Semi-Assisted Signal Authentication Based on Galileo ACAS

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ABSTRACT

A GNSS signal authentication concept named semi-assisted authentication is proposed. It is based on the re-encryption and publication of keystream sequences of some milliseconds from an already existing encrypted signal. Some seconds after the keystreams are transmitted in the signal-in-space, the signal broadcasts the key allowing to decrypt the sequences and the a-posteriori correlation at the receiver. The concept is particularized as Galileo Assisted Commercial Authentication Service, or ACAS, for Galileo E1-B, with OSNMA used for the decryption keys, and E6C, assumed to be encrypted in the near future. This work proposes the ACAS cryptographic operations and a model for signal processing and authentication verification. Semi-assisted authentication can be provided without any modification to the signal plan of an existing GNSS, without the disclosure of signal encryption keys, and for several days of receiver autonomy, depending on its storage capabilities.

INTRODUCTION

Global Navigation Satellite Systems (GNSS) location is based on two main inputs: the satellite positions and time data, and pseudorange measurements. GNSS data authentication is already in the signal in space for Galileo through OSNMA (Open Service Navigation Message Authentication) [1] and possibly other GNSS in the future. Pseudoranges are more difficult to authenticate, as they are generated in the receiver. However, as they are based on the GNSS signal spreading codes, so by authenticating the spreading code sequence some level of protection can be achieved: DS-SS (Direct Sequence – Spread Spectrum) techniques bury the signals below the noise power level in the receiver, so it difficult for an adversary to estimate any hidden chips if not provided by the system. This is why spreading code total or partial encryption is proposed as the most effective way to authenticate GNSS signals and measurements. Other methods can use signal unpredictability from NMA cryptographic bits or symbols [2], vestigial signal monitoring [3], or consistency checks [4]. Spreading code authentication (SCA) does not mean that measurement is authenticated against all threats, because it could be still replayed under some circumstances, but this is considerably more difficult.

Civil SCA was proposed almost two decades ago [5] and can be implemented in many ways, many recollected in [6]. In standalone mode, i.e. without any assistance, it is based on watermarks in the spreading code that are correlated a posteriori, when a decrypting key is disclosed [7]. If the receiver is assisted, i.e. it has a network connection, it can capture an encrypted signal snapshot and have it authenticated in a server [8] [9]. The server may, or may not [10], know the decryption key. Another approach is that the receiver
receives from the server a posteriori the correlation replica [11]. In these approaches, the receiver connects to the server for each authenticated position. Both standalone-through-watermarking and assisted methods are under test for GPS Navigation Technology Satellite (NTS)-3 as CHIMERA [12]. Dedicated schemes for Galileo range authentication in its future 2nd Generation are also under study [13].

The proposed scheme here, named semi-assisted authentication, is intended to provide spreading code authentication to civil users in Galileo 1st generation, but it can be extrapolated with other systems. To the knowledge of the authors, it has never been implemented by any GNSS. The GNSS has to provide NMA, or at least regular unpredictable bits that can be used as a cryptographic key and are known a priori by the system and not by the receivers, and have an encrypted signal, e.g. a military or commercial one as Galileo's E6C, which remains unchanged. The purpose is to maximize receiver autonomy to several days, yet allowing regular spreading code authentications.

This concept is being applied to Galileo through the E1-B OSNMA and the E6C pilot signal, soon to be encrypted. Once the Galileo program officially confirmed in 2017 its intention to provide signal authentication [14], this concept was proposed to alleviate receiver requirements yet providing SCA based on the already existing signal plan [15].

After this introduction, we present our motivation and the general concept. Then, we describe the proposed scheme in detail, and how it is particularized for the Galileo system, including cryptographic operations, definition of the E6C snapshot, some signal processing parameters, and a proposed signal authentication verification check. We finalize with the conclusions.

**MOTIVATION AND GENERAL CONCEPT**

Currently, all GNSS provides SCE e.g. for military or governmental services: GPS P(Y) or M-code, Galileo's PRS and CS (E6C), and so on. Regarding NMA, it is already provided by Galileo, but can also be provided by another GNSS in the near future. Our main motivation is to provide SCA by a GNSS system that can already transmit a fully encrypted signal and NMA, as Galileo. We also want to maximize the receiver autonomy and not force the receiver to use a secret key. For the system, this means not changing the signal plans or satellite payload generating the spreading codes, or its key management scheme. If the signals can be designed from scratch to provide SCA, other schemes may be more optimal.

