Research Center Space
Universität der Bundeswehr München

Session B5: Receiver Design, Signal Processing, and Antenna Technology 1

Receiver Clock Estimation for RTK-Grade Multi-GNSS Multi-Frequency Synthetic Aperture Processing (SAP)

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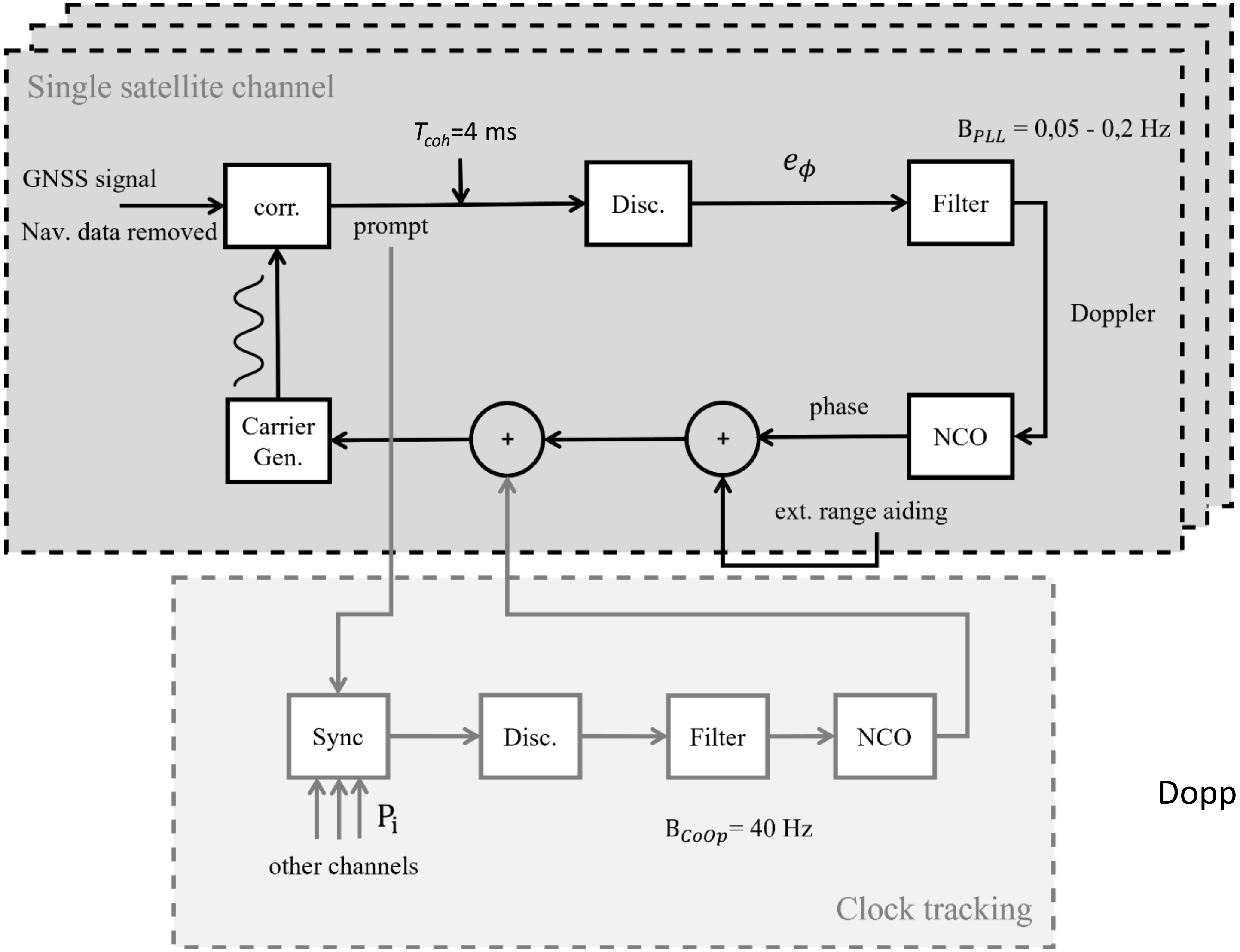
Motivation

- Why synthetic aperture processing (SAP), why ultra-low bandwidth PLL?
  - ➢ increased tracking robustness
  - ➢ increased sensitivity
  - ➢ increased position accuracy
- Goal:
  - ➢ RTK-grade GNSS observations!
  - ➢ Overcome signal degradation, e.g. canopies, with fixed carrier-phase ambiguities

- Other works on SAP, ultra-Low-bandwidth PLL:
  - Co-Op tracking for carrier phase (Zhodzishsky M. et al., 1998)
  - GNSS Synthetic Aperture Processing with Artificial Antenna Motion (Pany T. et al., 2013)
  - “*Supercorrelation*” from FocalPoint
  - Improving GNSS carrier phase tracking using a long coherent integration architecture (Feng X. et. al, 2022)
  - …

Doppler/CoOp-Aided PLL With Ultra-Low Bandwidth

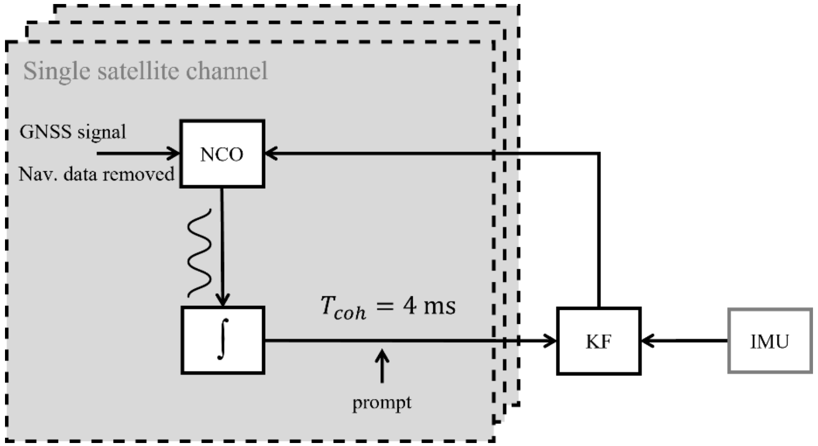


Doppler-Aided PLL (Tight Coupling)

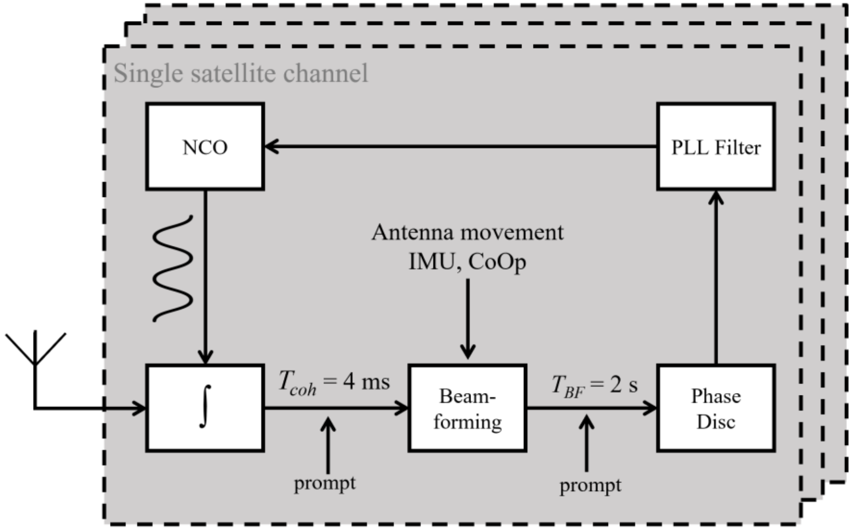
- Conventional PLL is aided by IMU data and CoOp loop
- Clock jitter is tracked by separated loop (CoOp loop)
- PLL bandwidth is main parameter and can be set to very low values for well tuned IMU/CoOp-aiding

Alternative Approaches: SAP or Deep Coupling

- Deep Coupling
  - Kalman Filter (KF) receives prompt correlator and IMU data
  - State vector includes clock states
  - KF parameters determine effective bandwidth as main parameters



- Synthetic Aperture Processing (SAP)
  - Prompt correlator values are captured at different spatial locations due to antenna movement
  - Beam-forming algorithm combines prompt correlator values making us of prior knowledge of antenna movement (IMU-based) and clock jitter (from CoOp loop)
  - Beam-forming results in longer coherent integration times for beam-formed prompt correlator, driving conventional PLL
  - Beam-forming interval time, strategy and PLL bandwidth main parameters



