The E1 Galileo Signal

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System	Carrier [MHz]	Signal	Type	Modulation	Chipping rate	Code Length	Full length [ms]
GPS	**L1** 1575.420	**C/A**	Data	BPSK	1.023Mcps	1023	1
		P(Y)	Military	BPSK	10.23Mcps	for 7days	7 days
		M	Military	BOC(10,5)	5.115Mcps	-	-
	L2 1227.60	L2 CM	Data	TM and BPSK	0.5115Mcps	10230	20
		L2 CL	Pilot		0.5115Mcps	767250	1500
		P(Y)	Military	BPSK	10.23Mcps	for 7 days	7 days
		M	Military	BOC(10,5)	5.115Mcps	-	-
	L5 1176.450	I	Data	QPSK	10.23Mcps	10230	1
		Q	Pilot		10.23Mcps	10230	1
Galileo	**E1** 1575.42	A	PRS	BOCc(15, 2.5)	10.23Mcps	25575 * 1	10
		B	Data	BOC(1,1)	1.023Mcps	4092 * 1	4
		C	Pilot		1.023Mcps	4092 * 25	100
	E6 1278.750	A	PRS	BOCc(15, 5)	5.115Mcps	51150 * 1	10
		B	Data	BPSK(5)	5.115Mcps	5115 * 1	1
		C	Pilot		5.115Mcps	10230 * 50	100
	E5 1191.795 a:1176.450 b:1207.140	a-I	Data	AltBOC(15,10)	10.23Mcps	10230 * 20	20
		a-Q	Pilot		10.23Mcps	10230 * 100	100
		b-I	Data		10.23Mcps	10230 * 4	4
		b-Q	Pilot		10.23Mcps	10230 * 100	100

BOC(f_s/f_0, f_c/f_0); f_0 reference frequency [MHz], f_s subcarrier frequency [MHz], and f_c chip rate [Mc/s]. For BOC(1,1) we have $f_0 = 1.023$ MHz, $f_s = 1.023$ MHz, and $f_c = 1.023$ Mc/s.

Specifics for the Galileo Signals

The E1 signal is composed of *three channels*, called A, B, and C. E1-A (meaning the A channel within E1) is a restricted access signal. Its ranging codes and navigation data are encrypted. The data signal is E1-B and the data-free signal is E1-C. A data-free signal is also called a ***pilot signal***. It is made of a ranging code only, not modulated by a navigation data stream.

The E1 signal has a 4092 code length with a 1.023 MHz chipping rate giving it a repetition rate of 4 ms; on the pilot signal a secondary code of length 25 chips extends the repetition interval to 100 ms.

Under some circumstances it may be difficult to separate the wanted signal from the unwanted ones and the unwanted one is often a cross correlation from another satellite as the inherent CDMA isolation of the codes is only around 21 dB. The cross-correlation problem is solved by using *very long codes*. However, longer codes also delay the acquisition process. To search the very long code lengths proposed for the new signals would be impractical, so the codes have been designed with escape routes. The most common one is called a *tiered code*. This means it is built in layers so that when you have a strong signal you can acquire on a simple layer, with less time-domain possibilities, only switching to the full-length code when required.

The minimum *bandwidth* is generally twice the chipping rate for simple codes, while for BOC codes it is twice the sum of chipping rate and offset code rate. Thus, the minimum practical bandwidth for the Galileo E1 is 8 MHz.

Within this 4 ms period the signal-to-noise ratio (SNR) prevents the downloading of data for signals weaker than 25 dB/Hz. The data-download situation is improved by using *forward error correction codes* (standard Viterbi coding), and *block interleave* also covers for burst errors. Forward error convolutional codes spread the information from one user data bit over many transmitted symbols. If some of these are lost, the data bit can be recovered from the others. However, a burst error may destroy all the relevant symbols. Interleaving, which transmits the symbols in a scrambled sequence (30 columns $\times$ 8 rows) , means that a single burst error cannot destroy all the symbols relevant to a single user data bit. The downside is that it adds latency to the message, to allow for the interleaving/de-interleaving process.

The 4 ms repetition rate is ideal because there is one symbol per code epoch. When the code is synchronized, we know that we will not hit a data bit edge because these always occur at the start of a code sequence.

On the pilot channel, acquisition can be done in two stages and for peak sensitivity, 25 consecutive 4 ms correlation results can be saved. Then re-correlated with the secondary code to generate the final result. The effect of the tiered codes is $n + m$ processing effort rather than $n \times m$.

The signal is the product of carrier, spreading code, BOC, and data. Traditionally, the RF hardware removes the carrier, the correlators remove the BOC(1,1) code, leaving the data and the residual Doppler to be removed/measured by a processor. With the BOC(1,1) codes, the BOC component should have been considered part of the spreading code for tracking and positioning; but it is equally viable to consider it part of the carrier during the acquisition phase, and remove it prior to the empirical correlation of acquisition.

The ACF of a BOC(1,1) code has three peaks, not just one, so care must be taken to ensure that the correct one has been found.

Details on the Galileo E1 Signal

We describe and combine all elements necessary to generate the E1 Galileo signal.

The transmitted bandwidth is $24 \times 1.023\,\text{MHz} = 24.554\,\text{MHz}$. The minimum received power for the E1 signal is $-157\,\text{dBW}$ for elevation angles between 10° and 90°. The chip length of the ranging code is

$$T_{c,\text{E1-B}} = T_{c,\text{E1-C}} = 1/1.023\,\text{Mchip/s} = 977.5\,\text{ns}. \tag{1}$$

The actual chips for the individual satellites are pseuro-random memory sequences provided in a hexadecimal representation. ***Higher chipping rates provide better accuracy. Longer codes reduce cross correlation to more acceptable levels, although acquisition time is longer.***

The corresponding *ranging code rates* are

$$R_{c,\text{E1-B}} = 1/T_{c,\text{E1-B}} = 1.023\,\text{Mchip/s},$$
$$R_{c,\text{E1-C}} = 1/T_{c,\text{E1-C}} = 1.023\,\text{Mchip/s},$$

and subcarrier rates

$$R_{sc,\text{E1-B}} = R_{sc,\text{E1-C}} = 1.023\,\text{MHz}.$$

Channel C uses both a primary code of length $N_P = 4092$ chips and a secondary code of length $N_S = 25$ chips. The *primary code* is a pseudo-random memory code sequence, so when the number of 4092 chips is reached, the register is reset to its initial state. There are defined 50 memory codes for the satellites.