**General Concept**

The service operator knows a priori the key used to encrypt the signal (or at least its keystream), and the future NMA keys transmitted in an open signal. These OSNMA keys which be unpredictable. For example, a TESLA chain like OSNMA's [16] fits this purpose. With these two elements, the operator can re-encrypt parts of the encrypted signal, at known instants, with the NMA cryptographic material to be later disclosed, to create re-encrypted code sequences (RECS), and publish them in advance.

Before starting the autonomy period, the receiver downloads the RECSs, with their start and end times. At, or around, those times, the receiver records a signal snapshot of the encrypted signal, then waits for the NMA key to be disclosed, and then it decrypts the RECS and correlates a-posteriori the signal snapshot and the decrypted keystream sequence (or ECS). If correlation occurs, and under certain conditions and hypotheses, the receiver can assume that the signal is not spoofed. A key assumption is that the receiver has a loose synchronization time source, sufficient to prevent an adversary to replay the ECS after the NMA key is disclosed. This requirement is already in place for Galileo OSNMA.

The concept is depicted in Figure 1 for the system side and Figure 2 for the receiver side. Figure 1 shows an encrypting key $K_{encr}$ used to generate a keystream of the encrypted signal. The keystream will be used,
at the required spreading code rate, multiplexed with the GNSS signal, encrypting it. Some sequences of the keystream $ECS_j, ECS_{j+1}, \ldots$ are selected for re-encryption at predefined slots. These sequences are then re-encrypted with an NMA key $K_j, K_{j+1}, \ldots$ that is already known to the system operator, but will be publicly disclosed in the NMA bitstream with a certain delay after the ECS time. The keystream sequences are encrypted with the NMA keys, forming $RECS_j, RECS_{j+1}, \ldots$ and then these $RECS$, together with their associated time tags and other metadata are published in a server, for a certain period that can be of several days or even weeks, depending on the system operation and key management.

At the receiver, as shown in Figure 3, the receiver stores a signal snapshot from the encrypted signal, waits until the related NMA key ($K_j$) is disclosed to decrypt the pre-stored $RECS$ ($RECS_j$) and performs the correlation, obtaining the de-spreading gain if the signal is found. Then, the receiver can consider that the pseudorange obtained with this correlation is authenticated.

**PARTICULARIZATION FOR GALILEO ACAS**

This section describes the concept in detail and particularize it to Galileo E1B/E6C signals. The concept is currently under implementation and testing as Galileo Assisted Commercial Authentication Service, or ACAS. It has also been prototyped in the EC NACSET project [17]. ACAS is based on two already existing Galileo signals: On the one side, the Galileo E1-B [18], including OSNMA [19]. On the other side, the Galileo E6C pilot signal [20], which provides the keystream. This signal is currently unencrypted, but it will soon be encrypted to provide Galileo ACAS. The semi-assisted authentication in Galileo through ACAS is depicted in Figure 3. A concept for operation is proposed based on the following steps:
1. The publication, in the European GNSS Service Center (GSC) server, of RECS files applied to the E6C signal based on OSNMA keys, allowing to correlate RECS with different periods. The server also provides the satellite broadcast group delays (BGDs) between the E1 and E6 signals in advance, as this information is not in the broadcast I/NAV message and therefore not authenticated by OSNMA.

2. The RECS/BGDs, or a subset of them, are downloaded from the server and stored in the receiver.

3. The receiver starts up and receives the Galileo E1-B signal, and synchronizes with it and obtaining a data-authenticated PVT.

4. At the time RECS are expected, the receiver records a snapshot of E6C samples and stores it for later use.

5. After some time, the E1 I/NAV OSNMA key is received.

6. For each satellite, the RECS is decrypted with the OSNMA key, obtaining the ECS.

7. The ECS and the E6C snapshot are correlated. If the correlation is successful, an E6C pseudorange is generated.

8. E6C pseudoranges together with I/NAV authenticated data and E6 BGDs are used for a spreading code-authenticated position calculation.

**RECS and BGD files**

Apart from the sequences, RECS files need to define the start time and file duration, satellite ID for which RECS are provided, RECS period $\tau_{RECS}$, i.e. how often a RECS is provided, and $NChips$, or number of chips per RECS. The RECS files provide tree additional parameters: a RECS Offset, which defines the position of the start of the RECS with respect to the start of an integer GST second, a SLRECS (Slow RECS) Offset, which defines whether the RECS belongs to the current OSNMA key to be provided within the next 30 seconds (SLRECS = 1), or later, and a $\Delta T_{MAX}$, which is a parameter to optionally randomize the position of each RECS. These parameters will be contained in the RECS file header, which will be followed by the RECS. The file content authenticity can be assured by a digital signature. RECS parameters are depicted in

*Figure 3 – Assisted CAS scheme, including the steps to deliver the service.*
Figure 4. The top plot shows no time randomization ($\Delta \tau_{\text{MAX}} = 0$), and the bottom plot shows randomization in the RECS start ($\Delta \tau \leq \Delta \tau_{\text{MAX}} \neq 0$). The receiver can determine $\Delta \tau$ after the OSNMA key of the related period is disclosed.