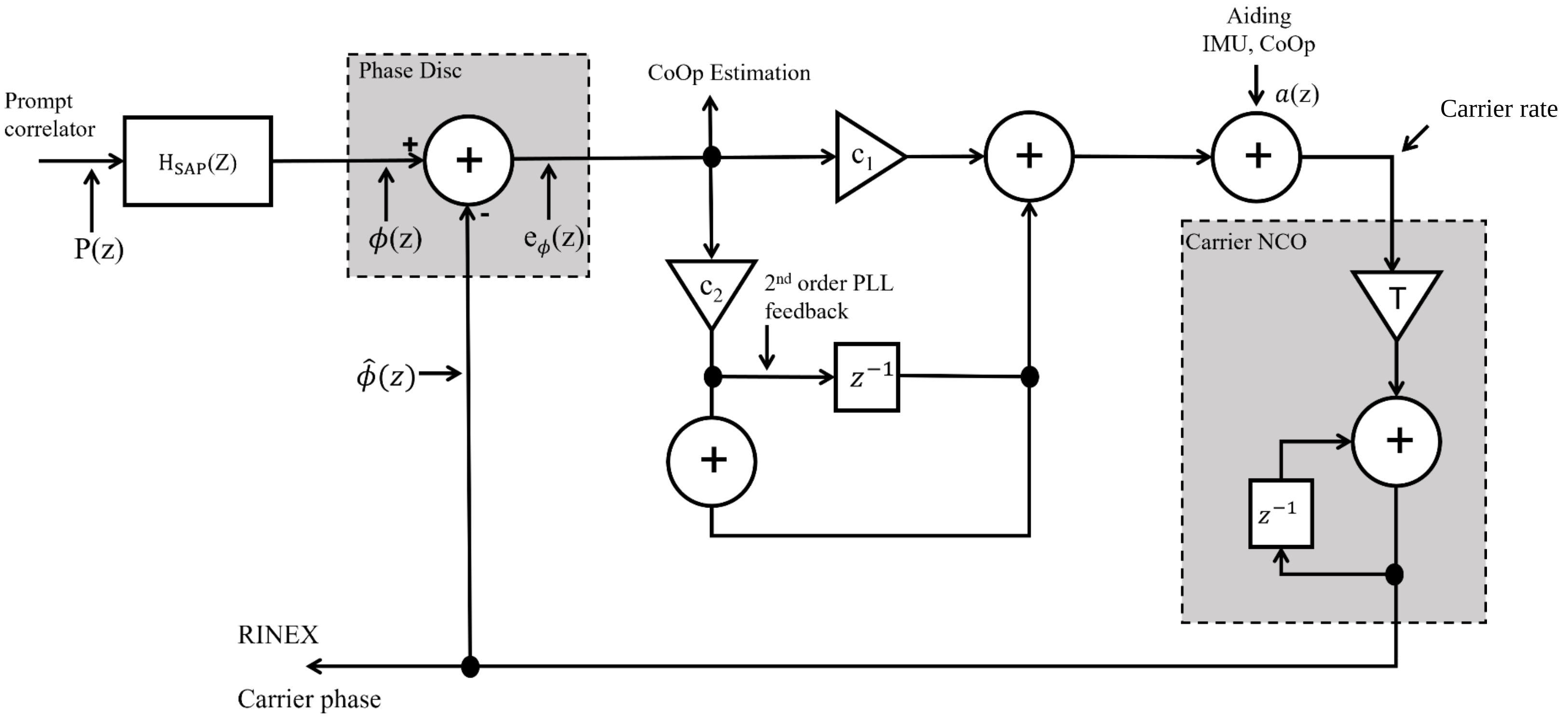
Thermal Noise Analysis (Aided PLL vs. SAP)

- Definition of phase discriminator
  - $e_{\phi} = angle\{P\}$
    - e_{ϕ} … 4-quadrant phase discriminator
    - P … complex valued prompt correlator based on an integration time of T_{coh}
  - Note: independent of amplitude, but affected by squaring loss
  - Under AWGN, e_{ϕ} is of zero mean with a variance of $\sigma^2_{e_{\phi}} = \frac{1}{2C/N_0 T_{coh}}\left(1 + \frac{1}{2C/N_0 T_{coh}}\right)$
- Aided PLL
  - Carrier phase noise is determined by PLL loop bandwidth: $\sigma^2_{PLL} = 2B_{PLL}T_{coh}\sigma^2_{e_{\phi}} = \frac{B_{PLL}}{C/N_0}\left(1 + \frac{1}{2C/N_0 T_{coh}}\right)$
- Synthetic Aperture Processing (SAP)
  - Beam-forming strategy: maximize line-of-sight signal power
  - Assumption: antenna movement and clock jitter perfectly known
  - Thus: $P_{BF} = \int_{t=t_0}^{t_0+T_{BF}} P(t)dt$; P_{BF} … beam-formed prompt correlator, T_{BF} … beam-forming interval
  - $e_{\phi,BF} = angle\{P_{BF}\}$; $e_{\phi,BF}$ … beam-formed phase discriminator
  - Including PLL, we obtain in a carrier phase noise of $\sigma^2_{PLL,BF} = \frac{B_{PLL}}{C/N_0}\left(1 + \frac{1}{2C/N_0 T_{BF}}\right)$
- Conclusion:
  - Aided PLL and SAP show almost the same thermal noise performance; SAP slightly better due to decreased squaring loss

Multipath Analysis of Aided PLL

- Phase discriminator model under influence of clock oscillation and multipath (neglect noise, assume perfect code phase and Doppler lock)
  - $e_\phi(t) = angle\{P(t)\} = angle\left\{ \underbrace{e^{\frac{2\pi j}{\lambda}(\phi(t)+a_c \sin\omega_c t - \hat{\phi}(t))}}_{\text{LOS-signal}} + \underbrace{\beta e^{\frac{2\pi j}{\lambda}(\phi(t)+a_c \sin\omega_c t + v_{mp}t - \hat{\phi}(t))}}_{\text{MP-signal}} \right\}$
    - λ … carrier wavelength [m]
    - $\phi(t)$ … true carrier phase [m], including geometry, tropo, iono, etc., but excluding clock
    - a_c … amplitude of clock oscillation [m]
    - ω_c … frequency of clock oscillation [Hz]
    - $\hat{\phi}(t)$ … estimated carrier phase [m]
    - β … relative multipath amplitude
    - v_{mp} … multipath velocity relative to line of sight
- Linearization for phase lock conditions and $\beta \ll 1$
  - $e_\phi(t) \approx \frac{1}{\lambda}\left(\phi(t) + a_c \sin\omega_c t - \hat{\phi}(t)\right) + \beta \sin\left(\frac{v_{mp}t}{\lambda}\right)$
- Conclusion
  - For small multipath amplitudes and good phase tracking conditions, PLL tracking can be analyzed in frequency domain

z-Transform of Channel Structure (aided PLL, with and without SAP)



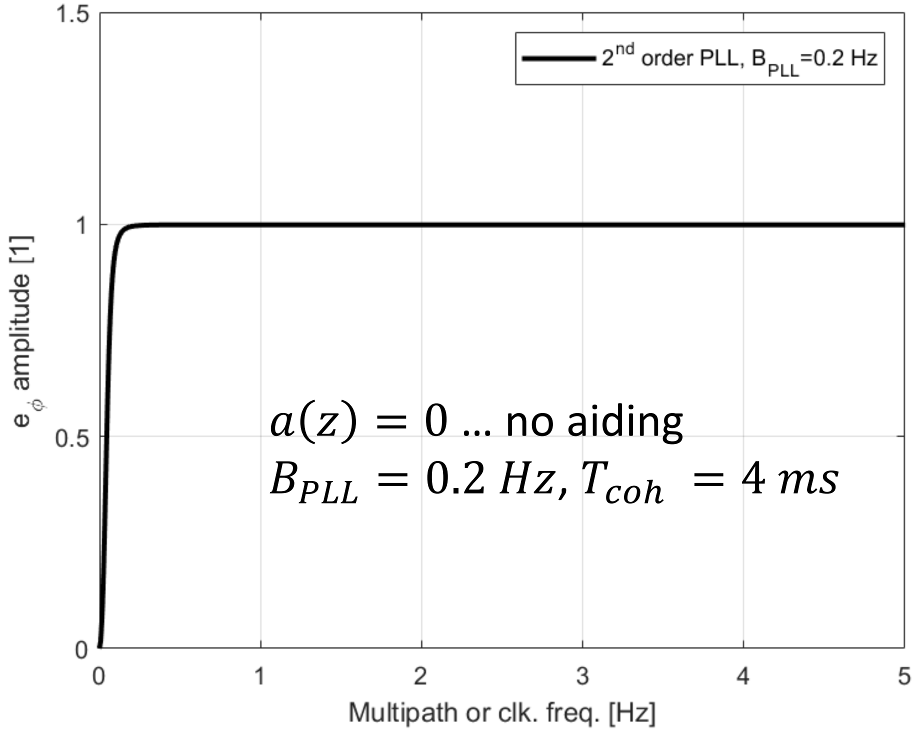
- $\phi(z)$ … true carrier phase
- $\hat{\phi}(z)$ … estimated carrier phase
- $e_\phi(z)$ … phase discriminator
- $a(z)$ … rate aiding, based on IMU, CoOp

