GNSS Signals and Spectra

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Second meeting of the International Committee on Global Navigation Satellite System (ICG-02), Sept.4-7, 2007, Bangalore, India

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Overview

- Introduction to conventional and new signal waveforms
- Importance of Interoperability and Compatibility
- Galileo Signal Baseline
- GNSS Signals in E5
- GNSS Signals in E6
- GNSS Signals in E1
  - Performance of MBOC

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From BPSK to MBCS

- BPSK is used for satellite navigation for already a long time:
  - GPS C/A and P(Y) Code
  - GLONASS signals
- Easy to implement
- Least performing signal for a given bandwidth
- Limited potential to spectrally separate signal

$$G_{BPSK}\left(f_c\right) = f_c \frac{\sin^2\left(\frac{\pi f}{f_c}\right)}{\left(\pi f\right)^2}$$

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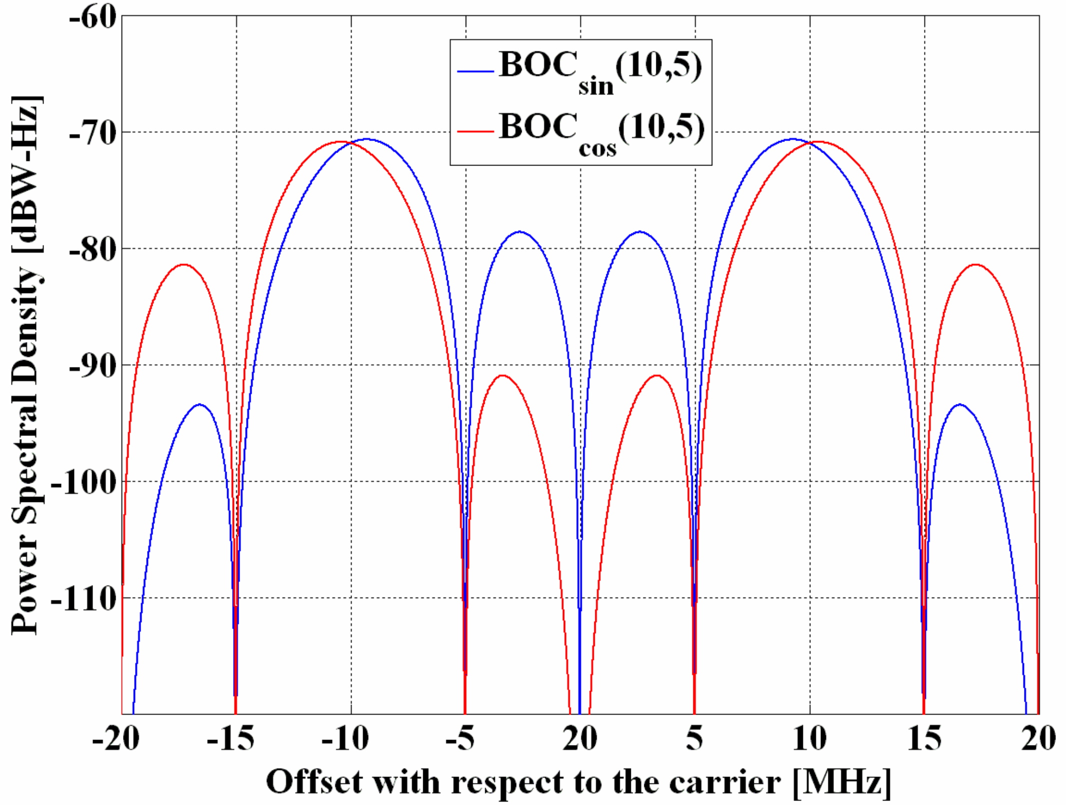
Binary Offset Carrier Signal



$$G_{BOC_{\sin}(f_s,f_c)} = f_c \left[\frac{\sin\left(\frac{\pi f}{f_c}\right)\sin\left(\frac{\pi f}{2 f_s}\right)}{\pi f \cos\left(\frac{\pi f}{2 f_s}\right)} \right]^2$$

$$G_{BOC_{\cos}(f_s,f_c)} = f_c \left[\frac{2\sin\left(\frac{\pi f}{f_c}\right)\sin^2\left(\frac{\pi f}{4 f_s}\right)}{\pi f \cos\left(\frac{\pi f}{2 f_s}\right)} \right]^2$$

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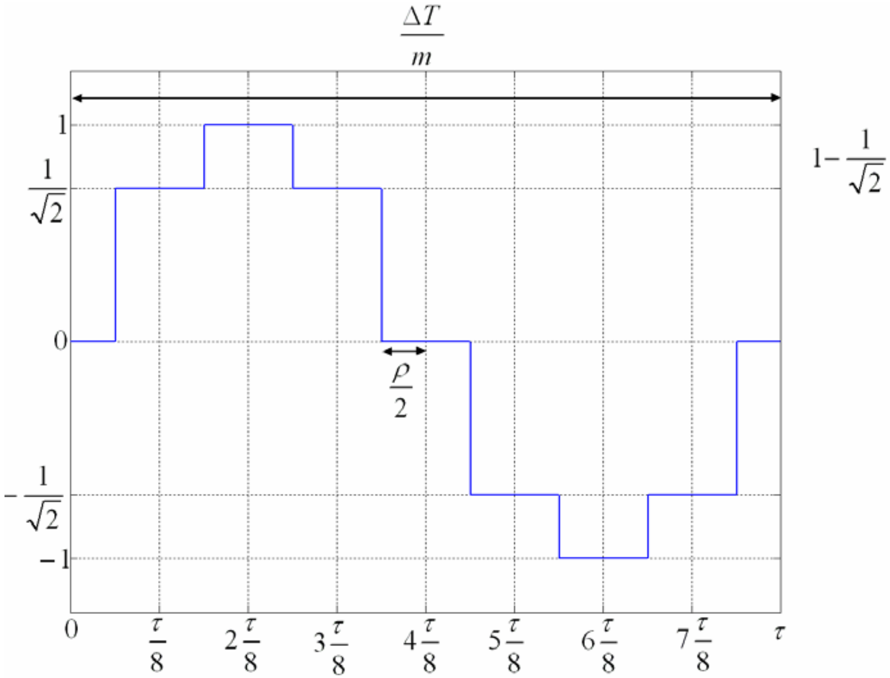
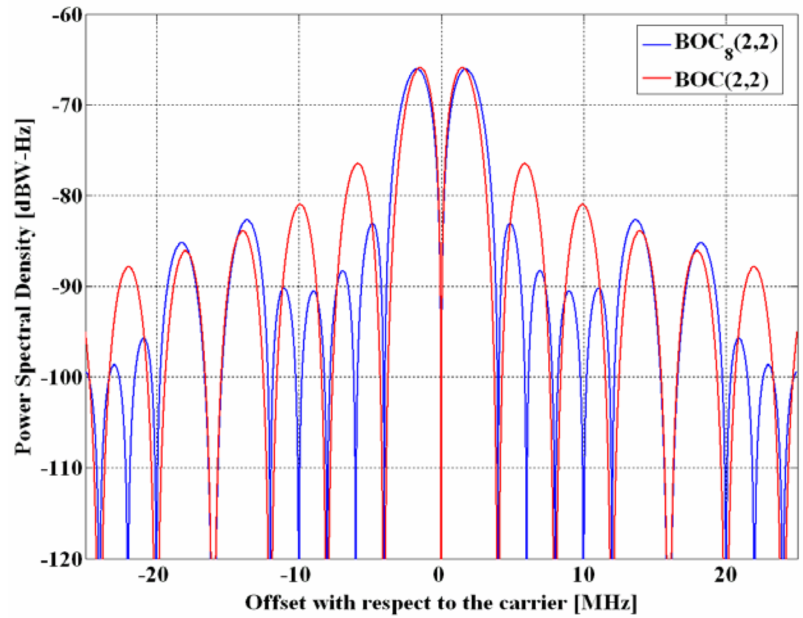
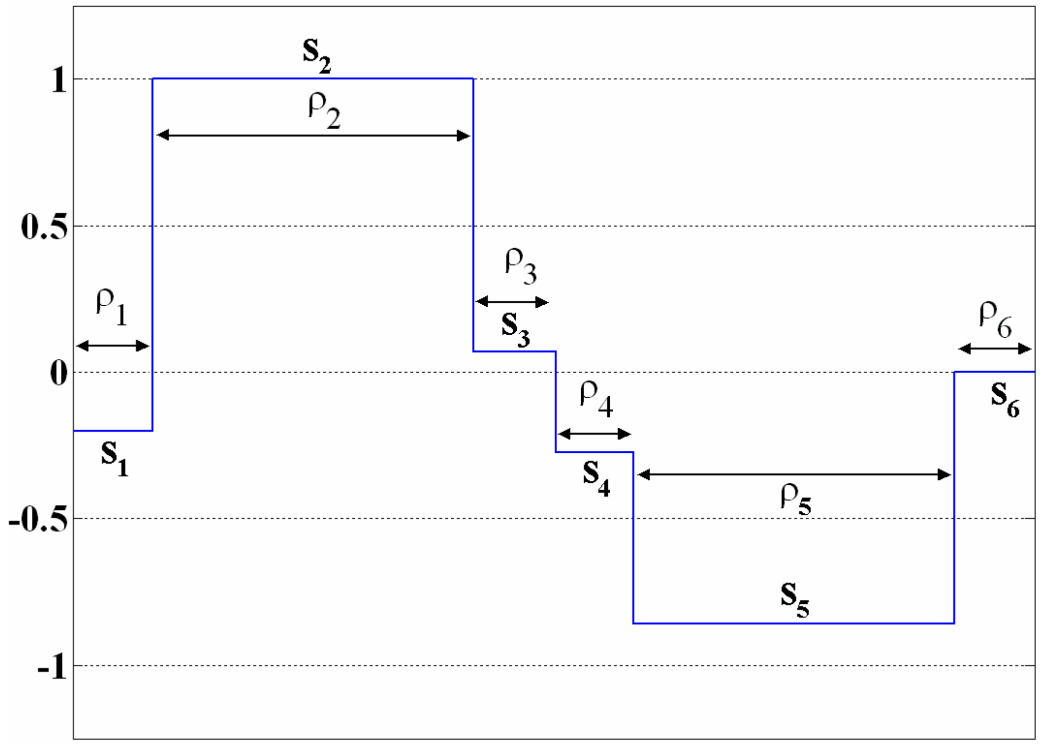
PSK BOC Signal Modulation





$$G_{BOC^{8}_{\sin}(f_s,f_c)}(f) = 2 f_c \left[\frac{\sin\left(\frac{\pi f}{8 f_s}\right)\left[1+\sqrt{2}\cos\left(\frac{\pi f}{4 f_s}\right)\right]\sin\left(\frac{\pi f}{f_c}\right)}{\pi f \cos\left(\frac{\pi f}{2 f_s}\right)} \right]^2$$

