GALILEO CHARACTERISATION AS INPUT TO SAFETY-OF-LIFE APPLICATIONS

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ABSTRACT

This paper provides insight into the Galileo feared event (FE) characterisation results based on measurements, which are input elements needed in Safety-of-Life (SoL) applications like Advanced Receiver Autonomous Integrity Monitoring (ARAIM) and Satellite Based Augmentation Systems (SBAS). The FE characterisation is a major contributor to the Integrity Failure Modes and Effects Analysis (IFMEA) process put in place by the Galileo programme to establish a detailed characterisation and understanding of Galileo Failure Modes and their impact on SoL Users. The overall study includes the characterisation of several kinds of FEs using so called FE monitors. This paper describes two of these monitors in terms of methodology and results including identified FEs and their respective probabilities: the Code-Carrier Incoherency (CCI) monitor to characterise one of the physical ranging signal FEs based on data between 04/2015 and 06/2018 (39 months) and the Signal-In-Space Error (SISE) monitor to characterise FEs related to excessive range errors based on data between 01/2017 and 06/2018 (18 months, after initial service declaration). A preliminary set of FEs is presented including the results of the assessment if the identified FEs would have occurred with future Galileo system configurations.

INTRODUCTION

The Galileo Open Service (OS) is foreseen to be used for Safety-of-Life (SoL) applications like ARAIM (Advanced Receiver Autonomous Integrity Monitoring) and Satellite Based Augmentation Systems (SBAS) as basis for aviation. The Galileo programme has put in place the Integrity Failure Modes and Effects Analysis (IFMEA) process to establish a detailed characterisation and understanding of Galileo Failure Modes and their impact on SoL Users [1]. Additional use cases including rail applications, reliable guidance and autonomous driving may be considered in the future. The monitoring of real measurements with identification of Feared Events (FEs) is a major contributor to this process and is the main scope of this paper. A set of monitors have been developed to identify FEs on each operational Galileo satellite. FEs are defined to be anomalies in the satellites’ signal-in-space (SIS) or navigation message that could impact the positioning integrity. The identification and characterisation of these events is a precondition to allow derivation of as-observed feared event probabilities, needed in order to use the signals with the trust required by SoL applications, in particular with regard to SBAS and ARAIM. Therefore this investigation is not driven by the majority of data that is supposed to be of good quality, but focuses on the few faults that may affect the integrity of the Galileo users.
Fig. 1. Processing Overview on the Galileo SoL FE Characterisation

Fig. 1 gives an overview on the FE processing approach including the necessary input data that is used in the FE monitors and the further processing steps that result in the output error time series. According to Fig. 1, the current set of monitors allows identifying different kinds of feared events, namely: ranging signals FEs (code and carrier-phase measurements, E1 & E5a) and navigation message feared events (F/NAV & I/NAV). Based on data streams from Galileo Sensor Stations (GSS), the core characterisation is performed independently for each satellite and frequency. In order to increase the robustness of the characterisation of the ranging signals, in addition data streams of Galileo Experimental Sensor Stations (GESS) from TGVF and International GNSS Service (IGS) stations have been used for the related monitors.

The data processing for FE characterisation is performed at Airbus site in Munich using high performance computing systems. Within Airbus, these activities date back to the investigations done in BayNavTech and its performance assessment facility [2]. It is worth pointing out that the results of SISE characterisation presented in this paper have been cross-checked with the ones obtained by a group led by the European Commission that developed an independent ARAIM demonstrator and ISM prototype generator in the framework of the ARTEX project.

The identification of feared events is done in a two-step approach starting with (i) an automatic identification of outliers in the monitor output time series followed by (ii) a detailed inspection of the outliers in order to discriminate between false detections and actual FEs (cf. Fig. 1). The feared event probabilities of occurrence are then derived for input to Safety-of-Life applications taking also into account the length of the observation period.

