Universal-SBAS: A Worldwide Multimodal Standard

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Abstract—**This paper describes a generalisation of the aeronautical GNSS Space Based Augmentation System (SBAS) air interface, in a true worldwide multimodal standard named Universal S-BAS. Examples of usages of this multifrequency future standard are presented in the area of science and precise positioning, timing, security, robust positioning, maritime and reflectometry applications.**

Keywords : SBAS, GPS, GLONASS, GALILEO, COMPASS, GINS, Science, Precision, U-SBAS, EGNOS, NSGU, frequency, WAAS, QZSS, IRNSS, SDCM, PCW, ionosphere, GNSS

I. INTRODUCTION

Several studies have been done or have been started in order to extend the current aeronautical Space Based Augmentation System (SBAS), called DO-229D Minimum Operational Performance Specification (MOPS) SBAS standard mainly defined by the US Radio Technical Commission for Aeronautics (RTCA, Inc) corporation, Sub-Committee 159, Working Group 2. The SBAS message is transmitted by geostationary satellites using a modulation scheme similarly to GPS wherein the same Gold code family, chipping rate, BPSK modulation of the same GPS carrier frequency of 1575.42 MHz with the difference being that a 500 bps bit stream is also modulated instead of the 50 bps data stream as in GPS. The 500 bps data stream is symbol bits which encode a 250 bps SBAS data stream, containing messages such as satellite integrity and differential corrections. These messages are documented in Appendix A of RTCA/DO-229D, which also serves as the Signal-In-Space (SIS) Interface Control Document (ICD) for SBAS. RTCA/DO-299D has been adopted by ICAO and has become the ICAO aeronautical SBAS standard. As an international standard, aeronautical SBAS can be adopted by any state. Aeronautical SBAS main purpose was to provide near real-time GNSS integrity world-wide. That concept evolved to also providing differential corrections and optionally a ranging signal. In addition, every aeronautical SBAS service provider has the ability to certify and then designate his service for Safety-of-Life (SoL) service. Once certified as a SoL service, the respective aeronautical SBAS service provider would also transmit the appropriate messages and data indicating that the particular transmission (and data) can be used for SoL applications. Data within the aeronautical SBAS message indicate over which regions the differential messages can be used. Aeronautical SBAS is capable of supporting LPV (Localizer with Precision Vertical) approaches to about 66 meters minimums. These are CAT-I ILS equivalent approaches. For further technical details, the reader is referred to the RTCA/DO-229D MOPS.

The idea of the worldwide multimodal Universal-SBAS (U-SBAS) standard is that it could be used in all the regions of the world, by all the civil aviations of the world, but also by all other types of non-aeronautical Safety of Life (SoL) users, and in-addition by non-SoL users of any countries. The worldwide multimodal U-SBAS standard could carry additional channels (signals and messages) to cover the non-aeronautical specific SoL services, and also High Precision Positioning Services (HPPS), Position Velocity Time (PVT) authentication services, safety services, scientific application services, High Precision Timing Services (HPTS), etc. Since the aeronautical and non-aeronautical SoL services would be carried out by the U-SBAS multimodal worldwide standard, the privileged bands addressed by this standard should be a priori all the ARNS/RNSS bands (Aeronautical Radio Navigation Service/Radio Navigation Satellite Service), that is 1164-1215 and 1159-1610 MHz. This standard shall be open to (and compatible with) GPS/WAAS (Wide Area Augmentation System), GLONASS/SDCM (System of Differential Correction and Monitoring), GALILEO/EGNOS (European Geostationary Navigation Overlay Service), COMPASS, QZSS/MSAS, IRNSS/GINS/GAGAN (Indian Radio Navigation Satellite System/Global Indian Navigation System/GPS And Geo Augmented Navigation), and potential other GNSS systems using L band. Backward compatibility with the current and validated L1-C/A SBAS aeronautical standard should be mandatory to avoid modification of the existing single frequency SBAS receivers. The services including robust governmental cryptography would be excluded from the SBAS multimodal worldwide standard. The multimodal worldwide U-SBAS standard is suggested to be elaborated at international worldwide level. As in the field of wireless mobile communication, many researches are under progress to develop a universal broadband communication system (a future version of WiMax or LTE), the universal SBAS standard will facilitate the continuity of service when the client changes the country or the area of the globe. Also the cost of services will be greatly reduced by ensuring automatic switching receivers.

II. PROPOSED DEFINITIONS AND WAY FORWARD

The international U-SBAS multimodal standard covers systems using GNSS payload overlaying one or several GNSS constellations in Medium Earth Orbit (MEO). The U-SBAS multimodal payloads take part of regional GNSS, and the related orbits are therefore geosynchronous in a way to permanently cover the region for which the multimodal services are provided. These multimodal U-SBAS orbit could therefore be Geostationary (GEO), Inclined Geo Stationary Orbit (IGSO), or Highly Elliptical Orbit (HEO) used by QZSS (Elliptical and Inclined GeoSynchroneous Orbit: EIGSO [1]) and closed to the so called "Tundra Orbit" [2] introduced by Russia. One or several SBAS-multimodal system(s) could be also the basis and the first step for a future worldwide national or multinational worldwide "MEO +GEO +IGSO" GNSS system, following the approach of EGNOS+GALILEO, GAGAN+IRNSS+GINS, BEIDOU-1+BEIDOU-2/COMPASS, etc. One U-SBAS-multimodal system could also overlay one or preferably 2 or 3 MEO constellations, when it is implemented in the frame of the evolution of a GNSS MEO system, like GLONASS-K or GPS IIF-GPS III.

The way forward to use a multimodal worldwide SBAS standard could be for each region to extract « à la carte » from the worldwide U-SBAS multimodal standard 1, 2, 3 or 4 SBAS frequency(ies)/modulation(s) necessary to cover optimally its needs. The multinational worldwide SBAS standard "encapsulate" the aeronautical SBAS standard, and provide other services (like the one described in the introduction) not covered by the SBAS frame. This multimodal worldwide SBAS standard could be named U-SBAS (Universal SBAS) for instance as mentioned before.

International names to the ARNS/RNSS bands are suggested:

$\mathbf{B_A1}$: 1164 -1188 MHz $\mathbf{B_A2}$: 1188 -1215 MHz
$\mathbf{B_A3}$: 1559 -1591 MHz $\mathbf{B_{A4}}$: 1591 -1610 MHz

Only those bands can support the aeronautical and non-aeronautical SoL services, and the navigation-only component of these services. At least one GNSS MEO system is occupying each of the 4 ARNS/RNSS bands. It is suggested that at least one of the selected band of each U-SBAS system be part of the ARNS bands of the eventual parent GNSS MEO system, in order to ease the compatibility of the mentioned U-SBAS with the receivers processing signals of the said parent GNSS system. International names to the RNSS-RDSS (Radio Determination Satellite System) bands which are not ARNS are suggested:

$\mathbf{B_{NA}1}$: 1215-1240 MHz $\mathbf{B_{NA}2}$: 1240-1260 MHz
$\mathbf{B_{NA}3}$: 1260-1300 MHz $\mathbf{B_{NA}4}$: 2483.5-2500 MHz

It has to be noted that the region 3 (Russia, Asia, Australia, …) of International Telecommunication Union (ITU) is already open for RDSS-RNSS, which should be open in the world (regions 1, 2 & 3 of the ITU) with a PFD (Power Flux Density) limit to be defined after the WRC (World Wide Conference) in 2012 [4], [33]. No risk of global harmful interferences to RDSS GNSS signal in $\mathbf{B_A3}$ band has been identified in interference system studies [4]. Of course, the risk of some local interference is common to all the eight $\mathbf{B_Ai}$ and $\mathbf{B_{NA}i}$ bands. The following table describes the band-usages by the current and planned GNSS systems, as understood from the public information available to the authors. It has also to be added to this table (which concern the MEO GNSS having a global coverage and the related regional systems) that the next generation of GALILEO has an option alternative or complementary to the $\mathbf{B_{NA}4}$ band, that is currently the C-band 5.01-5.03 GHz option [33], but with only a regional directional coverage for power budget reasons.

TABLE 1: UNDERSTOOD BAND-USAGES OF THE CURRENT AND PLANED GNSS SYSTEMS

	Band name	**B_A1**	**B_A2**	**$B_{NA}1$**	**$B_{NA}2$**	**$B_{NA}3$**	**B_A3**	**B_A4**	**$B_{NA}4$**
	Frequency range (MHz)	1164 -1188	1188 - 1215	1215-1240	1240-1260	1260-1300	1559 - 1591	1591 - 1610	2483.5-2500
MEO GNSS systems (global converage)	GPS (IIF, III-A)	X		X			X		
	GLONASS (current)				X			X	
	GLONASS K-initial		X		X			X	
	GLONASS K-final	X (option)	X		X		X (option)	X	
	GALILEO (current)	X	X			X	X		
	GALILEO 2	X	X			X	X		X (option)
	COMPASS-initial (14 –tbc- 1st SVs)		X			X	X		
	COMPASS-final (15th -tbc- and follow up SVs)	X	X			X	X		X (option)
	GINS	X	X (option)				X (option)		X
Regional GNSS systems	WAAS (current)	X(experiment)					X		
	WAAS-final	X (option)					X		
	MSAS	X (option)					X		
	QZSS	X		X		X	X		
	ETS VIII (experiment)						X		X
	GAGAN	X					X		
	IRNSS	X					X (option)		X
	SDCM						X		
	BEIDOU-1								X
	EGNOS (current)						X		
	EGNOS NG	X (option)	X (option)				X		
	SNAS								
	Malaysian SBAS								
	Korean SBAS								
	PCW	X (option)	X (option)			X (option)	X (option)		

From Table 1 it appears that the more often chosen GNSS bands are $\mathbf{B_A1}$, $\mathbf{B_A2}$ and $\mathbf{B_A3}$ for ARNS, and, $\mathbf{B_{NA}3}$ and $\mathbf{B_{NA}4}$.