Multilevel Coded Symbols (MCS)



$$G_{MCS([s],f_c)}(f) = f_c \frac{\sin^2\left(\dfrac{\pi f}{n f_c}\right)^2}{(\pi f)^2} \left\{ 2\sum_{i=1}^{n}\sum_{k'=i}^{n} s_i s_{k'} \cos\left[(k'-i)\frac{\omega T_c}{n}\right] - \sum_{i=1}^{n} s_i^2 \right\}$$

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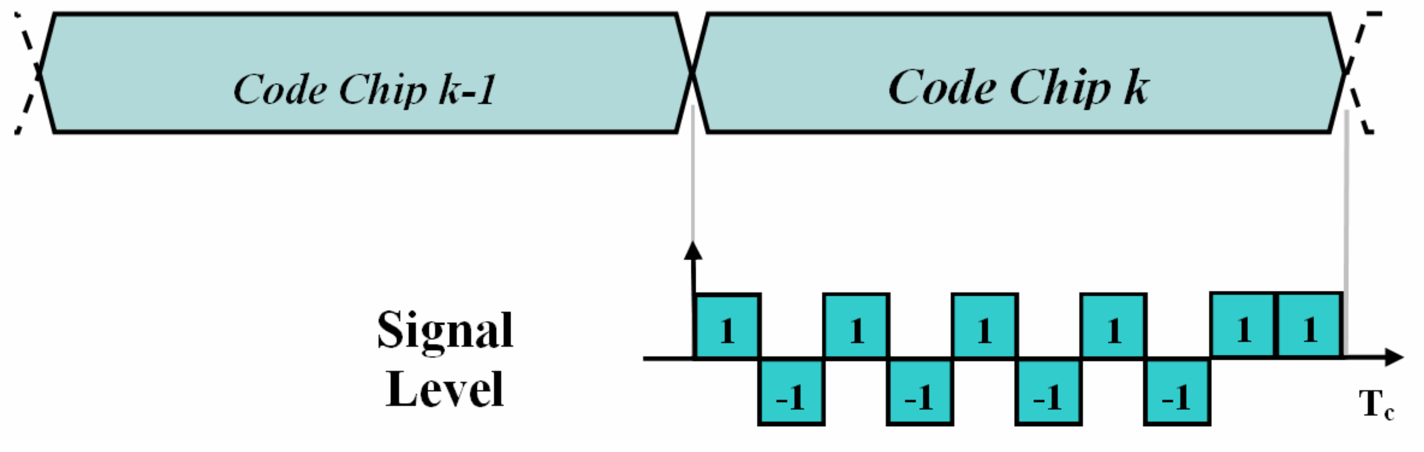
Binary Coded symbols (BCS)



$$G_{BCS([s],1)}(f) = f_c \frac{\sin^2\left(\frac{\pi f}{n f_c}\right)}{(\pi f)^2}\left\{ n + \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} 2 s_i s_j \cos\left[(j-i)\frac{2\pi f}{n f_c}\right]\right\}$$

- **General definition also includes blending of two or more BCS signals – Multiplexed BCS (MBCS)**
- **The BPSK and BOC modulation are particular cases of BCS**

From BPSK to MBCS

- Modernized signals have a better Spectrum Conditioning
  - Improved Spectral Separation
- Modernized signals have better control of the spectral emissions and allow thus for higher levels of compatibility
- MBOC is the result of blending BOC(1,1) and BOC(6,1)
- Allocates the power in that part of the spectrum where the spectral separation with the rest of signals in the band is maximized
- Having the same spectrum guarantees compatibility and facilitates interoperability.
  - However, having same spectrum does not mean having same signals

Interoperability and Compatibility 1

- **The importance of interoperability and compatibility:**
  - ***Compatibility*** **refers to the ability of space-based positioning, navigation, and timing services to be used separately or together without interfering with each individual service or signal, and without adversely affecting national security.**
  - ***Interoperability*** **refers to the ability of civil space-based positioning, navigation, and timing services to be used together to provide better capabilities at the user level than would be achieved by relying solely on one service or signal.**

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Interoperability and Compatibility 2

- ITU Negotiations are a MANDATORY
- But additional negotiations are a NEED
- Compatibility is VITAL for the coexistence of different GNSSes
  - Spectral Separation with other signals in the band
- Interoperability is DESIRABLE
  - Different levels of interoperability
  - Minimum:
    - Common centre frequency
    - Same antenna polarization
  - Medium
    - Common Signal Spectrum
  - Maximum
    - Same parameters (data rate, code family…)

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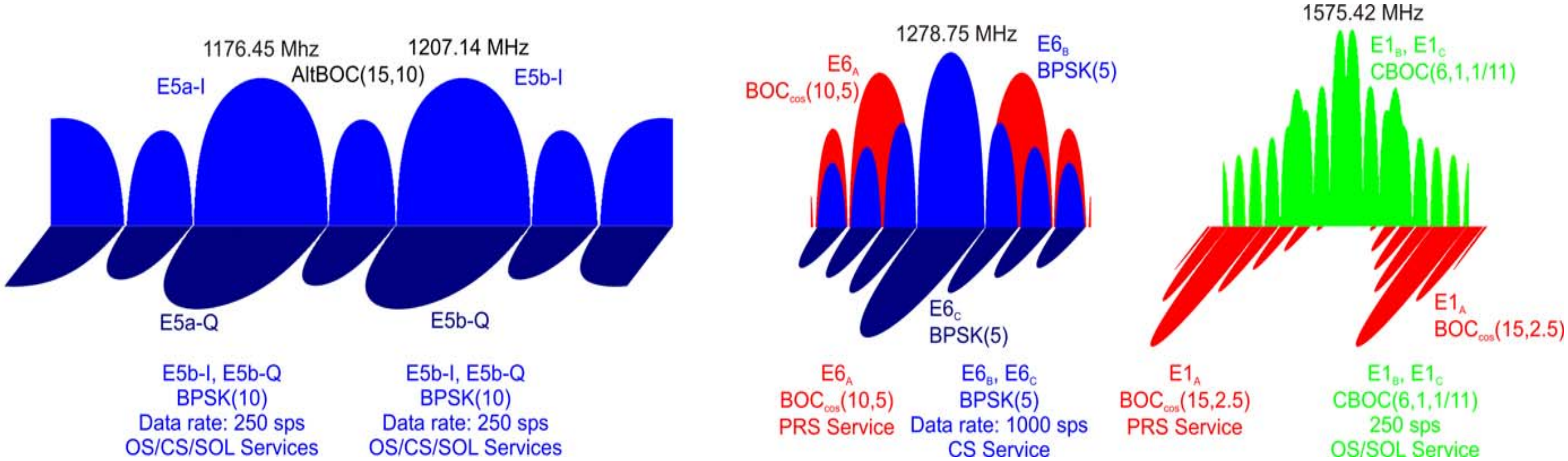
Galileo Services

Id	OS	SoL	CS	PRS	SAR
E5a					
E5b					
$E6_A$					
$E6_{B,C}$					
L6					
$E1_A$					
$E1_{B,C}$					

- **Open Service (OS)**
- **Commercial Service (CS)**
- **Safety of Life (SoL)**
- **Public Regulated Service (PRS)**
- **Search And Rescue (SAR)**

- **Galileo will provide five services – 3 frequency bands**

Galileo Signal Baseline



- **E5: AltBOC(15,10) – 2 x BPSK(10)**
- **E6: BPSK(5) and BOC_{cos}(10,5)**
- **E1: MBOC(6,1,1/11) and BOC_{cos}(15,2.5)**
  - **Latest joint EU/US decision to implement MBOC in 2007**

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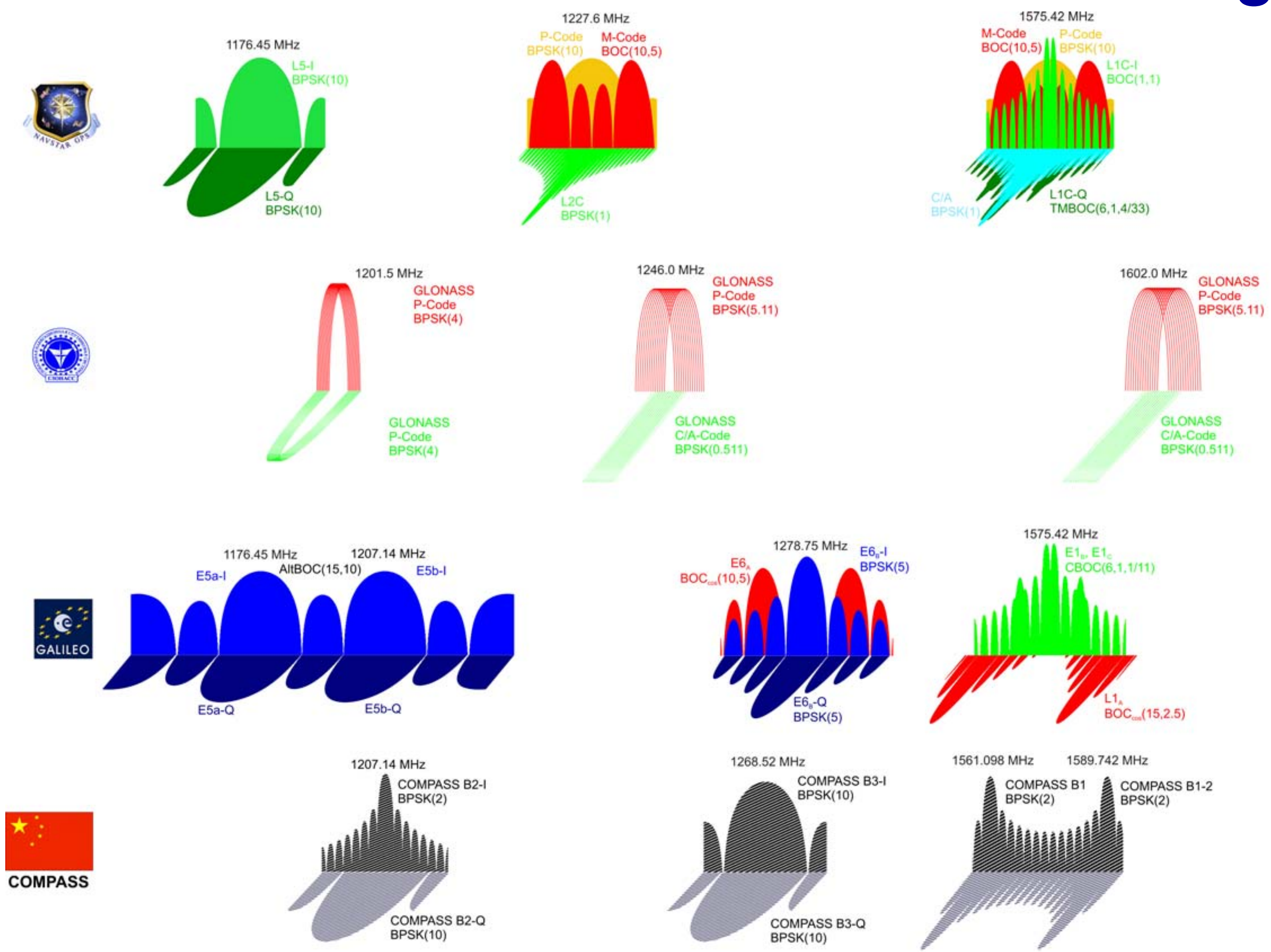
Current and Intended GNSS Signals



