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ENSICAEN
ÉCOLE NATIONALE SUPÉRIEURE D'INGÉNIEURS DE CAEN
& CENTRE DE RECHERCHE

CDMA Technology :

Principles of CDMA/DS Decoding

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CDMA Technology :

- Introduction to Spread Spectrum Technology
- CDMA / DS : Principle of operation
- Generation of PN Spreading Codes
- Advanced Spreading codes
- Principles of CDMA/DS decoding
- CDMA/DS receiver design
- Radio Cells & System Capacity
- Basics of Global Navigation Satellite Systems

- **Galileo : European GNSS**

CDMA Technology :

Galileo : European GNSS

- Motion in Europe to overcome US monopoly in Global Navigation Satellite system (GPS) by installation of an European (civil) GNSS "Galileo"
- Galileo should be operated by an international (European) agency and independently of military considerations (no deterioration in political crises)
- Official go-ahead by the European Union Transport Ministers on March 26th, 2002
  Intended start of commercial operation: 2015 (may be delayed to about 2018)
  85% of Galileo costs are funded by Germany, Italy, France, and Great Britain (UK)
- Galileo provides for interoperability with GPS (political obligation to overcome US concerns and opposition;
  agreements on compatible signal formats on 06/26/2004 and 07/26/2007)
- Galileo consists of 30 satellites on 3 planes with 9 operational and 1 spare satellites each ;
  inclination: 56° ; orbit altitude: $\approx$ 23 616 km (better polar coverage than GPS)

- Galileo (full configuration) consists of 30 satellites on 3 planes
  - 9 operational and 1 spare satellites on each plane;
  - inclination: 56° ; orbit altitude: ≈ 23 616 km (better polar coverage than GPS)

- Services:
  - open service: public use free of charge; accuracy comparable to GPS C/A code
  - commercial service: high precision + efficient data link for registered subscribers
  - public regulated serv.: high precision & immunity against jamming and spoofing for law enforcement
  - safety-of-life service: position monitoring with high system integrity and reliability
  - search and rescue : SAR service to be integrated in existing COSPAS/SARSAT

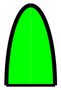
- Signal carriers:
  - 1176.45 MHz (E5a) ; 50 symbols per second
  - 1207.14 MHz (E5b) ; 250 symbols per second
  - 1278.75 MHz (E6) ; 3 subcarriers with data and pilot channel
  - 1575.42 MHz (E2-L1-E1) ; 3 subcarriers with BOC modulation; colocation with GPS

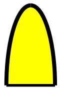
- **If 2 or more different signals are to be allocated to the same rf frequency the modulation schemes for the signals have to be chosen carefully to enable signal separation in the rx.**

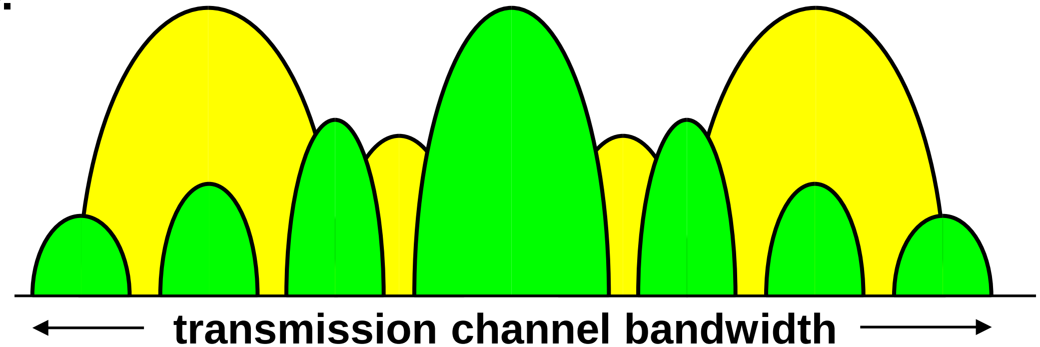
- **The most common modulation scheme for CDMA signals on rf carriers is Binary Phase Shift Keying (BPSK) or Differential Phase Shift Keying (DPSK) with a spectrum envelope proportional to:** $si^2(\pi f T_C) = \sin^2(\pi f T_C) / (\pi f T_C)^2 = \mathrm{sinc}^2(\pi f T_C)$

- **The BPSK power density spectrum concentrates around the (suppressed) carrier frequency and has an envelope roll off to the band limits.**

- **Additional signals or data carriers on the same rf frequency should have "inverse" power density spectrum envelopes with maxima near to the band limits and minima around the center frequency.**

 **BPSK power density spectrum (schematic)**

 **desired power density spectrum (schematic) of colocated signal**



- **Binary Offset Carrier (BOC) modulation offers the desired option (for details see below)!**

