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BIOGRAPHIES

Isidre Mateu graduated in Telecommunications engineering from the Universitat Politècnica de Catalunya in 2008. He currently works as a navigation engineering in the CNES' Signal and RadioNavigation department, and collaborates with the ESA-CNES integrated team for EGNOS evolutions.

Cyrille Boulanger graduated as a microwave electronic engineer from ENSTBr. He joined CNES in 1995 to work on Travelling Wave Tubes technology and high data rate applications. After one year at the Japanese Space Agency (JAXA) he joined the Localization and Navigation department, where he is responsible of the CNES GIOVE experiments, the CNES studies in future Precise Positioning Service and in new GNSS frequencies.

Jean-Luc Issler is head of the Instrumentation Telemetry and Propagation department of the CNES Radiofrequency sub-directorate since august 2009. He is one of the CBOC inventors, and proposed the GALILEO E5 signal using the ALTBOC 8-PSK invention made by Laurent Lestarquit. He graduated first from the Ecole Supérieure d'Electronique de l'Ouest (ESEO). He received the Astronautic Prize of AAAF (french aeronautical and space association) in 2004, and the EADS Science and Engineering prize delivered in 2008 by french Academy of Sciences, for his work on GNSS frequencies and modulations, and, spaceborne RF equipments.

Lionel Ries is head of the Signal and RadioNavigation department of the CNES Radiofrequency sub-directorate since august 2009. He was a navigation engineer in the Transmission Techniques and signal processing department, at CNES since June 2000. He is one of the CBOC inventors. He graduated from the Ecole Polytechnique de Bruxelles, at Brussels Free University (Belgium) and received a M.S. degree from the Ecole Nationale Supérieure de l'Aéronautique et de l'Espace (SUPAERO) in Toulouse (France)

José-Ángel Ávila-Rodríguez is research associate at the Institute of Geodesy and Navigation at the University of the Federal Armed Forces Munich. He is responsible for research activities on GNSS signals. Avila-Rodriguez is one of the CBOC inventors and has actively participated in the developing innovations of the CBOC multiplexing. He is involved in the Galileo program, supporting the European Space Agency, the European Commission, and the GNSS Supervisor Authority, through the Galileo Signal Task Force.

Stefan Wallner studied at the Technical University of Munich and graduated in 2003 with a Diploma in Techno-Mathematics. He is now research associate at the Institute of Geodesy and Navigation at the University of the Federal Armed Forces Germany in Munich. His main topics of interests can be denoted as the Spreading Codes, the Signal Structure of Galileo together with Radio Frequency Compatibility of GNSS.

Thomas Kraus is research associate at the Institute of Geodesy and Navigation at the University of the Federal Armed Forces Munich. He graduated as an electronics engineer at the University of Applied Sciences Nuremberg in 2005 and received a M.S. degree from the University of Darmstadt in 2008. Currently, his main subjects of interest are GNSS signal structure and GNSS receiver design.

Bernd Eissfeller is Full Professor of Navigation and Vice-Director of the Institute of Geodesy and Navigation at the University FAF Munich. He is responsible for teaching and research in navigation and signal processing. Until the end of 1993 he worked in industry as a project manager on the development of GPS/INS navigation systems. He received the Habilitation (venia legendi) in Navigation and Physical Geodesy in 1996 and from 1994 to 2000 he was head of the GNSS Laboratory of the Institute of Geodesy and Navigation.

Sylvain Germaine graduated as a microwave electronic engineer from ENSTBr in 2005. He joined ANFR in 2006, the French national spectrum agency, as a spectrum engineer to work on international frequency management, in particular in the satellite field. He is the French coordinator for WRC-12 Agenda Item 1.18, on the possibility to make a global primary allocation to the radiodetermination-satellite service (space-to-Earth) in the band 2 483.5-2 500 MHz.

Jean-Yves Guyomard is working in ANFR which is the French frequency management body. He is the chairman of SE40, the group from the European Conference of Posts and Telecommunications (CEPT) responsible for technical studies related to satellite issues, in particular those related to the European preparation of WRC-12 Agenda Item 1.18 on a possible worldwide frequency allocation to RDSS in S-band.

Jérémie Godet is the chairman of the Galileo Signal Task Force and has security and frequency responsibility in the Galileo Unit of the European Commission. He is notably in charge of compatibility and interoperability discussions with GPS, GLONASS, COMPASS, IRNSS/GINS and QZSS for the Galileo program. He graduated from the Ecole Nationale Supérieure des Télécommunications de Bretagne (Télécom Bretagne, France) and received a M.S. degree from the International Space University.

Frédéric Bastide is working at the European Commission where he is in charge of Galileo signals. He is also involved in the coordination activities with other GNSS. He graduated as an electronics engineer at the ENAC in 2001 and obtained a PhD on GNSS from the Institut National Polytechnique de Toulouse in 2004.

Dominic Hayes manages Galileo's radio regulatory issues at the European Commission and led the EC team at WRC-07 that pushed to put S-band RDSS on the agenda for WRC-12; to further this work he is now the CEPT coordinator for this issue. A Chartered Engineer, he cut his regulatory teeth at the UK's Radiocommunications Agency, then Ofcom, and has a Spacecraft Technology MSc from University College London, and a BEng from Southbank University London.

Damien Serant is graduated as an electronics engineer in 2008, from ENAC. He is now a Ph.D student in the signal processing lab of the ENAC and working on hybridization of GNSS and OFDM signals.

Paul Thevenon is a PhD student in the signal processing laboratory of ENAC. He graduated as electronic engineer from Ecole Centrale de Lille in 2004 and obtained in 2007 a research Master at ISAE (Institut Supérieur de l'Aéronautique et de l'Espace). His current research interest is OFDM signal processing for positioning.

Olivier Julien is an assistant professor at the signal processing laboratory of ENAC (Ecole Nationale de l'Aviation Civile), Toulouse, France. His research interests are GNSS receiver design, GNSS multipath and interference mitigation and GNSS interoperability. He received his B.Eng in 2001 in digital communications from ENAC and his PhD in 2005 from the Department of Geomatics Engineering of the University of Calgary, Canada.

Guenter W. Hein is Head of the Galileo Operations and Evolution Department of the European Space Agency. Before he was Full Professor and Director of the Institute of Geodesy and Navigation at the University FAF Munich. In 2002 he received the prestigious "Johannes Kepler Award" from the US Institute of Navigation (ION) for "sustained and significant contributions to satellite navigation".

Mario Caporale is since 2000, with the Italian Space Agency (ASI), serving as head of satellite navigation. He represents ASI on matters pertaining to Galileo nationally and internationally. He is a delegate to the European Space Agency's Program Board on Satellite Navigation, and delegate to the GNSS Committee, and a member of the Galileo Signal Task Force. He is also a member of the EU/USA National Security Compatibility Compliance Group and the European Radio Navigation Plan Group. Previously, he co-chaired the GNSS Action team of the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) and following the establishment of the ICG (International Committee on Satellite Navigation) he is the Italian representative in the Committee. Before joining the Italian Space Agency in 2000, Dr. Caporale worked many years for aerospace industries where he got various management responsibilities.

