Potential candidates for new SBAS signals

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***Abstract*—Satellite-Based Augmentation Systems (SBAS) provide single-frequency services for aeronautical users by broadcasting corrections and integrity information on L1 frequency. Future dual-frequency services for aeronautical users will be broadcast on L5-I/E5a-I frequency. New services that could be potentially provided by SBAS to non-aeronautical community are currently being investigated. These services may require higher data rates that challenge current SBAS signal definitions. Considering there is, at this time, no standardized SBAS signal neither on L5/E5a-Q component nor on E5b frequency band, an opportunity to evaluate new signal candidates is identified. In this paper, several candidates are proposed and compared with a baseline candidate. The baseline candidate is the current signal structure of SBAS signals, L1-I and L5-I/E5a-I. The comparison is made in terms of data rate, latency, data demodulation performance and receiver complexity as number of real additions and multiplications. It is observed that it is possible to increase the data rate and to reduce the latency without degrading the data demodulation threshold and with a reasonable complexity increase. Moreover, a compatibility analysis has been conducted which shows an impact smaller than 0.1dB of C/N_0 degradation in any signal processing operation of any L5/E5a frequency band signal.**

Keywords—SBAS signals, SBAS E5b, BPSK, CSK, high data rate, complexity, demodulation.

I. INTRODUCTION

Disclaimer: This paper is the result of preliminary R&D activities and does not necessarily reflects the plans for the evolutions of SBAS.

SBAS provides Safety of Life (SoL) services for single-frequency aeronautical users on L1 frequency. A new aeronautical standard, that will allow to provide Dual-Frequency Multi-Constellation (DFMC) services broadcast on L5-I/E5a-I component, is under development. The DFMC SBAS L5-I/E5a-I signal has been designed as an evolution of SBAS L1 signal [1][2] in 2012 [3][4][5]. SBAS L5-I/E5a-I signal was introduced in order to take advantage of the new GNSS signals in the L5 band as well as to tackle new performance targets and system modifications. Among new features, SBAS L5-I/E5a-I signal includes the capacity to enhance multi-constellation GNSS and to provide L1/L5 iono-free combination corrections. These new capacities have been brought by the modification of the SBAS L5-I/E5a-I message content with respect to SBAS L1 message content, in order to have an SBAS signal generation transition as smooth as possible. In fact, the SBAS L5-I/E5a-I signal was designed to efficiently use the data rate inherited from the SBAS L1 signal structure that is set to 250 bits/s.

Further SBAS evolutions are already investigated for performance improvements, complementary functionalities such as authentication, or definition of additional SoL services for new communities that include railway or automotive users. The performance objectives identified for these evolutions are very ambitious and it can be expected that higher data rates will be needed. Considering the design limits imposed by current SBAS standards in L1 frequency band and L5-I component, an investigation of potential candidates for new SBAS signals that would achieve high data rates and lower latencies is proposed in this paper. Note that a previous work was already conducted to analyze potential candidates for the SBAS L5/E5a signal with a higher rate [19] since the potential need for higher data rates was already identified in the past. [19] focused mainly on the demodulation performance and proposed different options defining I and Q components, whereas the new proposal made in this paper must cope with an existing definition of SBAS L5-I/E5a-I component.

From the current situation, the existence of a standardized SBAS L5-I/E5a-I signal, there are two opportunities that would potentially allow for dissemination of new identified services: the L5-Q/E5a-Q component or the E5b frequency band. It is expected that the transmission of non-aeronautic services in L5-Q/E5a-Q could be considered as undesirable by the aviation community. E5b, on the contrary to L5-Q/E5a-Q, would allow to avoid conflict between aeronautic and non-aeronautic applications. Currently, there is no signal standard defined on the E5b band for SBAS. At the ground segment, the impact of a new E5b SBAS signal would be the data collection and signal generation. At the space segment level, an additional frequency would need to be introduced. This frequency is already implemented on some EGNOS GEO payloads. At the user level, demodulation of the new signal would need to be added.

The aim of this paper is thus to analyze various SBAS E5b and L5-Q/E5a-Q signal candidates that can provide different data rates and different latencies while respecting the constraints of other services occupying the respective frequency band. The assessment of the strengths and weaknesses of each candidate and their overall comparison is also performed.

This paper is structured as follows. First, the introduction and motivations of this work are given. Second, the objectives of the work are defined. Third, the SBAS signal expected functionalities as well as the signal performance requirements and key parameters to analyze are determined. Fourth, the potential SBAS signal candidates are presented. Fifth, the signal performance analysis is conducted. Sixth, comparison and recommendations between signal candidates are made. Finally, the work is concluded.

II. Objectives

A. *Signal design objectives*

Signal design objectives set in the frame of this study are defined with respect to the current SBAS L1 and L5-I/E5a-I signal designs and are stated as follows:

1. To achieve higher data rate;
2. To achieve lower latency (shorter time needed for the user to receive all necessary symbols to start the decoding of the message);
3. To have no (or very limited*) impact on performance of the SBAS L5-I/E5a-I signal at user and at ground segment receiver level;
4. To have no (or very limited*) impact on performance of other GNSS signals in the L5/E5a-band;
5. To maintain or improve the robustness of the SBAS signal, such as scintillation and interference;
6. To introduce minimum possible impact on user receiver complexity;
7. To have quantifiable impact on GEO-payload complexity.

* "Very limited impact" can be defined as a degradation of the final link margin smaller than 0.1dB. Note that link margin refers to the difference between the C/N_0 signal link budget (signal power-to-noise power density, C/N_0, at the GNSS receiver radio-frequency front-end output) and the operation threshold (acquisition, tracking, demodulation).

B. *Signal frequency band candidates*

There are two candidates identified that could accommodate the new signal designs: E5b and L5-Q/E5a-Q.

SBAS E5b frequency band could provide new services data for non-aeronautical users although the same data services as for aeronautical users could be envisioned to be transmitted on this band. Galileo system currently transmits on this frequency band.

TABLE I. SBAS SIGNALS FUNCTIONALITIES

SBAS Signal/ Component	Acquisition	Tracking	Word Synchro	Data Delivery
L5/E5a-I	Mandatory	Mandatory	Mandatory	EGNOS Message
L5/E5a-Q	Not required	Not required	Not required	Authentication, alerts, etc.
E5b	Mandatory	Mandatory	Mandatory	Precise Positioning, Emergency Services, etc.

SBAS L5-Q/E5a-Q could provide more data to aviation users for new services (e.g. authentication), could improve the existing services (e.g. short alerts, 0.5 second messages), could provide more demanding aviation positioning services operations (e.g. Cat I autoland), etc. This frequency band could also potentially provide non-aviation applications data if the signal design would be improved.

III. SBAS Signal Functionalities and Signal Performance

In this section, the functionalities assumed to be conducted by each signal component of the SBAS L5/E5a and E5b signals are determined first. Second, the interpretation of signal processing performance requirements of targeted signal components, L5/E5a-Q and E5b, are given. Finally, the signal performance analyzed in this paper are presented and justified.

A. *SBAS signals functionalities*

Functionalities for SBAS L5/E5a signal (I and Q components) are summarized in TABLE I. These functionalities are provided taking into account that SBAS L5-I/E5a-I signal component was designed as a standalone component and thus the users should be able to obtain all the required functionalities with the necessary requirements from this component alone. Therefore, SBAS L5-Q/E5a-Q can either be used to improve the overall SBAS L5-I/E5a-I component performance or can just focus on data delivery (objectives 1 and 2 of section II.A). Moreover, note that since the SBAS L5-I/E5a-I legacy signal should remain unmodified, objectives 3, 4, and 5 defined in section II.A should be already partially fulfilled. The remaining ones are the objectives associated to the complexity (objectives 6 and 7 of section II.A), but only the receive user complexity will be analyzed in section V.B.