Green and blue signals: Open or commercial signals
Red signals: Military signals, Public Regulated Services
Grey signals: Usage of filed signal not yet defined officially

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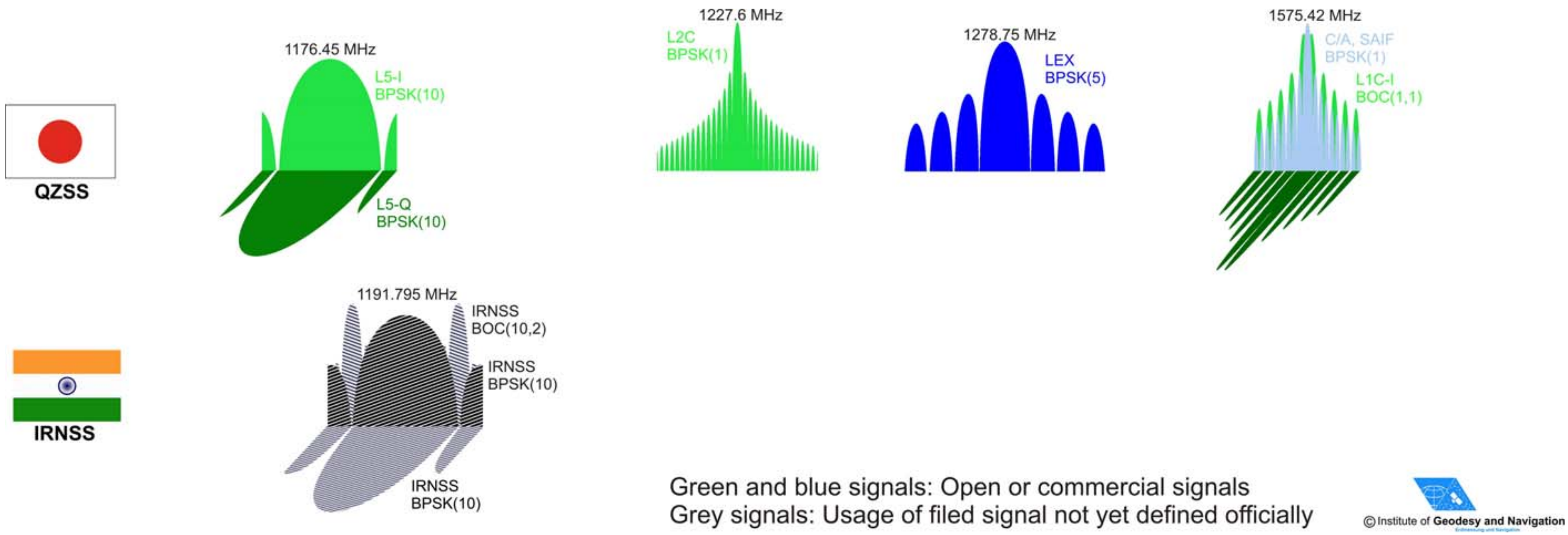
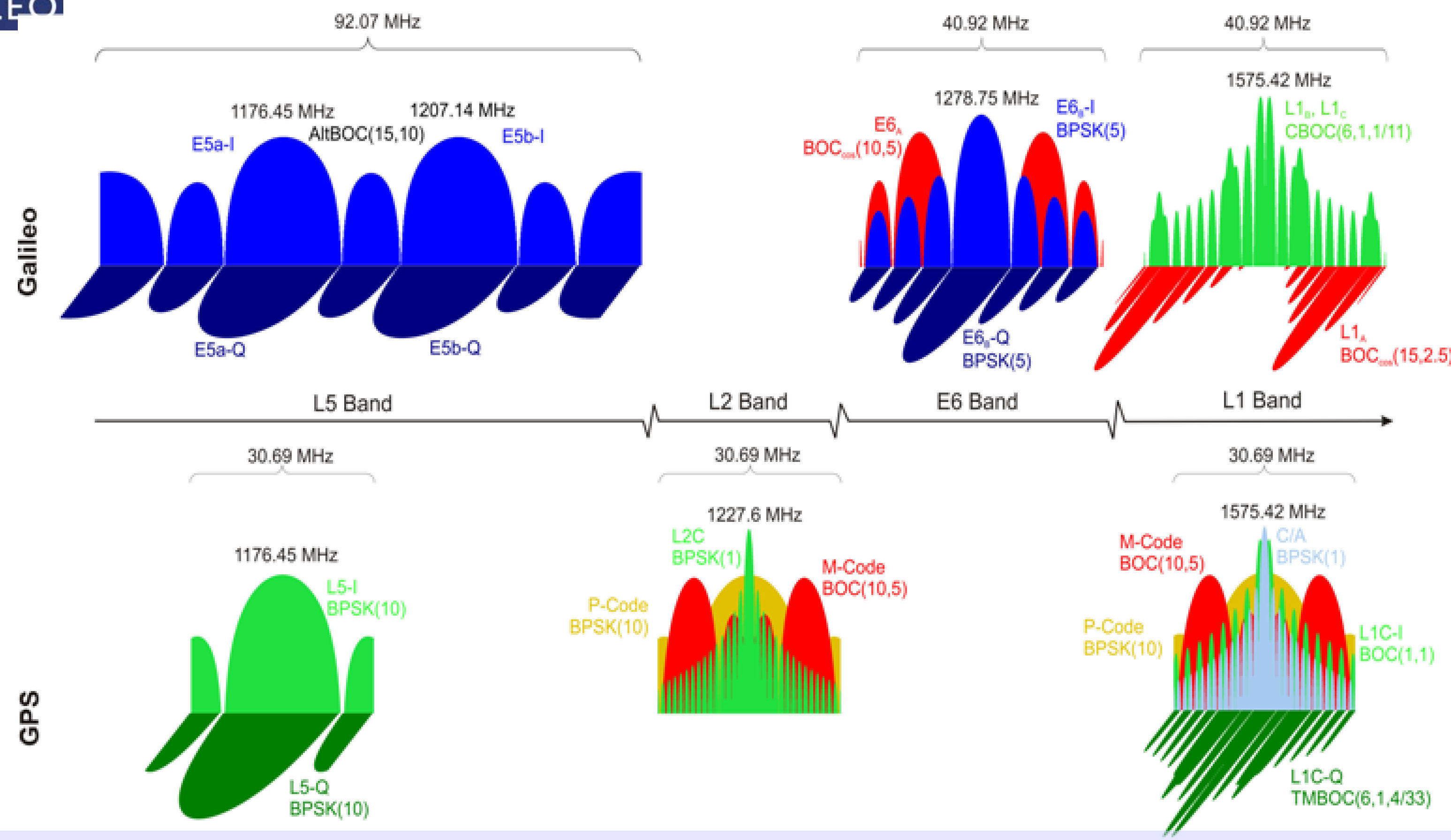
GSA

Regional Systems



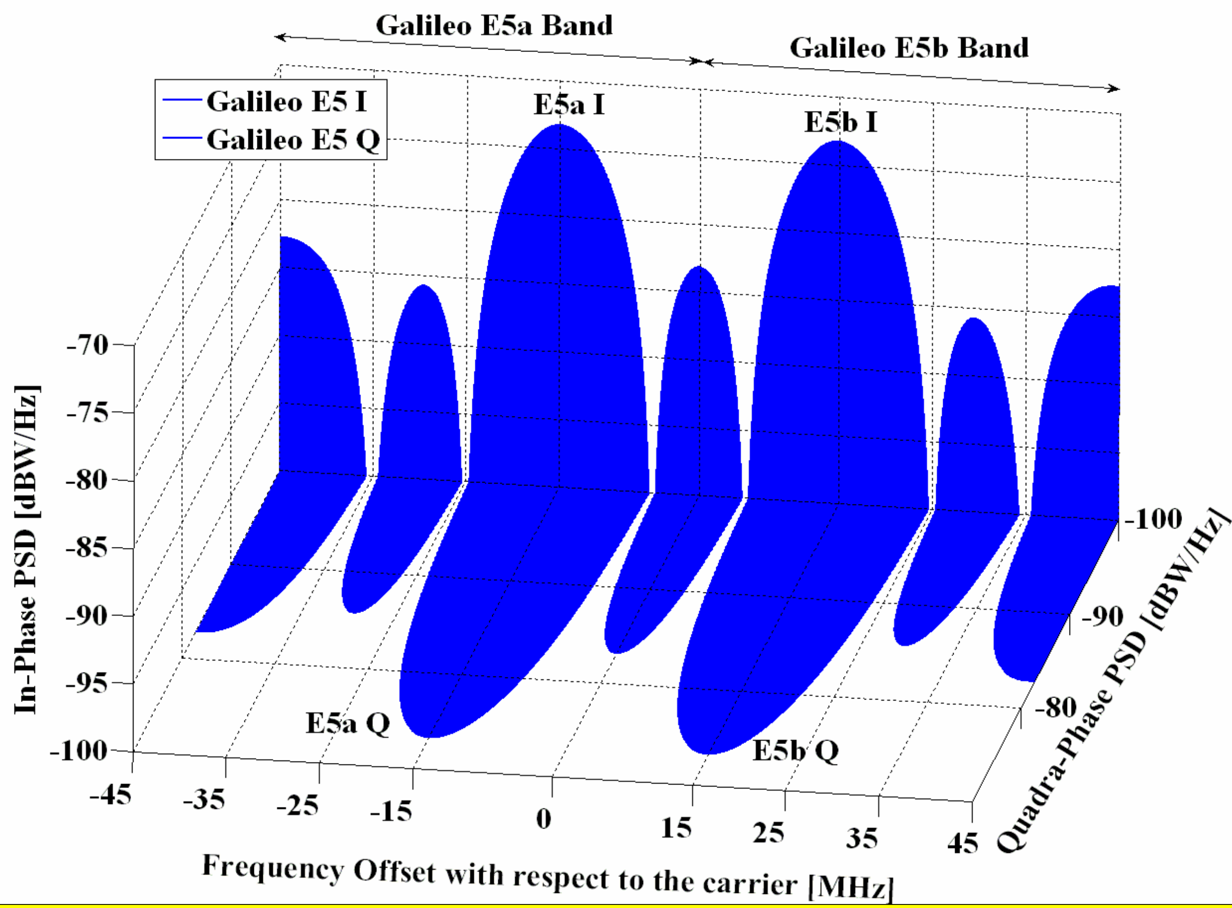
- **GPS and QZSS have reached the highest level of interoperability – 5 signals out 6 are equal**