The *secondary code* modulates 25 specific repetitions of the primary code. For each subcarrier all satellites transmit the same secondary code: the octal sequence 34012662. The resulting code length is 4092×25. It is called a *tiered code*.

Let the primary code generator work with chip rate R_P. The secondary code generator has chip rate $R_S = R_P/N_P$, where N_P is the length in chips of the primary code. In all signal modulations the logical levels 1 and 0 are defined as signal levels -1 and 1 (polar non-return-to-zero representation).

Now we have information for defining the binary signal components for channels B and C. However, information on channel A is not available.

The signal component for channel B results from the modulo-2 addition of the navigation data stream d_{E1-B}, the PRN code sequence c_{E1-B}, and the B subcarrier sc_{E1-B}. The final component is called e_B.

Likewise, the C channel results from the modulo-2 addition of the C channel PRN code sequence c_{E1-B} with the C channel subcarrier sc_{E1-C}. The component is e_C. The binary signal components are as follows:

$$e_A(t) = \text{not available}, \tag{2}$$

$$\begin{aligned} e_B(t) = \sum_{i=-\infty}^{+\infty} \Big(& c_{E1-B,(i \bmod 4\,092)} d_{E1-B,(i \bmod 4)} \operatorname{rect}_{T_{c,E1-B}}(t - iT_{c,E1-B}) \\ & \times \operatorname{sign}\big(\sin(2\pi R_{c,E1-B} t)\big)\Big), \end{aligned} \tag{3}$$

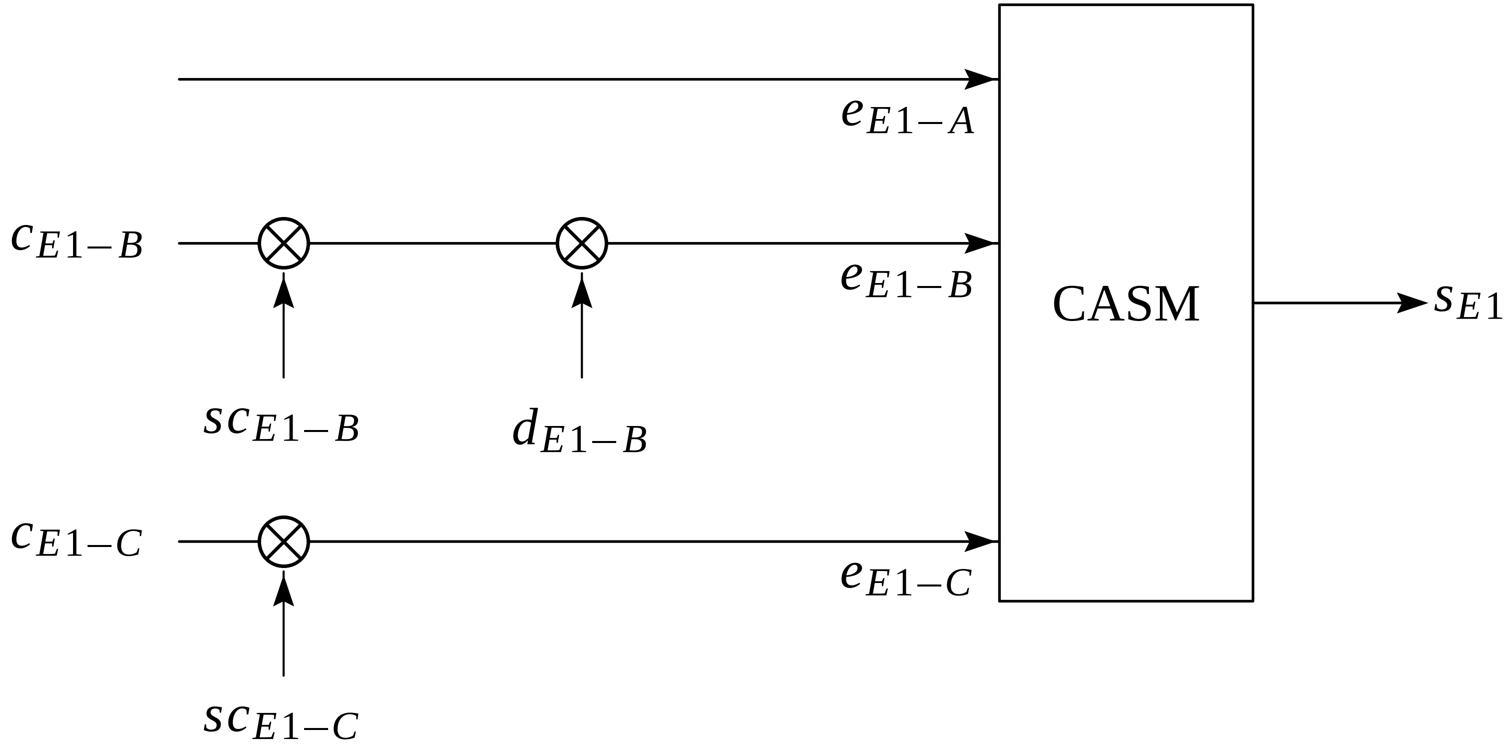
$$\begin{aligned} e_C(t) = \sum_{i=-\infty}^{+\infty} \Big(& c_{E1-C,(i \bmod 4\,092)} \operatorname{rect}_{T_{c,E1-C}}(t - iT_{c,E1-C}) \\ & \times \operatorname{sign}\big(\sin(2\pi R_{c,E1-C} t)\big)\Big). \end{aligned} \tag{4}$$

Coherent Adaptive Subcarrier Modulation

The three channel signals $e_A(t)$, $e_B(t)$, and $e_C(t)$ of the E1 signal are multiplexed using CASM which is a multichannel modulation scheme also known as tricode hexaphase modulation (or interplex modulation).

CASM is used to ensure that the signal transmitted from the satellite has a constant power envelope, i.e., the total transmitted power does not vary over time. Thus, ***the transmitted information is not contained in the signal amplitude*** and the transmitted signal amplitude becomes less critical. This is a very desirable property of the signal since it allows the use of efficient "class C"-like power amplifiers.

Galileo Modulation Scheme



The Galileo modulation scheme is based on the principle of Coherent Adaptive Sub-Carrier Modulation (CASM)

The E1 data and pilot signals are modulated onto the carrier in-phase component while the E1-A signal is modulated onto the quadrature component. The combined signal is

$$\begin{aligned} S(t) = \big(\alpha e_B(t) - \alpha e_C(t)\big) \cos(2\pi f_1 t) \\ - \big(\beta e_A(t) + \gamma e_A(t) e_B(t) e_C(t)\big) \sin(2\pi f_1 t). \end{aligned} \tag{5}$$

In this expression α, β, and γ are amplification factors that determine the distribution of useful power among the channels A, B, and C. We assume B and C have equal power.

