Evaluating the Robustness of EGNSS Based Timing Services

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***Abstract*—This paper proposes a set of Key Performance Indicators (KPIs) for European GNSS (EGNSS)-based timing services that are relevant from the user perspective; these KPIs quantify the accuracy, integrity, and stability of the services. Furthermore, the instrumentation and procedures required for reproducing the threats and evaluating the proposed KPIs are described. The proposed test setup makes use of a precise time/frequency reference distributing a Coordinated Universal Time (UTC) realization and is intended for post-processing. The test results provide an indication of the performance of the envisioned Galileo and EGNOS timing services in terms of the proposed KPIs when the receiver is subject to various abnormal conditions.**

Keywords—EGNOS; Galileo; global navigation satellite system; satellite-based augmentation system; timing

I. Introduction

GNSS-based time and/or frequency transfer is utilized in several critical infrastructures, e.g., electrical grids, telecommunications networks, and banking [1]. However, no GNSS constellation currently offers timing as a service; instead, timing is regarded as a capability of positioning services. The timing performance of positioning services is typically specified in terms of the timing accuracy and the frequency stability for a given analysis interval such as 24 hours. The performance requirements of timing applications, however, are often specified in terms of different key performance indicators (KPIs). In particular, since GNSS timing users typically operate stationary receivers with known antenna locations, only one satellite is needed to estimate time; consequently, the availability commitments of positioning services, determined based on the requirement of four or more satellites, are not accurately valid for timing applications.

Furthermore, it is well known that the use of GNSS signals is subject to various threats ranging from errors in the broadcast navigation data to radio frequency interference and spoofing. If GNSS timing would fail to meet the expected performance in critical infrastructure, severe consequences could follow. For instance, the January 2016 GPS timing glitch distorted digital audio broadcasts in the U.K. [2].

To address these shortcomings, the European Commission has launched a H2020 research and development project titled "Advanced Mission Concepts: R&D for Robust EGNSS Timing Services" which aims at defining proper timing services for EGNSS, i.e., Galileo and EGNOS. The purpose of these services is not to improve the accuracy of EGNSS timing; instead, the focus is on ensuring the robustness of the time determination. In the context of this project, a threat analysis was at first performed to identify the most relevant threats and their impact for timing users. In this context, a threat is defined as anything that would prevent the receiver from retrieving the correct time. Robustness against the identified threats is achieved by including various techniques, most importantly Time Receiver Autonomous Integrity Monitoring (T-RAIM), in the receiver processing chain.

In the literature, there exist studies on the characterization of certain timing receivers, e.g., [14],[4]. More recently, very high GNSS-based timing accuracies have been obtained using carrier phase observables [3]; however, the ambiguous nature of the measurements degrades its suitability for robust services. GNSS vulnerabilities have received considerable attention during the past years; in particular, signal spoofing has been an active research topic in the positioning community. Spoofing has been shown to be a significant threat for timing users as well [6].

The goal of this paper is twofold. First, we identify KPIs that are relevant for EGNSS-based timing services from the user perspective. Second, we propose test instrumentation that can be used to evaluate the proposed KPIs in the presence of various threat conditions. Since the envisioned services are designed to be resilient against several threat scenarios, the test setups are intended for post-processing where measurement faults and several other abnormal conditions are easy to inject and analyze.