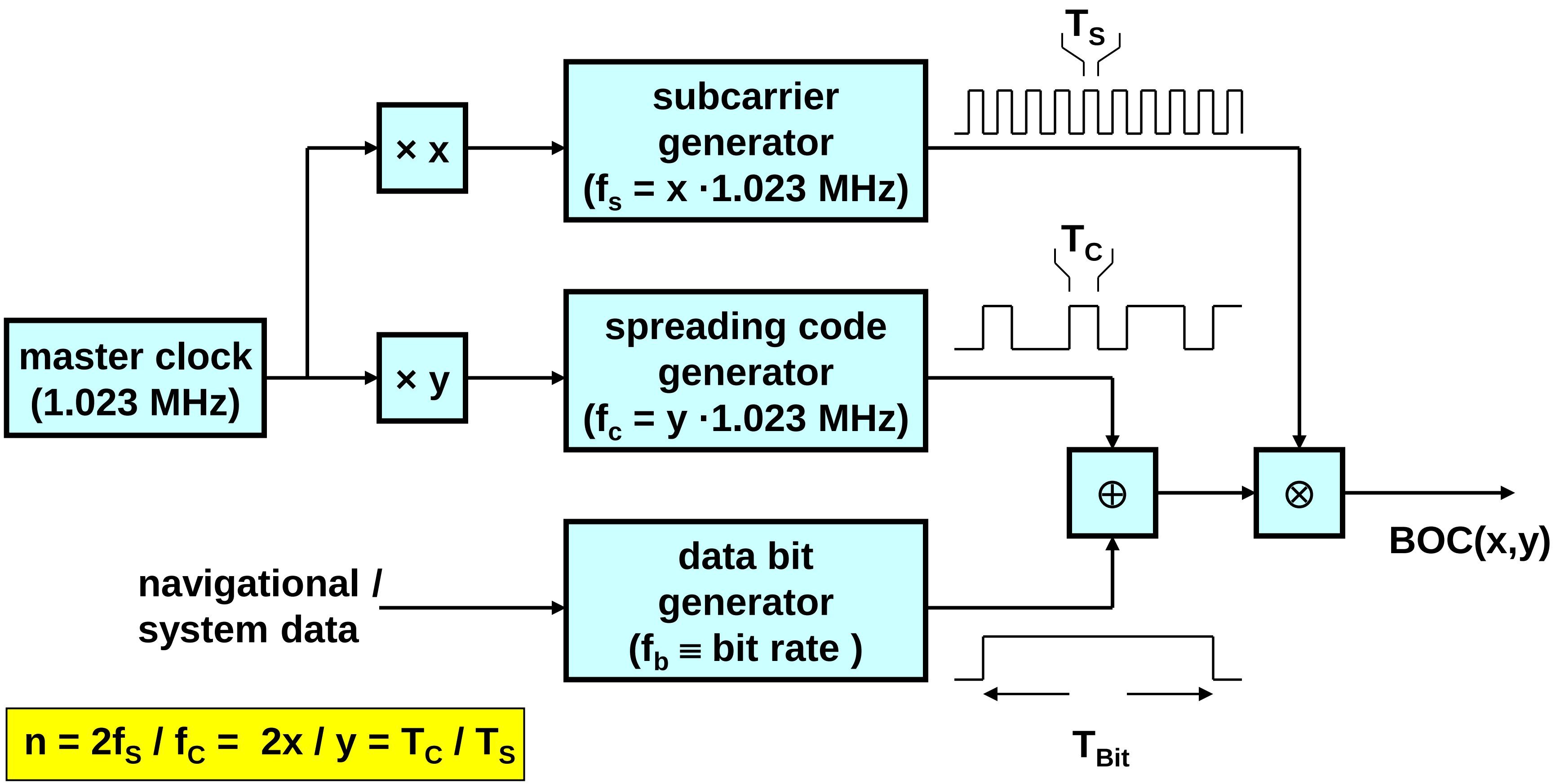
- Binary Offset Carrier (BOC) modulation offers power density spectra with minima in the channel center and maxima offset to the center frequency.

- <u>Generation of BOC Signals:</u>
  A CDMA/DS signal (chip sequence) is additionally multiplied (modulated) with a bipolar binary square signal as subcarrier. Basically BOC signals are denoted as BOC (f_S , f_C) with: $f_S \equiv$ subcarrier frequency and $f_C \equiv$ chip rate

- For GPS & Galileo SATNAV systems the frequency denotation is normalized to the system master clock frequency of 1.023 MHz. Instead of denoting f_S and f_C as true frequencies they are expressed as multiples x and y of the system master clock:
  e.g. BOC (10,5) with f_S = 10.23 MHz and f_C = 5.115 Mchip/s

- A basic BOC system parameter is: $n = 2f_S / f_C = 2x / y$ with $n \in \mathbf{N}$ (integer)
  examples: BOC(2,2) $\rightarrow$ n = 2 (even) BOC(10,5) $\rightarrow$ n = 4 (even)
  BOC(15,2.5) $\rightarrow$ n = 12 (even) BOC(7,2) $\rightarrow$ n = 7 (odd)

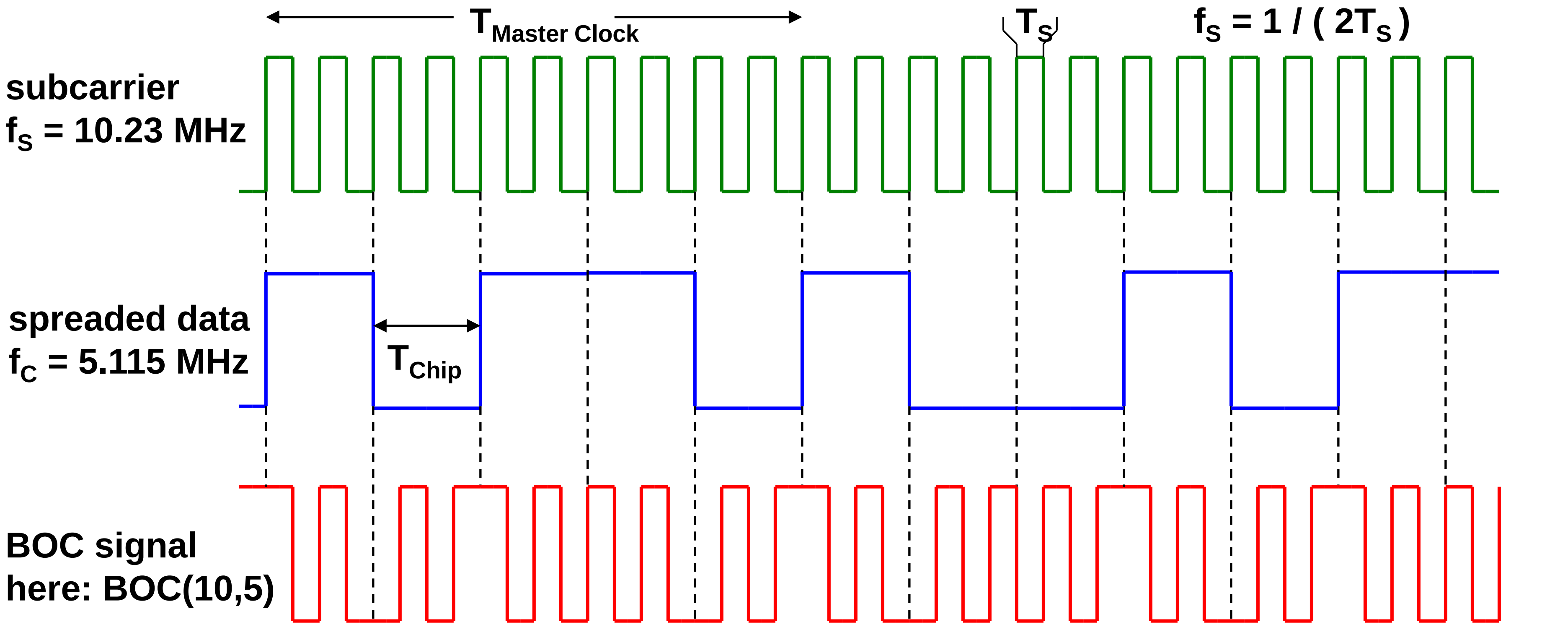
- BOC power density spectra differ in principal shape depending on n even or n odd!