Paolo Mulassano received the Master Degree in Electronics Engineering (Summa Cum Laude) at Politecnico di Torino in December 1998, and a Ph.D. in Communications Engineering from the same University in December 2003. From January 1999 to December 2000 he worked as researcher under grant in the Signal Analysis and Simulation Group (Politecnico di Torino, Electronics Eng. Department) with specific responsibilities on R&D programs related to satellite communications. In 2000 he was one of the founders of the Navigation Signal Analysis and Simulation Group (NavSAS) focused on navigation research activities. Since the end of 2003 Paolo Mulassano is a senior researcher at Istituto Superiore Mario Boella - ISMB where he is the head of the Navigation Lab. Such a lab operates on specific topics related to GPS and Galileo, and it represents a research environment where Politecnico di Torino as well as ISMB researchers (including Ph.D. students and Master students) co-operates. The research interests of Paolo Mulassano cover the field of digital signal processing applied to localization and navigation with specific focus on the development of innovative GNSS receiver technologies and applications. He is member of several technical committee related to satellite navigation and project manager for ISMB of different initiatives funded by National and European institutions. Paolo Mulassano is author of more then 70 papers on journals and international conferences

ABSTRACT

Satellite navigation has become such a worldwide priority that many countries are actively deploying or considering their own systems or modernizing those that already exist. As a consequence, the number of signals transmitted in L band will be significantly increased in the next few years so that only scant spectrum will be available for new systems or signals. Since current signals will have to be maintained many years in order to guarantee backward compatibility for legacy receivers, we can foresee that the search for new frequency allocations will be ranked at the highest level with a view to future evolutions of current systems.

In this context S-band spectrum between 2483.5 and 2500 MHz, which is already allocated to the radio determination satellite service (RDSS), can be used for satellite navigation – although the allocation in the Radio Regulations is only primary in parts of Asia, Africa and the Americas – is a particularly interesting possibility as synergies with future mobile communication systems in the band immediately above could be exploited to provide both navigation and communication services using one unique S-band terminal with an efficient, common antenna. Only at the next World Radiocommunications Conference in 2012 will the decision be made whether to make the existing patchwork of RDSS allocations global, but the studies completed so far show this to be promising. A global allocation will provide an important opportunity for a worldwide convergence between systems of the mobile satellite service (MSS) and the radio determination/navigation satellite service (RDSS / RNSS).

This paper aims to analyze the suitability of this band for navigation purposes as well as the effects that the introduction of these kind of signals would produce on the other radio services present in the same and adjacent bands. We will also present the results obtained from link and error budget calculations and interference assessment that have been performed using various hypothethical of navigation signals in S band.

Opportunities for Galileo-2 signals are currently being studied having in mind possible additional frequencies in C and/or S band and/or L band, in complement to the E5a, E5b, E6 and E1 legacy OS, SoL, CS and PRS signals.

The paper will give special attention to possible synergies between a hypothetical Galileo-2 S-band signal, IRNSS/GINS and Beidou/COMPASS, which will use L and S bands, other RNSS/RDSS systems and mobile satellite service systems such as GLOBALSTAR-2. These signals will be compared, and synergies between them explored.

Several possible waveforms centred on a frequency close to 2491 MHz will be analysed in terms of intersystem interference and in terms of navigation and data transmission performance. The analysed waveforms in S-band will be BPSK(1*1.023 Mcps), BPSK(4*1.023 Mcps), BPSK(8*1.023 Mcps), BOC(1,1) and MBOC.. Power flux density (pfd) and interference computations showing compatibility between a potential Galileo-2 S-band component, S-band GNSS signals, GLOBALSTAR, mobile services (MS) and fixed services (FS) will be presented.

INTRODUCTION

Why S-band for GNSS?

The new possible allocations for RDSS/RNSS services have been explored from a regulatory point of view in [28], [29], which mention mainly S and C bands in addition to L band (note that the ITU Radio Regulations defines the RNSS (radionavigation satellite service) as a subset of the RDSS (radiodetermination satellite service). Although the allocations are differentiated (RDSS usually has a paired uplink), both can be used for satellite navigation). The eventual need for additional Galileo frequencies and signals in S-band or C-band in addition to those currently used is not about improving the pseudoranging or timing performance, but primarily about introducing new services. In fact, the pseudoranging or timing performances could be improved with new CDMA signals in L band alone. These could be jointly defined by Galileo and GLONASS in the so-called G1 band, where some room is still available (but subject to compatibility with the adjacent radio astronomy band). Such a signal could have an MBOC-like spectrum, for instance, so that it could be processed independently, or in association with its L1/E1 MBOC counterpart, in order to achieve a very wide signal in a similar manner to AltBOC. This so-called Alt-CBOC (or any similar alternative solution) would be backward compatible with the L1 CBOC and its pseudoranging accuracy would be necessarily very good as it is also the case for the Galileo AltBOC in E5a/L5-E5b/L3/B2 bands. In any case, such a wide band E1/G1 signal should be symmetrical in the spectral and correlation domains, to avoid pseudoranging bias. Furthermore, having a very wide band signal in the lower and upper L bands would allow significant progress in terms of pseudoranging performance thanks to very accurate dual frequency, wideband ionospheric correction and raw pseudoranges. This is the only way to significantly improve performance compared to C and S RDSS/RNSS bands, since C band is only 20 MHz wide and S band is restricted to only 16.5 MHz. It could also be noted that the CBOC-like counterparts of the presented signal in E1/G1 bands could be itself improved in term of related accuracy compared to the current CBOC [9], while still preserving the necessary backward compatibility with CBOC in E1. An example of studies on this issue is given in [10]. Moreover, another very important field to improve accuracy worldwide without needing extra frequency bands in addition to L band is Integer Ambiguity Resolution on Undifferenced Phase (IARUP) [11] or possible equivalent techniques, which will allow very precise positioning accuracies close to a few cm in real time [fig 1].

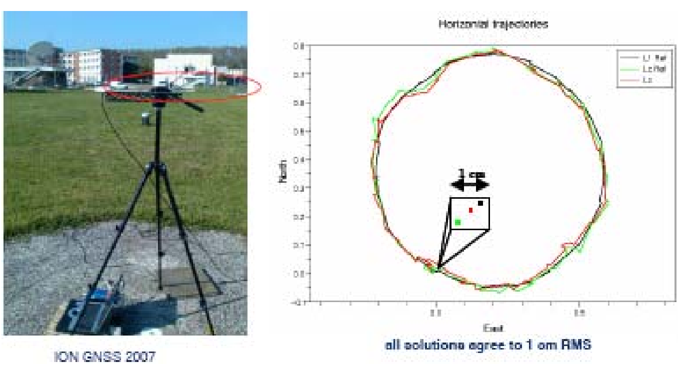

Figure 1 : Example of accuracy close to 1 cm provided by IARUP using GPS L1 and L2 signals.

Having this and the fact that the paper focuses on S-band, in mind, the C and L band alternative solutions will not be further developed in this work, except for relevant L-S band link budget comparisons. The paper will show that potentially interesting services in S-band are technically feasible, from the link budget and radio frequency compatibility point of views.