INTEGRITY FAILURE MODES AND EFFECTS ANALYSIS OVERVIEW

The Integrity Failure Modes and Effects Analysis (IFMEA) for Galileo is a structured process aiming at the quantitative and qualitative characterisation of the feared events affecting Safety-of-Life applications. The process described here is similar to the IFMEA process that was executed in the past for GPS [3]. In detail, the IFMEA relies upon design analysis, monitoring of real measurements, and detailed root cause identification upon feared event occurrence, for the identification of failures with their causes, effects, probabilities of occurrence and the related barriers for detection. In addition, recommendations for design improvements are an essential outcome of this process in order to improve the system’s robustness against the onset of FEs. As second output of the IFMEA process relevant information is obtained to feed the utilisation of Galileo OS in SoL applications. The outcomes of the IFMEA are collected into a Feared Event Characterisation Sheet (FECS) Report and activities are piloted by the FECS board which involves all main Galileo programme stakeholders (EC, ESA and GSA). The high level description of the IFMEA process implemented in Galileo is provided in Fig. 2.

DATA BASE AND GROUND STATION NETWORK

Ranging signal FE characterisation is based on data collected by a set of receivers located on ground. In order to allow a robust monitoring on a global scale, the following criteria for ground station and network selection have been defined:

- Provision of Galileo observation data with a sampling rate of 1 Hz,
- Stable receiver clock on short term,
- Adequate data availability within the analysis period,
- Degree of coverage (number of stations in view of a satellite) of at least five for any satellite location in space.
The selection of tracking stations according to these criteria was performed by taking the GSS (first priority), TGVF GESS (second priority) and IGS/MGEX (third priority) networks into consideration. It should be emphasized that based on the GSS and TGVF GESS networks alone a degree of coverage of at least five over the whole service area cannot be realized. As such, the selection of IGS/MGEX stations was done strategically in order to fill gaps in the degree of coverage. In any case, the C1C, C5Q, L1C, and L5Q observables (in Rinex notation) were given first priority. Some of the IGS/MGEX station receivers are not configured to track these signals; in this case the C1X, C5X, L1X, L5X observables were used. With the criteria above, the FE monitoring network consists of 15 GSS, 15 TGVF GESS and 29 IGS/MGEX stations (see Fig. 3).
METHODOLOGY

This section presents the methodologies for two of the FE monitors, namely the Code-Carrier Incoherency (CCI) monitor (to characterise the corresponding ranging signal FE) and the SISE monitor (which captures a wide range of feared events including navigation message anomalies).

It is worth pointing out that the CCI monitor, along with other SIS RF ranging feared events monitors, has been defined thanks to extensive work performed by the Universitat Politècnica de Catalunya (UPC) in Barcelona, Spain [4].

Code-Carrier Incoherency Monitor

The Code-Carrier Incoherency FE is defined as follows: a single satellite provides a good quality ranging signal before time $T_0$ and provides a degraded ranging signal after time $T_0$ due to a code/cARRIER divergence (change of the code minus carrier phase at the output of satellite antenna on L1 (E1) and/or L5 (E5a) greater than X meters over a period of 100 seconds.

The code-carrier combination $M_{c,m,n}(t)$ is computed according to (1) as the difference of measured code observations $R_{c,m,n}(t)$ and measured carrier observations $\Phi_{c1,m,n}(t)$ accounting for the ionosphere using the ionospheric correction based on E1 and E5a carrier observations $\Phi_{c1,m,n}(t)$ and $\Phi_{c2,m,n}(t)$ respectively.

$$M_{c,m,n}(t) = R_{c,m,n}(t) - \Phi_{c1,m,n}(t) - 2 \frac{1}{\gamma_c - 1} (\Phi_{c1,m,n}(t) - \Phi_{c2,m,n}(t))$$ (1)

Carrier phase observation $\Phi_{c1,m,n}(t)$ and $\Phi_{c2,m,n}(t)$ can be affected by cycle slips due to receiver loss of lock or atmospheric degradation which would strongly impact the monitor output. Therefore, epochs affected by cycle slips are excluded based on a triple time difference detection approach.

