A Galileo E6-B/C Receiver: Signals, Prototype, Tests and Performance

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ABSTRACT
Galileo satellites are transmitting the E6-B/C signals reserved for the Galileo Commercial Service (CS), which aims at providing precise point positioning (PPP) and authentication services, mainly for professional users, through a 492-bps signal and encrypted spreading codes. IfEN GmbH developed and tested a full CS E6-B/C receiver whose results are presented in this paper. This paper mainly covers four aspects: the Galileo E6-B/C signals, the Galileo CS receiver prototype, the testing campaign and the test results.

The first part of the paper focuses on the CS signal definition. While most elements of the CS signal are in the public domain, there is no single reference that provides a full description of all the information required to process the E6-B/C (un-encrypted) signals in a receiver. This paper presents a comprehensive description of the E6-B/C signal frequencies, power, modulation, primary and secondary codes, data coding scheme and message structure. It must be noticed that the full data structure will partly depend on the future high accuracy service providers and its access may be controlled. While the Galileo Commercial Services will foreseeably be access-controlled, the signals will be partly openly accessible, so that receivers can freely use the 3 frequencies of Galileo (E1, E5 and E6). The second part of the paper describes the Galileo E6-B/C receiver prototype, based on IFEN's NTR receiver. The receiver incorporates E1, E5ab and E6 front-ends and is able to process GPS, Galileo, GLONASS, BDS, SBAS and IRNSS signals. Some receiver specificities related to the E6-B/C signals are also described, as the handling of encrypted codes, the record and storage of sample streams for remote authentication based on encrypted spreading codes, or on-the-fly CS encryption key handling. The third part of the paper presents the test campaign carried out by IFEN GmbH. This part presents an overview of the test scenarios, which included both simulated and real data testing, in static and dynamic (urban, suburban) scenarios. The fourth part of the paper addresses the test results obtained with the CS receiver prototype. The paper finalizes by presenting some conclusions and proposing further work.

INTRODUCTION
Galileo satellites are already transmitting E6-B and E6-C radio navigation signals in the Galileo E6 band, centred at 1278.75 MHz. These signals are aimed at delivering the Galileo Commercial Service (CS) in the future. The Galileo CS foresees to provide high accuracy services based on the transmission of precise point positioning (PPP) corrections in the E6-B (data) signal component, providing approximately 500 bits per second per satellite,

and authentication, based on the encryption of the spreading codes.

This band and signals are relatively new for GNSS and present some challenges and opportunities. The main challenges relate to interference from radio amateurs and radars, and the high bit-rate, which may complicate signal reception and demodulation in difficult environments. The main opportunities relate to the good frequency diversity of the E6 signal with respect to L1 and L5 signals, the possibility of transmitting high accuracy PPP corrections thanks to the high bandwidth and ground-to-space low latency of the Galileo system, and the possibility of encrypting the signal spreading codes to provide signal authentication to professional users.

As part of the AALECS (Authentic and Accurate Location Experimentation with the Commercial Service) project, resulting for the CS Demo tender of the European Commission, IfEN GmbH developed a full CS E6-B/C receiver, including the complete E6-B/C processing chain. The CS receiver was developed during 2014, tested during 2015 and accepted by the end of the last year for integration in the CS Demonstrator platform. The main purpose of this paper is to present the CS receiver design, development and testing activities.

GALILEO E6-B/C SIGNALS

The present European GNSS (Galileo) signal-in-space definition is already provided in the Open Service Signal of Space Interface Control Document [1] (OS SIS ICD) that describes the Galileo signals as in Figure 1, but excluding the PRS (E1-A, E6-A) and partly CS (E6-B, E6-C) signals. In the absence of a public CS ICD, which is foreseen to be published by the Galileo Program once the CS specification is formalised, this section provides a description of the E6-B and E6-C signals allowing the development of E6-B/C-capable receivers. Note that previous specifications of the signals have been provided in the past [2], but without detailing all the parameters needed in an E6-B/C receiver.

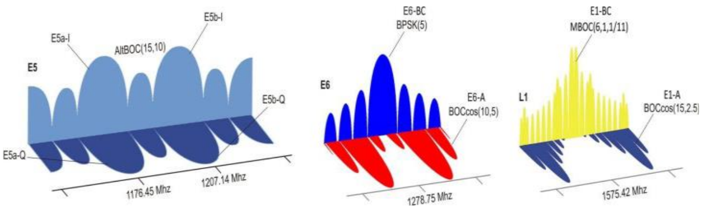

Figure 1 - Galileo signal overview

The Galileo signals in the E6 band are:

- The E6 CS data channel (E6-B component): this signal is the result of the modulo-two addition of the a FEC-encoded data stream with a Binary Phase Shift Keying (BPSK) spreading modulation at 5.115 MHz, or BPSK(5) for short.
- The E6 CS pilot channel (E6-C component): this signal is the result of the modulo-two addition of a 100-ms secondary code sequence also modulated with a BPSK(5) primary code.
- The E6 PRS channel (E6-A), whose signal is generated together with E6-B and E6-C but falls out of the scope of this paper as it is not part of the CS.

E6-B/C signal properties

The E6-B/C signal properties are summarised in Table 1.