Regarding the BGD files, the system can forward estimate the E1 I/NAV-E6C BGDs and provide them in a separate file to be downloaded and cryptographically signed. Additional information may include the accuracy estimation over time, so its related uncertainty can be accounted for. The BGDs are very stable and in nominal conditions can be stably predicted for several days. In any case, their contribution to the satellite position error is expected to be small, as discussed in later sections.

**Cryptographic Operations**

The cryptographic operations required in the receiver and described in this section are the generation of the RECS decryption key, the generation of the randomization parameter, and the RECS decryption. Other possible operations, such as the digital signature verification of the RECS/BGD files can be based on standards and are not described here.

**RECS decryption key:** Once the OSNMA key $K_j$ belonging to MACK (MAC and key) block $j$ is received and verified by the OSNMA keychain, the RECS decryption key $K_j'$ can be generated as follows:

$$K_j' = \text{SHA256}(K_j)$$ (1)

where $\text{SHA256}()$ is the hash function SHA-256 as per [21]. As SHA256 is a one-way function, this allows that the RECS can be decrypted only when the OSNMA related key is disclosed, but, at the same time, the OSNMA keychain itself is not used at the moment of RECS encryption. Therefore, ACAS and OSNMA can be independent processes, provided that when the OSNMA keychain is generated, a parallel set of $K_j'$ for the OSNMA keychain is generated as well.

**RECS Location Randomization:** RECS location randomization is bounded by the parameter Maximum Delta RECS Period $\Delta \tau_{\text{MAX}}$. If $\Delta \tau_{\text{MAX}} = 0$, there is no randomization, and the RECSs are deterministically located for each RECS period. If $\Delta \tau_{\text{MAX}} \neq 0$, RECS locations in the keystream are delayed by a random
time $\Delta r$ between zero and $\Delta_{\text{MAX}}$. For example, if $\Delta_{\text{MAX}} = 3$, the RECS can be located with a delay of 0, 10, 20 or 30 ms (i.e. $\Delta r = 0, 1, 2, 3$). For each satellite and period, $\Delta r$ can be generated as follows:

$$(C_1, \ldots, C_N) = \text{AES256}_{\text{OFB}}(K', 0, \text{IV})$$ (2)

where $(C_1, \ldots, C_N)$ is the cyphertext block array from which the $\Delta r$s are generated, consisting of $N$ 128-bit blocks, $\text{AES256}_{\text{OFB}}(a, b, IV)$ is the AES cypher in OFB (Output Feedback) mode where $a$ is the key, $b$ is the plaintext, and IV is the initialisation vector, as per [22]. The IV used for $\text{AES256}_{\text{OFB}}$ is generated as follows:

$$\text{IV} = \text{trunc}(128, \text{SHA256}(P_j))$$ (3)

Where $\text{trunc}(n, p)$ is the truncation function that retains the $n$ MSBs of the input $p$, of the related RECS file, and $P_j$ is the 128-bit plaintext generated as follows:

$$P_j = (\text{GST}_{SF,j} | p1)$$ (4)

where $\text{GST}_{SF,j}$ is the 32-bit GST associated to the OSNMA key $K_j$ as per (osnmasisicd); and $p1$ is a padding array with 96 zeros. The cyphertext block array is allocated to the $\Delta r$s as follows:

$$C_1 = \left[B_{k_1}^1, B_{k_1}^2, \ldots, B_{k_1}^{16}\right], C_2 = \left[B_{k_2}^{17}, B_{k_2}^{18}, \ldots, B_{k_2}^{32}\right], C_3 = \left[B_{k_3}^{33}, B_{k_3}^{34}, \ldots, B_{k_3}^{48}\right],$$

$$C_4 = \left[B_{k+1}^1, B_{k+1}^2, \ldots, B_{k+1}^{16}\right], C_5 = \left[B_{k+1}^{17}, B_{k+1}^{18}, \ldots, B_{k+1}^{32}\right], C_6 = \left[B_{k+1}^{33}, B_{k+1}^{34}, \ldots, B_{k+1}^{48}\right],$$

$$C_7 = \left[B_{k+2}^1, B_{k+2}^2, \ldots, B_{k+2}^{16}\right], C_8 = \left[B_{k+2}^{17}, B_{k+2}^{18}, \ldots, B_{k+2}^{32}\right], C_9 = \left[B_{k+2}^{33}, B_{k+2}^{34}, \ldots, B_{k+2}^{48}\right],$$