$M_{c,m,n}(t)$ is computed individually for each combination of receiver $m$, satellite $n$, epoch $t$ and for both frequency combinations $c$ and the associated squared frequency relation factor $\gamma_c$ according to Table 1. Based on the time series of code-carrier combination $M_{c,m,n}(t)$ the CCI is computed according to (2), in which $MS_{c,m,n}^\gamma(t)$ denotes a time series of smoothed code-carrier combinations resulting from a sliding window mean over the previous $N_{\text{smooth}} = 100$ samples $[t-N_{\text{smooth}} t-N_{\text{smooth}}+1, ..., t-1]$ and $MS_{c,m,n}^\gamma(t)$ denotes the smoothed (using mean) combination computed over a sliding window containing the current plus the next $N_{\text{smooth}}$ samples $[t, t+1, ..., t+N_{\text{smooth}}]$. Smoothing is performed for noise reduction.

$$CCI_{c,m,n}(t) = MS_{c,m,n}^\gamma(t) - MS_{c,m,n}^\gamma(t-1)$$ (2)

The CCI monitor combines observations from all receivers in view of a satellite. In order to account for the elevation dependent noise behaviour, the combination is realised using an elevation dependant weighted averaging according to (3). This combination needs to ensure (i) that potential FE (affecting all receivers simultaneously) are reflected and (ii) that site related effects (affecting single receivers only) are suppressed. Therefore, the number of receivers $N_{\text{Stat,obs}}$ that need to observe the satellite at the same time is set to the minimum of $N_{\text{Stat,obs}} = 5$ (to account for (i)) and the worst (i.e. absolutely largest) $CCI_{c,m,n}(t)$ is excluded from this weighted averaging (to account for (ii)). This includes the reduction of the number of receivers that are used for the averaging to $N = 5 - 1 = 4$ (in the minimum case for $N_{\text{Stat,obs}} = 5$). If $N_{\text{Stat,obs}} > 8$, the two worst $CCI_{c,m,n}(t)$ are excluded from the averaging.

$$CCI_{c,n}^{WA}(t) = \frac{\sum_m\left(\frac{CCI_{c,m,n}(t)}{\sigma_{CCI,elev,bin,median}^2}\right)}{\sum_m\left(1/\sigma_{CCI,elev,bin,median}^2\right)}$$ (3)

<table>
<thead>
<tr>
<th>Table 1. Frequency Combinations for Code and Carrier Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency combination $c$</td>
</tr>
<tr>
<td>---------------------------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
</tbody>
</table>
The combined CCI time series $CCI_{c,n}^{WA}(t)$ is computed for each satellite $n$ and frequency combination $c$ based on the CCI time series according to (1) and an elevation dependant weighting factor $\sigma_{c,m}^{CCI,\text{elev.bin,median}}$. This weighting factor is determined per receiver, per frequency and per elevation bin, and allows for a receiver- and elevation-dependent weighting. It results from estimates of the sample standard deviation $\sigma_{c,m,n}^{CCI,\text{elev.bin}}$ of $CCI_{c,m,n}(t)$ over 5 degree elevation bins in the range of 0…90 degree elevation. In order to determine one set of standard deviations per receiver, per frequency and per fixed elevation bin, a combination of the sample standard deviations $\sigma_{c,m,n}^{CCI,\text{elev.bin}}$ over all $N_{sat}$ satellites $n = 1, \ldots N_{sat}$ is performed according to (4) using the median.

$$\sigma_{c,m}^{CCI,\text{elev.bin,median}} = \text{median}(\sigma_{c,m,n}^{CCI,\text{elev.bin}})_{n = 1, \ldots N_{sat}}$$

The weighted-average CCI error time series $CCI_{c,n}^{WA}(t)$ according to (3) that are available per satellite $n$ and per frequency combination $c$ are the main output of the CCI monitor. Outliers in these time series form the list of potential FEs and the error time series itself are the basis to derive achievable occurrence probabilities.

**Signal-In-Space Error Monitor**

The Signal-In-Space Error (SISE) is derived from the orbit prediction error and clock prediction error. These error components are combined and projected to user location at the earth surface to represent the orbit and clock error at user level. The computation of SISE can be considered as a three-step-procedure: 1) determination of satellites orbit prediction error, 2) determination of satellites clock prediction error, and 3) combination of clock and orbit errors and projection to user location.

