Improving the Performance of Galileo E1-OS by Optimizing the I/NAV Navigation Message

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BIOGRAPHIES

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Eric Chatre graduated as an aeronautical engineer from the School of Civil Aviation in Toulouse, France. He started his career working with the French Air Navigation Service Provider and followed the early developments of EGNOS, dealing in particular with the preparation of safety demonstration files. He then joined the European satellite navigation management teams set up by the European Commission to supervise the development of EGNOS and Galileo. He is now the head of sector for Exploitation and Evolutions of the European satellite navigation programmes. He is responsible for the definition of services for the European satnav systems. He is also leading the definition work for the 2nd Generation of Galileo in the European Commission.

Marc Jeannot graduated from ENAC (Ecole Nationale d'Aviation Civile, France) in 1984 and entered CNES, the French Space Agency, in 1989. After several years working in operations, he has been working in the field of Satellite Navigation since 2002, mainly dealing with applications. In 2009, he joined the ESA/CNES EGNOS integrated team for new services test beds. Since 2015, he is in charge of Mission and System aspects for the Galileo Program at the European Commission.

Jeremie Godet joined the European Commission (EC) in 2003, after an initial career at CNES, the French Space Agency and the European Space Agency. He was involved for the last 20 years in the Galileo Programme at various positions. He was leading the technical negotiation on the GPS Galileo agreement in 2004. He was also Head of the security department at the European GNSS Agency in Prague. Then he was in charge of overseeing the Galileo infrastructure deployment. He is now deputy Head of Unit of the EU GNSS programme unit in the EC. He has both an engineering degree from National Superior School for Telecommunications in France and a Master's degree from the International Space University.

Dominic Hayes works for the European Commission where he manages the radio regulatory activities for the European GNSS programmes. Dominic is the chairman of the Compatibility, Signals and Interoperability Working Group, within the European GNSS Programme Directorate of DG GROW.

ABSTRACT

The paper describes three new technical solutions that will be soon introduced within the Galileo E1 I/NAV message. The work leading to the design of the three solutions started with the 2012 Galileo Programme decision to re-profile the Safety-of-Life (SoL) service, thus making available a significant portion of the I/NAV message, initially marked as "reserved" in the Galileo Open Service Signal In Space Interface Control Document (OS SIS ICD, [1]). The main driver originally identified for the I/NAV message optimization work was to reduce the Time-To-First-Fix for the Galileo OS users. In particular, the design targeted on one side a shorter time to access the data necessary for the first fix (i.e. Clock and Ephemeris Data, CED) for the non-connected users and on the other a faster re-synchronization with the Galileo System Time (GST) for the connected (or assisted) users. Another key objective was to improve substantially the demodulation robustness of the Clock and Ephemeris Data (CED).

At the end of a long activity including several iterations of design and performance assessment, three different solutions at data and symbol level have been selected for implementation:

- Secondary Synchronisation Patterns (SSP)
- Reduced Clock and Ephemeris Data (RedCED)
- FEC2 Reed-Solomon encoding of the Clock and Ephemeris Data (FEC2 RS CED)

The paper discusses how these new I/NAV message elements aim at the improvement of the speed and the robustness of the reception of Clock and Ephemeris Data (CED) and of Galileo System Time (GST) from each satellite. The legacy mechanism to broadcast CED and GST is maintained, and is complemented with the additional features.

The Secondary Synchronisation Pattern (SSP) is introduced with the aim of enabling for the users the possibility to reconstruct the broadcast GST from each satellite without the need to wait for an actual GST broadcast, provided that the receiver is already coarsely

synchronised with the GST (within +/- 3 seconds). SSPs are provided every two seconds and can be detected at symbol level, without decoding the navigation message. Successful detection of a single SSP is sufficient to resolve the GST ambiguity.

Reduced CED consists of a compressed set of Clock and Ephemeris Data in an optimised format that fits within one I/NAV word. Especially in environments with substantial fading and shadowing a single I/NAV word is typically faster and much easier to receive than the nominal CED consisting of four I/NAV words. In exchange and due to the compression, Reduced CED is less accurate and is expected to contribute in the order of 3m (1 sigma) to the User Equivalent Ranging Error. Reduced CED is therefore intended for a fast coarse PVT fix after start-up.

The nominal I/NAV CED provided within the E1 OS signal is further protected and supported by means of the introduction of Reed Solomon based outer Forward Error Correction (FEC2). The nominal CED forms the systematic part of the code word. Four more I/NAV words of Reed Solomon parity are included into the message broadcast to the users. The Minimum Distance Separation (MDS) property of the Reed Solomon, combined with the protection of I/NAV words through the legacy Viterbi inner FEC and CRC, provides a very powerful flexibility to decode CED from all combinations of four different correctly received words (erasure correction). This yields a significant and systematic advantage in speed of reception of the nominal CED, in nearly every environment. If needed, the outer FEC2 can also be used for combined erasure and error correction, to further improve robustness of CED reception.

After the three solutions are introduced and explained, an overall assessment of the anticipated performance of a Galileo receiver implementing each of them is provided, highlighting the advantages of the implementation, discussing different possible approaches and comparing the results with the typical performance of a Galileo user processing the legacy signal.

INTRODUCTION

The 2012 Galileo Programme's decision to re-profile the Safety of Life (SoL) service represented as a matter of fact an opportunity for improving the Galileo Open Service (OS) performance. One of the main consequences of that decision was that a significant portion of the I/NAV message originally intended to regularly carry data related to SoL service became available, initially marked as "reserved" in the Galileo Open Service Signal In Space Interface Control Document (OS SIS ICD, [1]). Following this fact, the Programme requested the Galileo Compatibility, Signals and Interoperability Working Group (CSI WG) to study and propose technical solutions to use this newly available resource to possibly improve the performance of the Galileo Open Service.