$$C_{10} = \left[B_{k+3}^1, B_{k+3}^2, \ldots, B_{k+3}^{16}\right], C_{8} = \left[B_{k+3}^{17}, B_{k+3}^{18}, \ldots, B_{k+3}^{32}\right], \ldots$$

where $B^b_k$ is a byte that allows calculating $\Delta r^b_a$, expressed as an integer number of 10-millisecond periods, as follows:

$$\Delta r^b_a = B^b_a \mod (\Delta_{\text{MAX}} + 1)$$ (6)

where mod is the modulo operator; $\Delta_{\text{MAX}}$ is the bitstring described in the RECS file; $a$ is the RECS index for a given satellite in the period; and $b$ is the SVID index (where only values from 1 to 36 are expected). For example, if $\Delta_{\text{MAX}} = 3$ and $B_2^1 = 5$, then $\Delta r^1_2 = 1$ (10 ms), which relates to the 2$^{nd}$ RECS of the period for SVID=1. Note that, while the randomization can protect against some denial of service attacks by making the part of the signal used for correlation less predictable, it can also make the signal snapshot bigger, therefore increasing the receiver storage requirements. Figure 5 shows how to generate $C_i$ based on AES in OFB mode. The figure is based on the AES modes of operation as described in [22].
RECS decryption: Finally, the ECS decryption process, particularised for the decryption key $K'_j + SLRECS$, taking into account the delay introduced by the Slow RECS offset, SLRECS, can also be performed by using AES. The Initialisation Vector (IV) for the cipher, applicable to all decryptions in a given RECS file, is determined as per (3). Then, each RECS$_{j,i}$ is decrypted as follows:

$$ECS_{j,i} = AES256_{CBC}^{-1}(K'_j + SLRECS, RECS_{j,i}, IV)$$  \hspace{1cm} (7)

where $ECS_{j,i}$ is the decrypted keystream and $AES256_{CBC}^{-1}(a, b, IV)$ is the inverse cypher AES, configured for 256-bit keys (AES-256) in CBC mode to decrypt a plaintext $b$ with 256-bit key $a$. Note that the $j$ index defines the decrypting key, and the $i$ index allows for more than one RECS per decrypting key. Note also that RECS$_{j,i}$ must be an integer number of blocks of 128 bits, as required by the proposed AES implementation [23], configured to operate in CBC mode. Figure 6 shows how to generate the ECS based on AES in CBC mode. The figure is based on the AES modes of operation as described in [22].

The RECS decryption process for several OSNMA blocks is depicted in Figure 7, where two ECS/RECS per 30-second OSNMA block are depicted, and SLRECS=1.
This section presents an implementation of the ACAS signal correlation process. The ACAS signal correlation process is generalized and further discussed in [24], including some simulated results.

**E6C snapshot definition:** We assume E1+OSNMA signal is trustable a priori and verify this hypothesis with the E6C ECS correlation. Therefore, at the time of the capturing the snapshot, the receiver is synchronized with GST through E1. Then, for a certain satellite \( k \) and \( ECS_j^k \) (we drop the index \( i \) for simplicity but without loss of generality), associated to a GST second \( GST_j \), the a priori E6 snapshot start time \( t_{\text{start},j}^k \) referred to an absolute time reference GST, is defined as

\[
t_{\text{start},j}^k = GST_j + \delta_{\text{RECS}} + \tau_{\text{prop}}^k - \delta_{\text{sat},E1}^k + \delta_{\text{tx},E1} + \delta_{E1,E6}^k
\]

(8)

Where \( \delta_{\text{RECS}} \) is the RECS offset, \( \tau_{\text{prop}}^k \) is the estimated propagation time of the satellite (typically between 77 ms and 97 ms for Galileo), \( \delta_{\text{sat}}^k \) is the satellite clock offset at the time of the snapshot in the E1 signal, which is known at the receiver, \( \delta_{\text{tx},E1} \) is the receiver clock bias, also estimated by the receiver, based on an E1 signal solution, and \( \delta_{E1,E6}^k \) is the estimated time bias between the E1 and E6 signals, detailed later. \( \delta_{E1,E6}^k \) ensures that the ECS is fully contained in the snapshot. Note that our definition of \( t_{\text{start},j}^k \) neglects the errors in the estimations of its related parameters, which may be in the order of a few meters and therefore usually below one E6C chip (~30m).

