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Institute of Geodesy and Navigation
Institut für Erdmessung und Navigation

RECEIVER DEVELOPMENT, SIGNALS, CODES AND INTERFERENCE

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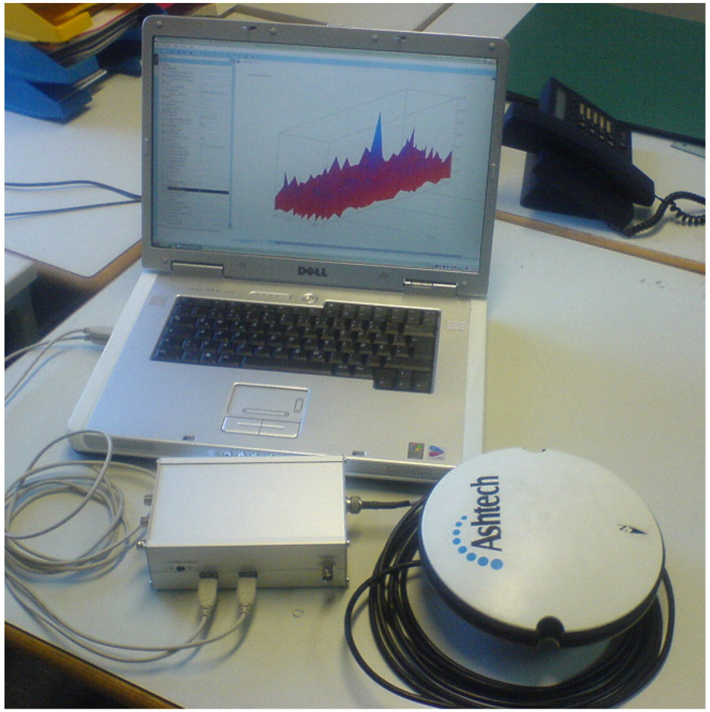
CONTENTS

SOFTWARE GNSS RECEIVER - ipexSR

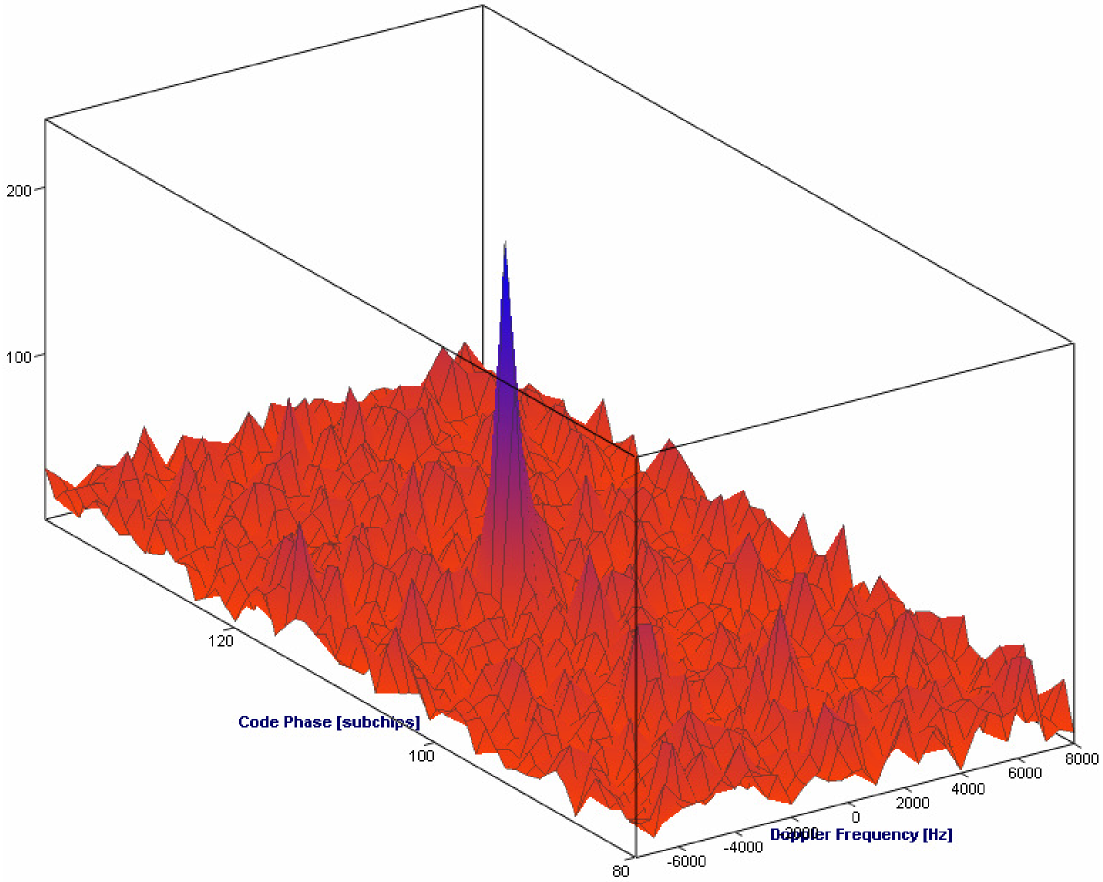
- ✓ High end, multi-frequency, real-time capable
- ✓ Civil signal tracking of all-in-view GPS/Galileo/SBAS satellites
- ✓ Development in C++ classes and modules
- ✓ To be run on conventional PC
- ✓ Input IF samples from
  - ✓ Triple frequency (L1/E1, L2, L5/E5a) USB Front-End
  - ✓ Data files in post-processing mode



