, stores and displays the data provided by:
  - the Core Modules
  - the Navigation PC Software
  - the Integrity PC software
  - The PAS can control the RF signal and constellation simulators, recover the "truth data" from the simulator and compare with the Receiver outputs. The PAS can also send commands and control the operating parameters of the different subsystems in order to enable automated tests (MMI and configuration files).
- The Data Server Module to process the data interface between the different software module and the Core receiver.
- A security SW, to implement the security function (excepted the NAVSEC function) (PRS Version only).

Certain services impose Service-specific constraints and/or mandate particular algorithms. These are defined for each specific service.

Figure 4 shows the relationship between the main algorithms to be implemented by the TUS PC Application Unit:

- Pseudorange and Phase Measurements
- Navigation Message Recovery
- Position, Velocity, and Time Determination
- Integrity Determination (only for TUR versions including integrity), including the following algorithms

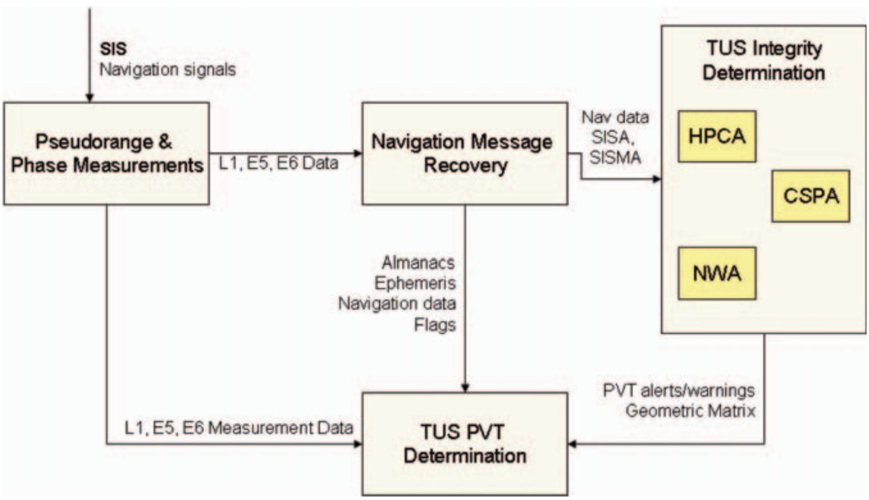

Fig. 4. PC Application unit algorithms overview.

- NWA (Navigation Warning Algorithm)
- HCPA (HMI Probability Computation Algorithm)
- CSPA (Critical Satellite Prediction Algorithm)

4.3.1 Pseudorange and Phase Measurements. This function is in charge of performing pseudo-range measurements on the SIS ranging codes and pseudo-phase measurements on the SIS carrier. The following tasks are executed:

- Generation of reference clock
- Acquisition of SIS
- Carrier tracking
- Carrier phase measurement
- Ranging code tracking
- Ranging code measurement
- Multipath mitigation
- Interference mitigation
- Cycle-slip detection and correction

4.3.2 Navigation Message Recovery. This function is in charge of recovering the navigation data transmitted by the Navigation Signals (satellite parameters, integrity flags, SISA, . . .).

4.3.3 Position, Velocity, and Time Determination. This function is in charge of elaborating the navigation solution based on valid Pseudorange Measurement.

The following tasks are executed:

- Measurement pre-processing including correction of the code phase and carrier phase measurements
- Determination of navigation solution (Position, Velocity and Time)

4.3.4 Integrity Determination. The TUR versions including the integrity service implements a set of algorithms to determine the integrity and continuity of the position solution computed at each 1 second fixing epoch.

To this purpose the following service-specific functionalities are implemented at each epoch:

1. Authentication of the integrity information extracted from the received message. This check is performed to verify that the received integrity data stream is the integrity information generated by the integrity function of the Galileo ground infrastructure;
2. Selection of the redundant and positively checked integrity data-streams the integrity data stream to be used;
3. Determination from the selected and positive checked integrity information and the navigation information which signals are valid;
4. Computation through the HPCA of the integrity risk at the specified Vertical/Horizontal Alert Limits;
5. Computation through the CSPA of the number of critical satellites for the critical operation period;

6. Determination through the NWA of the availability of the service and generation of warnings to the end user.

More details on the integrity determination function are given in the next section.

5 Integrity Determination

5.1 Integrity Information Authentication

The integrity information generated by the integrity function of the ground segment is signed (authenticated) so that it can be validated by the user receiver. This validation has to be performed in the integrity information validation function. The validation will ensure that only integrity information that was not changed at all or that was changed during dissemination with the allocated probability will be positively checked.