Table 1 – CS signal properties

	E6-B	**E6-C**
Component	**Data**	**Pilot**
Carrier Frequency	1278.75 MHz	1278.75 MHz
Signal Polarization	RHCP	RHCP
Spreading modulation	BPSK(5)	BPSK(5)
Chip Rate	5115 Mcps	5115 Mcps
Primary Code Length	5115 chips	5115 chips
Primary Code Duration	1 ms	1 ms
Secondary Code Length	N/A	100 chips
Secondary Code Duration	N/A	100 ms
Symbol Rate	1000 sps	N/A
Data Rate	492 bps	N/A
Data Encoding	See below	N/A
Data Interleaving (col x row)	123 x 8	N/A
Spreading Code Encryption Capability	Yes	Yes
Power Sharing	50%	50%
Received Minimum Power (E6-B + E6-C)	-155 dBW	

The E6-B/C signal generation is outlined in Figure 2. The correspondence between the logic level code/bit and signal level is reflected to Table 2, and is in line with other Galileo signals. As for other signals, the start of a primary code coincides with the start of a data symbol (E6-B) or secondary code (E6-C), and the edges of data symbols and secondary code chips coincide with the edges of primary code chips.

While the primary codes of both E6-B and E6-C are not formally presented in an ICD, they are already in the public domain [3]. Concerning the E6-C secondary codes, they are listed in Section 3.5 of the OS SIS ICD [1], and allocated to E6-C in a similar fashion as for E5a-Q.

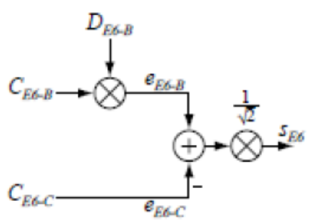

Figure 2 - E6-B/C signal generation

Logic Level	Signal Level
1	-1.0
0	+1.0

Table 2 – Logic to Signal level allocation

E6-B data structure

The E6-B data structure is called C-NAV. It is encoded at 1000sps. Out of the 1000 sps, the first 16 represent the binary synchronization pattern "1011011101110000". The remaining 984 symbols encode the 492-bps CS data. The data is encoded into symbols following the R=1/2, K=7 FEC encoding described in [1]. The interleaving dimensions are 123 columns x 8 rows. The data is divided in 14 bits for the page type, 448 bits for CS data, a 24-bit CRC and a 6-bit tail of zeroes, as per Figure 3. The CRC field is equivalent to that described in section 5.1.9.4. of [1].

Sync Symbols	Data Symbols				Total
16	984				1000 symbols
	Page type	**CS data**	CRC	Tail	492 bits
	14	**448**	24	6	

Figure 3 – Galileo C/NAV structure

The 14-bit 'page type' field has been inherited for the first C/NAV definition but it may be integrated with the 448-bit CS data field, for a total of 462 bps. Notice that CS data is filled in by satellites connected to the Galileo ground segment. At Galileo Full Operational Capability, 20 uplink antennas are foreseen, allowing 20 satellites to be connected most of the time. When a satellite is not connected, it will transmit repeatedly a dummy bit sequence every second. Another relevant feature of the E6-B/C signals, is that their spreading codes can be encrypted, providing both access control and authentication.

The 448 (or 462) bps are foreseen to be allocated to the following functions:

- Most of the bandwidth will be used to transmit CS PPP corrections (for Galileo as well as potentially for other GNSS) from external CSPs (Commercial Service Providers). The CS HA (CS High Accuracy) service will be based on this data.
- To transmit over-the-air rekeying (OTAR) information for the CS Authentication service.
- To transmit any additional navigation parameters required to navigate with encrypted E6 codes, for CS Authentication, as e.g. the BGDs for E1-E6 navigation.

As the CS-HA and CS Authentication will rely on external providers, the service-to-bit allocation will depend on the agreement with such providers and therefore will be fixed at a later stage. It is foreseen that different data blocks (e.g. OTAR, or information from different CSPs) may occupy not only different parts of the 448/462-bit field, but also different satellites and different slots in time.

Theoretical considerations on E6 B/C demodulation

One of the problems encountered in the allocation of Galileo commercial services to signals is that, according to the market studies performed during the service definition phase, CS HA and CS Authentication should be offered separately. CS-HA needs to rely on the E6-B component, and CS Authentication needs to rely on any component encrypted at spreading-code level. At the same time, the Galileo program intends to offer at least one signal component open, allowing open users to use the three Galileo frequencies for free (E5, E6 and E1). The only solution to achieve these objectives (i.e. separate service provision of high accuracy and code-based authentication, and an open E6 signal) with the current signals is by encrypting the E6-C pilot and leaving the E6-B data component unencrypted, controlling access to the PPP corrections by encrypting the data, but not the E6-B primary codes. However, this approach has some disadvantages:

- The non-availability of E6-C by non-authorized users will affect the carrier phase measurement performance.
- The non-availability of the E6-C by non-authorized users might affect the E6-B demodulation performance.

The first item is known, especially given that a receiver processing only E6-B could in principle only integrate coherently for 1 millisecond. The advantages of pilot components for carrier-phase tracking are well known, and there is no doubt that the use of pilot components can extend the tracking threshold in several dB (roughly on the order of 7 to 10 dB) and provide more accurate carrier-phase estimates. E6-B-only users could this overcome this issue employing a data wipe-off service allowing longer integration times. Note that the E6-B data to be broadcast will arrive at the Galileo Service Centre (GSC) some seconds before broadcast, so it can be made available to the users. More details on the foreseen Galileo CS architecture, involving the CSPs, the GSC, and the Galileo core infrastructure, are provided in [4].

On the second item, the question is whether the use of the pilot component (E6-C) is necessary for the demodulation & decoding of the data component (E6-B). The availability of an accurate carrier-phase estimate can never be deleterious, but the carrier-phase estimates from E6-C are not necessary to decode the data on E6-B. The convolutional code used at E6-B with $R = 1/2$ and $K = 7$ has the following performance [5]:

BER	E_b/N_0 for Viterbi Soft Decoding [dB]	C/N_0 for Viterbi Soft Decoding [dBHz]	E_b/N_0 for Viterbi Hard Decoding [dB]	C/N_0 for Viterbi Hard Decoding [dBHz]
10^{-3}	3.0	30.0	5.0	**32.0**
10^{-5}	4.5	31.5	6.5	33.5
10^{-7}	5.5	32.5	7.5	34.5

Table 3 – Performance of Viterbi Decoder for R=1/2 and K=7 convolutional code [5].