For *given* relative signal powers we want to solve for these variables. So let us assume a relative signal power of 50% for A, and 25% for both B and C.

The given choice of relative signal powers defines the following signal:

$$S(t) = \frac{\sqrt{2}}{3}\big(e_B(t) - e_C(t)\big)\cos(2\pi f_1 t) \\ - \frac{1}{3}\big(2e_A(t) + e_A(t)e_B(t)e_C(t)\big)\sin(2\pi f_1 t). \quad (6)$$

The product $e_A(t)e_B(t)e_C(t)$ is the intermodulation product E1 Int in CASM, which ensures the constant envelope property of the transmitted signal. The transmitted power is distributed as follows:

E1, data	$\alpha^2 = \left(\frac{\sqrt{2}}{3}\right)^2 = 22.22\%,$
E1, pilot	$\alpha^2 = \left(\frac{\sqrt{2}}{3}\right)^2 = 22.22\%,$
E1, restrict	$\beta^2 = \left(\frac{2}{3}\right)^2 = 44.44\%,$
E1 Int	$\gamma^2 = \left(\frac{1}{3}\right)^2 = 11.11\%.$

This means that only 88.88% of the total transmitted power is useful. The power offered for the E1 Int signal is wasted; apparently this waste is the price we must pay to obtain a constant envelope for the signal $S(t)$.

Binary Offset Carrier Modulation

The Galileo signals and the planned modernized GPS signals inherit improved performance compared to the existing GPS signals. One of the improvements is the introduction of the ***binary offset carrier (BOC) modulation***. BOC modulations offer two independent design parameters

- subcarrier frequency f_s in MHz, and
- spreading code rate f_c in Mchip/s.

These two parameters provide freedom to *concentrate signal power within specific parts of the allocated band* to reduce interference with the reception of other signals.

Furthermore, the redundancy in the upper and lower sidebands of BOC modulations offers practical advantages in receiver processing for signal acquisition, code tracking, carrier tracking, and data demodulation.

Most Galileo signals come in pairs: a data signal and a data-free signal. They are aligned in phase and consequently have the same Doppler frequency.

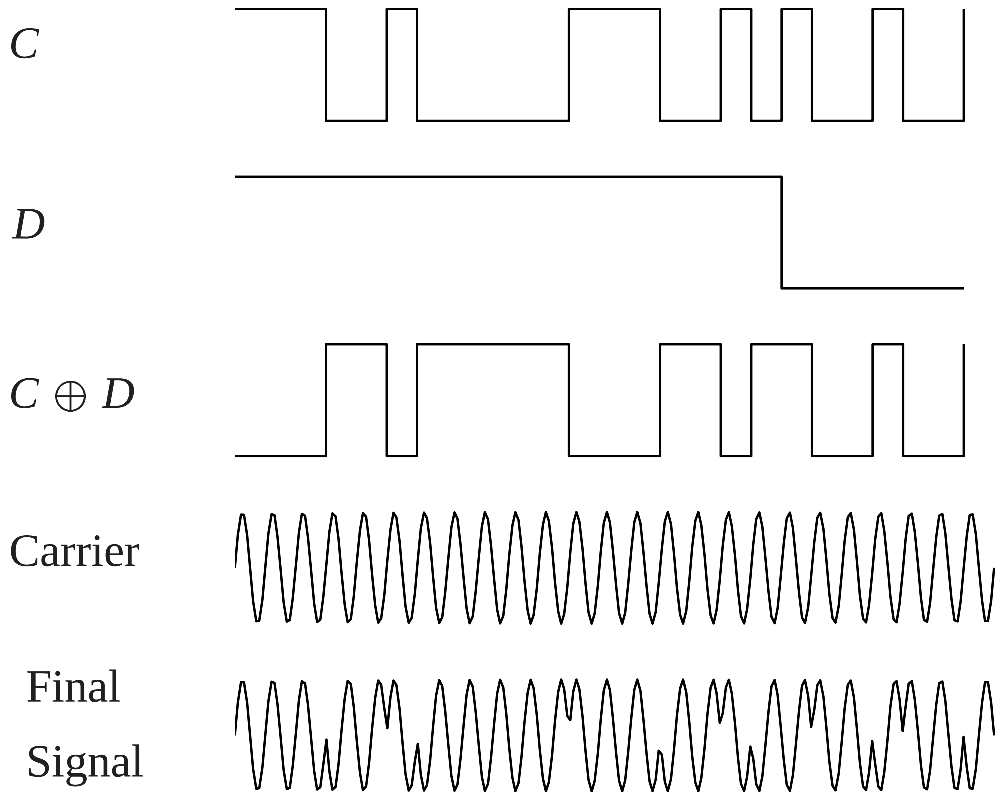
A BOC(m, n) signal is created by modulating a sine wave carrier with the product of a PRN spreading code and a square wave subcarrier having each binary ± 1 values. The parameter m stands for the ratio between the subcarrier frequency and the reference frequency $f_0 = 1.023\,\text{MHz}$, and n stands for the ratio between the code rate and f_0. Thus, BOC(10, 5) means a 10.23 MHz subcarrier frequency and a 5.115 MHz code rate.

The aim of the subcarrier modulation is to split the classical BPSK spectrum in two symmetrical components with no remaining power on the carrier frequency.

The product is a symmetric split spectrum with two main lobes shifted from the carrier frequency by the amount equal to the subcarrier frequency, confer a subsequent figure. We concentrate on $\mathrm{BOC}(m, n) = \mathrm{BOC}(1, 1)$ as this is likely to be used by the E1 signal transmitted by Galileo.