The validation information is provided in the integrity information data stream to the user receiver at every epoch, even if no other integrity information is broadcast to the user. This allows the user to determine at any epoch whether all integrity information has been received or not.

The validation will be performed for every integrity data stream that the user receiver will receive during nominal operation. There are at least two independent data streams that the user receiver receives.

5.2 Integrity Information Selection

Out of the positively checked integrity information data streams the user receiver has to select one integrity data stream to be used for further processing. This will normally be the same integrity data stream used at the epoch before.

The integrity information from one of the other positively checked data streams will only be used, if the integrity data stream selected at the epoch before is no longer available or if it is predicted that the integrity data stream selected at the epoch before will be not available for at least one epoch during the integrity exposure time.

If both streams are positively checked at the beginning of the operation one of them has arbitrary to be selected.

5.3 Valid Signal Determination

The valid signals to be included in the user geometry at each position fixing epoch are all the signals that are predicted to be received above the defined masking angle over the continuity exposure time, and have

1. the satellite health status flag not set to “healthy”,
2. the integrity flag not set to “OK”
3. the user receiver has not detected internally any anomalous condition
4. Valid navigation data batch and valid integrity data over the continuity exposure time

5.4 HMI Probability Computation Algorithm -HPCA

The HPCA provides the computation of the probability of HMI using the Galileo Integrity Equation given in Appendix A.

The computation is based on the knowledge of the applicable user geometry, the SISA data and SISMA data extracted from the navigation messages, as well as other data stored inside the TUR memory such as satellite failure rate and “a priori” estimate of range error component due to TUR local effects (thermal noise, multipath, interference and troposphere).

The predicted HMI probability rate represents the contribution due to the following events:

- adverse stochastical combination of random pseudorange errors and user geometry leading to anomalous behaviour in the position domain (Fault Free HMI)
- system integrity failures resulting in an undetected degradation of the signal measurement accuracy, so that one and only one faulted satellite is included in the user geometry currently used for computation of the position solution (Single Failure HMI).

5.5 Critical Satellite Prediction Algorithm (CSPA)

The CSPA provides the prediction, at each epoch the position fixing epoch To, of the service continuity performance by counting the number of critical satellites.

Indeed, a critical satellite is defined as a satellite in the current user geometry whose loss or exclusion unconditionally leads the HMI probability to exceed the tolerated value. This means that the service discontinuity risk at a given epoch can be predicted by

- counting the number of critical satellites included in the current geometry, and
- taking into account the discontinuity risk allocated to each satellite in the Galileo system continuity tree

Given the current Galileo system discontinuity allocation to each satellite, the continuity performance at a given epoch To is fulfilled when no more than 6 critical satellites are included in the user geometry applicable over the time interval To + 15 s.

The CSPA computes the number of critical satellites using an istance of the Galilelo integrity equation given in appendix A. The input geometries used for such computation correspond to the reduced geometries achieved excluding one at the time the satellites included in the current user geometry. The number of critical satellites is then achieved by counting the number of satellites whose exclusion leads the HMI probability to exceed a prefixed value.

5.6 Navigation Warning Algorithm (NWA)

The NWA provides the implementation of the set of rules, in order to decide whether the navigation service with integrity is available or not at the current epoch To, as well as to predict its availability for the incoming critical period Tc. To this end, this algorithm shall provide three levels of outputs, namely:

1. "normal operation" or "use" message, which indicates that the navigation service is available at epoch To, and foreseen to be available over the next critical operation period with the required level of end-to-end performance. In this condition the user is enabled to start or continue operations at epoch To.
2. "don't initiate" warning message, which indicates that the system is available at epoch To, but discontinuity risk is not guaranteed to be acceptably low in the next critical operation period. This warning message indicates that a critical operation (e.g. aircraft approach) must not be commenced, but a user shall be permitted to finish his current Critical Operation.
3. "don't use" alert, which indicates that the user must instantly abort its current critical operation because the HMI probability exceeds the specified value or the PVT (position, velocity, and time) solution is lost.

6 Conclusions

In order to cope with the very challenging Galileo system requirements and driver criteria, the Test User Receivers will be developed by using the technology at the state of the art. The design has been conceived by trying to satisfy all Galileo major driver criteria, that are very challenging specially if compared with GPS and EGNOS. The receiver will have very sophisticate functions such as multipath and interference mitigation. Moreover, a sensible effort has been made in order to meet the integrity requirements: dedicated integrity algorithms have been identified and will be tested as part of TUS activities.

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