The main objectives of the optimization work were to improve the E1-OS performance in terms of robustness and timeliness, and to improve service continuity especially when used with assisted GNSS networks and location based services. 'Robustness' here refers to the capability of the navigation message to be received within the shortest possible time including in challenging environments with high signal multipath effects and varying attenuation, e.g. in urban canyons and tree shadowed areas. Such enhanced message robustness allows for better resilience of receivers that are required to retrieve this message, to degraded environmental conditions but also to temporary interference. As the time to receive clock corrections and ephemeris data is a major contribution to the Time-to-First-Fix in many starting conditions, a reduction of this time will support in general all applications that require reception of this data from navigation signals. Users which receive navigation data from other channels like mobile communication networks, as well as receivers performing a warm start with clock and ephemeris data still available, can profit from any support that allows rapid and robust reconstruction of transmit time from each received navigation signal. If such connected receivers can maintain an internal clock at sufficient accuracy, or receive time information e.g. from connected 3GPP networks or other sources, provision of means on the navigation signals to resolve a certain transmit time ambiguity interval is sufficient to allow the receiver to reconstruct the transmit time.

Considering the advanced stage of the Galileo Programme at the moment the work was performed, significant modifications to the signal structure were no longer feasible since they would have affected too many elements of the system, including the current OS SIS ICD used by the Galileo receiver manufacturers. Therefore, the carried out E1-OS optimization activity was limited to the addition of new content to the I/NAV message. Backward compatibility with the public released Galileo OS SIS ICD was a condicio sine qua non. Any identified solution had to guarantee no impact on receivers already on the market. The Galileo OS user receivers have always been expected to be able to recognize page types, to identify their content, and to react in a well-controlled manner to unknown page types as well as to variations in the order of received pages. Consequently, as soon as these contents will be published in the Galileo OS SIS ICD, receiver manufacturers can optionally decide to exploit them, while they will be fully transparent to legacy or non-participative users. Furthermore, the impact on the Galileo infrastructure had to be carefully controlled, i.e. compatibility with legacy satellites had to be ensured. Hence, only such measures were eligible that could be applied through software updates of space and ground segments. Following those elements, the conceived technical solutions consisted in designing new I/NAV words and new contents on a small number of message bits in existing words that are currently marked as “reserved” to provide the additional information in order to enhance the Open Service performance robustness and timeliness.

Following some years of work from different parties, resulting in several proposals and different approaches [2], including detailed performance assessments and various iterations to ensure maximum benefit for users and a smooth implementation within the already deployed system elements, three different solutions have been selected for implementation:

- Secondary Synchronization Pattern (SSP) at symbol level, to improve the capability of user receivers to reconstruct Galileo System Time using weak signals, without the need to demodulate the navigation message.
- Reduced Clock and Ephemeris Data (RedCED): a compact set of satellite orbit and clock information with reduced accuracy and validity time, broadcast at a repetition rate short enough to allow substantial reduction of the Time to First Fix for an initial position solution with reduced accuracy [3],[6]. Optionally, receivers that do not require the accuracy of the full navigation message can reduce their operational duty cycle to retrieve only this shortened RedCED information.
- Additional forward error correction capability (FEC-2), improving the time to retrieve the clock and ephemeris data (CED) by the introduction of an outer coding scheme based on Reed-Solomon codes [5]. This solution provides improvements both in terms of Time-to-Data and data demodulation robustness.

SECONDARY SYNCHRONIZATION PATTERNS (SSP)

The introduction of Secondary Synchronization Patterns (SSP) targets the improvement of the capability of user receivers to reconstruct Galileo System Time using weak signals and without necessarily demodulating the navigation message.

Galileo signals offer several ways to determine signal transmit time building upon receiver clock and time knowledge. At spreading code level, the Galileo E1-C secondary code offers a 100 ms periodicity. At symbol level, the Galileo E1-B I/NAV message offers a 10-symbol (40 ms) page synchronization pattern at a 1 s periodicity, which would require a priori knowledge of Galileo SIS transmit time within +/- 0.5 s. If the E1-B I/NAV message can be decoded, i.e. if the received Galileo signals provide sufficiently high C/N_0, the I/NAV even and odd pages can be distinguished through a dedicated bit and allow the resolution of a 2 s period. Should the accuracy of the receivers knowledge of time exceed this threshold, the remaining option to determine transmit and system time is to decode Time of Week (TOW) and Week Number from the navigation message.

The use of the navigation message, however, is less robust, since the required information may only be retrieved when the receiver is operating above the data demodulation threshold, increasing at the same time the TTFF. The solution that will be implemented within the Galileo E1-B I/NAV message to overcome this limitation is a Secondary Synchronization Patterns (SSP) at symbol level, offered with a repetition period of 6 s and a 64 ms length per pattern, so as to answer to different use cases. Exploiting this solution, future Galileo receivers will be able to solve a +/- 3 s time ambiguity..

Before FEC encoding, three different deterministic data bit sequences of 8 bits each are set at the end of three consecutive I/NAV pages. After FEC encoding, the last symbols of E1 I/NAV pages then provide three pre-defined SSP1, SSP2 and SSP3 patterns of 16 symbols (which corresponds to a length of 64 ms), each with well-defined cross correlation properties. The transmission of the resulting SSP sequences is synchronised with the Galileo System time (GST). After having detected or confirmed the I/NAV page synchronisation pattern (sequence of 10 successive symbols defined in [1]) the page symbols need to be de-interleaved in order to rebuild the SSP symbols within one block at the end of the I/NAV page. A receiver can then perform a correlation at symbol level to find occurrences of the SSPs in the incoming symbol stream. After successful SSP detection the following ambiguous Time Of Week (TOW) information can be retrieved from the identified SSP configuration sequence:

