APPENDIX C

SATELLITE NAVIGATION

GPS SIGNAL CODING

App C 001. The GPS L1 Band

The GPS L1 band (1575.42 MHz) has turned out to be the most important band for navigation purposes. Indeed most of the applications in the world nowadays are based on the signals transmitted at this frequency. Three signals are transmitted at the moment by GPS in L1: C/A Code, P(Y) Code and M-Code. In the future, an additional new civil signal, known as L1C, will also be transmitted. We describe all of them in the next lines:

- The Coarse/Acquisition (C/A) code signal was primarily thought of for acquisition of the P (or Y) code and has become nowadays the most important signal for mass market applications.
- The P Code is the precision signal and is coded by the precision code. Moreover the Y-Code is used in place of the P-code whenever the Anti-Spoofing (A/S) mode of operation is activated as described in the GPS ICDs 203, 224 and 225.
- The modernized military signal (M-Code) is designed exclusively for military use and is intended to eventually replace the P(Y) code [E. D. Kaplan and C. Hegarty, 2006]. The M-Code provides better jamming resistance than the P(Y) signal, primarily through enabling transmission at much higher power without interference with C/A code or P(Y) code receivers [B.C. Barker et al., 2000]. Moreover, the M-Code provides more robust signal acquisition than is achieved today, while offering better security in terms of exclusivity, authentication, and confidentiality, along with streamlined key distribution. In other aspects, the M-Code signal provides much better performance than the P(Y) Code and more flexibility.
- The L1 Civil signal (L1C), defined in the [GPS ICD-800], consists of two main components; one denoted $L1C_P$ to represent the pilot signal, consisting of a time-multiplexing of Binary Offset Carrier BOC(1,1) and BOC(6,1), thus without any data message, and $L1C_D$ with a pure BOC(1,1), for the data channel. This is spread by a ranging code and modulated by a data message. The pilot channel $L1C_P$ is also modulated by an SV unique overlay secondary code, $L1C_O$.

For more details on the code generation refer to the [GPS ICD 200] and [GPS ICD-800]. Finally, the technical characteristics of the existing and planned GPS signals in the L1 band are summarized in the following Table 001.

GNSS System	**GPS**	**GPS**		**GPS**	**GPS**
Service Name	C/A	L1C		P(Y) Code	M-Code
Center Frequency	1575.42 MHz	1575.42 MHz		1575.42 MHz	1575.42 MHz
Frequency Band	L1	L1		L1	L1
Access Technique	CDMA	CDMA		CDMA	CDMA
Signal Component	Data	Data	Pilot	Data	N/A
Modulation	BPSK(1)	TMBOC(6,1,1/11)		BPSK(10)	$BOC_{sin}(10,5)$
Sub-carrier Frequency [MHz]	-	1.023	1.023 & 6.138	-	10.23
Code Frequency	1.023 MHz	1.023 MHz		10.23 MHz	5.115 MHz
Primary PRN Code Length	1023	10230		6.19×10^{12}	N/A
Code Family	Gold Codes	Weil Codes		Combo and short cycling of M-sequences	N/A

Table 001. GPS L1 signal technical characteristics.

GNSS System	GPS	GPS		GPS	GPS
Secondary PRN Code Length	-	-	1800	-	N/A
Data Rate	50 bps/ 50 sps	50 bps/ 100 sps	-	50 bps/ 50 sps	N/A
Minimum Received Power [dBW]	-158.5	-157		-161.5	N/A
Elevation	5°	5°		5°	5°

Table 001. GPS L1 signal technical characteristics.

Of all the signals shown in Table 001, the C/A Code is the best known as most of the receivers that have been built un-til today are based on it. The C/A Code was open from the very beginning to all users, although until May 1, 2000, an artificial degradation was introduced by means of the **Select Availability** (**SA**) mechanism which added an intentional distortion to degrade the positioning quality of the signal to non-desired users. As we have already mentioned, the C/A Code was thought to be an aid for the P(Y) Code (to realize a Coarse Acquisition). The M-Code is the last military sig-nal that has been introduced in GPS.

For a long time different signal structures for the M-Code were under consideration [J.W. Betz, 2001] being the Manchester code signals - **Binary Phase Shift Keying** (**BPSK**) and the **binary offset carrier** (**BOC**) signals the two favored candidates. Both solutions result from the modulation of a non-return to zero (NRZ) pseudo random noise spreading code by a square-wave sub-carrier. While the Manchester code has a spreading code of rate equal to that of the square-wave, the BOC signal does not necessar-ily have to be so, being the only constraint that the rate of the spreading code must be less than the sub-carrier frequency.

The interesting aspect about these signals is that, like the conventional sub-carrier modulation, the waveform presents a zero at the carrier frequency due to the square-wave sub-carrier. In fact, their split-power spectra clearly facilitate the compatibility of the GPS military M-Code sig-nal with the existing C/A Code and P(Y) Code. See Figure 001 - *Spectra of GPS signals in L1*.

We can clearly recognize that GPS L1C concentrates more power at higher frequencies - due to BOC(6,1) - in the pilot channel than in the data channel.

Finally, it is important to note that for all the figures next the commonly used expressions for bandwidths in MHz must be understood as multiplied by the factor 1.023. Thus BPSK(10) refers in reality to a BPSK signal with a chip rate of 10.23 MHz. This remains valid for all the band-widths in this thesis, unless different stated otherwise

App C 002. The GPS L2 Band

GPS is transmitting in the L2 band (1227.60 MHz) a modernized civil signal known as L2C together with the P(Y) Code and the M-Code. The P(Y) Code and M-Code were already described shortly in the previous chapter and the properties and parameters are thus similar to those in the L1 band. In addition, for Block IIR-M, IIF, and subsequent blocks of SVs, two additional PRN ranging codes will be transmitted. They are the L2 Civil Moderate (L2 CM) code and the L2 Civil Long (L2 CL) code. These two signals are time multiplexed so that the resulting chipping rate is double as high as that of each individual signal. We further describe them in the next lines more in detail:

- L2 CM Code is transmitted in the IIR-M, IIF, and subsequent blocks. The PRN L2 CM Code for SV number i is a ranging code, $CM_i(t)$, which is 20 milliseconds in length at a chipping rate of 511.5 Kbps. The epochs of the L2 CM Code are synchronized with the X1 epochs of the P-code. The $CM_i(t)$ sequence is a linear pattern which is short cycled every count period of 10,230 chips by resetting with a particular initial state. Furthermore, for Block IIR-M, the navigation data is also Modulo-2 added to the L2 CM Code. It is interesting to note that the navigation data can be used in one of two different data rates selectable by ground command: 1) D(t) with a data rate of 50 bps, or 2) D(t) with a symbol rate of 50 symbols per second (sps) which is obtained by encoding D(t) with a data rate of 25 bps coded in a rate 1/2 convolutional code. Finally, the resultant bit-train is combined with the L2 CL Code using time-division multiplexing.
- L2 CL Code is transmitted in the IIR-M, IIF, and subsequent blocks. The PRN L2 CL Code for SV number i is a ranging code, $CL_i(t)$, which is 1.5 seconds in length at a chipping rate of 511.5 Kbps. The epochs of the L2 CL Code are synchronized with the X1 epochs of the P Code. The $CL_i(t)$ sequence is a linear pattern which is generated using the same code generator polynomial as of $CM_i(t)$. However, the $CM_i(t)$ sequence is short cycled by resetting with an initial state every count period of

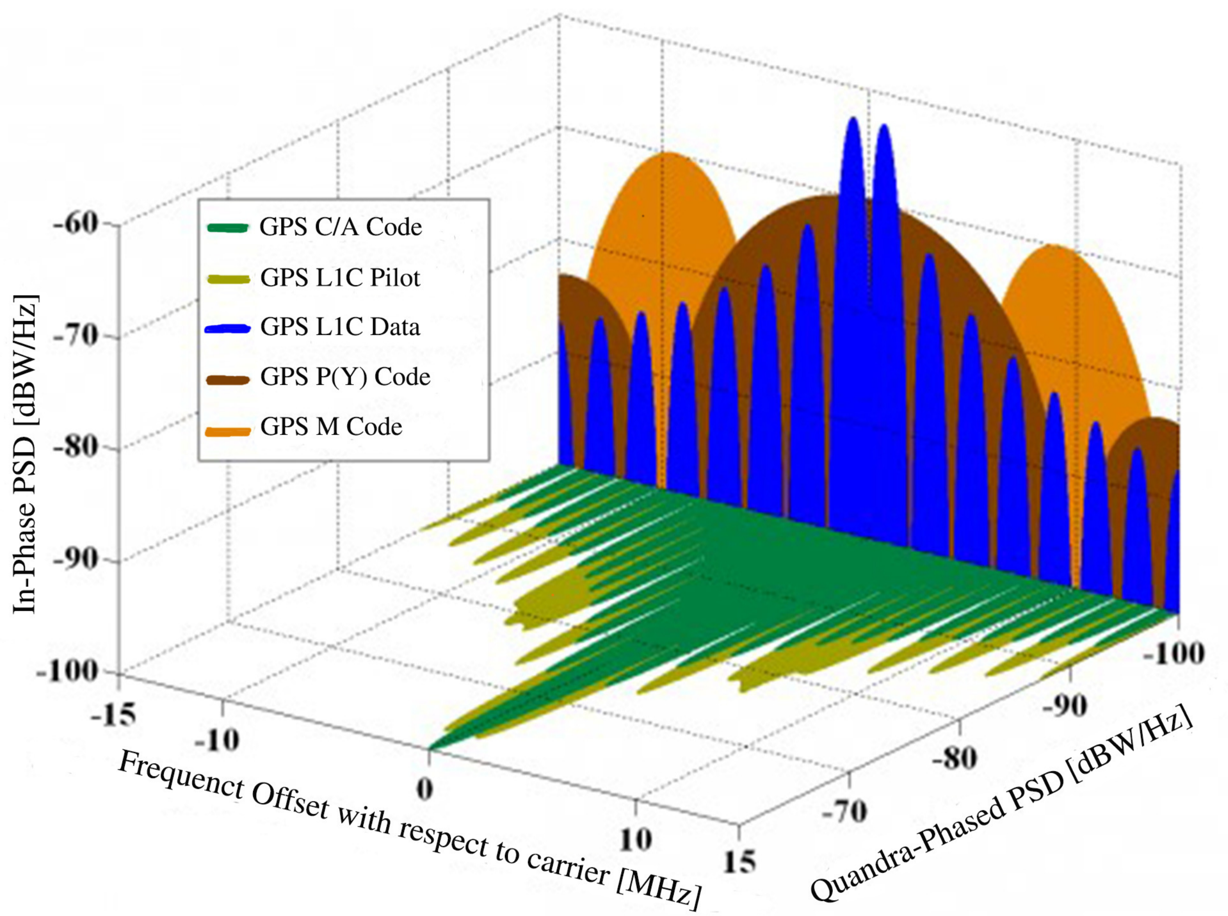

Figure 001. Spectra of GPS signals in L1. Image courtesy of Dr. Jose Angel Avila Rodriguez.