TABLE I. also summarizes the SBAS E5b signal functionalities. In this case, since there is no SBAS legacy signal in E5b, the new designed signal should provide all the functionalities.

B. *Interpretation of signal processing performance requirements*

The signal processing performance requirements of any signal component can be usually translated in terms of minimum C/N_0, or threshold, required to conduct a signal processing operation (such as acquisition, tracking demodulation). This interpretation allows to determine whether the signal component fulfills the imposed requirements or not by just comparing the threshold associated to a given requirement with the C/N_0 obtained from the signal link budget, also called $C/N_{0,eff}$. The comparison of the two allows to calculate the link margin, see equation (1), and thus, a positive link margin means that the requirement is fulfilled. Moreover, the inspection of this link margin in new potential situations or scenarios, such as the addition of a new signal component, SBAS L5-Q/E5a-Q, also allows to inspect whether the previous situation performance (such as robustness to scintillation and interference) is degraded or not; such a degradation is found when the link margin is decreased. Therefore, in this paper, the signal processing performance requirements will be analyzed from the link margin analysis (signal design objectives 3, 4 and 5).

$$Link\ Margin = C/N_{0,eff} - Threshold \quad (1)$$

In the case of SBAS L5-Q/E5a-Q and taking into account that in this paper, a very limited impact was previously defined as a degradation of 0.1dB of the link margin, the specific chosen methodology will consist in imposing the following three conditions:

a) The C term (minimum signal power) of the received signal is the same as for SBAS L5-I/E5a-I (-158*dBW*),

b) To allow a maximum degradation of 0.1dB of $N_{0,eff}$ due to presence of more navigation signals, SBAS L5-Q/E5a-Q coming from other GEO satellites than the one being targeted (adressed in the next section in the I_{GNSS} evaluation term),

c) To impose that the operation threshold, $Threshold$, must be the same as for the standalone processing of SBAS L5-I/E5a-I signal.

Therefore, by fulfilling these three conditions, it will be guaranteed that a degradation of the 0.1dB of the link margin is never exceeded.

Focusing on the operation thresholds and considering that, as presented in the previous section, the new signal component SBAS L5-Q/E5a-Q is only required to deliver data and not even word synchronization is necessary since it is already achieved by SBAS L5-I/E5a-I, the only signal performance requirement which will be targeted for SBAS L5-Q/E5a-Q is demodulation performance: SBAS L5-Q/E5a-Q must be able to provide the data message to the receiver with at least the same minimum C/N_0, threshold, as SBAS L5-I/E5a-I.

The derivation of the demodulation performance of SBAS L5-I/E5a comes from the derivation of SBAS L1 legacy signal demodulation performance: the SBAS message loss rate, WER_T, should be less than 1 in a 1000 [11]. This value is derived from the probability of missed alert requirement, $P_{md} = 10^{-8}$, since the number of consecutive broadcasted alerts and the WER_T determine P_{md} (or the other way around):

$$P_{md} = 10^{-8} = (WER_T)^n \quad (2)$$

where *n* is the number of consecutive alerts.

Therefore, assuming that at least 3 consecutive alerts are broadcasted (currently this number has been increased to 4), the WER_T should be at least equal to 10^{-3}.

Moreover, for a pure data component, the WER_T depends on two factors: on the WER of the implemented channel code in the presence of AWGN-only when assuming carrier phase tracking without cycle slips, P_w or WER_C, and on the cycle slip rate per second, P_{slip}P$_{\text{slip}}$. The relationships between these two factors can be expressed as:

$$WER_T = 10^{-3} = 1 - \left(1 - P_{slip}\right)^l (1 - P_w) \quad (3)$$

where *l* is the number of seconds the codeword spans. Note that for SBAS L1-I and L5-I/E5a-I, abusing the definition of codeword for a convolutional code, a codeword is equivalent to a SBAS L1-I or L5-I/E5a-I message.

For the DFMC SBAS MOPS definition [5], the codewords span 1 second. Therefore, assuming a classical cycle slip rate of $10^{-5}/s$, the P_w P$_{\text{w}}$has to be equal to 10^{-3}. A $P_w = 10^{-3}$ is obtained for a $C/N_0 = 29.5dBHz$ (same carrier tracking errors as defined before) [12]. However, since this value C/N_0 is lower than the value necessary to obtain a cycle slip rate of $10^{-5}/s$, the demodulation performance threshold is finally set to 30*dBHz* [18]. This demodulation threshold is the value which will be thus targeted in section V.C.

Concerning SBAS E5b, since this signal is not built to complement or to improve any legacy signal, it must provide all the functionalities and thus signal performance requirements should be defined for all of them. Nevertheless, since there are not any consolidated applications yet, no strict requirements can be derived. Therefore, for SBAS E5b signal, a best link margin effort is pursued in this paper. More specifically, since the $C/N_{0,eff}$ term can be considered (simplification) to not depend on the signal structure, the best effort will be reduced to obtain the lowest possible threshold; note that the threshold depends on the signal structure). For example, this means that a specific target of $WER = 10^{-3}$ at $C/N_0 = 30dBHz$ (threshold) is not pursued since this component does not have to specifically target aeronautical services. Therefore, since no specific target is defined (no concrete applications), the objective will be to obtain the best possible threshold for a specific requirement or need (such as targeted data rate); and this means that, contrary to SBAS L5-Q/E5a-Q, signal structures which do not fulfill the $WER = 10^{-3}$ at $C/N_0 = 30dBHz$ can be potential candidates.

C. Analyzed signal performance

The analyzed signal performance is divided in two categories; needs and constraints. The analyzed signal performances are used to determine which signal design objectives are fulfilled.

First of all, the needs are described. The needs are analyzed in section IV in the signal candidates description section since they solely depend on the signal candidate structure if the signal processing performance constraints are fulfilled. The needs are defined as follows:

1) *Increase of the useful data rate with respect to SBAS legacy signals:* This increase will be given in absolute bits per second values. This analyzed signal performance is used to evaluate objective 1 of section II.A.

2) *Latency:* The message latency represents the time that a receiver must wait from the moment the first bit of a message is received until the message can be processed. This analyzed signal performance is used to evaluate objective 2 of section II.A.

The performance constraints are analyzed in section V since they depend on the receiver implementation, propagation channel and interfering environment in addition to the signal candidate structure. The constraints are defined as follows:

1) *User demodulation/decoding complexity:* The user complexity is defined in terms of number of real operations, summations and multiplications, that a receiver needs to make in order to demodulate/decode the transmitted message. This analyzed signal performance is used to evaluate objective 6 of

section II.A. Note that thanks to the maintaining of SBAS L5-I/E5a-I component, the additional complexity introduced to the user receiver will only depend on SBAS L5-Q/E5a-Q component.

2) *Demodulation performance:* The demodulation performance is represented differently depending on whether the signal candidate is for SBAS L5-Q/E5a-Q signal component or for SBAS E5b signal. For the former, the demodulation performance is expressed in terms of fulfilling the demodulation threshold, 30*dBHz*, required to achieve a WER_T equal to 10^{-3}; and for the latter, the demodulation performance is expressed in terms of the C/N_0 required to achieve a WER_T equal to 10^{-3}. This analyzed signal performance is used to evaluate objective 3 of section II.A from the link margin analysis: remember that the demodulation threshold is one of the three elements required to evaluate the link margin, $Threshold$ term of equation (1). Objective 3 is fully evaluated by inspecting that the link margin is not degraded by more than 0.1dB.