Frequency	Bandwidth	Sample Rate	ADC Res.
L1, E1	15/20 MHz	40.96 MHz	2/4 Bits
L2	15/20 MHz	40.96 MHz	2/4 Bits
L5, E5a	15/20 MHz	40.96 MHz	4 Bits

ARCHITECTURE – ACQUISITION

- ✓ Two acquisition procedures depending on available information
  - ✓ Acquisition by navigation solution
  - ✓ Two level FFT-based acquisition
- ✓ Acquisition of strong signals by conventional coherent integration
- ✓ High sensitivity acquisition
  - →Combination of coherent and non-coherent integration, including parallel interference cancellation



3D Acquisition plot generated by the software receiver when acquiring a GPS satellite.

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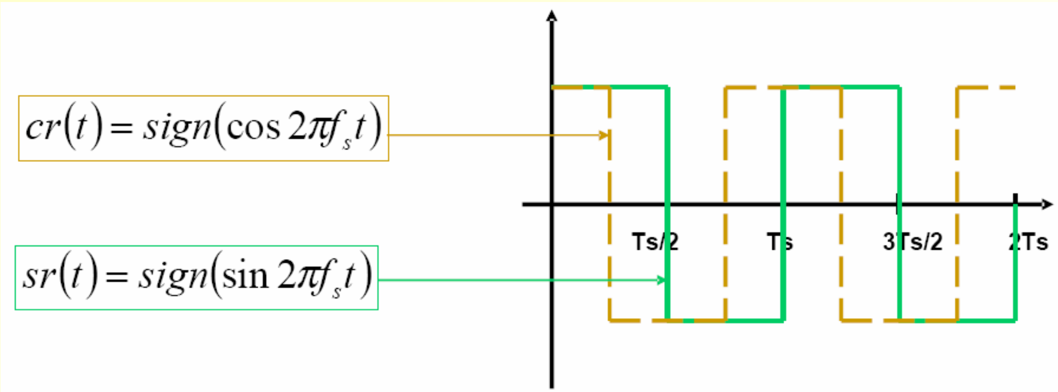
GALILEO E5 AltBOC SIGNAL

- ✓ Objectives of Alternative BOC (AltBOC) on E5a/b
  - ✓ Multiplexing of 2 or 4 navigation signal components each with own PRN code on 2 nearby frequencies
- ✓ Solution 1
  - ✓ Generation of 2 QPSK separately and combine them with OMUX
    → Band limitation of OMUX removes high frequency component → loss of accuracy
- ✓ Solution 2
  - ✓ Combination of signals at base-band, up-conversion to mean frequency
    → One carrier → phase coherency between two frequencies guaranteed
    → One amplification chain
    → Higher bandwidth → higher accuracy
  - ✓ Constant envelope modulation has to be assured

GALILEO E5 AltBOC SIGNAL

- ✓ Complex BOC subcarrier



$$er(t) = cr(t) + j\ sr(t)$$

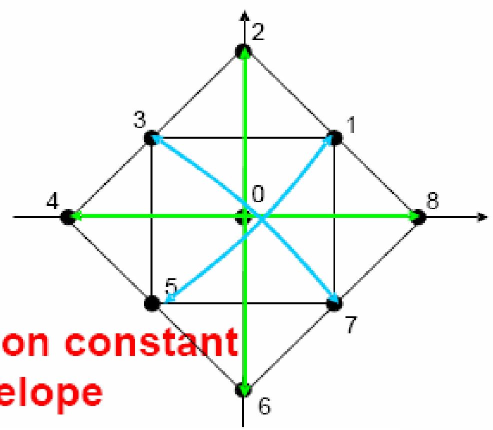
- ✓ 4 component AltBOC

$$x(t) = \left(c_1(t) + c_1'(t)\right) er(t) + \left(c_2(t) + c_2'(t)\right) er^*(t)$$

Modulation Table

Signal C1		-1	-1	-1	-1	-1	...
Signal C2		-1	-1	-1	-1	1	...
Signal C'1		-1	-1	1	1	-1	...
Signal C'2		-1	1	-1	-1	1	...
t mod Ts	[0, Ts/4[	5	0	4	3	6	...
	[Ts/4, Ts/2[	1	8	0	7	0	...
	[Ts/2, 3Ts/4[	1	0	8	7	2	...
	[3Ts/4, Ts [	5	4	0	3	0	...