- SSP1 detected $\rightarrow \mathrm{TOW} \text{ modulo } 6\mathrm{s} = 1\mathrm{s}$
- SSP2 detected $\rightarrow \mathrm{TOW} \text{ modulo } 6\mathrm{s} = 3\mathrm{s}$
- SSP3 detected $\rightarrow \mathrm{TOW} \text{ modulo } 6\mathrm{s} = 5\mathrm{s}$

Note that the epoch denoted by TOW in the above-mentioned expressions follows the Galileo System Time definition for the navigation messages within which the SSP sequences are transmitted. Each SSP symbol sequence is repeated every 6 seconds, since an I/NAV page has a duration of 2 seconds. As already mentioned, prerequisite to exploit the SSP symbol sequences for time information retrieval is that the user receiver is already coarsely synchronised with GST, i.e. the receiver time t_{RX_clk} should be within the following uncertainty interval:

$$t_{\mathrm{RX\_clk}} \in \,]\mathrm{GST} - 3\mathrm{s} \quad \mathrm{GST} + 3\mathrm{s}[\tag{1}$$

This level of coarse synchronisation can be achieved e.g. by means of A-GNSS or by locally propagating a previous time synchronization, depending on the receiver clock stability.

POSSIBLE STRATEGIES FOR AN SSP IMPLEMENTATION WITHIN THE RECEIVER

As already mentioned, the received I/NAV page symbols do not provide the SSP configuration pattern within one common block (unlike the Page Synchronisation pattern, see [1]), since there are gaps in-between doublets of the SSP symbols due to page interleaving. In the case the receiver performs an SSP detection even before applying any further page processing, i.e. also before de-interleaving of the page, then the coherency of the carrier phase needs to be preserved due to the above mentioned gaps in-between the doublets of received SSP symbols. Another interesting architecture that could be considered is one that combines I/NAV page synchronization symbol detection and SSP symbol detection into one overall detection mechanism.

An alternative SSP processing strategy is described hereafter, where frame synchronization and page de-interleaving are performed first. In either case, the receiver has initially no knowledge about the location of the even and odd I/NAV page part. A robust SSP detection implementation should take this into account in order to ensure control on the probability of false detections while still keeping the time to SSP detection respectively low.

After successful I/NAV page synchronisation, the user receiver knows the system time information with an ambiguity of 1 second thanks to the 10 symbols synchronisation pattern added to both I/NAV even and odd part pages. However, the receiver cannot unambiguously identify yet whether it is processing an even or odd I/NAV page. In Figure 1 the received I/NAV symbols after de-interleaving are depicted, including the SSP sequence. In the figure it is also shown how a complete SSP sequence is repeated every 6 seconds within the I/NAV sub-frame.

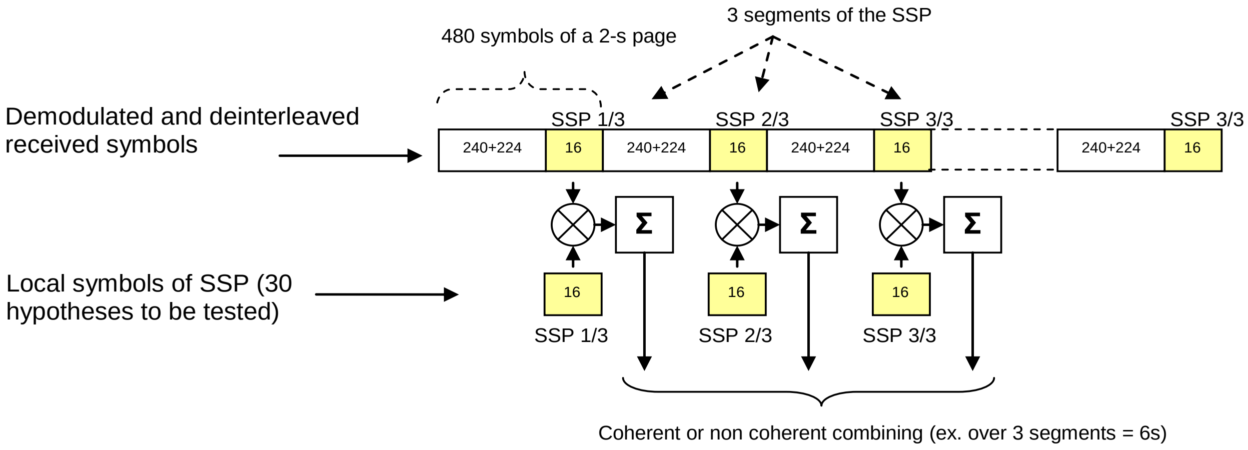

Figure 1: Coherent / Non-coherent combination of encoded SSP configurations

In order to retrieve the system time information with a 6-seconds ambiguity interval a correlation between the de-interleaved symbols and the encoded reference SSP sequences can be performed. It should be noted that it is not necessary to wait for the demodulation of six seconds of I/NAV message on E1-B to perform the detection of the complete SSP sequence of 48 symbols, since the sequence is split into three unambiguous sub-sequences of 16 symbols located at the end of each 2-seconds I/NAV page. As shown in Figure 1, it is possible to combine the correlations performed on every encoded SSP configuration of 16 symbols either coherently or non-coherently. Coherent combination has the drawback of being sensitive to FLL instabilities. The integration length can be extended to more than three SSP configuration sequences, if required, to further reduce the probability of false SSP detections.

Receivers which for different reasons (e.g. architectural, processing capability, …) may not implement symbol level correlation to perform the synchronization as described above might still benefit from the introduction of the SSP by simply decoding the value of the 8 SSP configuration bits comprised in the I/NAV message. It is however very important to underline how in this case the important advantage of working below the data demodulation threshold would not be exploited, and consequently the time synchronisation operation would not be as robust as the full correlation approach previously discussed enables.