**Orbit Prediction Error**

The orbit prediction error is computed by comparison of broadcast orbits observed at TGVF GESS with high precision reference orbits provided by the Galileo Time and Geodetic Validation Facility (TGVF). Broadcasted satellite ephemeris are discretised in order to get a series of satellite coordinates $r_{NAV}^n(t)$ with a sampling rate of 5 min and to the identical epochs as of the reference orbits $r_{REF}^n(t)$. According to (5) the 3D orbit error $e_{3D,POS}^n(t)$ of the observed F/NAV and I/NAV message is determined computing the difference between the ephemeris coordinates $r_{NAV}^n(t)$ and the reference coordinates $r_{REF}^n(t)$ for each satellite $n$.

$$e_{3D,POS}^n(t) = |e_{POS}^n(t)| = |r_{NAV}^n(t) - r_{REF}^n(t)|$$

The TGVF reference orbits used in this characterisation are fully available on the considered period (no data gaps). As such, it ensures that all FEs have been captured.

**Clock Prediction Error**

Equivalent to the orbit prediction error, the clock prediction error is determined using broadcast clocks observed at TGVF GESS and reference clock from TGVF. Since the TGVF reference clocks are provided in GPS time in relation to a changing reference clock per day and the broadcast clocks are related to the Galileo System Time (GST), the reference clocks are aligned to GST (accounting for the difference between the ‘changing reference clock’ in GPS time and the GST, which has two contributors: the Inter System Bias (ISB) and the GSS-PTF clock correction). This results in the strictly aligned reference clock data $CLK_{NAV}^n(t)$. The broadcasted satellite clock offsets are discretised in order to get a series of clock values $CLK_{NAV}^n(t)$ with a sampling rate of 5 min and to the identical epochs as of the reference clocks. The clock error $CLK_{NAV}^n(t)$ of observed F/NAV and I/NAV message is obtained by computing the difference of the broadcast clock to the strictly aligned reference products:

$$e_{CLK}^n(t) = CLK_{NAV}^n(t) - CLK_{REF}^n(t)$$

The monitor for the characterisation of the clock prediction error relies on the availability of TGVF reference data, which are (i) high precision clock files (for satellite and GSS-PTF) and (ii) bias files containing Inter System Biases (especially for GSS-PTF) and Differential Code Biases for all satellites and GSS-PTF. These biases are essential for the correct alignment of reference satellite clocks.

In addition the “common clock offset removal” approach has been put in place to ensure a complete characterisation over time in case some reference products are unavailable. In this case, $e_{CLK}^n(t)$ is first computed not removing the GSS-PTF clock and ISB (i.e. $CLK_{REF}^n(t)$ is in GPS time while $CLK_{NAV}^n(t)$ is in GST), and then the GSS-PTF clock and ISB
The obtained time series $\epsilon_{CLK,corrected}(t)$ are used to fill gaps of the original clock error time series.

**Signal In Space Error (SISE)**

The satellite’s orbit and clock prediction error time series $\epsilon_{POS}^n(t)$ from (5) and $\epsilon_{CLK}^n(t)$ from (6) are the input to derive the SISE in two steps: (i) transformation of the [x,y,z] orbit error $\epsilon_{POS}^n(t)$ to local orbit components along-track $A^n(t)$, cross-track $C^n(t)$, radial $R^n(t)$, (ii) combination of orbit error components $A^n(t)$, $C^n(t)$, $R^n(t)$ and the total SIS clock prediction error $\epsilon_{CLK}^n(t)$ and their projection to user level at Worst User Location (WUL) following:

$$SISE_{WUL}^n(t) = \text{abs}(R^n(t) + \epsilon_{CLK}^n(t)) + 0.2154 \cdot \text{sign}(R^n(t) + \epsilon_{CLK}^n(t)) \cdot \sqrt{A^n(t)^2 + C^n(t)^2}. \quad (9)$$

**RESULTS**

The main output of the two FE monitors investigated in this paper is the error time series (cf. Fig. 1). Those are the CCI errors $CCI_{NAV}^n(t)$ according to (3) and the SISE errors $SISE_{WUL}^n(t)$ according to (9). The error time series form the basis for the FE characterisation results which include (i) a list of potential feared events and its extrapolation to the Galileo Full Operational Capability (FOC) system configuration, (ii) FE probabilities with and without taking a confidence level into account. Both are presented hereafter.