Galileo and GPS Signal Structure



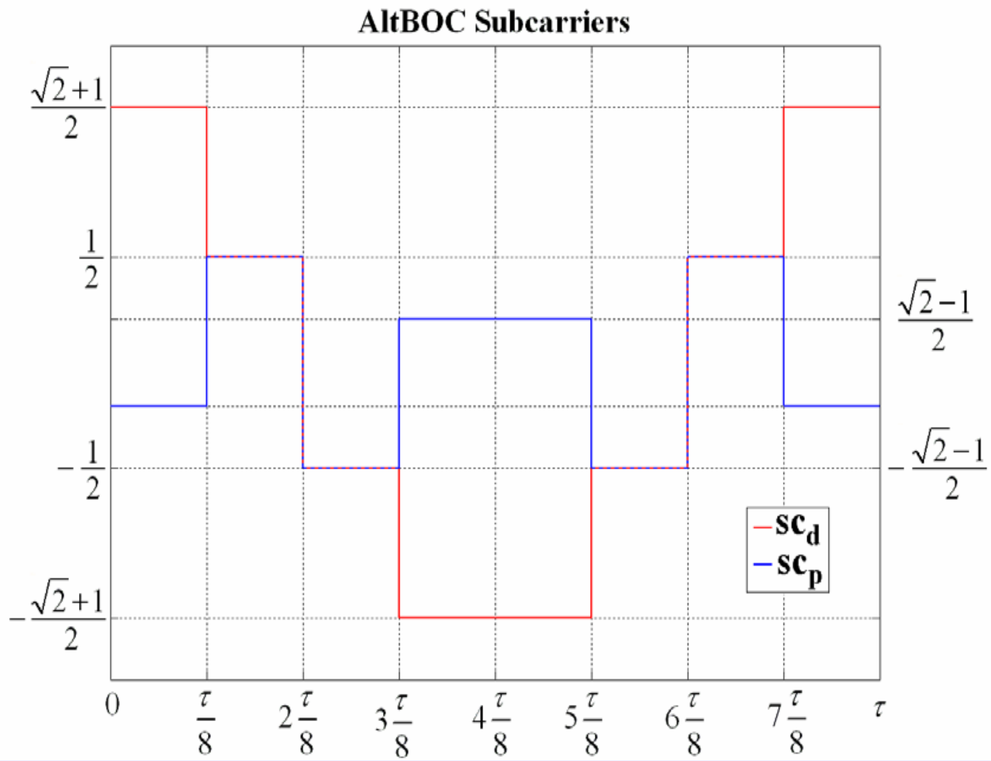
- **GPS and Galileo aimed at reaching compatibility and the highest interoperability from the beginning**
- **Many WG meetings were required to achieve the objectives**

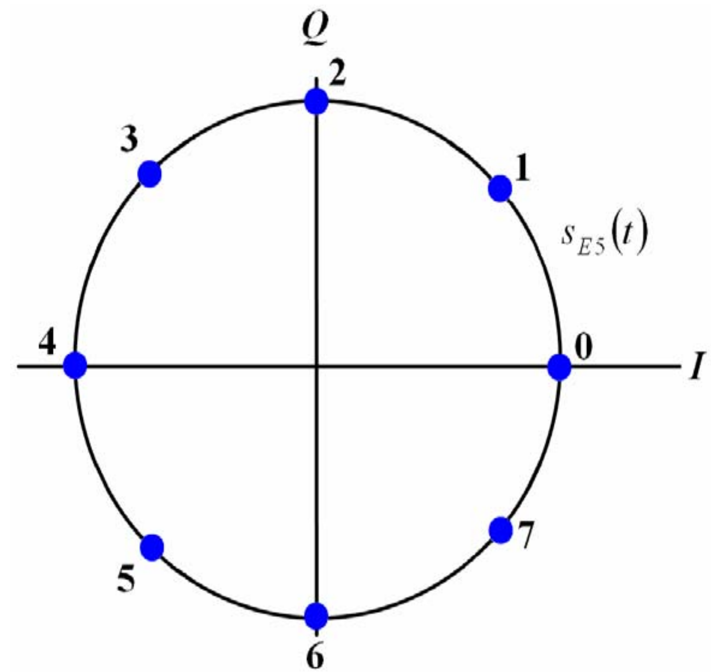
Galileo Signals in E5



$$G_{AltBOC}^{\Phi_{odd,c}}(f) = \frac{4 f_c}{\pi^2 f^2} \frac{\cos^2\left(\pi f T_c\right)}{\cos^2\left(\pi f \frac{T_c}{n}\right)} \left[\cos^2\left(\frac{\pi f}{2 f_s}\right) - \cos\left(\frac{\pi f}{2 f_s}\right) - 2\cos\left(\frac{\pi f}{2 f_s}\right)\cos\left(\frac{\pi f}{4 f_s}\right) + 2 \right]$$

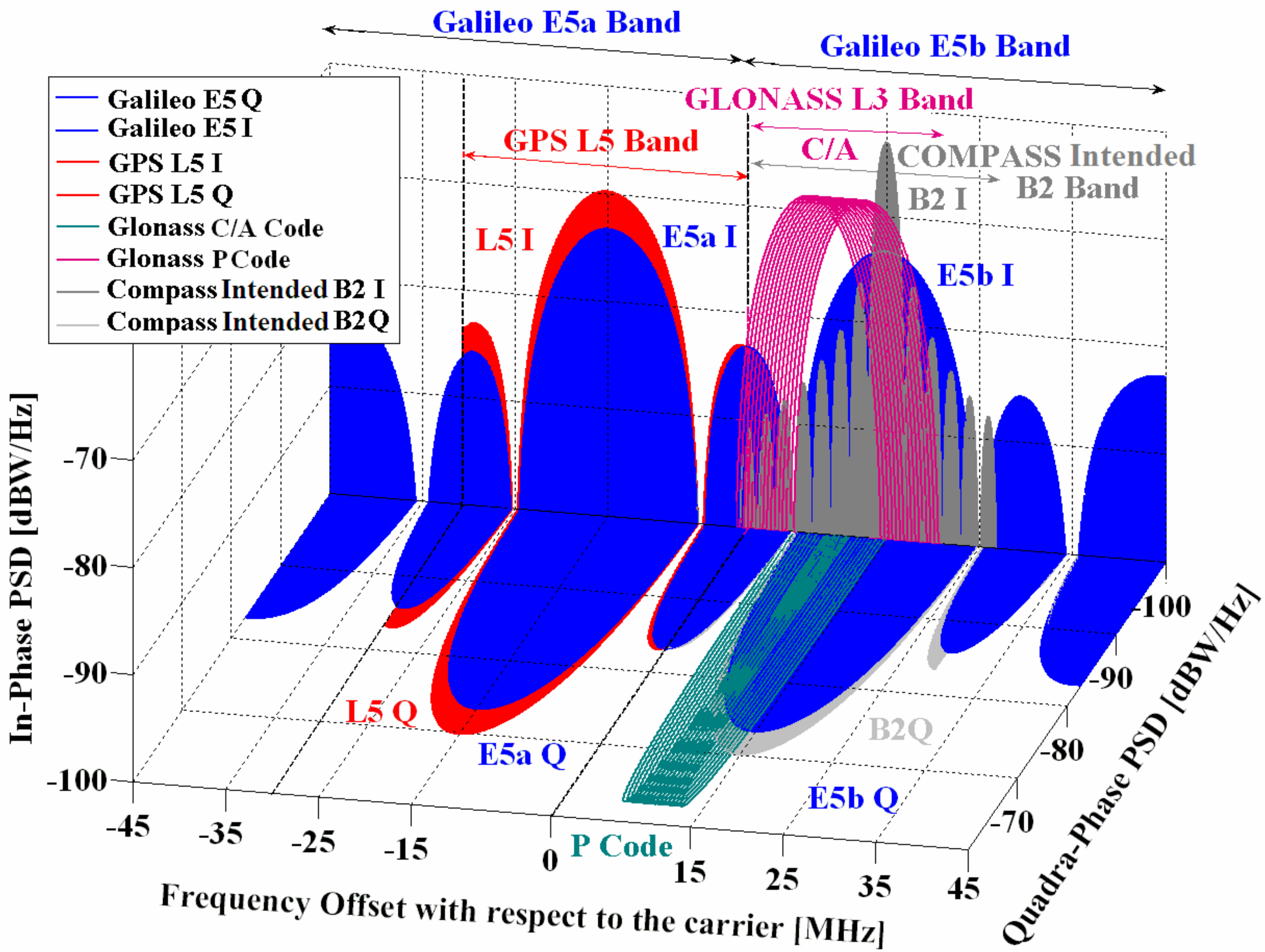
AltBOC Modulation





- AltBOC 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
- Transmitted at 1191.795 MHz with constant amplitude
- The AltBOC multiplexing combines E5a and E5b in a composite constant envelope