- $H_{SAP}(z)$ … beamforming ($H_{SAP}(z)$=1 for standard PLL
- T_{coh} … coherent integrate time (e.g. 4 ms)
- c_1 … 2nd order PLL coefficient ($= 1.89\sqrt{2}B_{PLL}$)
- c_2 … 2nd order PLL coefficient ($= (1.89B_{PLL})^2\, T_{coh}$)

Use of PLL-Discriminator for Clock-Estimation

- True carrier phase includes
  - Geometry, iono, tropo,
  - receiver/satellite clock
- Task of CoOp is to estimate clock jitter
  - Common to all signals
  - High frequency
  - Does not include clock drift or other low frequency processes
- Transfer function from true carrier phase to phase discriminator
  - $e_\phi(z) = \phi(z)D(z) + A(z)a(z)$
  - $D(z) = \frac{-1+2z-z^2}{1+z(T_{coh}(c_2-c_1)-2)+z^2(1+c_1T_{coh})}$
  - $A(z) = \frac{-zT_{coh}+z^2T_{coh}}{1+z(T_{coh}(c_2-c_1)-2)+z^2(1+c_1T_{coh})}$
  - Perfect aiding $a(z) = \phi(z)\frac{D(z)}{A(z)} = -\phi(z)\frac{1}{T_{coh}}\frac{1-2z+z^2}{z^2-1} = -\phi(z)\frac{1}{T_{coh}}\frac{z-1}{z+1}$

Transfer function from true carrier phase to phase discriminator

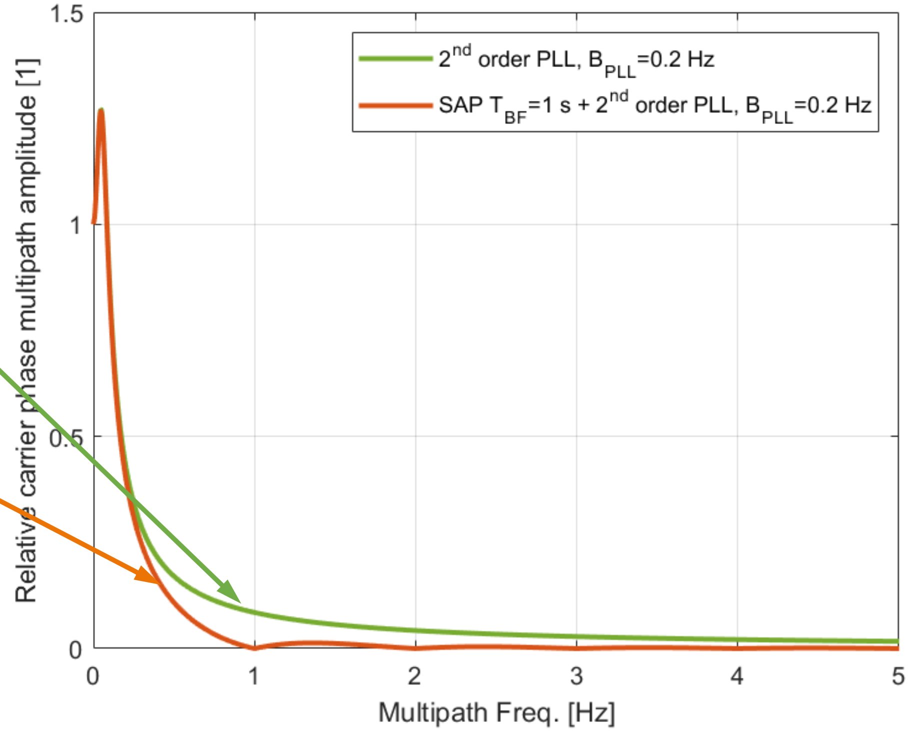


Conclusion: phase discriminator contains clock jitter, if no CoOp-aiding is applied

Aided PLL with and without Beamforming

- Standard PLL Transfer Function (no SAP)
- $\hat{\phi}(z) = H(z)\phi(z) + A(z)a(z)$
  - $H(z) = \frac{zT_{coh}(c_2-c_1)+z^2T_{coh}c_1}{1+z(T_{coh}(c_2-c_1)-2)+z^2(1+c_1T_{coh})}$
    - $H(z)$ … standard 2nd order PLL transfer function
    - $A(z)$ … Rate aiding transfer function
- PLL Transfer Function with SAP
  - Assuming perfect aiding, line-of-sight beamforming can be realized as a coherent integration of prompt correlation values
  - E.g. realized as moving averaging
  - $H_{SAP,LOS}(z) = \frac{1}{K}\sum_{k=1}^{K} z^{-k}$
  - Beam-forming time $T_{BF} = KT_{coh}$
  - PLL + SAP transfer function -> $H_{SAP,LOS}(z)\ H(z)$
- Further Remarks
  - Beamforming coefficients have the potential to be tuned, nulling etc.
  - No mitigation capability in static situations
    - at least for MEO-GNSS
    - LEO-PNT will exhibit higher multipath frequency even in static situations

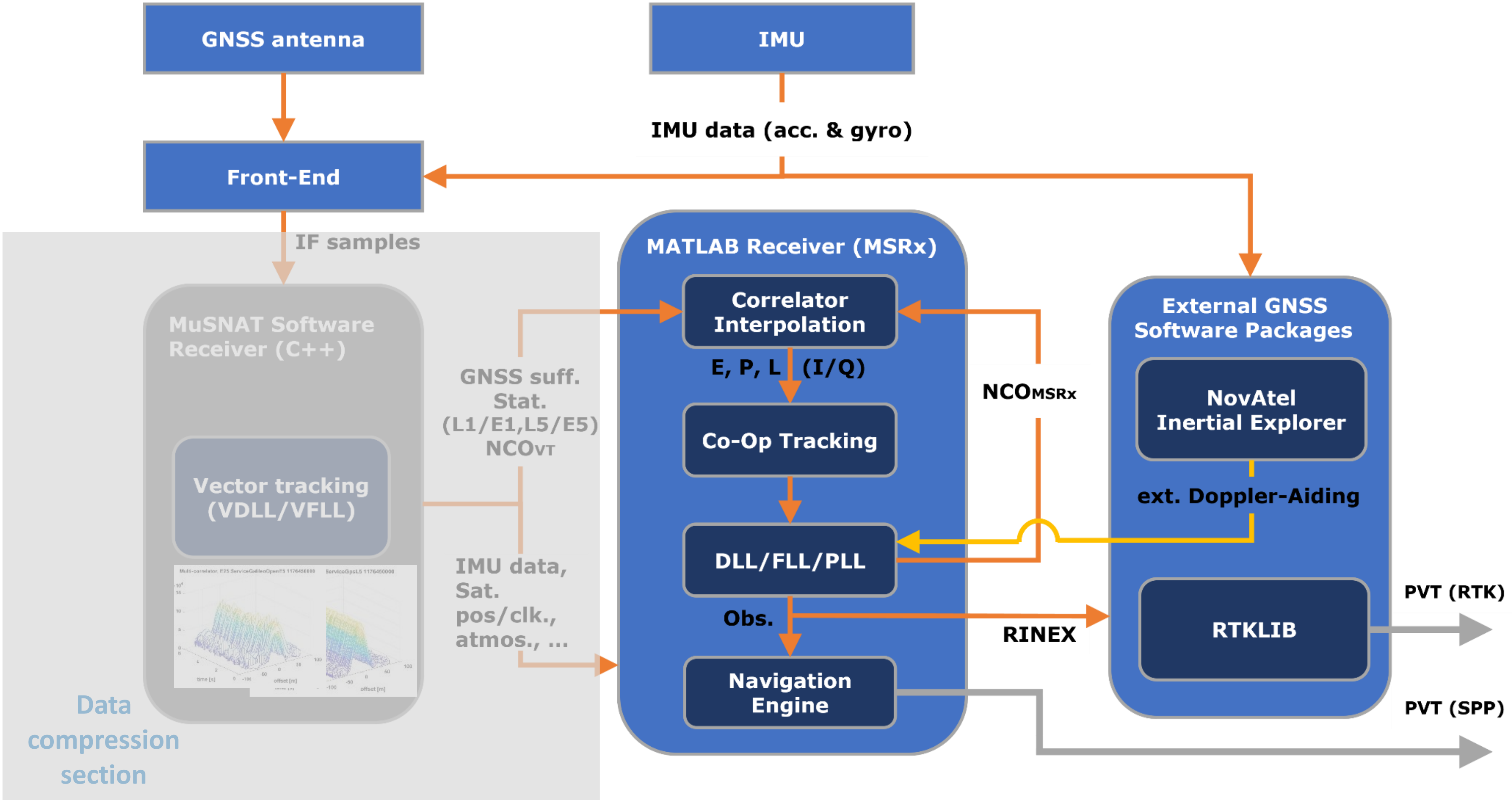
Transfer function from true carrier phase to estimated carrier phase