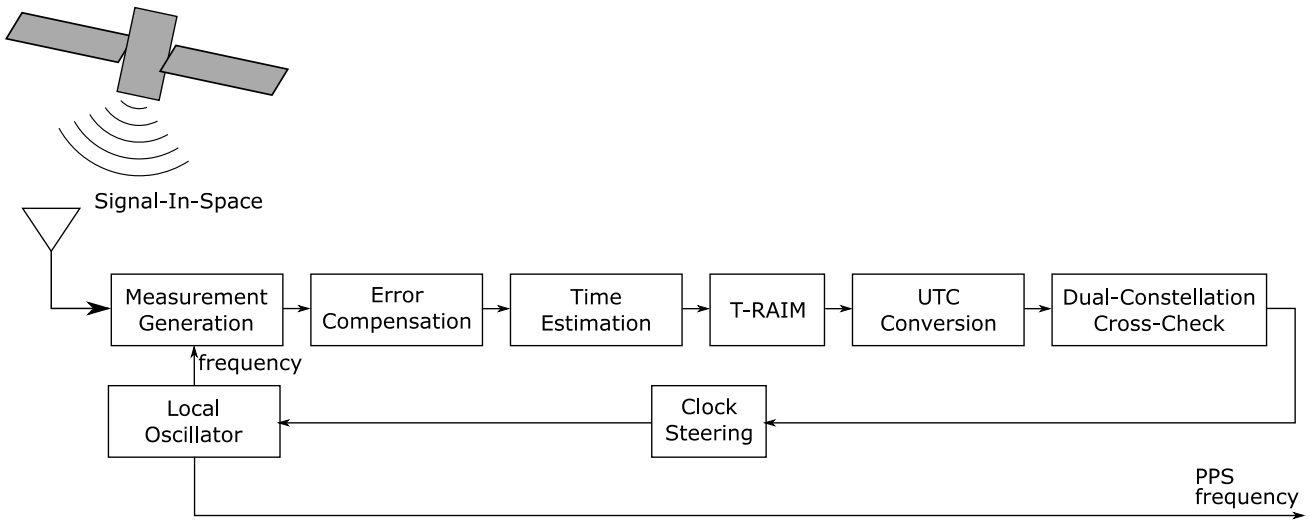


Fig. 1 Overview of the robust processing chain proposed for the retrival of EGNSS-based timing.

A hardware receiver is used to produce the basic GNSS observables which are post-processed using a software-defined navigation engine. Test results are presented to give a preliminary indication of the performance of the envisioned EGNSS timing services; the International Telecommunication Union (ITU) recommendation for primary reference clocks [5] is used as the benchmark application with which the evaluated KPIs are compared.

II. Basics of EGNSS Timing

The most important difference between timing GNSS receivers and regular receivers is the possibility to output a time and/or frequency reference signal. A timing receiver typically provides a pulse per second (PPS) output which is synchronized to a reference time scale. Another property we assume for a timing receiver is the availability of an oscillator that can be steered based on the GNSS measurements. This can be either the local oscillator (LO) driving the receiver itself or an external GNSS-disciplined oscillator. In both cases, the oscillator can continue operating autonomously in cases where GNSS becomes temporarily unavailable; the state where the receiver oscillator is used without GNSS is called "holdover". Obviously, the timing performance degrades gradually in the absence of GNSS updates. The maximum holdover time is defined by the quality of the oscillator and the application-specific performance requirements.

Galileo satellites are synchronized to the Galileo System Time (GST). They broadcast open signals at the E1 and E5 frequencies, which allows the elimination of the first-order ionospheric delay effect by constructing the so-called ionosphere-free linear combination. Single-frequency users can utilize the NeQuick G ionospheric model with the parameters broadcast in the Galileo navigation data to compensate for most of the ionospheric delay.

EGNOS is a satellite-based augmentation system whose purpose is to provide additional integrity and correction data for other GNSSs; at the moment, it only supports GPS. EGNOS has its own system time called EGNOS Network Time (ENT) which is steered towards GPS Time (GPST). EGNOS is currently a single-frequency system; ionospheric corrections are provided in the form of a grid model. As an augmentation system, EGNOS can only be utilized for timing in conjunction with GPS measurements; for the time being, it does not support direct pseudorange measurements from the geostationary EGNOS satellites [7].

The proposed processing chain for EGNSS-based timing is illustrated in Fig. 1. In order to retrieve the system time, the receiver needs to obtain at least one pseudorange measurement assuming that the location of the antenna is fixed and known. The receiver is expected to run an interference/jamming detection algorithm and automatically trigger holdover if the signals are suspected to be compromised; the detection can be based on, e.g., monitoring the automatic gain control of the radio front-end [8]. With the necessary measurements available, the receiver applies all necessary information such as satellite clock corrections, and computes a residual error budget for each measurement using the signal-in-space accuracy estimates and other available integrity information.

Using a set of pseudoranges and associated standard deviations, the process of receiver clock bias estimation reduces to weighted averaging when the antenna location is precisely known. Although one pseudorange is sufficient for time determination, the envisioned timing services require at least two simultaneous measurements in order to provide resilience against outliers by verifying the mutual consistency of the pseudorange measurements by means of T-RAIM [15]. If there are enough redundant measurements, it is possible to identify and exclude the faulty ones as long as the majority of the measurements are intact.