$n = 2f_S / f_C = 2x / y = T_C / T_S$

The BOC(x,y) signal is a rectangular (baseband) signal. For rf transmission this BOC(x,y) signal will modulate a harmonic sine wave carrier. A typical modulation scheme is BPSK.

BOC(10,5) has a subcarrier frequency of 10 × 1.023 MHz and a period of 1/10.23MHz = 97.752ns. The spreading code has a chip frequency of 5 × 10.23 MHz with a chip duration of 195.50ns. The chip sequence section shown below is: +1 -1 +1 +1 -1 +1 -1 -1 +1 -1 +1 +1



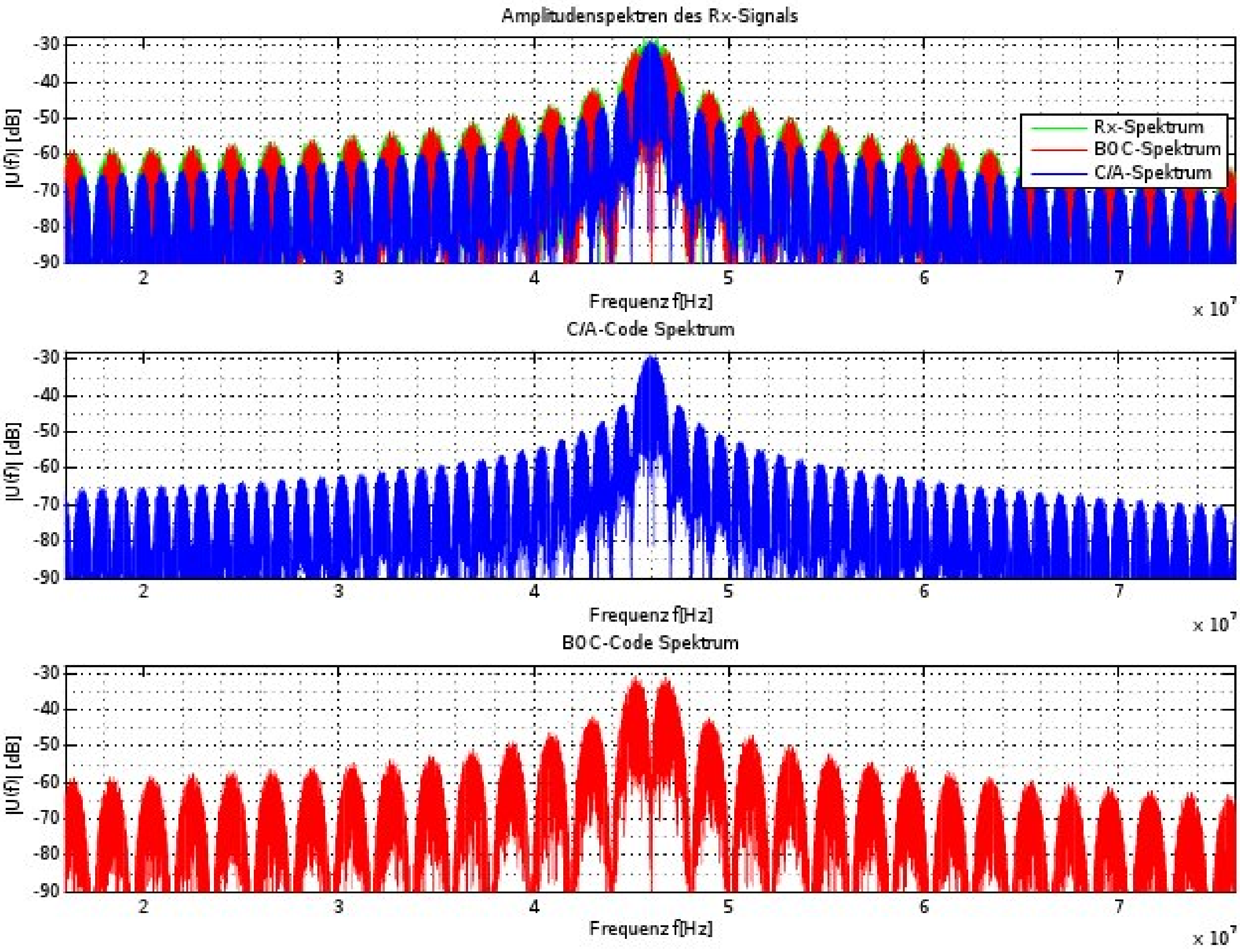
<u>Attention:</u> **BOC signal is shown as product of bipolar signals (subcarrier ⊗ spread data); no ⊕ operation!**

Power Density Spectra ≡ PDS of BOC signals depend on n even or odd:

BOC PDS:

$$S_{BOC\,(f_S,\,f_C)}(f) \;=\; f_C \cdot \left(\frac{\sin\left(\frac{\pi \cdot f}{2 \cdot f_S}\right) \cdot \sin\left(\frac{\pi \cdot f}{f_C}\right)}{\pi \cdot f \cdot \cos\left(\frac{\pi \cdot f}{2 \cdot f_S}\right)} \right)^2 \quad \text{for} \quad n = 2\, f_S/f_C \;\text{ even}$$

$$S_{BOC\,(f_S,\,f_C)}(f) \;=\; f_C \cdot \left(\frac{\sin\left(\frac{\pi \cdot f}{2 \cdot f_S}\right) \cdot \cos\left(\frac{\pi \cdot f}{f_C}\right)}{\pi \cdot f \cdot \cos\left(\frac{\pi \cdot f}{2 \cdot f_S}\right)} \right)^2 \quad \text{for} \quad n = 2\, f_S/f_C \;\text{ odd}$$