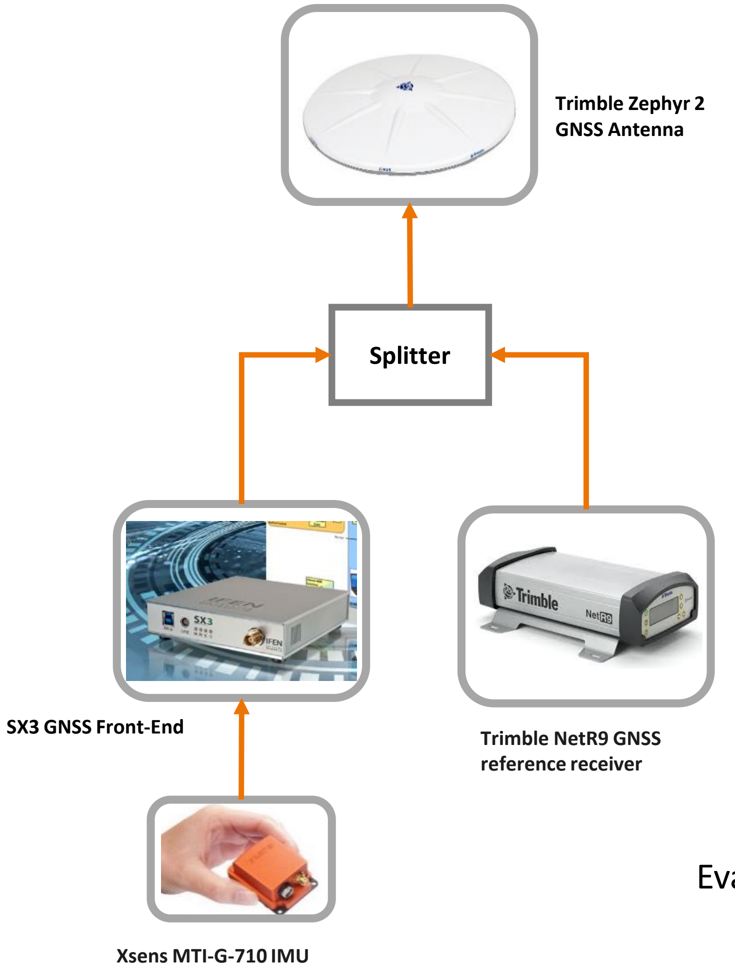
Conclusion: Aided PLL suppress multipath in dynamic situations, SAP will further improve multipath mitigation

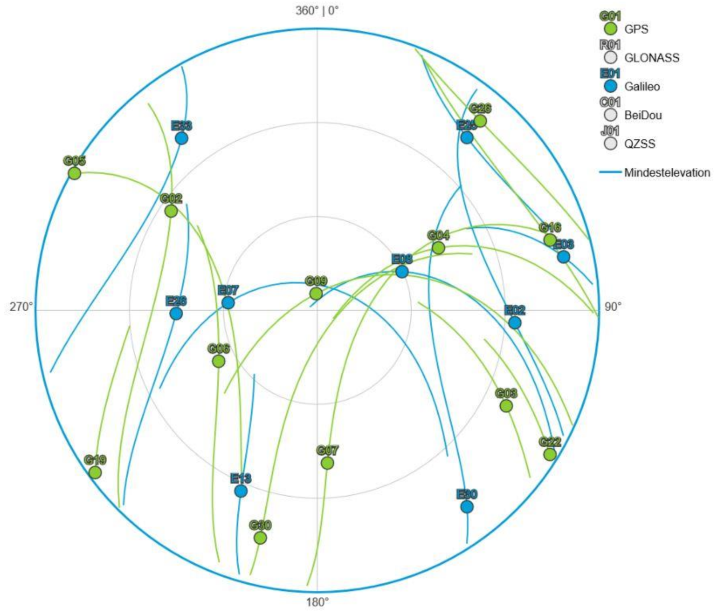
Test Implementation MSRx

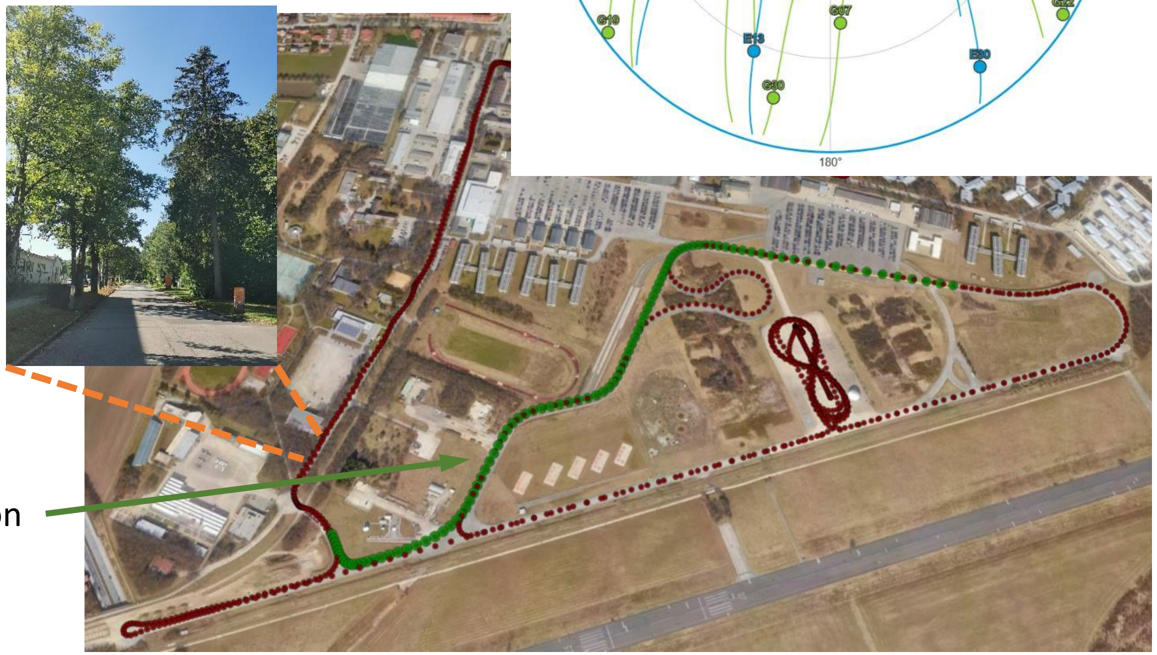
- MATLAB based GNSS SDR using compressed signals as input (Bochkati et al., 2022)
- Supported frequencies: GPS L1 C/A (with data bit wipe-off), L5Q & Galileo E1C, E5aQ