Foreseen benefits of S-band for navigation applications.

The new functions/services specifically provided by S-band do not include the improvement of the ionospheric correction, since a new signal in the G1 L band would also improve significantly the ionospheric correction efficiency. The new functions/services provided by S-band are rather hybridisations between mobile communication services and navigation services.

Some examples of imaginable applications are provided next:

- An accurate self positioning of future GLOBALSTAR [35, 36, 37] mobile phones using Galileo, without the need to add any L-band hardware in the GLOBALSTAR (or other mobile com) terminal to save costs in this equipment. Single frequency S-band ionospheric correction could be provided using techniques like the one described in [3, 4, 5, 23, 24, 25, 26, 27, 39].
- Assistance of Galileo acquisition in-door using GLOBALSTAR signals, or using other mobile communication signals also transmitted in S-band
- To perform the orbit and time determination of both Galileo and GLOBALSTAR satellites, thanks to a single ground network of updated Galileo Sensor Station (receivers), using double difference measurements in S-band, single frequency ionospheric determination in S-band, and intersystem assistance/cross-validations thanks to L-band measurements. The Galileo system could then offer the time and orbit determination of GLOBALSTAR and/or other MSS systems.
- To assist the acquisition of MSS signals like the GLOBALSTAR ones, providing an accurate time, without requiring any L-band specific hardware in the mobile com terminal.
- To use the communication channel providing assisted-GNSS (using the OMA-SUPL approach for instance) to the GNSS embedded receiver. Therefore, communication would also help GNSS.
- To allow RDSS multiconstellation positioning in S-band by means of Beidou/Compass future S-band signals or from the Indian IRNSS/GINS, which is also planned to transmit at 2491 MHz. (the Chinese GSO RDSS signal at 2491 MHz - see Figure 2 - could be employed.) The Beidou GNSS S-band PN code spectrum lines have been measured and analysed in [38]. As we can see, this is the same central frequency employed by GLOBALSTAR. We also noticed that the Japanese HAC GNSS signal experiment already uses a 1023 chips - 1.023 Mcps code at 2491 MHz transmitted from the ETS VIII geostationary satellite of JAXA [6], [7]. It is also noted that current modernized GPS satellites are provided with an experimental Search and Rescue payload transmitting in S-band.

- It should also be noted that with equivalent signal bandwidths, L+S ionospheric corrections are more accurate than L+L ones. This advantage remains for dual frequency ionospheric corrections without the benefit of wide bandwidths, but not for single frequency ionospheric corrections: the higher the carrier frequency, the smaller the ionospheric delay, but the smaller the code-carrier divergence. Since this code-carrier slipping also allows retrieval of the ionospheric delay, the single frequency ionospheric delay after this correction is approximately the same whatever the central carrier frequency [3], [4], [5], [23], [24] , [25], [26], [27], [39].

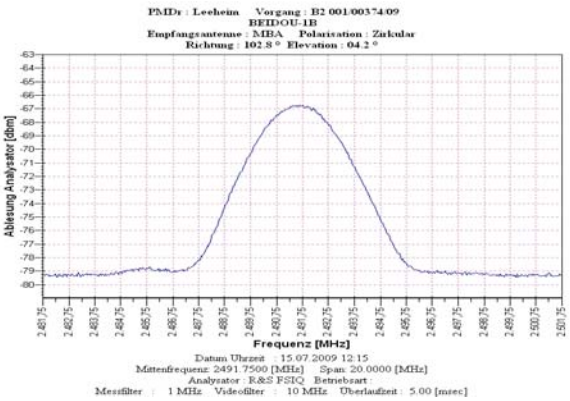

Figure 2 : Spectrum of Beidou 1-B in S-band (measurement made the 15-07-2009 at Leeheim)

- To allow RNSS multiconstellation positioning and inter-system assistance in S and L band, thanks to the previously mentioned Asian, US and European systems.

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 low cost design study involving a 2.4 GHz downlink [32]. S-band is also used for Formation Flying RF GNSS technology, using GPS-like C/A codes [33, 34].

The potential services to be provided by Galileo in a hypothetical future S-band system are still under study.

LINK BUDGET

A link budget has been calculated to quantify the impact of the signal upon the power consumption onboard the satellite. For the sake of the comparison between signals in L band and the potential signal in S band, it is assumed that the new signal will guarantee at least the same received power on the ground, and offer the same performance in terms of pseudorange accuracy, as the Open Service in E1/L1.

Table 1 Calculation of the transmitted power in S band to obtain the same power level at the ground as for E1-OS

E1 minimum received power level [dBW]	-157.25
Total losses in S band at 5° elevation [dB]	190.95
Required EIRP in S-band [dBW]	33.70

The Galileo ICD sets a minimum received power of -157.25 dBW for its open service on E1 at an elevation angle of 5°. Table 1 shows that an EIRP of 33.7 dBW would need to be transmitted in S band to obtain the same power on the ground, which represents an increase of 4 dB from what is required in E1. This is necessary to compensate for the higher free space losses in S band.

In order to assess the pseudo range accuracy, the signal modulation has to be taken into account. Four different hypothesis were considered:

- BPSK(1): "Globalstar like" or "IRNSS like" signal, occupying only the central Globalstar channel.
- BPSK(4): analogue to the signal transmitted by the Beidou-1 geostationary satellites.
- BPSK(8): example of signal with main lobe(s) occupying the whole S-band RDSS spectrum.
- BOC(1,1): having the same spectrum as the central signal of the GPS/GALILEO CBOC at E1 central frequency.

Future studies will be made also with CBOC instead BOC(1,1) to benefit from the CBOC performance. The use of OFDM modulation is also explored later in the paper. For each of the modulations considered here, we have calculated the power that is required to be transmitted to obtain the same pseudo range error as that of E1-OS, which we calculate through the following simplified expression deduced in [1]:

$$\sigma_{pr} = \frac{c}{R_c}\sqrt{\frac{B_c d}{6\,C/N_0}\left(1+\frac{2B_{FI}}{C/N_0}\right)}$$

Where $c = 3*10^8\ m/s$ is the speed of light, $Rc=1.023\ Mcps$ is the signal chip rate, $d=0,5$ the chip spacing, $Bc=1\ Hz$ the code loop bandwidth, $B_{FI}=250\ bps$ the data rate, and C/N_0 is the carrier to noise density ratio. The C/N_0 value has been obtained from the table 2 link budget.