ASSESSMENT OF THE TIME-TO-GST REDUCTION (ASSISTED MODE)

While the time to recover the Clock and Ephemeris Data (Time-To-CED) is the major contributor to the TTFF for GNSS receivers working in stand-alone mode (e.g. not relying on assistance data), user receivers operating in assisted mode already know the full-precision CED from data provided by an external source. However, in most of the cases those receivers still need to fix the system time ambiguity, since network operators typically provide only an approximate time estimate with uncertainties in the order of +/-2 seconds due to network latencies. The newly introduced Secondary Synchronisation Pattern (SSP) on E1-B I/NAV allows receivers to resolve system time ambiguities up to +/-3 seconds without the need to retrieve the full Galileo System Time (GST) information. Receivers may even operate below the data demodulation threshold by correlating the received symbols with the expected SSP configuration patterns at symbol level. This is a clear advantage for those receivers which are already coarsely synchronized. I.e. there is no need for them to retrieve the full GST information from the navigation message by decoding the Time of Week (TOW and the Week Number (WN). Therefore, the introduction of the SSP increases the synchronisation robustness in challenging environments.

In principle, the detection of one single de-interleaved SSP pattern configuration (being this either SSP1 or SSP2 or SSP3) allows receivers to recover the GST (modulo 6 seconds). To do so, receivers have to be already coarsely synchronised to GST, e.g. via an assistance channel or thanks to a recent fix. Considering that the SSP field is transmitted every 2 seconds, the time-to-synchronization with SSP is 4 seconds (worst-case), 3 seconds (mean value), and 3.9 seconds (95%). The probability of false SSP detections can be reduced by searching for the corresponding next SSP pattern configuration relative to the first detection of an SSP pattern configuration.

REDUCED CLOCK AND EPHEMERIS DATA DEFINITION

The idea of Reduced Clock and Ephemeris Data (RedCED) is to introduce a dedicated set of clock corrections and ephemerides to enable a rapid position fix, despite an initially degraded ranging performance. This approach, initially discussed in [3], represents a trade-off that mass-market GNSS users might well tolerate. After processing the RedCED from only one I/NAV word and performing a rapid fix with slightly degraded accuracy, the user can retrieve the nominal CED from four different I/NAV words with some delay and compute a position fix with full accuracy thereafter. The RedCED are computed on-board the satellites by re-fitting the full CED batches received from the ground segment to a shorter validity period. They are compact enough to be transmitted within one single I/NAV word. The short length of these data allows for decoding with higher robustness in harsh environments and results in a shorter Time-to-Data.

Following the results presented in [3], an optimized implementation of the RedCED concept targeting Galileo I/NAV has been developed and presented for the first time in [6]. The main focus of the work was to limit the ranging accuracy degradation due to the reduced ephemeris as far as possible. The result is a set of 6 orbital parameters using tailored equinoctial representation instead of the original Keplerian representation and 2 clock minus radial error correction coefficients. The reduced ephemeris data is only composed of a total of 94 bits compared to 342 bits used for full-precision ephemeris parameters broadcast within the Galileo I/NAV message. The full-precision clock correction parameters (58 bits within the Galileo I/NAV message) are reduced to a combined set of clock-minus-radial-error correction parameters compressed into 28 bits. As a result, for an initial position fix it is sufficient to decode successfully only one word (i.e. containing the data bits above described) rather than having to decode successfully four words.

As the notation “Reduced CED” already suggests, a user position solution computed from this set of parameters results in an accuracy that is lower than the one obtained from the full-precision CED. It is important to note that the Galileo SIS Ranging Accuracy Minimum Performance Levels (MPLs) as published in [4] exclusively refer to the usage of full-precision CED, and therefore will not apply when using the Reduced CED parameter set instead.

A set of Reduced CED parameters will be usable for 10 minutes from its reference time, which is computed as:

$$t_{0r} = \mathrm{TOT}_{\mathrm{RedCED}} - \mathrm{modulo}(\mathrm{TOT}_{\mathrm{RedCED}}, 30\mathrm{s}) + 1\mathrm{s} \quad \text{[modulo 604800 seconds]}, \tag{2}$$

where $\mathrm{TOT}_{\mathrm{RedCED}}$ is the start time of transmission of the Reduced CED word in GST.

The 6 equinoctial orbital parameters transmitted for each satellite are introduced in the following table:

Parameter	Unit	Definition
ΔA_{red}	meters	Difference between the Reduced CED semi-major axis and the nominal semi-major axis
e_{xred}	-	Reduced CED eccentricity vector component *x*
e_{yred}	-	Reduced CED eccentricity vector component *y*
Δi_{0red}	semi-circles	Difference between the Reduced CED inclination angle at reference time and the nominal inclination
Ω_{0red}	semi-circles	Reduced CED longitude of ascending node at weekly epoch
λ_{0red}	semi-circles	Reduced CED mean argument of latitude

Table 1 Reduced Ephemeris Orbital Parameters

The transformation from the tailored equinoctial representation back to the well-known Keplerian representation reads as follows:

$$e = \sqrt{e_x^2 + e_y^2} \tag{3}$$

$$\omega = tan^{-1}\left(\frac{e_y}{e_x}\right) \tag{4}$$

$$M_0 = \lambda_0 - \omega \tag{5}$$

Where e is the eccentricity, ω the argument of perigee and M_0 the orbital mean anomaly.