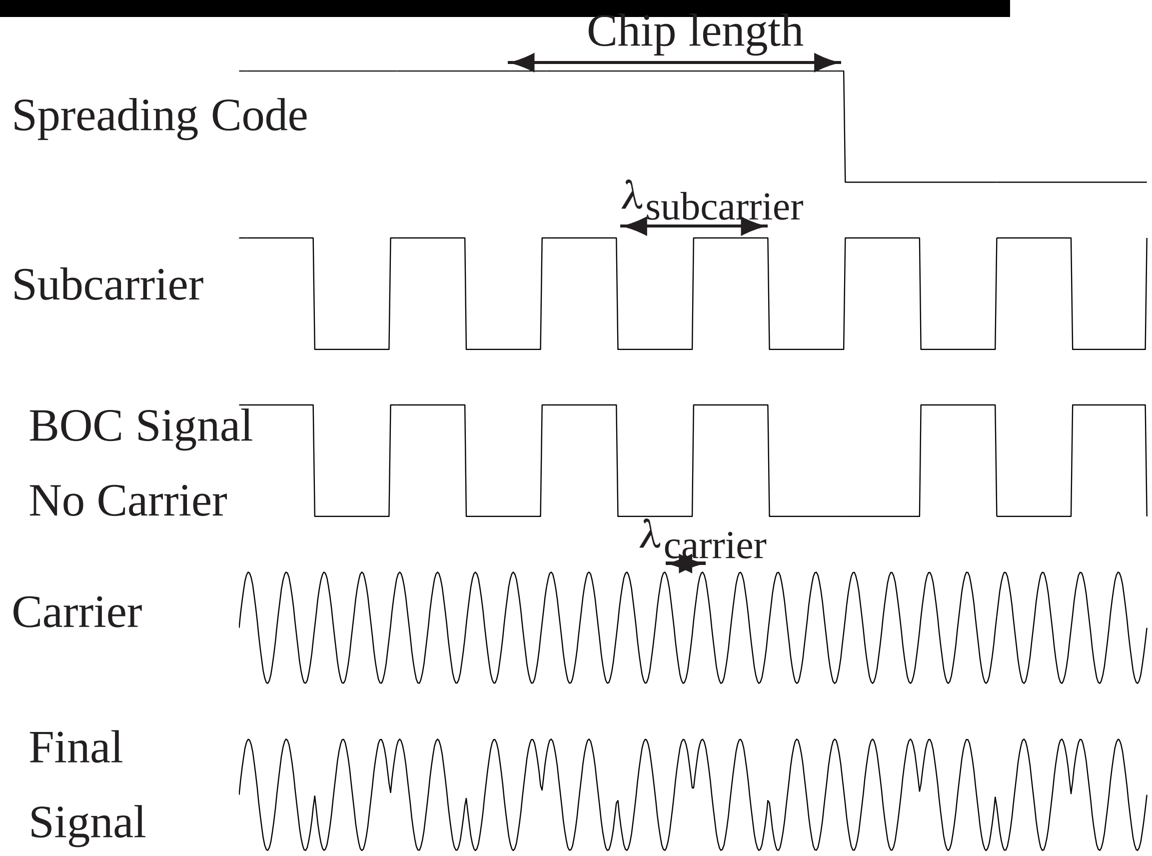
The ACF of BOC signals has a profile with more peaks that may be tracked. For BOC signals it is important to make sure the channel is tracking the main peak of the correlation pattern. So additional correlators are needed for measuring the correlation profile at half a subcarrier phase from prompt correlator at either side. If one of the output values of these so-called *very early and very late correlators* is higher than the punctual correlation, the channel is tracking a side peak and corrective action is taken.

BPSK Modulation of L1 Carrier Wave as in GPS



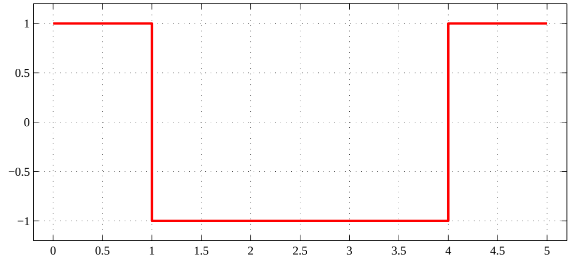
The effect of BPSK modulation of the L1 carrier wave with the C/A code and the navigation data for one satellite. The data are modulo-2 added to the C/A code, the resultant bit-train is used to modulate the L1 carrier. The plot contains the first 25 chips of the Gold code for PRN 1.

Principle of BOC Modulation of Galileo Signals

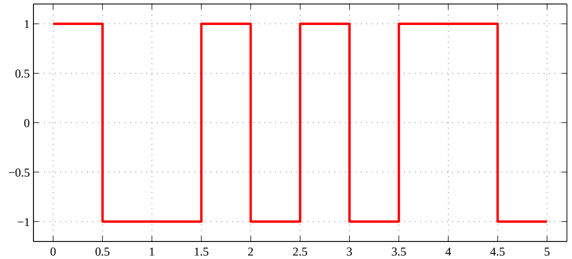


Spreading code, subcarrier, carrier, and signal as result of the BOC modulation principle. This figure does not show the navigation data.

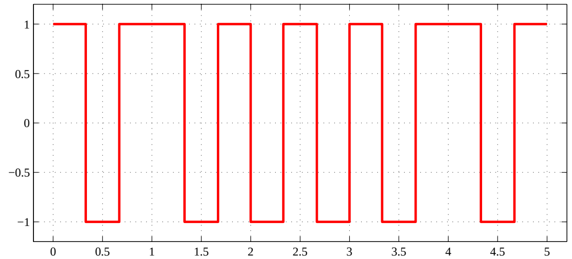
Examples of Time-domain Waveforms for BOC($f_s/f_0,\ f_c/f_0$) Modulated Signals



BPSK



BOC(1,1), e.g.



BOC(15,10), e.g.