Some of the information provided in Table 1 are detailed and commented hereafter:

GPS III system will have its first satellites till 2014. GPS is the first and more widely used GNSS system. GPS III (block III-A) bands are the GPS II-F bands, i.e. $\mathbf{B_A1}$, $\mathbf{B_{NA}1}$ and $\mathbf{B_A3}$ [56]. A signal option in $\mathbf{B_{NA}3}$ at 1278 MHz was sometimes mentioned for GPS III evolutions and this band has been filed by the United States of America for GPS potential evolutions.

It is worth noting that L/S-band frequency was selected for low-cost radio development (commercial wireless technology) in a GPS II F Search And Rescue (SAR) low cost design study involving a 2.4 GHz downlink [39]. In the Caribbean and South American Countries, the Caribbean and South American Test Bed (CSTB) is based on WAAS (Wide Area Augmentation System), covering USA and a part of Canada.

The Polar Communication and Weather (PCW) Canadian satellite project will include two spacecrafts in Molnya orbit to cover Artic regions, with an optional GNSS payload on board, possibly compatible with EGNOS-Evolution and GALILEO signal formats [76], [77].

In 2007, Russia issued a decree outlining the matters of GLONASS applications [7]. Russia promotes governmental users mandatory equipped with combined GLONASS/GPS receivers [7]. More than 10 types of on board GLONASS/GPS receivers are developed in Russia for civil aviation [7], and several GLONASS/GPS/GALILEO simulators are manufactured in Russia [27]. Russian civil aviation authorities mount these receivers on board some aircrafts [7]. The GLONASS-K bands filled by the Russian Federation at ITU in $\mathbf{B_A2}$ are close to approximately 1196-1212 MHz. Russia apparently did not filed a GLONASS band in $\mathbf{B_A1}$ and $\mathbf{B_A3}$. Russia is developing SDCM (System for Differential Correction and Monitoring), using 2 GEO satellites.

GAGAN is the Indian early SBAS system, using dual frequency $\mathbf{B_A1}$ and $\mathbf{B_A3}$ payloads, the next to be launched being on board of at least GSAT-8 and GSAT-9 geostationary satellites [40]. The IRNSS (Indian RadioNavigation Satellite System) will have $\mathbf{B_A1}$ and $\mathbf{B_{NA}4}$ as core frequency bands [40]. The core IRNSS constellation will be made of 3 geostationary satellites, and 4 IGSO satellites. The Global Indian Navigation System (GINS) worldwide system will follow up.

For the 2013-2016 period, the Chinese Aeronautical Association (CAAC) considers using Compass [8]. For the period 2017-2025, the CAAC will use multi-system GNSS receivers, including consideration of using Compass [8]. The CAAC plans to equip the aircrafts with GNSS navigation system to implement RNP-4, RNP-2, RNAV-2, RNAV-1, RNP-1, RNP APCH and other operations. GNSS receivers compatible with Compass will be the preferred navigation system for future Chinese general aviation [8]. The Compass-initial and Compass-final frequencies are presented in [13], [34]. The Beidou-1 RDSS geostationary satellites transmit a downlink GNSS signal in $\mathbf{B_{NA}4}$ band [4], [38]. China prepares SNAS (Satellite Navigation Augmentation System) [51]. China also made a CAPS-V1 navigation experiment [57, 58], using a telecom repeater of retired satellites [57] originally on GEO orbit and now in SIGSO (Slightly Inclined GeoSynchroneous Orbit), to test BOC and BPSK navigation signal performances [58]. The used frequency is close to 3.8 GHz and is not in a RNSS band for the CAPS-V1 experiment. China and Nigeria deploy NIGCOMSAT-1 geostationary satellite provided with a $\mathbf{B_A1}$-$\mathbf{B_A2}$-$\mathbf{B_A3}$ repeater, as in some other geostationary satellites like the one hosting the future EGNOS repeaters [75]. NIGCOMSAT-1 has a suboptimal coverage of Nigeria and of a part of China.

In Europe, the GNSS constellations generally preferred for future aeronautical navigation are GPS and GALILEO, and a symmetrical situation is expected in the USA. More details on possible evolutions of EGNOS, presently broadcasting a SARPs compatible channel at $\mathbf{f_A3}$ frequency, are given in a next paragraph. A frequency evolution is related to the $\mathbf{B_A1}/\mathbf{B_A2}$ band extension decided on ARTEMIS GEO spacecraft replacement [35]. In the frame of standards evolution, standardisation of $\mathbf{B_A1}$ and $\mathbf{B_A2}$, and $\mathbf{B_A3}$ MBOC is ongoing [35]; augmentation of new GNSS systems is under study [35]. An example of new additional service is the possible critical communication message (ALIVE concept) [35]. The current EGNOS C/A signal at $\mathbf{f_A3}$ frequency has an “entry of service” planned for mid-2010, for an expected life time of 20 years [35]. The 1256-1260 MHz upper band portion of $\mathbf{B_{NA}2}$ has been filed by Europe.

In Japan, the MSAS system planned an expansion of the used $\mathbf{B_A3}$ band width portion for the future [32]. QZSS will not only transmit in $\mathbf{B_A3}$ band C/A and MBOC navigation signals, but also a third signal, named SAIF (Sub-meter class Augmentation with Integrity Function), compatible with ICAO SARPs [1]. QZSS will have the advantage to transmit on four frequencies [32] to cover a wide variety of services [32]. The ETS VIII geostationary satellite provides a navigation in time experiment using navigation PN codes in $\mathbf{B_A3}$ and $\mathbf{B_{NA}4}$ bands [30], [31].

In Malaysia, an SBAS system is under study, for a development phase planned between 2011 and 2015 [41].
In Korea, the development of a GNSS Augmentation System has also been studied [42].

III. ARNS FREQUENCIES AND MODULATIONS

Generic frequencies for a future worldwide SBAS standard could cover, for the aeronautical and non-aeronautical SoL and other services like:

- aeronautical applications (and covered non-aeronautical SoL applications),
- some precise positioning-time service (HPPS, HPTS, …) providing a positioning accuracy better than 10 cm, which can be SoL or non-SoL,
- science applications (described in a later paragraph),
- integrity of ARNS or non-ARNS channels, …
- broadcast of small command messages eventually encrypted by the customers provided with remote platforms having GNSS receivers on board,
- etc …

These generic frequencies could be:

- f_A1: 1176.45 MHz or close
- f_A2: in the range 1204 - 1208 MHz preferably 1207.14 MHz or close
- f_A3: 1575.42 MHz or close
- f_A4: in the range 1604-1608 MHz preferably 1606.11 MHz or close

Generic modulations for a future worldwide SBAS standard could be, for the SoL and other services

- At f_A1: **QPSK(10)** or **QPSK(2)** or **QPSK(1)** (or **BOC** to cope with PFD limit mentioned later on) or equivalent with time multiplexing
- At f_A2: **QPSK(1)** or **QPSK(2)** or **QPSK(4)** or **QPSK(5)** or **QPSK(10)** or equivalent with time multiplexing
- At f_A3: **BPSK(1)** [legacy] eventually multiplexed with **BPSK(1)** or **MBOC** or **BOC(1,1)**
- At f_A4: **MBOC** or **BOC(1,1)** or **QPSK(0.5)** or **QPSK(1)** or **QPSK(2)** or ?

If QPSK or BOC signals are used simultaneously at f_A1 and f_A2 or at f_A3 and f_A4, they could be combined using an ALTBOC signal structure.

The interest of a multi-signal multimodal SBAS standard is to provide some kind of frequency diversity, and therefore more robustness to unintentional interferences and multipath. For instance, a f_A3-C/A code combined to a BOC(1,1) or a MBOC signal provides such robustness useful for multimodal SoL services. It has to be noted that the GPS III system will offer such robustness at L1 frequency, which it could be good also for future multimodal SBAS systems to reach. For instance, if a narrow band involuntary interference (like a CWI or a spectrum line resulting from transmission harmonics) "falls" in the middle of the main spectral lobe of the BPSK(1) signal, such an interference would not be at the same time in the middle of the BOC(1,1) or MBOC main spectral components. This multi frequency approach could provide resistance against some types of intentional jamming, when all the frequencies are not jammed at the same time. This way, unintentional but also some intentional interferences could be avoided.