The newly obtained time solution can be converted from the system time scale to a UTC realization using the broadcast conversion parameters. Furthermore, GST can be converted to GPST (or vice versa) directly by applying the Galileo/GPS Time Offset parameters. If the receiver supports GPS, an additional consistency check can be implemented by verifying the consistency of the EGNSS-based time solution and the one

computed using GPS measurements. Note that EGNOS receivers are inherently GPS-capable, and Galileo signals have been designed to facilitate interoperability with GPS. The constellation-level cross-checking can reveal the presence of system-level failures such as faulty broadcast UTC conversion parameters or erroneous Earth orientation parameter realizations. It is noteworthy that two systems are not sufficient for identifying the failing one; for that purpose, a third constellation (GLONASS or BeiDou) would be needed.

If the EGNSS-based timing solution successfully passed all the consistency tests, it can be used to steer the LO (or the disciplined oscillator). The steering process can serve as an additional robustness measure: if the stability properties of the oscillator are known, implausible EGNSS solutions can be discarded in favor of holdover. For instance, the evolution of the LO errors can be monitored with a Kalman filter [9].

III. Key Performance Indicators for Robust EGNSS Timing Services

The performance requirements of various timing applications are specified in terms of different KPIs. In this section, we discuss metrics that are suitable for quantifying the performance of robust EGNSS based timing.

A. Time Accuracy

The time accuracy is obviously an important KPI and readily specified for many GNSS positioning services. The accuracy can be specified as a quantile (e.g., 95 %) of the series of time offsets, Δt, computed as

$$\Delta t_i = t_{GNSS}(i) - t_{ref}(i) \quad (1)$$

where t_{GNSS} and t_{ref} denote the GNSS-based and reference times, respectively, and i is the time index. Note that different accuracies may be specified for time estimates computed for different time scales in order to account for the uncertainty in the conversion models.

For evaluating the accuracy, it is important to calibrate out any hardware delays occurring during the signal propagation through the antenna, cables, and the receiver itself. These biases can depend both on the carrier frequency and the type of signal modulation [10].

B. Frequency Stability

Frequency stability refers to the fluctuations in the frequency of an oscillator. Stability is a function of the analysis interval (often called averaging time); in general, the short-time stability is dominated by (uncorrelated) noise while long-term stability is affected by frequency random walk and other types of correlated effects. As opposed to accuracy, stability does not consider constant time estimation biases such as hardware delays.

The classical metric for stability characterization is the Allan Deviation (ADEV) [12], but it has been largely superseded by more modern variants [13]. In this paper, we will consider two stability measures: Time Deviation (TDEV) and Maximum Time Interval Error (MTIE). Both of these can be evaluated from time offset measurements, although direct formulas for computing TDEV using frequency offset measurements exist. For an analysis interval, τ, consisting of m samples, TDEV is computed from $(M+1)$ time offset measurements as [13]

$$TDEV(\tau) = \frac{\sum_{j=1}^{M-3m+2}\left(\sum_{i=j}^{j+m-1}(\Delta t_{i+2m} - 2\Delta t_{i+m} + \Delta t_i)\right)^2}{m\sqrt{6(M-3m+2)}}. \quad (2)$$

The MTIE refers to the largest observed change in the time offset within any duration equal to the analysis interval τ, which can be mathematically formulated as follows [13]:

$$MTIE(\tau) = \max_k \left(\max_{(k-1)m+1 \le i \le km} \Delta t_i - \min_{(k-1)m+1 \le i \le km} \Delta t_i \right). \quad (3)$$

An important difference between the two stability metrics introduced above is the fact that TDEV is insensitive to a constant frequency bias causing a linearly increasing time offset error whereas MTIE is affected by such a factor. There exist many alternative stability metrics; for an extensive description, the reader may refer to [13].

C. Integrity

Since robustness is a key property of the envisioned EGNSS timing service, KPIs related to integrity are of particular importance. First, the user needs to specify false alarm and missed detection probabilities, p_{FA} and p_{MD}, respectively, which define the statistical detection threshold and the time protection level for the integrity monitoring algorithm.