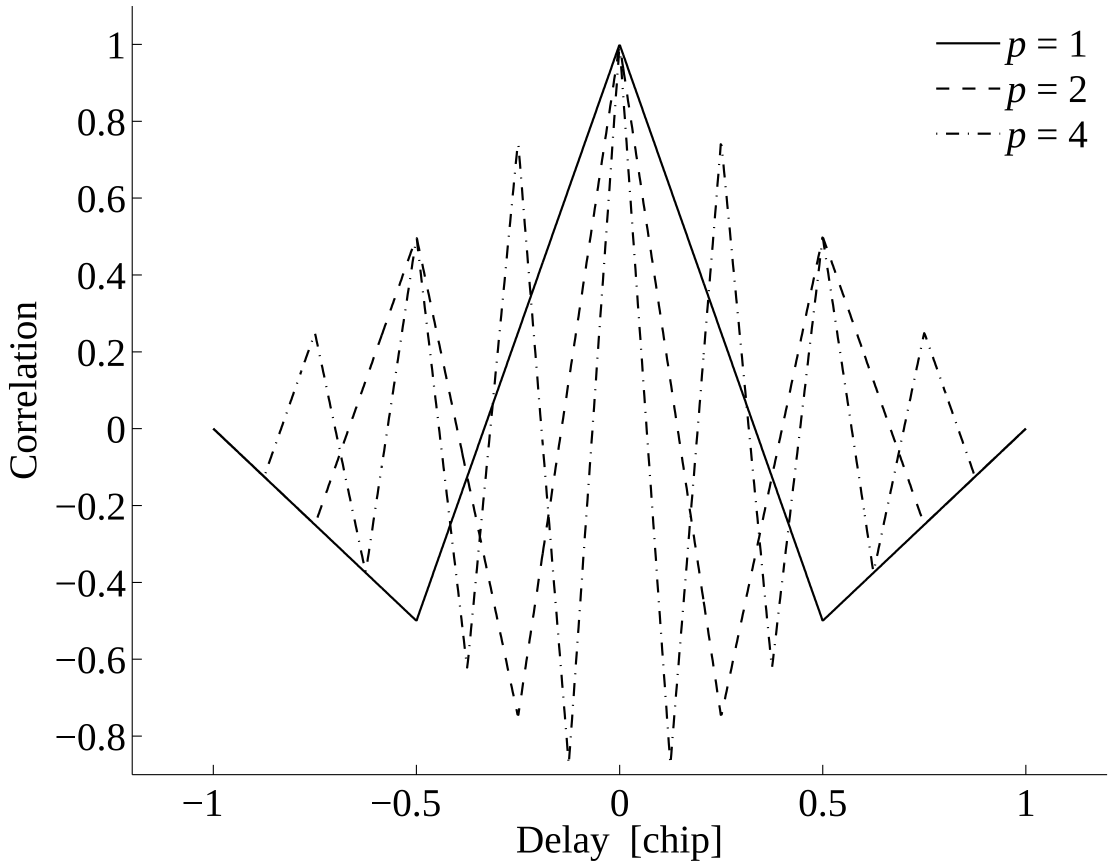
ACF for BOC(pn, n) Signal

According to Nunes et al. (2004), the ACF for BOC(pn, n) with $p = 1, 2, \ldots$ and $k = \text{ceil}(\frac{2p|\tau|}{T_c})$ is given as

$$r(\tau) = \begin{cases} (-1)^{k+1}\left(\frac{1}{p}(-k^2 + 2kp + k - p) - (4p - 2k + 1)\frac{|\tau|}{T_c}\right), & \text{for } |\tau| \leq T_c, \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

This ACF is plotted in the figure on the next slide. For $p = 1$ this is

$$r(\tau) = \begin{cases} (-1)^{k+1}\left(-k^2 + 3k - 1 - (5 - 2k)\frac{|\tau|}{T_c}\right), & \text{for } |\tau| \leq T_c, \\ 0, & \text{otherwise.} \end{cases}$$



ACF for the BOC(pn, n) signal as function of delay τ and p.

ACF for BOC(n, n) for Varying Bandwidth b

According to Winkel (2000), the ACF for the BOC(n, n) signal with bandwidth b is given as

$$
\begin{aligned}
r_{\mathrm{BOC}}(\tau) = \sum_{k=-n+1}^{n-1} (n - |k|)\Big(2r_{\mathrm{BL}}(\tau/T_c - 2k) - r_{\mathrm{BL}}(\tau/T_c - 2k - 1) \\
- r_{\mathrm{BL}}(\tau/T_c - 2k + 1)\Big),
\end{aligned} \tag{8}
$$

where

$$
\begin{aligned}
r_{\mathrm{BL}}(t) = \tfrac{1}{\pi}(t+1)Si\big(2\pi b(t+1)\big) + \frac{1}{2\pi^2 b}\cos\big(2\pi b(t+1)\big) \\
+ \tfrac{1}{\pi}(t-1)Si\big(2\pi b(t-1)\big) + \frac{1}{2\pi^2 b}\cos\big(2\pi b(t-1)\big) \\
- \tfrac{2t}{\pi}Si\big(2\pi bt\big) - \frac{1}{\pi^2 b}\cos\big(2\pi bt\big)
\end{aligned} \tag{9}
$$

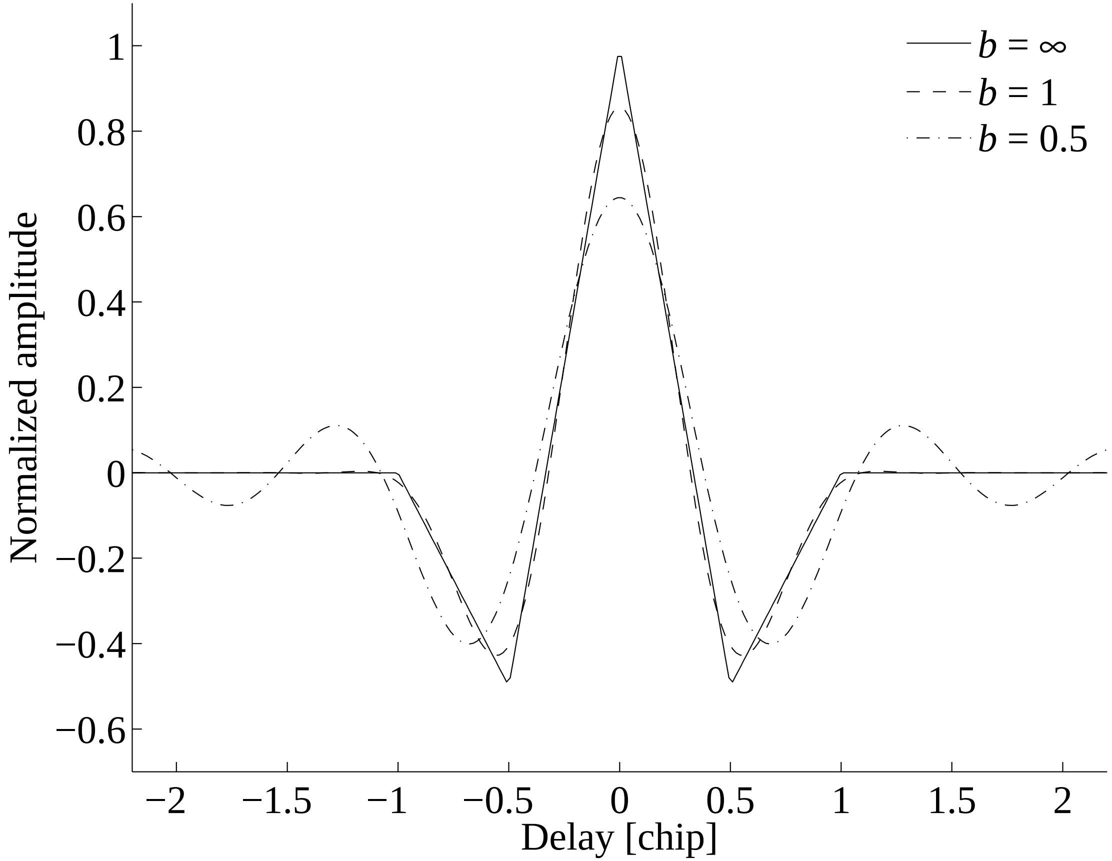
and the sine integral is defined as

$$Si(x) = \int_0^x \frac{\sin(y)}{y}\, dy.$$

If we plot the function $r_{\mathrm{BOC}}(n, n)$, we get the result shown in the next figure for $n = 1, 2, 4$.