The 2 clock minus radial error correction coefficients transmitted for each satellite are defined in the following table:

Parameter	Unit	Definition
a_{f0red}	seconds	Reduced CED satellite clock bias correction coefficient
a_{f1red}	s/s	Reduced CED satellite clock drift correction coefficient

Table 2 Reduced Clock Correction Parameters

The clock minus radial error correction term $\Delta t_{SV,clk-radial}(E1, E5b)$ is computed as:

$$\Delta t_{SV,clk-radial}(E1, E5b) = a_{f0red} + a_{f1red}[t - t_{0r}] + \Delta t_r \tag{6}$$

where t is the GST time in seconds, t_{0r} is the Reduced CED reference time as above described and Δt_r is the relativistic correction term defined in [1]. It is important to note that week roll-overs have to be taken into account when computing the time difference $[t - t_{0r}]$. Also the clock minus radial error correction coefficients a_{f0red} and a_{f1red} comprised in the Reduced CED parameter set refer to the $(E1, E5b)$ clock model described in [1]. The pseudo-range correction term $\Delta t_{SV,clk-radial}(E1, E5b)$ has to be applied for both dual-frequency (E1/E5b) users and single-frequency (E1) users. As usual, the single frequency (E1) pseudo-range accuracy can be improved by compensating for the group delay as described in [1].

A coarse position estimate of the SV antenna phase centre $\left(x_{SV,red}, y_{SV,red}, z_{SV,red}\right)$ at GST time t can be computed from the standard algorithm for ephemeris determination introduced in [1],

$$(x_{SV}, y_{SV}, z_{SV}) = f_{ephemeris}\left[t, t_{0e}, A^{1/2}, i_0, \Omega_0, e, \omega, M_0, \Delta n, \dot{\Omega}, i, C_{uc}, C_{us}, C_{rc}, C_{rs}, C_{ic}, C_{is}\right], \tag{7}$$

by replacing the full-precision CED parameters with the Reduced CED parameters (and zeros)

$$\begin{gathered}(x_{SV,red}, y_{SV,red}, z_{SV,red}) = f_{ephemeris}\Big[t, t_{0r}, (29600000m + \Delta A_{red})^{\frac{1}{2}}, 0.3\overline{1}\cdot\pi + \\ \Delta i_{0red}, \Omega_{0red}, \sqrt{e_{xred}^2 + e_{yred}^2}, tan^{-1}\left(\frac{e_{yred}}{e_{xred}}\right), \lambda_{0red} - tan^{-1}\left(\frac{e_{yred}}{e_{xred}}\right), 0,0,0,0,0,0,0,0,0\Big].\end{gathered} \tag{8}$$

The conversion of the angular parameters from ‘semi-circle’ (broadcast message) to ‘radian’ needs to be taken into account as usual before processing the angular parameters. It has to be noted that the radial component of the SV antenna position estimate is rather inaccurate. Therefore it is essential that $(x_{SV,red}, y_{SV,red}, z_{SV,red})$ and $\Delta t_{SV,clk-radial}(E1, E5b)$ are computed from a common set of Reduced CED parameters, i.e. originating from the same Reduced CED I/NAV word, and that they have to be used in the subsequent PVT computation together in order to allow for mutual discretization error compensation.

RedCED PERFORMANCE ASSESSMENT

As previously explained, the position solution computed from Reduced CED parameters is less accurate than the position solution computed from full-precision CED parameters. Nevertheless, the overall accuracy degradation stays within well-defined limits. The additional contribution to the User Equivalent Range Error (UERE) budget when processing Reduced CED parameters instead of full-precision CED parameters will be denoted here as Fitting Range Error (FRE). The FRE, which depends on the satellite elevation angle, is defined as the sum of the absolute value of the clock minus radial error and the absolute value of the tangential satellite position error, as follows:

$$FRE = |\Delta T_{ClkRadial}| + \Delta X_{Tangential} \cdot \frac{R_E}{R_O}\cos(E) \tag{9}$$

The clock minus radial error, $\Delta T_{ClkRadial}$, is computed a

$$\Delta T_{ClkRadial} = c \cdot \left(\Delta t_{SV,clk,full} - \Delta t_{SV,clk-radial,red}\right) - \left(r_{SV,full} - r_{SV,red}\right) \cdot \sqrt{1 - \left(\frac{R_E}{R_O}\cos(E)\right)^2} \tag{10}$$

where c is the speed of light, R_E is the radius of the earth, R_O is the radius of the orbit, E is the elevation angle and:

- $(r_{SV,full} - r_{SV,red})$ is the radial satellite position error component resulting from the transition from full-precision CED to Reduced CED,
- $(\Delta t_{SV,clk,full} - \Delta t_{SV,clk-radial,red})$ is the satellite time correction error resulting from the transition from full-precision CED to Reduced CED.

The tangential satellite position error component, $\Delta X_{Tangential}$, is computed from the satellite coordinates $(x_{SV,full}, y_{SV,full}, z_{SV,full})$ derived from full-precision CED, the satellite coordinates $(x_{SV,red}, y_{SV,red}, z_{SV,red})$ derived from Reduced CED and the radial satellite position error component $(r_{SV,full} - r_{SV,red})$ as

$$\Delta X_{Tangential} = \sqrt{\left(x_{SV,full} - x_{SV,red}\right)^2 + \left(y_{SV,full} - y_{SV,red}\right)^2 + \left(z_{SV,full} - z_{SV,red}\right)^2 - \left(r_{SV,full} - r_{SV,red}\right)^2} \tag{11}$$

The FRE comes on top of the OD&TS (Orbit Determination & Time Synchronization) error, which is present when working with full-precision CED. It holds that the magnitude of the FRE is mainly driven by discretization errors, since the 6 orbital parameters and 2 clock minus radial error correction coefficients have to be compressed into one single I/NAV word (122 total information bits).

In [6] representative statistics of the Reduced CED Fitting Range Error are provided, based on processing of 3 months of data from 9 Galileo satellites. The FRE results are represented in Figure 2 as a function of the satellite elevation angle and, in particular, the maximum observed FRE, the 95th percentile and the 68th percentile of the FRE are plotted. The indicated Fitting Range Errors refer to a Reduced CED age of data interval from 0 minutes to 10 minutes.