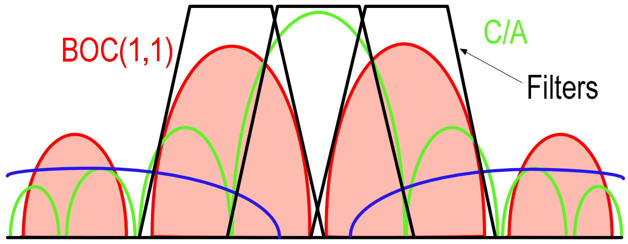

Figure 1. Possible MBOC F_A3 U-SBAS channel, and possible receiver digital filtering (not to scale)

It has to be noted that the bandwidth of the modulation at f_A3 frequency has to be limited, in order not to spectrally overlap significantly the GPS M code signal and the GALILEO PRS signal, which are very sensitive and not interoperable with other signals, and have the anteriority in their allocation at the ITU [35].

The data rates for the ARNS channels involving SoL in a future worldwide SBAS standard could be:

- R_A1: 25 bits/s to 250 bits/s (not more, due to ARNS ground aids and other transmissions, other pulsed interferences and more generally, robustness to interferences).
- R_A2: 25 bits/s to 250 bits/s (not more, due to ARNS ground aids and other transmissions, other pulsed interferences, and more generally, robustness to interferences).
- R_A3: 250 bits/s for the BPSK(1) legacy f_A3-C/A SBAS aeronautical standard: the goal is no changes in the current validated aeronautical standard since there is a real need for backward interoperability. For the multiplexed new multimodal component suggested to be added, the data rate should be also 250 bits/s as a maximum.
- R_A4: 25 bits/s to 250 bits/s, for the same reasons of robustness to interferences in general.

N. B.: The legacy 250 bits/s data rate is also proposed in order not to increase the transmitted power too much in a given frequency band, and to preclude from an overshoot of the multi RNSS system aggregated PFD limit in the 1164-1215 MHz band (-121.5 dBW/m2/MHz) agreed at UNO/ITU level, in order to protect the aeronautical ground navigation aids like DMEs (Distance Measurement Equipment) from armful interference coming from the GNSS systems. In other words, the higher the rates in B_A1 and B_A2 would be, the higher the transmitted power would be for a given energy per bit, and therefore the higher the risk of overshooting the mentioned PFD limit would be. This aggregated PFD limit is for 5 degrees: -122.46 dBW/m2/MHz, and for 1 degree: -122.34 dBW/m2/MHz. Moreover, it can be noted that in the B_A1 band, the PFD limit is very close to be reached. To protect the aeronautical ground navigation aids, it is recommended for the current systems in that band, and for the new systems having already declared a signal in B_A1, to stick with the current or declared power, without any power increase, and to care about their signal spectral shape. For new systems envisioning the use of B_A1, quite low power should be used in case of a BPSK or QPSK signal. More power could be transmitted in case of a

BOC signal, whose maximum energy is not placed in the central frequency, where the PFD limit issue dramatically appears. Before and during coordination meetings regarding the $\mathbf{B_A1}$ and $\mathbf{B_A2}$ bands at ITU level, UNO members accepting evolutions of current systems, or new systems, which creates an overpass of the PFD limit, would take the responsibility of endangering the ARNS ground services in these bands.

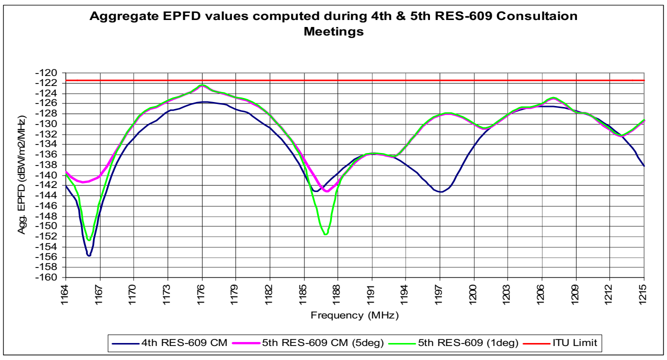

Figure 2. Aggregate EPFD values computed during RES-609 ITU consultation meetings for B_A1 and B_A2 bands

There is also a serious issue related to high level of intersystem GNSS interferences in the $\mathbf{B_A3}$ band, which is already congestioned (Table 1). Inter GNSS system noise degradation computations in this band show a critical situation [44], with an equivalent noise level in $\mathbf{B_A3}$ that will be so high before 2020 as 8.5 dB above a thermal noise of -204 dBW/Hz, just considering GPS, GALILEO and COMPASS presently declared transmitted powers [44]. Moreover, this critical degradation doesn't take into account the case of quasi-stationary C/A codes, subject to an extra C/No degradation which can reach 0.5 dB [37].

IV. NON ARNS FREQUENCIES AND MODULATIONS

Non ARNS frequencies and modulations can be useful for future multimodal SBAS, for:

- some precise positioning-time service (HPPS, HPTS, …) providing a positioning accuracy better than 10 cm,
- science applications (described in a later paragraph),
- non-SoL applications (integrity of non-ARNS channels, …),
- broadcast of small command messages encrypted by the customers provided with remote platforms having GNSS receivers on board,
- etc …

Generic frequencies for a future worldwide SBAS standard could be, for the non-SoL services:

- $\mathbf{f_{NA}1}$: 1227.60 MHz or close,
- $\mathbf{f_{NA}2}$: in the range 1240-1260 MHz preferably 1248,06 MHz,
- $\mathbf{f_{NA}3}$: 1278,75 MHz or close,
- $\mathbf{f_{NA}4}$: 2491 MHz or close (N.B.: $\mathbf{f_{NA}4 = 2{*}f_{NA}2}$**;** it is very interesting for carrier phase ambiguity resolution, due to a huge augmentation of the narrow lane wavelength which could provide a very important advantage).

Generic modulations for a future worldwide SBAS standard could be, for non-SoL services:

- At $\mathbf{f_{NA}1}$: **BPSK(1)** assuming time multiplexing of pilot and data channels,
- At $\mathbf{f_{NA}2}$: **QPSK(2)** or **QPSK(4)** or **QPSK(5)** or …
- At $\mathbf{f_{NA}3}$: **QPSK(2)** or **QPSK(4)** or **BPSK(5)** or **QPSK(5)** assuming data/pilot time or phase multiplexing,
- At $\mathbf{f_{NA}4}$: **QPSK(1)** or **QPSK(1.23)** or **QPSK(2)** or **QPSK(4)** or … [4]

It has to be noted that the already the most used modulation at $\mathbf{f_{NA}3}$ is QPSK(5) (QZSS, GALILEO, …), which can be combined with another QPSK(5) signal thanks to several possible multiplexing techniques (time multiplexing, phase multiplexing, ALTBOC multiplexing, etc …). A BPSK(1)-like time multiplexed modulation already exists at $\mathbf{f_{NA}1}$ for QZSS.

It has to be also noted that the bandwidth of the modulation at $\mathbf{f_{NA}1}$ and (resp. $\mathbf{f_{NA}3}$) frequency has to be limited, in order not to spectrally overlap significantly the GPS M code signal (resp. PRS signal), which are very sensitive and not interoperable with other signals, and have the anteriority on other GNSS systems in their allocation at the ITU.

The goal of the multimodal SBAS standard would be to reduce as far as possible the number of standardized modulations per frequency, but a very limited number of remaining modulation per frequency (1, 2 or 3 for example) should be acceptable. Moreover, in most of the non-commercial space radio link standards, like in the CCSDS (Consultative Committee for Space Data Systems) the number of standardized modulations is generally not one, but 2 or 3. The suggested multimodal worldwide U-SBAS standard is therefore in line with the international normalisation logic, and the technological evolution trends, which goes toward highly digital and flexible GNSS receivers.

The data rates for the ARNS channels involving "non-SoL only" services in a future worldwide SBAS standard could be:

- $\mathbf{R_{NA}1}$: between 50 bits/s (like for the BPSK(1) $\mathbf{f_{NA}1}$ QZSS operational standard) and 2000 bits/s,
- $\mathbf{R_{NA}2}$: between 50 and 2000 bits/s,
- $\mathbf{R_{NA}3}$: between 50 and 2000 bits/s (like for the BPSK(5) $\mathbf{f_{NA}3}$ QZSS Lex signal at 2000 bits/s),

- $R_{NA}4$: between 50 and 2000 bits/s.

V. PAYLOAD AND RANGING ISSUES

The interest of using transparent repeaters in high altitude orbits came originally from several needs:

- to rent or build a payload while the coding, PN-codes, and message structure of the SBAS signal(s) weren't finalized,
- to minimize complexity of the space segment, even if the impact is a complex ground segment.

The transparent payloads presents however several inconveniences:

- The servo-loop of the long loop through the Navigation Land Earth Station (NLES) and the said transparent payloads creates non-Gaussian phase noise which decreases the accuracy of the carrier phase measurements.
- The code/carrier divergence at the output of the payload is not perfect, and fluctuates with time.
- The code phase itself has some extra-residual errors.
- On board the satellite, the signal pass through a reception antenna and a transmission antenna, this situation being more complicated to keep signal quality during spacecraft attitude manoeuvres, than with a single transmitting antenna.
- It is also more complicated to keep the long loop signal quality during spacecraft orbital manoeuvres, than with an on board signal generation.
-The phase noise of the on board oscillator involved in the transparent repeater is generally higher than in the case of generative navigation payloads.