Test Scenario - Drive on UniBw M Campus

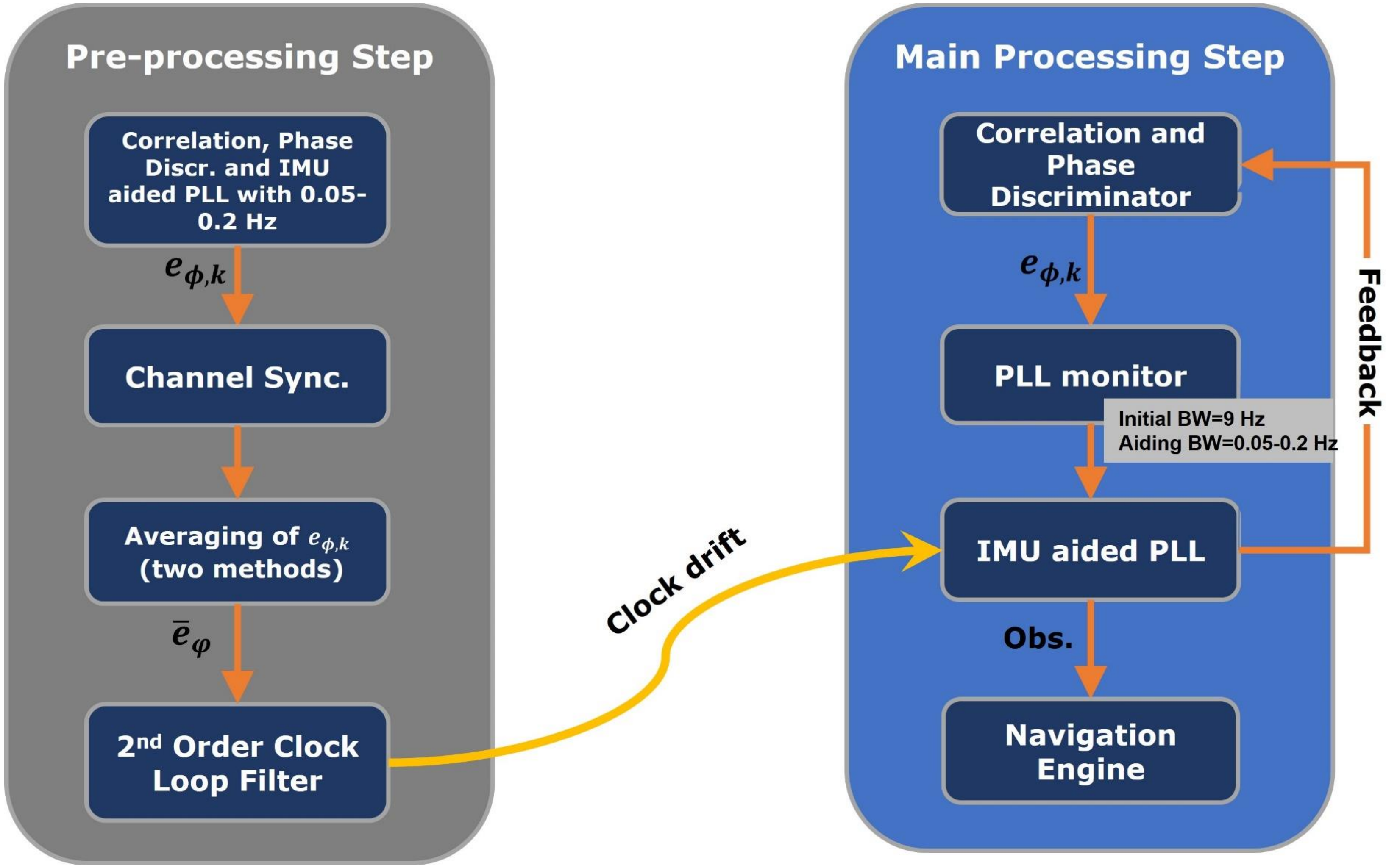






Evaluated trajectory section

CoOp-Estimation – Block Diagram



CoOp-Estimation – Procedure

- Pre-processing step:
  1. Synchronization of the PLL tracking channels
     - PLL working with IMU aiding at low bandwidth (0.05-0.2 Hz) → $e_{\varphi,k}$ will contain clock jitter
  2. Build mean value of phase discriminator from all available channels
     - Method A: Mean of unwrapped phase discriminator
     - Method B: dynamically aligned prompt correlator
  3. Apply second order clock loop filter (CLL) → similar to 2order conventional PLL and DLL loop filter syntax

$$\begin{bmatrix} \varphi_{k+1} \\ \theta_{k+1} \end{bmatrix} = \begin{bmatrix} 1 & t_{coh} \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \varphi_k \\ \theta_k \end{bmatrix} + \begin{bmatrix} C_2 \\ C_1 \end{bmatrix} \cdot e_{\varphi,k} + \begin{bmatrix} t_{coh} \\ 0 \end{bmatrix} \cdot \delta \dot{t}_{coOp,k}$$

     Where $C_1 = \sqrt{2} \cdot t_{coh} \cdot \omega_0, \omega_0 = 1.89 \cdot PLL_{Bw}$ and $\delta \dot{t}_{coOp,k}$ is the CoOP clock feedback inserted as carrier rates. θ_k represent the linear feedback register

  4. Store of the CLL rates for the main processing step run

- Main processing step:
  1. The CLL rates are applied directedly to the PLL in the same as the IMU-based Doppler-Aiding
  2. Monitoring of PLL necessary, as instable tracking behavior can occur (if occurs, reset PLL to initial high BW of 9 Hz)

Method A: Mean of Unwrapped PLL Discriminator

- k … channel index
- λ_k … carrier wavelength in channel k
- $e_{\phi,k}(t)$ … PLL phase discriminator in pre-processing step of channel k and at epoch t in [cyc]
- $\overline{e_\phi}(t)$ … Clock lock loop (CLL) discriminator in [m]

1) Unwrap phase discriminator time series

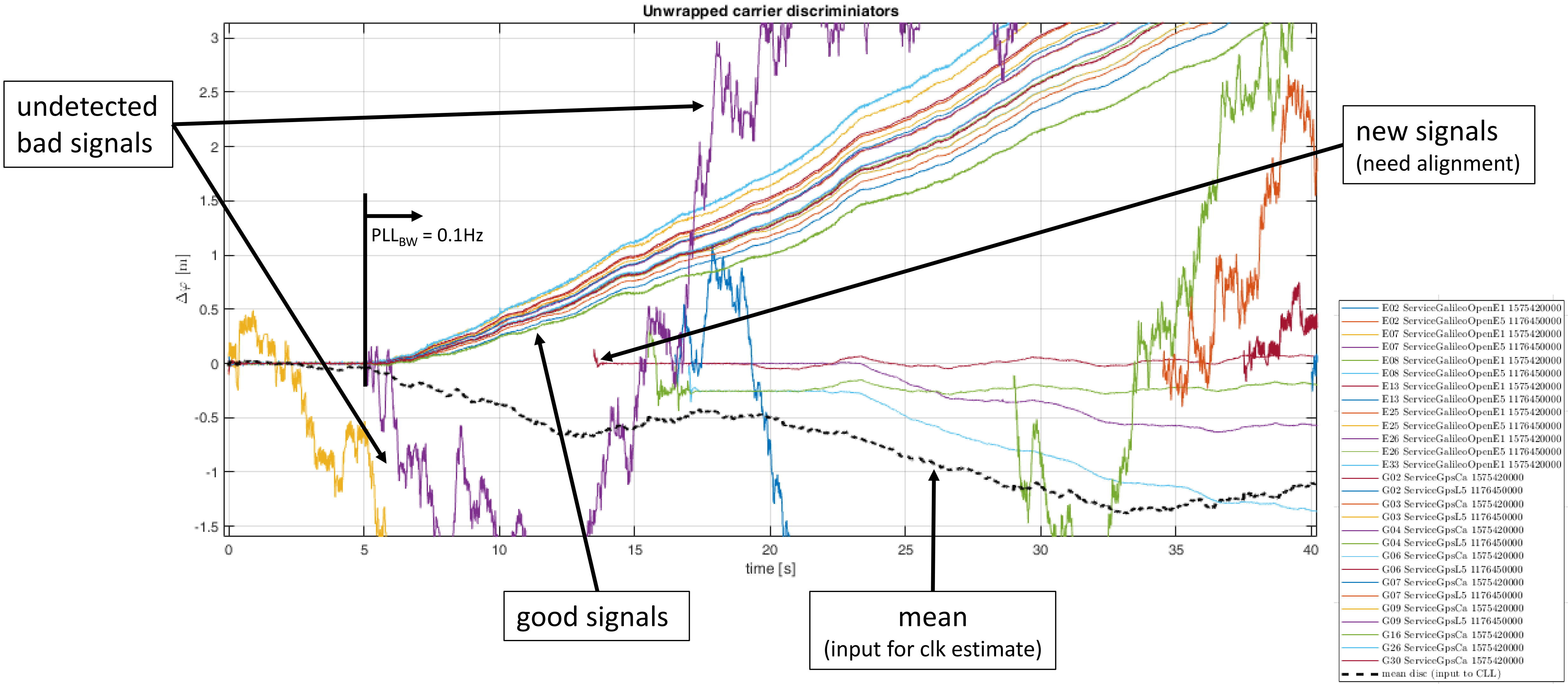
2) Sync. all phase discriminator values to common epoch (via interpolation)

$$e_{\phi,k;unwrap+sync}(t) = \text{unwrap}\{e_{\phi,k}(\text{t})\}$$

3) Averaging

$$\overline{e_\phi}(t) = \frac{1}{K}\sum_{k=1}^{K} \lambda_k e_{\phi,k;unwrap+sync}(t)$$