Phase Plot



→ non constant envelope

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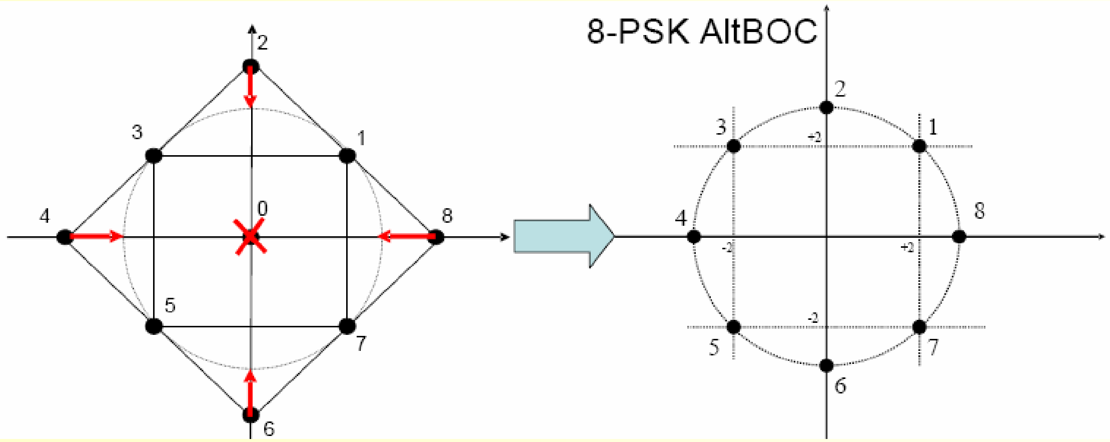
GALILEO E5 AltBOC SIGNAL

- Achieving the constant envelope



Constellation points

$$\exp\left(\frac{jk\pi}{4}\right), \quad k \in \{1, \ldots, 8\}$$

- New signal description

$$x(t) = \frac{1}{2\sqrt{2}} \left[\begin{array}{l} \left(c_1(t) + jc_1'(t)\right) er(t) + \left(c_2(t) + jc_2'(t)\right) er^*(t) \\ \left(\bar{c}_1(t) + j\bar{c}_1'(t)\right) \bar{er}(t) + \left(\bar{c}_2(t) + j\bar{c}_2'(t)\right) \bar{er}^*(t) \end{array} \right]$$

with $\bar{c}_1 = c_2\, c_1'\, c_2'$ $\quad \bar{c}_1' = c_1\, c_2\, c_2'$

$\bar{c}_2 = c_1\, c_1'\, c_2'$ $\quad \bar{c}_2' = c_1\, c_2\, c_1'$ and

$$er(t) = sc_d(t) + j\ sc_d(t - T_s/4)$$
$$\bar{er}(t) = sc_p(t) + j\ sc_p(t - T_s/4)$$