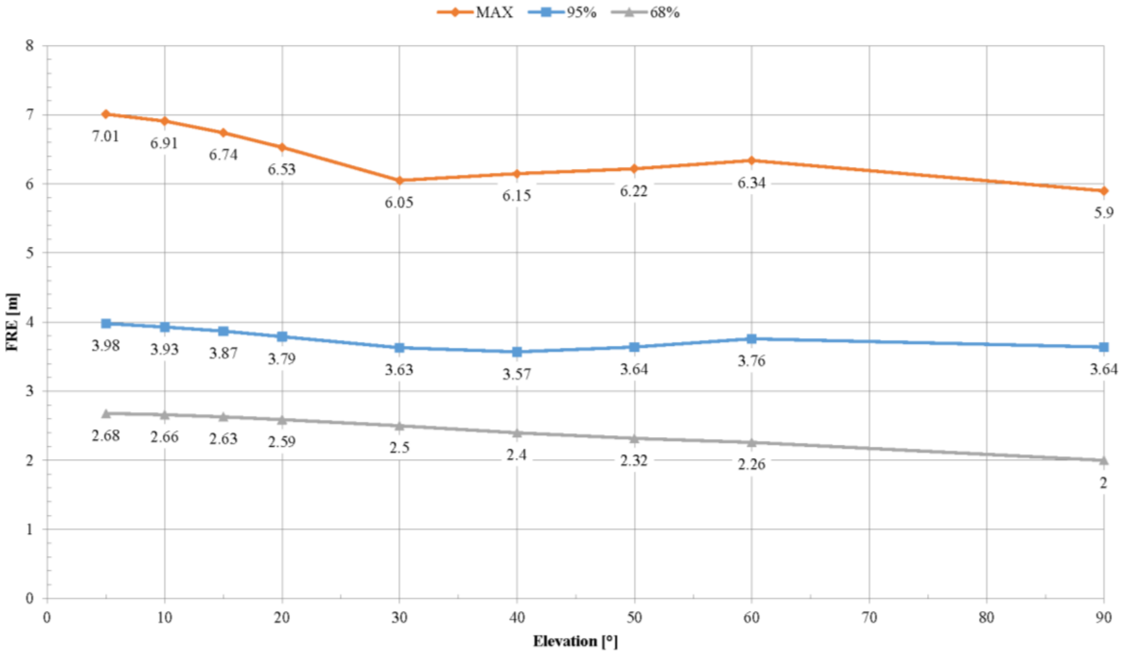

Figure 2: Reduced CED Fitting Range Error as a function of the elevation angle

As one can observe, the 68th percentile of the FRE does not exceed 3 meters, which is quite a remarkable performance for such a compact set of clock and ephemeris data. It can be also observed how the elevation dependency of the FRE is kept quite limited by the Reduced CED fitting algorithm within the complete elevation range from 5° to 90°.

A positioning accuracy comparison when using Reduced CED parameters or full-precision CED parameters was also performed in [7] and the main results are provided hereafter. In order to perform such an analysis, 159 MGEX stations distributed all over the globe were considered and the dual-frequency E1/E5b positioning accuracy for each of them was assessed.

In Table 3 the horizontal and vertical dual-frequency E1/E5b user positioning accuracy (95%) at Worst User Location (WUL) is shown for 6 consecutive days in February 2018. For the purpose of the test the Reduced CED were generated in post-processing based on the actual broadcast full-precision CED data as observed from the operational Galileo satellites during the days the test took place. Real measurement data recorded by the MGEX stations was processed.

	Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**
	Horizontal Positioning Accuracy (95%)					
Reduced CED	7.9 m	7.8 m	8.1 m	9.8 m	7.8 m	7.7 m
Full CED	5.5 m	4.2 m	5.5 m	8.8 m	6.7 m	5.1 m
Delta	2.4 m	3.6 m	2.6 m	1.0 m	1.1 m	2.6 m
	Vertical Positioning Accuracy (95%)					
Reduced CED	14.8 m	11.8 m	14.4 m	24.3 m	13.8 m	11.4 m
Full CED	11.3 m	7.7 m	12.3 m	21.4 m	10.5 m	7.5 m
Delta	3.5 m	4.1 m	2.1 m	2.9 m	3.3 m	3.9 m

Table 3 Dual-frequency E1/E5b Positioning Accuracies at Worst User Location

From the results provided in Table 3 follows that the horizontal positioning accuracy at WUL when using Reduced CED instead of full-precision CED was degraded by 2.2 meters on average over the 6 days, while the vertical positioning accuracy was degraded by 3.3 meters. To be noted that the values for the day 4 were partially affected by one station resulting in an anomalous high value, affecting in particular the vertical accuracy. The effect of such outlier is visible only when considering the WUL, as in Table 3.

In Table 4 the horizontal and vertical dual-frequency E1/E5b user positioning accuracy (95%), averaged over the MGEX stations, are shown. As it can be seen, the horizontal positioning accuracy at Global Average when using Reduced CED instead of full-precision CED is degraded by 3.1 meters on average, while the vertical positioning accuracy is degraded by 5.4 meters on average.

	Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**
			Horizontal Positioning Accuracy (95%)			
Reduced CED	6.0 m	6.1 m	6.0 m	6.0 m	5.9 m	5.8 m
Full CED	2.8 m	2.8 m	2.8 m	2.9 m	2.9 m	2.8 m
Delta	3.2 m	3.3 m	3.2 m	3.1 m	3.0 m	3.0 m
			Vertical Positioning Accuracy (95%)			
Reduced CED	9.9 m	9.9 m	9.8 m	10.1 m	10.0 m	9.8 m
Full CED	4.5 m	4.4 m	4.6 m	4.8 m	4.6 m	4.5 m
Delta	5.4 m	5.5 m	5.2 m	5.3 m	5.4 m	5.3 m

Table 4 Dual-frequency E1/E5b Positioning Accuracies at Global Average

From the results presented above it is concluded that the positioning accuracy degradation when processing Reduced CED instead of full-precision CED is very well bounded: at Global Average, the E1/E5b user positioning accuracy (95%) is degraded by a factor of approximately two. Even at Worst User Location, the horizontal positioning accuracy (95%) stays below 10 meters when using Reduced CED. Thus, the introduction of Reduced CED allows for a fast initial position fix with reasonable accuracy by having to decode only one single I/NAV word. Positioning accuracy can be improved as soon as full-precision CED have successfully been decoded.