It is important to note that the Galileo system configuration currently available and which has been characterised so far is not fully representative of the FOC system configuration. A dedicated root cause analysis for each identified measured outlier has been conducted. In cases where the analysis conducted concludes that the observed measurement outlier relates to a root cause which is planned to be resolved by system upgrades (e.g. additional redundancy at infrastructure level), such outlier is not considered as representative of the future Galileo system and is thus excluded from the measurement history.

**List of FEs and Extrapolation to Galileo FOC System Configuration**

Potential FEs are identified as outliers in the FE monitors output error time series which exceed a defined threshold. For this study a critical CCI threshold of 0.719 m is assumed and SISE outliers are recorded if an assumed threshold of 7 m is exceeded.

Within the analysis period 04/2015 - 06/2018, the CCI monitor results do not contain a single FE whose amplitude is larger than the considered threshold of 0.719 m. Therefore CCI results will be presented only in terms of FE probabilities in the next section.

Concerning the results of the SISE monitor, some events have been identified in the analysis period between 01/2017 (after initial service declaration) and 06/2018. Those potential FEs resulting in a SISE of larger than 7 m have been investigated in detail and are listed in Table 2 for F/NAV. The table includes the date when the event occurred, on which satellite and the corresponding SISE magnitudes as well as the duration of the event. The duration is dependent on the threshold since it is the period in which the threshold is exceeded. If the error time series consist of several peaks that exceed the threshold, they are combined and counted as one FE as long as they are less than 20 min apart. The right half of Table 2 reflects the extrapolation to FOC. On a per event basis, the root cause has been investigated and it has been assessed whether the event would still be representative of the future Galileo system configuration. These investigations are part of an ongoing process as the observation period is continuously extended so that the results presented are to be understood as an intermediate status covering the period up to 06/2018. As it can be seen from the right side of Table 2, in total four SISE events which exceeded the 7 m threshold on single satellites are identified, out of which only one event was exceeding a threshold of 40 m.

As for the list of I/NAV events, this is identical to the F/NAV events listed in Table 2: Number and dates of the events are the same, only the duration and magnitude are slightly different. Further results for I/NAV are presented later in this paper.
Table 2. List of SISE events on F/NAV (E1,E5a) larger than 7 m and their extrapolation to FOC system configurations

<table>
<thead>
<tr>
<th>Date</th>
<th>Satellite-ID</th>
<th>PRN</th>
<th>Potential FEs derived from monitor’s output</th>
<th>Extrapolated to FOC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Duration</td>
<td>Max. error magnitude</td>
</tr>
<tr>
<td>15/02/2017</td>
<td>GSAT0204</td>
<td>E22</td>
<td>50 min</td>
<td>8.5 m</td>
</tr>
<tr>
<td>07/03/2017</td>
<td>GSAT0206</td>
<td>E30</td>
<td>45 min</td>
<td>342 m</td>
</tr>
<tr>
<td>09-10/05/2017</td>
<td>GSAT0211,</td>
<td>E02,</td>
<td>09/05/17:</td>
<td>09/05/17:</td>
</tr>
<tr>
<td></td>
<td>GSAT0208,</td>
<td>E08,</td>
<td>10 min</td>
<td>75.7 m</td>
</tr>
<tr>
<td></td>
<td>GSAT0102</td>
<td>E12</td>
<td>10/05/17:</td>
<td>(E02 only)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>95 min</td>
<td>10.1 m</td>
</tr>
<tr>
<td>14-15/05/2017</td>
<td>All FOC</td>
<td></td>
<td>up to</td>
<td>up to</td>
</tr>
<tr>
<td></td>
<td>satellites</td>
<td></td>
<td>~26 h</td>
<td>240 m</td>
</tr>
<tr>
<td>06/06/2017</td>
<td>GSAT0203</td>
<td>E26</td>
<td>~23.6 h</td>
<td>up to</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>492 m</td>
</tr>
<tr>
<td>14/10/2017</td>
<td>GSAT0210</td>
<td>E01</td>
<td>40 min</td>
<td>8.3 m</td>
</tr>
<tr>
<td>28/11/2017</td>
<td>GSAT0205</td>
<td>E24</td>
<td>190 min</td>
<td>16.9 m</td>
</tr>
<tr>
<td>26/12/2017</td>
<td>GSAT0101</td>
<td>E11</td>
<td>~11.5 h</td>
<td>27.6 m</td>
</tr>
<tr>
<td>07/05/2018</td>
<td>All</td>
<td></td>
<td>up to 70</td>
<td>10.6 m</td>
</tr>
<tr>
<td></td>
<td>All sat.</td>
<td></td>
<td>min</td>
<td></td>
</tr>
</tbody>
</table>