➡ **4-level signal!**

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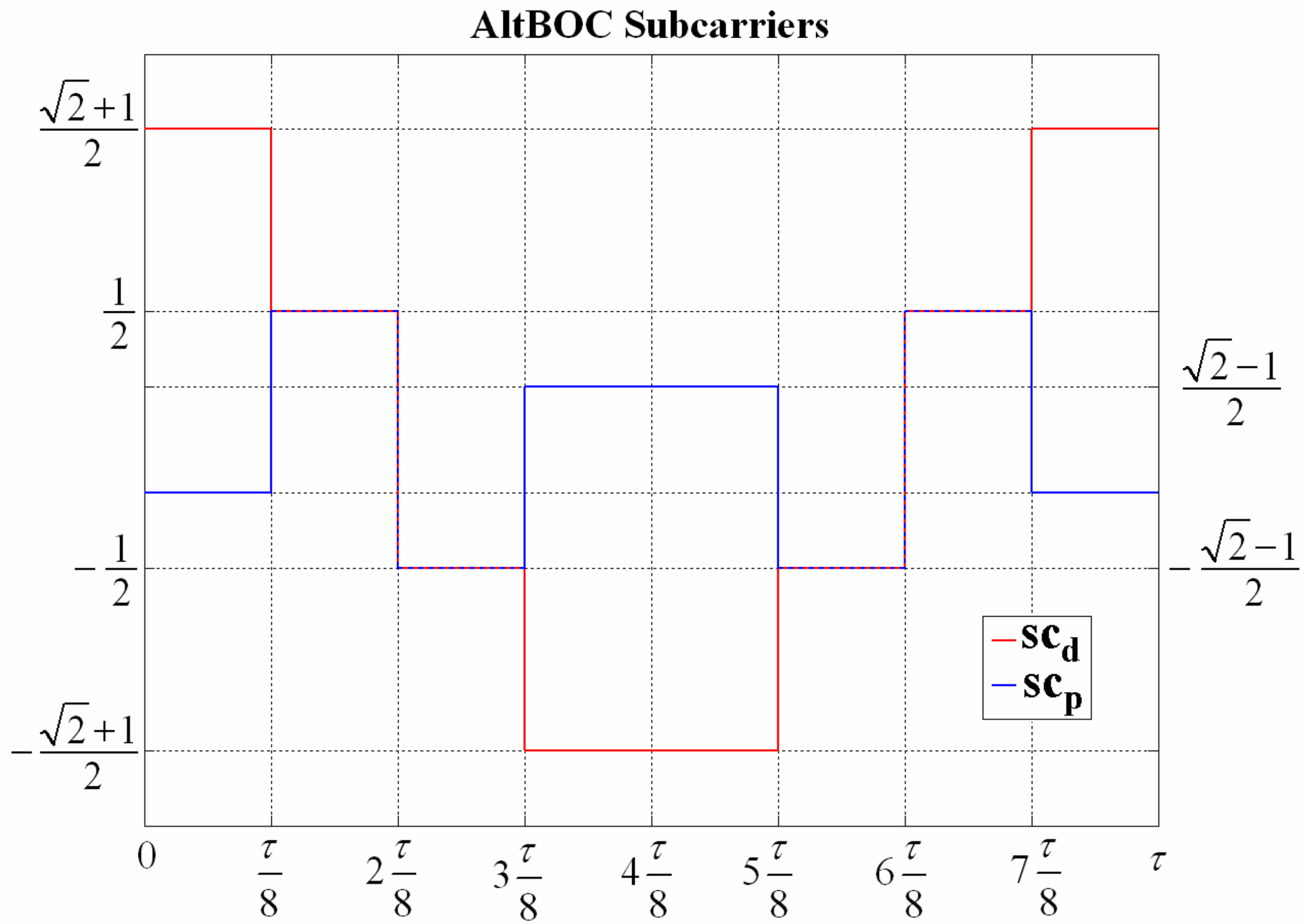
GALILEO E5 AltBOC SIGNAL

- Achieving the constant envelope



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PSEUDO RANDOM NOISE CODES

- ✓ Pseudo Random Noise (PRN) codes are essential element in every CDMA based GNSS
- ✓ Keystone to distinguish one SV from another
- ✓ All currently implemented civilian codes based on Linear Feedback Shift Registers (LFSR)

  → Identical approach as in 1st generation GPS
- ✓ Galileo E1 OS and GPS L1C are bringing up new code concepts
  - ✓ Galileo E1 OS: random codes ⟵ **Focus**
  - ✓ GPS L1C: Weil-based codes

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OPTIMIZATION CRITERIA

- ✓ Optimization for every receiver implementation and application not feasible

  → Use code centric approach

- ✓ Code centric approach based on
  - ✓ Auto- and crosscorrelation
    - ✓ Concentration on maximum or distribution possible

      GPS approach (maximum) / **Galileo approach** (distribution possible)

- ✓ Consideration of
  - ✓ Even and odd correlation (data bit or secondary code bit flip)
  - ✓ Doppler frequency offsets

GALILEO CODE OPTIMIZATION CRITERIA

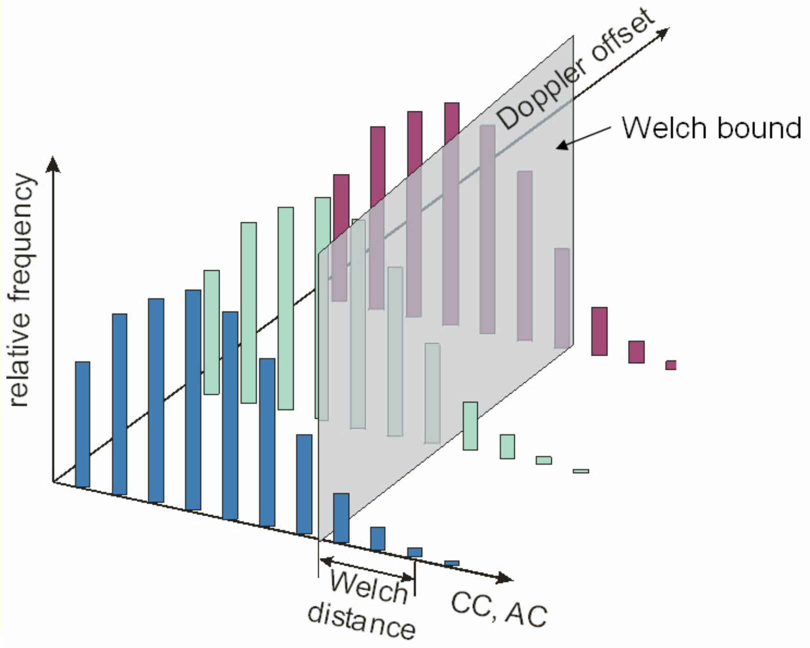
✓ Correlation values compared against Welch-bound