The table represents the required E_b/N_0 and C/N_0 to decode the message with a given probability of error (C/N_0 values are referred to the E6-B component only). Let us take the conservative case that BER=10^{-3} is acceptable (note however that this is often considered a poor BER and a lower value may be desirable) and the realistic assumption that hard decoding is used in the receiver. This implies that the required C/N_0 for data demodulation is 32 dBHz.

Now the question is whether the E6-B component can stand phase tracking up to C/N_0=32dBHz. The corresponding symbol-energy to noise-spectral density ratio is E_s/N_0=2dB, and it can be checked that a Costas loop can maintain tracking up to these levels. For instance, this result is in-line with those in [6]. The E6-C component can be used to keep carrier tracking below C/N_0=32dBHz, and this may be useful for applications, but it is not mandatory for decoding the E6-B data. Below C/N_0=32dBHz, the decoding of the E6-B data is too prone to errors even if perfect carrier phase estimation is available. Note that if a lower BER is targeted, then the required C/N_0 is higher, and hence carrier tracking even only with E6-B is further facilitated.

The study of phase estimation for coded signals is a known issue among the communications community [7] [8] and has attracted a lot of interest. Many techniques have been proposed, usually in the context of much more powerful codes (e.g. turbo codes and LPDC). There, the required E_b/N_0 for data decoding is even lower, and with the proposed synchronization techniques, tracking can be keep up to data decoding threshold. In the case of E6-B, the code is a very simple one, and hence the decoding threshold is not very low, so there is no need to resort to sophisticated synchronization techniques. Nevertheless, carrier tracking can be possible even at lower E_s/N_0 values, basically up the decoding threshold, if the appropriate techniques are used.

The receiver test results shown in the following sections confirm that, in the case of our receiver, the fact that E6-C has no or little impact in E6-B data demodulation, as E6-B-only phase tracking is maintained beyond high values of BER. Therefore, carrier phase tracking at lower C/N_0 values thanks to E6-C does not increase the demodulation performance of the receiver.

GALILEO CS RECEIVER PROTOTYPE

The Galileo CS Receiver is part of the RXP (Receiver Platform) developed under the AALECS project [9]. The RXP is complemented by a PVT client, that allows computing PPP corrections for high accuracy [10], as well as an Authentication client, that allows performing Navigation Message Authentication [11]. As regards authentication, we will focus on spreading code authentication features, which are implemented in the signal processing block of the receiver.

Galileo CS Receiver

The Galileo CS Receiver prototype is based on IFEN's NavX-NTR receiver. Its main features are:

- A flexible FPGA-based (software defined) multi-GNSS receiver test and verification platform.
- Multi-GNSS features (GPS L1, L2/L2C, L5 | Galileo E1, E5, E6 | GLONASS G1, G2 | BeiDou B1, B2 | IRNSS L5, S-band) by handling up to four frequency bands with 50MHz bandwidth each simultaneously.
- The receiver channels are designed to track data and pilot signals in parallel or separately, plus being configurable on signal BOC structures (sine/cosine BOC, TM-BOC, CBOC, AltBOC).
- A USB3 streaming interface allows the user to collect high bandwidth samples in parallel to receiver operation.
- It runs on an embedded Linux on two Arm Cortex A8 processor with the possibility to implement customer specific software algorithms.

The NavX-NTR receiver is accommodated in a 19 inch, rack mountable 1 HU frame, as shown in Figure 4. A portable housing is optional and can be powered either by AC or DC.

The RF front-end board allows up to four different standard or customer-selected RF signals to be down-converted to an intermediate frequency. Typically, the selection of L1, L2, E5 and E6 with 50MHz bandwidth covers all existing frequencies (except for IRNSS S band, that could be supported by a modified frequency setup). The use of ceramic RF filters guarantees very stable group delay and thus inter frequency biases; for instance, the absolute group delay variations over 24 hours at a temperature range of 21°C ± 1.5°C is better than 100 ps (1 sigma). Code minus carrier stability over the same time interval of 24 hours is better than 120 ps. A four channel, high-speed analogue-to-digital converter (ADC) on the RF front-end board digitizes the analogue signal. The front end ADC has a range of 16 bits. This gives sufficient head room for interference investigation and adaption to several environmental conditions.

Figure 4 – Multi-frequency GNSS receiver NavX®-NTR

Digital signal conditioning in terms of digital filtering and complex down-conversion is performed in a field programmable gate array (FPGA) located in the main-board, which also communicates with the RF modules for signal identification or automatic gain control. In addition, this FPGA is responsible for interference mitigation by pulse blanking and a notch filtering.

In order to facilitate direct signal inspection, the receiver is equipped with a fast USB3 interface that allows logging of IF samples from all frequency bands on a sample rate of 50MHz I/Q and selectable bit width. The digital complex data stream of all four analogue channels is streamed to the base-band pre-processor modules, realized by additional FPGAs on dedicated modules. These modules incorporate the correlation engine with up to 50 channels per module.