Table 2 L band link budget

EIRP[dBW]	30.60
Total losses [dB]	186.92
Receiver antenna gain at low elevation [dB]	-3
Noise level [dBW] (T=600K)	-200.82
C/N_0 [dBHz]	41.29
Pseudo range error [m]	0.74

From the obtained E1-OS pseudo range error, we can deduce the C/N_0 required for each of the considered modulations in S band. In the case of BOC(1,1) it will be the same as for E1 (as the pseudo range error does not vary with the carrier frequency), namely 41.3 dBHz. The use of CBOC [9] instead of BOC(1,1) would be of course better. For BPSK modulations, C/N_0 is obtained by inversing the classical pseudo range error expression for BPSK signals, as follows:

$$\sigma_{pr} = \frac{c}{R_c}\sqrt{\frac{B_c d}{2C/N_0}\left(1+\frac{2B_{FI}}{C/N_0}\right)} \Rightarrow$$

$$\Rightarrow \frac{C}{N_0} = \frac{c^2 B_c d}{4R_c^2 \sigma_{PR-L1}^2}\left(1+\sqrt{1+16B_{FI}\frac{R_c^2\sigma_{PR-L1}^2}{c^2 B_c d}}\right)$$

Once the C/N_0 is obtained, the required transmitted power is calculated making a reverse link budget calculation. The obtained results are summarized in table 3.

Table 3 Calculation of the transmitted power in S band to obtain the same the same pseudo range errors as for E1-OS

	BOC(1,1)	BPSK(1)	BPSK(4)	BPSK(8)
Required C/No [dBHz]	41.29	45.96	34.56	34.02
Noise level [dBWHz^{-1}] (T=600K)	-200.82			
Receiver antenna gain at 5º[dB]	-3			
Total losses in S band at 5° elevation [dB]	190.95			
Transmitter antenna gain [dB]	15.40			
Transmitted power in S band [dBW]	19.23	23.92	12.5	7.64

Table 4 Transmitted power and maximum pfd level for each modulation.

Modulation	BOC(1,1)	BPSK(1)	BPSK(4)	BPSK(8)
Tx Power [dBW]	19.23	23.92	18.3	18.3
Pfdmax [dBW/MHz/m²]	-129.1	-121.0	-131.5	-134.2

We see that for BPSK(4) and BPSK(8) modulations the limiting factor for the transmitted power is the received power on the ground, while for BOC(1,1) and BPSK(1) it is the pseudo range accuracy, which is coherent with the fact that the pseudo range error decreases when increasing the signal bandwidth. Table 4 summarizes the obtained values for the transmitted power, as well as the corresponding maximum power flux density level on the ground within the band, which has been calculated through integration of one MHz of the signal's power spectral density around the maximum of its main lobe. To improve the comparison, a multipath analysis will be done in the future for the signals presented in table-4, including also the CBOC instead BOC(1,1). A Multipath analysis related to CBOC is presented in [12], [13], [14] and [15].

RADIO FREQUENCY COMPATIBILITY

Interference with Globalstar:

Globalstar [35], [36], [37], uses the 2483.5–2500 MHz band for its downlink communications from the satellite to the user terminals. The system uses multi-beam antennas to allow frequency reuse. Inside each beam, the 16.5 MHz bandwidth is divided into 13 FDM channels (fc=2491.77±k*1.23 MHz (k=0,1,…6)), each one supporting up to 128 simultaneous users in a CDMA scheme (see appendix 1 for a more accurate signal description).

Interference between Globalstar and the different hypothetical Galileo signals in S band is assessed through calculation of the C/N_0 degradation that each system induces on the other one. C/N_0 degradation is calculated as the difference between the C/N_0 of the interfered system when there is no external interference and the C/N_0 taking into account the interfering system.

$$\Delta_{dB} = \left(\frac{C}{N_0+P_0}\right)_{dBHz} - \left(\frac{C}{N_0+P_0+I_0}\right)_{dBHz} =$$
$$= \left(\frac{N_0+P_0+I_0}{N_0+P_0}\right)_{dB}$$

where N_0 is the thermal noise floor, P_0 the intra-system interference and I_o the external interference. The external interference level is calculated as follows,

$$Io[dBW/Hz] = G_{agg}[dB] + \int_{Bw} G_i(f)df[dBW]$$
$$+ G_{Ant}[dB] + SSC[dB/Hz] + L_x[dB]$$

Where G_{agg} is the aggregate gain taking into account the interference introduced by all the satellites in view, $\int_{Bw} G_i(f)df$ is the normalized power spectral density of the signal corresponding to the interfering system at the receiver antenna, integrated along the receiver bandwidth (*Bw)*, G_{Ant} the receiver antenna gain and *SSC* the Spectral Separation Coefficient between the interfering and the interfered signals. The SSC has been introduced by EC as "COEFF" in [8]. *Lx* refers to any processing loss that might appear within the receiver.

The spectral separation coefficient (SSC) is accepted by the GNSS community as an effective parameter in order to characterize the mutual interference, since it gives a measure of how both the power and the spectral shape of the interfering signal affects the performances of the receiver. The SSC definition is derived from the SNIR expression which, for a coherent early-late processing, is given by the following expression[2]:

$$SNIR = \frac{2TC_s\left[\int_{-\beta_r/2}^{\beta_r/2} G_s(f)df\right]^2}{\int_{-\beta_r/2}^{\beta_r/2} G_w(f)G_s(f)df}$$

where T is the correlator period, C_s the carrier power, β_r the receiver front-end bandwidth, $G_s(f)$ the desired signal's power spectral density normalized to unit power over infinite bandwidth and $G_w(f)$ the power spectral density of the interference. $G_w(f)$ can be decomposed into the sum of white noise and nonwhite interference, so that the previous expression becomes:

$$SNIR = \frac{2TC_s\left[\int_{-\beta_r/2}^{\beta_r/2} G_s(f)df\right]^2}{N_0\int_{-\beta_r/2}^{\beta_r/2} G_s(f)df + C_i\int_{-\beta_r/2}^{\beta_r/2} G_i(f)G_s(f)df}$$

The impact of the interference on the SNIR is given by the second term of the divisor. The factor

$\int_{-\beta_r/2}^{\beta_r/2} G_i(f)G_s(f)df$ is the SSC

In our specific case, the following assumptions have been made for the SSC calculation:

- Both Galileo and Globalstar signals are filtered in emission with a 16.5MHz (2483.5-2.500MHz) square filter. This means that the considered $G_i(f)$ and $G_s(f)$ correspond to the theoretical spectra truncated and normalized over a 16.5 MHz bandwidth.
- The interference from Galileo to Globalstar has been assessed assuming a receiver bandwidth equal to one Globalstar FDMA channel width (1.23 MHz), for the worst case corresponding to the Globalstar channel closest to the main lobe of the Galileo signal.
- In the case of the interference from Globalstar to Galileo, the receiver bandwidth is supposed equal to the width of the main lobe of the Galileo signal, and the interfering signal is assumed to be the aggregate of all 13 Globalstar channels. Note that this is also a worst case, as Globalstar channels are not active all the time.

Globalstar operates below the power flux density threshold set in Appendix 5 of the radio communications regulation for the 2483.5-2500 MHz band. According to this, a threshold value of -126 dBW/m²/MHz per satellite has to be considered. With the purpose of assessing a worst case interference, calculations have been performed based on this maximum pfd value for both Globalstar and Galileo satellites. Note that the pfd levels that we have calculated for our hypothetical Galileo signals in S band (table 4) are below that threshold except for the case of BPSK(1), which exceeds the tolerable value by 5 dB. This might indeed be a significant drawback for this option. The other studied modulations (BPSK(4) for instance) do not exceed the pfd threshold because we are not considering the same transmitted power for all the modulations. For each modulation, we use the minimum transmitted power that ensures the same pseudo range error as the one obtained for E1-OS.