Then, the snapshot end time \( t_{\text{end},j}^k \) can be defined as

\[
t_{\text{end},j}^k = t_{\text{start},j}^k + \Delta \tau_{\text{MAX}} + \frac{N_{\text{chips}}}{R_c}
\]

(9)

where \( \Delta \tau_{\text{MAX}} \) is the maximum random offset, \( N_{\text{chips}} \) is the RECS length, in number of chips, and \( R_c \) is the chip rate (\( R_c = 5.115 \times 10^6 \) chips per second for E6C). If the receiver captures only one snapshot for all satellites \( k=1..K \), then the snapshot needs to be broadened by some tens of ms, as defined by \( t_{\text{start},j}^{all} \) and \( t_{\text{end},j}^{all} \):

\[
t_{\text{start},j}^{all} = GST_j + \delta_{\text{RECS}} + \min(t_{\text{sat,prop}}^{all}) + \delta_{\text{tx},E1}
\]

(10)

\[
t_{\text{end},j}^{all} = GST_j + \delta_{\text{RECS}} + \max(t_{\text{sat,prop}}^{all}) + \delta_{\text{tx},E1} + \Delta \tau_{\text{MAX}} + \frac{N_{\text{chips}}}{R_c}
\]

(11)
Where \( \max() \) and \( \min() \) are the maximum and minimum operators and \( \tau_{\text{sat,prop}}^{\text{all}} \) is a vector with propagation times and signal time offsets:

\[
\tau_{\text{sat,prop}}^{\text{all}} = (\tau_{\text{prop}}^1 - \delta t_{\text{sat,E1}}^1 + \delta_{E1,E6}^1, \ldots, \tau_{\text{prop}}^K - \delta t_{\text{sat,E1}}^1 + \delta_{E1,E6}^K)
\]

This guarantees that the snapshot starts at the earliest-to-arrive satellite, and finishes at the end of the ECS of the latest satellite, considering both propagation, satellite clock, and biases.

After the snapshot is captured and \( K'_{\text{SLECS}} \) is determined, the random times \( \Delta t_j^k \) are calculated as per (6). Then, the snapshot of samples used for acquisition of each satellite \( k \) can be narrowed as follows:

\[
t_{\text{acq-start},j}^k = t_{\text{start},j}^k + \Delta t_{a,j}^k \tag{13}
\]
\[
t_{\text{acq-end},j}^k = t_{\text{acq-start},j}^k + \frac{N_{\text{chips}}}{R_c} \tag{14}
\]

**E1-E6 time and frequency offsets:** The term \( \delta_{E1,E6}^k \) models the time bias estimation between the E1 and E6 pseudoranges. It is the term that allows to estimate the E6 measurement from the already available E1 measurement. It includes all the time offsets that are different between signals. It therefore can be modelled as

\[
\delta_{E1,E6}^k = \hat{\text{BGD}}_{\text{sat,E1,E6}}^k + \delta I_{E1,E6} + \hat{HWB}_{\text{rx,E1,E6}}
\]

With the following definitions:

- \( \hat{\text{BGD}}_{\text{sat,E1,E6}}^k \) is the estimation (denoted as \( \hat{\delta} \) in the proposed notation, when both measured and estimated values are used) of the satellite bias, or broadcast group delay (BGD) between E1B/C and E6C signals, as transmitted by satellite \( k \). In particular:

\[
\delta t_{\text{sat,E6}}^k = \delta t_{\text{sat,E1}}^k - \hat{\text{BGD}}_{\text{sat,E1,E6}}^k \tag{16}
\]

Where \( \delta t_{\text{sat,E6}}^k \) is the satellite time offset as observed in the E6 signal. \( \hat{\text{BGD}}_{\text{sat,E1,E6}}^k \) is an input for ACAS from the abovementioned ACAS file, as shown in Figure 3. Galileo E1-E6 BGDs are usually in the order of a few meters and, while the BGD files are generated a priori, the BGDs are expected to be stable, allowing the correlation process.

- \( \hat{HWB}_{\text{rx,E1,E6}} \) is the receiver hardware bias between E1B/C and E6C (in this case, to be added to the receiver bias in E1, \( \delta r_{\text{rx,E1}} \). As the E6 signal is grabbed in snapshot mode, hardware biases may be higher than in standard multi-frequency receivers. \( \hat{HWB}_{\text{rx,E1,E6}} \) should be calibrated in the receiver and estimated a priori. An example of real biases in a prototype device compatible with ACAS is available in [25].

- Finally, the term \( \delta I_{E1,E6} \) is an additional offset due to the frequency dispersive effect of the ionosphere, which deserves particular attention and is treated in the following subsection.