3) I_{GNSS} *evaluation*: The I_{GNSS} term evaluates the interference generated by all global, regional and SBAS systems in the L5/E5a band (in this case) to any GNSS/SBAS L5/E5a or DFMC receiver. The I_{GNSS} term allows thus to see the degradation of the interference environment (compatibility) when a new signal is added to the existing ones in the analyzed frequency band (L5/E5a in this case). More specifically, the I_{GNSS} allows to calculate the effective N_0, $N_{0,eff}$, observed by the receiver [18].

Therefore, the analysis of the I_{GNSS} is used to complete the evaluation objective 3 of section II.A. Moreover, the analysis of the I_{GNSS} is also used to evaluate objectives 4 and 5 of section II.A. For these two objectives, since "other GNSS signals in the L5/E5a-band" are unmodified (objective 4) and, at least, the unmodified SBAS L5-I/E5a-I will be used to track the signal (objective 5), the operation thresholds will not be modified. Therefore, the only element which varies and which could degrade the signal link margin is the $C/N_{0,eff}$ or directly $N_{0,eff}$ is C is supposed to be the same as for SBAS L5-I/E5a-I.

IV. Signal Candidates

In this section, the signal candidates analyzed for SBAS E5b and L5-Q/E5a-Q are presented in addition to the common signal characteristics which are imposed by GPS and Galileo E5 signals. The candidates are separated depending on whether they can be proposed for SBAS L5-Q/E5a-Q or not. Moreover, additional requirements for the implementation of the candidates are commented in each section.

Note that the signal candidate's characteristics are summarize in TABLE III. Each candidate is given a notation, 'option XY' where the term X refers to the candidate's data rate increase with respect to the baseline candidate (option 1) which is the SBAS legacy signals, and Y refers to the proposed option variant with X data rate increase. For example, option 2B refers to option B with twice (x2) the signal data rate.

A. *Mandatory Signal Characteristics*

SBAS L5-Q/E5a-Q signal candidates must have the same PRN code characteristics as its counterparts in GPS L5 and Galileo E5 signals. Despite the fact that E5b SBAS signal is not necessarily restricted by the SBAS legacy signal constraints, such as demodulation performance, it is still assumed that this signal should be compatible with Galileo E5b signal in order to reduce the complexity of processing the two signals in the same receiver. Therefore, the new SBAS E5b signal should ideally keep the same chip rate, PRN code length and PRN code family as Galileo E5b. The mandatory signal characteristics are summarized in TABLE II.

TABLE II. PRN CODE CHARACTERISTICS OF PROPOSED SIGNAL CANDIDATES

Signal Component	Chip Rate	PRN code length	PRN code duration
SBAS E5b	1.023 Mchips/s	10230 chips	1ms
SBAS L5/E5a-Q	10.23 Mchips/s	10230 chips	1ms

TABLE III. SIGNAL CANDIDATES CHARACTERISTICS

Option	Mod.	Chanel Code	Word Size	Symb. length	Data rate	Word length
Baseline	BPSK	CC	500	2ms	250	1s
Option 2A	BPSK	CC	500	1ms	500	0.5s
Option 2B	BPSK	LDPC (500,250)	500	1ms	500	0.5s
Option 2C	BPSK	LDPC (1000,500)	1000	1ms	500	1s
Option 3A	CSK (6,4)	LDPC (750,375)	750	4ms	750	0.5s
Option 3B	CSK (6,4)	LDPC (1500,750)	1500	4ms	750	1s
Option 3C	CSK (12,8)	LDPC (750,375)	750	8ms	750	0.5s
Option 3D	CSK (12,8)	LDPC (1500,750)	1500	8ms	750	1s
Option 4A	CSK (4,1)	LDPC (1000,500)	1000	2ms	1000	0.5s
Option 4B	CSK (4,1)	LDPC (2000,1000)	2000	2ms	1000	1s
Option 4C	CSK (8,2)	LDPC (1000,500)	1000	4ms	1000	0.5s
Option 4D	CSK (8,2)	LDPC (2000,1000)	2000	4ms	1000	1s
QZSS A	CSK (8,8)	RS (2000,1742)	2000	8ms	871	2s
QZSS B	CSK (8,4)	RS (2000,920)	2000	4ms	920	1s
Option H	BPSK/ CSK (6,4)	LDPC (500,250) / LDPC (750/375)	500 / 750	1ms / 4ms	625	0.5

*CC= Convolutional Code, RS= Reed-Solomon
LDPC = Low Density Parity-Check Code

Concerning the power allocations assumptions, in this paper, it is assumed that the *minimum* received power of SBAS E5b and L5/E5a-Q signal candidates is the same as the one for SBAS L5/E5a-I signals.

B. Option 1: Baseline

Baseline option simply consists in copying the structure of SBAS L1 and SBAS L5/E5a-I signals: the Deep Space Communications Convolutional Code with code rate 1/2, with symbol duration equal to 2 PRN codes (2ms) and each symbol is modulated with Manchester encoding. The baseline candidate is considered since it is the option demanding the lowest evolution effort for Satellite payload and receiver evolutions. Moreover, the baseline will also be used as a comparison with other candidates and the potential improvements they bring. TABLE III. summarizes the baseline candidate characteristics.

C. Option 2: BSPK Candidates – E5b and L5/E5a-Q

BPSK candidates can be implemented for either SBAS E5b signal or for SBAS L5/E5a-Q signal. These candidates propose two families of channel codes, convolutional codes and Low Density Parity-Check (LDPC) channel codes [13], and to double the baseline symbol rate in order to double the final signal data rate. The implemented LDPC codes are LDPC(1000, 500) and LDPC(500, 250) where the first value refers to the number of coded bits and the second value refers to the number of information bits. These LDPC channel codes have been specially designed for these sizes in a 3 step methodology described in [14]: first, the optimal variable node degree-distribution is derived; second, the LDPC matrix of the code is constructed by using the progressive edge growth (PEG) algorithm; third and last, a postprocessing is conducted to obtain a systematic code.

Three different candidates have been identified in order to keep a maximum latency of 1 second. As it can be seen two options also present a decrease of the latency to 0.5 seconds. Note that the word synchronization for these two options is made by achieving synchronization with blocks of 1s in SBAS L5-I/E5a-I for SBAS L5-Q/E5a-Q. In the case of SBAS E5b, either the synchronization is achieved by introducing preamble bits (outside the channel code for LDPC) or it is achieved by the introduction of another component (E5b-I and E5b-Q).

TABLE III. summarizes the candidate's characteristics where the data rate means the number of information bits transmitted per second.

D. Options 3, 4 and QZSS: CSK Candidates - E5b and potentially L5/E5a-Q

Code Shift Keying (CSK) modulation with Bit-Interleaved Coded-Modulation (BICM) can be analyzed as a potential data modulation for SBAS E5b signal candidates. Moreover, in theory, CSK with BICM could also be used for other SBAS signals such as L5-Q/E5a-Q and in even in a potential SBAS L1-Q/E1-Q (which is out of the scope of this study). However, not all existing satellites (or satellites to be launched in the near future) may be able to apply CSK with BICM in L5/E5a or L1/E1 bands. Therefore, CSK with BICM candidates are mainly analyzed for SBAS E5b signal. For notation simplification purposes, in the remaining part of the article, the BICM mention will be omitted although any CSK implementation, candidate and analysis are made with respect to a BICM implementation. A brief description of the CSK modulation is given next.