767,250 chips.

Finally, it is important to note that the GPS L2 band will have a transition period from the C/A Code to L2C and mixed configurations could occur. Figure 002a shows the baseband L2 signal generation scheme. As we can recog- nize, although the chipping rate of the L2 CM and L2 CL signals is of 511.5 Kbps individually, after the time multi-plexing the composite signal results in a stream of 1.023 MHz.

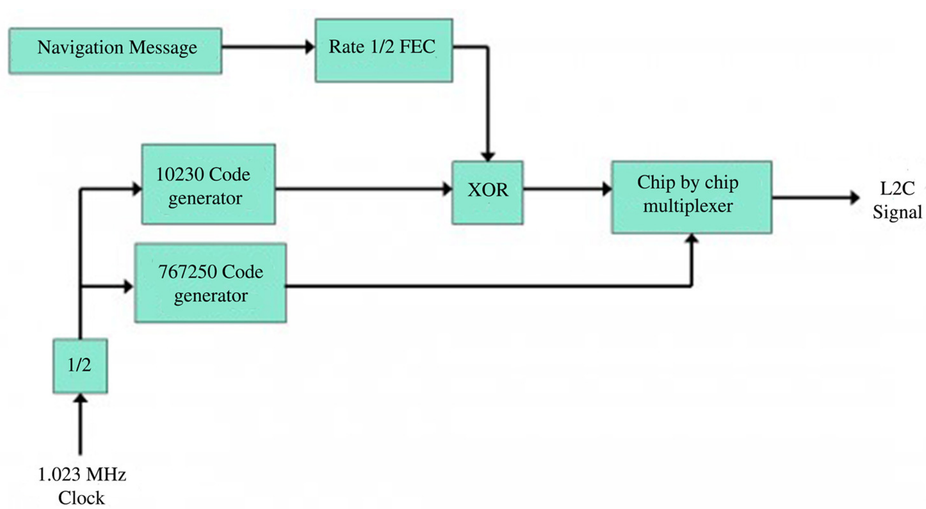

Figure 002a. Modulation scheme for the GPS L2 signals. Image courtesy of Dr. Jose Angel Avila Rodriguez.

The technical characteristics of the GPS L2 signals are summarized in Table 002a and the spectra of the different sig- nals (L2C, P(Y) Code, and M-Code) are given in Figure 002b.

GNSS System	GPS	GPS	GPS	GPS
Service Name	L2 CM	L2 CL	P(Y) Code	M-Code
Center Frequency	1227.60 MHz	1227.60 MHz	1227.60 MHz	1227.60 MHz
Frequency Band	L2	L2	L2	L2
Access Technique	CDMA	CDMA	CDMA	CDMA
Spreading Modulation	BPSK(1) result of multiplexing 2 streams at 511.5 kHz		BPSK (10)	$BOC_{sin}(10,5)$
Sub-carrier Frequency [MHz]	-	-	-	10.23
Code Frequency	511.5 kHz	511.5 kHz	10.23 MHz	5.115 MHz
Signal Component	Data	Pilot	Data	N/A
Primary PRN Code Length	10,230 (20 ms)	767,250 (1.5 seconds)	6.19×10^{12}	N/A
Code Family	M-sequence from a maximal polynomial of degree 27		Combo and short cycling of M-sequences	N/A
Secondary PRN Code Length	-	-	-	N/A
Data Rate	IIF 50 bps / 50 sps IIR-M Also 25 bps 50 sps with FEC	-	50 bps/ 50 sps	N/A
Minimum Received Power [dBW]	II/IIA/IIR -164.5 dBW IIR-M -161.5 dBW IIF -161.5 dBW		II/IIA/IIR -164.5 dBW IIR-M -161.4 dBW IIF -160.0 dBW	N/A
Elevation	5°		5°	5°

Table 002a GPS L2 signal technical characteristics.

App C 003. The GPS L5 Band

The GPS L5 (1176.45 MHz) signal will be transmitted for the first time on board IIF satellites. The GPS carriers of the L5 band are modulated by two bit trains in phase quadrature: the L5 data channel and the L5 pilot channel. Moreover, two PRN ranging codes are transmitted on L5: the in-phase code (denoted as the I5-code) and the quadraphase code (denoted as the Q5-code). The PRN L5-codes for SV number i are independent, but time synchronized ranging codes, $X_I^i(t)$ and $X_Q^i(t)$, of 1 millisecond in length at a chipping rate of 10.23 Mbps [GPS ICD-705]. For each code, the 1-millisecond sequences are the modulo-2 sum of two sub-sequences referred to as XA and XBi with lengths of 8,190 chips and 8,191 chips respectively, which restart to generate the 10,230 chip code. The XBi sequence is selectively delayed, thereby allowing the basic code generation technique to produce the different satellite codes.

See Figure 003a for the modulation scheme for the GPS L5 signals. See Figure 003b for the spectra of the GPS signals in L5. For more detail on L5, refer to (E.D. Kaplan and C. Hegarty, 2006). See Table 003 for the technical characteris-tics of the GPS signal in L5.

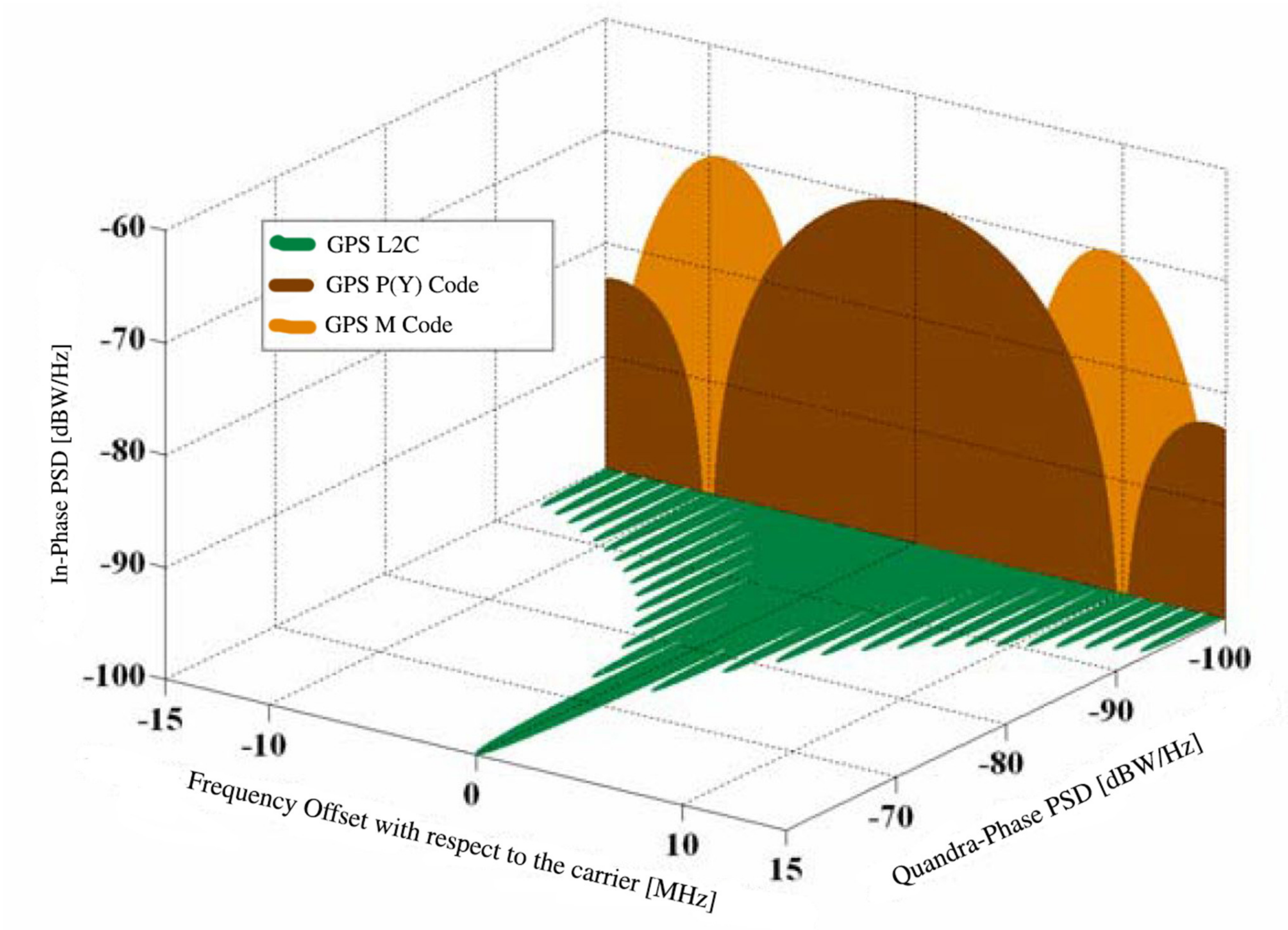

Figure 002b. Spectra of the GPS signals in L2. Image courtesy of Dr. Jose Angel Avila Rodriguez.

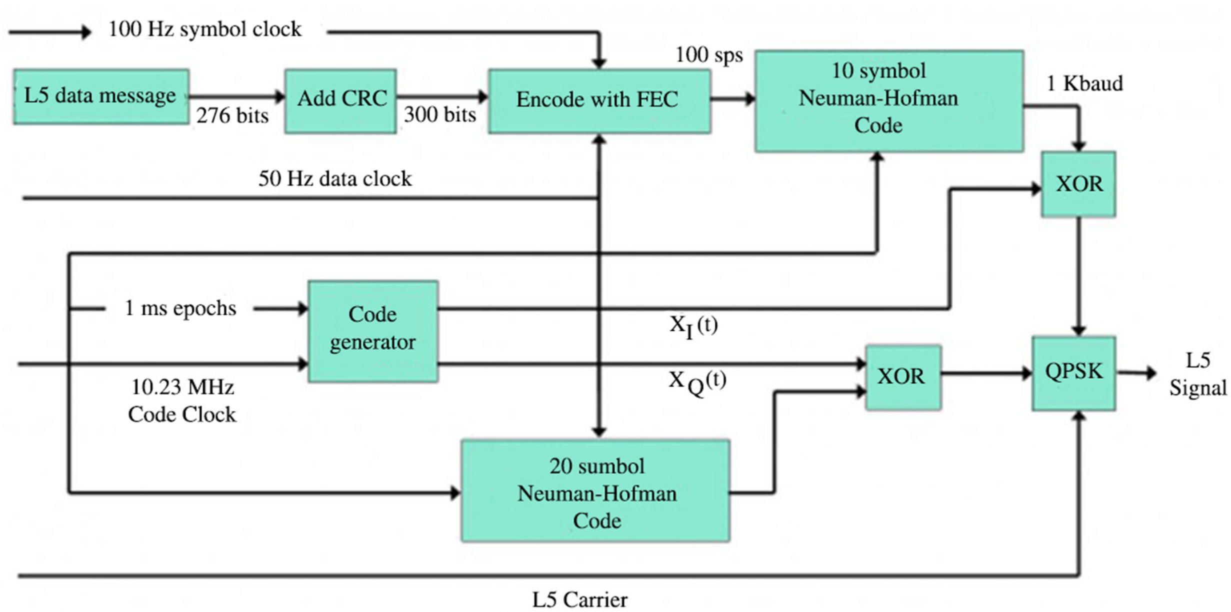

Figure 003a. Modulation scheme for the GPS L5 signals. Image courtesy of Dr. Jose Angel Avila Rodriguez.