**E1 vs. E6 ionospheric delay:** In order to clarify \( \delta I_{E1,E6} \) we define the pseudorange equation for E1, in the time domain, and after applying the atmospheric correction models, as follows

\[
\tau_{E1}^k = \frac{r^k}{c} + \delta t_{\text{rx,E1}} + \delta t_{\text{sat,E1}} + \epsilon_1 + \epsilon_T + \epsilon_{MP,E1} + \epsilon_{n,E1} \tag{17}
\]

Where \( r^k \) is the receiver-satellite \( k \) range, \( c \) is the light speed, \( \epsilon_1 \) is the remaining ionospheric error for the E1 measurement, after applying an ionospheric model, \( \epsilon_T \) is the tropospheric error after applying a
tropospheric model, $\epsilon_{MP,E1}$ is the multipath error in E1 and $\epsilon_{n,E1}$ is the receiver noise (filtering, sampling, quantization) error also for the E1 measurement. This equation constitutes the basic pseudorange equation.

The total ionospheric error in E1, before correction, can be defined as follows

$$I_{E1} \approx \frac{40.3 \text{TEC}}{f_1^2} = \hat{I}_{E1} + \epsilon_{I,E1}$$  \hspace{1cm} (18)

Where TEC is the total electron content, $\hat{I}_{E1}$ is the corrected part from the ionospheric model, and $\epsilon_{I,E1}$ is the non-corrected part. We assume that the ionospheric error is estimated from a given ionospheric model, such as Galileo's NequickG [26], which corrects a certain percentage of the ionospheric error, e.g., the Klobuchar model is claimed to correct about 50% of the ionospheric error in average ionosphere conditions.

Then, the term $\delta I_{E1,E6}$ needs to account for the fact that, due to the frequency dispersion in the ionosphere, the error in E6 is higher, $I_{E6} \approx \frac{40.3 \text{TEC}}{f_6^2}$, so $\hat{I}_{E6}$ must be factored accordingly, as the ionospheric correction is inversely proportional to the squared frequency. Therefore, in the absence of a more refined model, a user can estimate $\delta I_{E1,E6}$ as follows:

$$I_{E6} \approx \frac{40.3 \text{TEC}}{f_6^2} = \frac{40.3 \text{TEC}}{f_6^2} \cdot \frac{f_1^2}{f_6^2} = I_{E1} \cdot \frac{f_1^2}{f_6^2} = \hat{I}_{E1} + \delta I_{E1,E6}$$  \hspace{1cm} (19)

$$\delta I_{E1,E6} = \hat{I}_{E1} \left( \frac{f_1^2}{f_6^2} - 1 \right)$$

Where $\hat{I}_{E1}$ is the ionospheric correction estimation in the E1 based on the model used (e.g., NequickG), at a carrier frequency of $f_1 = 1575.42$ MHz, $f_6 = 1278.75$ MHz is the E6 carrier frequency. Note that the NequickG ionospheric parameters are authenticated as part of Galileo OSNMA.

**E1 vs E6 Frequency Offset:** Regarding the frequency domain, the carrier frequency of the signal as processed by the receiver is mainly affected by the relative satellite-receiver velocity (Doppler effect) and the receiver clock oscillator drift. This adds a different frequency offset in the E1 and E6 bands, as the frequency carriers have a different wavelength, and can be modelled as:

$$\Delta f_{j,E6}^k = \Delta f_{j,E1}^k \cdot \frac{\lambda_1}{\lambda_6} = \Delta f_{j,E1}^k \cdot \frac{f_6}{f_1}$$  \hspace{1cm} (20)

Where $\Delta f_{j,E6}^k$ and $\Delta f_{j,E1}^k$ are the frequency deviations in the E6 and E1 bands, and $\lambda_1$ and $\lambda_6$ are the carrier wavelengths ($\lambda_1 = c/f_1$; $\lambda_6 = c/f_6$).

**E6C Signal Correlation and Measurement Generation:** The receiver can use as an input the code phase and frequency estimations, $\tau_{j,E1}^k$ and $f_{j,E1}^k$ respectively, from E1, for a given satellite $k$ and instantaneous identified by $j$ and, where $\tau_{j,E1}^k$ can be defined as the start of the correlated (4-ms) spreading code in E1, which is synchronized with the start of the ECS sequence in E6C, $\hat{\tau}_{j,E6}^k$, except for $\delta_{E1,E6}^k$:

$$\hat{\tau}_{j,E6}^k = \tau_{j,E1}^k + \delta_{E1,E6}^k$$  \hspace{1cm} (21)

With $\hat{\tau}_{j,E6}^k$ and $\Delta \hat{f}_{j,E6}^k$ the receiver can acquire the ECS in snapshot mode, by correlating the ECS replica modulated with $\Delta \hat{f}_{j,E6}^k$ with the snapshot.
As there is some uncertainty associated to $\Delta f^j_{E6}$ and $\hat{\tau}^k_{j,E6}$, mainly from the error contributions that are different for each frequency, typical snapshot acquisition strategies can be used, as for example, code phase parallel FFT-based acquisition [27], followed by interpolation of the peak results [28], but here for a very reduced window of a few samples thanks to the E1 acquisition aiding.