The time protection level corresponds to the timing error caused by marginally detectable measurement errors, i.e., the magnitude of measurement faults that cause the statistical integrity test, with detection threshold determined based on p_{FA}, to be erroneously passed with a probability equal to the pre-defined p_{MD}. Then, given an alarm limit defined by the application-specific requirements, integrity is available whenever the protection level is smaller than the alarm limit.

Protection levels are specific to the integrity monitoring algorithm selected; for instance, it is possible to design integrity monitoring methods that yield stricter protection levels at the expense of an increased solution variance [11]. The results presented in Section V correspond to the T-RAIM algorithm described in [15].

D. Availability

The availability of an EGNSS timing service refers to the percentage of time when the signals providing the service can be accessed and the service delivers its specified performance. The evaluation of availability requires long observation time series or simulations. Both of these are beyond the scope of this paper, therefore, availability will not be considered in the experimental results presented in Section V.

IV. Instrumentation for Evaluating the KPIs Under Threat Conditions

In order to evaluate the resilience of the envisioned EGNSS timing services to the most relevant threat scenarios, specialized instrumentation is needed. The test setup is illustrated in Fig. 3. First of all, one needs access to a stable reference time, such as a UTC realization. In this paper, the reference time is provided in the form of a 1 PPS signal, and a time interval counter is used

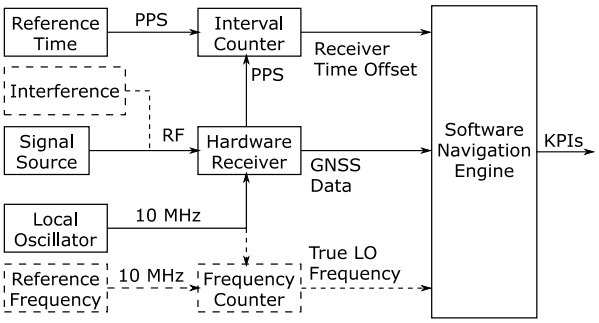


Fig. 2 Signals, measurement instruments and data outputs necessary for the evaluation of the KPIs with a software-defined GNSS navigation engine. Dashed lines indicate optional components.

to measure the offset between this reference signal and the 1 PPS output of the hardware GNSS receiver that is generating the GNSS observables. These offsets correspond to the $t_{ref}(i)$ values needed to compute the time offsets Δt_i according to (1). The GNSS observations are saved for processing with a custom navigation engine where the KPIs are evaluated using the reference data measured by the counters. The radio frequency (RF) signal source can be either an antenna measuring authentic GNSS signals, or it can be a GNSS signal simulator; both of these can be combined with a source of RF interference simply by using an inverted signal splitter.

In order to gain access to the LO, a free-running external oscillator is used as frequency input for the hardware receiver. This allows the evaluation of the improvement in stability achieved with the use of GNSS and of the impact of the holdover mode. If the 1 PPS output of the GNSS receiver is derived directly from the frequency input, the measured time offsets in the setup output are sufficient for evaluating the stability of the LO; otherwise, a separate frequency counter can be used to measure the LO frequency. Since the LO is running freely, actual GNSS-based steering corrections are not generated. The effect of clock steering can be simulated by comparing the GNSS-based time/frequency solution with the values measured by the interval and frequency counters.

As a result, the proposed test setup produces time series of the measured receiver clock offset and GNSS observables including the navigation data; the LO frequency offset can be measured if necessary. Measurement and navigation data errors can be introduced into the data logged before processing with the custom navigation engine.

V. Experimental Results

In this section, we present results on the evaluation of the proposed KPIs with the envisioned EGNSS timing services under various threat conditions. ITU recommendation [5] is used as a benchmark application for interpreting the results. In the tests, a NovAtel Propak6 hardware receiver was driven by a low-cost oscillator [16], and the Finnish UTC(MIKE) realization was used as reference time. The receiver was stationary and the antenna coordinates were known; the tests were conducted in Espoo, Finland, which is located relatively close to the boundary of the EGNOS service area. The frequency offset of the low-cost LO was roughly 1.7 Hz with respect to its nominal 10 MHz frequency, equivalent to a normalized offset of 1.7×10^{-7}.