GNSS Signals around E5



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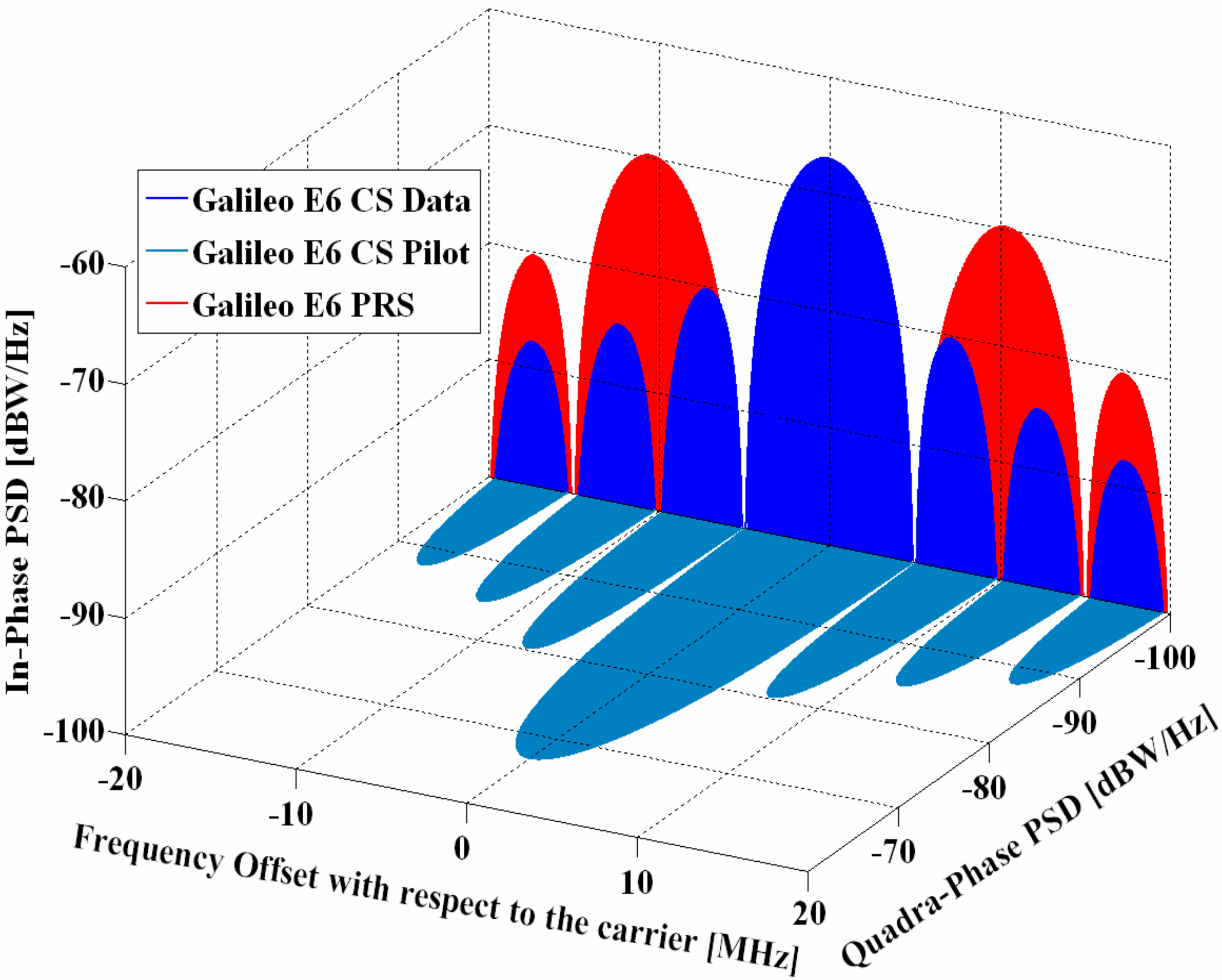
Galileo E6 Signals



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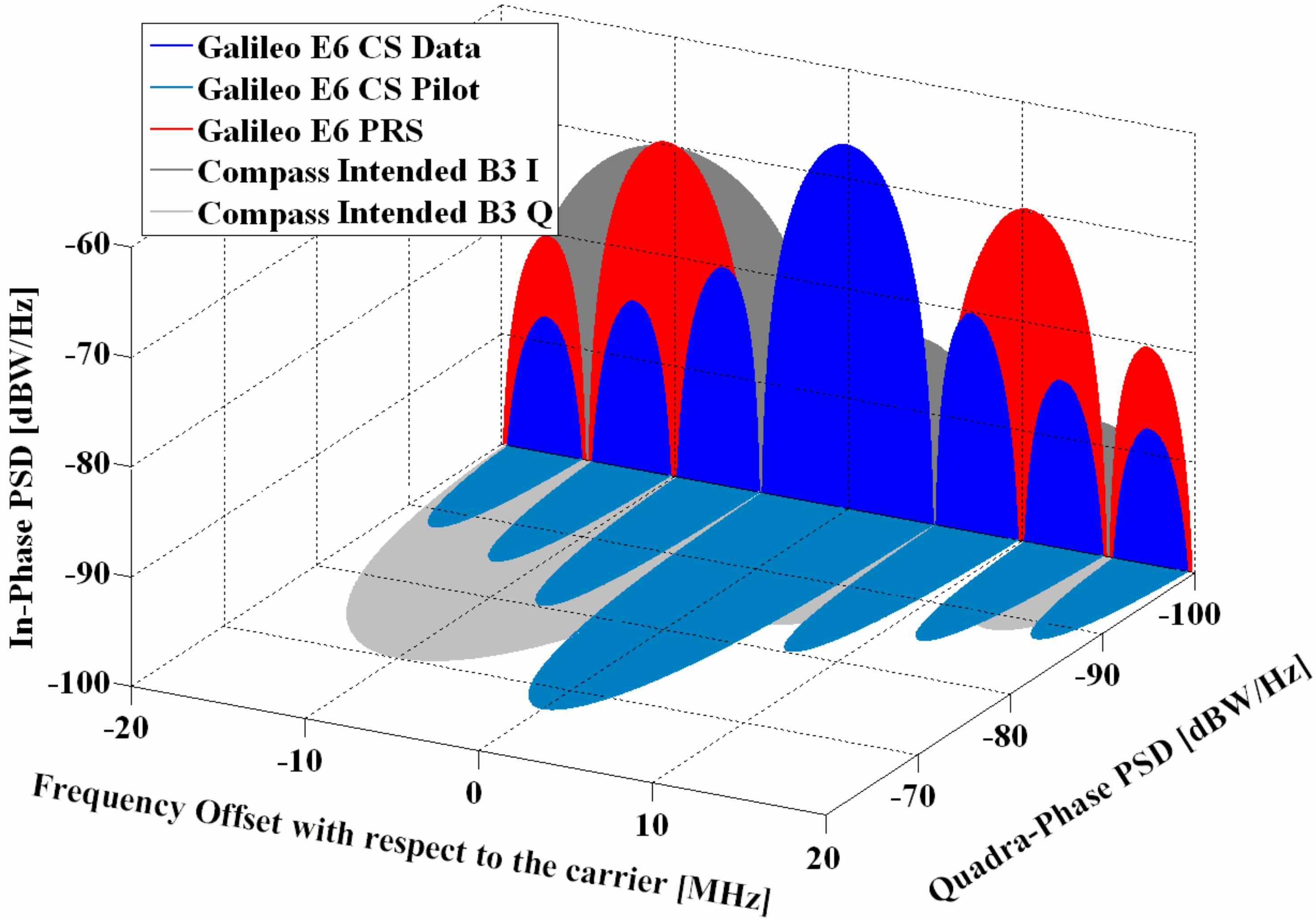
GNSS Signals Around E6



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Background Of MBOC

- The EU-US July 2004 Agreement on Galileo and GPS foresaw as baseline the common modulation BOC(1,1) for Galileo L1 OS and GPS L1C
- It also left explicitly the possibility for the optimization of this baseline modulation
- After almost two years of extensive work of the EU-US Working Group A on Interoperability between Galileo and GPS, an alternative modulation was recommended at the March 2006 Stockholm meeting: MBOC(6,1,1/11)

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MBOC Power Spectral Density

$$G_{MBOC}(f) = \frac{10}{11} G_{BOC(1,1)}(f) + \frac{1}{11} G_{BOC(6,1)}(f)$$

- The joint EU-US signals for Galileo E1 OS and GPS L1C have identical power spectral density when computed using the combination of pilot and data components
- This normalized (unit power) power spectral density is specified without the effect of band-limiting filters and payload imperfections
- Two implementations fulfill these properties:
  - Composite BOC (CBOC) – Based on the Interplex modulation
  - Time-Multiplexed BOC (TMBOC) – Based on time multiplexing

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New Galileo E1 OS Signal Baseline

EUROPEAN COMMISSION
DIRECTORATE-GENERAL FOR ENERGY AND TRANSPORT

Director-General

Brussels, 18 JUL. 2007
TREN/G5/MR/EA D(2007) 316635

Ms. Claudia A McMurray
Assistant Secretary for Oceans, Environment and Science
U.S. Department of State
Washington DC 20520
USA

Dear Ms McMurray,

In line with Article 11 paragraphs 5, 6 and 7 of the *Agreement on the promotion, provision and use of GALILEO and GPS satellite-based navigation systems and related applications* (the Agreement), I would like, on behalf of the European Community and its Member States, to notify you of our decision to change the Galileo Open Service, Safety of Life Service and Commercial Service signal from that described in the second bullet of paragraph (1) of the Annex of the Agreement to the Multiplex Binary Offset Carrier (MBOC) modulation. The description of the MBOC modulation is attached to this letter. I would also like to inform you that the European Community and its Member States would welcome the United States changing concurrently its signal structure from that described in the last sentence of the third bullet of paragraph (1) of the Annex to the MBOC modulation.

ours sincerely,

Matthias Ruete

United States Department of State

Assistant Secretary of State for Oceans and International Environmental and Scientific Affairs

Washington, D.C. 20520

JUL 25 2007

Dear Mr. Ruete:

Thank you for your letters dated June 22 and July 18, 2007, regarding the adoption of the Multiplex Binary Offset Carrier (MBOC) modulation for certain Galileo signal structures. Your July 18 letter specifically notifies the United States, in accordance with Article 11, paragraphs 5, 6, and 7 of the *Agreement on the Promotion, Provision and Use of GALILEO and GPS Satellite-Based Navigation Systems and Related Applications* ("*Agreement*"), of the European Commission's decision to change the signal structures specified in bullet two of paragraph (1) of the Annex to the *Agreement*.