Welch Bound Φ_{min} is the theoretical minimum of correlation that can be obtained for a code length n within a set of M codes:

$$\Phi_{min} = n\sqrt{\frac{M-1}{Mn-1}}$$

→ every correlation value above Welch bound degrades performance

→ Criteria of **Welch distance** for auto- and crosscorrelation considering Doppler dependency applied (slight modifications to achieve acquisition and tracking criteria)



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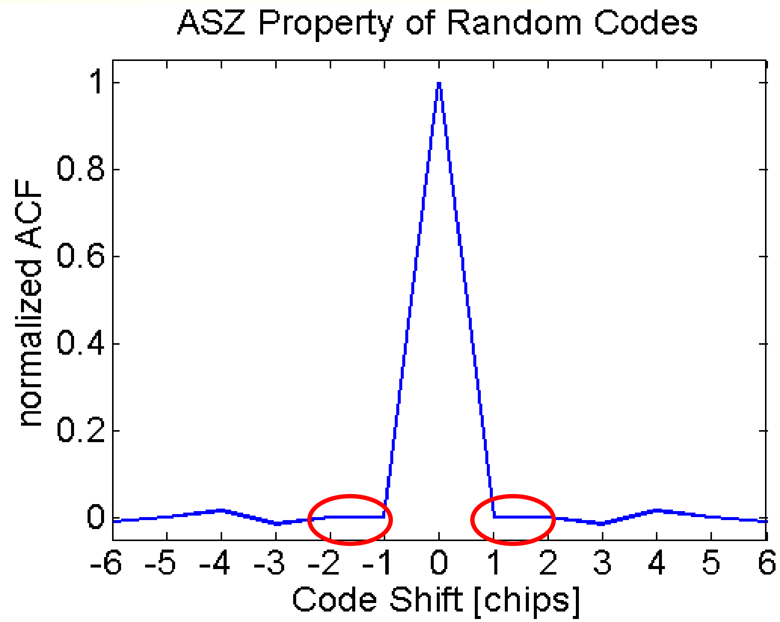
GALILEO E1 OS / E6 CS CODE OPTIMIZATION

- ✓ **Random codes** (memory codes) for Galileo E1 OS and E6 CS
- ✓ Most flexible code generation and optimization approach
- ✓ Codes can be driven to fulfill special properties
  - ✓ Autocorrelation Sidelobe Zero (ASZ) property
  - ✓ Ideal or weakened balance



However

- ✓ Number of choices to set 0's and 1's unimaginably high

→ Application of **genetic algorithms** for optimization

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SOURCES OF INTERFERENCE

- ✓ Interference introduced from external sources
  - ✓ Radar
  - ✓ DVB-T
  - ✓ DME, TACAN, JTADS
  - ✓ Unintentional interference
  - ✓ …

Focus

- ✓ Interference within GNSS
  - ✓ Signal interference
  - ✓ PRN code interference

} Radio frequency compatibility

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SIGNAL INTERFERENCE

- ✓ **Intrasystem Interference**
  - ✓ Within each system
- ✓ **Intersystem Interference**
  - ✓ Interference that a GNSS/RNSS will suffer due to other GNSS/RNSS, augmentation systems to be considered
  - ✓ Intersystem Interference too high

    → correct functioning of current working GNSS receivers could be affected if new GNSS is entering the stage

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INTERFERENCE CRITERION $\Delta(C/N_0)_{eff}$

✓ Degradation of C/N_0 due to intersystem interference

$$\Delta\left(\frac{C}{N_0}\right)_{\text{eff}}[\text{dB}] = 10\log_{10}\left(1 + \frac{I_{\text{inter}}}{N_0 + I_{\text{intra}} + I_{\text{interop}}}\right)$$

where:

$$I_{\text{inter}} = \frac{\sum_{i=1}^{M_{\text{inter}}}\sum_{j=1}^{N_{\text{inter}}} C_j^i \kappa_{js}^i}{\int_{-\frac{\beta_r}{2}}^{\frac{\beta_r}{2}} G_s(f + f_{\text{dop}_s})\,\text{d}f}$$

with Spectral Separation Coefficient (SSC):

$$\kappa_{js}^i = \int_{-\frac{\beta_r}{2}}^{\frac{\beta_r}{2}} G_j^i(f + f_{\text{dop}_j})\,G_s(f + f_{\text{dop}_s})\,\text{d}f$$

C_j^i	Rec. power of signal i from SV j
N_{inter}	Number of visible SV from non-desired system
M_{inter}	Number of interfering signals from **non-desired** system in scenario
G_s	PSD of desired signal
G_j^i	PSD of signal i from SV j
β_r	Front-end bandwidth
N_0	Noise floor: -201.5 dBW/Hz
f_{dop_j}	Doppler frequency for SV j
f_{dop_s}	Doppler frequency of desired signal