Method A: Mean of Unwrapped PLL Discriminator



Method B: Dynamically Aligned Prompt Correlator

- k ... channel index
- λ_k ... carrier wavelength in channel k
- $e_{\phi,k}(t)$ ... phase discriminator in pre-processing step of channel k and at epoch t
- $\varphi(t)$ ... clock lock loop (CLL) phase in [m]
- $\theta(t)$ ... CLL rate in [m/s]
- arg ... argument (i.e. angle) of complex number
- $\bar{x}$ ... complex conjugate of x
- $\overline{e}_{\phi}(t)$... CLL discriminator in [m]

1) Convert discriminator to prompt correlator value $P_k(t) = e^{2\pi j e_{\phi,k}(t)}$

2) Sync. all prompt correlator values to common epoch (via interpolation)

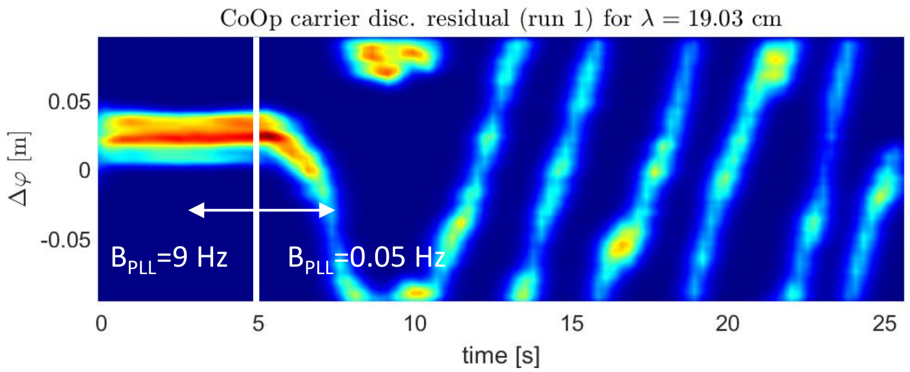
3) Define reference prompt value at beginning of processing (or after outlier detection): $P_{k,off} = P_k(t_0)e^{-2\pi j\varphi(t_0)/\lambda_k}$

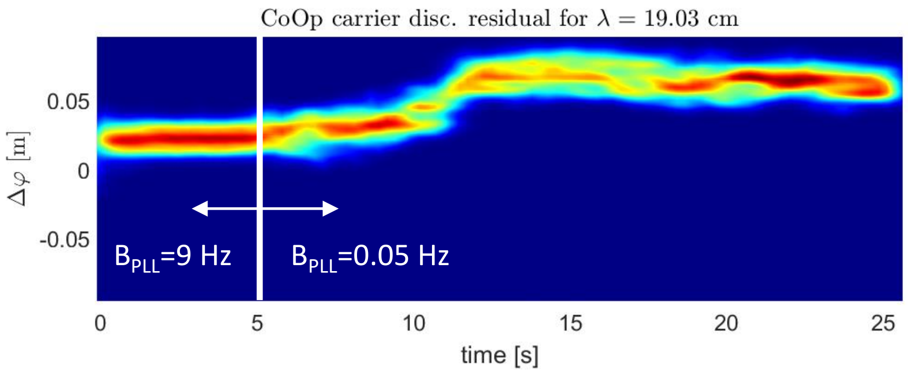
4) Averaging: $\overline{e}_{\phi}(t) = \frac{1}{K}\sum_{k=1}^{K} \lambda_k \arg\{\overline{P}_{k,off} \cdot P_k\ (t)e^{-2\pi j\varphi(t)/\lambda_k}\}$

CoOp-Results -Method B: Dynamically Aligned Prompt Correlator

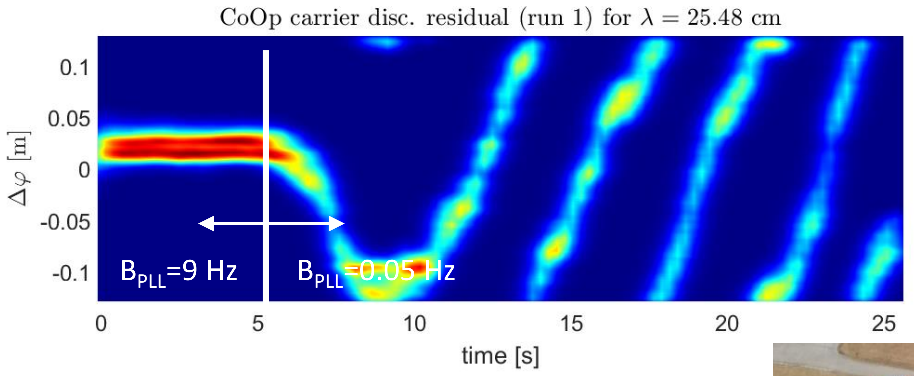
Histogram of phase discriminator values for all channels (separated for L1/E1 and L5/E5a)

t_0=383750 s (car moving, see lower right corner)

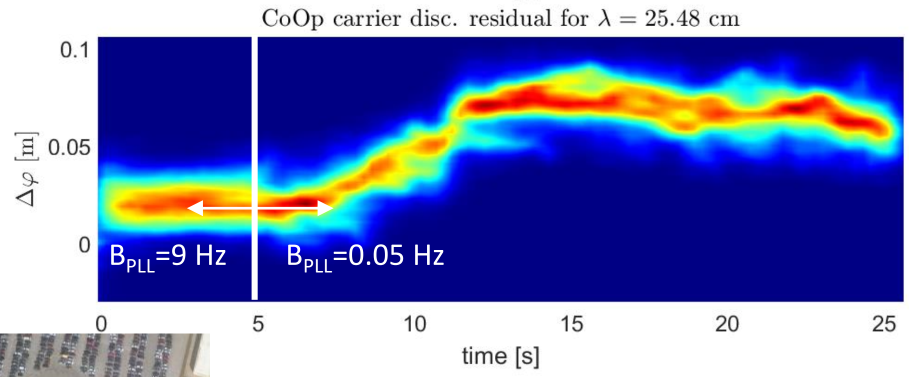




L1/E1



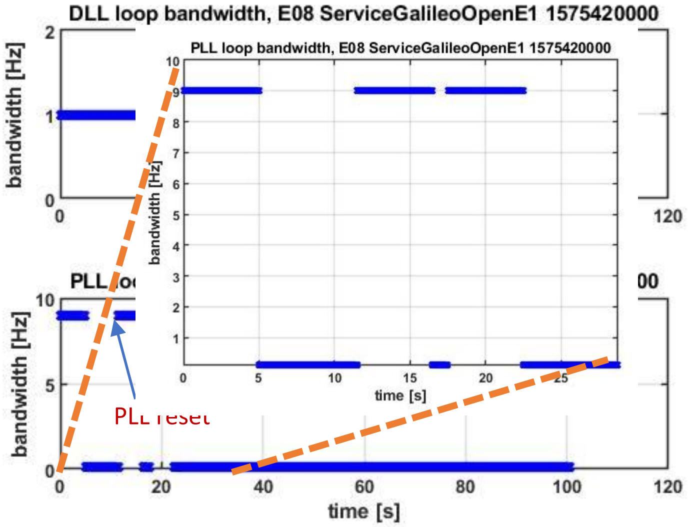
L5/E5a

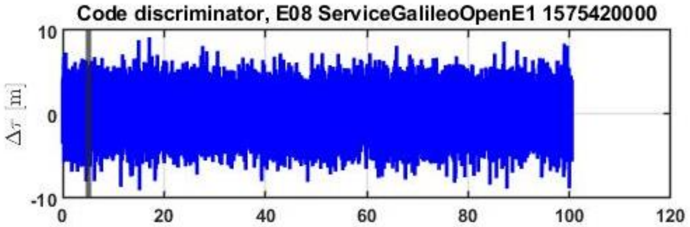


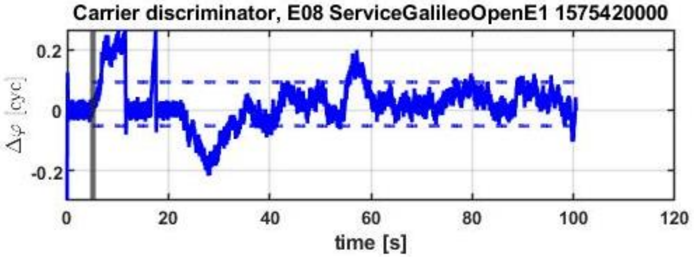
Without CoOp-Aiding (pre-processing step)