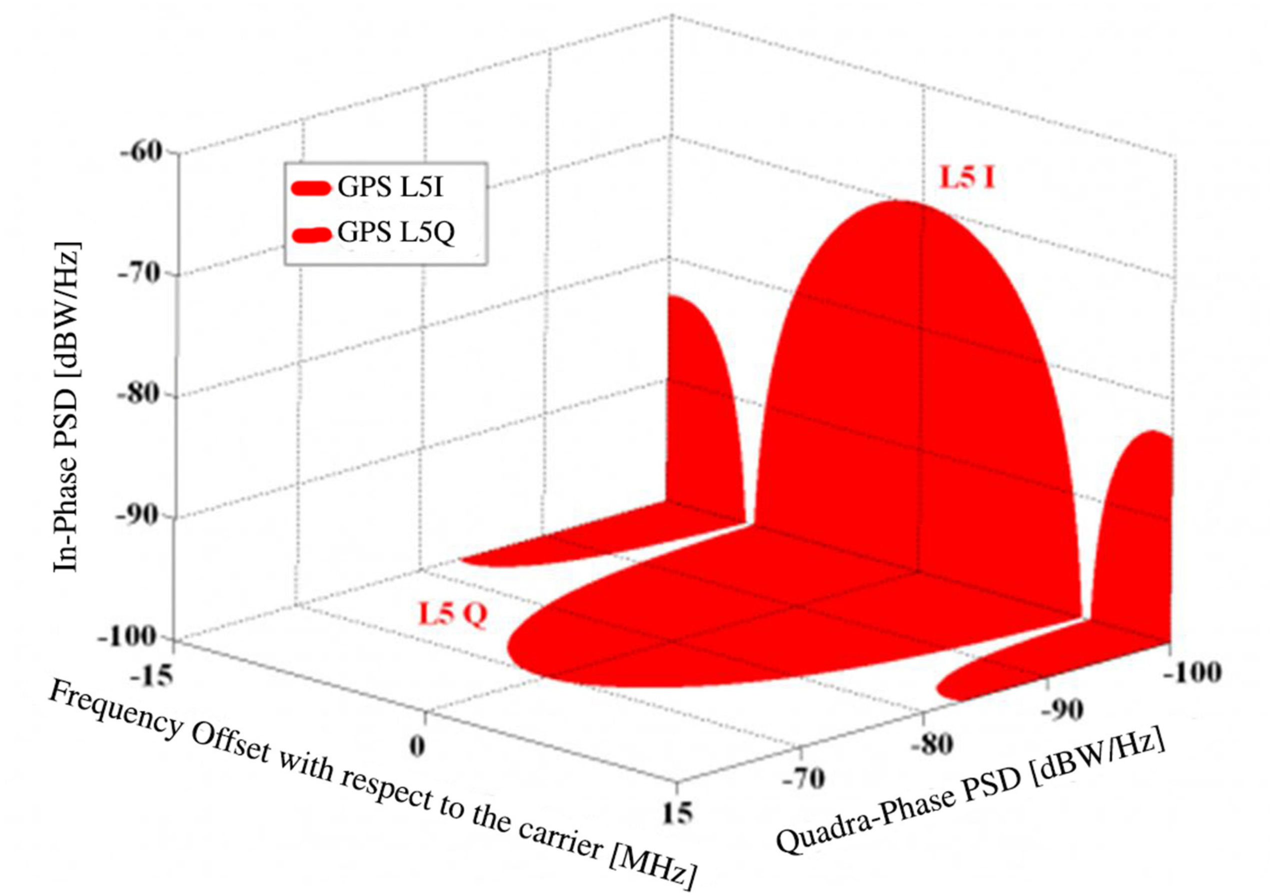

Figure 003b. Spectra of the GPS signals in L5.Image courtesy of Dr. Jose Angel Avila Rodriguez.

GNSS System	**GPS**	**GPS**
Service Name	L5I	L5Q
Center Frequency	1176.45 MHz	1176.45 MHz
Frequency Band	L5	L5
Access Technique	CDMA	CDMA
Spreading modulation	BPSK(10)	BPSK(10)
Sub-carrier Frequency	-	-
Code Frequency	10.23 MHz	10.23 MHz
Signal Component	Data	Pilot
Primary PRN Code Length	10230	10230
Code Family	Combination and short-cycling of M-sequences	
Secondary PRN Code Length	10	20

Table 003 GPS L5 signal technical characteristics.

GNSS System	GPS	GPS
Data Rate	50 bps/ 100sps	-
Minimum Received Power [dBW]	-157.9 dBW	-157.9 dBW
Elevation	5°	5°

Table 003 GPS L5 signal technical characteristics.

THE GALILEO SIGNAL PLAN

App C 004. Galileo E1 Open Service Band

The E1 Open Service (OS) modulation receives the name of CBOC (Composite Binary Offset Carrier) and is a particular implementation of MBOC (Multiplexed BOC) [J.-A. Avila-Rodriguez et al., 2007]. MBOC(6,1,1/11) is the result of multiplexing a wide band signal - BOC(6,1) - with a narrow band signal - BOC(1,1) - in such a way that 1/11 of the power is allocated, in average, to the high frequency component. This signal was the last one to be defined.

The normalized (unit power) power spectral density, specified without the effect of band-limiting filters and payload imperfections, is given by $G_{MBOC(6,1,1/11)}(f) = \frac{10}{11}G_{BOC(1,1)}(f) + \frac{1}{11}G_{BOC(6,1)}(f)$.

As in [Galileo SIS ICD, 2010], the generic view of the E1 Open Service signal generation can be depicted as follows [J.-A. Avila-Rodriguez et al., 2007] in Figure 004a - *Modulation Scheme for Galileo E1 OS Signals:*

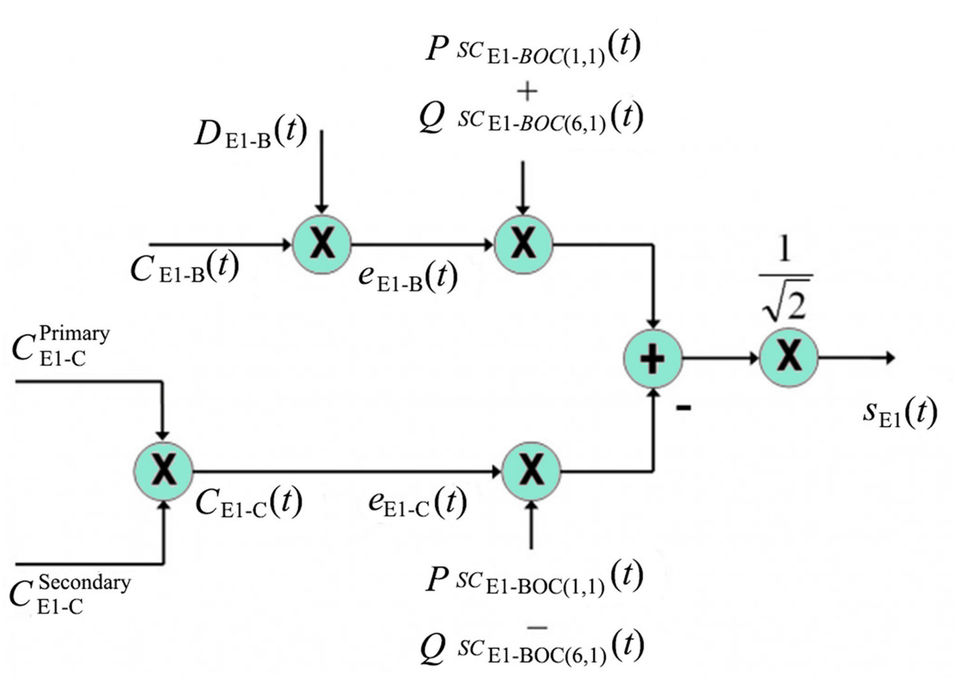

Figure 004a. Modulation scheme for Galileo E1 OS signals.Image courtesy of Dr. Jose Angel Avila Rodriguez.

The whole transmitted Galileo E1 signal consists of the multiplexing of the three following components:

- The E1 Open Service Data channel $e_{E1-B}(t)$ is generated from the I/NAV navigation data stream $D_{E1-B}(t)$ and the ranging code $C_{E1-B}(t)$, which are then modulated with the sub-carriers $SC_{E1-BOC(1,1)}(t)$ and $SC_{E1-BOC(6,1)}(t)$ of BOC(1,1) and BOC(6,1) respectively.
- The E1 Open Service Pilot channel $e_{E1-C}(t)$ is generated from the ranging code $C_{E1-C}(t)$, including its secondary code, which is then modulated with the sub-carriers $SC_{E1-BOC(1,1)}(t)$

and $SC_{E1-BOC(6,1)}(t)$ in anti-phase.

- The E1 PRS channel, also denoted as E1-A, which results from the modulo-two addition (respectively product if we consider the physical bipolar representation of the signal) of the PRS data stream $D_{PRS}(t)$, the PRS sequence $C_{PRS}(t)$ and the sub-carriers $SC_{PRS}(t)$. This sub-carrier consists of a BOC(15,2.5) in cosine phasing.