The CSK modulation was specially designed to increase the transmission rate of a band-limited spread spectrum signal without affecting the PRN code structure. The main idea of a CSK modulation consists in increasing the number of different PRN codes transmitted on the data component. The new PRN codes are obtained by circularly shifting a fundamental PRN code (see Fig. 1). Therefore, since each PRN code represents one symbol, CSK modulation increases the number of available symbols with respect to BPSK modulation. Increasing the number of symbols of the modulation alphabet implies that more bits can be mapped by each symbol (four symbols can transmit two bits, eight symbols corresponds to 3 bits, and so on). So, if each PRN code period is equal to the data symbol duration, the bit transmission rate of a CSK modulation compared to a BPSK modulation (where one PRN code spans one symbol) is increased proportionally to the number of bits mapped by a CSK symbol. A further refinement of the bit rate increase can be made by changing the duration of the CSK symbol with respect to the BPSK symbol duration; the CSK symbol duration extension can be easily achieved without changing the PRN code properties of the chip rate by simply repeating PRN codes (which limits the symbol duration variation but facilitates its implementation). Final increase of the data rate with respect to BPSK modulation is summarized in equation (4). Finally, the demodulator only needs to identify which PRN code was transmitted to estimate the corresponding symbol and set of bits.

$$R_b^{CSK} = R_b^{BPSK} \cdot U/N \tag{4}$$

Where R_b^{CSK} is the CSK modulation data rate, R_b^{BPSK} is the BPSK modulation data rate, U is the number of bits mapped per CSK symbol and N is the number of repeated PRN code constituting a CSK symbol. From now on, CSK configurations will be defined as $CSK(U,N)$ to indicate a CSK modulation mapping U bits per CSK symbol and having N repeated PRN codes constituting the symbol.

For CSK candidates, two types of channel codes families have been analyzed. First, as well as for option 1, LDPC channel codes are considered with sizes LDPC(750, 375), LDPC(1500, 750) and LDPC(2000,1000). Both LDPC codes were specifically developed for these sizes and for an iterative decoding (BICM-ID, see section V.A) with the methodology proposed in [14]. Second, Reed-Solomon (RS) channel codes have been implemented in order to analyze similar signal structures to the only satellite navigation signal which implements a CSK modulation up to now: QZSS L6 signal for the Centimeter Level Augmentation Service (CLAS) [9]. The same Reed-Solomon code as QZSS L6 signal has been chosen, RS(2000, 1742) with the same symbol duration in order to compare the demodulation performance attainable with the QZSS L6 signal with respect to other CSK candidates with LDPC channel code. Moreover, another RS channel code, RS(2000,920), has been analyzed.

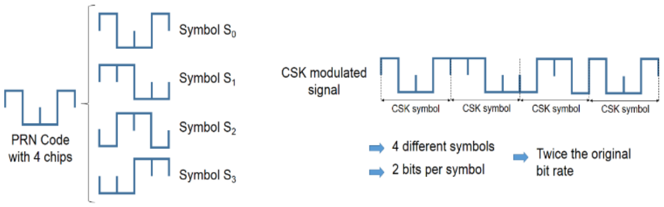

Fig. 1. CSK symbol generation and CSK modulated signal

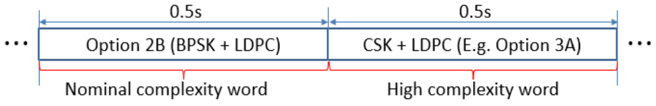

Fig. 2. Hybrid option candidate example

TABLE III. summarizes the candidate's characteristics where the maximum data rate increase obtained by a CSK modulated candidate has been set to 4 times the baseline data rate (1000 bits/s). The reason for choosing this limit is that, as shown in section V.C, these candidates already require a demodulation threshold above 30dB-Hz. Nevertheless, for SBAS E5b there is no constraint to have an even higher data rate imposing a higher demodulation threshold.

Finally, it must be remarked that a CSK modulation does not allow to use the signal for acquisition or tracking purposes. Therefore, the receiver should use another component in order to acquire and track the signal. For SBAS L5-Q/E5a-Q, these signal operations can be conducted on the SBAS L5-Q/E5a-I signal component which has been designed as a standalone component as specified in section III.A. However, for SBAS E5b signal candidate, the use of a CSK modulation implies that the signal has an additional component to the CSK modulated one. Alternatively, the acquisition and tracking of SBAS E5b from SBAS L5/E5a-I could be explored as it has been explored for other signal components [15].

E. Options Hybrid: BPSK/CSK Candidates - E5b and potentially L5/E5a-Q

One last candidate has been analyzed in this work. This candidate combines segments of the signal with a BPSK modulation and other segments of the signal with a CSK modulation. The main idea is to apply a kind of time multiplexing to the signal component: half a second modulated with a BPSK modulation (e.g. option 2B) and the other half a second with a CSK modulation (e.g. option 3A), see Fig. 2.

The main motivation of presenting such a candidate is to search for a trade-off between the advantages and drawbacks of the inspected data modulations, BPSK and CSK. On one hand BPSK requires a lower user complexity (see section V.B), but also has a limited data rate increase capability. On the other hand, CSK modulation is more complex to be processed (see section V.B) but provides a higher flexibility of the targeted data rate allowing to obtain higher values. Therefore, by applying this time multiplexing with 0.5 seconds segments, the signal allows the receiver to decide which signal segment is exploited: low-complexity receiver will just target and process the BPSK modulated segments whereas high complexity receivers will target both parts, BPSK and CSK modulated segments.

Moreover, note that this division could eventually allow the SBAS signal provider to target different levels of robustness to the broadcasted data, where more critical applications will be transmitted at a lower data rate (lower demodulation threshold, see section V.C).

Concerning the application of this hybrid solution to SBAS L5-Q/E5a-Q signal component, and assuming that CSK modulation can be implemented in the existing or near future satellites, its selection is seen as a good trade-off. On the one hand, GNSS civil aviation receivers could just process BPSK modulated segments with a nominal processing complexity (half the complexity required for SBAS L5/E5a-I, see section V.B); and still get the same amount of information as if the baseline option was implemented since option 2B transmits at twice the data rate of baseline option (but for hybrid option, only half of the time). Moreover, since the demodulation threshold is below 30dB-Hz (see section V.C), the demodulation performance required will be fulfilled. Therefore, it could be concluded that for users allowing only nominal processing complexity, the hybrid solution will be seen as the baseline solution in terms of complexity and demodulation performance. On the other hand, users interested in exploiting the CSK modulated segments could also benefit of additional services (new data) at the price of having a higher complexity receiver.

V. Signal Performance Analysis

In this section, the signal performance classified under the category of constraints in section III.C is analyzed where the deinterleaver between demapping and decoding is omitted for simplicity and for negligible complexity increase impact. However, before presenting the analysis, the generic structure of the data recovery block will be presented since the complexity and demodulation performance depends on the chosen architecture.

A. General structure of the data recovery block

A generic GNSS receiver data recovery structure is constituted of 3 blocks: the demodulator, the demapper and the decoder.

1) Demodulator: This element is in charge of correlating (matched filter application) the symbol received from the propagation channel with the vectors of the modulation basis [16]. In the case of a BPSK modulation, the correlation is made with the signal fundamental PRN code and in the case of a CSK modulation, the correlation is made with all the shifted versions of the fundamental PRN code which represent a symbol (CSK symbols). In the CSK case, this correlation can be made in the time domain, bank of correlators, or in the frequency domain, FFT/IFFT block [6][7].