As abovementioned, the base band processing currently supports the complete Galileo spectrum (OS and CS) including CBOC and AltBOC, GPS L1 (including TMBOC), L2 (semi-codeless P(Y), L2C) and L5, SBAS L1 and L5, GLONASS G1 and G2, IRNSS L5 and S and BeiDou B1. As already presented in former receiver generation [12], each channel follows the so-called SC^3 architecture including up to typically ten correlators, that could be assigned freely to two memory codes or to a code generator, or additional de-modulators of BOC/TMBOC codes. Apart from this, a channel may be equipped with a cipher code generator to handle encrypted codes, or a cross correlation unit needed e.g. for GPS L2P tracking. This architecture has the advantage of supporting in a single channel data and pilot tracking. This gives the opportunity to freely and coherently support separate pilot/data tracking for signal assessment, tracking on pilot and grabbing the data navigation bit, or running combined pilot/data tracking. Each of these channels is freely assignable to any of the four input data streams. The modules have a direct connection to a feature expansion board, allowing additional functionalities to be implemented like IF data streaming interface or PRS tracking.

Additionally, the preprocessing FPGAs may be equipped with a fast acquisition correlation unit. In the presented paper this was not done, and acquisition relies on slower Tong acquisition because this has the full flexibility to support encrypted codes.

Using a general purpose memory interface, the modules can be easily accessed using a standardized general purpose memory controller (GPMC) interface, which is commonly available on many modern processors and provides fast hardware/software interaction. The hardware board allows plugging in up to two so-called System-On-Module (SOM) boards, of which one has a tight connection to all base-band pre-processing modules. The SOM modules are based on an ARM Cortex A8 processor core running at 1 GHz. The SOM module connected with the hardware runs the software part of receiver navigation processing. This covers acquisition control of the hardware, loop closure on a per-correlation hardware/software interchange, navigation decoding, computation of the PVT and setting up the front end. The second SOM module either acts as a network router, or could be extended with controlling software, e.g. to provide a built-in user interface.

The main receiver interface is realized through a 100BASE-T LAN interface. Commanding is performed through an ASCII-based telnet interface, or optionally by a TFT touch display. All measurements (observations, navigation message, etc.) can be transmitted either through UDP or TCP datagrams in ASCII, proprietary binary format or RTCM 104 format in real time.
This platform is used in a variety of flavors, e.g. as monitor receiver for the German Galileo Test Bed (GATE), as payload test receiver for the Galileo IOT phase or as test user receiver within GATE or the Indian IRNSS system.

For the AALECS project, it was specifically required to provide observations and navigation data in a standard RTCM format. For this, the receiver was extended to include RTCM 104 version 3.2 support, which incorporates also Galileo observations and navigation messages. Additionally, proprietary RTCM messages were introduced to make raw E6 C/NAV navigation bits available to external clients.

Implementation of Spreading Code Encryption and Authentication

In the frame of the AALECS project, the receiver has been extended to test several signal authentication approaches:

- Spreading code encryption: this functionality includes the encryption of E6-B/C primary codes that bound to a key and an initial time stamp, and the on-the-fly key change, which in turn requires the exact trigger of a new cipher generation after a key change.

- Assisted authentication, based on Remote Processing Authentication (RPA) [13] and signal authentication sequences (SAS) [14], which are described below.

For **spreading code encryption**, the receiver tracking channels may be set up to modulate the replica with a long keystream generated from the symmetric key and the cipher in use. The basic challenge is to synchronize the keystream generation with the reference time. For this a hand over from open service signals is performed. It is also required to change the key while tracking, in case a new key enters in force. For this a scheme was developed to predict the key change, and to upload the new key to hardware within less of a primary code period (1ms).

In **remote processing authentication** (RPA), snippets of raw samples that contain an encrypted signal are collected and sent to an external server that validates the authenticity of the tracking signal. The advantage is that no key has to be exchanged and the user does not need to keep a secret. This scheme requires that these samples have a precise time tag matching the receiver processing.

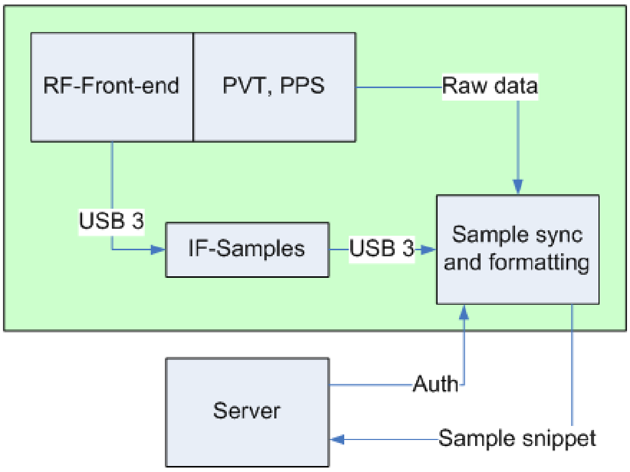

Figure 5 – CS receiver architecture for Remote Processing Authentication

In the implemented approach, the receiver USB interface provides messages with raw samples. Additionally, time stamps with PPS information are included in the messages. On the other hand, while tracking, the receiver steers the PPS signal to GNSS system time. The external software then is capable to slice arbitrary numbers of samples with a precise time tag that then are provided to an external server. In the current implementation, the interface is file-based but it easily could be extended to network provision.

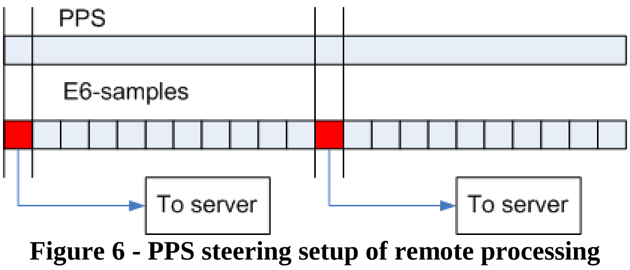

Figure 6 - PPS steering setup of remote processing scheme

A different authentication approach, called **Signal Authentication Sequences** (SAS), has also been implemented. This scheme also allows authentication without key exchange, but here the server provides short sequences of encrypted code that match to the encrypted signal on a certain time. The receiver has to correlate the signal with these sequences, and it decides on signal presence/absence the authentication of a tracked signal.