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INTERFERENCE CRITERION $\Delta(C/N_0)_{eff}$

✓ Degradation of C/N_0 due to intersystem interference

$$\Delta\left(\frac{C}{N_0}\right)_{\text{eff}} [\text{dB}] = 10\log_{10}\left(1 + \frac{I_{\text{inter}}}{N_0 + I_{\text{intra}} + I_{\text{interop}}}\right)$$

where:

$$I_{\text{intra}} = \frac{\sum_{i=1}^{M_{\text{intra}}}\sum_{j=1}^{N_{\text{intra}}} C_j^i \kappa_{js}^i}{\int_{-\frac{\beta_r}{2}}^{\frac{\beta_r}{2}} G_s(f + f_{\text{dop}_s})\,\mathrm{d}f}$$

with Spectral Separation Coefficient (SSC):

$$\kappa_{js}^i = \int_{-\frac{\beta_r}{2}}^{\frac{\beta_r}{2}} G_j^i(f + f_{\text{dop}_j})\,G_s(f + f_{\text{dop}_s})\,\mathrm{d}f$$

C_j^i	Rec. power of signal i from SV j
N_{intra}	Number of visible SV from **desired** system
M_{intra}	Number of desired and interfering signals from **desired** system
G_s	PSD of desired signal
G_j^i	PSD of signal i from SV j
β_r	Front-end bandwidth
N_0	Noise floor: -201.5 dBW/Hz
f_{dop_j}	Doppler frequency for SV j
f_{dop_s}	Doppler frequency of desired signal

INTERFERENCE CRITERION $\Delta(C/N_0)_{eff}$

✓ Degradation of C/N_0 due to intersystem interference

$$\Delta\left(\frac{C}{N_0}\right)_{\text{eff}}[\text{dB}] = 10\log_{10}\left(1+\frac{I_{\text{inter}}}{N_0+I_{\text{intra}}+I_{\text{interop}}}\right)$$

where:

$$I_{\text{interop}} = \frac{\sum_{i=1}^{M_{\text{interop}}}\sum_{j=1}^{N_{\text{interop}}} C_j^i \kappa_{js}^i}{\int_{-\frac{\beta_r}{2}}^{\frac{\beta_r}{2}} G_s(f+f_{\text{dop}_s})\,\mathrm{d}f}$$

with Spectral Separation Coefficient (SSC):

$$\kappa_{js}^i = \int_{-\frac{\beta_r}{2}}^{\frac{\beta_r}{2}} G_j^i(f+f_{\text{dop}_j})\,G_s(f+f_{\text{dop}_s})\,\mathrm{d}f$$

C_j^i	Rec. power of signal i from SV j
N_{interop}	Number of visible SV from **non-desired** system
M_{interop}	Number of interoperable signals from **non-desired** system
G_s	PSD of desired signal
G_j^i	PSD of signal i from SV j
β_r	Front-end bandwidth
N_0	Noise floor: -201.5 dBW/Hz
f_{dop_j}	Doppler frequency for SV j
f_{dop_s}	Doppler frequency of desired signal

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INTERFERENCE CRITERION $(C/N_0)_{eff}$

- Min. effective C/N_0

$$\left(\frac{C}{N_0}\right)_{\mathrm{eff}} [\mathrm{dB-Hz}] = \frac{C}{N_0 + I_{\mathrm{intra}} + I_{\mathrm{inter}} + I_{\mathrm{interop}}}$$

- Degradation of C/N_0 and min. effective C/N_0 are complementary criteria
  - Degradation of C/N_0 criteria limits impact of every single GNSS/RNSS
  - Min. effective C/N_0 criteria provides full picture of interference environment

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INTERSYSTEM CROSSCORRELATION

- ✓ GPS L1C and Galileo E1 OS implementing both MBOC(6,1,1/11)

  → Interoperability
- ✓ However: PRN codes could interfere with each other
- ✓ Different strategies
  - ✓ Pure code correlation
  - ✓ Rx (receiver based) code correlation ← **Focus**
  - ✓ Further strategies to be investigated