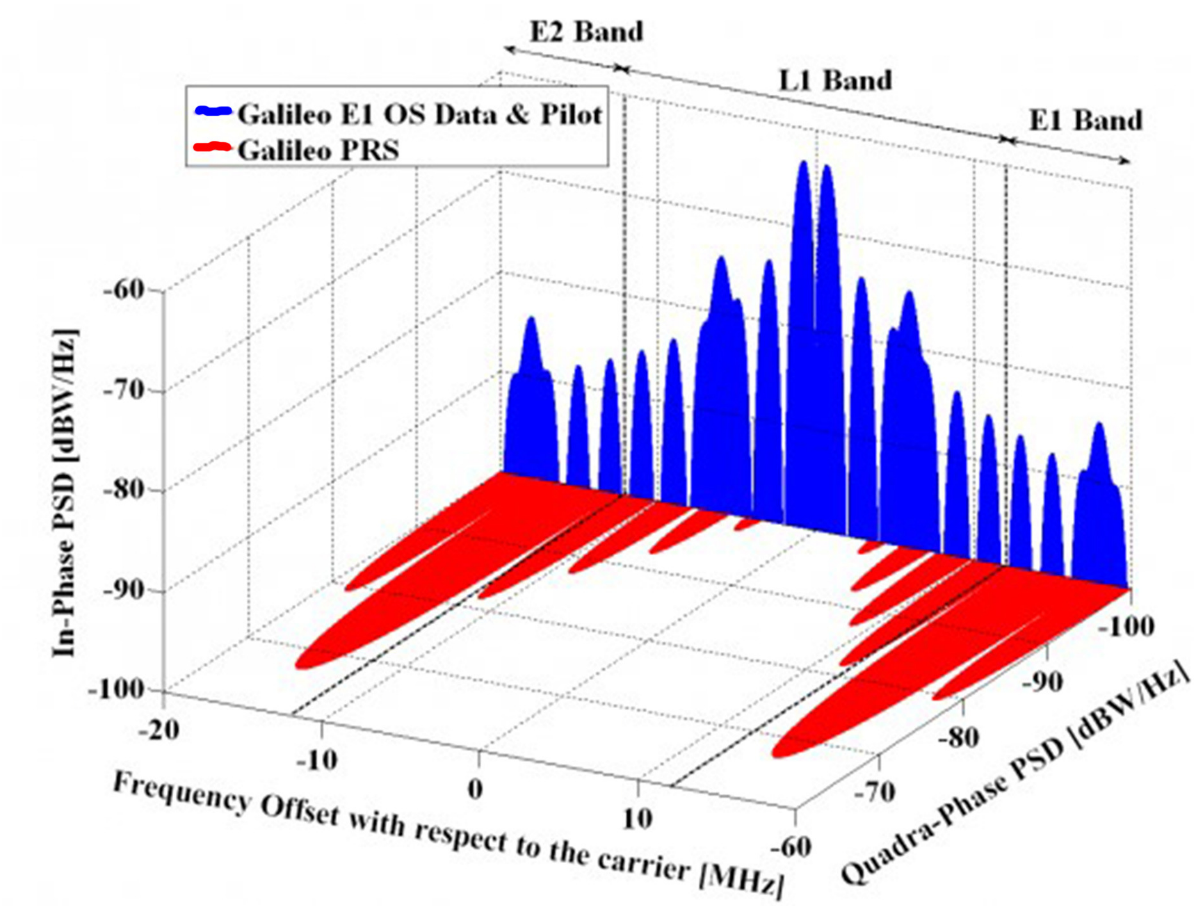

Figure 004b. Spectra of Galileo signals in E1. Image courtesy of Dr. Jose Angel Avila Rodriguez.

See for the Spectra of Galileo Signals in E1 (see Figure 004b) and for the Spectra of both GPS and Galileo Signals in L1 (see Figure 004c).

It is important to recall that for a long time the actual E1 band received the name of L1 band in analogy with GPS and it was not until the publication of the [Galileo SIS ICD, 2008] that L1 changed to the current E1.

The E1 Open Service (OS) codes are, as well as the E6 CS codes that we will see later, also random memory codes. The plain number of choices to set the 0's and 1's for the whole code family is enormous and thus special algorithms have to be applied to generate random codes efficiently [J.-A. Avila-Rodriguez et al., 2007].

Finally, the technical characteristics of all the Galileo signals in E1 are summarized in Table 004.

App C 005. Galileo E6 Band

As shown in [Galileo SIS ICD, 2010], the transmitted Galileo E6 signal consists of the following three components:

- The E6 Commercial Service (CS) data channel: this modulating signal is the modulo-two addition of the E6 CS navigation data stream $D_{CS}(t)$ with the CS data channel code sequence $D_{CS}^{D}(t)$. This last one is already modulated by a BPSK(5) at 5.115 MHz.
- The E6 Commercial Service (CS) pilot channel: this modulating signal is the modulo-two addition of the E6 CS pilot channel code $C_{CS}^{P}(t)$ with a BPSK(5) at 5.115 MHz.
- Finally, the E6 PRS channel is the modulo-two

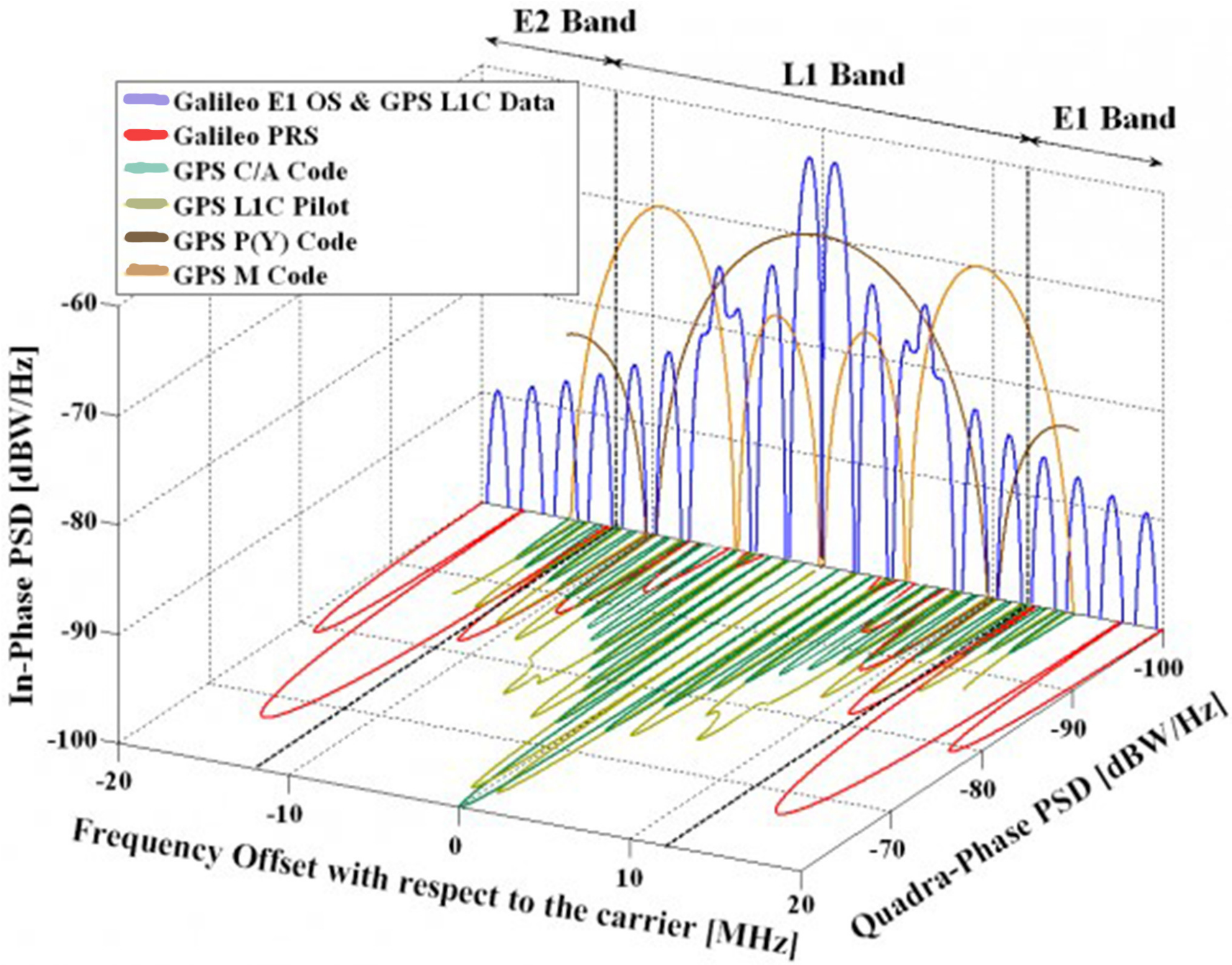

Figure 004c. Spectra of GPS and Galileo signals in L1. Image courtesy of Dr. Jose Angel Avila Rodriguez.

GNSS System	Galileo	Galileo	Galileo
Service Name	E1 OS		PRS
Center Frequency	1575.42 MHz		
Frequency Band	E1		
Access Technique	CDMA		
Spreading modulation	CBOC(6,1,1/11)		BOC_{cos}(15,2.5)
Sub-carrier Frequency	1.023 MHz and 6.138 MHz (two sub-carriers)		15.345 MHz
Code Frequency	1.023 MHz		2.5575 MHz
Signal Component	Data	Pilot	Data
Primary PRN Code Length	4092		N/A
Code Family	Random Codes		N/A

Table 004. Galileo E1 signal technical characteristics.

GNSS System	Galileo	Galileo	Galileo
Secondary PRN Code Length	-	25	N/A
Data Rate	250 sps	-	N/A
Minimum Received Power [dBW]	-157 dBW		N/A
Elevation	10°		N/A

Table 004. Galileo E1 signal technical characteristics.

addition of the E6 PRS navigation data stream $D_{PRS}(t)$ with the PRS channel code sequence $C_{PRS}(t)$ at 5.115 MHz. This signal is further modulated by a sub-carrier of 10.23 MHz in cosine phasing.

This is graphically shown in Figure 005a - *Modulation Scheme for the Galileo E6 Signals* and Figure 005b - Spectra of Galileo signals in E6. Table 005a provides the technical characteristics of the Galileo E6 signal. The E6 Commercial Service (CS) codes are random codes [J. Winkel, 2006]. The main idea behind is to generate a family of codes that fulfills the properties of randomness as well as possible [J.-A. Avila-Rodriguez et al., 2007]. The codes can be driven to fulfill special properties such as balance and weakened balance, where the probability of 0's and 1's must not be identical but within a well-defined range, or to realize the autocorrelation side-lobe zero (ASZ) property. This latter property guarantees that the autocorrelation values of every code correlate to zero with a delayed version of itself, shifted by one chip.