For the case of the interference caused by Galileo on Globalstar, we calculate the maximum accumulated power flux density at the receiver antenna for a worst case in which 12 satellites are in view and the receiver gets the maximum power from all of them. A maximum receiver antenna gain of 3 dB is also assumed for all the satellites. (Note that this is a very pessimistic and worst case scenario, as we are supposing that all 12 interferer satellites are at the zenith, but sets an upper-bound for the pfd). A similar assumption applies for the assessment of the interference from Globalstar to Galileo, however the maximum number of Globalstar satellites in view of a Galileo receiver has been fixed to 4 satellites at the same time in this case.

A CNES intern simulation tool named "Interference Assessment Software", has been used in order to assess the intra-system interference of both Galileo and Globalstar constellations. This tool takes into account the geometry of the constellation to calculate the power received by a receiver placed on the ground. The obtained results show that the Galileo intra-system interference is always below -222 dBW/Hz,, while for Globalstar it reaches a maximum level of -205 dBW/Hz. A typical noise PSD of -201.5 dBW/Hz has been considered.

Tables 5 and 6 present the results of the interference analysis that have been performed, from Globalstar to Galileo and from Galileo to Globalstar respectively. From table 6, we see that Galileo slightly degrades the C/N_0 of Globalstar only in the case of a BPSK(1) modulation, while the degradation is negligible for the rest of studied S-band signal solutions. On the other hand, table 5 shows that Globalstar signal induces degradations in the order of some tenths of dBs to Galileo (except 1,2 dB in the worst case, corresponding to a BPSK(8)). Based on these results, we see that in all cases –except the BPSK(8)– the interference between the two systems stays within very reasonable values which should not suppose an issue for a new Galileo signal in S band.

Table 5 Galileo C/No worst case degradation due to Globalstar emissions.

	BPSK(1)	BPSK(4)	BPSK(8)	BOC(1,1)
PSD Globalstar (1 satellite) [dBW/MHz]	-155,4			
Maximum number of satellites in view	4			
Cumulated PSD [dBW/MHz]	-149,4			
Gain antenna [dB]	3,0			
Receiver bandwidth [MHz]	2,0	8,2	16,4	4,1
SSC [dBHz]	-72,4	-72,3	-72,0	-72,5
Io [dBW/Hz]	-215,7	-209,5	-206,2	-212,8
Po [dBW/Hz]	-222,0			
No [dBW/Hz]	-200.82			
C/No deg.(dB) Po=-220 dBW/Hz (95% of time)	0,2	0,6	1,2	0,3

Table 6 Globalstar C/No degradation due to Galileo emissions.

	BPSK(1)	BPSK(4)	BPSK(8)	BOC(1,1)
GALILEO pfd per satellite ($dBW/m^2/MHz$)	-126			
PSD_{GAL} (dBW/MHz)	-155.4			
G_{Ant}(dB)	3			
Maximum number of satellites in view	12			
Maximum GALILEO aggregate pfd ($dBW/m^2/MHz$)	-115.2			
Bw(MHz)	1.23			
SSC(dB/Hz)	-72.8	-77.1	-79.9	-77.1
Io'(dBW/Hz)	-213.5	-217.8	-220.6	-217.8
No(dBW/Hz)	-201.5			
	0.19	<0.1	<0.1	<0.1

Interference with Mobile Service:

The 2483.5-2500 MHz band is used in some countries by Services Ancillary to Broadcasting (SAB) and Services Ancillary to Programme-making (SAP). SAB/SAP services include ENG/OB applications. The European Conference of Postal and Telecommunications Administrations (CEPT) gives the following definitions for Electronic News Gathering (ENG) and Outside Broadcasts (OB)[16]:

ENG : Electronic News Gathering is the collection of television news stories without the use of film, using small hand held, electronic, colour cameras with microwave links to the news room and/or portable video tape recorders.

OB : Outside Broadcasts is the temporary provision of programme making facilities at the location of on-going news, sport or other events, lasting from a few hours to several weeks. Outside Broadcasts are generally planned in advance, but it is often necessary to accommodate short notice changes of venue or unforeseen requirements. Video links are required for mobile links, portable links and cordless cameras at the OB location. Additionally, video links may be required as part of a temporary point to point connection between the OB van and the studio.

To assess interference, a typical scenario involving a radio camera operating with the parameters summarized in table 7, is considered.

Table 7 Radio-camera parameters

Field	Value	Comments
Bandwidth (MHz)	8 MHz	DVB-T standard channel width (OFDM modulation)
EIRP(dBW)	0	
Antenna pattern	Isotropic	
Antenna height (m)	2	Assumed value.

Considering a threshold interference criterion of -146 dBW/MHz[17] at the RNSS receiver antenna input, the use of a dual slope propagation mode shows that radio-cameras would interfere with RNSS receivers up to a distance of 18.4 km.

On the other hand, interference at the MS receiver has been assessed for the four hypothetical studied Galileo signals. The criterion that has been followed is that the interference-to-noise ratio must be below -6 dB. That is, the interfering power at the receiver must be below -133.6 dBW (considering -127.6 dBW of noise power[18]). Interference caused by GLOBALSTAR emissions has also been taken into account for sake of comparison. The resulting interference has been calculated through the following formula:

$$I = P_r + G_{agg} + L_{pol} + K_{\%} \quad (1)$$

where:

- *Pr* is the received Galileo power per satellite at the receiver antenna input. Considered power levels are summarized in table 8. They have been calculated considering the same maximum pfd value as for Globalstar. That is, -126 dBW/MHz/m^2
- *Gagg* is the aggregated gain taking into account the maximum possible number of satellites in view (12 for the Galileo constellation, 4 for Globalstar). Each Galileo modulation has been analyzed in combination with all the antennas summarized in table 9, which are commonly used antennas for this kind of applications. We distinguish the worst case where a satellite falls inside the antenna main beam from the case where all the satellites are in the secondary lobes.
- L_{pol} are the polarization mismatch losses, assumed 3dB
- $K_{\%}$ is the percentage of power that falls within the receive bandwidth. It is calculated as follows:

$$K_{\%} = \frac{\int_{8MHz} PSD(f)df}{\int_{16.5MHz} PSD(f)df}$$

where PSD(f) is the theoretical power spectrum density of the modulation.

Table 8 Equivalent power level for a maximum pfd of -126 dBW/MHz/m²

Modulation	BPSK(1)	BPSK(4)	BPSK(8)	BOC(1,1)
Pr [dBW]	-154.3	-149.4	-146.7	-150.9

Table 9 aggregated gain calculation

Atenna	Omni	Hand-held helix	Disk yagi	0.6m dish
Main lobe gain[dB]	3	12	16	21
Sidelobe relative gain[dB]	-	-14	-17	-16
Aggregated gain- 12 satellites (one inside the main beam)	13,80	13,60	16,90	22,10
Aggregated gain- 12 satellites (all in the secondary lobes)	13,80	8,80	9,80	15,80

The obtained results are summarized in tables 10 (one satellite inside the main beam of the antenna) and 11 (all the satellites in the secondary lobes), where interference levels higher than the -133.6 dBW threshold are highlighted in red and bold. We can notice that there is no interference in any case without any satellite inside the main beam of the antenna. On the other hand, a 0.6 m antenna dish is interfered by all modulations but BPSK(1) when a satellite falls inside its main lobe. The rest of antennas are safe from interference except for a very slight interference (0,1 dB above the threshold) that appears when a disk yagi antenna receives a BPSK(8) modulated signal.