If the E6C encrypted signal was available in the snapshot, at the end of this step the receiver obtains a pseudorange and Doppler frequency measurement in E6C, synchronized with E1, which can be verified for position authentication. The process is depicted in Figure 8. In this figure, the subindex $j$ is omitted for simplicity. The pseudorange (in the time domain) and frequency Doppler measurements from the ECS correlation are represented as $\tau^k_{E6}$ and $\Delta f^k_{E6}$. They are expected to be in the acquisition window defined in the Figure by $F_{\text{max}}^k$ and $T_{\text{max}}^k$, outlined in the next section. Also, the term $\Delta f^k_{E1,E6}$ is shown for convenience but can be obtained easily from (18). In particular, $\Delta f^k_{E1,E6} = \Delta f^k_{E1}(1 - \frac{\lambda_1}{\lambda_6})$.

Position Authentication Check based on E6 Measurements: There are several ways by which the authentication verification can be performed. Aspects like the E6C vs E1 processing gain, or the difference in an E6C and E1-based positions can be assessed. For simplicity, here we propose a model based the difference between $\tau^k_{j,E6}$ and $\hat{\tau}^k_{j,E6}$. The difference between the measured and estimated pseudorange can be compared to a threshold, defined by an upper bound of the estimated measurement error, as already outlined in [29].

For a given verification $ECS^k_j$ associated to measurement $\hat{\tau}^k_{j,E6}$, we define a test variable for every measurement $\xi^k_j$ and the following verification is proposed.

$$\left|\tau^k_{j,E6} - \hat{\tau}^k_{j,E6}\right| \leq y_{\text{auth}} \rightarrow \xi^k_j = 1 \text{ (measurement authenticated)}$$

$$\left|\tau^k_{j,E6} - \hat{\tau}^k_{j,E6}\right| > y_{\text{auth}} \rightarrow \xi^k_j = 0 \text{ (measurement not authenticated)}$$

$$\prod_{k=1}^{K} \xi^k_j = 1 \rightarrow E1 \text{ I/NAV}_j \text{ position authenticated} \quad (23)$$
Then, define the authentication threshold, with the assumption that, in the absence of attacks, i.e. in nominal conditions, the errors contributions follow zero-mean normal distributions, and therefore the overall error of the test variable is also a zero-mean normal distribution.

\[ \gamma_{\text{auth}} = K \sigma_{\text{auth}} \] (24)

Integrity faults will fall under the 'measurement not authenticated' case, and discernment between integrity faults and spoofing is left out of scope of this work. In order to define \( \sigma_{\text{auth}} \), we need to model the a priori error contributions of all components, as follows (\(j \) is dropped for simplicity):

\[
\tau_{E6}^k - \tau_{E6}^k = \tau_{E6} - \tau_{E6} - \delta_{1,E6}^k = \frac{r^k}{c} + \delta_{t_{rxE1}} + \frac{HWR_{rxE1,E6}}{c} + \frac{BGL_{rxE1,E6}}{c} + (\tau_{E1} + \tau_{E1}) \frac{f_2}{f_6} + \tau + \epsilon_{MP,6} + \epsilon_{n,6} - \\
\left( \frac{r^k}{c} + \delta_{t_{rxE1}} + \tau + \epsilon_{rxE1} + \tau + \epsilon_{MP,1} + \epsilon_{n,1} \right) - (BGL_{rxE1,E6} + \delta_{t_{rxE1}} + \frac{f_2}{f_6}) + HWR_{rxE1,E6} = \\
(HWR_{rxE1,E6} - HWR_{rxE1,E6}) + (BGL_{rxE1,E6} - BGL_{rxE1,E6}) + (\tau_{E1} \frac{f_2}{f_6} - 1) + \epsilon_{MP,6} - \epsilon_{MP,1} + \epsilon_{n,6} - \epsilon_{n,1} = \\
\epsilon_{HWR_{rxE1,E6}} + \epsilon_{BGL_{rxE1,E6}} + \epsilon_{t_{rxE1}} \frac{f_2}{f_6} - 1 + \epsilon_{MP,6} - \epsilon_{MP,1} + \epsilon_{n,6} - \epsilon_{n,1} \\
\]