2) Demapper: For modern binary channel codes which use soft decoding metrics, the demapper is an intermediate step after the demodulator and before the application of the forward error correction decoding of the channel code. This step, denoted as demapping, calculates a soft output metric for each individual bit of each individual demodulated symbol (for binary codes). This metric is generally the logarithm of the likelihood ratio of the bit (probability of the bit to be equal to 1 divided by the probability of the bit to be equal to 0). In the case of BPSK, the demapping step is straightforward since a BPSK symbol carries

a single bit. However, for a non-binary modulation such as CSK, the demapping can have significant complexity. There are several demapping algorithms which can be used: Maximum a-Posteriori (MAP), MAP using $\boldsymbol{max}^*(\cdot)$ and Look-Up Table (log-MAP-LUT), and the Max-log-MAP [7]. For clarification, note that $\boldsymbol{max}^*(\cdot)$ is an operator defined as $\boldsymbol{max}^*(x_1;x_2) = \max(x_1;x_2) + \ln(1+\exp(-|x_1-x_2|))$. Each one has its own performance and associated complexity where MAP is the optimal algorithm and the other two are less complex suboptimal variants.

3) Decoder: This element is responsible for applying the Forward Error Correction: to detect if any received bit was erroneous, to correct the bits values in this event and to provide the transmitted information bits. The inputs of the decoder are the metrics produced by the demapper. The decoder structure depends on the implemented channel code. In this work, three types of channel codes have been analyzed: Convolutional Code (CC), LDPC and Reed-Solomon (RS) codes. For CC, the Viterbi algorithm [17] is applied. For RS, a combination of decoding steps is applied (Berlekamp's iterative algorithm, Chien procedure, Forney evaluator [17]). For LDPC, several iterative algorithms can be implemented, from the more performing implementable one, logarithm Sum Product Algorithm (log-SPA), to less complex and less performing variants, logarithm SPA with LUT (log-SPA-LUT), Min-Sum algorithm (MSA), Offset MSA (OMS) and Scaled MSA (SMS) [17]. These algorithms operate by passing message over the LDPC code graph structure, i.e. between variable nodes and check nodes, where one iteration is defined as a back and forth passing message between a variable and check node. Therefore, the algorithms complexity depends on this number of iterations, I_{dec}.

The general block diagram of the data recovery block of a GNSS receiver can be found in Fig. 3 with the concatenation of the demodulator, demapper and decoder where the deinterleaver between demapping and decoding is omitted for simplicity. This generic block is used for the data recovery of a BPSK modulation and a CSK modulation with BICM implementation. However, note that CSK modulations with BICM allows for a more complex and more performing implementation of the data recovery block: to iterate between the demapper and the decoder blocks in order to refine their respective estimations (likelihood ratios and coded bits); this type of implementation is called Bit-Interleaved Coded Modulation with Iterative Decoding (BICM-ID), see Fig. 4, and will also be analyzed in this work. For a more detailed explanation of the BICM-ID data recovery block, the reader is referred to [6][7]. Note that since the LDPC decoding algorithm is iterative by definition, any moment this paper is going to refer to iterative decoding, it is going to refer to the iterative process between the demapper and the decoder (BICM-ID) and the iterations will be denoted as I_{demap}. Nevertheless, note that the decoder can also iterate inside itself (between variable and check nodes); this means that for each iteration between the demapper and the decoder, the decoder can run $I_{dec}^{1-demap}$ internal iterations. In this analysis, for simplification purposes, $I_{dec}^{1-demap}$ is always equal to 1 and thus the total number of decoder internal iterations, I_{dec}, is always equal to the number of demapper iterations, I_{demap}.

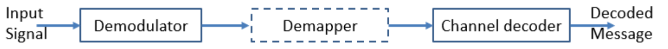

Fig. 3. Block diagram of a generic data recovery block

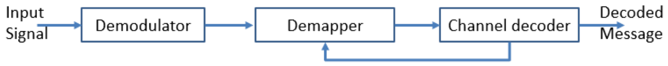

Fig. 4. Block diagram of a generic data recovery block with BICM-ID

A more detailed explanation of the generic structure of the data recovery block can be found in [7].

B. User complexity analysis

In this section, the user complexity analysis of the different candidates is conducted. This analysis consists in determining the number of real additions and multiplication required by the data recovery block. The mathematical formulas used to calculate these numbers can be found in [7]. In any case, the numbers presented in this section should only be used for relative comparison purposes.

There are several algorithms which can be implemented for demapping a CSK modulation and for decoding a LDPC code, but only the most significant ones have been analyzed in this work. TABLE IV. provides the analyzed configurations. QZSS options have not been analyzed. TABLE V. presents the check nodes and variable node average degree used for calculating the complexity of the LDPC decoding algorithm. TABLE VI. presents the number of real additions, real multiplications and binary operations/comparisons which are necessary for each inspected option implementing CSK with BICM decoding (no iterative decoding) and with a number of iterations for LDPC decoding equal to 20 ($I_{dec} = 20$).

TABLE IV. DATA RECOVERY BLOCK ANALYZED CONFIGURATIONS

Modulation	***BPSK***		***CSK***			
Demodulation algorithm	Correlator-Based		Correlator-based		FFT/IFFT-based	
Channel code	CC	LDPC	LDPC	LDPC	LDPC	LDPC
Decoding Algorithm	Viterbi	log-SPA-LUT	BICM	BICM-ID	BICM	BICM-ID
			log-SPA-LUT	log-SPA-LUT	log-SPA-LUT	log-SPA-LUT
Demapper Algorithm	None	log-MAP	log-MAP-LUT	log-MAP-LUT	log-MAP-LUT	log-MAP-LUT

TABLE V. CHECK NODES AND VARIABLE NODES AVERAGE DEGREE

Optimized Code	***BPSK***	***CSK with BICM-ID***	***BICM and BICM-ID trade-off***
Average degree check node	8	4	5
Average degree variable node	4	2	2.5

TABLE VI. SIGNAL CANDIDATES COMPLEXITY ANALYSIS FOR CSK WITH BICM DECODING

Option	Real X per second	Real + per second	Binary operations per second
Baseline	1.02e7	1.03e7	1.6e4
Option 2A	1.02e7	1.04e7	3.2e4
Option 2B	1.02e7	1.05e7	1e5
Option 2C	1.02e7	1.05e7	1e5
Option 3A	6.5e8	6.6e8	2e5
Option 3B	6.5e8	6.6e8	2e5
Option 3C	9.8e8	1.4e9	6.2e6
Option 3D	9.8e8	1.4e9	6.2e6
Option 4A	1.6e8	1.6e8	1.7e5
Option 4B	1.6e8	1.6e8	1.7e5
Option 4C	9.8e8	1.4e9	6.2e6
Option 4D	9.8e8	1.4e9	6.2e6

TABLE VII. BASELINE OPTION COMPLEXITY ANALYSIS

	Demodulator	*Demapping*	*Decoder*
Rx per second	1.023e7	0	0
R+ per second	1.023e7	0	6.4e4
Bin. per second	0	0	1.6e4

TABLE VIII. OPTION 2B COMPLEXITY ANALYSIS WITH $I_{DEC} \approx 5.1$, (FOR C/N_0 = 30 DB-HZ), LOG-MAP-LUT, LOG-SPA-LUT

	Demodulator	*Demapping*	*Decoder*
Rx per second	1.023e7	2e3	0
R+ per second	1.023e7	0	7.91e4
Bin. per second	0	0	2.55e4

TABLE IX. OPTION 3B COMPLEXITY ANALYSIS WITH $I_{DEMAP} \approx 8.3$, $I_{DEC} = 1$ (FOR C/N_0 = 30 DB-HZ), LOG-MAP-LUT, LOG-SPA-LUT

	Demodulator	*Demapping*	*Decoder*
Rx per second	6.55e8	1.6e4	0
R+ per second	6.55e8	1.92e6	9.34e4
Bin. per second	0	7.72e5	3.74e4