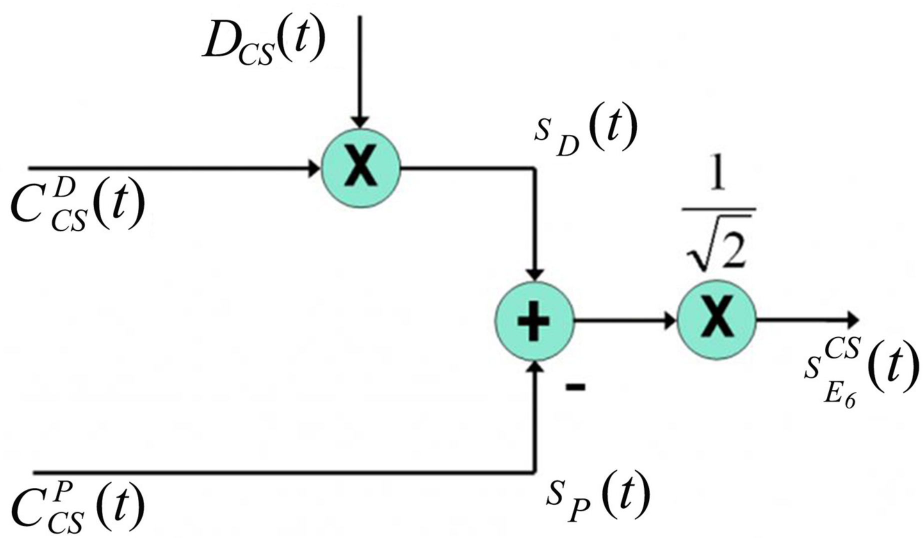

Figure 005a. Modulation scheme for Galileo E6 signals. Image courtesy of Dr. Jose Angel Avila Rodriguez.

App C 006. Galileo E5 Band

The different Galileo E5 signal components are generated according to the following [Galileo SIS ICD, 2010]:

- The **E5a data channel**: This channel is the modulo-two addition of the E5a navigation data stream $D_{E5a}(t)$ with the E5a data channel PRN code sequence $C^D_{E5a}(t)$ of chipping rate 10.23 MHz.
- The **E5a pilot channel**: This channel is the E5a pilot channel PRN code sequence $C^P_{E5a}(t)$ of chipping rate 10.23 MHz.
- The **E5b data channel**: This channel is the modulo-two addition of the E5b navigation data stream $D_{E5b}(t)$ with the PRS channel code sequence $C_{PRS}(t)$ with the E5b data channel PRN code

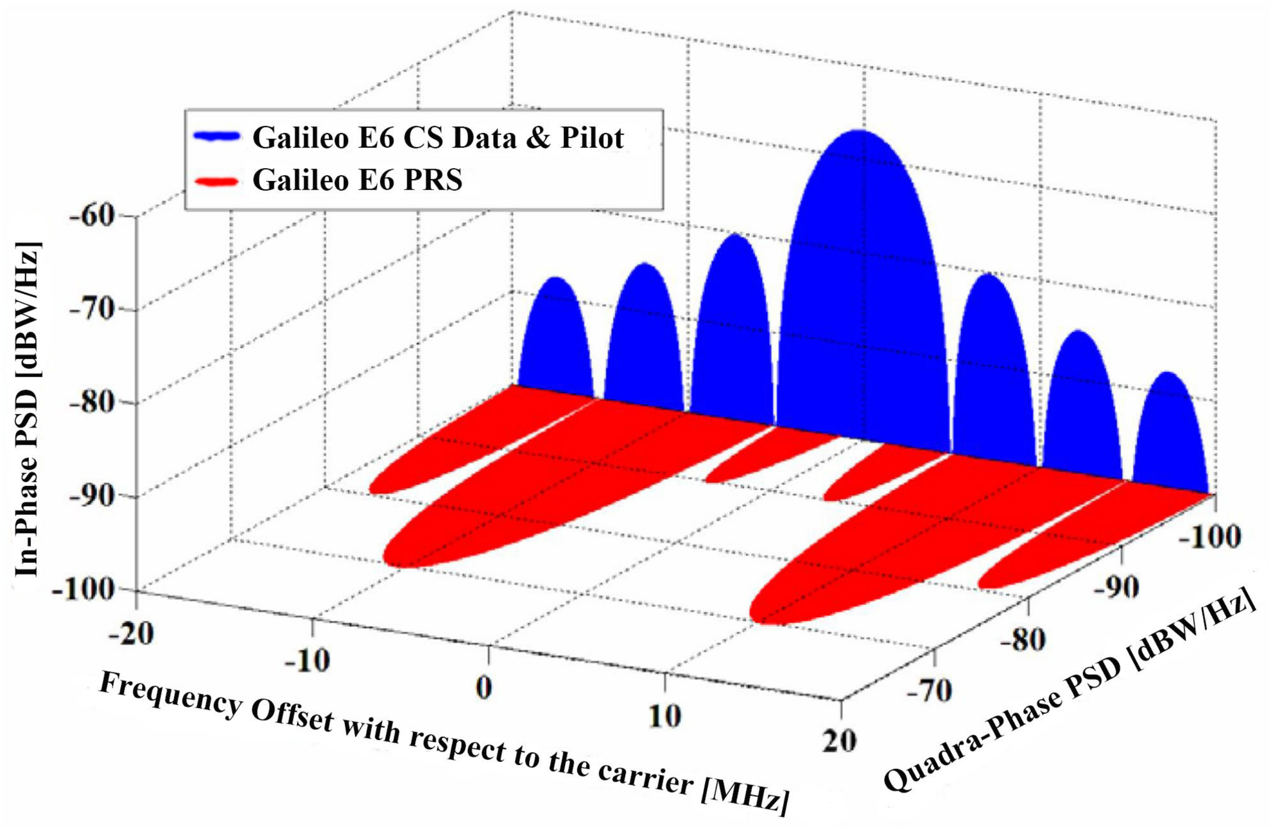

Figure 005b. Modulation scheme for Galileo E6 signals. Image courtesy of Dr. Jose Angel Avila Rodriguez.

GNSS System	Galileo	Galileo	Galileo
Service Name	E6 CS data	E6 CS pilot	E6 PRS
Center Frequency	1278.75 MHz		
Frequency Band	E6		
Access Technique	CDMA		
Spreading modulation	BPSK(5)	BPSK(5)	$BOC_{cos}(10.5)$
Sub-carrier Frequency	-	-	10.23 MHz
Code Frequency	5.115 MHz		
Signal Component	Data	Pilot	Data
Primary PRN Code Length	5115	5115	N/A
Code Family	Memory codes		N/A
Secondary PRN Code Length	-	100	N/A
Data Rate	1000 sps	-	N/A
Minimum Received Power [dBW]	-155 dBW		N/A

Table 005a. Galileo E6 signal technical characteristics.

GNSS System	Galileo	Galileo	Galileo
Elevation	10°		N/A

Table 005a. Galileo E6 signal technical characteristics.

sequence $C^{D}_{E5b}(t)$ of chipping rate 10.23 MHz.

- The **E5b pilot channel**: This channel is the E5b pilot channel PRN code sequence $C^{P}_{E5b}(t)$ of chipping rate 10.23 MHz.

The E5 modulation receives the name of AltBOC and is a modified version of a Binary Offset Carrier (BOC) with code rate of 10.23 MHz and a sub-carrier frequency of 15.345 MHz. AltBOC(15,10) is a wideband signal that is transmitted at 1191.795 MHz. Figure 006a shows the Galileo E5 signal modulation diagram.

The power spectral density for the modified AltBOC(15,10) modulation with constant envelope is shown to adopt the form:

$$G_{\mathrm{AltBOC}}(f) = \frac{4f_c}{\pi^2 f^2} \frac{\cos^2\left(\frac{\pi f}{f_c}\right)}{\cos^2\left(\frac{\pi f}{2f_z}\right)}\left[\cos^2\left(\frac{\pi f}{2f_z}\right) - \cos\left(\frac{\pi f}{2f_z}\right) - 2\cos\left(\frac{\pi f}{2f_z}\right)\cos\left(\frac{\pi f}{4f_z}\right) + 2\right]$$

The spectrum of the E5 signal modulation is shown in Figure 006b.

As we can recognize from both figures, the AltBOC(15,10) modulation is very similar to two BPSK(10) signals shifted by 15 MHz to the left and right of the carrier frequency. Indeed, since to acquire all the main lobes of the modulation a very wide bandwidth is necessary, many receivers will operate correlating the AltBOC signal with a BPSK(10) replica.

To have a better feeling about the overlapping between GPS and Galileo in E5, Figure 006c shows all the signals de-scribed so far for this band.

The E5 primary codes can be generated with shift registers. Indeed, the outputs of two parallel registers are modulo-two added to generate the primary codes. For more details on the start values of the primary codes and the corresponding secondary codes of each satellite, refer to [Galileo SIS ICD, 2010]. Finally, some details on the tech -nical characteristics of the E5 signal are presented in Table 006a.

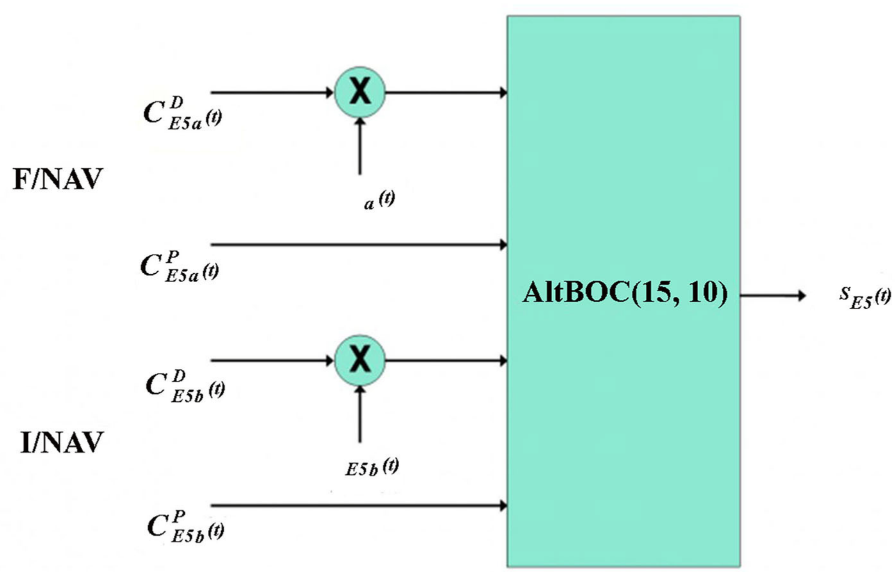

Figure 006a. Modulation scheme for Galileo E5 signals. Image courtesy of Dr. Jose Angel Avila Rodriguez.

THE GLONASS SIGNAL PLAN

App C 007. GLONASS Signal Coding

GLONASS, unlike the other GNSS systems, makes use of a different DSSS technique [G.W. Hein et al., 2006c] based on Frequency Division Multiple Access (FDMA) to transmit its ranging signals..