It has to be noted that during the processing period up to 06/2018 no FE was identified that affected more than one satellite at a time and due to the same root cause (such FEs are referred to as wide FEs). The extrapolation to the future Galileo system configuration has been applied here.

FE Probabilities

Besides the list of FEs, the error time series resulting from the monitors output are used to derive the two following statistics. In both cases, to include all available information is critical as the statistics are driven by very few events (if any). Missing even one outlier has a strong impact.

The Cumulative Distribution Function (CDF) gives the ratio of samples in the time series above a given threshold. It can be interpreted as the instantaneous probability (at a time T) to be in a feared event state. However, the CDF does not account for any confidence level. As such, it should be carefully handled in the extrapolation of past observation to future expected values.

The probability of occurrence (Pocc) – or fault rate – represents the probability that the FE occurs in the next hour (is usually expressed per hour, but can also be expressed over e.g. 150 sec). It can be computed as function of the number of events k and the observation time T assuming that (i) the probability of occurrence is constant over time and (ii) that observed events are uncorrelated. Based on these assumptions [5] proposes to further consider that the fault rate is a priori unknown and follows a uniform distribution, it then derives the expected Pocc value knowing that k events have been observed during the observation period T:

\[
P_{\text{occ}\mid k} = \frac{k + 1}{T}
\]  

In short, if an infinite number of experimentations were performed where the Pocc is randomly set, and where the number of events k occurring over a fixed observation time T is counted, \(P_{\text{occ}\mid k}\) would be the average Pocc over all experimentations that result in exactly k events.

Alternatively to an average approach, the Pocc could be computed as the fault rate value which gives a probability of X% to observe exactly k events or less over the observation time T (often referred as the chi-square approach). This value is referred as the probability of occurrence with an X% confidence level, as fixing the X value allows to give some additional confidence in the results in term of margin. In this paper a confidence level at 95% is considered as an example.

\[
P(k_{\text{obs}} \leq k) = \sum_{i=0}^{k} \left( \frac{(P_{\text{occ}X\%} \cdot T)^i}{i!} \right) e^{-P_{\text{occ}X\%}/T} = X\%
\]

It can be noted that the expected probability of occurrence \(P_{\text{occ}\mid k}\) and the probability of occurrence at 60% confidence level \(P_{\text{occ},60\%}\) give similar results.
**CCI FE probabilities**

The probabilities of occurrence derived for CCI are presented in Fig. 4 considering both approaches. They are given per satellite per hour. The number of FEs as well as the total observation time has been aggregated over all satellites of a same block – i.e. IOV and FOC separately – because different design might lead to different error behaviour and probability. In Fig. 4, the last point of each of the two lines representing IOV and FOC Pocc respectively is related to the number of zero FEs. As it can be seen, the largest CCI error has a magnitude between 0.5 and 0.6 m. Also, there is no conclusive difference between results obtain for FOC and IOV satellites. However, due to a longer observation time aggregated over all FOC satellites compared to IOV, the achievable Pocc of FOC is smaller than those of IOV satellites. Fig. 5 shows the 1-CDF of the CCI time series. It includes every single observation within in the analysis period both for IOV and FOC satellites as well as for E1 and E5a frequency.