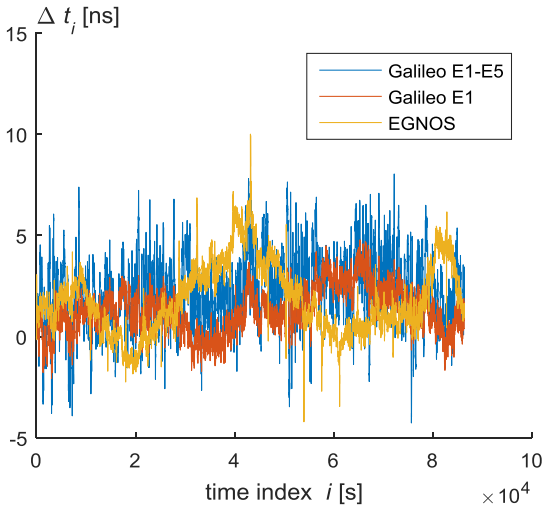


Fig. 3 Time offset as evaluated for the fault-free case

The NovAtel receiver is not calibrated for internal hardware delays. In order to account for this additional bias, the Δt_i time series shown in this paper are shifted to start from zero. This procedure also eliminates errors in the system time to UTC conversion parameters which constitute a significant factor affecting the accuracy of GNSS-based timing. This operation is expected to correspond the calibration performed in timing receivers.

Each test covers a time span of 24 hours; the receiver logged Galileo measurements on the E1 and E5b bands, GPS L1 and L5 measurements, and EGNOS messages. The results presented correspond to the values that would be used to generate the steering corrections for the LO, i.e., those filtered by the Kalman filter proposed by [9]; this makes it possible to compute time estimates during GNSS unavailability. It should be noted that the results presented in this paper are not intended to serve as performance specifications of the envisioned Galileo and EGNOS timing services.

A. Baseline Test: No Faults Present

The KPIs are at first evaluated using clean, fault-free data. Fig. 3 shows the time offsets obtained with dual- and single-frequency Galileo processing as well as single-frequency EGNOS. Although the short-term variations in the EGNOS solution are the smallest, spikes and correlated changes can be clearly seen. The short term noise is due to a generally higher number of available satellites with the peaks being caused by varying availability of the corrections. In particular, the EGNOS solution is obtained by correcting GPS measurements. Overall, the dual-frequency Galileo solution is noisier than the corresponding single-frequency solution. This effect is due to the amplification in the ionosphere-free measurement combination.

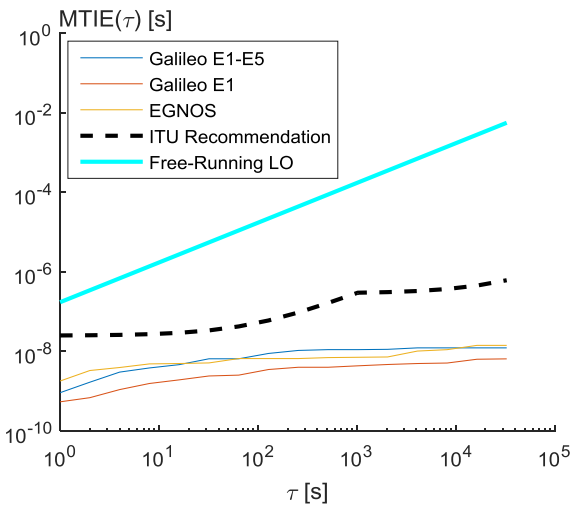


Fig. 4 MTIE obtained in the fault-free case.

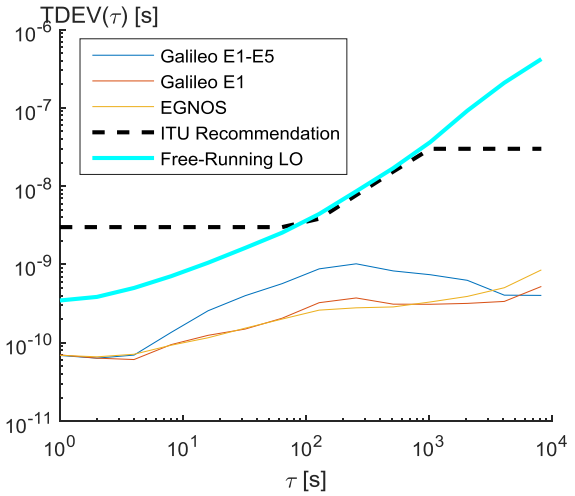


Fig. 5 TDEV evaluated in the fault-free case.