GLONASS uses FDMA in both the L1 and L2 sub-bands. According to this scheme, each satellite transmits

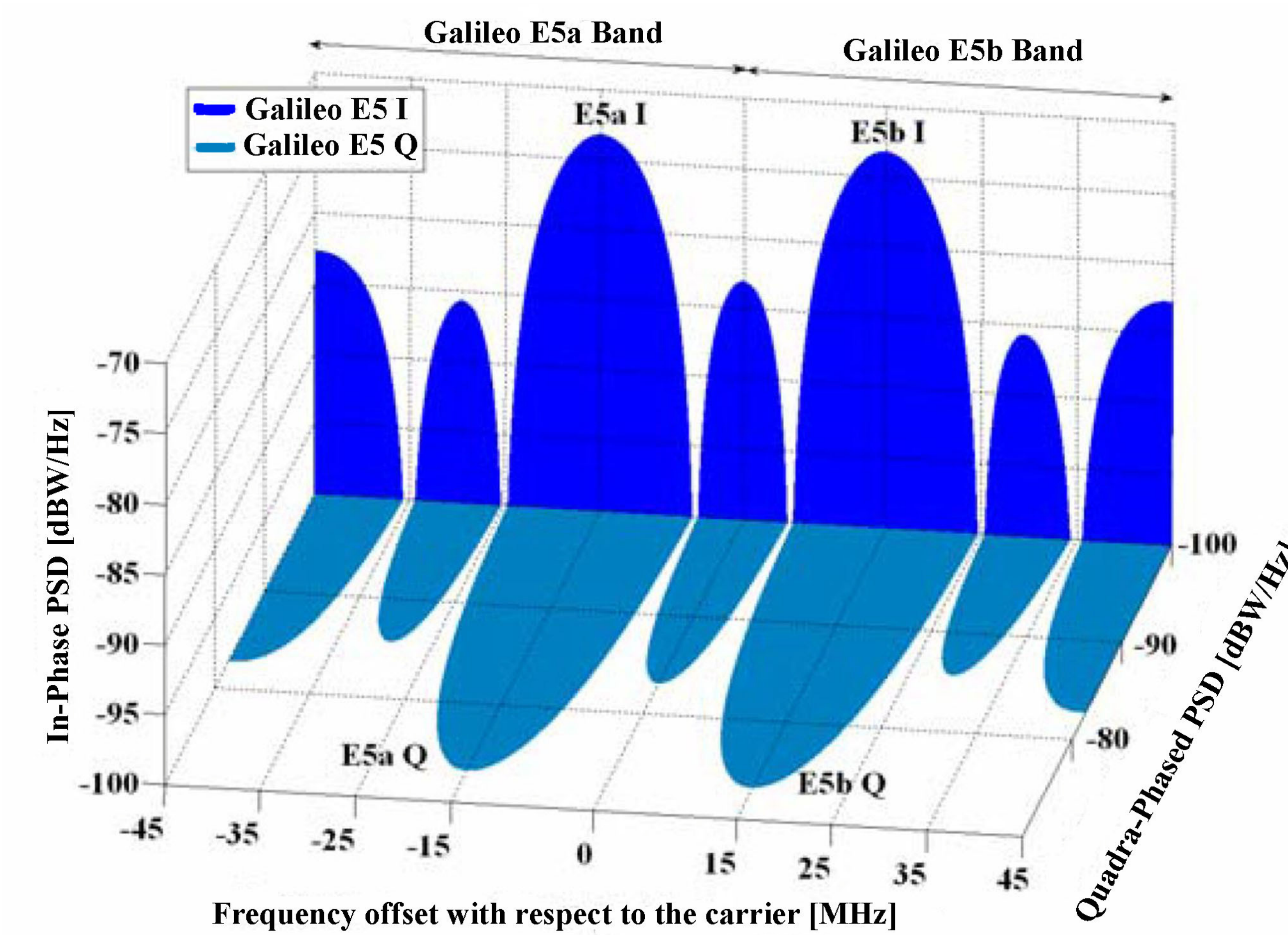

Figure 006b. Spectra of Galileo signals in E5.Image courtesy of Dr. Jose Angel Avila Rodriguez.

navigation signals on its own carrier frequency, so that two GLONASS satellites may transmit navigation signals on the same carrier frequency if they are located in antipodal slots of a single orbital plane [GLONASS ICD, 2002]. Indeed the actual constellation is taking advantage of this property since 2005 when the higher frequency channels had to be turned off to fulfill the CCIR Recommendation 769. We can clearly see this if we have a look at the satellites assigned to each of the GLONASS planes as shown in the following figure with status as of May 2008. As is clear to see, antipodal satellites are transmitting at the same frequency.

See Figure 007 for a depiction of the three GLONASS orbital planes.The red slots indicate that the satellite is in maintenance. Blue means correct operation. Moreover, two different types of signals [GLONASS ICD, 2002] are transmitted by GLONASS satellites: Standard Precision (SP) and High Precision (HP) in both the L1 and L2 bands. The GLONASS standard accuracy signal, also known as C/A Code, has a clock rate of 0.511 MHz and is designed for use by civil users worldwide while the high accuracy signal (P Code) has a clock rate of 5.11 MHz and is modulated by a special code which is only available to users authorized by the Ministry of Defense. Since GLONASS-M, both L1 and L2 provide users with the standard accuracy code C/A. Moreover, the modernized GLONASS will also transmit FDMA signals on the L3 band and CDMA signals in L1 and L5.

The nominal values of the FDMA L1, L2 and L3 carrier frequencies are defined as:

$$\begin{aligned} f_{kL1} &= f_{0L1} + k\Delta f_{L1} \\ f_{kL2} &= f_{0L2} + k\Delta f_{L2} \\ f_{kL3} &= f_{0L3} + k\Delta f_{L3} \end{aligned} \quad (1)$$

where:

k represents the frequency channel,

f_{0L1} = 1602 MHz for the GLONASS L1 band,

Δf_{L1} = 562.5 kHz frequency separation between GLONASS carriers in the L1 band,

f_{0L2} = 1246 MHz for the GLONASS L2 band,

Δf_{L2} = 437.5 kHz frequency separation between

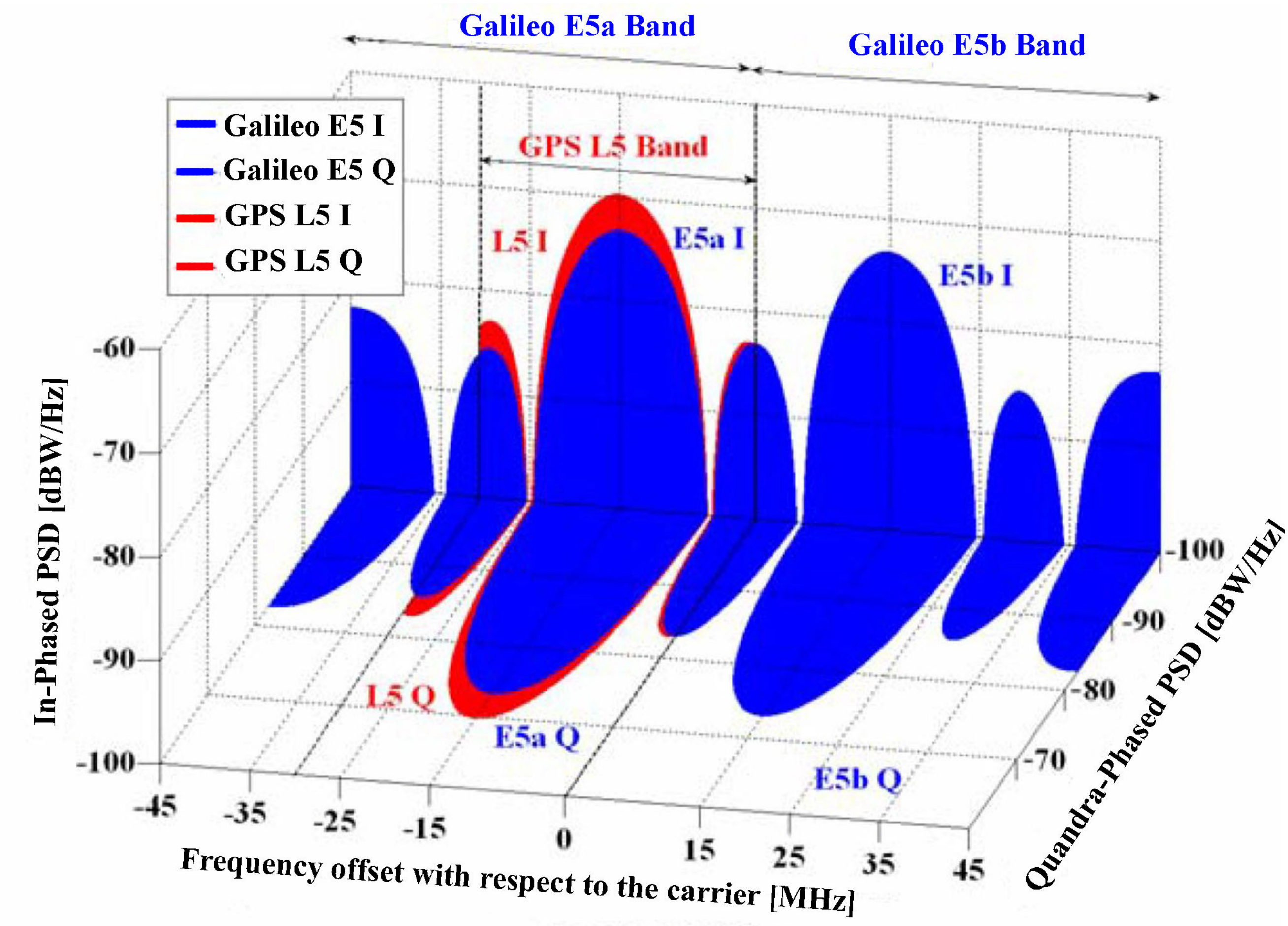

Figure 006c. Spectra of GPS and Galileo Signals in E5.Image courtesy of Dr. Jose Angel Avila Rodriguez.

GNSS System	Galileo	Galileo	Galileo	Galileo
Service Name	E5a data	E5a pilot	E5a data	E5b pilot
Center Frequency	1191.795 MHz			
Frequency Band	E5			
Access Technique	CDMA			
Spreading modulation	AltBOC(15, 10)			
Sub-carrier Frequency	15.345 MHz			
Code Frequency	10.23MHz			
Signal Component	Data	Pilot	Data	Pilot
Primary PRN Code Length	10230			
Code Family	Combination and short-cycling of M-sequences			
Secondary PRN Code Length	20	100	4	100

Table 006a. Galileo E5 signal technical characteristics.