Moreover, time has passed, and the interest of using transparent payloads could vanish if some guidelines which could be implemented in the worldwide multimodal U-SBAS standard are taken into account:

- 1) The U-SBAS on board standardized NSGU (Navigation Signal Generation Unit) are compatible with:

- 1a) SoL and non-SoL modulations mentioned above, or finally the modulations which could be finally retained in the worldwide SBAS standard,
- 1b) SoL and non-SoL data rate mentioned above, or finally the modulations which could be retained in the worldwide SBAS standard,
- 1c) Every type of navigation message and coding, including high performance coding like free versions of LDPC (Low Density Parity Check) Chanel Coding (CC). This means that the message and the related coding(s) are elaborated outside the standardized SBAS NSGU.
- 1d) On board memories implemented in the NSGU allows storing any type of periodical PN code, with a maximum length which has to be defined in the U-SBAS standard.
- 1e) The NSGU design should be compatible with user defined potential SBAS authentication services.
- 1f) The NSGU is driven by a rubidium clock for instance or at least an Ultra Stable Oscillator (e.g. quartz USO), thus allowing the SBAS ground segment to upload not so often clock coefficients describing the on board clock drift. Of course, if a scientific experiment involving stable clocks in orbit take part of the mission, such a clock ("cold atom", "optical", etc) could be added.

- 2) The message and coding upload ground segment is simplified:

- 2a) In the case of a proprietary satellite, the U-SBAS on board NSGU receives the navigation/integrity/HPPS/… message and the coding from the On Board Computer (OBC), itself receiving these informations from the standard Telecommand station of the used high altitude satellite (GEO, IGSO, Tundra, etc). In other world, there is no need any more for each SBAS satellite of a specific NLES (Navigation Land Earth Station) in that case.
- 2b) In the case of a multimodal U-SBAS payload offered for rental by a satellite operator, this operator has also to provide (in addition to the NSGU) an on board receiver, to collect the navigation/integrity/HPPS/… message and coding coming from a small station replacing the NLES, using one of the 2 RNSS uplink bands standardized at ITU: $\mathbf{B_{up}1}$ = 1300-1350 MHz (L band, quite large), or $\mathbf{B_{up}2}$ = 5000-5010 MHz (C band, not so large). RNSS C band $\mathbf{B_{up}2}$ uplink multichannel receivers have already been developed for GALILEO, QZSS and other GNSS programs. RNSS L band $\mathbf{B_{up}1}$ uplink multichannel receiver has also already been manufactured [10], [11] for GEO missions, to provide significant performance improvement by the introduction of pseudolite-tracking and message demodulation capability at $\mathbf{f_{up}1}$ frequency ($\mathbf{f_{up}1}$ = 131x10.23 = 1340.13 MHz), these receivers being able to simultaneously track $\mathbf{f_{up}1}$ and $\mathbf{f_A3}$ C/A data-modulated signals [10, 11]. The interest for the satellite operator is that this RNSS uplink receiver can be also used as a pseudolite (and eventually GNSS) receiver for timing and navigation purposes of the spacecraft itself [11], [12]. An on board production of time and orbital ephemeris can therefore be broadcasted to the multimodal SBAS users, alternatively or complementary to the on-ground ODTS production (Orbit Determination and Time Synchronisation). Moreover, the accuracy of the on board ODTS can be improved thanks to the architecture shown in Fig. 3, where pseudorange and phase measurements made on GNSS monitoring receivers co-localized with the uplink stations are retransmitted toward the SBAS satellites, to be combined to the measurements made on the uplink signal. This combination can form true ranging and velocity measurements, if the receivers and generators, on board (Fig. 4) and on the ground, are connected to the same frequency references (Fig. 3 and Fig. 4) and if they use a calibration loop (Fig. 4) [12]. Of course, the one-way measurements are still usable for synchronization purposes. Moreover, the ODTS performed thanks to the downlink navigation signals can be compared to the ODTS made with the measurements using the uplink signals, the comparison

between both types of measurements providing integrity informations.

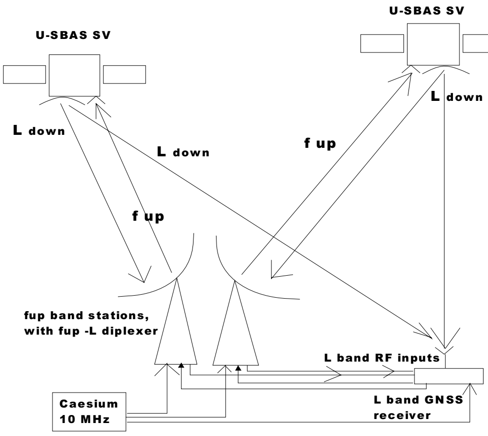

Figure 3. Possible RF ground architecture of a SBAS system provided with on board signal generators

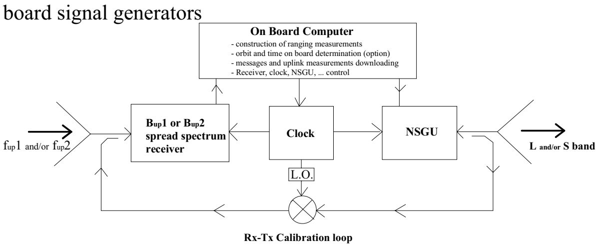

Figure 4. Possible U-SBAS payload architecture

VI. FULL SIGNAL OF A U-SBAS SYSTEM

The full signal of a multimodal SBAS system comprises the signals covering the SoL aeronautical services and other services enabled by the same signals, and the signals covering eventual non-aeronautical SoL services and other services not covered by the first signals. This could be illustrated thanks to the example of EGNOS evolutions presently studied in Europe [35]:

The current EGNOS signal is compatible with the SBAS aeronautical standard, validated like GPS and GLONASS C/A codes in the SARPs (Standard And Recommended Practices) at ICAO (International Civil Aviation Organisation of the UNO). In addition to this C/A code signal at $\mathbf{f_A3}$, three optional signals are under consideration, the related basic signal-service matching plan being illustrated in Fig. 5:

- The first option is a CBOC [35] or BOC(1,1) signal at $\mathbf{f_A3}$ frequency [35], multiplexed with the legacy signal, as described in Fig. 1 and the related paragraph. This signal would provide a kind of frequency diversity, more global transmitted power while spreading the PFD, and would allow the $\mathbf{f_A3}$ EGNOS channel to cope with the GPS-3 $\mathbf{f_A3}$ channel. This option could carry ranging, and authentication features, and a HPPS message providing accuracy better than 10 cm.

- The second option is a QPSK(10) signal at $\mathbf{f_A1}$ frequency. It would likely complement the aeronautical legacy signal.

- The third option is a QPSK(10) signal at $\mathbf{f_A2}$ frequency [35]. This option would provide frequency diversity in the lower bands ($\mathbf{B_A1}$, $\mathbf{B_A2}$) [5]. This option could carry ranging, authentication, and a HPPS message. An example of HPPS technique is given in [6], [36]: a technique invented by CNES mentioned later on in this paper allow a real time robust positioning accuracy close to one centimetre [4], if three frequency bands are used:
- to allow simultaneous phase measurements without cycle slips on 2 carriers,
- to retrieve the high orders of the ionospheric delay.

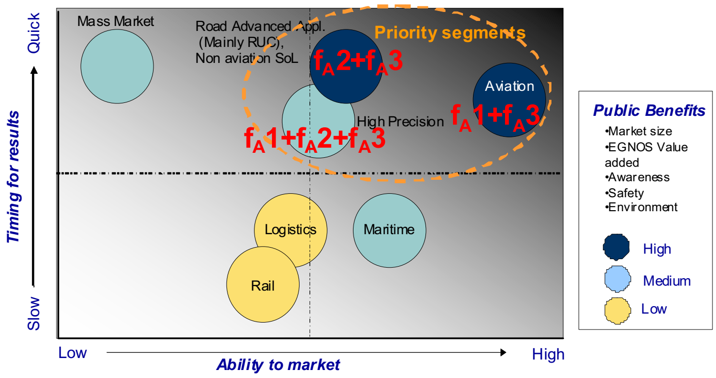

Figure 5. Possible service/signal plan of EGNOS evolutions

In order to preserve all the mentioned options during the system and radiofrequency architecture studies, the rent of two 3-ARNS frequency $\mathbf{f_A1+f_A2+f_A3}$ geostationary repeaters (so called "GEO-1" and "GEO-2") has been ordered by Europe. The "GEO-1" EGNOS payload will be located on SIRIUS 5 satellite, which will be launched in the second half of 2011 to 5 degrees East. The "GEO-2" EGNOS payload will be hosted on the ASTRA 5B satellite, to be launched in 2013 and positioned at 31.5 degrees East. Some details on the SIRIUS 5 $\mathbf{B_A1+B_A2/B_A3}$ payload are given in [75]. Experimentations of new services should be initially performed thanks to this 3-frequency repeater. What is interesting to notice is that the rental cost of a "GEO-1" $\mathbf{f_A1+f_A3}$ repeater would have been very close to the choosen $\mathbf{f_A1+f_A2+f_A3}$ repeater, due to the proximity of $\mathbf{f_A1}$ and $\mathbf{f_A2}$. Moreover, the cost of a $\mathbf{f_A1+f_A2+f_A3}$ radiofrequency long loop through the NLES (Navigation Land Earth Stations) and the repeater can be very close to the one of a $\mathbf{f_A1+f_A3}$ long loop, when wise architectures are chosen. Inversely, the rental cost of a single frequency repeater is significantly cheaper than the one of a multi-frequency repeater, except in the case of close frequencies, like, for instance $\mathbf{f_A1+f_A2}$ or $\mathbf{f_A3+f_A4}$. In multimodal EGNOS hosting spacecraft following "GEO-1" and "GEO-2", a 3- or 4-frequency on board Navigation Signal Generative Unit (NSGU) is aimed in order to offer with EGNOS the same accuracy and robustness advantages than GALILEO. An onboard NSGU avoids signal imperfections created by the use of in-orbit transparent repeater, and simplify the ground segment

VII. SOME MESSAGE AND CODING ISSUES

The legacy (7, ½) convolutional message coding of the legacy aeronautical SBAS standard at $\mathbf{f_A3}$ has of course to be kept for backward compatibility reasons, since already many civil aviation aircrafts are equipped with aeronautical SBAS receivers. However, it is proposed to adopt free versions of LDPC CC not only for new multimodal SBAS signals, but also for the evolving worldwide GNSS systems, following a suggestion of India [3], USA and ESA [9]. GNSS represents one service in which standardization for FEC and Interleaving would go far in ensuring a better interoperability of systems.