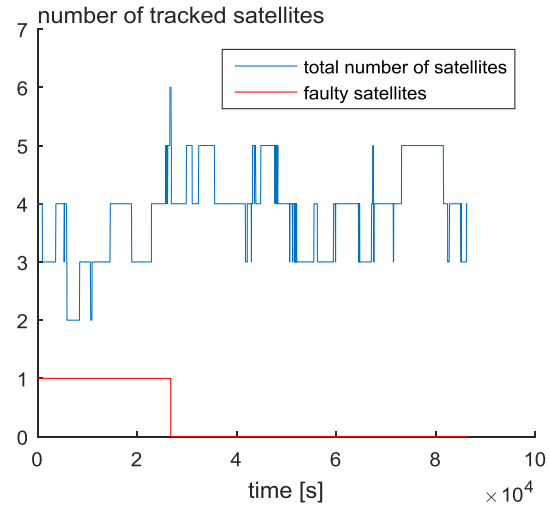


Fig. 6 Number of available satellites in the satellite clock failure test

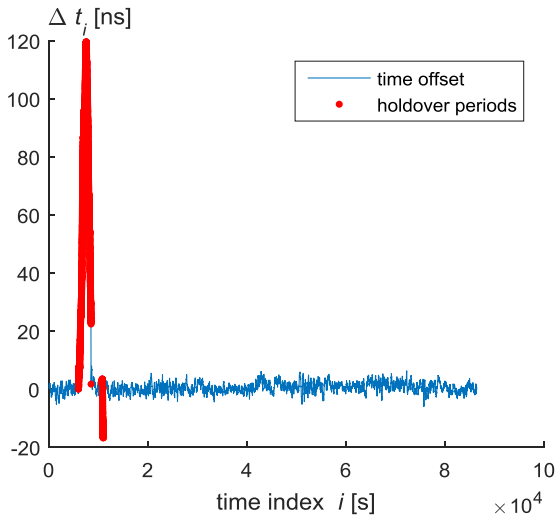


Fig. 7 Resulting time offset in the satellite clock failure test with T-RAIM enabled

The corresponding MTIE and TDEV values are shown in Fig. 4 and Fig. 5, respectively; the higher noise levels of the dual-frequency Galileo solution are reflected in the TDEV curve. Nevertheless, all three solutions meet the ITU recommendations in terms of both stability metrics. Fig. 4 and Fig. 5 also show the stability of the LO in free-running mode without GNSS corrections; it can be seen that the LO is not stable enough to meet the ITU recommendations.

B. Satellite Clock Failure

To show the importance of T-RAIM, we investigate a case where the broadcast clock correction parameters of one Galileo satellite were manually altered in order to simulate a satellite clock failure. The total number of available satellites in the test is plotted in Fig. 6 along with an indication of the epochs where the faulty satellite was present. It can be seen that there are epochs where only two satellites are available, one of these being faulty. In such cases, it is impossible to exclude the faulty one, leading to holdover. This effect can be seen in the resulting time offsets shown in Fig. 7 where the timing error temporarily exceeds 100 ns during the long holdover period of approx. 42 minutes. Time and frequency offsets for the holdover periods were estimated using the Kalman filter proposed in [9]. Note that this error accumulated during holdover is not subject to the T-RAIM protection levels (Fig. 8); when T-RAIM is available, the variation in the time offset is well bounded by the time protection level. It is noteworthy that the number of available satellites was low because the Galileo constellation is not yet complete; in the future, a better performance can be expected as the number of Galileo satellites increases.

The effect of T-RAIM on the stability in this case is shown in the TDEV and MTIE plots in Fig. 9 and Fig. 10, respectively. It can be seen that without the mitigation provided by T-RAIM, the resulting stability is grossly exceeding the ITU recommendation. Enabling T-RAIM improves the situation and the results meet the goal, but it can be seen that the prolonged holdover period has a significant effect, particularly dominating the MTIE.