It is interesting to notice that in all cases where the interference criteria is not respected, the obtained interference is well below that induced by Globalstar for the same case. No internal compatibility problem between Globalstar and the rest of Mobile Services has been reported, which leads us to the conclusion that the interference criterion that we have considered is, in reality, by far too conservative. As a conclusion, the introduction of any of the considered Galileo modulations in S band is not expected to cause harmful interference to the MS.

Table 10 Interference from RNSS to MS (1 satellite inside the main lobe)

	Omni dipole	Hand-held helix	Disk yagi	0.6 m dish
BPSK(1)	-143.6	-143.8	-140.4	-135.3
BPSK(4)	-138.9	-139.1	-135.8	**-131.0**
BPSK(8)	-136.6	-136.8	**-133.5**	**-128.3**
BOC(1,1)	-140.3	-140.5	-137.2	**-132.0**
Globalstar	-140.4	-136.9	**-133.1**	**-128.1**

Table 11 Interference from RDSS to MS (all the satellites in the secondary lobes)

	Omni dipole	Hand-held helix	Disk yagi	0.6 m dish
BPSK(1)	-143.6	-148.6	-147.6	-141.6
BPSK(4)	-138.9	-143.9	-142.9	-136.9
BPSK(8)	-136.6	-141.6	-140.6	-134.6
BOC(1,1)	-140.3	-145.3	-144.3	-138.3
Globalstar	-140.4	-145.4	-144.4	-138.4

Interference with WiMax:

The 2483.5-2500 MHz band is also planned for the deployment of WIMAX. ITU-R M.2116 specifies the parameters summarized in table 12 for WIMAX base and mobile stations. The same analysis performed for MS is applied here: first, dual-slope propagation model is used to calculate the minimum separation distance that prevents interference to RDSS receivers from WIMAX stations; and in a second step, an I/N criterion of -6dB is assumed to assess the interference that our hypothesis of Galileo signals would cause on the Wimax stations.

Table 12 Wimax parameters

	WIMAX Base Station	WIMAX Mobile Station
Channel bandwidth (MHz)	5	
Average power (dBm)	36	20
Antenna Gain (dB)	18	0 to 6
Antenna height (m)	15 to 30	1.5
Line loss(dB)	2	0

WIMAX base stations and mobile stations would cause interference to RDSS receivers even if they are far away: assuming a 15m height antenna and a dual-slope propagation model, the base station would interfere with the receivers that are in a radius of 122 km, while a typical mobile station would interfere with receivers within a 15 km radius. It has to be noted that for base stations, the obtained results have to be considered as a worst case which will only occur a low percentage of the time, as they only apply when the RDSS receiver is inside the narrow, main beam of the high gain antenna.

To analyze the interference that Galileo would cause on to Wimax, we focus on the base stations case, as they are more likely to suffer interference due to the higher gain of their antenna. Considering the same protection criterion that has been used for ENG/OB applications (maximum interference-to-noise ratio of -6 dB), the maximum interfering power at the station should be below -135.6 dBW in order not to cause interference. Interference is calculated through expression (1) in a similar way as for MS. Same power levels apply and again, the situation where one satellite is inside the main beam of the antenna has been analyzed separately from the situation where all the satellites are in the secondary lobes.

Obtained results are shown in table 13. We see that with one satellite inside the main beam, interference is above the threshold for all modulations except BPSK (1). However, as Wimax is still to be deployed, it will have to be compatible with the signals already present in the band, particularly with Globalstar. As we can see, the interference levels for Globalstar are similar to the ones obtained for Galileo. Accordingly, we believe that if Wimax signals are robust enough against Globalstar interference, they should consequently also be sufficiently robust against any hypothetical additional Galileo signal.

Table 13 Interference from RDSS to Wimax

	One satellite inside the main beam	All satellites inside the secondary lobes
BPSK(1)	-135.6	-142.7
BPSK(4)	-131.1	-138.1
BPSK(8)	-130.0	-137.1
BOC(1,1)	-132.5	-139.6
Globalstar	-130.2	-141.4

Interference with Fixed Service:

Fixed services are another service allowed in our band of discussion. Specifically, the fixed service occupies the band from 2450 MHz to 2690 MHz and consists of long range point-to-point links between two high directive antennas. The parameters of this service are summarized in table 14.

Considering a dual-slope propagation model, RDSS receivers inside the main beam of a 30 meters high antenna would receive interference up to distances of 210 km. However, the probability of this happening would be quite low, as FS links are very narrow point to point links. For example, for a 3m dish antenna, the width of the main lobe is approximately 6º, based on [19]

Table 14 Fixed service parameters

Frequency band (GHz)	2.45-2.69	
Modulation	MSK	4-PSK
Capacity	2 x 2 Mbit/s	34 Mbit/s
Channel spacing (MHz)	14	
Antenna gain (maximum) (dBi)	25	35.4
Feeder/multiplexer loss (minimum) (dB)	4	
Antenna type	1.2 m dish	3 m dish
Maximum Tx output power (dBW)	5	–2
e.i.r.p. (maximum) (dBW)	26	33
Receiver IF bandwidth (MHz)	3	
Receiver noise figure (dB)	4	
Receiver thermal noise (dBW)	–135	

In order to protect the fixed service from interference, Recommendation ITU-R M.1477 states that a maximum PSD level of -150 dBW/MHz can not be exceeded more than 20% of the time (long term criterion), and a level of -114 dBW/MHz shall not be exceeded more than 0.005% of the time (short term criterion). Strictly speaking, these limitations are only appropriate for the band 1 559-1 610 MHz, but have been considered in absence of information concerning the band under consideration.

In order to assess the short term criterion, we have considered the worst case where a satellite falls inside the main lobe of the antenna. In that situation, the antenna is receiving a maximum of interference, so it is possible to calculate the maximum pfd that keeps the interference below the established threshold. Due to the high gain of the antenna, the effect of the rest of satellites in view can be neglected. Indeed, ITU recommendation [19] states a front-to-rear relative gain in the order of -40 dB for this kind of antennas, and a maximum sidelobe relative gain in the order of -15 dB. In a worst case, assuming one satellite inside the main lobe we could have a second satellite near the main lobe (thus amplified by -15 dB) but then the rest of them would fall in the rear lobes. Table 15 summarizes the obtained results. We see that a pfd lower than -118.3 dBW/MHz/m² is required in order to assure respect of the criterion, which is well beyond the maximum pfd foreseen in the paper, -126 dBW/MHz/m².