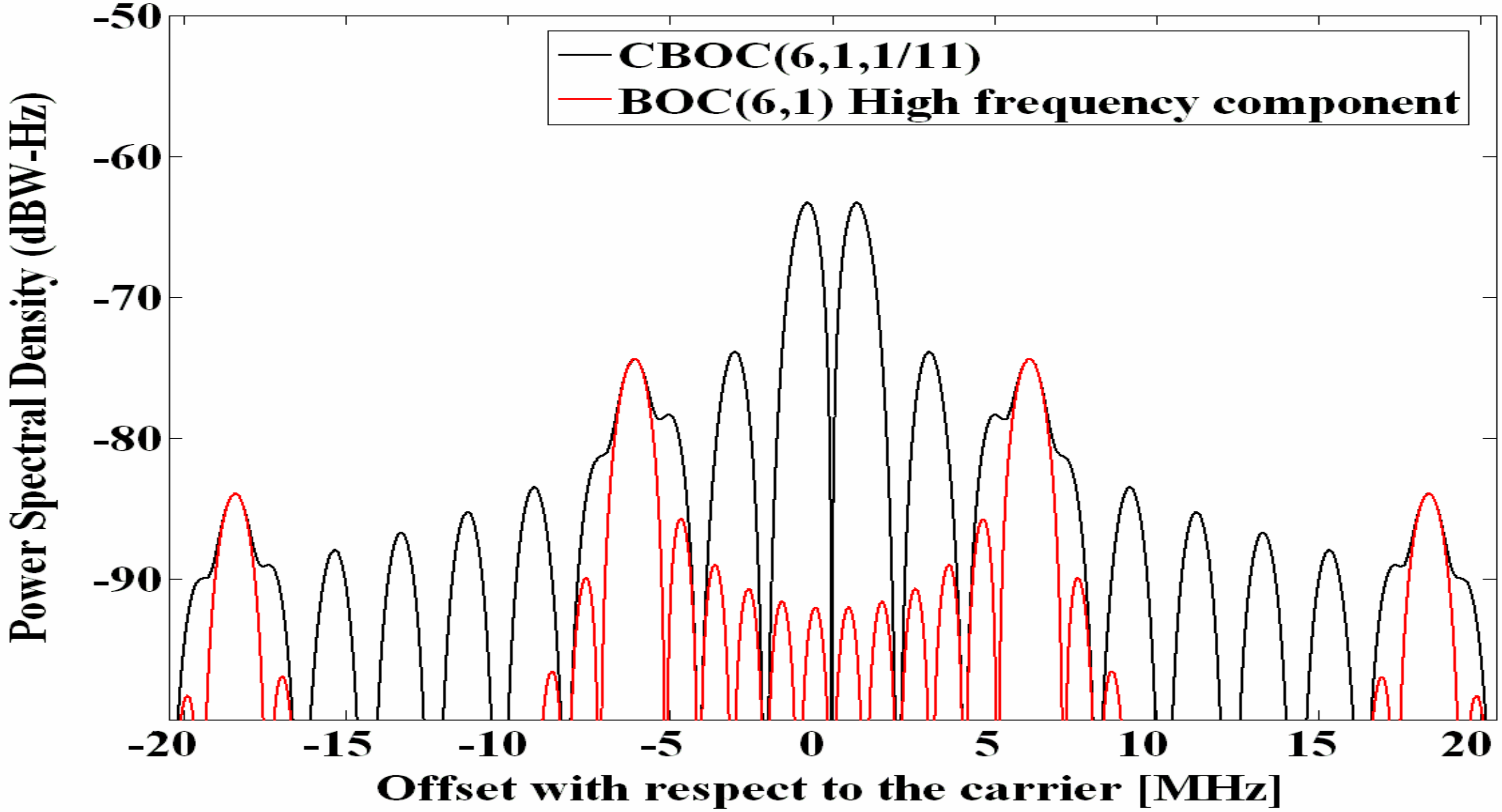
On behalf of the United States of America, and in accordance with the language of Article 11 paragraph 6 of the *Agreement*, I am pleased to inform the European Community and its Member States 1) that the United States will not oppose the adoption and implementation of the alternative signal structure specified in your notification; and 2) that, as a result of the close cooperation and collaboration fostered by the parties in Working Group A on radio frequency compatibility and interoperability for civil satellite-based navigation and timing services, the United States has decided to change its signal structure from that described in the last sentence of the third bullet of paragraph (1) of the Annex the aforementioned *Agreement* to the MBOC modulation (see Enclosure).

We are very happy about the progress we have made in this area and look forward to continuing our mutually beneficial cooperation.

Sincerely,

Reno L. Harnish, Acting

Galileo CBOC



$$G_{MBOC}(f) = \frac{10}{11} G_{BOC(1,1)}(f) + \frac{1}{11} G_{BOC(6,1)}(f)$$

Galileo CBOC Implementation

- The power split between pilot and data is 50% / 50%
- CBOC(6,1,1/11) for both pilot and data

$$G_{\mathrm{Pilot}}(f)=\frac{10}{11}G_{\mathrm{BOC}(1,1)}(f)+\frac{1}{11}G_{\mathrm{BOC}(6,1)}(f)$$

$$G_{\mathrm{Data}}(f)=\frac{10}{11}G_{\mathrm{BOC}(1,1)}(f)+\frac{1}{11}G_{\mathrm{BOC}(6,1)}(f)$$

$$G_{\mathrm{Signal}}(f)=\frac{10}{11}G_{\mathrm{BOC}(1,1)}(f)+\frac{1}{11}G_{\mathrm{BOC}(6,1)}(f)$$

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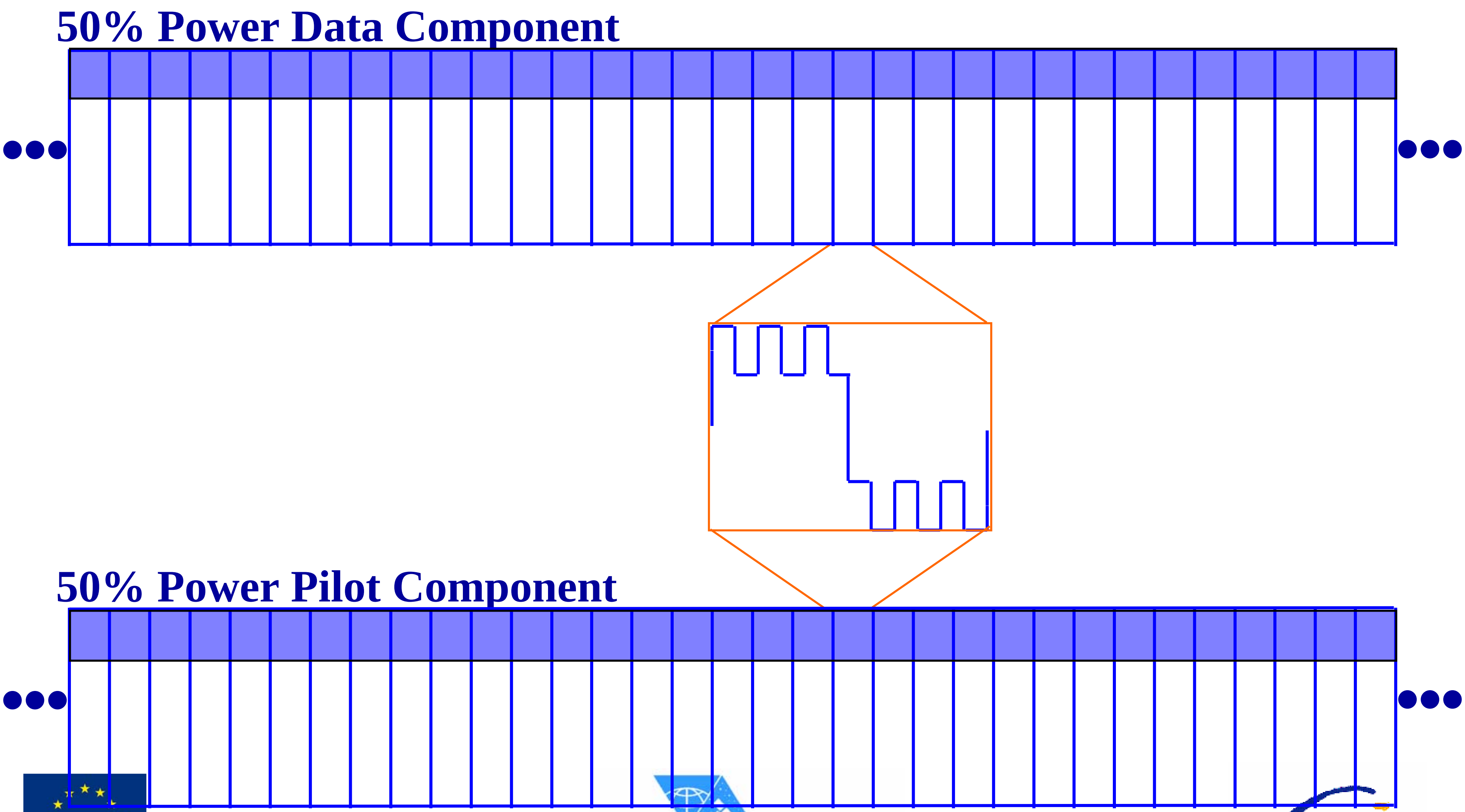
CBOC(6,1,1/11) Time Series 50%/50% Power Split



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GPS TMBOC Implementation

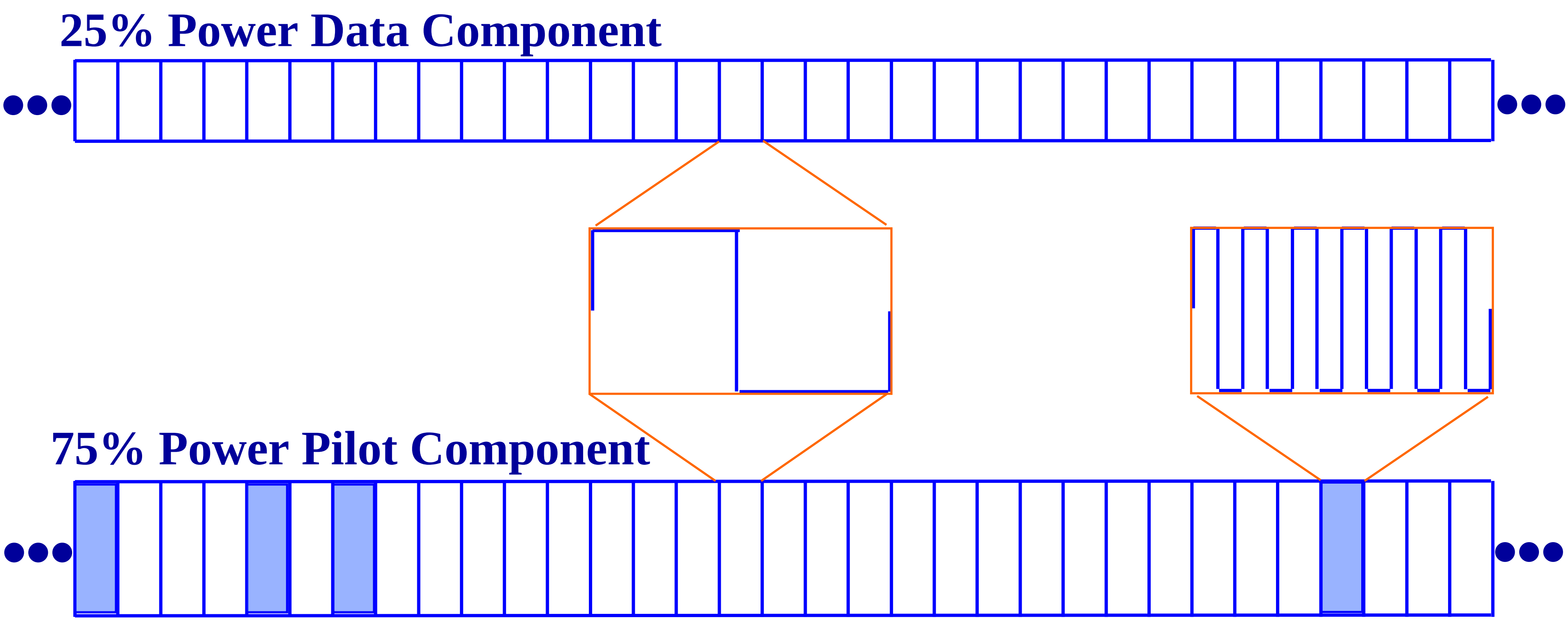
- **The power split between pilot and data is 75% / 25%**
- **TMBOC(6,1,4/33) for pilot, BOC(1,1) for data**

$$G_{\text{Pilot}}(f) = \frac{29}{33} G_{\text{BOC}(1,1)}(f) + \frac{4}{33} G_{\text{BOC}(1,1)}(f)$$