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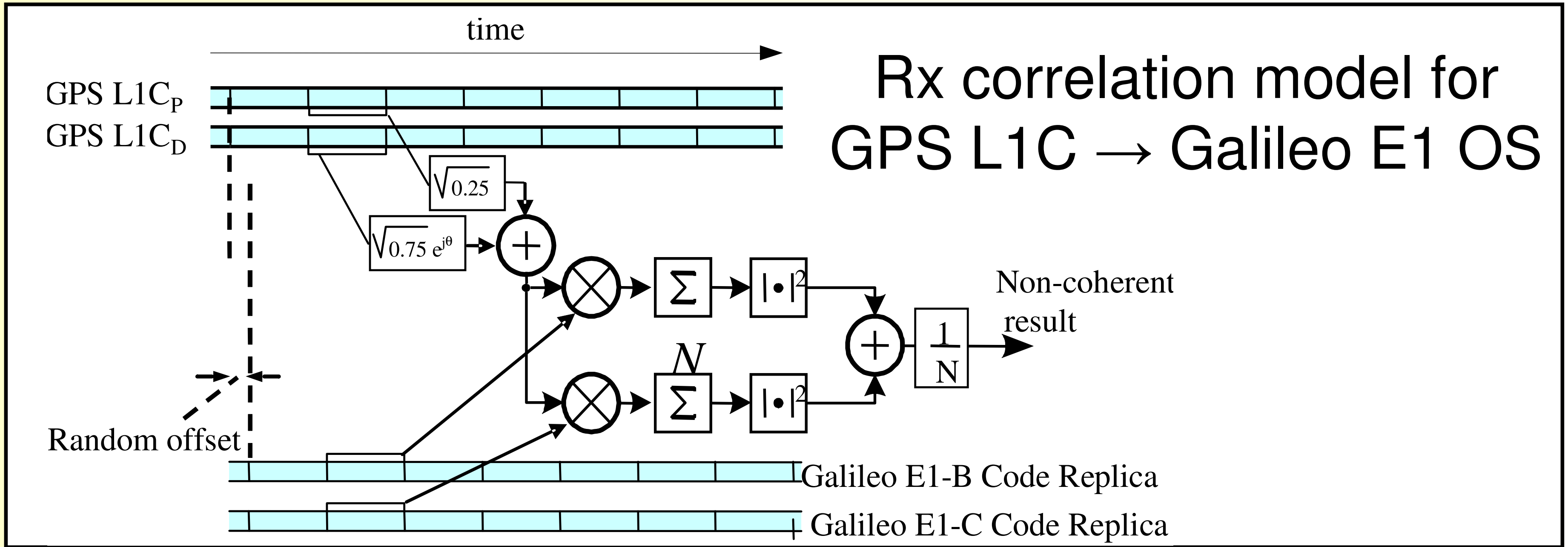
RX CORRELATION APPROACH

- ✓ Receiver centric approach
- ✓ Non-coherent integrations
- ✓ Pre-correlation time identical to primary code duration
- ✓ Consideration of modulation scheme and power split