TABLE X. OPTION 3B COMPLEXITY ANALYSIS WITH $I_{DEMAP} \approx 2.2$, $I_{DEC} = 1$ (FOR C/N_0 = 32 DB-HZ), LOG-MAP-LUT, LOG-SPA-LUT

	Demodulator	*Demapping*	*Decoder*
Rx per second	6.55e8	1.6e4	0
R+ per second	6.54e8	4.72e5	2.48e4
Bin. per second	0	2.05e5	9.90e3

From TABLE VI. , some conclusions can be extracted. First, comparing baseline and options 2, it can be seen that there is no significant difference between the number of real additions and multiplications. In fact, the only significant difference is found for options 3 and 4 which implement a CSK modulation. Therefore, it can be concluded that the data recovery complexity is driven by the correlator/demodulator block. This means that the additional complexity necessary to implement a LDPC code instead of CC channel code is negligible with respect to the demodulation complexity. Second, it can be observed that the increase of complexity of a CSK modulation with respect to a BPSK modulation is significant for a high number of bits. In fact, the increase of complexity can be summarized as follows:

1) If $U \leq 6$ bits, *Number Operations CSK* $\approx 2^{num\_bits}$ · *Number Operations BPSK.*

2) If $U > 6$ bits:

   a. *Real additions CSK ≈ 110·Real additions BPSK*

   b. *Real multiplications CSK ≈ 100·Real multiplications BPSK*

This difference as a function of the number of bits mapped by a CSK symbol is due to the change of demodulator structure, from a bank of correlator for $U \leq 6$, to a FFT/IFFT block for $U > 6$ (where the driven parameter is the PRN code length, which is fixed).

In order to better represent the additional complexity brought by the demapper and the decoder when implementing a LDPC channel code and a CSK modulation, the complexity analysis is presented individually for each element for some candidates/options. TABLE VII. presents the complexity analysis for the baseline option. TABLE VIII. presents the complexity analysis for option 2B for log-MAP-LUT demapping and log-SPA-LUT decoding; I_{dec} has been chosen equal to 5.1 since this is the average number of iterations required to successfully decode the message when the received signal has a C/N_0 equal to 30*dBHz* (demodulation threshold for SBAS L5/E5a-Q). TABLE IX. and TABLE X. present the complexity analysis for option 3B when using BICM-ID data recovery block structure with log-MAP-LUT demapping and log-SPA-LUT decoding (assuming $I_{dec}^{1-demap} = 1$, $I_{dec} = I_{demap}$); two values for I_{demap} have been used: 8.3 which is the number of demapping iterations required when the received signal has a C/N_0 equal to 30*dBHz*, and 2.2 for a C/N_0 equal to 32*dBHz*.

From these tables, several conclusions can be extracted. First, from TABLE VII and TABLE VIII. , it can be seen that the additional number of operations required to implement a LDPC code instead of a CC is negligible. Therefore, the choice between baseline option and BPSK + LDPC options should be driven by the demodulation performance, data rate increase and receiver evolution cost. From TABLE VII, TABLE IX. and TABLE X. , it can be observed that the inclusion of the CSK modulation will not increase the complexity associated to the decoder; however, the complexity associated to the demapper will. The final relative increase of the demapper complexity will depend on the received signal C/N_0 which will drive the number of iterations required to successfully recover the information

(I_{demap}). Therefore, the final increase of complexity will depend on the percentage of time the received signal is equal to a given C/N_0. For inspected option 3B, real additions per second will increase about ~7~37 times the number of real additions of baseline option, and the number of multiplications will grow from 0 to ~3e4~1.3e5.

C. *Demodulation performance analysis*

In this section, the demodulation performance analysis of the identified signal candidates in section TABLE IV. is presented.

The calculated demodulation performance is set as the calculation of the demodulation threshold, $Threshold$; which is defined as the minimum C/N_0 necessary to obtain a message loss rate of 10^{-3}, $WER_T = 10^{-3}$ (required values for SBAS L5-Q/E5a-Q and traditional targeted value for GNSS navigation messages [6]). This demodulation threshold will be calculated as presented in equation (3) from the WER of the implemented channel code in the presence of AWGN-only when assuming carrier phase tracking without cycle slips, P_w or WER_C, and from the cycle slip rate per second, P_{slip}. Assuming a $P_{slip} = 10^{-5}$, $WER_T = WER_C$. Therefore, demodulation threshold will be calculated as the maximum C/N_0 between the C/N_0 required to obtain a $P_{slip} = 10^{-5}$, and the C/N_0 required to obtain a $WER_C = 10^{-3}$:

$$Threshold = max(C/N_0|_{WER_T=10^{-3}}, C/N_0|_{P_{slip}=10^{-5}}) \quad (5)$$

On one hand, the WER_C of each candidate has been calculated through simulations. The simulations are done through the application of an emulator which generates the correlator outputs (or matched filter outputs) from their mathematical model. The correlator outputs are used to track the carrier phase of the signal and to recover the transmitted information. The implemented PLL is a 3rd order PLL with 10Hz bandwidth and an arctangent discriminator. The carrier phase tracking was conducted on an additional component with SBAS L5-I/E5a-I signal characteristics. The code delay tracking is assumed to be perfectly achieved as well as the word/message synchronization. Log-MAP is used as demapping algorithm and log-SPA is used as decoding algorithm; for an analysis with the other algorithms, the reader is referred to [7]. The error sources affecting the PLL are only AWG noise. On the other hand, in this work, it is assumed that the carrier tracking phase will be conducted in a SBAS L5/E5a-I type of signal, which means that a $P_{slip} = 10^{-5}$ is obtained for a C/N_0 equal to 30 dB-Hz [11].

TABLE XI. presents the demodulation threshold analysis for the inspected candidates; for the inspected candidates implementing a CSK modulation, a BICM-ID data recovery structure was implemented. From this table, it can be seen that an increase of the data rate is possible without any degradation of the demodulation treshold for BPSK candidates (option 2) if a LDPC channel code is implemented. However, this statement is not fulfilled for a CC. From TABLE XI. , it can also be seen that an increase of 3 times the useful data rate with respect to the baseline and without data demodulation threshold degradation is possible when implementing a CSK modulation with a BICM-ID structure (options 3B and 3D). Moreover, the latency can be reduced to a 0.5s instead of 1s with a slight threshold degradation (options 3A and 3C). It can also be observed that the increase of the data rate with respect to the baseline for values equal or higher than 4 is only possible with a degradation of the demodulation threshold, around 1dB. Finally, QZSS options provide a lower data increase and a worse demodulation threshold degradation performance than options 4. Therefore, CSK modulation with LDPC channel code and BICM-ID data recovery structure is a better solution than QZSS options in terms of demodulation performance. However, a user complexity analysis should be conducted to complete the comparison.

D. *I_{GNSS} evaluation*

The I_{GNSS} term represents the increase of the efficient noise power density, N_0, called efficient N_0, $N_{0,eff}$, due to the global, regional and SBAS systems transmitting in the frequency band of interest. The methodology used to evaluate the I_{GNSS} term is described in [20].