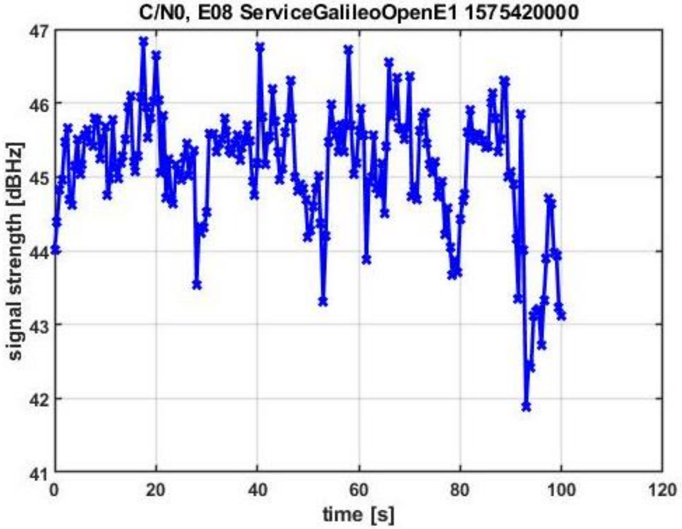
With CoOp-Aiding (main processing step)

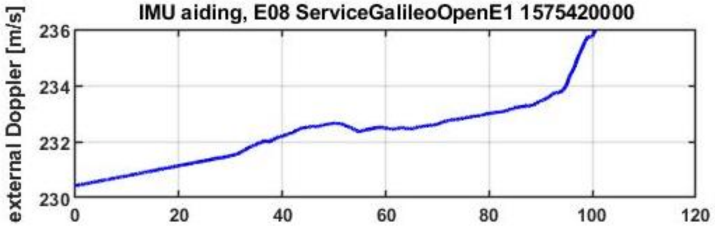
Inside the Ultra-Low-Bandwidth PLL Impact of Bandwidth (with CoOp-Aiding)

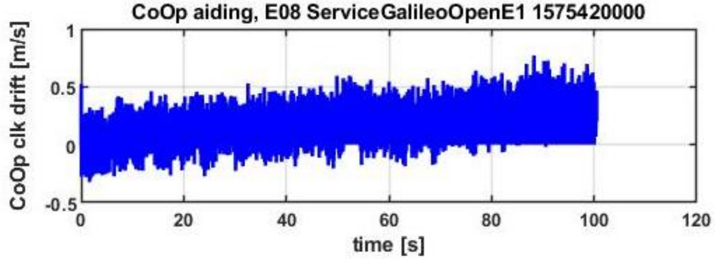


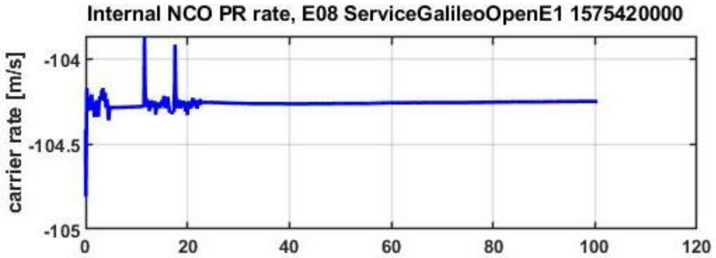


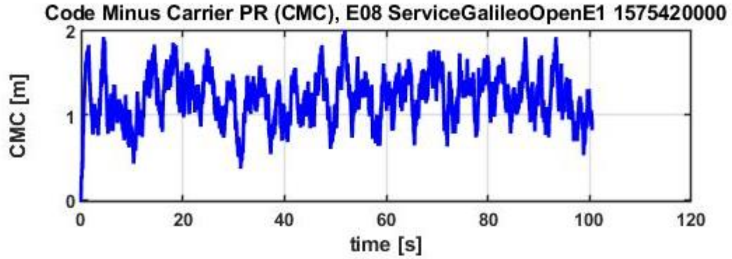






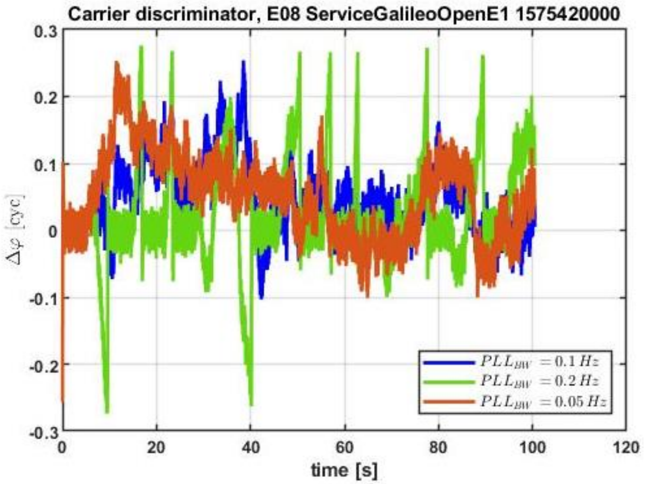


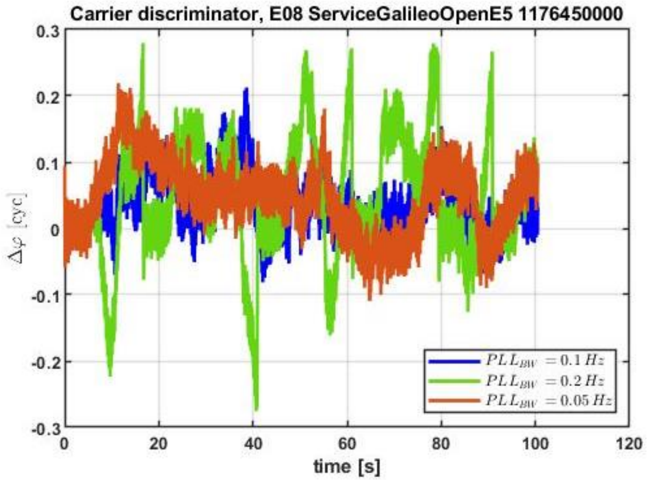




Impact of Bandwidth (with CoOp-Aiding)

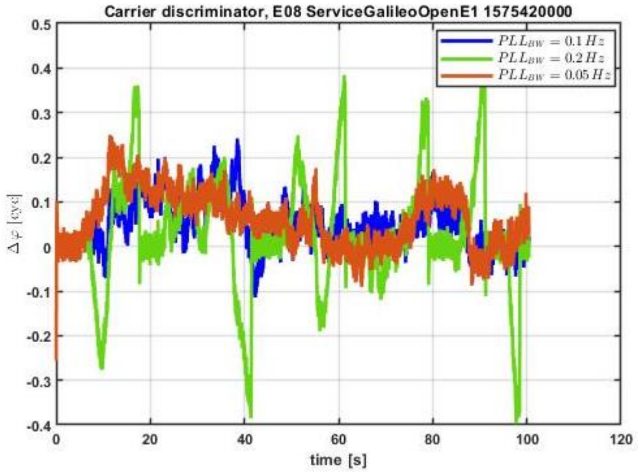
- Galileo E1C
- Galileo E5aQ



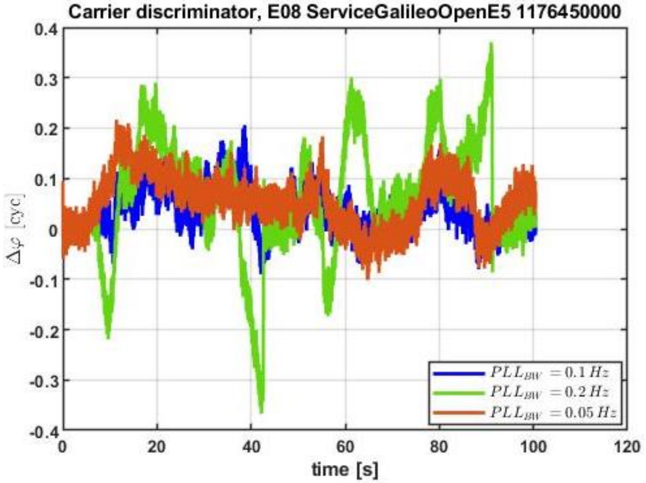


CLL-threshold = 15

CLL_{thres} … PLL discriminator threshold applied in low bandwidth PLL mode (0.05-0.2 Hz); if exceeded -> reset PLL to initial bandwidth of 9 Hz