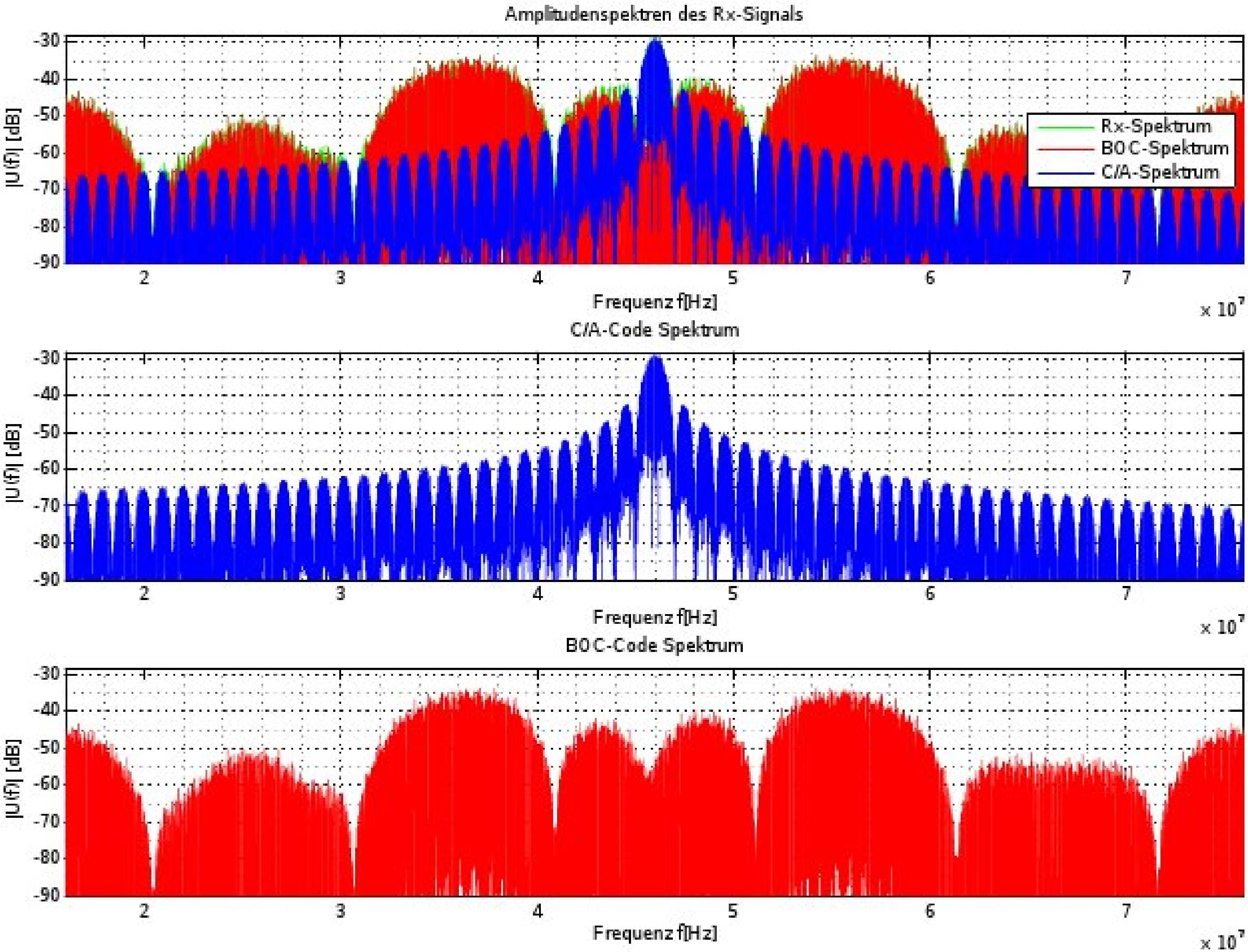


amplitude spectra:

- BPSK (blue)
- BOC (1, 1) (red)
- signal sum (green)

BPSK (C/A code) only

BOC (1,1) only



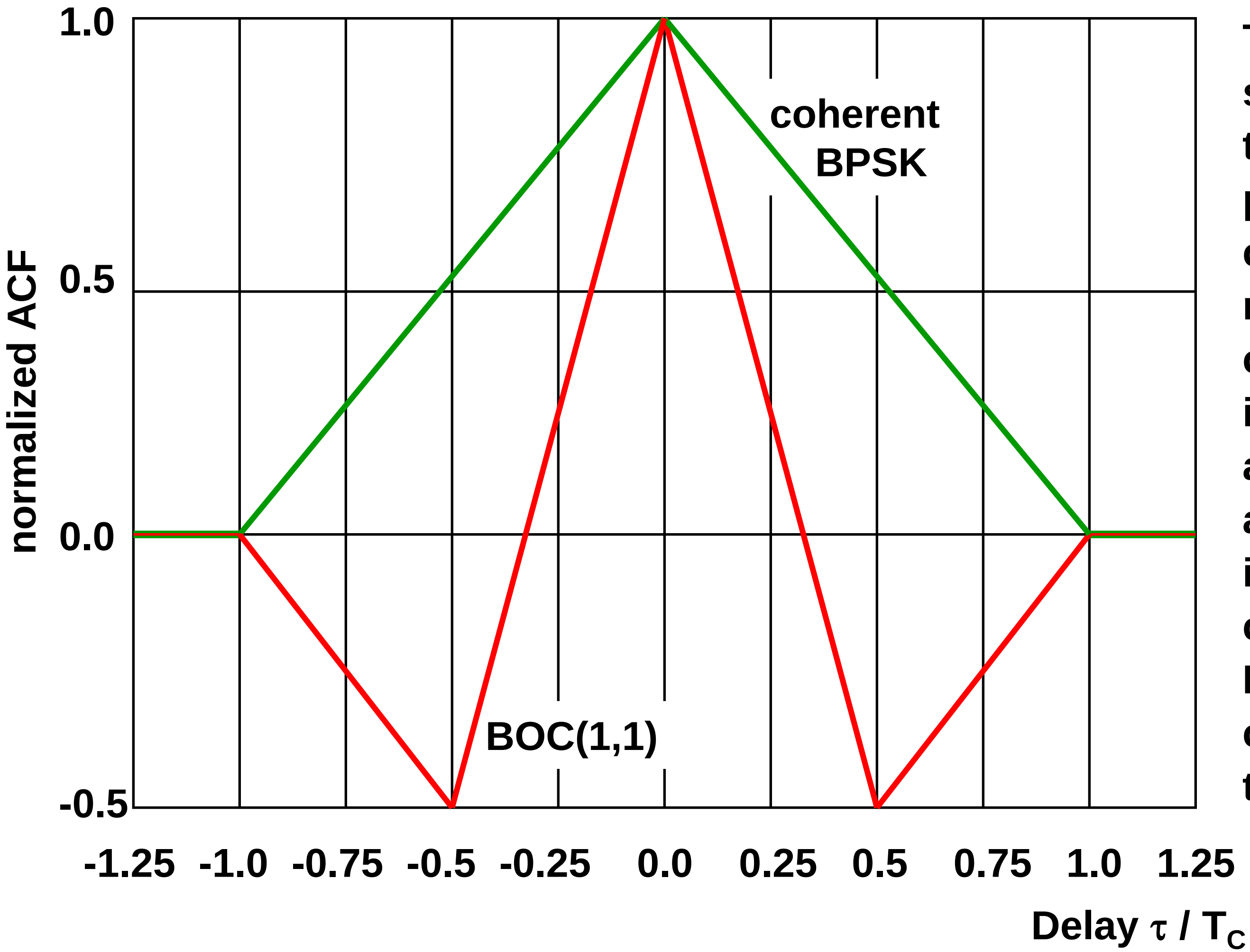
amplitude spectra:

- BPSK (blue)
- BOC (10, 5) (red)
- signal sum (green)

BPSK (C/A code) only

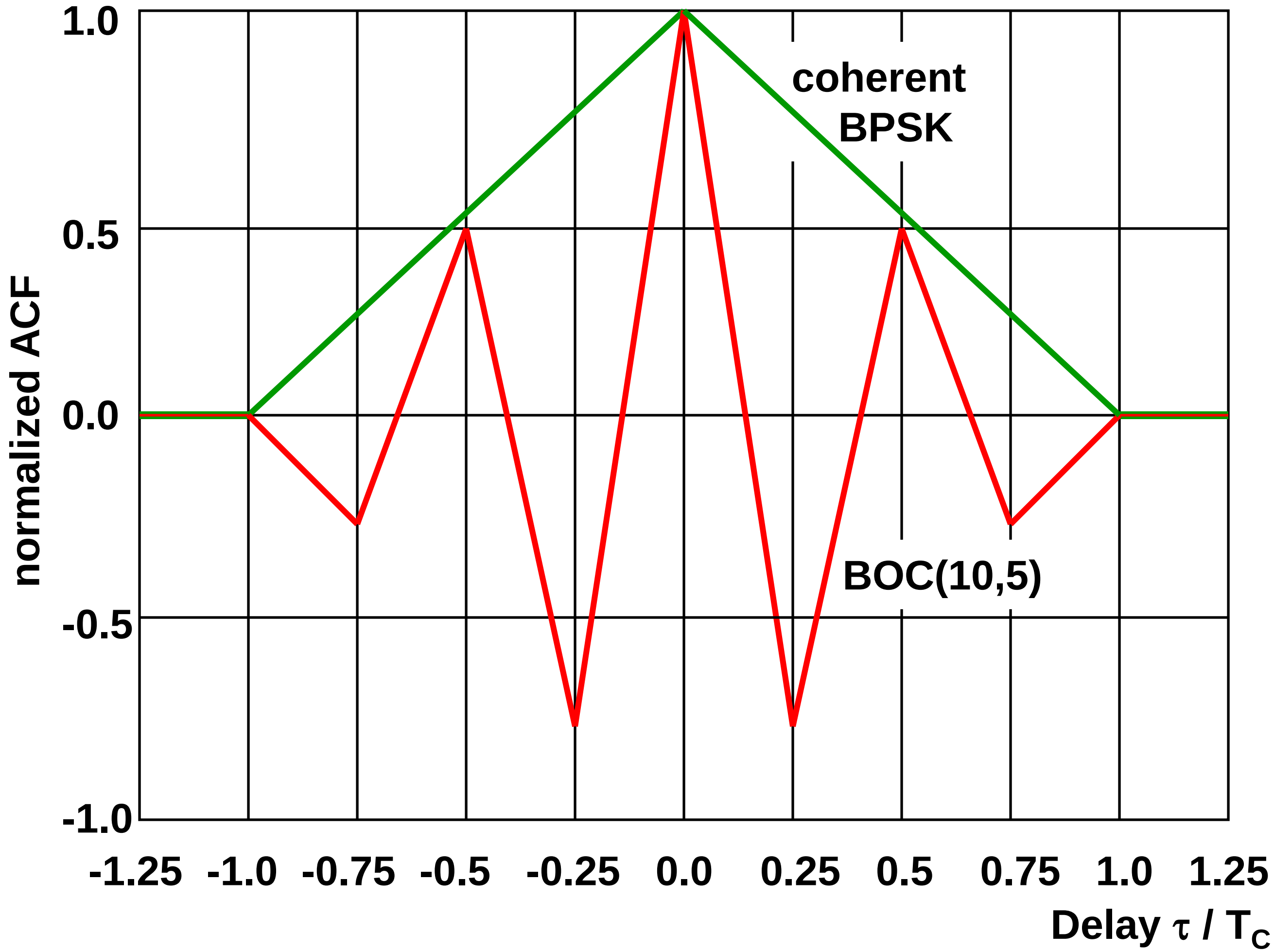
BOC (10, 5) only

Normalized Autocorrelation Function (ACF) of different Modulation Schemes:



The subcarrier signal structure causes more than 1 correlation peak. The maximum correlation peak is narrower than that of coherent BPSK. This increases timing accuracy. But additional side peaks in the ACF may confuse the Delay Locked Loop (DLL) and can cause irregular timing.