For limited bandwidth the peak value is less than one; this reflects the fact that not all power is available in the signal. Part of the power is blocked by the bandlimiting. For $b = 1$ the bandlimiting results in a slight rounding off at the edges of the ACF. For $b = 0.5$ the frequencies lower than twice the square wave frequency are stopped by the filter. This results in oscillations outside the chip length region. This could lead to undesirable side-lobe effects in case of multipath.

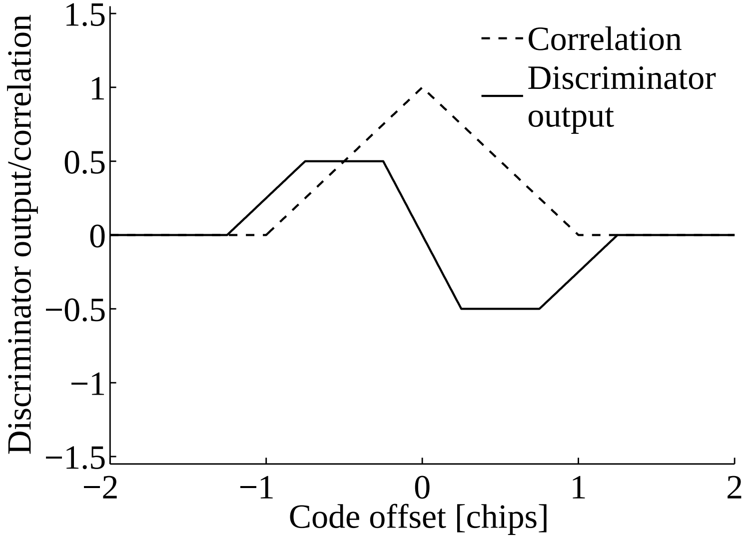
ACF for Bandlimited BOC(1,1) Signal

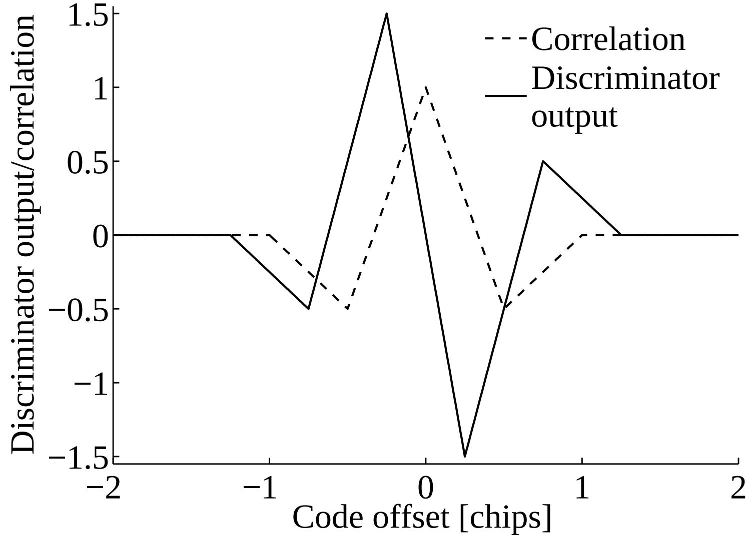


The normalized bandlimit is $b = 0.5$, 1, and ∞. The function for $b = \infty$ is identical to BOC(1,1).

The BOC ACF profile results in a DLL discriminator curve that is a bit more complicated than that of GPS. The figure in the next slide shows the ideal band-unlimited correlation function for both a C/A code signal and a BOC(1,1) signal. Shown are as well early minus late discriminator curves for a chip spacing of 0.5 chip.

ACF and Discriminators for C/A and BOC(1,1)





Autocorrelation function (ACF) and early minus late discriminator curves. The left panel illustrates the situation for the C/A code, and the right panel illustrates the BOC(1,1) situation

We observe various facts. Both discriminator curves are linear around the center of the ACF. In both cases the linear region extends from -0.25 to 0.25 chip code offset. The slope of the BOC discriminator in the linear region is three times the slope of the C/A discriminator. The C/A code discriminator output is used to adjust the code NCO to align the code phase better with the incoming signal; this adjustment will succeed for tracking errors less than 1.25 chips. The C/A discriminator is stable in the entire region where the discriminator curve is non-zero and the DLL will converge. The BOC discriminator has stable regions next to the linear region as well, but tracking errors in the outer regions (absolute errors less than 1.25 and greater than 0.625 chip) will cause the DLL to diverge and loose lock.