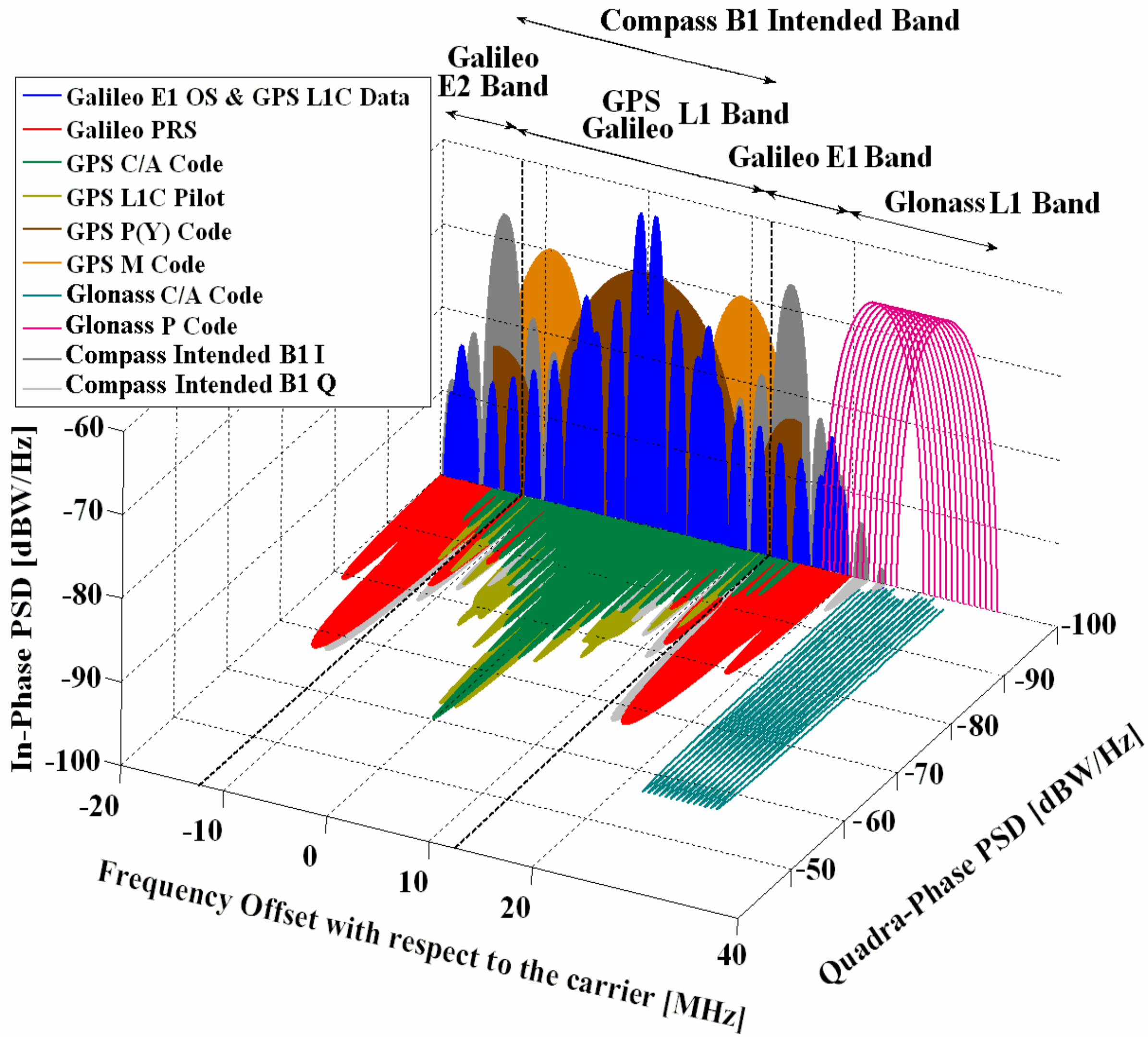
$$G_{\text{Data}}(f) = G_{\text{BOC}(1,1)}(f)$$

$$\begin{aligned} G_{\text{Signal}}(f) &= \frac{3}{4} G_{\text{Pilot}}(f) + \frac{1}{4} G_{\text{Data}}(f) \\ &= \frac{10}{11} G_{\text{BOC}(1,1)}(f) + \frac{1}{11} G_{\text{BOC}(6,1)}(f) \end{aligned}$$

GPS TMBOC Time Series
75 % / 25 % Power Split



GNSS Signals in E1



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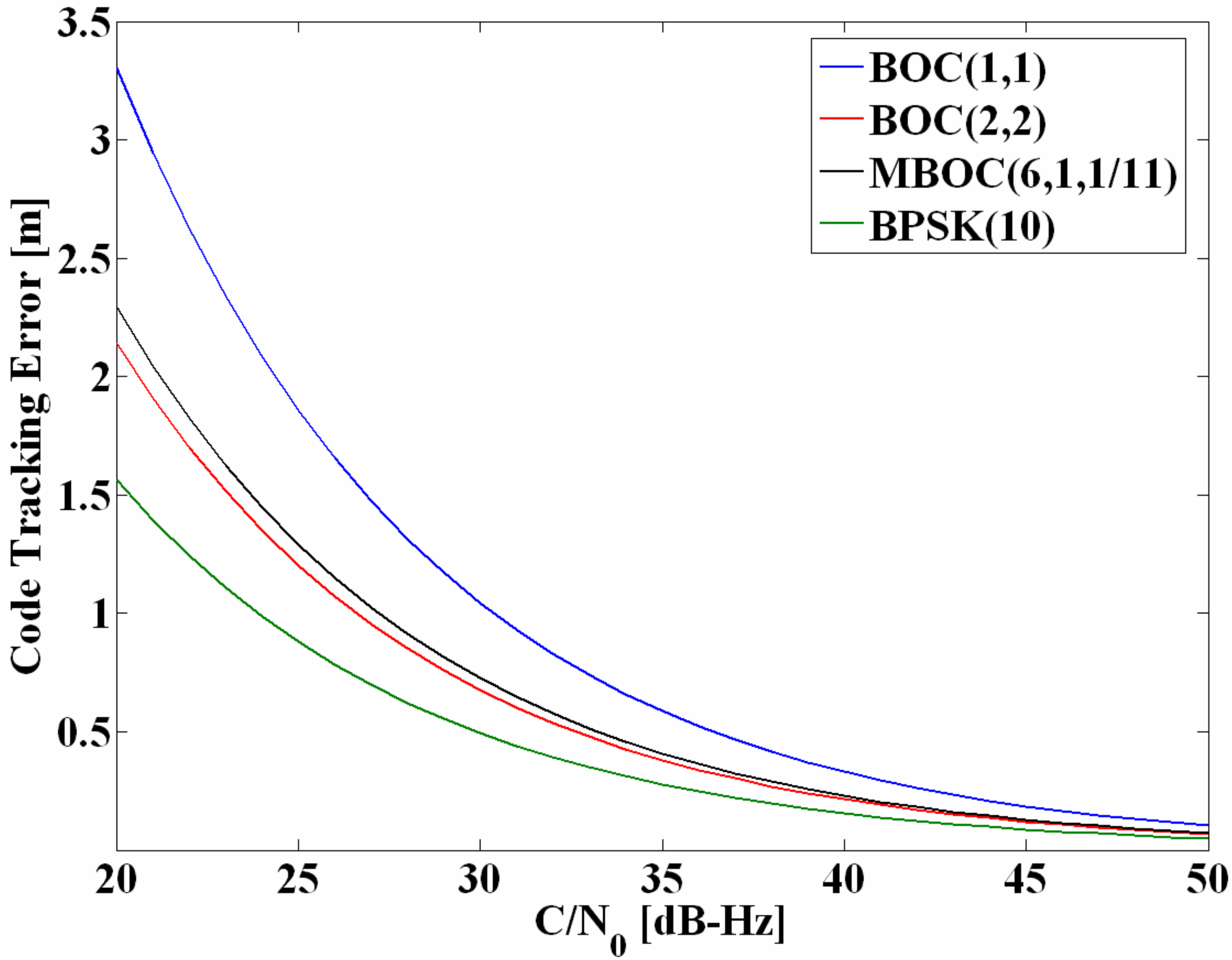
MBOC Code Noise