Normalized Autocorrelation Function (ACF) of BOC(10,5) Signal versus coherent BPSK:



ACF plots for unlimited bandwidth!

With increasing ratio of subcarrier frequency : chip frequency = f_S / f_C the ACF of a BOC(x,y) signal contains more and more side peaks and offers more and more stable slopes for the DLL!

- The autocorrelation functions (ACF) of BOC(x,y) signals show a multiple saw tooth character and offer multiple stable slopes for the DLL.

- For optimum and precise timing the DLL has to synchronize on the ACF maximum. The DLL must get additional support to find the ACF maximum peak.

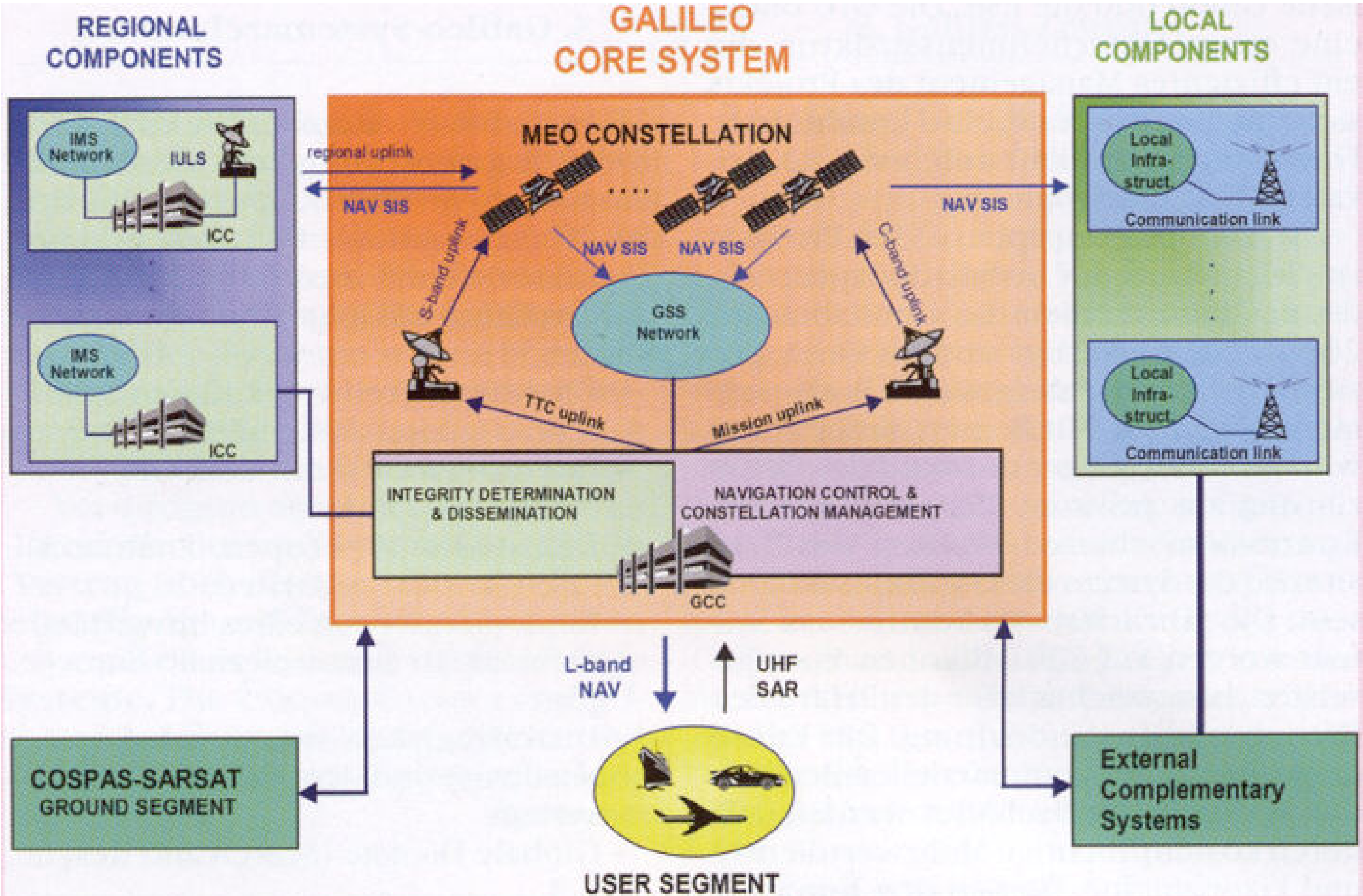
- Several approaches to deliver additional information to the DLL have been proposed, simulated, and tested. Some proposals are still subject of research and optimization.

- One proposal recommends the induction of a "very early gate" and a "very late gate" into the DLL block. These additional gates detect the raise and the fall of the ACF peaks and allow for a discrimination of the ACF center.

- From the balance between the outputs of the "very early gate" and the "very late gate" the original DLL can be activated inside the desired area of the correlation maximum with the appropriate stable section of the discriminator curve.

- Simulations have shown, that this "very early - very late" gate processing is susceptible to noise and interference. Satisfying performance requires a rather comfortable signal-to-noise or signal-to-interference ratio.