\((r_{j,E6}^k - \delta_{j,E6}^k)\) is expressed as a sum of independent error contributions that we can model as Gaussian, zero-mean, and independent, with some assumptions. In particular, multipath in E1 and E6 have different envelopes and are modelled independently, although they may be dependent, and also non-zero mean for short durations of time. The selected variance should be large enough to account for this, as well as the environment. With these assumptions, \(|\tau_{j,E6}^k - \delta_{j,E6}^k|\) can be modeled as a zero-mean Gaussian distribution with variance \(\sigma_{\text{auth}}^2\), \(N(0, \sigma_{\text{auth}}^2)\), where

\[
\sigma_{\text{auth}}^2 = \sigma_{HWR_{rxE1,E6}}^2 + \sigma_{BGL_{E1,E6}}^2 + \sigma_{t_{rxE1}}^2 \left( \frac{f_2}{f_6} - 1 \right) + \sigma_{MP,6}^2 + \sigma_{MP,1}^2 + \sigma_{n,6}^2 + \sigma_{n,1}^2 \\
\] (26)

With these assumptions, and given values of \(\sigma\) from the receiver and environment, the value of \(K\) can be defined for the desired level of confidence (e.g. \(K = 2\) for a 95% or \(K = 3\) for a 99.7% confidence interval, respectively). This can be defined on a per-user basis. An example of error variance characterization is proposed in [29].

**Further Considerations**

Other considerations left for further work are:

- In this approach, the E6C position is not calculated. This can be done, but it requires to incorporate time offsets between ECS, when they are not synchronized, in addition to the different time of arrival.
- The computation of \(T_{max}^k\) and \(f_{max}^k\) for the acquisition is left out of the scope. \(T_{max}^k\) can be based on the \(\sigma_{\text{auth}}\) error models and \(f_{max}^k\) can be arbitrarily defined based on standard frequency noise assumptions without much impact in the process.
- The expression of (26) can be generalized to other frequencies \(f_a\) and \(f_b\). In that case, the frequency term needs to be expressed in absolute value \(\left| \frac{f_{a}}{f_{b}} - 1 \right|\).
- Full protection against replay attacks may require to look for vestigial ECS during the uncertainty time in the receiver. This process is not described in this work.
Example of ACAS configurations including autonomy period and time between authentications will be analyzed in next occasions.

CONCLUSIONS AND FURTHER WORK

A semi-assisted authentication concept proposed for Galileo ACAS (Assisted Commercial Authentication Service) has been described. It is based on the re-encryption of sequences of the E6C, assumed to be encrypted in the near future, and provision a priori for a user receiver over a ground channel, and the a posteriori decryption once the Galileo OSNMA keys are disclosed. The purpose of this approach is to provide signal authentication without any modification to the signal plan, and without the disclosure of signal encryption keys.

ACAS is particularized for Galileo in detail, including the re-encrypted sequences (RECS) and the E1-E6 broadcast group delays (BGDs) and related parameters. The cryptographic operations to be performed in the receiver are described. These include the generation of the RECS decryption key from the OSNMA key, the computation of the random location offsets of the RECS, and the decryption of the RECS into the transmitted code sequence, or ECS.

An implementation of the ECS signal correlation is presented. It is based on the storage of an E6C signal snapshot for all satellites, and the adjustment of the samples to be correlated for each satellite, once the RECS decryption key is disclosed. In this proposal, the correlation samples are adjusted based on the a-priori synchronization of the receiver to the E1 signal, whose authenticity is verified with the ECS correlation. The receiver needs to account for the satellite BGD (available a priori from the ACAS files), the receiver hardware bias between the E1 tracking and the E6 snapshot, and the frequency dispersive effect of the ionospheric delay. Taking into account this parameters, together with the E1-E6 frequency offset, the receiver can perform the E6 snapshot correlation in a very narrow window in both the time and frequency domains, obtaining an E6C pseudorange measurement based on the ECS, in case the encrypted signal was found.

In order to authenticate the E1 position, an authentication verification is proposed whereby the consistency of the E6C and E1 pseudoranges is assessed, defining a threshold based on the a-priori variances of the error contributions. Other methods are possible, whereby an E6C position can be directly computed, or the E1 vs E6C position differences can be compared. Some aspects not detailed in this work are the authentication status definition in case the signal cannot be authenticated; the combination with other checks from other steps, such as the E6C processing gain, or other sensors; and the verification of vestigial RECS in the receiver loose time interval, to protect against replay attacks. Apart from the abovementioned, further work will also include the verification with real and simulated signals, and the definition of working points for the RECS length and frequency, taking into account real receiver constraints.

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