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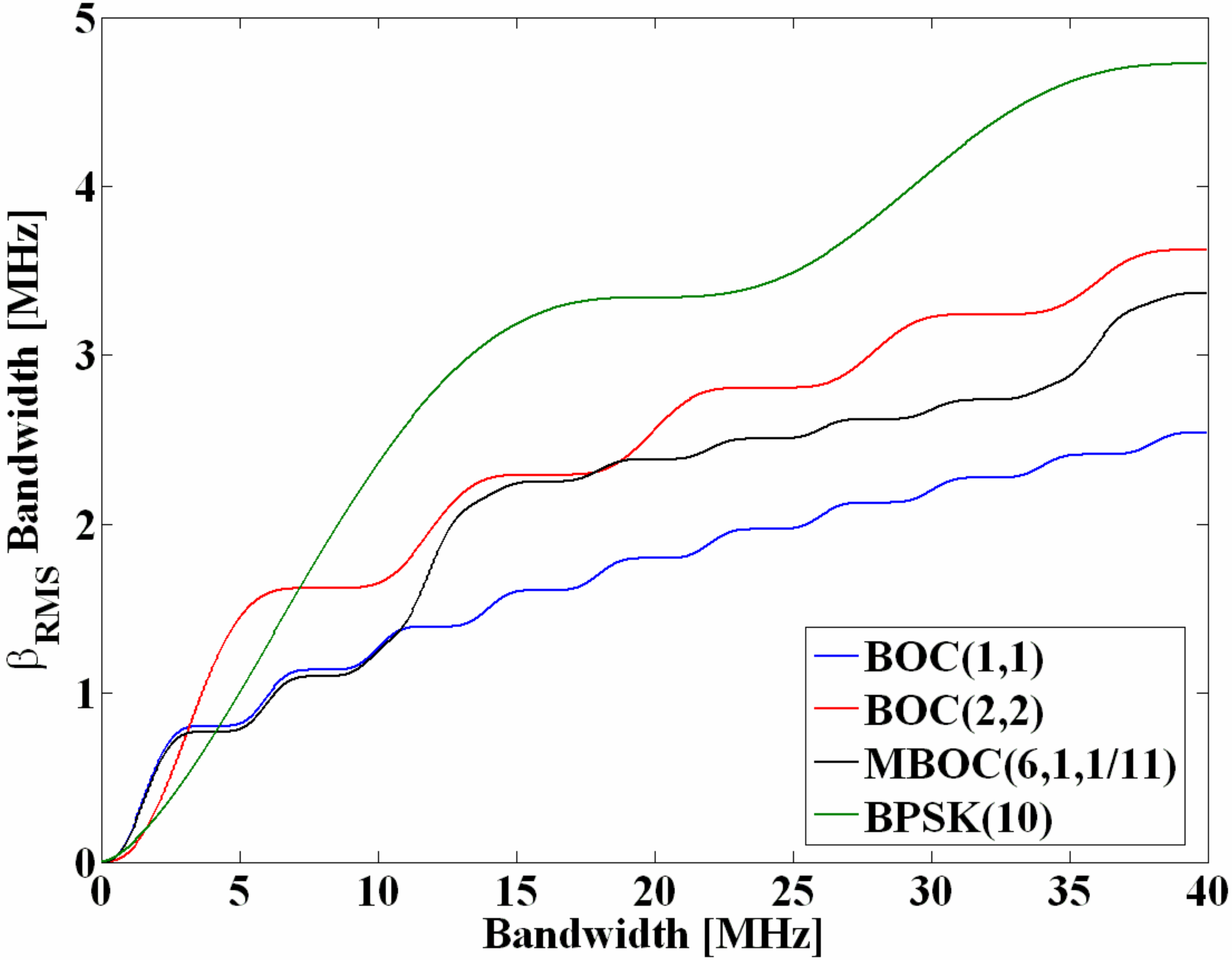
MBOC Root Mean Square Bandwidth



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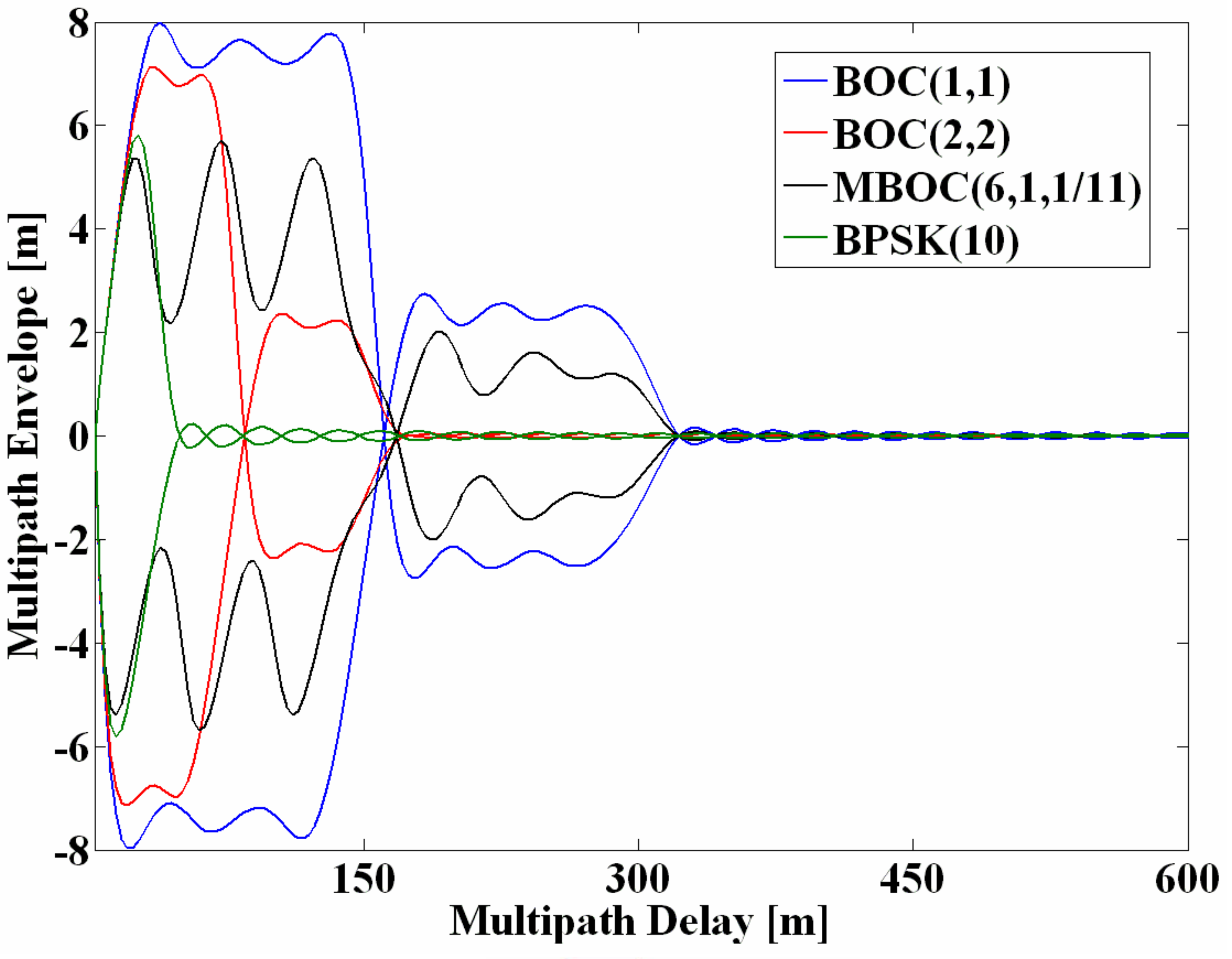
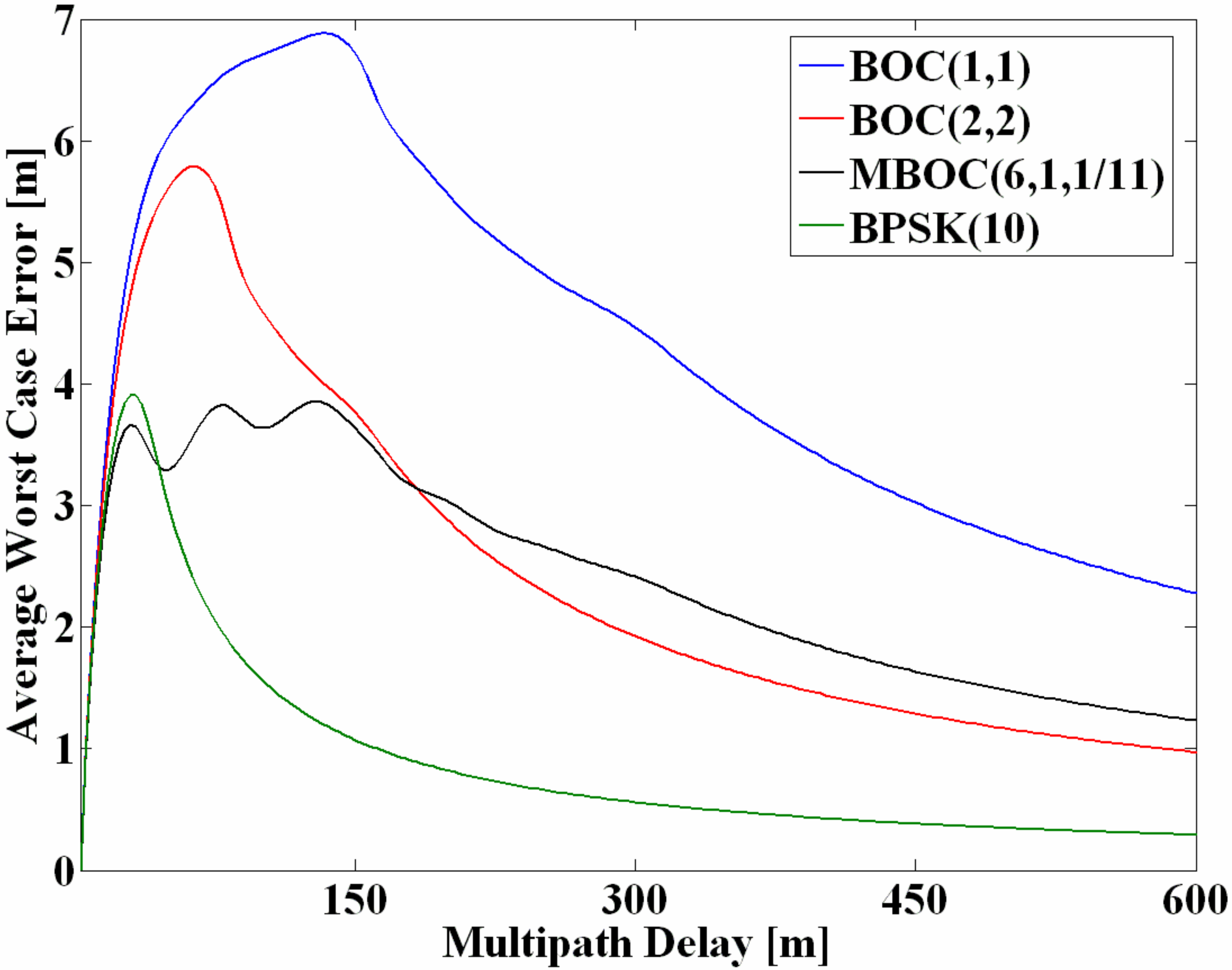
MBOC Multipath Error



MBOC Multipath Running Average Error



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C-Band for Satellite Navigation

- During the World Radio Conference 2000 the Galileo program obtained authorization to use C-Band frequencies.
- Serious candidate for one or several additional signals of the next generation of Galileo

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thank you for your attention

further information can be found at:

http://ec.europa.eu/dgs/energy_transport/galileo/documents/index_en.htm
gsa.europa.eu
www.esa.int
www.giove.esa.int

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