Part 4 :   Galileo System Constellation



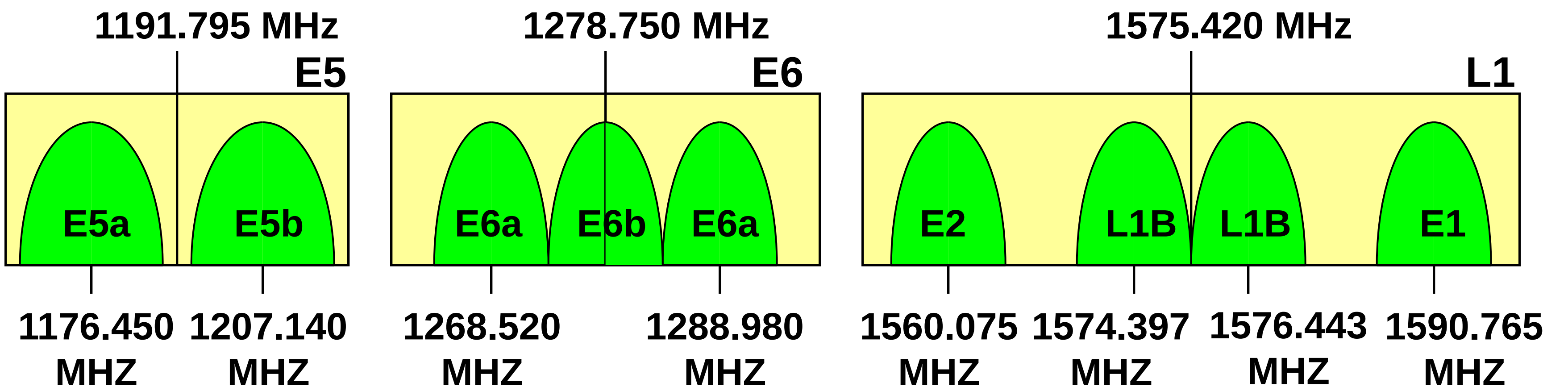
Source: ESA

Part 4 : Present Galileo Status

- 2 experimental satellites "Galileo In Orbit Vehicle Experimental" (GIOVE A + B) launched 2005 and 2008 and "retired" in July 2012
- October 21st, 2011: first 2 Galileo "In Orbit Vehicle" (IOV) launched
- October 12th, 2012: another 2 IOV SATs launched
- March 12th, 2013: first position determination on Galileo signals only
- August 22nd, 2014: first 2 fully operational capabilities SATs launched, but into an incorrect orbit (partial correction achieved)
- 2014: 4 further Galileo FOC to be launched
- 2015: 4 further Galileo FOC to be launched
- Mid of 2015: 14 fully operational capabilities SATs in orbit will form "initial operational capability" constellation
- after 2015: another 13 FOC SATs will be launched
- after 2020: full constellation of 30 SATs in orbit + 2 spares on ground planned → funding not yet decided

Service Acronym	Service Name and Service Description	Receiver Specification	Position Accuray (2σ ; 95%) horizontal	vertical
OS	Open Service (comparable to GPS)	single frequency	15 m	35 m
OS	Open Service (OS is free of charge)	dual frequency	4 m	8 m
CS	Commercial Service (encrypted; liable to tax)	dual frequency	< 1 m	< 1 m
PRS	Public Regulated Service (encrypt.; secure operat.)	single frequency	6.5 m	12 m
SoL	Safety of Life Service	dual frequency	4 ... 6 m	4 ... 6 m
SAR	Search and Rescue (supports existing syst.)	call back facility	similar to SoL ; combined with COSPAS/SARSAT	

RF band & frequency [MHz]	signal name	frequency of spectr. maxima [MHz]	dedicated to service	modulation / signal format	data rate [bit/s]
E5: 1191.795	E5a E5b	1176.450 1207.140	OS; CS OS; CS; SoL	altBOC(15,10) altBOC(15,10)	50 250
E6: 1278.750	E6b E6a	1278.750 1268.520 & 1288.980	CS PRS	BPSK(5) BOCcos(10,5)	1000 N/A
L1: 1575.420	L1B E2 & E1	1574.397 & 1576.443 1560.075 & 1590.765	OS; CS; SoL PRS	CBOC(6,1,1/11) BOC(15,2.5)	250 N/A



- **Galileo employs optimized modulation schemes and special spreading codes. The major design criteria are compatibility with other navigation signals in the same rf band, improved signal acquisition (particularly for weak signals), and multipath resistance.**

- **<u>Modulation schemes / signal formats:</u>**

  - **altBOC(15,10):** **the baseband signal s(t) is multiplied with a complex subcarrier**
    $s_S(t) = s(t) \cdot \text{sign}\,[\exp(j2\pi f_S t)]$ ○—● $S_S(f) \approx S(f) \otimes \delta(f - f_S)$
    this produces 1 sideband only; independent sidebands are possible

  - **BOC_{cos}(10,5):** **the subcarrier is not a "sign sin(x)" square wave but a "sign cos(x)" square wave, which changes the phase relation between the subcarrier and the code signal. This format further reduces mutual interference with traditional GPS narrowband signals of BPSK(1) type.**

  - **CBOC(6,1,1/11): MBOC(6,1,1/11)** **"Composite" BOC; special version of "Multiplexed BOC" (MBOC) which multiplexes a BOC(6,1) wideband signal and a BOC(1,1) narrowband signal. On average 1/11 of the signal power is transmitted in the high frequency components (wideband signal).**

- **Spreading Codes:**

For Galileo special spreading codes have been developed. Main criteria were:

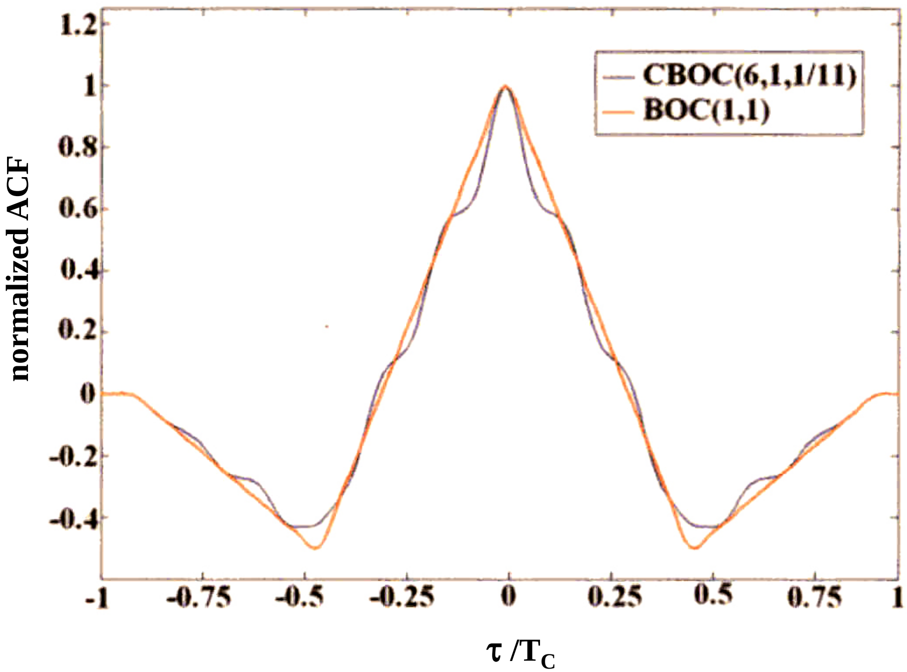
- optimized autocorrelation function shape with reduced ACF sidelobe maxima & minima (improves acquisition and codetracking in the presence of noise and interference)
- optimized balance of 1 and 0
- sufficient number of codes in code families