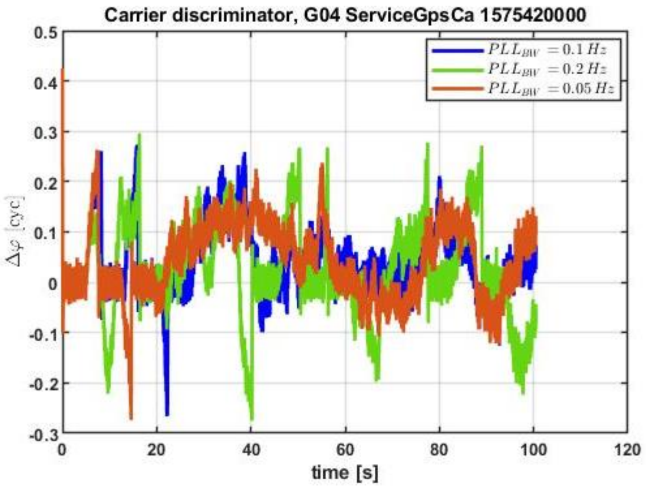


CLL-threshold = 999

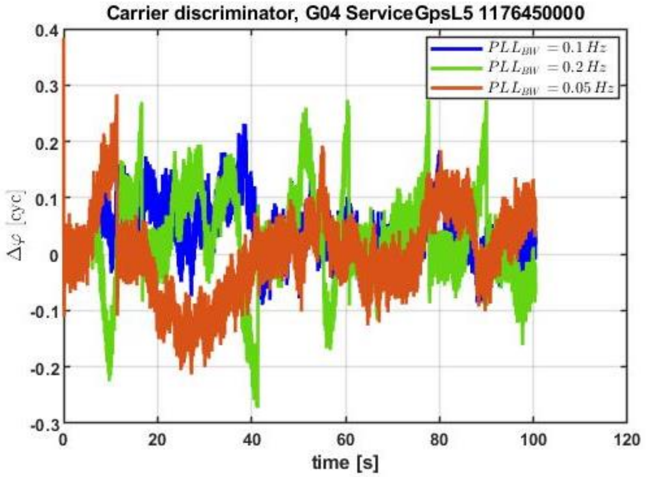


Impact of Bandwidth (with CoOp-Aiding)

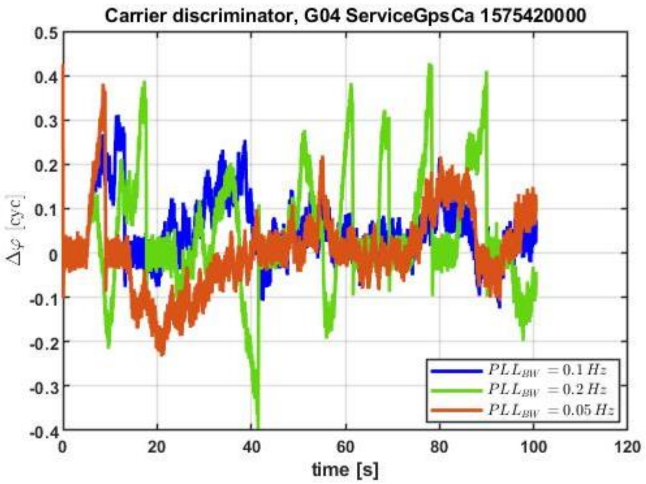
- GPS C/A
- GPS L5Q



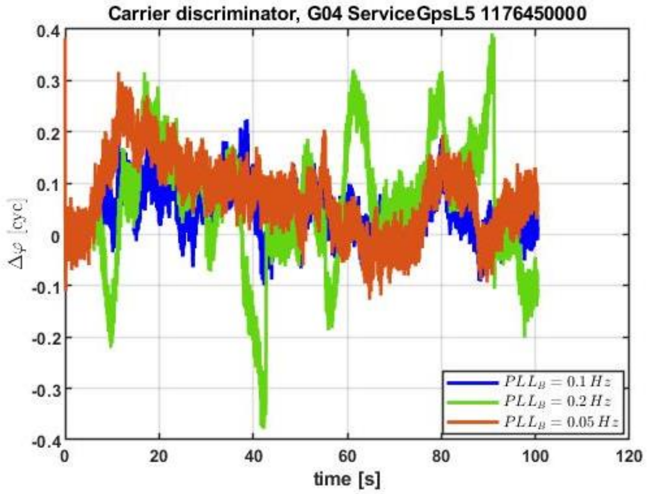
CLL-threshold = 15



CLL_{thres} … PLL discriminator threshold applied in low bandwidth PLL mode (0.05-0.2 Hz); if exceeded -> reset PLL to initial bandwidth of 9 Hz



CLL-threshold = 999



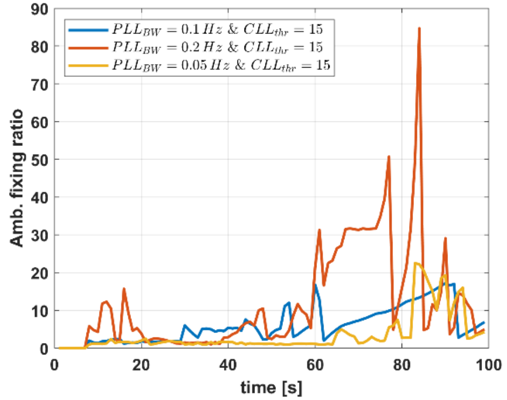
RTK Ambiguity Fixing Performance

- Post-processing with the open-source GNSS software package „RTKLIB“
- Following RTKLIB-setting have been adapted for all scenarios to process the input RINEX-file

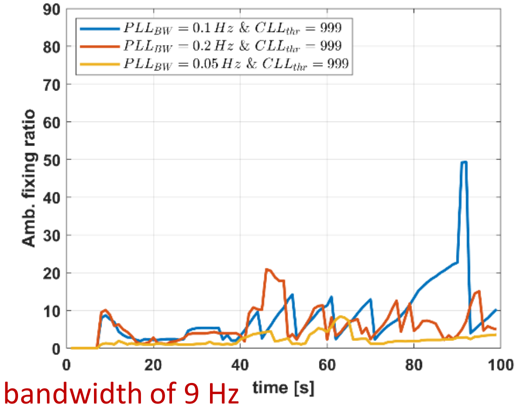
Parameter	Selected settings
RTKLIB version	V2.4.3 b34g (Demo5) GUI
Positioning mode	kinematic
Frequencies	L1/E1C and L5/E5aQ
Satellite system	GPS & Galileo
KF-processing direction	forward
Ambiguity resolution method	continuous
Ambiguity resolution threshold	3

RTK Ambiguity Fixing Performance

- Processing strategies:
  - 3 X MSRx – RINEX files with $\mathrm{PLL_{Bw}}$= 0.05, 0.1 and 0.2 Hz & $\mathrm{CLL_{thres}}$= 15
  - 3 X MSRx – RINEX files with $\mathrm{PLL_{Bw}}$= 0.05, 0.1 and 0.2 Hz & $\mathrm{CLL_{thres}}$= 999
- Performance parameters: Fixing rates and Fixing ratio



Scenario	Ambiguity fixing rates [%]
$\mathrm{PLL_{BW}} = 0.05\ \mathrm{Hz}\ \&\ \mathrm{CLL_{thres}} = 15$	34.3
$\mathrm{PLL_{BW}} = 0.1\ \mathrm{Hz}\ \&\ \mathrm{CLL_{thres}} = 15$	80.8
$\mathrm{PLL_{BW}} = 0.2\ \mathrm{Hz}\ \&\ \mathrm{CLL_{thres}} = 15$	78.8
$\mathrm{PLL_{BW}} = 0.05\ \mathrm{Hz}\ \&\ \mathrm{CLL_{thres}} = 999$	46.5
$\mathrm{PLL_{BW}} = 0.1\ \mathrm{Hz}\ \&\ \mathrm{CLL_{thres}} = 999$	92.9
$\mathrm{PLL_{BW}} = 0.2\ \mathrm{Hz}\ \&\ \mathrm{CLL_{thres}} = 999$	83.8



$\mathrm{CLL_{thres}}$ … PLL discriminator threshold applied in low bandwidth PLL mode (0.05-0.2 Hz); if exceeded -> reset PLL to initial bandwidth of 9 Hz

Conclusions / Future Work

- Conclusions
  - Analyzed aided PLL and synthetic aperture processing with z-transform
  - Prototype CoOp L1/E1/E5/L5 implementation working with dynamic real-world data, ultra-low bandwidth PLL demonstrated
  - Solution RTK-capable, but further tuning required to achieve 100 % in open sky
- Future Work:
  - Develop deeper understanding of error budget (transient errors due to slightly incorrect aiding apparently relevant)
  - Test the performance of Doppler-aided PLL + CoOp oscillator tracking in urban canopies.
  - Elaborate deeper understanding for the trade-off between the aided PLL bandwidth and the CoOp bandwidth
  - Implementation of the SAP algorithms to further improve and support the tracking capability of the MSRx receiver
  - Replace CoOp Method “Aligned Prompt Correlator” by Kalman Filter (including data screening, CN0 threshold, etc.)

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