To take into account the long term criterion, we proceed in a similar way to the previous case. This time, however, we consider 12 satellites in view but outside the main lobe of the antenna (interfering through secondary lobes). The accumulated gain of the 12 satellites is calculated as follows: knowing the geometry of the Galileo constellation, it is possible to calculate the aperture angle of the antenna that defines a region in the space around the main lobe which is empty of satellites 80% of the time. Thus, ensuring that interference caused by satellites outside that region does not exceed the long term criterion threshold will ensure that the criterion is respected 80% of the time, as required.

Table 15 Maximum pfd calculation based on the short term criterion

	MSK	QPSK
Maximum PSD at the receiver	-114 dBW/MHz	-114 dBW/MHz
Gant	25 dB	35.4 dB
Maximum isotropic power at the antenna input	-139 dBW/MHz	-149.4 dBW/MHz
Maximum pfd at 5° elevation	-109.6 dBW/MHz/m²	-120 dBW/MHz/m²
Path loss difference between 5° and zenith	1.7 dB	1.7 dB
Maximum pfd	-107.9 dBW/MHz/m²	-118.3 dBW/MHz/m²

The worst case (maximum gain) for a satellite that is outside the region occurs when it is at the borderbetween the two regions. In that situation we can consider that the rest of satellites are in view with a minimum gain determined by the antenna at the rear of the main lobe. Accordingly, the accumulated gain is:

$$G_{acc} = 10 * \log\left(G\left(\frac{\Delta\varphi}{2}\right) + 11 G_{\min} \right)$$

ITU-R Recommendation [19] is used to calculate the gain values that are shown in table 16. Using these values we derive next the pfd limitation according to the long term criterion. Results are shown in table 17. As we can see, the thresholds are more restrictive than the short term criterion. Nevertheless, they are still higher than the threshold resulting from applying the radio regulatory limit (-126 dBW/MHz/m²), that means no additional limitation has to be imposed on the RDSS pfd to ensure no harmful interference to the fixed service.

Table 16 Accumulated gain calculation

	MSK	QPSK
$\Delta\varphi$	36°	36°
$G\left(\frac{\Delta\varphi}{2}\right)$	2.62 dB	0.63 dB
$G_{\min}$	-10 dB	-10.75 dB
G_{acc}	4.67 dB	2.53 dB

Table 17 Maximum pfd calculation based on the long term criterion

	MSK	QPSK
Maximum PSD at the receiver	-150 dBW/MHz	-150 dBW/MHz
Gant	4.67 dB	2.53dB
Maximum isotropic power at the antenna input	-154.67 dBW/MHz	-152.53 dBW/MHz
Maximum pfd	-125.27 dBW/MHz/m²	-123.13 dBW/MHz/m²

ANOTHER POSSIBLE MODULATION : OFDM

Orthogonal Frequency Division Multiplexing (OFDM) is a modulation technique retained for numerous existing and forthcoming telecommunication and broadcasting standards such as Wi-Fi, WiMAX, DVB-T(-H)(-SH), DAB, etc.

It consists in transmitting data symbols over several orthogonal narrow-band subcarriers (one symbol per sub-carrier). Each sub-carrier is narrow enough so that the channel response can be considered as flat over the width of a subcarrier. Therefore the impact of the propagation channel on the signal can be easily corrected using simple channel equalization techniques. Sub-carriers narrowness and orthogonality ensures excellent spectral efficiency (the signal PSD is almost square) and, despite the low symbol rate, a large number of subcarriers transmitted in parallel guaranties a high global data rate.

The digital implementation of OFDM makes use of the efficient FFT algorithm. An OFDM symbol is generated by passing N data symbols through an inverse-FFT and results in N samples. Reciprocally, the N data symbols are recovered through the FFT of the N samples of an OFDM symbol.

Additionally, a guard interval is added before the OFDM symbol in order to avoid Inter-Symbol-Interference (ISI) between two consecutive OFDM symbols. This guard interval exactly replicates the end of the OFDM symbol and is usually referred to as Cyclic Prefix (CP). Thus, even if the FFT window begins within the CP, the data symbols are properly recovered (only affected by a phase rotation). As a result demodulation does not require precise timing synchronization. The block diagram of the basic transmission chain is presented in Fig. 3.

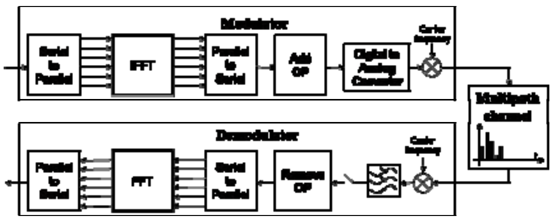

Figure 3: Transmission chain of OFDM [30]

Such a modulation is extremely convenient since it can use multipath to better demodulate the data using simple channel estimation algorithm. It can thus also be used in synchronized Single-frequency Networks (all emitters broadcast in the same frequency band) as long as the received signals are all received within the CP duration, thus requiring a synchronization of each emitter.

To demodulate properly the OFDM symbols the receiver has to perform several operations:

- rough timing synchronization to ensure that the FFT window starts at the beginning of the OFDM symbol or at the end of the CP,
- fine frequency synchronization to maintain the sub-carrier orthogonality and thus avoid Inter-Carrier Interference (ICI), and
- channel equalization to compensate for the channel effects.

To perform these operations, an OFDM symbol contains several pilot sub-carriers that carry known symbols. These pilot sub-carriers ease the Channel Impulse Response (CIR) estimation algorithm. Once the CIR has been estimated, it is then possible to deduce the propagation time of the first received signal and thus compute a pseudorange. Obviously, for ground networks, the propagation channel in urban environment is such that isolating the Line-Of-Sight signal is a great challenge [22].

The European Telecommunications Standard Institute (ETSI) developed the DVB-SH (Digital Video Broadcasting - Satellite to Handheld) 0 standard for use in S-band. DVB-SH could be use in mobile television systems and can provide positioning functions [30]. A DSP of such a DVB-SH signal is shown in Fig. 4. It is planned to use a combination of ground stations and geostationary complement in a synchronous SFN network.

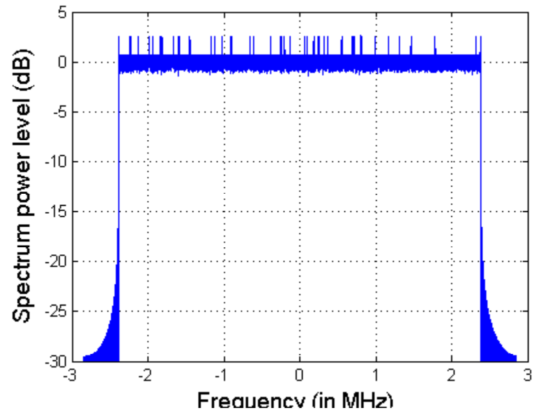

Figure 4 : DSP of a DVB-SH OFDM signal in S-band

A positioning principle using DVB-SH signal in SFN network is presented in [30]. This article shows how it is possible to compute pseudorange measurements in a SFN and in an urban environment using ground-stations based on the correlation of the pilot sub-carriers. This technique is thus also applicable for MEO stations. The position computation can then be obtained from Time-Difference Of Arrival (TDOA) measurements since emitters are assumed synchronized.