The receiver supports SAS by means of the two code memories in the tracking channels. While one code memory provides the replica for tracking an unencrypted signal (e.g. Galileo E6-B), the other one could be loaded with the encrypted sequence. A free correlator will be set to this second code memory. When the time of applicability for the encrypted sequence is reached, the correlator generates a peak that could be checked for authentication significance with respect to correlation length, C/N_0 and coherent accumulation. The challenge in this implementation lies in ensuring that the code is loaded at right time, and that several of the encrypted sequences can be handled.

CS RECEIVER TEST CAMPAIGN

In the frame of the AALECS project receiver acceptance, several tests were performed to verify receiver compliance to requirements, and to get insight in the signal capabilities. These tests can be grouped in following areas:

- Demonstration of basic receiver capabilities on simulated signals/fixed position SIS signals.
- Simulator tests with support from JRC (Joint Research Centre), Ispra.
- Tailored test setup to handle the specific extensions on authentication and interference mitigation
- Real signal tests on a receiver static/dynamic setup in free space or urban environment.

The specific CS receiver signal processing tests are summarized in Table 4, including its description and main pass/fail criteria. All the reported tests were passed. More details about the results are provided in the next section.

CS RECEIVER TEST RESULTS

This section presents the test results obtained with the NAVX NTR CS receiver.

Signal processing tests

The receiver tests covered the signal processing of GPS L1 and L2P, Galileo E1, E5a, E5b, E6 acquisition and tracking, processing latency, signal acquisition sensitivity, and time to first fix. A signal generator was used to provide the GPS and Galileo signals. To test signal acquisition and sensitivity, the signal generator was set to a certain power level that corresponds to a C/N_0 =34dB Hz for acquisition, and was decreased to a C/N_0 = 28dB Hz while tracking. The implemented Tong acquisition is known to have a limited sensitivity of approximately C/N_0 = 34dBHz [15]. At this C/N_0, the prototype receiver was capable of acquiring all assigned six signals on E1 and almost all on E6 at first trial. This is shown for Galileo E1 and E6 in Figure 7.

Table 4 – CS Receiver Signal Processing Tests

Test	Description	Metric/Criteria
Multi-Signal	Acquire and track GPS L1 and L2P, Galileo E1, E5a, E5b, E6	All signals acquired ad tracked, PVT is obtained for all signals
E6 encrypted code	Acquire and track spreading code encrypted E6 signal with key change	Tracking of encrypted signal; maintain C/N_0 during key change
Signal sensitivity	Acquire and track weak signals	Tong acquisition on 34dBHz, Tracking on 28dBHz
Cold/Warm start acquisition	Measure the acquisition time	Acquisition time in line with Tong search time
Measurement Quality	Check tracking observation tracking noise vs. expectations	Tracking code range/carrier range noise in line with theory
Interference handling	Show pulse blanker and spectral filter performance	Recovery of signal when interference mitigation enabled
SAS	Test the Signal Authentication Sequences approach	Provision of correlation values when using primary code as signal sequence
RPA	Remote Processing Authentication sample collection	Check if correlation in samples is at zero code phase

For code tracking performance assessment, the expected code tracking error was calculated according [15], Sect. 5.6. For the test setup a typical Walker constellation setup with C/N_0 = 45dBHz and 1 ms coherent integration time for all signals was used. The code error is estimated from code minus carrier observables.

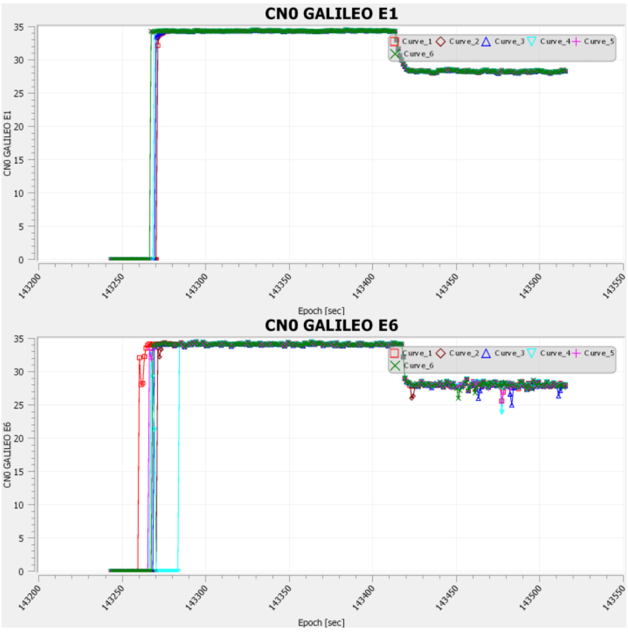

Figure 7 - Acquisition and tracking behavior on Galileo E1/E6 for 6 satellites

Table 5 - Measured code tracking errors

Signal(s)	DLL Early/Late spacing	DLL bandwidth [Hz]	Expected code noise [m]	Measured code noise [m]
GPS-L1	0.2	1	0.55	0.45
GPS L2-P	N/A	0.01	0.6	0.46
Galileo E1-B	0.1	1	0.25	0.17
Galileo L1-C	0.1	1	0.25	0.18
Galileo E5a-I	0.2	1	0.059	0.055
Galileo E5a-Q	0.2	1	0.059	0.055
Galileo E5b-I	0.2	1	0.059	0.055
Galileo E5b-Q	0.2	1	0.059	0.055
Galileo E6-B	0.2	1	0.087	0.085
Galileo E6-C	0.2	1	0.087	0.085

For carrier tracking assessment, the same setup was used, but here taking the 3rd difference of carrier ranges between two satellites (to avoid clock noise impairment). In some cases, the carrier range error was larger than expected but in general less than 1ps (0.3 mm).