REED-SOLOMON CODES FOR IMPROVING THE ERROR RESILIENCE OF THE I/NAV MESSAGE

Despite the growing number of connected user devices, the reception of the clock and ephemeris data (CED) is still a major factor impacting the TTFF. The current approach for the dissemination of these data can be defined as "data carouseling": the data are repeatedly sent to the users with a certain repetition rate. For example, the repetition rate of the CED contained in the Galileo E1 OS message is equal to 1 every 30 s. A different approach is offered by Maximum Distance Separable (MDS) codes like Reed-Solomon (RS) codes, whose erasure correction capability allows retrieving the entire information contained in k data blocks from any combination of k different received blocks of the codeword.

Galileo will provide Reed-Solomon (RS) coded Clock and Ephemeris Data within the E1-B I/NAV message, with an approach initially presented in [5]. The new RS CED words will provide both *erasure* and *error* correcting properties. Erasure correction can be applied as soon as parts of the received information can be labelled as reliable or unreliable. Such reliability it determined on the basis of the CRC, i.e. if the CRC reports errors in a page after Viterbi decoding, this page is usually discarded – or erased – hence the name *erasure*. In the legacy scheme, a CED page containing errors is not used in the receiver. Instead, the receiver has to wait for the reception of the same page in the next sub-frame. With RS CED pages this is not necessary, as an RS CED page can “replace” any of the CED pages. So the receiver just needs to wait for the next RS CED page. The optimal erasure correction property will therefore allow recovering the complete CED by receiving a set of any four different CED related words (being either legacy CED or RS CED words). In addition to the erasure correction capability, RS decoding can be applied in error correction mode. Error correction can be used when the received (RS) CED pages contain residual errors after Viterbi decoding, i.e. when erasure-only decoding is not possible.

The *optimal erasure correction* capability of RS codes can be exploited, since the current setup of I/NAV message pages consists of an (inner) convolutional code and a CRC which indicates whether a page could be correctly decoded or not, e.g. by a Viterbi decoder. The Viterbi decoder and the CRC emulate an almost ideal *erasure channel*.

When a page is marked as containing errors, because the CRC flags residual errors after Viterbi decoding, this page cannot be used for *erasure-only* decoding (as above described), and in a legacy receiver would be just discarded. However, such a page *can instead still be used* with an errata (errors and erasures) decoder, using e.g. the Berlekamp-Massey algorithm, in order to correct residual errors *and* erasures in an outer RS decoding stage. Using an errata decoder, the erased symbol positions (e.g. the positions of the symbols contained in the not yet received pages) are provided to the decoder together with the symbols of the received pages, disregarding whether they contain errors or not. Of course, an errata decoder can also be operated in erasure-only decoding mode as a special case, when no residual errors are present.

The RS CED pages are created from the original set of four CED pages by means of RS encoding. These RS CED pages have the ideal property (MDS property) that the original set of four CED pages can be recovered *from any four CED or RS CED pages*. An RS CED page hereby acts like a joker page i.e. the four pages used for erasure decoding have just to be different. For erasure-only decoding it is always assumed that the corresponding received pages are error-free (no CRC error) after Viterbi decoding.

The legacy requirement of receiving all four CED pages to recover the complete CED can therefore be loosened to the RS requirement of receiving a set of any four different CED related pages (CED or RS CED pages). Since the RS requirement can be fulfilled in a much shorter amount of time, it is obvious that the RS coding approach significantly reduces the TTD by improving the robustness against channel noise or fading and allows a faster CED reception.

TIME-TO-CED IMPROVEMENT

The two I/NAV improvements *Reduced CED* and *FEC2 RS coded CED* enable receivers to reduce the time to retrieve the CED in different ways. In the case of successful reception of a Reduced CED word, the CED is immediately available with a reduced precision. In order to obtain the CED with full precision *at least* four different CED or RS CED words need to be received. In perfect channel conditions it is *exactly* four different CED or RS CED words.

The time to (full or reduced) CED is provided in the figures hereafter for perfect channel conditions (open sky environment), for a vehicular user (50 km/h) in an urban environment and for a pedestrian user (5 km/h) in an urban environment. For the latter two scenarios a 2-state Land Mobile Satellite (LMS) narrowband channel model [9] was used to simulate the performance. This model is an extension of the one proposed in [8]. The Time-to-CED has been obtained for received signals with effective Line Of Sight (LOS) C/N_0 equal to 40.5 dB/Hz. For all cases the Time-to-CED expected with the legacy I/NAV data is always provided as a means of comparison.

The “legacy” I/NAV sub-frame layout corresponds to the nominal sub-frame layout of [1], where CED words (I/NAV words 1 to 4) are transmitted within the E1-B sub-frame at T=1s, T=3s, T=21s and T=23s. In the “legacy” scenario the user retrieves the CED only from I/NAV words 1 to 4. In the “RS2+RedCED” scenario, in addition to the legacy CED words, two new Reduced CED words are transmitted at T=15s and T=29s together with four new FEC2 RS CED words which are transmitted in two consecutive sub-frames at T=11s, T=13s, T=41s and T=43s. Note that in the following figures the time axes represent the 95% success rate.