Power Spectral Density

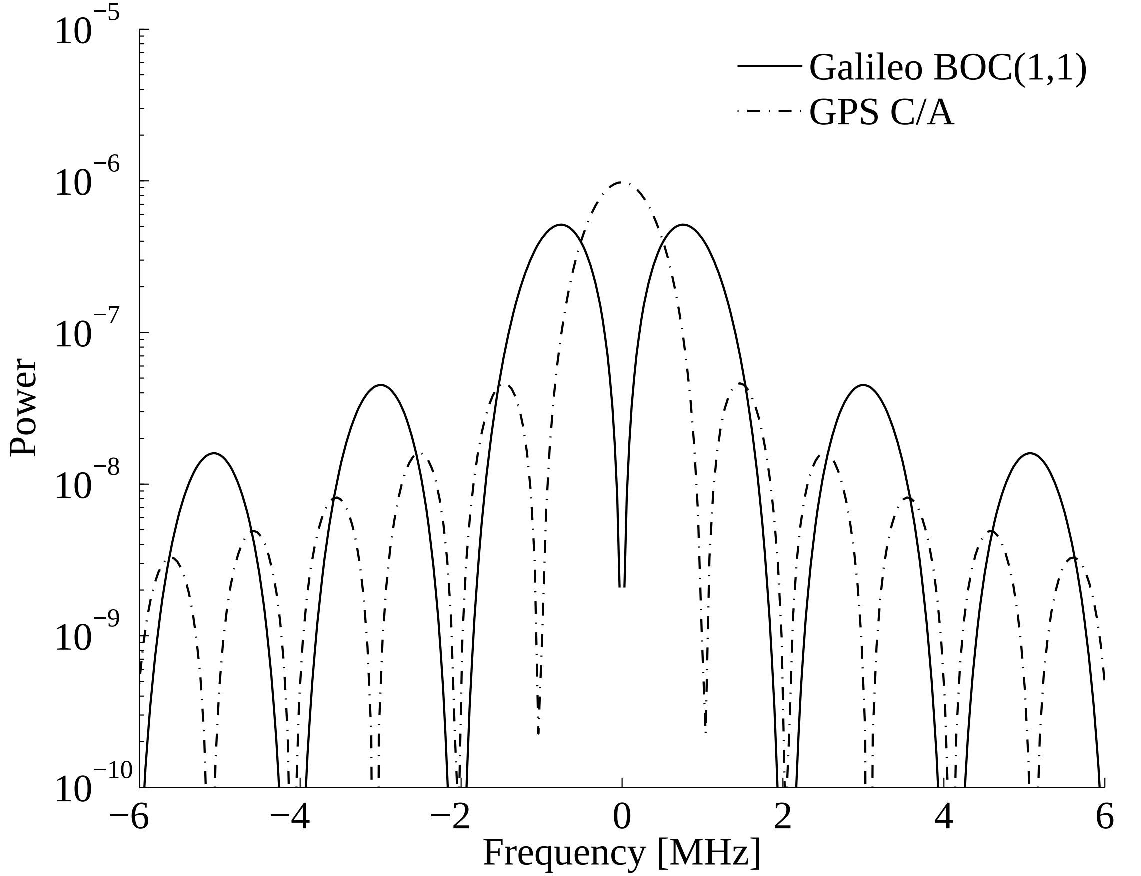
The power spectral density of the BOC($f_s/f_0, f_c/f_0$) centered at the origin can be written as

$$S(\omega) = f_c \left(\frac{\tan(\frac{\pi\omega}{2f_s})\sin(\frac{\pi\omega}{f_c})}{\pi\omega} \right)^2, \qquad \frac{2f_s}{f_c} = n \quad \text{even}, \tag{10}$$

$$S(\omega) = f_c \left(\frac{\tan(\frac{\pi\omega}{2f_s})\cos(\frac{\pi\omega}{f_c})}{\pi\omega} \right)^2, \qquad \frac{2f_s}{f_c} = n \quad \text{odd}. \tag{11}$$

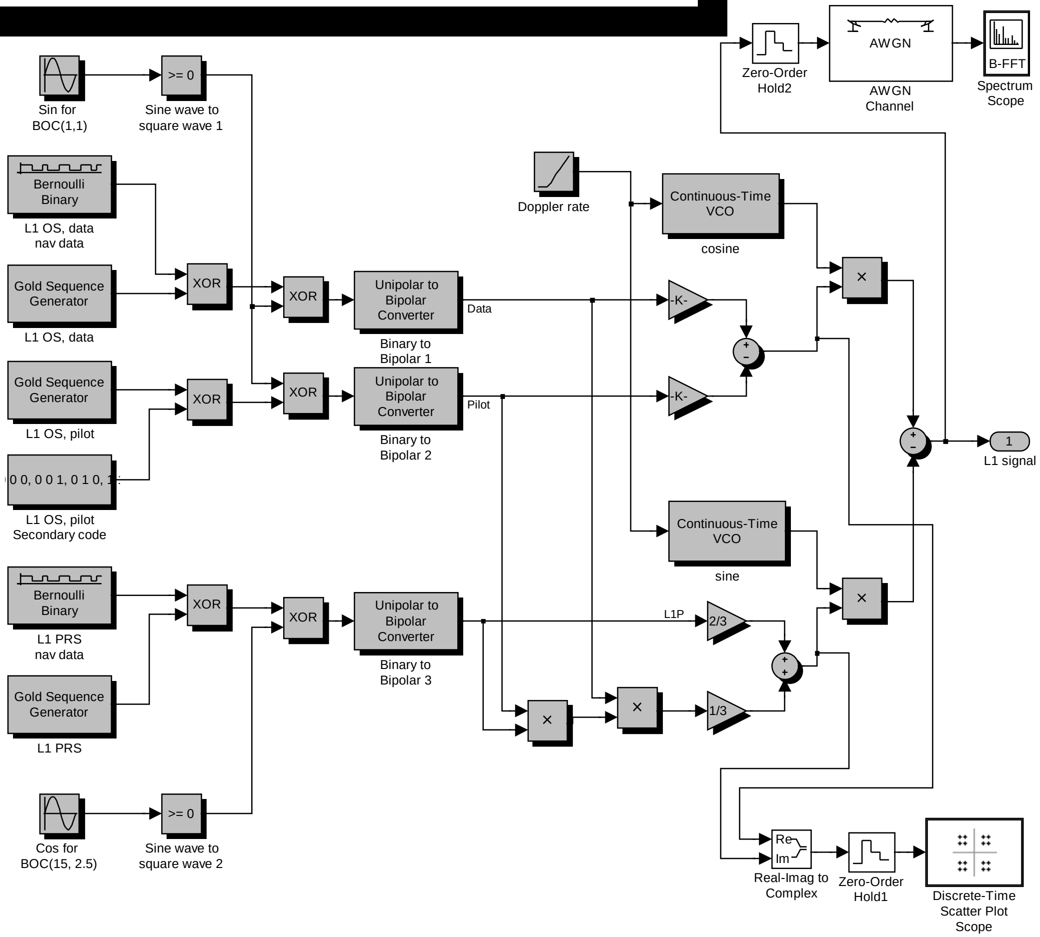
The number of negative and positive peaks is $2n - 1$ in the ACF separated in delay by $T_s = 1/2p$.

L1/E1 Spectrum Shared Between GPS and Galileo



GPS C/A and Galileo BOC(1,1) sharing the L1/E1 spectrum. The center frequency is 1575.42 MHz.