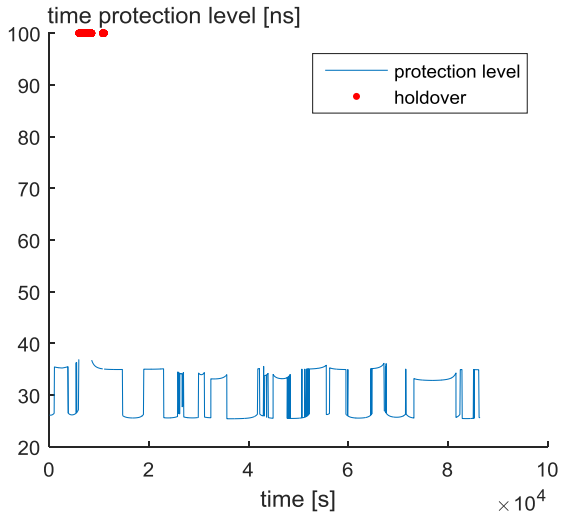


Fig. 8 Protection levels estimated for the T-RAIM algorithm in the satellite clock failure test with $p_{FA} = 10^{-5}$ and $p_{MD} = 10^{-3}$. Note that the value of 100 ns for the holdover period was chosen arbitrarily to indicate unavailability of T-RAIM.

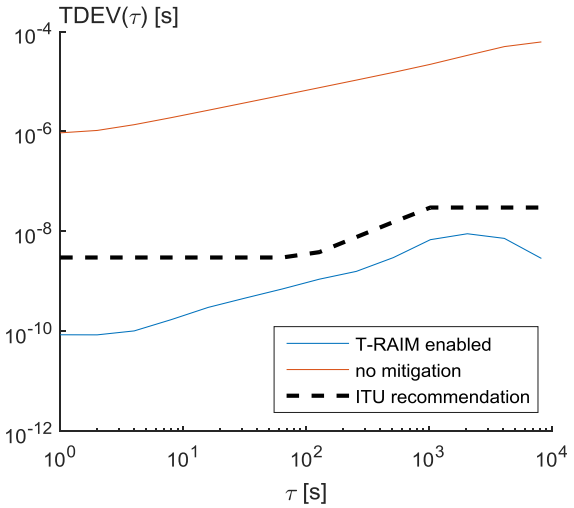


Fig. 9 TDEV with and without T-RAIM in the case of a satellite clock failure.

C. *Ionospheric Errors*

Ionospheric effects were simulated by injecting occasional pseudorange errors corresponding to 75 TECU (40 ns at the E1 and 67 ns at the E5 band) to the measurements of two Galileo satellites. Note that this approach does not simulate the scintillation effect. Applying all the processing steps described in Section II, the resulting time offsets are plotted in Fig. 11. It can be seen that there are several spikes visible in the E1-only solution, originating from the artificial ionospheric errors. As expected, the dual-frequency solution shows no distinct peaks, but the inherently increased noise level is practically voiding that advantage. This is illustrated in the stability metrics shown in Fig. 12 and Fig. 13: the MTIE for the dual-frequency solution is better for short analysis intervals, but it eventually exceeds the single-frequency solution MTIE; the non-mitigated case is

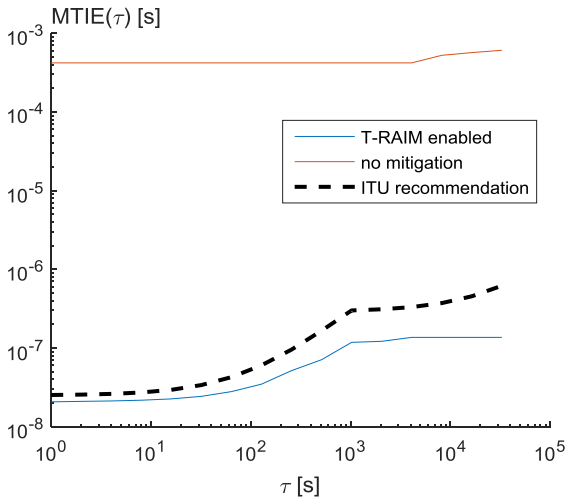


Fig. 10 MTIE with and without T-RAIM in the case of a satellite clock failure.

clearly worse and does not meet the ITU recommendation. The E1 MTIE is dominated by the single spikes which are close to 10 ns in magnitude. In terms of TDEV, all solutions meet the recommendation, with the non-mitigated case showing higher deviation at very short analysis intervals. By comparing with the fault-free stabilities shown in Fig. 4 and Fig. 5, it can be seen that the dual-frequency solution is not notably affected by the ionospheric errors, as can be expected.