Assuming one OFDM emitter, the pseudorange accuracy in presence of strong LOS is comparable to that of CDMA with a similar bandwidth, since the tracking techniques are similar. The theoretical standard deviation of tracking error is illustrated in Fig. 5. The parameters are: mode 2K (2048-FFT size), signal bandwidth of 5 MHz and loop noise bandwidth of 10 Hz. The tracking performance is quite good even for low SNR.

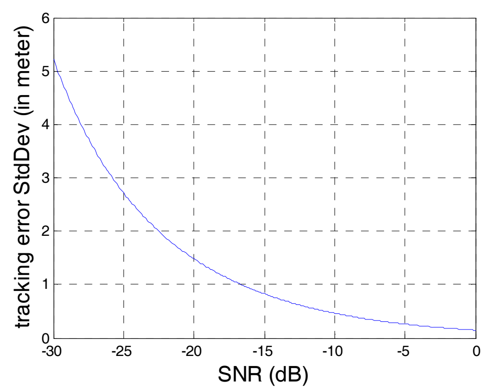

Figure 5: Tracking error standard deviation versus SNR

The multipath error envelope is detailed in Fig. 6. The second path is considered to have an amplitude half of the LOS. As the mode 2K and a 5 MHz signal bandwidth are used., the envelope presents some oscillations due to the secondary lobes of the correlation function. Nevertheless the ranging error is limited compared to GPS C/A for instance.

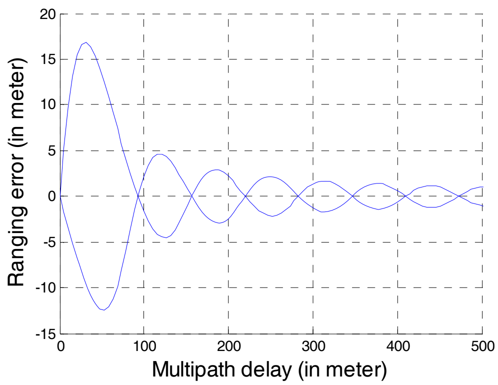

Figure 6: Multipath error envelope

A RDSS system using OFDM instead of DSSS/CDMA could provide comparable pseudorange measurements [31] while offering an efficient use of the available bandwidth and a communication service which could be interesting to supply additional purposes (LBS, integrity, aiding data, messages, other data channels, etc) and/or navigation data (ephemeris, almanacs, other references data, etc…).

CONCLUSIONS

This paper shows that hypothetical S band GALILEO signals could add new interesting services potentially combining mobile satellite communications and S-band navigation solutions.

Performance improvement is not the main driver for other frequencies additional to L-band; but rather the opportunity for novel new uses.

Other frequency band options are studied for GALILEO evolutions, but in any case any hypothetical new signal would be added to the legacy current complement of GALILEO signals, to preserve the backward compatibility essential for users.

The paper shows the radio frequency compatibility between S-band RDSS systems, Globalstar, and other terrestrial mobile or fixed services. The results presented could be compared to radio frequency compatibility work that may be required in five to ten years time in the more crowded L1 band, where in the worst case a C/No degradation close to 2.5 dB occurs as a result of other L1 RNSS systems, without even considering non-RNSS interference which has many sources in L1.

Potential additional Galileo signals in S-band therefore look promising. But they need to be studied in more detail with trade-offs considered between the various potential new frequency band options. Possible modulations for GNSS in S-band are BPSK, BOC, MBOC or OFDM. To support potential future signals a Galileo 2 filing, including 2.5GHz, has already been submitted to the ITU and is available on their website.

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APPENDIX 1: GLOBALSTAR SIGNAL.

Globalstar uses the 2483.5–2500 MHz band for its downlink communications between the satellite and user terminals. The system uses multi-beam antennas to allow frequency reutilization. In every beam, the 16.5 MHz bandwidth is divided into 13 FDM channels, each 1.23 MHz wide, as shown in the figure 7.

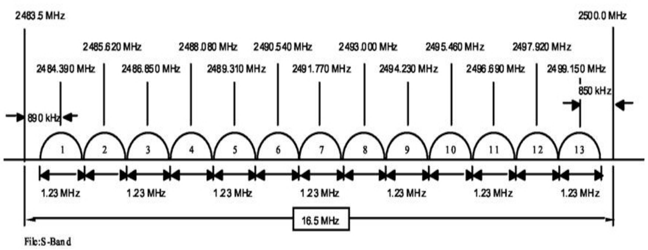

Figure 7: Globalstar FDMA scheme.

CDMA with a chipping rate of 1.2288 Mcps is implemented inside every FDM channel. 128 chips long Walsh codes are used to distinguish the users, which gives 128 orthogonal codes per channel. The data + Walsh code stream is first modulated by an outer PN sequence (1200 chips length). An inner PN sequence pair is then used to get a QPSK modulation, as shown in figure 2. One inner PN sequence period exactly fits into a single outer PN chip. The outer PN modulates the inner PN sequence to produce the actual spreading sequence resulting in a period of 240 ms. It is noted that the inner PN sequence pair identifies the satellite orbital plane; so there are eight different pairs. The outer PN sequence identifies the satellite, and finally, each satellite beam is identified by a different time offset of the outer PN sequence.

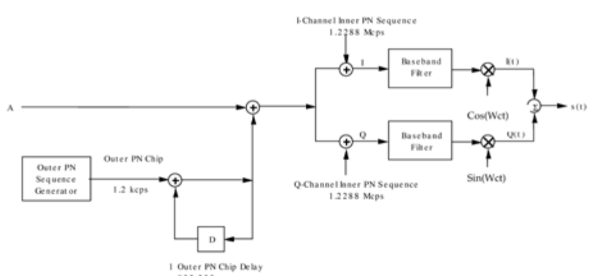

Figure 8 : Generation of the Globalstar signal

Before modulation of the carrier, both I and Q components are filtered by a Nyquist-square-root raised-cosine (SRC) filter with roll-off factor ρ=0.2. The use of the raised cosine filter yields the following power spectral density (PSD) for a given kth FDMA channel in baseband:

$$G^{k}_{SRC}(f) = \begin{cases} 1 & if \quad |f-kB| \le \frac{B}{2}(1-\rho) \\ 0 & if \quad |f-kB| \ge \frac{B}{2}(1+\rho) \\ g(f) & if \quad \frac{B}{2}(1-\rho) \le |f-kB| \le \frac{B}{2}(1+\rho) \end{cases}$$

k=-6…6

Where:

- $$g(f) = 1+\cos\left(\frac{\pi}{2\rho f_c}(f-\rho f_c - kB)\right)$$
- f_c is the cut-off frequency of the filter, f_c=B/2, being B=1.23 MHz the bandwidth of a single FDMA channel.
- ρ the roll-off factor.

Finally, the whole Globalstar signal PSD can be expressed as the sum of the PSDs of the 13 FDMA channels:

$$G_{GLOB}(f) = \sum_{k=-6}^{6} G^{k}_{SRC}(f)$$