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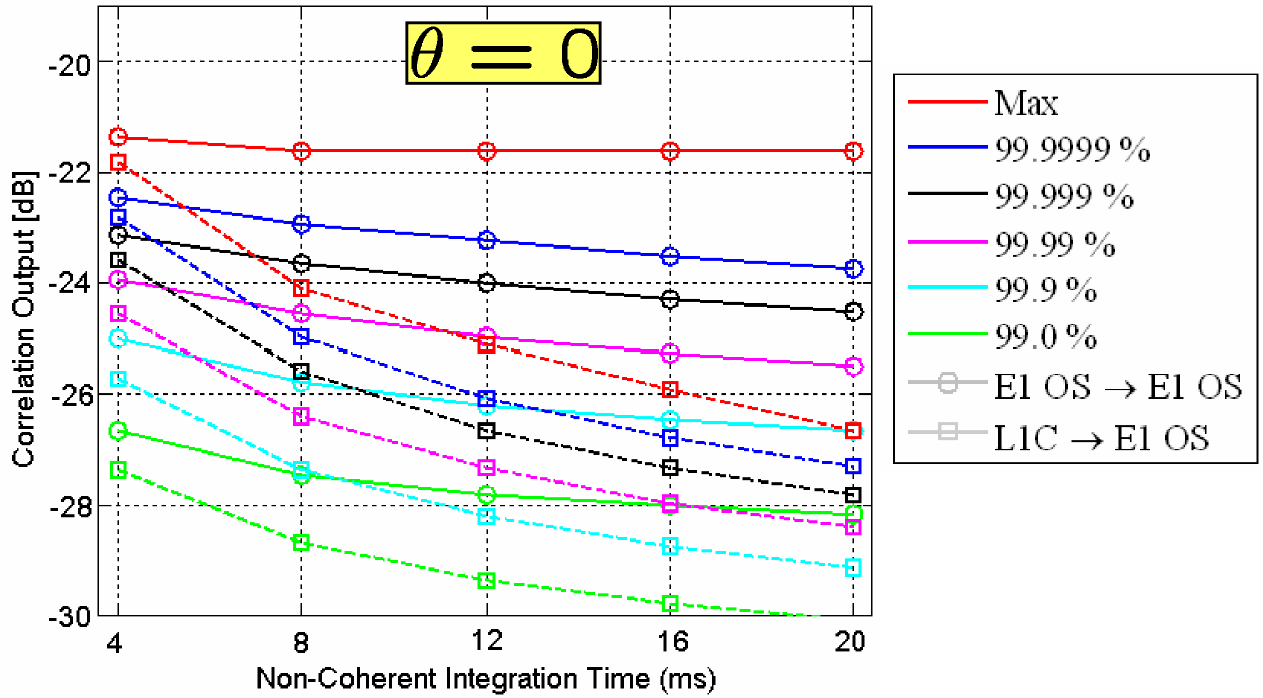
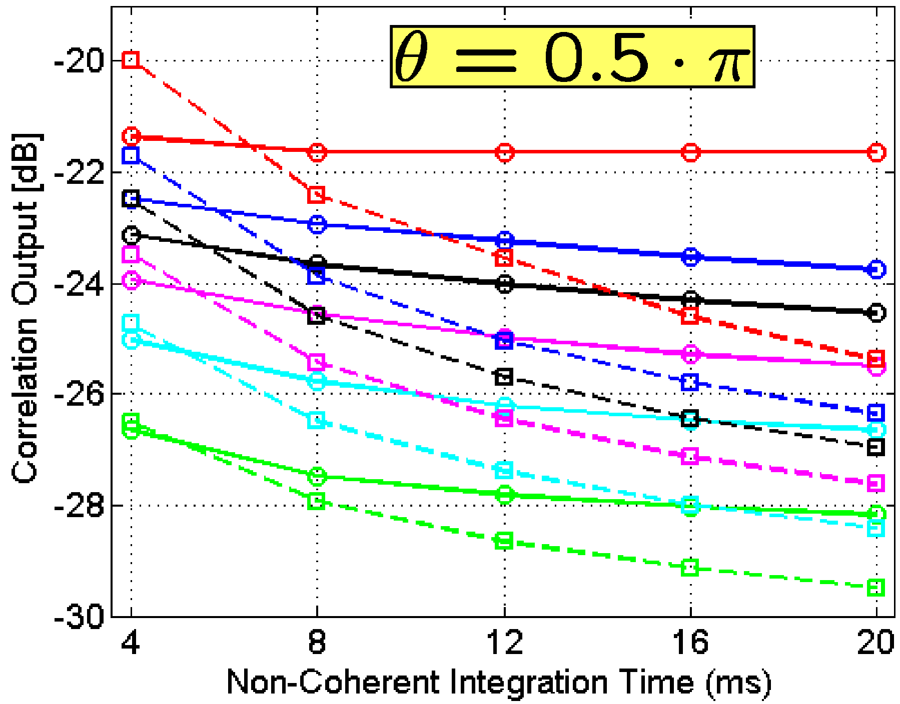
RX CORRELATION ONTO GALILEO E1OS





- ✓ For more than 1 non-coherent integration max. and all percentiles of intersystem correlation smaller than intrasystem correlation
- ✓ Reason: due to different code length no superposition of correlation values in intersystem case

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SUMMARY

Receiver development

- ✓ Presentation of ipexSR Software receiver developed at Institute of Geodesy and Navigation, University FAF Munich

Signals

- ✓ AltBOC in E5 is Galileo's signal with largest bandwidth → best performance achievable
- ✓ Innovative multiplexing technique

PRN codes

- ✓ Random codes and Weil codes completely new code design approaches

Interference

- ✓ Assessment of signal and code interference extremely important with more and more GNSS/RNSS systems transmitting in identical frequency bands

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THANKS FOR YOUR ATTENTION !!

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RECEIVER DEVELOPMENT, SIGNALS, CODES AND INTERFERENCE

Reference Documents

Receiver Development

- ✓ **Anghileri M. et al.**, *"Performance Evaluation of a Multi-frequency GPS/Galileo/SBAS Software Receiver"*, Proceedings of ION GNSS 2007, 25-28 September 2007, Fort Worth, Texas, USA

Signals

- ✓ **Rebeyrol E. et al.**, *"BOC Power Spectrum Densities"*, Proceedings of ION NTM 2005, 24-26 January 2005, Long Beach, California, USA

PRN Codes

- ✓ **Wallner S. et al.**, *"Galileo E1 OS and GPS L1C Pseudo Random Noise Codes – Requirements, Generation, Optimization and Comparison"*, Proceedings of ION GNSS 2007, 25-28 September 2007, Fort Worth, Texas, USA
- ✓ **Soualle F. et al.**, *"Spreading Code Selection Criteria for the Future GNSS Galileo"*, Proceedings of GNSS 2005, 19-22 July 2005, Munich, Germany

Interference

- ✓ **Titus B.M. et al.**,*"Intersystem and Intrasystem Interference Analysis Methodology"*, Proceedings of ION GPS 2003, 09-12 September 2003, Portland, Oregon, USA
- ✓ **Wallner S. et al.**, *"Interference Calculation between GPS and Galileo"*, Proceedings of ION GNSS 2005, 13-16 September 2005, Long Beach, California, USA