VI. Conclusions

This paper presented a set of KPIs that are relevant for EGNSS based timing services from the user perspective, and an experimental setup for evaluating these metrics in the presence of various abnormal conditions. The proposed setup was used to give an indication of the performance of envisioned timing services for EGNSS, using the recommendations for primary

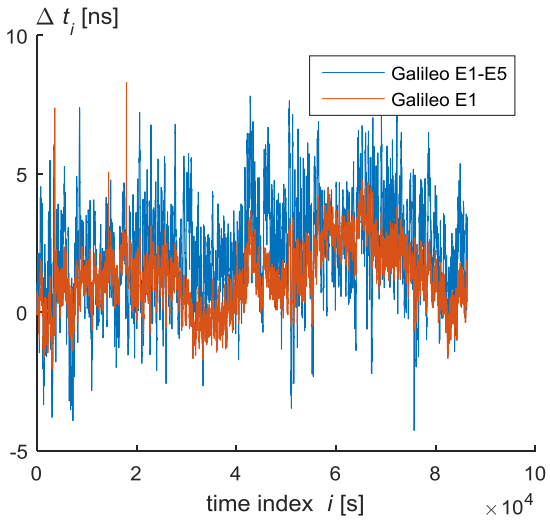


Fig. 11 Resulting time offsets in the presence of occasional ionospheric disturbance

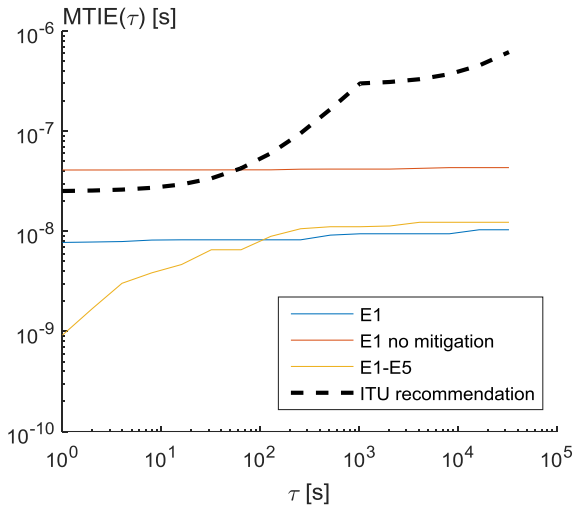


Fig. 12 MTIE in the presence of occasional ionospheric disturbance

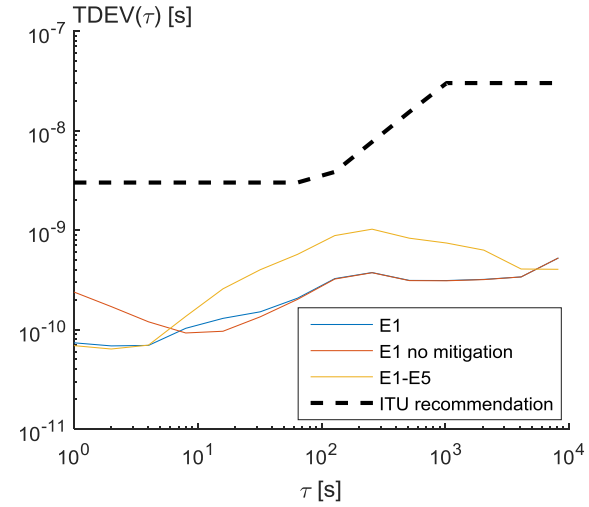


Fig. 13 TDEV in the presence of occasional ionospheric disturbance

reference clocks in telecommunications [5] as the performance requirements of an example application.

The test results showed that adding robustness techniques to the processing of EGNSS measurements made it possible for a low-cost oscillator to meet the requirements of the example application. However, it was observed that the oscillator does not perform well in holdover, with a clear degradation in stability caused by prolonged lack of GNSS corrections. More tests of holdover, e.g., with jamming present, need to be conducted for more profound analysis.

As future work, recommendations for the choice of oscillator to be used with the services under different performance requirements are to be designed. Along with well-defined timing services for EGNSS, this can pave the road for the standardization of EGNSS timing receivers.

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