This worldwide standard would allow multimodal U-SBAS to overlay the 10 following constellation pairs: GPS/GLONASS, GPS/GALILEO, GPS/COMPASS, GPS/GINS, GLONASS/GALILEO, GLONASS/COMPASS, GLONASS/GINS, GALILEO/COMPASS, GALILEO/GINS, COMPASS/GINS.

It allows to overlay the 10 following constellation triplets: GPS/GLONASS/GALILEO, GPS/GLONASS/COMPASS, GPS/GLONASS/GINS, GLONASS/GALILEO/COMPASS, GLONASS/GALILEO/GINS, GLONASS/COMPASS/GINS, GALILEO/COMPASS/GPS, GALILEO/GINS/GPS, GALILEO/COMPASS/GINS, GALILEO/GLONASS/GINS.

How the different constellations could be overlaid by international multimodal SBAS is described hereafter: Each SBAS channel could broadcast integrity and/or navigation and/or authentication and/or precise positioning and/or other messages related to 2 constellations at one given constellation frequency for each of the two constellations. Table 3 and Table 4 would have therefore to be explored.

TABLE 2: EXAMPLE OF FREQUENCY ALLOCATION OF DUAL CONSTELLATION U-SBAS SERVICE

1 frequency per line	GPS	GLONASS	GALILEO	COMPASS	GINS
Constellation 1, frequency **a**		$\mathbf{f_A2}$			
Constellation 2, frequency **b**				$\mathbf{f_A2}$	

The following examples could be given:

Constellation 1: **GPS**; frequency **a** = $\mathbf{f_A3}$ = 1575.42 MHz;
Constellation 2: **GALILEO**; frequency **b** = $\mathbf{f_A3}$ = 1575.42 MHz.

Constellation 1: **GINS**; frequency **a** = $\mathbf{f_A1}$ = 1176.45 MHz;
Constellation 2: **COMPASS-final**; frequency **b** = $\mathbf{f_A1}$ = 1176.45 MHz.

Constellation 1: **GLONASS-K-initial**; frequency **a** = $\mathbf{f_A2}$: inside 1204-1208 MHz range;
Constellation 2: **COMPASS-initial**; frequency **b** = $\mathbf{f_A2}$ = 1207.14 MHz.

Alternatively, the message in a single SBAS channel could broadcast integrity and/or navigation and/or authentication and/or precise positioning and/or other messages for a single constellation, but for two frequencies of the given constellation:

TABLE 3: EXAMPLE OF FREQUENCY ALLOCATION OF A SINGLE CONSTELLATION DUAL FREQUENCY SBAS SERVICE

1 frequency per line, frequency in only one column	GPS	GALILEO	GLONASS	COMPASS	GINS
Constellation frequency 1	$\mathbf{f_A1}$				
Constellation frequency 2	$\mathbf{f_A3}$				

Examples:

- Constellation: **GPS**; constellation frequency 1: $\mathbf{f_A1}$ = 1176.45 MHz; constellation frequency 2: $\mathbf{f_A3}$ = 1575.42 MHz.

- Constellation: **GLONASS-K-initial**; constellation frequency 1: $\mathbf{f_A2}$ between 1204 and 1208 MHz; constellation frequency 2: $\mathbf{f_A3}$ **=**1595-1610 MHz.

One U-SBAS frequency channel can be used to broadcast constellation-related information (integrity and WADGNSS or precise positioning and time, etc) for:

- 1 constellation and 2 frequency bands,
- or 2 constellations with 1 frequency band each.

Two U-SBAS frequency channels can be used to broadcast the same constellation-related information (integrity and WADGNSS, or precise positioning and time, etc) for:

- 2 constellations and 2 frequency bands,
- 1 constellation and 2 frequency bands, another constellation and one frequency band, and other services,
- 1 constellation and 3 frequency bands, and 1 other constellation with 1 related frequency band,
- 1 constellation and 3 frequency bands, and 1 other service,
- 3 constellations and 1 frequency band, and 1 other service,
- or 4 constellations and 1 frequency band.

Three U-SBAS frequency channels can be used to broadcast the same constellation-related informations (integrity and WADGNSS, or precise positioning and time, etc) for:

- 3 constellations and 2 frequency bands,
- 2 constellations and 3 frequency bands,
- 1 constellation and 3 frequency bands, 1 other constellation and 2 frequency bands, and 1 other service,
- 1 constellation and 4 frequency bands, 1 other constellation and 1 frequency band, and 1 other service,
- or 4 constellations and 1 frequency band, 2 other constellations with 1 related frequency band,
- etc …

One of the U-SBAS frequency channel can be partly used to broadcast (or multicast) small safety and/or navigation related messages to be received by mobile users provided with a GNSS receiver, and certain to stay in the regional coverage of the concerned U-SBAS satellite(s). For mobile users which can navigate everywhere in the world, or even in Low Earth Orbit, the use of MEO worldwide GNSS systems is more appropriate for this type of small messaging. In any case, the small messaging service customer would address its messages (encrypted or not) to the U-SBAS or MEO GNSS system control center. The encrypted messages (multicast) could be used only by authorized users, to receive some reactive telecommand or orders or informations, to be processed by the GNSS receiver itself or one of its related application layer on board the user mobile platform. The small messages broadcasted in “clear” could be exploited by any GNSS receiver taking into account the public Interface Control Document related to these open messages. Examples of U-SBAS small messaging usages are given in the “Robust and secured navigation” paragraph.

VIII. SCIENCE AND PRECISE POSITIONING

The « fix » aspect of a geostationary satellite above the Earth surface, or the « quasi-fix» feature of a Tundra-like or a IGSO orbit is very interesting for science applications, like ionospheric observations and related earthquake signatures, and very accurate positioning or timing for instance. In that respect, QZSS and the possible EGNOS and IRNSS evolutions toward a 3-frequency system are good examples. For ionospheric sciences, to benefit from a quasi-fix “control point” in the ionosphere allows calibration of ionospheric tomographic and cartographic applications.

Such “quasi-fix” triple or quadruple frequency RNSS “satellite → station” links [63] allows to perform fine monitoring of low temporal variations of the ionosphere coming, for instance, from gravity wave [63] having diverse causes, like seismic or tsunaminic origins. An ionospheric earthquake potential precursor can be monitored accurately without discontinuity during several days thanks to geostationary multifrequency signals complementing signals coming from MEO satellites [64].

These at least trifrequency links allows to measure accurately the second order terms (term in $1/f^3$) of the ionosphere [16], [61], [79]. This issue is not only important for science or operational ionospheric applications, but also for operational precise positioning applications, especially the ones targeting an accuracy better than 10 cm, thanks to HPPS coefficient broadcasting in $\mathbf{B_A2}$ or $\mathbf{B_{NA}3}$ for instance. The interest of at least trifrequency multimodal SBAS for such precise positioning applications is clearly shown hereafter. Moreover, 3-frequency links allow for better retrieving the second order term variations [16], [61], [62], [79], in order to better observe ionospheric delay variations, and therefore tropospheric delay variations for meteorological or climatologic applications.

Such links [63] also allow to measure the polarization of the signals received, and therefore the Faraday effect [63], linked like the second order terms, to the terrestrial magnetic field.

Maintaining a terrestrial reference frame at a level that allows the determination of global sea level changes at the sub-millimeter per year level, pre-, co-, and post-seismic displacement fields associated with large earthquakes at the sub-centimeter level, timely early warnings for earthquakes, tsunamis, landslides, and volcanic eruptions, as well as the monitoring of mass transport in the Earth system at the few Gigatons level will be possible in the future. Over long-term studies, while plate tectonics and reference frame determination are presently done at the centimeter level, future millimeter-level deformations will allow further geophysical studies such as intraplate deformation and silent earthquakes. In real time, safety services could also involve surveillance of earthquake and tsunaminic events through centimetric monitoring of the ionosphere thanks to “fixed” paths between the geostationary multimodal SBAS satellites and a network of MEO+SBAS GNSS receivers [64]. For instance, QZSS, in association with other GNSS systems observable from Asian regions, will be used for a “disaster management” experiment [43], involving tsunami and earthquake monitoring [43], GNSS meteorology, and emergency broadcast via QZSS [43].