Simulink Model for Generating E1 Signal



The gray blocks generate the Galileo signal, and the white blocks are used to visualize the signal

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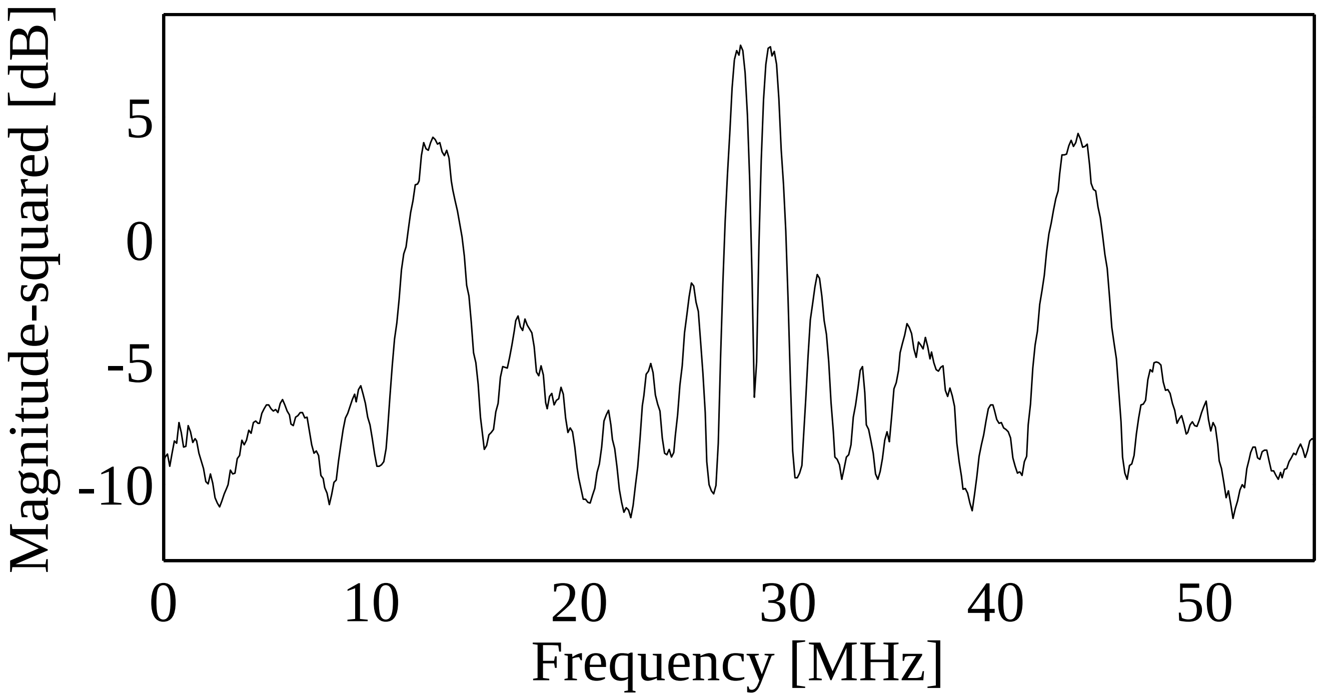
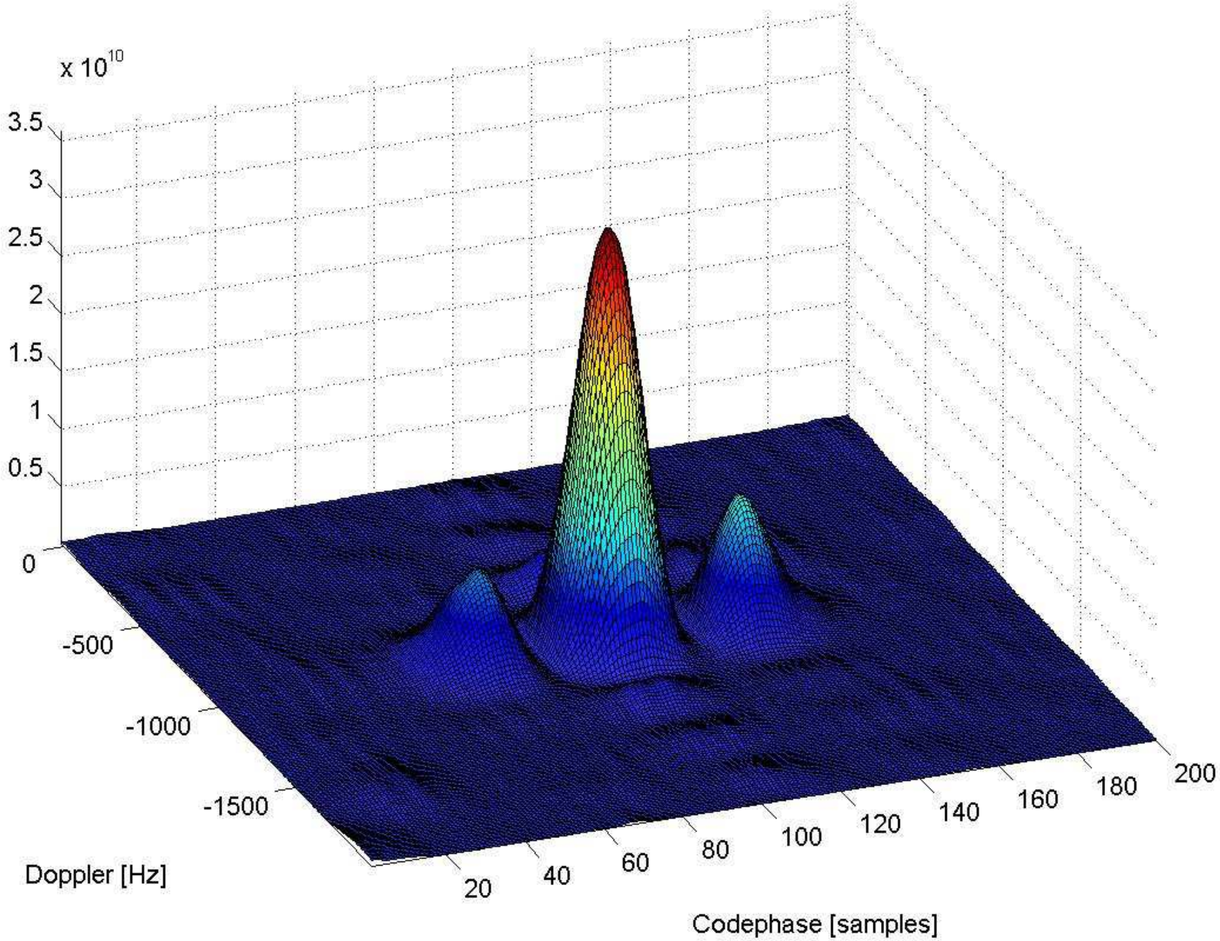
Generated Spectrum for E1 Galileo Signal



Search Result in Doppler Frequency and *m*-sequence for GIOVE-A



The data in this figure are reproduced by courtesy of Stanford University

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