![Fig. 4. Pocc of CCI error with a confidence level of 95% depending on the FE magnitude](image1)

**SISE FE probabilities**

Fig. 6 presents the 1-CDF for the SISE time series of Healthy SIS on a per satellite basis gathered between 01/2017 and 06/2018 (18 months, after initial service declaration) for F/NAV and I/NAV both based on the full monitors output (including all events) and extrapolated to a future system configuration (excluding FEs according to Table 2). In addition, Fig. 6 shows the extrapolated results in terms of 1-CDF of the SISE error aggregated over all satellites as well as the obtained probabilities of occurrence with the average approach (which relates to a confidence level of approx. 60%).

The obtained results indicate the very promising performance of the Galileo system once fully deployed. In order to establish H-ARAIM service availability based on Galileo and GPS, a User Ranging Accuracy (URA) – defined as a conservative overbound of the actual SISE – between 4.5 - 9 m (1 sigma) is needed. The corresponding threshold to declare a signal to be in SIS faulty state are in the range 19.9 – 39.8 m, which result from a multiplication of the URA values with a factor of 4.42.

A distinction between Wide and Narrow SIS fault state in line with the definitions provided in the ARAIM Milestone Report 3 [6] has been made. A *Wide SIS fault state* is defined as two or more satellites experience simultaneously, and due to a common cause, a SIS error exceeding a given threshold; other cases being covered by the *Narrow SIS fault state*.

Considering the SIS faulty state thresholds as identified above, it is observed that the Pocc derived from measurements only applying the average approach for
- Narrow SIS fault state is below 2e-5 /SV/h
- Wide SIS fault state is below 1e-4 /SV/h.

These probabilities refer to the onset probability and need to be multiplied with the Mean Time To Notify (MTTN) in order to obtain the probability of Satellite fault (Psat) and Constellation fault (Pconst). The MTTN is estimated to be approx. 60 minutes for a future Galileo system configuration as identified in [1]. Psat and Pconst are important parameters to be provided to the user for the determination of the protection level based on the ARAIM user algorithm. Continuous SISE monitoring is recommended in order to extend the measurement duration and eventually result in tighter occurrence probabilities or higher confidence levels. In particular what regards the characterisation of wide faults, an extension of the measurement period is essential to improve confidence.

Unlike the CCI FE results, the aggregation has been performed over all satellites regardless of the satellite block (IOV or FOC) as the SISE is also driven by the ground segment and there is no reason to distinguish between IOV and FOC satellites based on the observed data.
CONCLUSION

The monitoring of the Galileo Open Service Signal-in-Space shows promising results for the future use of Galileo system for SBAS and ARAIM Safety-of-Life applications. In particular, results on the physical ranging signal FEs (i.e. SIS stability) – that are directly relevant for overlay systems such as SBAS – are already showing very good performances. For instance, results on the Code-Carrier Incoherency monitor presented in this paper already demonstrate very low probability of occurrence at 95% confidence for both IOV and FOC satellites.

The SISE measurement results are also very promising when extrapolated to a future Galileo system configuration. During the relevant monitoring period (01/2017 – 06/2018) only the following events after extrapolation have been identified, that exceed a critical magnitude for H-ARAIM applications:
- Narrow SIS faults: One event occurring on GSAT0203 at 06/06/2017
- Wide SIS faults: None.

The resulting Pocc based on measurements and applying the average approach for the Pocc derivation is below 2e-5 /SV/h for the Narrow SIS fault state and below 1e-4 /SV/h for the Wide SIS fault state. When considering a Mean Time To Notify of 60 minutes [1] we result in a Psat value of 2e-5 and a Pconst below 1e-4 considering only the measurement collected during the monitoring period.

An extension of the observation period is essential in order to demonstrate that the good performance of Galileo with respect to faults is continued to be met. As per the identified IFMEA process, the measurement results are also to be complemented with feedback from design analysis, which however was not the scope of this paper. Future work will be performed to further consolidate the outcomes of the present characterisation.

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REFERENCES


Fig. 6. SISE FE characterisation results for F/NAV (left) and I/NAV (right)