GNSS observations are presently used to monitor the Earth’s ionosphere and troposphere targeting the high-end GNSS user community and scientific applications by taking advantage of the GNSS data available in the international services such as IGS (International GNSS Service). Already with first order terms TEC (Total Electron Content) maps estimated using the GNSS data with high resolution in time and space allow for instance to evidence small structures in the ionosphere. The use of second order terms will further increase the accuracy of these products mainly used for space weather. In order to show the importance of the ionospheric second order term for science and precise positioning, some computations and measurements of the contribution of this term has been performed thanks to a GPS receiver at $\mathbf{f_{NA}1}$ and $\mathbf{f_A3}$ frequencies. These measurements made during one week in October 2003 (Fig. 6, 7, 8, and Fig. 9 [64]) show errors close to or larger than 10 cm during one several-day ionospheric perturbation, corresponding to an augmentation of the planetary magnetic index during the perturbation.

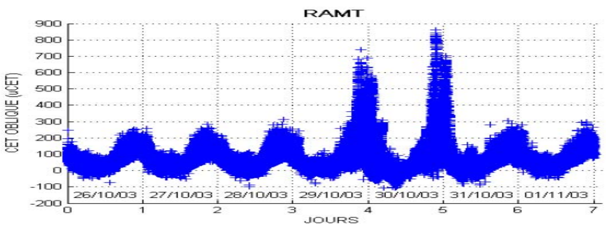

Figure 6. Oblical Total Electronic Content at RAMT station (USA), during a ionospheric perturbation

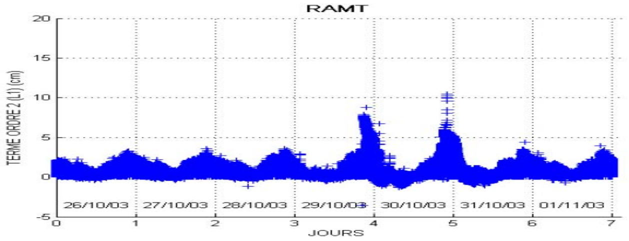

Figure 7. Ionospheric 2nd order pseudorange term at fA3 GPS frequency calculated for the RAMT station

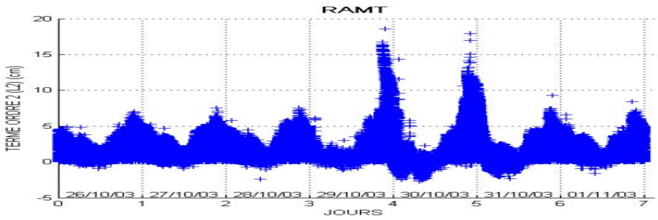

Figure 8. Ionospheric 2nd order pseudorange term at fNA1 GPS frequency calculated for the RAMT station

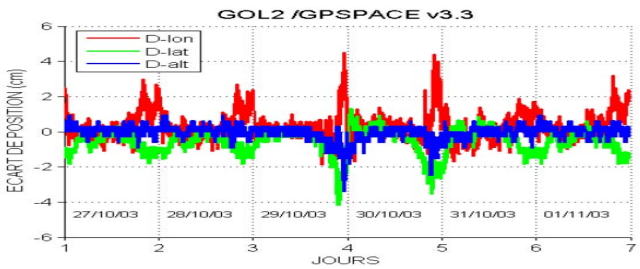

Fig. 9: GPS positioning error at GOL2 station without including the 2nd order ionospheric pseudorange term

Fig. 9 represents the positioning error made in neglecting the 2nd order ionospheric term if all the other parameters (receivers and clock biais, satellites orbits) were determined rigourously by means independent from the ionosphere.

The artic and antartic regions, present like the equatorial regions, some challenges to GNSS due to ionospheric irregularities. The large scale scintillation regions can be thousands of kilometres in extent. An ultra violet auroral imager could be used in conjunction with a 3 or 4 frequencies GNSS payload on board U-SBAS satellites covering these regions, to provide real time informations on the location of ionospheric disturbance, GNSS errors bounds to specify to users, and other real time space weather accurate informations

Another very important usage of future multimodal SBAS systems is to deliver precise positioning on a wide area, for Earth exploration using airborne gravimeter or gradiometer for example, using the broadcasting of HPPS coefficients. QZSS plans to broadcast a precise positioning message at $\mathbf{f_{NA}3}$ frequency, like GALILEO. Studies for the EGNOS evolutions consider broadcasting of such coefficients at $\mathbf{f_{A}2}$ frequency. These coefficients could use Integer Ambiguity Resolution on Undifferenced Phase (IARUP) [6], [14], or possible equivalent techniques, which will allow very precise positioning accuracies close to one cm in real time (Fig. 10).

To keep accuracy close to a few centimeters in real time for operational HPPS services, the involved techniques requires permanent phase tracking of at least two carrier frequencies at the same time. Since cycle slip could occur on a carrier at a given dates, at least 3-carrier tracking is required to ensure continuity of dual carrier phase tracking.

The 3-carrier tracking also allows retrieving the second order term due to the ionosphere.

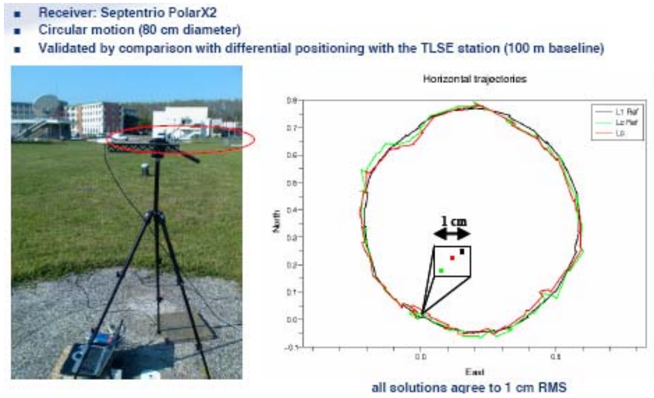

Figure 10. Example of accuracy close to 1 cm provided by IARUP using GPS signals at fNA1 and fA3 frequencies.

What is interesting to mention regarding the robustness of such HPPS services is the case of ALTBOC signals, for instance in $\mathbf{B_A1}$ and $\mathbf{B_A2}$, or $\mathbf{B_{NA}2}$ and $\mathbf{B_{NA}3}$, or $\mathbf{B_A3}$ and $\mathbf{B_A4}$. In the case study of an ALTBOC signal with main lobes at $\mathbf{f_A1}$ and $\mathbf{f_A2}$, 3 frequencies are actually available at the receiver level: $\mathbf{f_A1}$, $\mathbf{f_A2}$, and ($\mathbf{f_A1}$ +$\mathbf{f_A2}$)/2. In that case, if such an ALTBOC signal is associated to a signal at an upper band, like $\mathbf{B_A3}$, $\mathbf{B_A4}$ or $\mathbf{B_{NA}4}$, four frequencies would be actually available at the receiver level, providing, like the 4-frequency QZSS system, all the robustness necessary to procure continuous and accurate HPPS service. In addition, accurate ionospheric correction can be made ALTBOC signal [15] or equivalent multiplexing schemes like complex-LOC or complex-BOC [26], even if the upper frequency band is subject to interference [5], [15] or to cycle slips for instance. Another interest of triple or quadrifrequency MEO+U-SBAS tracking is the initialization time of the centimeter level precise positioning solution. This initialization time for carrier phase ambiguity resolution can be several minutes with two frequencies only, and much shorter with 3 or 4 frequency tracking, paving the way for truly robust real time centimetric positioning. Using multifrequency SBAS measurements, very high level of accuracy can be reached not only on position but also on velocity and acceleration measurements in real-time onboard an airplane, for example, with a worldwide coverage. Actual commercial airborne gravimeters are limited to about 5 Eotvos (5 x 10^{-9} m/s^2/m), but all the actual technologies are limited to RTK ranging and precisions and GPS-INS high grade resolution. Experiments have shown that none of the existing single-frequency SBAS system can give the targeted 1 Eotvos precision [48]. Triple or quadruple frequency MEO+U-SBAS tracking has also a big interest for very accurate real-time positioning of maritime platform, up to the centimetric level. U-SBAS maritime usages will help improve navigation, operations, traffic management (Vessel Traffic Service), seaport operations, inland waterways, casualty analysis, offshore exploration, exploitation and fisheries, and tug boat guidance [78].

Multimodal SBAS systems compatible with the suggested worldwide U-SBAS standard could serve the clock and time scientific community, providing a system allowing synchronisation, tracking and fine comparisons of clocks in the world, and to observe very accurately and permanently spaceborne clock drifts.