GNSS System	Galileo	Galileo	Galileo	Galileo
Data Rate	50 sps	-	250 sps	-
Minimum Received Power [dBW]	-155 dBW		-155 dBW	
Elevation	10°		10°	

Table 006a. Galileo E5 signal technical characteristics.

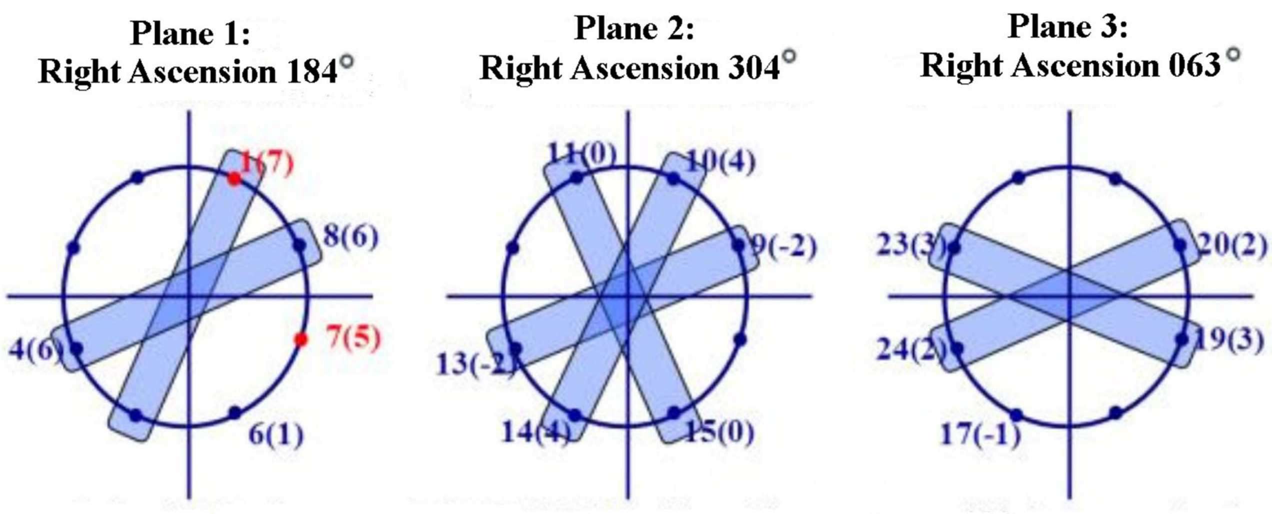

Figure 007. Antipodal assignment of GLONASS satellites. The parameter i(k) indicates that the satellite in almanac slot i transmits on frequency number k. Image courtesy of Dr. Jose Angel Avila Rodriguez.

GLONASS carriers in the L2 band,

f_{0L3} = 1201 MHz for the GLONASS L3 band, and

Δf_{L3} = 437.5 kHz frequency separation between GLONASS carriers in the L3 band.

As we can see, the GLONASS L2 carrier reference signal is 7/9 of the L1 carrier reference and the GLONASS L3 carrier reference is 3/4 of the L1 carrier reference. Moreover, it must be noted that until 2005 the GLONASS satellites used the frequency channels k = 0,...,12 without any restrictions and the channel numbers k = 0 and 13 for technical purposes.

Since then GLONASS is only using the frequency channels k = -7,...,+6 and all the satellites launched beyond that year will use filters, limiting out-of-band emissions to the harmful interference limit contained in CCIR-ITU Recommendation 769 for the 1610.6 - 1613.8 MHz and 1660 - 1670 MHz Radio-Astronomy bands. It is interesting to note that although the limitation to use the higher frequency channels does only affect the L1 band, since the parameter k determines the channel in both the L1 and L2 bands, the upper frequencies of L2 corresponding to channels +7 to +13 were automatically sacrificed.

To have a clearer insight into how the spectra of the GLONASS signals look like, we study next all the bands in detail.

App C 008. GLONASS L1 Band and Signal Structure

The transmitted navigation signal is in both services of L1 a bipolar phase-shift key (BPSK) waveform with clock rates of 0.511 and 5.11 MHz for the standard and accuracy signals respectively. The L1 signal is modulated by the Modulo-2 addition of the pseudo random (PR) ranging code, the digital data of the navigation message and an auxiliary meander sequence. All above-mentioned frequencies are generated coherently using a single onboard time/frequency oscillator standard [GLONASS ICD, 2002]. For the case of the standard accuracy signals (C/A), the PR ranging code is a sequence with length the maximum of a shift register (m-sequence) and a period of 1 millisecond with bit rate of 511 kbps. The navigation message is sent at 50 bps and the auxiliary meander sequence at 100 Hz.

Moreover, it is important to note that the GLONASS FDMA L1 band does not exactly coincide with the GPS and Galileo L1 band. In fact, the GLONASS L1 band ranges from 1592.9525 MHz to 1610.485 MHz when only the 14 channels k = -7...+6 are employed. In the next figures, each of the channels was filtered to only transmit the main lobe of the BPSK signal and the PSD was normalized to have unit power within the corresponding transmission bandwidth.

The PSDs of the GLONASS signals are shown in Figure 008a:

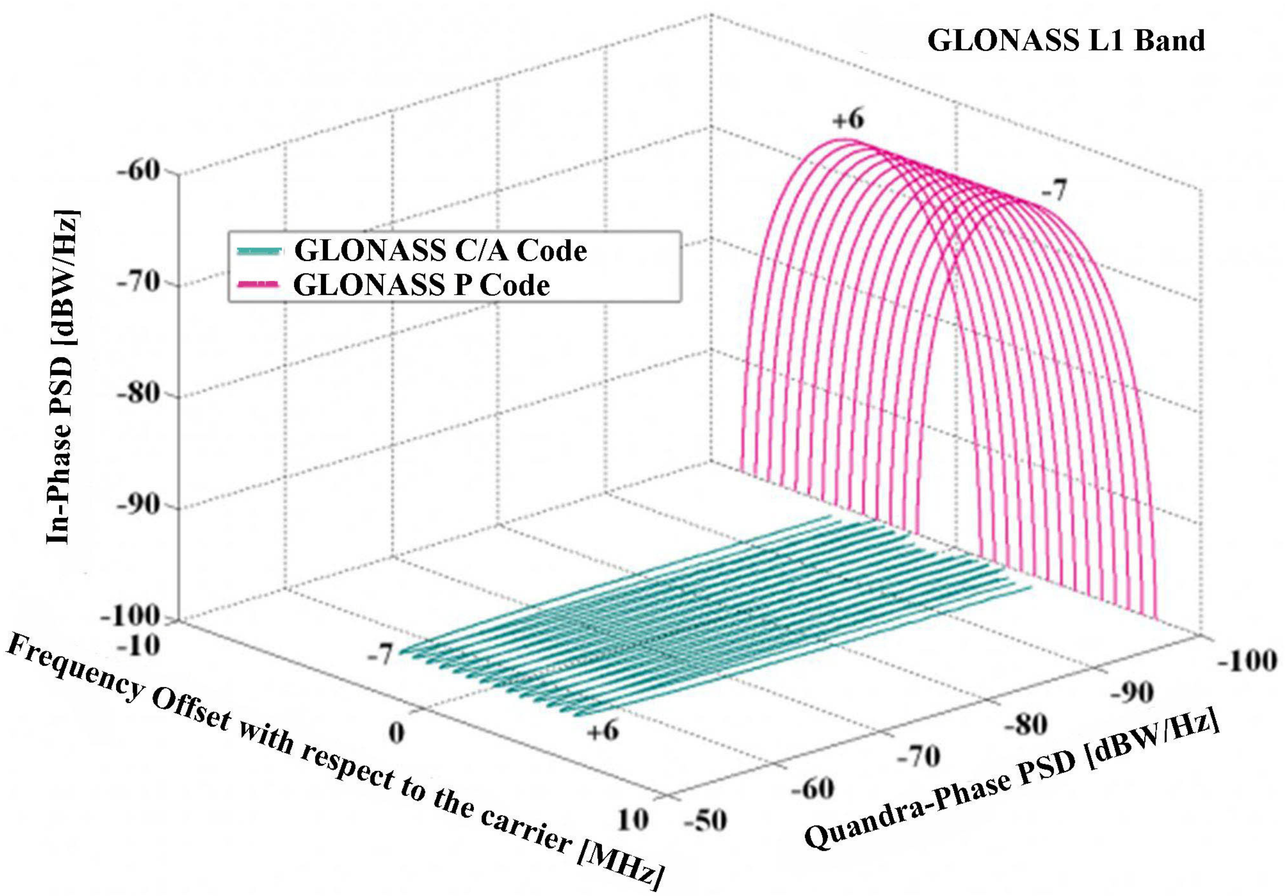

Figure 008a. Spectra of GLONASS signals in L1. Image courtesy of Dr. Jose Angel Avila Rodriguez.

Once again, in order to have a clearer picture of how overcrowded the RNSS bands are becoming as more and more countries claim their rights to have their own GNSS, Figure 008b hows GPS, Galileo and GLONASS signals in the E1/L1 band.

It is important to note that the GPS L1C pilot and data signals are shown in quadrature in Figure 008b although according to [GPS ICD-800, 2006] the final phasing is still open. To finalize some details on the technical characteristics of the GLONASS L1 signals are presented Table 008:

It is important to note that unlike for the case of GPS and Galileo, the frequencies do not have to be multiplied by the factor 1.023.

App C 009. GLONASS L2 Band and Signal Structure

The transmitted navigation signal is, as also in L1, a bipolar phase-shift key (BPSK) waveform with similar clock rates as in the L1 band. The L2 signal is modulated by the Modulo-2 addition of the PR ranging code and the auxiliary meander sequence. For the case of the standard accuracy signals (C/A), the PR ranging code is a sequence of the maximum length of a shift register (M-sequence) with a period of 1 millisecond and a bit rate of 511 kbps. The navigation message is sent at 50 bps and the auxiliary meander at 100 Hz.

Figure 009a shows the spectra of the GLONASS signals in L2 and Figure 009b shows spectra of both the GLONASS and GPS signals in L2.

Details on the technical characteristics of the GLONASS L2 signals are presented in Table 009.

It is important to note again that unlike for the case of GPS and Galileo in the previous chapters, the frequencies do not have to be multiplied by the factor 1.023.

App C 010. References

Ávila Rodríguez, José Ángel. (2008). *On Generalized Signal Waveforms for Satellite Navigation*. University FAF, Munich. **Sections reproduced with permission**.