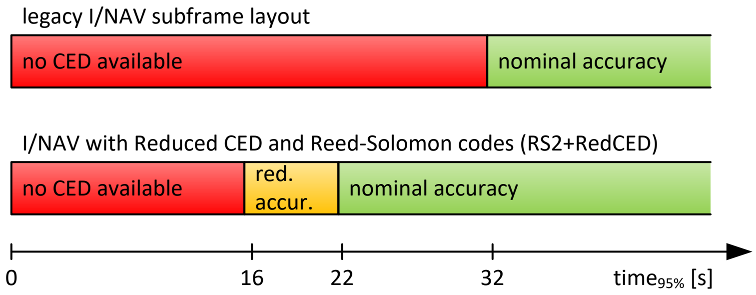

Figure 3: Time to CED (95%) for a user in an open sky environment

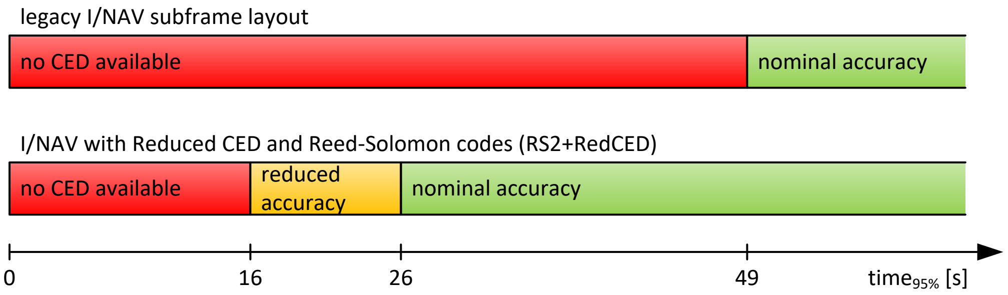

Figure 4: Time to CED (95%) for a vehicular user (50 km/h) in an urban environment

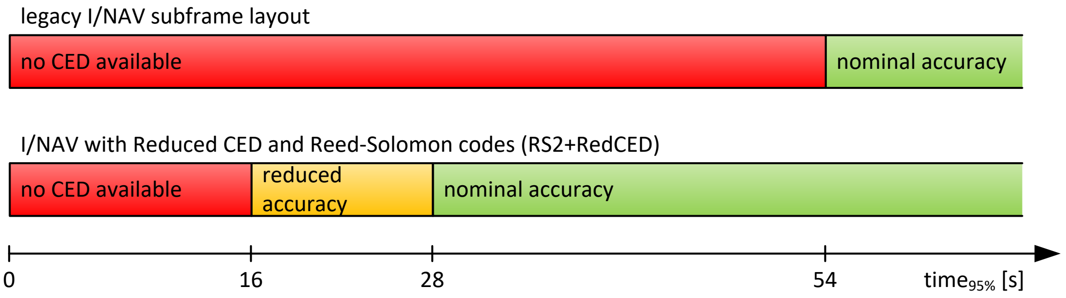

Figure 5: Time to CED (95%) for a pedestrian user (5 km/h) in an urban environment

From these results it can be easily understood that the provision of the Reduced CED is of great advantage for the computation of the first position fix, especially in challenging environments. The RedCED word repeated twice every 30 seconds allows the users having a much higher chance to receive CED during the good channel state conditions, even if these just hold for short time intervals. As expected, pedestrian users suffer more under bad channel conditions than vehicular users, as they are more likely to stay in bad channel conditions for longer time periods. At the same time it is also important to underline the great performance gain enabled by the Reed-Solomon coded CED pages, through which the time to achieve nominal accuracy is significantly reduced.

CONCLUSIONS

The paper describes three new technical solutions that will be soon introduced within the Galileo E1 I/NAV message. The work leading to the design of the three solutions started with the 2012 Galileo Programme decision to re-profile the SoL service, which made available a significant portion of the I/NAV message, initially marked as "reserved" in the Galileo Open Service Signal In Space Interface Control Document (OS SIS ICD, [1]).

The drivers originally identified for the I/NAV message optimization work were to reduce the Time-To-First-Fix and the time to re-synchronize with the Galileo System Time (GST). Another key objective was to improve substantially the robustness to decode the Clock and Ephemeris Data (CED) in GNSS degraded environments.
The long and complex design activity resulted with the introduction of the three following features:

- Secondary Synchronisation Patterns (SSP)
- Reduced Clock and Ephemeris Data (RedCED)
- FEC2 Reed-Solomon encoding of the Clock and Ephemeris Data (FEC2 RS CED)

Within this paper the details of each of the three technical solutions have been discussed and an assessment of the performance that is expected for different users in different working conditions has been presented. It was also shown how the solutions provide a clear boost for the Galileo OS service performance in terms of Time-To-CED and Time-To-GST, corresponding to a definitive improvement in Time-To-First-Fix (TTFF) for both non-connected and connected users.

The paper also discussed several elements related with the practical implementation within the user receivers, discussing for each of the three solutions different possible approaches and implementations strategies. It was shown in particular how the solutions can be implemented both within the space and the user segment without any substantial increase of complexity and/or processing capability.

It was also highlighted how the three proposed solutions are fully backwards compatible with previously released OS SIS ICDs and therefore completely transparent to legacy or non-participative users. Consequently, as soon as these new contents will be published in a new issue of the Galileo OS SIS ICD, receiver manufacturers can optionally decide to exploit them. At the same time the Galileo Programme will encourage and support the users to implement those features, considering the effective advantage introduced as widely discussed within this work.

ACKNOWLEDGMENTS

A new issue of the OS SIS ICD (v. 1.4) is expected to be published soon, and this will provide all the details for the users that want to exploit the technical solutions described in this work. This paper and the new OS SIS ICD are the culmination of a work that lasted several years and involved many different parties. Most of the work was performed in the framework of the EU Compatibility, Signals and Interoperability Working Group (CSI WG), and in that context the various elements have been improved and corrected with the contribution of the various participants all over the years. Thanks to all of them and to everyone else that contributed at different levels to the design, the assessment and the implementation of the new I/NAV features here presented and discussed.

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