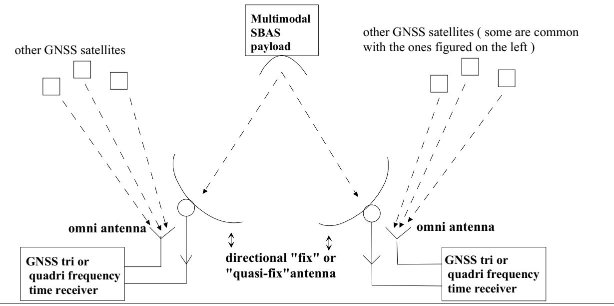

Figure 11. Very accurate time/frequency transfer using Multimodal SBAS+MEO one way common views

JAXA was a precursor in this area, thanks to the ETS VIII GNSS experiment (Table 1), which allowed to evaluate the behaviour, the accuracy and the stability of several atom clock types in geostationary orbit, and to synchronize different clocks, thanks to L and S band experimental GNSS signals [30], [31]. At the moment, opportunities to test the more stable clocks (like “miniaturized cold atom” or “optical” clock) in geostationary or quasi-stationary geosynchronous are very rare, despite the ideal situation of these type of orbit from the scientific point of view, since it allows clock tracking continuity for the short, mid and long terms, with only a few ground stations. The ACES (Atomic Clock Ensemble in Space) experiment, to be run in a few years on board the International Space Station (ISS) will give first results with the first cold atom clock in orbit (connected to a specific wide band spread spectrum microwave link) but will face inconveniences like non-continuous tracking and microvibration issues, 90 min thermal cycles, etc … specific to the Low Earth Orbit (LEO). The next paragraph will show how non-specific U-SBAS-based microwave links (one way, two ways) can be used for on board stable clock experiments, and clock synchronisation precise services.

The first U-SBAS precise timing application is very accurate common views, thanks to small GNSS antenna dishes pointed toward geostationary spacecrafts (Fig. 11), without needing any tracking device for the antennas in the case of geostationary U-SBAS payload. The GNSS-time stations (Fig. 11) are therefore made of a GNSS receiver provided with one omnidirectional antenna (Fig. 11) and one or several small antenna dish(es). This GNSS receiver will make datation (i.e. pseudorange) and phase (integrated pseudovelocity) measurements to use the “GNSS phase” synchronisation techniques [28], [29], [52], thanks to the omnidirectional antenna. Interest for using simultaneously several frequencies, like for instance $\mathbf{f_A1}$, $\mathbf{f_A2}$ and $\mathbf{f_A3}$ [60] for very accurate timing applications is underlined [60]. The present requirement for the clock precision and stability is at the level of the nanosecond over one day. The use of phase measurements in addition to code measurements and the use of all data instead of common view data have allowed improvement of the time transfer. Even combined solutions by using both code and phase measurements of geodetic receivers are used presently, which enhances the precision and accuracy of time transfer. Development of software (such as R2CGGTTS) has allowed this at present getting the CGGTTS files (file with a format compiled by the CCTF Group on GNSS Time Transfer Standards (CGGTTS), where CCTF stands for Consultative Committee for Time and Frequency) and the ionospheric free code P3 and based on C/A measurements in addition to the P code in order to detect and disregard bad satellite orbits [53], [54]. This GNSS receiver will also make very accurate time and phase measurements thanks to the antenna dish(es), which will benefit from the carrier phase ambiguity resolution made through the omnidirectional antenna. Three or four frequencies are necessary to retrieve high-order ionospheric effects, and to reduce globally the measurement errors. The antenna dishes reduce a lot the effects of multipath, and of RF interferences. The tropospheric delay could be accurately estimated thanks to specific processing of the GNSS raw measurements made through the omnidirectional antenna, which could be even improved thanks to an hybridization with measurements coming from one (or several) low cost lidar(s) (or equivalent device) pointed into the direction of the used U-SBAS signal(s), like the antenna dishes. The potential of antenna dishes to reduce the measurement noise due to thermal noise is analysed hereafter:

The measurement performance for each frequency due to thermal noise (without taking into account the non calibrated bias) for high C/No ratios are for Pseudo Range [BPSK signals or BOC(1,1), or (ALT)BOC signals excepted BOC(1,1)], and for Pseudo velocity is given by:

$$\sigma_{PRBPSK_{th}}(m) = \frac{c}{R_c}\sqrt{\frac{B_c d}{2\, C/N_0}} \qquad \textbf{(1)}$$

$$\sigma_{PR_{BOC(1,1)th}}(m) = \frac{c}{R_c}\sqrt{\frac{B_c d}{6\, C/N_0}} \qquad \textbf{(2)}$$

$$\sigma_{PR(ALT)BOC_{th}}(m) = \frac{c}{2\pi}\sqrt{\frac{B_c}{L_{corr}\, C/N_0\, F_{sc}^2}} \quad \textbf{(3)}$$

$$\sigma_{PV_{th}}(m/s) = \frac{c}{\sqrt{2}\pi f_e T}\sqrt{\frac{B_n}{C/N_0}} \quad \textbf{(4)}$$

These simplified equations implies the carrier loop noise bandwidth $\mathbf{B_n}$, and the PN code loop noise bandwidth $\mathbf{B_c}$, the carrier frequency $\mathbf{f_e}$, the subcarrier frequency $\mathbf{F_{sc}}$ when present, the correlation losses $\mathbf{L_{corr}}$, and the chip spacing **d** for the BPSK and BOC(1,1) processing considered here. The term **c** is the speed of light, and $\mathbf{R_c}$ the chipping rate.
The quadratic terms are neglected since the **C/No** ratio is considered high here. The average gain of an omnidirectional antenna is 0 dB, which is 1 in the linear domain. The typical gain of a parabolic dish having a 1 meter diameter is 20 dB, at a considered average L band frequency of 1.3 GHz. This gives a linear gain of 100. The improvement factor for the time (pseudorange) and phase thermal noise standard deviation is therefore 10 according to the previous formula, compared to the use of an omnidirectional antenna. The typical gain of a parabolic dish having a 2 meter diameter is 26 dB at 1.3 GHz. This gives a linear gain of 398. The improvement factor for the time (pseudorange) and phase thermal noise is therefore 20. Higher antenna diameters are possible if necessary. Since majority of the time GNSS receivers are presently $\mathbf{B_{NA}1}$ **-** $\mathbf{B_A3}$ BPSK(10) GPS receivers, some improvements are also possible with ALTBOC or equivalent wide band signals. An extra improvement factor of 2 (resp. 4) is possible with a receiver processing only the ALTBOC subcarrier (resp. fully or about the total bandwidth of the ALTBOC signal). Therefore, very important improvement factors are allowed for precise time and synchronisation services by a multimodal SBAS with 3 or 4 frequencies, in term of thermal noise, ionospheric high order corrections, multipath, and interference mitigations.

If the code loop discriminator is of the dot-product power type, the general expression for the code tracking noise standard deviation for AltBOC and BPSK modulation is (expressed in meters):

$$\sigma_{code-AltBOC} = cT_c\sqrt{\frac{B_L(1-R(d))}{2\alpha C/N_0 K^2}\left(1+\frac{1}{\alpha C/N_0 T_{int}}\right)}$$

$$\sigma_{code-BPSK} = cT_c\sqrt{\frac{B_L d}{2C/N_0}\left(1+\frac{1}{C/N_0 T_{int}}\right)}$$

Where:
- *d* is the Early-Late chip spacing;
- *R(d)* is the autocorrelation function evaluated at '*d*';
- T_c is the chip duration;
- T_{int} is the pre-detection integration time;
- *c* is the speed of light;
- B_L is the DLL loop bandwidth in Hz;
- C/N_0 is the carrier to noise ratio of the signal;
- α is the power sharing factor for the ALTBOC four signal components (e.g. for the pilot only channel $\alpha = 0.25$);
- *K* is the slope of the autocorrelation function evaluated at *d*/2, *K* = 9 for AltBOC(15,10) and *K*=30 for AltBOC(15,2).

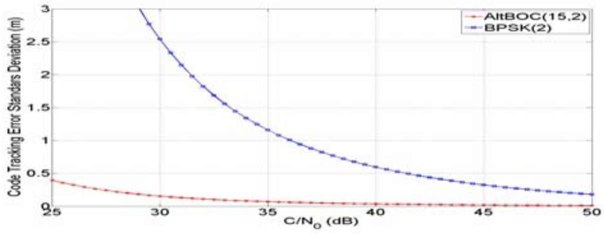

Figure 12. Code tracking error standard deviation for AltBOC(15,2) and BPSK(2) using 1ms of integration time

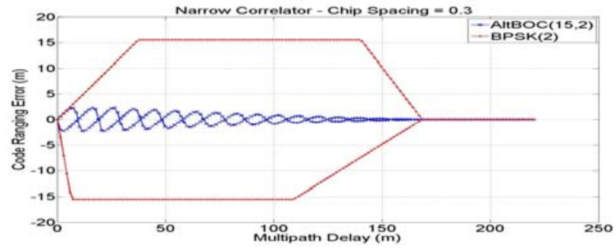

Figure 13. Code multipath error for AltBOC(15,2) and BPSK(2) using a 0.3 chip spacing, AND A 3 dB signal to multipath ratio of 3 dB

Fig. 12 and 13, as [46], [47], show clearly the very good accuracy offered by ALTBOC(15,x) modulations, for precise and or science applications, even when using standard omnidirectional GNSS antennas.

Very accurate two ways time transfer, orbit determination and clock synchronisation services can be reached thanks to the U-SBAS standard, thanks to an architecture already described in Fig. 3 and 4, and mentioned in [33] in the case of MEO systems. The GNSS multimodal SBAS downlink signals, tri- or quadri-frequency in that case, can be considered as a global coherent signal having a bandwidth close to 400 MHz, when considering the lower and upper downlink L bands. The addition of an eventual S band signal would even improve the situation. The uplink can also be in spread spectrum, in $\mathbf{B_{up}1}$and/or $\mathbf{B_{up}2}$ L/C bands. The uplink pseudoranges can be combined with the downlink pseudorange to form true very accurate ionosphere-free ranging and true Doppler measurements, and to perform an ultra precise orbit determination [33]. The one-way uplink and downlink measurements can be used separately, knowing a very precise orbit, to determine very precisely the time differences between the ground station clocks and the on board clock. This technique could be likely combined with optical links, like in the GEOSTAR concept [59] to obtain the more accurate time and frequency transfer.