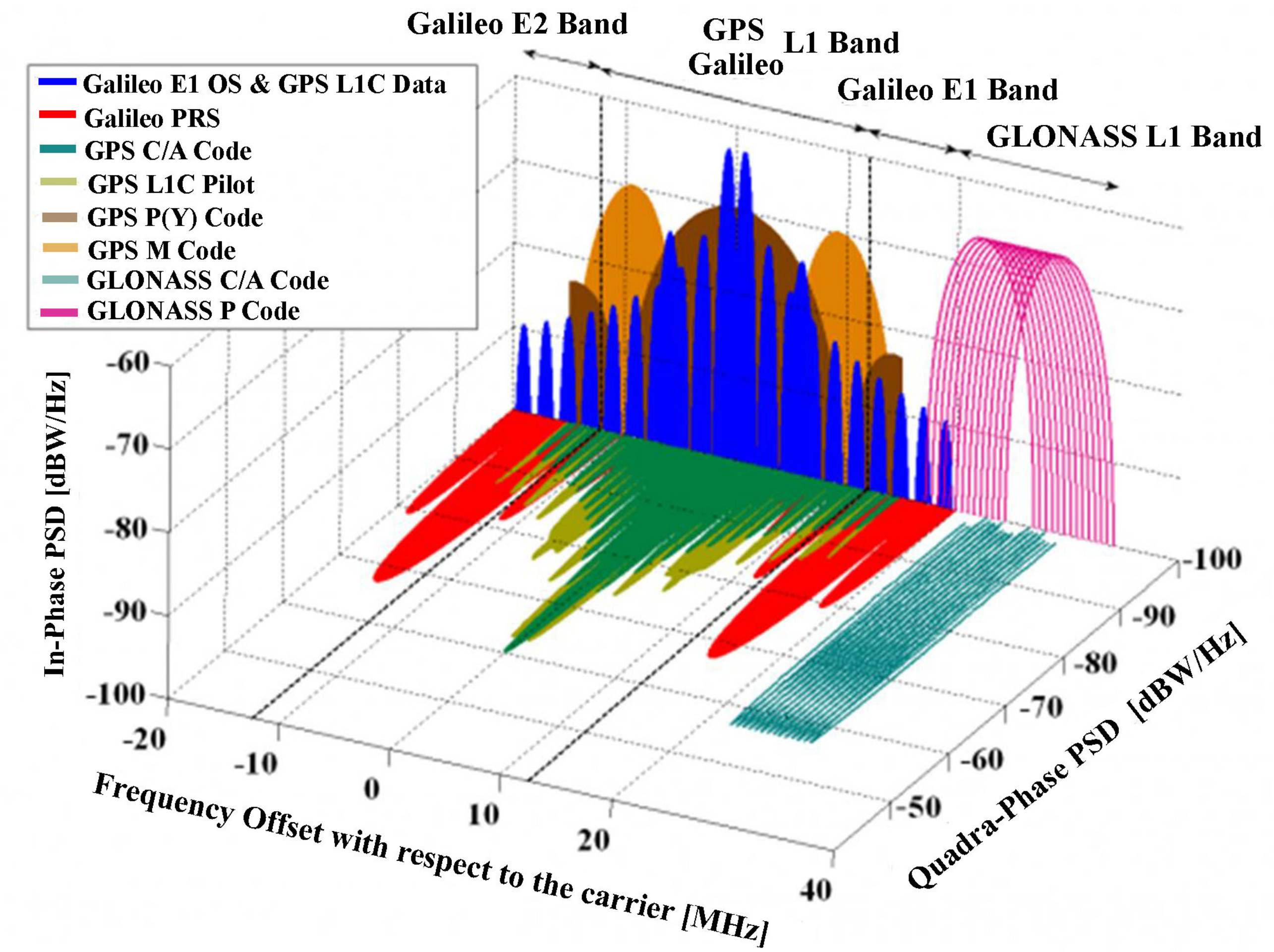

Figure 008b. Spectra of GPS, Galileo and GLONASS signals in E1/L1. Image courtesy of Dr. Jose Angel Avila Rodriguez.

GNSS System	**GLONASS**	**GLONASS**
Service Name	C/A Code	P Code
Center Frequency	(1598.0625-1605.375) MHz [+ or -] 0.511 MHz	
Frequency Band	L1	L1
Access Technique	FDMA	FDMA
Spreading modulation	BPSK(0.511)	BPSK(5.11)
Sub-carrier Frequency	-	-
Code Frequency	0.511 MHz	5.11 MHz
Signal Component	Data	Pilot
Primary PRN Code Length	511	N/A
Code Family	M-sequences	N/A
Meander sequence	100 Hz	N/A

Table 008 GLONASS L1 signal technical characteristics.

GNSS System	GLONASS	GLONASS
Data Rate	50 bps	N/A
Minimum Received Power [dBW]	-161 dBW	N/A
Elevation	5°	N/A

Table 008 GLONASS L1 signal technical characteristics.

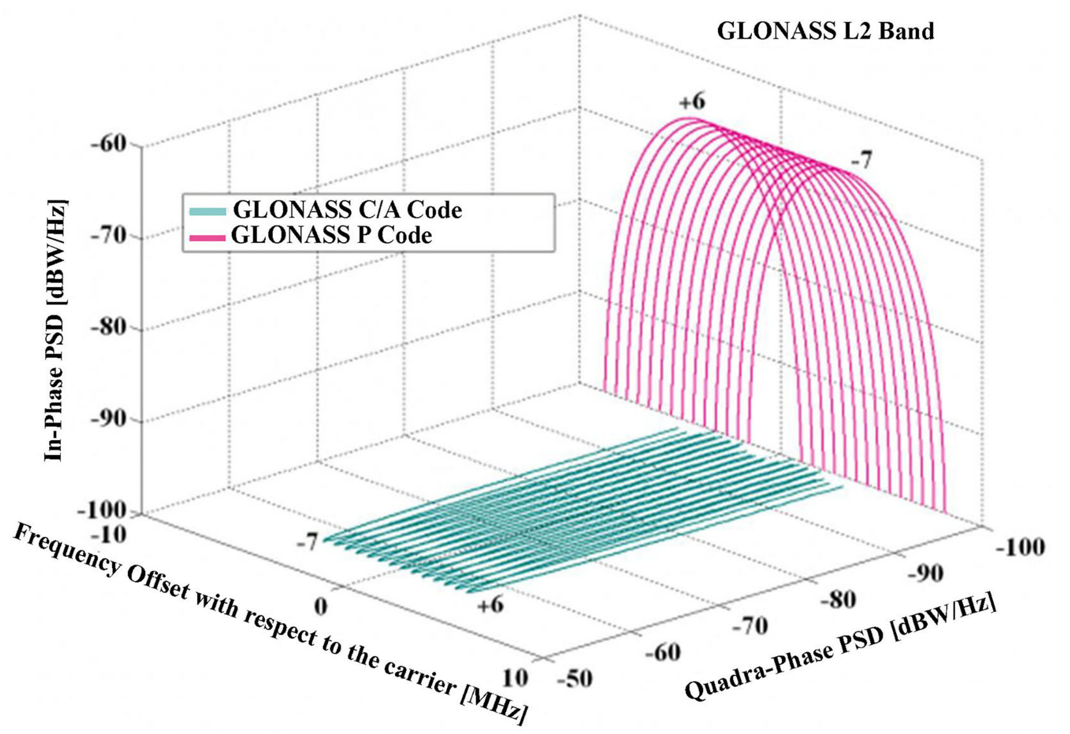

Figure 009a. Spectra of GLONASS signals in L2. Image courtesy of Dr. Jose Angel Avila Rodriguez.

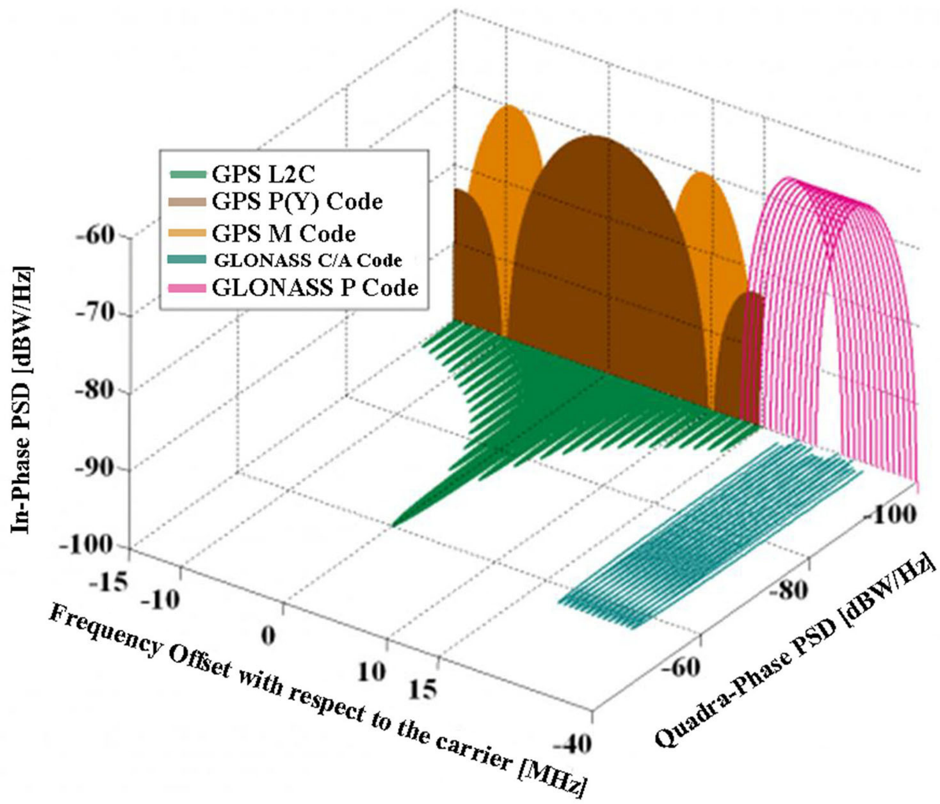

Figure 009b. Spectra of GPS and GLONASS signals in L2. Image courtesy of Dr. Jose Angel Avila Rodriguez.

GNSS System	**GLONASS**	**GLONASS**
Service Name	C/A Code	P Code
Center Frequency	(1242.9375-1248.625) MHz [+ or -] 0.511 MHz	
Frequency Band	L2	L2
Access Technique	FDMA	FDMA
Spreading modulation	BPSK(0.511)	BPSK(5.11)
Sub-carrier Frequency	-	-
Code Frequency	0.511 MHz	5.11 MHz
Signal Component	Data	Pilot
Primary PRN Code Length	511	N/A
Code Family	M-sequences	N/A
Meander sequence	100 Hz	N/A
Data Rate	50 bps	N/A
Minimum Received Power [dBW]	-167 dBW	N/A
Elevation	5°	N/A

Table 009 GLONASS L2 signal technical characteristics.