Interference tests

To test the pulse blanker, GPS/Galileo simulated signals are superimposed with a pulsed continuous wave (CW) signal from vector signal generator with a power of 55dBm. The pulse period was 1 ms while its duty cycle was 10%. During the test the pulsed CW was placed on the Galileo E1, E5a, E5b and E6 frequencies, and then the pulse blanker functionality was enabled for each input respectively. As a result, the pulse blanker was able to recover the signal with 0.5 dB loss in C/N_0 (as shown in Figure 9, which presents the C/N_0 during the interference, and after the pulse blanker is enabled).

For the interference notch filter, a single CW placed 1MHz away from the center frequencies was employed. According Figure 10, the impact of the CW almost completely is removed.

Table 6 - Measured carrier tracking errors

Signal(s)	PLL bandwidth [Hz]	Expected carrier noise [mm]	Measured carrier noise [mm]
Galileo E1-B	10	0.50	0.5
Galileo L1-C	10	0.50	0.5
Galileo E5a-I	10	0.54	0.75
Galileo E5a-Q	10	0.54	0.76
Galileo E5b-I	10	0.54	0.55
Galileo E5b-Q	10	0.54	0.45
Galileo E6-B	10	0.54	0.55
Galileo E6-C	10	0.54	0.65

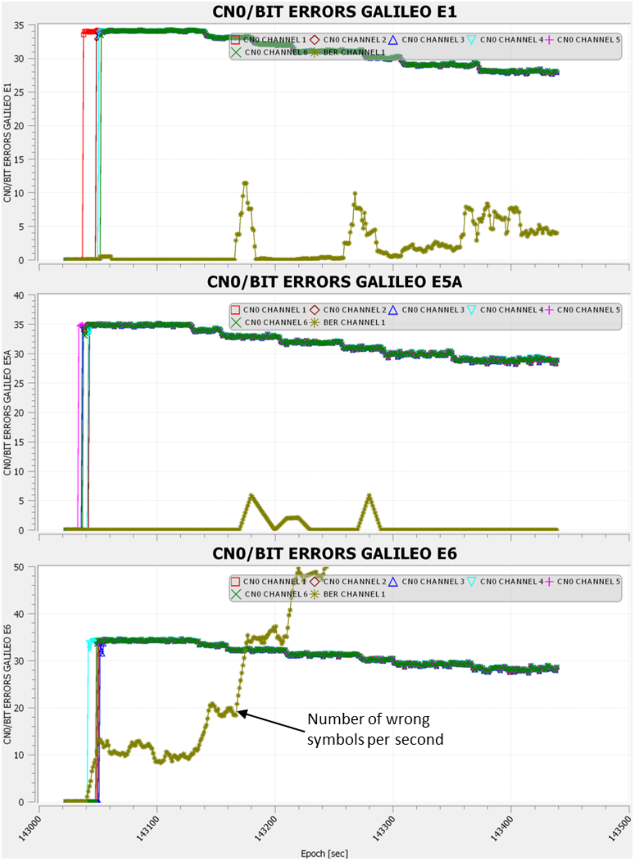

Figure 8 – C/N$_0$ vs. wrong symbols per second (estimated by Viterbi decoder) in Galileo E1, E5a, E6-B

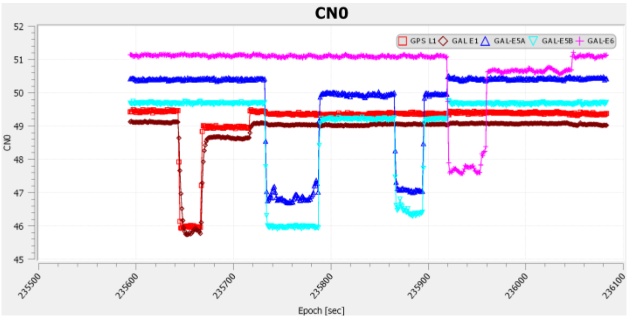

Figure 9 - Pulse blanker test result

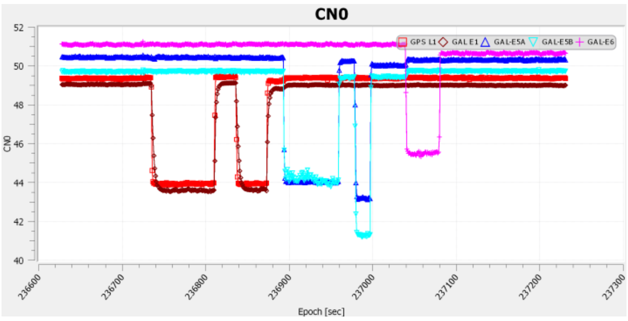

Figure 10 - Notch filter test result

Encrypted signal processing

For testing encrypted spreading codes, a raw sample streaming scheme as in Figure 11 was set up. The I/Q samples that carry the spreading code, the cipher, and the navigation data with correct time stamps are generated in software and replayed. Figure 12 shows the process of switching from one keystream to the next one, and Figure 13 shows that the C/N$_0$ was maintained during the transition proving that the key transition was managed successfully. As the encrypted signal processing is a cornerstone of the AALECS project, it also was verified integrated in an test setup with a third-party signal generator capable to provide encrypted signals at the Joint Research Centre (JRC) and with Galileo SIS in the EPOC [16].