TABLE XI. SIGNAL CANDIDATES DEMODULATION PERFORMANCE ANALYSIS FOR CSK WITH BICM-ID DATA RECOVERY STRUCTURE WITH LOG-MAP DEMAPPING AND LOG-SPA DECODING

Option	C/N_0 $WER_T = 10^{-3}$	C/N_0 $P_{slip} = 10^{-5}$	C/N_0 *Threshold*
Baseline	28.2*	30	30
Option 2A	31.2	30	31.2
Option 2B	29.6	30	30
Option 2C	29.4	30	30
Option 3A	30.05	30	30.05
Option 3B	29.75	30	30
Option 3C	30.15	30	30.15
Option 3D	29.9	30	30
Option 4A	31.3	30	31.3
Option 4B	30.9	30	30.9
Option 4C	31.2	30	31.2
Option 4D	30.7	30	30.7
QZSS A	31.5	30	31.15
QZSS B	31.45	30	31.45

* Perfect carrier phase tracking

TABLE XII. COMPLETE RECEIVER COMPLEXITY ANALYSIS COMPARISON

Option	DF SBAS Rx	DF SBAS Rx + Baseline	DF SBAS Rx + Option 3	DF SBAS Rx + Hybrid Option
Demodulation *ℝx/s and ℝ+/s*	28.03e7	30.07e7	158.97e7	94.52e7
Increase wrt baseline Rx inspired from DFMC MOPS	1	~1.1	~5.7	~3.4

Moreover, note that in addition to the I_{GNSS} term, there are other RF sources, such as DME/TACAN, JTIDS/MIDS, case emissions, PED, etc, [18] which also increase the effective N_0. In fact, note that these other RF sources are not intentionally searching to harm the processing of a L5 navigation signal but rather to provide its own service; however, they are still considered as interference sources from the processing of a L5 navigation signal (as well as the I_{GNSS} term).

The calculation of the I_{GNSS} term will depend on the power allocated to the SBAS L5-Q/E5a-Q component and more precisely, on the maximum allocated power. This remark is very important because whereas the maximum allocated power is used to calculate the generated intra/inter-interference term, I_{GNSS}, the minimum allocated power is used to calculate the received signal power on the C/N_0 link budget calculation. Therefore, in order to reduce the impact of the introduction of a new SBAS L5-Q/E5a-Q component, the optimal scenario consists of allocating the same minimum power as for the SBAS L5-I/E5a-I and of allocating, if possible, a lower maximum power than the maximum power allocated to SBAS L5-I/E5a-I. In fact, note that if less minimum power than the one of SBAS L5-I/E5a-I is allocated to SBAS L5-Q/E5a-Q, the C term in section III.B will not be the same as for the SBAS L5-I/E5a-I signal and thus the proposed methodology in section III.B could not be applied: the link margin will be further decreased and thus, analyzed signal candidates should have a derived threshold increased, with respect to 30*dBHz*, by the power allocation difference to have an equivalent worst demodulation situation for components SBAS L5-I/E5a-I and SBAS L5-Q/E5a-Q. TABLE XIII. presents the different power allocations considered in this analysis.

Fig. 5 presents the I_{GNSS} calculation worldwide when SBAS L5-Q/E5a-Q has not been implemented. Fig. 6 and Fig. 7 present the difference between the I_{GNSS} when SBAS L5-Q/E5a-Q has not been implemented and when SBAS L5-Q/E5a-Q has been implemented respectively with 25% and 100% of maximum power allocation with respect to SBAS L5-I/E5a-I maximum power. From these figures, it can be seen that the maximum degradation of I_{GNSS} is found over Africa with a value equal to 0.63dB for the 100% case and 0.16 for the 25% case. The variation of I_{GNSS} must now be translated into variation of efficient N_0. Simplifying the scenario and assuming that the I_{GNSS} term is the only term of interference, equation (6) shows the impact of the I_{GNSS} increase in the final $N_{0,eff}$.

$$N_{0,eff} = 10 \log_{10}\left(10^{\frac{N_0}{10}} + 10^{\frac{I_{GNSS}+Increase}{10}}\right) \quad (6)$$

From equation (6), taking the I_{GNSS} value at Asia (maximum I_{GNSS} value) or at Africa (maximum variation), it can be seen that the degradation of $N_{0,eff}$ is at most 0.25dB for the 100% case and at most 0.07dB for the 25% case. However, it must be remembered that in the presence of the additional interference this degradation term will be further reduced.

Finally, remembering the definition of "very limited impact" given in section II.A, degradation of the link margin of 0.1dB at most, it can be concluded that:

- Since in section V.C, demodulation threshold equal or lower than 30dB-Hz were obtained, the 25% maximum power allocated case allows to introduce a SBAS L5-Q/E5-Q component and fulfill objective 3.
- Objectives 4 and 5 are fulfilled for the 25% maximum power allocated case which allows to introduce a SBAS L5-Q/E5-Q.
- For the 100% case, a finer analysis should be conducted.

TABLE XIII. SBAS L5/E5A SIGNAL POWER ALLOCATIONS

Scenario (Power Allocation Percenatge)	SBAS L5-I/E5a-I		SBAS L5-Q/E5a-Q		SBAS L5/E5a
	Min Power (dBW)	Max Power (dBW)	Min Power (dBW)	Max Power (dBW)	Maximum Power (dBW)
100/0	-158	-150.5	---	---	-150.5
100/100	-158	-150.5	-158	-150.5	-147.5
100/25	-158	-150.5	-158	-156.5	-149.5

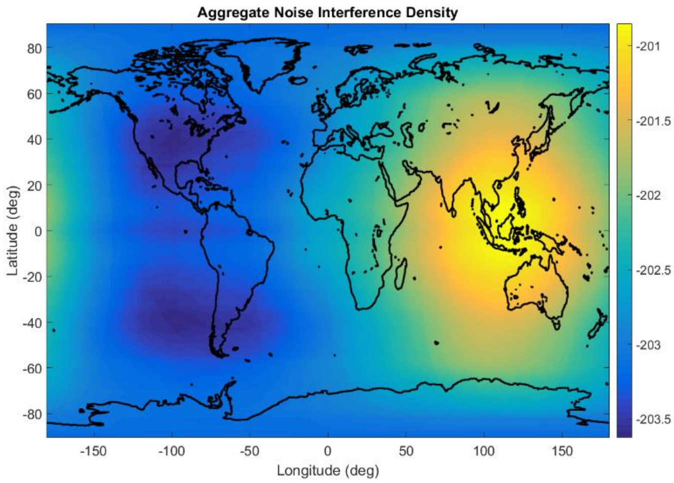

Fig. 5. I_{GNSS} evaluation for the L5/E5a band without SBAS L5-Q/E5a-Q

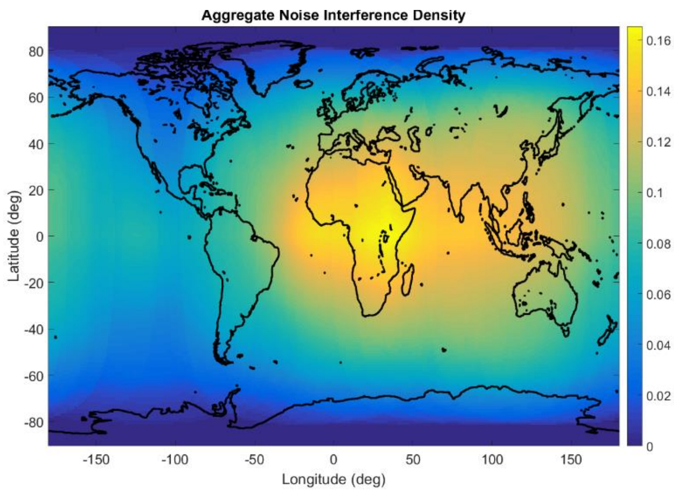

Fig. 6. Differential I_{GNSS} evaluation for the L5/E5a band with SBAS L5-Q/E5a-Q having 25% of maximum allocated power