IX. ROBUST AND SECURED NAVIGATION

Another application of U-SBAS standard could be in the security area. As wireless communications enable an ever-broadening spectrum of mobile computing applications, *location* or *position* information becomes increasingly important for those systems. Devices need to determine their own position, to enable location-based or location-aware functionality and services. Examples of such systems include: sensors reporting environmental measurements; sensors providing access control for banking or enterprise; cellular telephones or portable digital assistants (PDAs) and computers offering their users information and services related to their surroundings; mobile embedded units, such as those for road tolling, vessels border control, or Vehicular Communication (VC) systems seeking to provide transportation safety and efficiency; or, merchandize (container) and fleet (truck) management systems and in Fleet Management in secure supply chain management. Data about the goods and sensitive information can be protected by accessing it just on the specific locations. Also, lorry's routes can be bounded and controlled, such that they are not accessed outside zones determined in advance. We can use those systems together with the existing GNSS in order to enhance security.

However, commercial instantiations of GNSS systems are open to abuse: an adversary can influence the location information, $loc(V)$, of a node V and compromise the node operation. Adversary can just jam the receiver or spoof it. For example, in the case of a fleet management system, an adversary can target a specific truck. First, the adversary can use a transmitter of forged GNSS signals that overwrite the legitimate GNSS signals and are received by the victim node (truck) V. This would cause a false $loc(V)$ to be calculated and then reported to the fleet center, essentially concealing the actual location of V from the fleet management system. Once this is achieved, physical compromise of the truck (e.g., breaking in the cargo, hijacking the vehicle), is possible with reduced or no ability for the system to detect and react in time.

SBAS systems can be used to provide security for the spoofing scenario mentioned above and many others, providing secure distribution of the location and time such that the adversary is not able to emulate the positioning system. They can be used to provide to those systems additional layers of security needed for the distribution of constantly changing cryptographic parameters (between mobile nodes as in the VANETs – Vehicular Mobile Ad-Hoc Networks). Applications of VANETs are Safety-related applications, such as collision avoidance, cooperative driving, and traffic optimization. The common characteristic of this category is the relevance to life-critical situations where the existence or lack of a service may affect life-endangering accidents.

By using different modulations on different frequencies, jamming of the satellite receiver can be significantly reduced for the receiver using signal diversity successfully. This was discussed before.

There are other types of U-SBAS applications which can improve the security of the GNSS user:

For instance, earthquake or tsunami near-real time related data could be broadcasted in the U-SBAS message for instance. Despite the fact that there is unfortunately no reliable prediction signal for earthquakes identified for the moment, computation time for inversion of GNSS data (associated to InSaR and conventional seismology data) in terms of earthquake mechanism is decreasing and some information could certainly be uploaded, in principle, and disseminated.

Another example is a regional center dedicated to interference monitoring in the GNSS bands, centralizing all the available informations in the monitored region, which could be connected to the U-SBAS message generation center in order to alert the user about the interfered area(s).

In addition, U-SBAS messaging could also concern the monitoring of mobiles in a distress situation. Once a mobile in a critical situation has been detected and located, thanks to GALILEO Search And Rescue (SAR) or SARSAT or ARGOS beacons for instance, U-SBAS messages could be sent to the GNSS receiving part of the said beacon(s) to inform the user about the rescue process events.

X. QUASISTATIONARY GNSS REFLECTOMETRY

GNSS signals broadcast by the (quasi)geostationary satellites of the U-SBAS system components are a good source of opportunity for the bi-static radar systems. A bi-static radar system is composed of two antennas which receive the GNSS signals that come directly from the satellite and the signal reflected by a surface of interest. Nowadays this technique, which has been used in different applications, is limited by its precision and sensitivity. Geostationary satellites that broadcast GNSS signals on several frequencies with several pilot channels can help to overcome these limitations.

Bi-static radar using L-band signals transmitted by GPS satellites have been studied as application for altimetry [66], for wind speed measurements above the see surfaces [67] and for ocean roughness characterisation [68], [69]. Most of these works were dedicated to the modelling of the shape of the reflected waveform in order to characterise the surface [70]. A study of soil moisture as an application to land remote sensing is described in [71]. In this experimentation SNR (Signal to noise Ratio) of the direct and scattered GPS signals were compared. This dynamic airplane experimentation indicates that the technique is sensitive to temporal and spatial variations in soil moisture. In most of these works the receiving antenna is far from the ground in order to take into account the specular and fluctuating scattered power. For a perfectly flat, dielectric surface, the specular reflected power is coherent and governed solely by the Fresnel reflection coefficient of the active region. The fluctuating component is caused by the roughness of the reflected surface and affected principally the shape of the GNSS CDMA (Code Division Multiple Access) code function of correlation.

In these applications people measure the SNR of the reflected signal, analyse the distortion of the CDMA code function of correlation or estimate the pseudo range satellite receiver. The sensitivity of the system depends on its ability to work with low SNR. Its accuracy depends on the ability to provide precise measurements of the SNR, of the function of correlation and of the phase of the GNSS signal. These parameters can be improved with a perfect knowledge of the system geometry and with the long coherent integration of the GNSS signal. In the static case for example the geometry of the bi-static radar system can be perfectly known. The system uses the GNSS signal provided by the geostationary satellites as a source of opportunity and an antenna on a mast for the reception. In this context the phase of the GNSS signal evolves slowly if we consider an oscillator that provides low clock noise disturbances. We can then realize the long coherent integration of the signal at low SNR.

Water content in a soil appears to be the major changing constituent of its dielectric propriety. In this context soil moisture can be measured from the reflectivity or the emissivity of an electromagnetic wave by the surface. It has been showed by Njoku et al. [72] that the microwave (1-3 GHz) L-S band is optimal for sensing soil moisture. The GNSS signals in L-band constitute a good source of opportunity to measure the dielectric propriety of a surface. It has been shown, in the setting of an environmental study project [73], that a bi-static radar system can be used to estimate the dielectric properties and moisture content of sand. In this study it is shown that for the following values of permittivity ε={2.56, 2.84, 4.11, 4.82, 6.09, 7.65, 15, 30, 70} the power of the maximum value of correlation process with the received GPS open signal in $\mathbf{B_{NA}1}$ band and the signal generated by the receiver varies between 15dB et -12 dB. These values are obtained for a direct GPS C/A signal of 46 dBHz in $\mathbf{B_{A}3}$ band, and a satellite elevation of 60°. In this context a receiver cannot track the GPS signal and then it cannot provide the maximum values of correlation used to compute the SNR of the reflected signal [74].
For this kind of application the only way to work with low SNR is to have an accurate knowledge of the geometry of the system. In this case the parameters of the signal can be considered stationary (or slowly varying) and can be integrated on long period in order to extract the signal from the noise. In the dynamic case when we use a GPS satellite as a source of opportunity the method is limited with the accuracy of the satellite positions. This problem can be overcome with the use of (quasi)geostationary satellites.

We display in Fig. 14 the theoretical maximum value of the correlation and its value obtained by simulation when we use an OCXO (Ovenized Crystal Oscillator) oscillator model in our GPS simulator. In this simulation the satellite is fixed, so there is no variation of phase associated to its displacement. We consider the dateless pilot channel of the GPS open signals in $\mathbf{B_{A}1}$ and $\mathbf{B_{NA}1}$ bands (CL code).

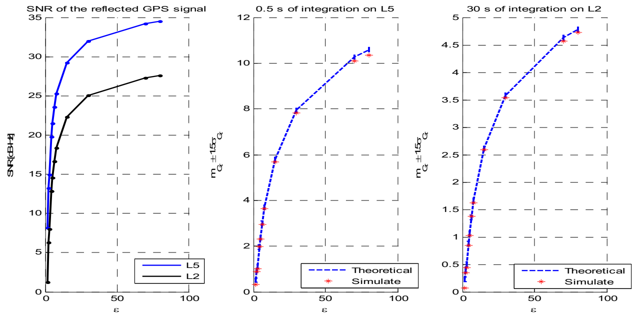

Figure 14 . Maximum of correlation $m_{C\tau}$ as a function of ε.

We show on this figure that the length of integration can be decreased for the same accuracy and sensitivity if the GNSS signal power is increased. This can also be done by fusing the GNSS signals broadcast by several (quasi)geostationary satellites on several carrier frequencies. The goal is to obtain short periods of integration in order to realize dynamic systems and to produce imaging of soil moisture.

XI. CONCLUSIONS

We have presented contributions to the multimodal worldwide SBAS standard, proposed to be named Universal-SBAS (U-SBAS) giving international names for RNSS bands and related frequency, suggesting some modulations, data rates and advanced coding schemes. Some services, multi-constellation message, payload, signal multiplexing and ranging issues have been also discussed. The U-SBAS standard is compatible with SoL and non-SoL services, including very precise and robust positioning / timing, and SBAS-related very accurate scientific applications. Systems like QZSS, IRNSS, SDCM, PCW, EGNOS and its evolutions, WAAS, SNAS, …, are compatible with the U-SBAS standard.

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