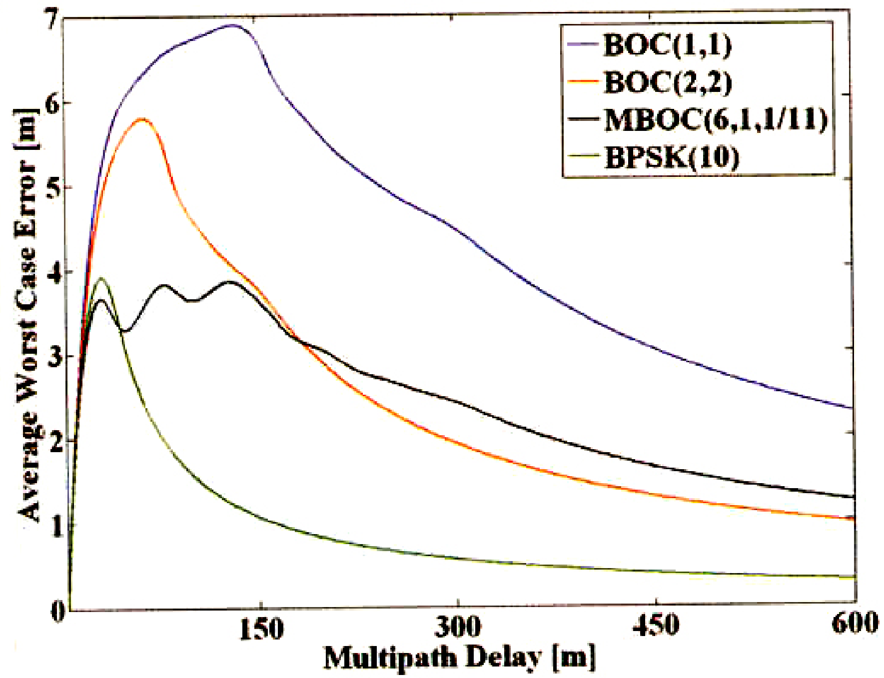
Codes have been selected by computer search with try and error. An exhaustive search was not achievable due to the extremely large number of possible code sequences. The search was optimized by a "search tree" following paths with promising code sequences and deliberately refining these sequences.

- **Selected Codes:** "Random Codes" or "Memory Codes"

The selected spreading codes can not be generated by an algorithm or a generator. The complete code sequence is stored in a memory ("memory code") and has to be read out serially from the memory. Compared to m-sequences or Gold codes bigger registers or memories are required. However, this is no problem with state-of-the-art memory technology.

- **Galileo rf carriers are I-Q-modulated (orthogonal carriers) with the navigation signal on the In-phase carrier (I) and a pilot signal on the Quadrature-phase carrier (Q)**
  → pilot carrier simplifies signal acquisition and doppler shift compensation
- **Galileo signals have narrower correlation peaks than traditional GPS signals**
  → higher position precision achievable
- **Galileo signals offer compatibilty with traditional GPS signals on behalf of optimized BOC modulation (<u>remark:</u> this is no interoperability because of different signal formats!)**
- **Galileo employs longer codes (L = 4092 or 10230 chips) than GPS C/A codes**
  → better ACF performance for improved accuracy
- **Galileo has 6dB higher rf signal transmission power than GPS**
  → better signal quality below trees or obstacles and better penetration of buildings
- **Built in system integrity and reliability messages and anti-spoofing capabilities**
  → provides application for security related and/or "Safety of Live" (SoL) services





Source: G. W. Hein et al.: The MBOC Modulation ; InsideGNSS September/October 2007 ; p.43

The ACF of CBOC(6,1,1/11) has a narrower peak as BOC(1,1). This allows for better time discrimination and more precise ranging, For $\tau/T_C = \pm 0.25$ and $|\tau/T_C| \geq 1$ both modulation schemes perfom equally.

The average worst case error depends on multipath delay and on the chip or subchip duration T_C or T_S. MBOC(6,1,1/11) performs well with a maximum error no worse than that of BPSK(10).

- **Galileo (as well as GPS, GLONASS, etc.) will be used as one system component in a variety of equipment like mobile phones, digital cameras, mobile sensors etc.**

- **Galileo will be faced with poor signal quality like inside buildings (in-door applications) → weak signal and interference tolerant design is required for Galileo/GNSS receivers**

- **Galileo has to be prepared to "electronic countermeasures" like jamming, spoofing and deception → receivers have to check and verify navigation signals ("authentication")**

- **In special cases positioning can not be based on SATNAV alone (e.g. in the basement of buildings, tunnels etc.) → SATNAV systems have to be assisted by other sensors**

- **"Assisted GNSS" may introduce "pseudolites" (terrestrical pseudo SATs), incorporate raw position date from mobile phones, or rely on other sensors like inertial systems**

- **Precise positioning will be extensively used for smart sensors and procedures like autonomous vehicle operation, automatic docking of ships, and precise farming**

- **Galileo (European GNSS) and Advanced GPS offer:**
    - **Higher Accuracy as conventional GPS**
    - **Improved system integrity**
    - **Additional services (Galileo: commercial service, public regulated service)**
    - **Coexistance between Galileo and GPS**

- **Key points :**
    - **Advances in GNSS by longer codes**
    - **Binary Offset Carrier (BOC) for improved carrier frequency coexistance**
    - **Complex code tracking loops for BOC Signals**

- **If needed, a few related readings in Global Navigation Satellite Systems :**

  - **Kaplan, Elliott D. et al.: Understanding GPS – Principles and Applications**
    Artech House Inc.; Norwood MA 2006

  - **www.insidegnss.com/magazine**