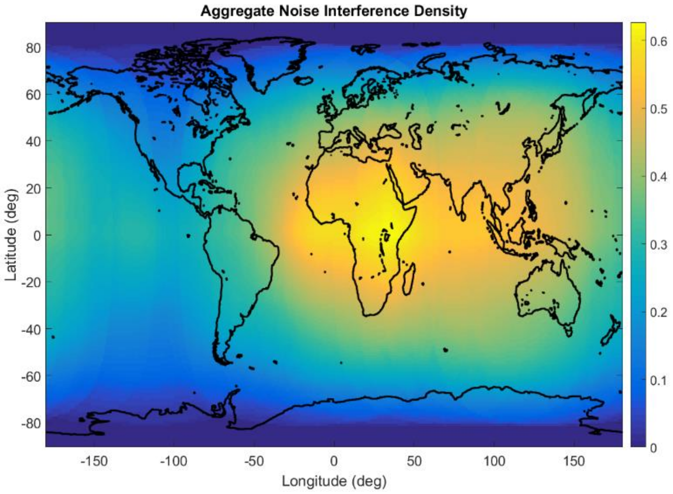

Fig. 7. Differential I_{GNSS} evaluation for the L5/E5a band with SBAS L5-Q/E5a-Q having 100% of maximum allocated power

VI. Signal Candidates Discussions

1) Baseline vs Options 2B and 2C (BPSK + LDPC): Baseline and options 2B and 2C present about the same complexity, dominated by the demodulation process, with only a slight increase of complexity in the demapping and decoding process for options 2B and 2C. However, these options are able to provide twice the data rate of the baseline option while maintaining the same demodulation threshold; and even option 2B is able to reduce the latency from 1s to 0.5s. Therefore, for SBAS L5-Q/E5a-Q and E5b signal components, options 2B or 2C are recommended in comparison to baseline option.

2) Baseline, options 2 vs Option 3A, 3B, 3C and 3D (CSK + LDPC): Baseline option is less complex than options 3 due to the higher number of operations necessary to demodulate a CSK modulation. The increase of complexity is about 64 times higher. Nevertheless, this complexity increase must be weighted with respect to the total complexity of the receiver: the total number of SBAS signals in-view is very low in comparison with the number of core constellation satellites in view. For example, assuming a legacy Dual Frequency receiver with 12 GPS satellites in-view (e.g. 12 GPS L1 C/A or GPS L1C signals, 12 GPS L5-I signals and 12 GPS L5-Q signals) and with 2 SBAS satellites in view (2 SBAS L1 signals and 2 SBAS L5/E5a-I signals), the increase of complexity brought by the processing of a new SBAS L5-Q/E5a-Q or SBAS E5b is summarized in TABLE XII. (only demodulator complexity is taken into account). From this table, it can be seen that the introduction of a new component with the baseline structure will increase the receiver complexity 1.1 times the initial value, whereas for option 3 structure it will increase around 5.7 times which is quite reduced with respect to the one-to-one component comparison (set to 64). Moreover, this increase of complexity is further reduced if Galileo satellites are considered (12 Galileo E1-B signals, 12 Galileo E1-C signals, 12 Galileo E5a-I signals, 12 Galileo E5a-Q). Finally, option 3 is able to increase the data rate 3 times without (or slightly) degrading the demodulation threshold. Therefore, for SBAS E5b signal component, options 3A or 3B are recommended if the receiver is able to accept a small overall increase of the complexity. Note that option 3A presents a slightly demodulation threshold degradation but allows to reduce the latency from 1s to 0.1s. If not, options 2B and 2C are recommended.

3) Baseline, options 2 vs Options 4 (CSK + LDPC): As well as options 3, options 4 have a complexity about ~75 to ~100 times higher than the baseline option (in one-to-one comparison). However, this complexity increase is mitigated when taking into account the complete complexity of the receiver (as in options 3 case). Moreover, options 4 always introduce a demodulation threshold degradation with respect to the baseline. Therefore, options 4 (or options with even higher data rate increases) are recommended for SBAS E5b signal component only if a very high data rate is required (higher or equal than 1000 information bits/s). If lower data rates are acceptable, options 2 or options 3 are recommended.

4) Options 4 vs QZSS options: QZSS options provide about the same data rate as options 4 (around ~1000 information bits) with a worse demodulation threshold. Therefore, except if QZSS options show to have a significant lower complexity than options 4, options 4 are recommended for SBAS E5b signal component if high data rates are targeted.

5) Baseline vs Hybrid options (BPSK/CSK + LDPC): Hybrid options, for example Time Multiplexing with the first half second implementing option 2B and the next half second implementing option 3A or 4A, are very interesting. On one hand, receivers aiming at keeping a low complexity will obtain the same data rate as for the baseline case but with half the complexity (in one-to-one component comparison) since they will have to process only half of the signal. On the other hand, receivers accepting an increase of the receiver complexity (about ~3.4, see TABLE XII.) could benefit from a higher data rate (more services or services with better performance) with the same demodulation threshold as the baseline option. Therefore, Hybrid options are the most recommended candidate for SBAS E5b.

VII. Conclusion

In this work, several signal candidates' structures for SBAS E5b and SBAS L5-Q/E5a-Q were presented. The proposed candidates were chosen to have the same PRN code characteristics as Galileo E5b and E5a signals, and GPS L5 signals in order to facilitate the interoperability between SBAS and core constellation systems: a PRN code length of 10230 chips with a chip rate of 10.23 Mchips/s for a code period of 1ms.

The candidates were compared using signal performance, divided into needs (data rate increase and latency) and constraints (user complexity and demodulation performance). Additionally, the I_{GNSS} term, used to compute the compatibility of the potential new SBAS L5-Q/E5a-Q component, was analyzed.

It was shown that the signal candidates introducing the BPSK modulation with the LDPC channel code provided twice the data rate whilst maintaining the same demodulation threshold. The latency was halved from 1s to 0.5. The complexity with respect to the baseline candidate remained unchanged.

Signal candidates introducing the CSK modulation with the LDPC channel code and the BICM-ID data recovery structure were shown to provide up to 3 times the data rate without demodulation threshold degradation with respect to the baseline candidate. Higher data rates can only be obtained with a cost of demodulation threshold degradation. In both cases, the price to pay is an increase of the receiver complexity driven by the increase of the number of operations required by the demodulator. Nevertheless, the total increase of the receiver's complexity would be mitigated by the fact that user usually tracks only two SBAS satellites. If the user is transiting between two SBAS providers, four SBAS satellites are tracked. This is a negligible number with respect to the total amount of tracked core constellations satellites and signals (GPS L1 C/A or GPS L1C, GPS L5-I and L5-Q, Galileo E1, Galileo E5a-I and E5a-Q). Note that CSK candidates may not be a valid option for SBAS L5-Q/E5a-Q component since current and near future satellites may not be prepared for its implementation.

Hybrid candidates were shown to be a very attractive trade-off option. On one hand, hybrid candidates allow the exploitation of SBAS signal component by low complexity users with half the complexity of the baseline candidate with the same data rate and with the same demodulation threshold. On the other hand, receivers accepting a higher signal processing complexity would be able to obtain higher data rates than the baseline candidate with equal or worse demodulation threshold (depending on the data rate increase).

Finally, the impact of the SBAS L5-Q/E5-Q component introduction on the compatibility (intra/inter-interference) depends on the maximum power being allocated to the new component. If the maximum allocated power is 25% of the maximum power allocated to SBAS L5-Q/E5a-Q, the link margin degradation is smaller than 0.1dB (and probably much less).

Future work will consist of refining the demodulation performance calculation by introducing clock imperfections and signal dynamics of an aircraft during the phase tracking operation. Moreover, the compatibility analysis performed by I_{GNSS} calculation will be further evaluated by taking into account the difference between BPSK and CSK modulation. Further analysis of the location impact and other RF sources (DME/TACAN, JTIDS/MIDS, etc) can be also envisioned.

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