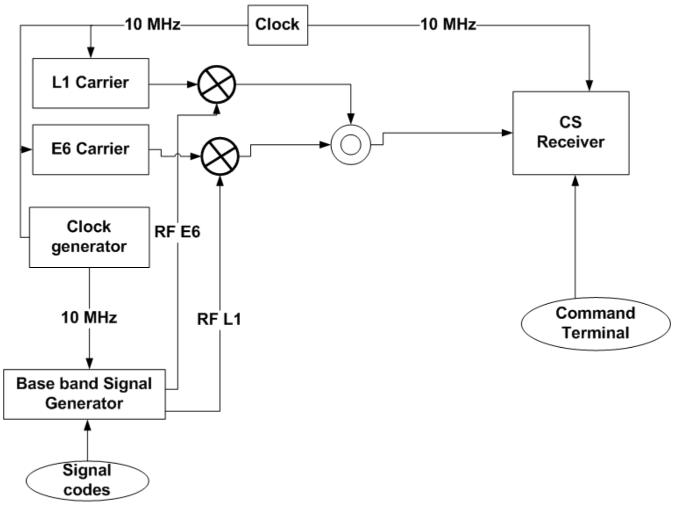

Figure 11 - Encrypted sample streaming setup

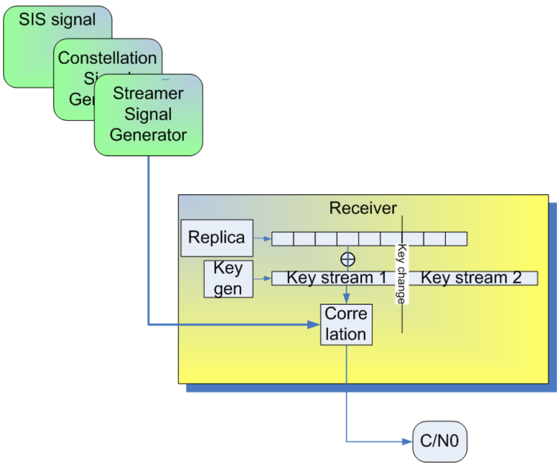

Figure 12 - Encrypted key change scheme

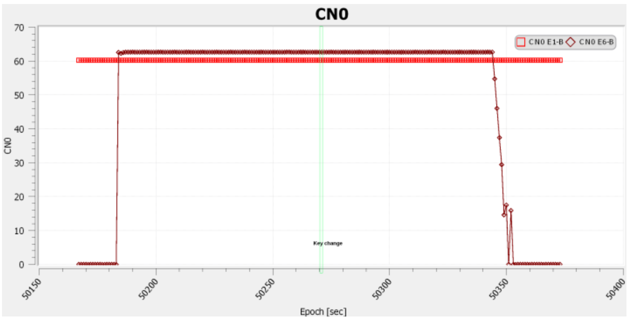

Figure 13 - Tracking encrypted key change result

SAS test

For a complete verification of the SAS scheme, an external server that provides the encrypted “snippets” of spreading code chips is needed, that is beyond the topic of the present paper (but is a target of the full AALECS project). The demonstration of the receiver fitness of this scheme is shown in Figure 14.

RPA test

The authentication scheme of providing samples to a remote server also requires a test setup that extends the single receiver verification. To ensure that the samples actually contain the intended signal, a constellation simulator was employed, but with a geo stationary signal. In this case, the sample triggering PPS was steered so that it was aligned with the E6 tracking navigation frame. Then, the sample batches were collected and externally cross correlated with the primary code. As an outcome, the correlation is expected to be highest at a zero code phase measurement. The outcome of the test actually showed that the code samples contain the signal at the expected code phase.

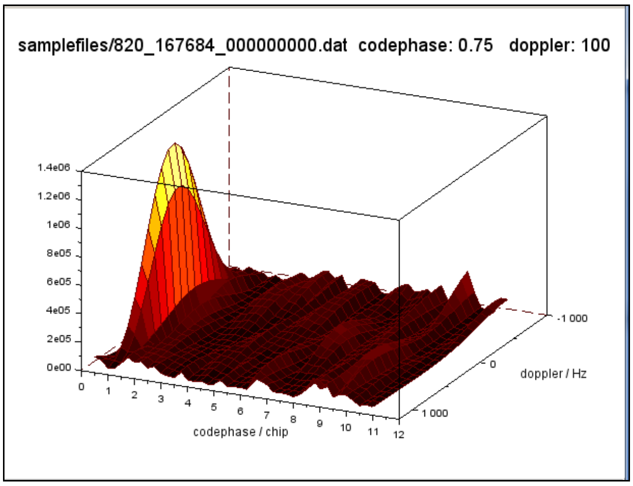

Figure 14 - Spreading code correlation with samples

Signal in Space tests

To check the receiver behavior with real signals, the following tests were executed:

- Acquisition, tracking and positioning on a statically mounted antenna with good satellite visibility
- A static test in a typical suburban environment
- A dynamic test where the antenna is mounted on a van following in suburban/urban route.

In the static setup the true antenna position was obtained from previous RTK measurements. For the dynamic test, a reference Novatel RTK SPAN unit receiver was used. All tests were executed in the vicinity of Munich, Germany in late October 2015. The availability of sufficient Galileo satellites was low; only 3 SV were in view. Therefore, even if the focus was on E6 testing, a combined GPS/Galileo position was calculated. Figure 15 and Figure 16 show the test equipment and trajectory respectively of the SIS kinematic tests. The location of the static suburban tests is also shown in Figure 16 (red circle). This belongs to a location where signals were partly obstructed. The dynamic test included partly free field areas and partly urban environment areas. Notice that these results are complemented by the results obtained with a former version of the CS Receiver, used for the CS Early Proof-Of-Concept testing in summer 2014, reported in [16] and [4].

Figure 15 - Testing van for CS Receiver SIS testing

Figure 16 - Test trajectory for CS Receiver SIS testing

Figure 17 and Figure 18 show the horizontal errors in the static and dynamic tests, respectively, using GPS+Galileo and different signals. Figure 19 shows the number of tracked Galileo satellites per frequency. Concerning the SIS tracking results, the tracking of all SV was stable and continuous. In the dynamic test, E1 signal had the best availability (86%), due to its longer integration time. E5a (44%), E5b (63%), E6-B (57%) had a comparable availability. In all cases between two and three Galileo SV were tracked. Concerning the PVT results, even if they cannot be representative of a Galileo-only PVT, the following can be observed (note that the Klobuchar ionospheric model was used for computing ionospheric corrections):

- All used signals are highly correlated, as in all cases GPS was used.
- E1 is slightly better than E6, also by its longer integration time allowing a higher sensitivity.
- There are periods without a dynamic position due to poor visibility.

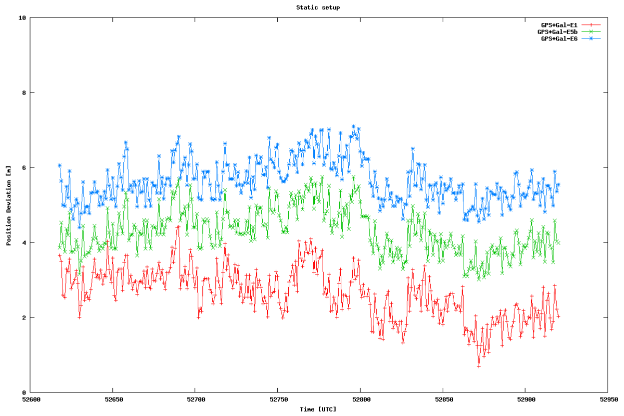

Figure 17 - Position deviation in static setup (red: GPS+Gal, E1; green: GPS+Gal, E5b; blue: GPS+Gal, E6)

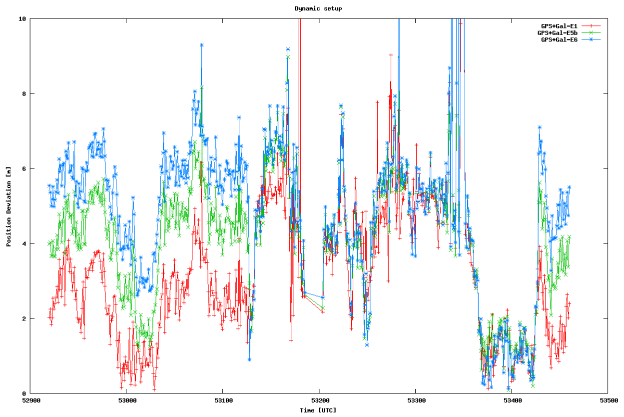

Figure 18 - Position deviation in dynamic setup (red: GPS+Gal, E1; green: GPS+Gal, E5b; blue: GPS+Gal, E6)

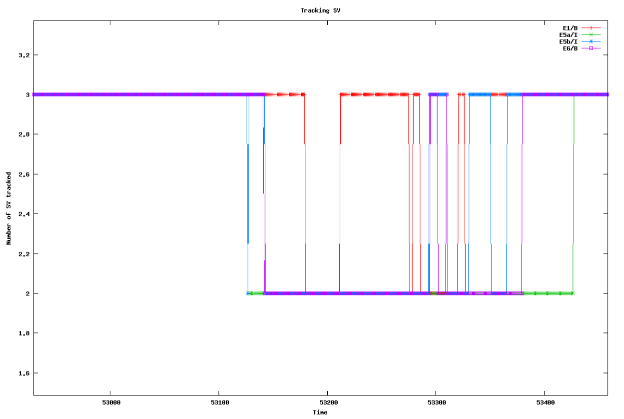

Figure 19 - Number of tracked satellites per frequency

Weak signal handling tests

Some tests on signal tracking at decreasing C/N_0 are reported here. The test setup is as follows:

- Several channels were assigned to the same signal type: Galileo E1/B, E5a/I, or E6-B
- A Tong Acquisition on C/N_0=34dBHz was performed, with A=8, B=1, and P_{fa}=0.12
- Tracking was maintained with decreasing C/N_0 down to 28dBHz.
- Tracking loop parameters used were DLL BW=1Hz, PLL BW=20Hz, and Tint=1ms

The results show that acquisition was achieved for all signals. Carrier tracking was also maintained for all signals, down to 28 dBHz. Figure 8 shows the estimated symbol error rate vs. C/N_0 for E1, E5a and E6-B. It shows that, as expected due to its lower E_b/N_0 with respect to E1 and E5a, E6-B symbol error rate estimated from receiver decoding becomes high when the C/N_0 is less than 32 dB Hz, in line with the theoretical results presented above. Carrier phase tracking on E6-B is maintained down to a C/N_0 of 28dB Hz while data modulation capability is lost at 32dB Hz. Note that, if E6-B BER needs to be brought down to the C/N_0 at which E6-B carrier tracking is lost, an additional coding layer could be added.

CONCLUSIONS AND FURTHER WORK

This paper has summarized the results of the IFEN CS Receiver testing in the AALECS project. The paper also included a full definition of the E6-B/C signals (when unencrypted) to a detail sufficient for the implementation of the E6-B/C signal processing. An IFEN NTR multi-GNSS receiver was adapted for E6-B/C, including signal decryption capabilities and client-server authentication. The receiver results, both with simulated and real signals, coincided with the expectations. In particular, the receiver E6-B tracking and demodulation capabilities (without pilot tone) were aligned to the theoretical results. However, due to the lack of Galileo satellites, more SIS tests will be executed in order to evaluate the Galileo E6 PVT performance. In any case, the CS prototype receiver has proven to be an important asset for the consolidation the Galileo CS and the translation of E6-B/C signals into meaningful services.

ACKNOWLEDGMENTS

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