08: Signal Tracking

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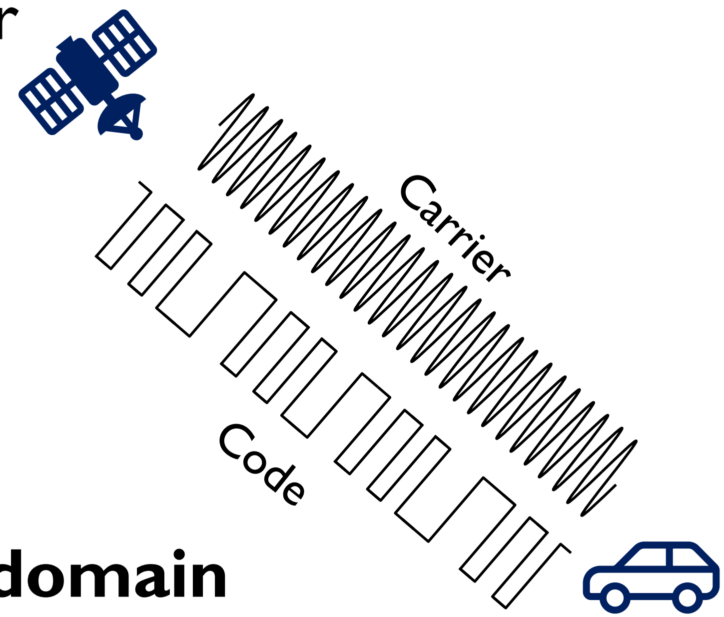
Signal Tracking

- Doppler frequency and code phase changes due to satellite and receiver motion and clock variations
- The purpose of signal tracking is to estimate (track) Doppler frequency and code phase as they vary with time

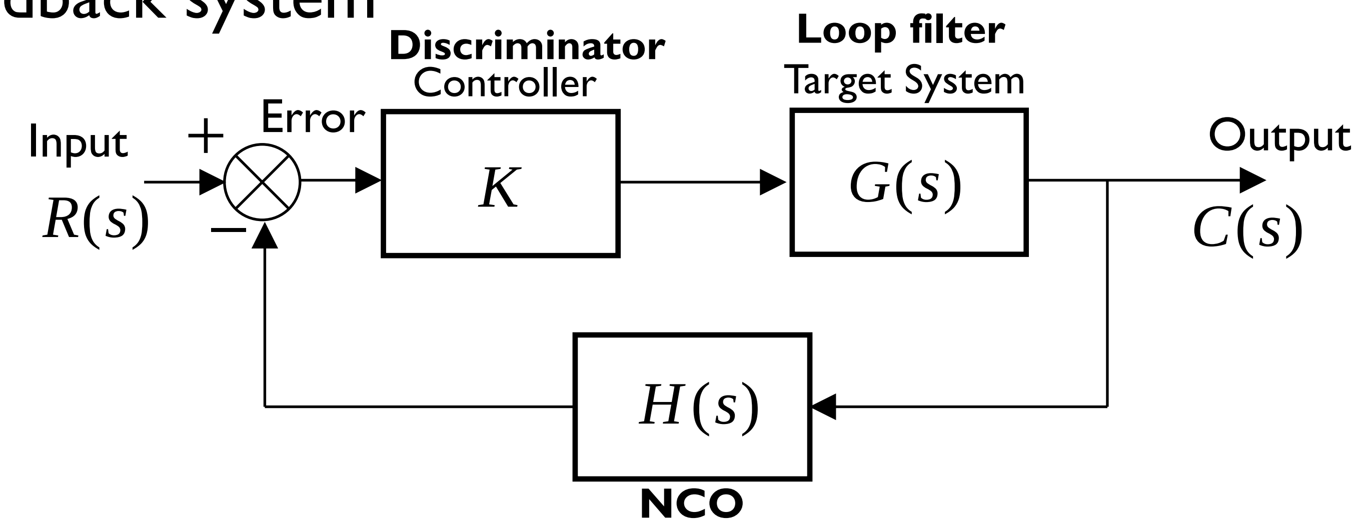


- Tracking is performed in the **time domain**

- By using feedback control, these two values can be tracked

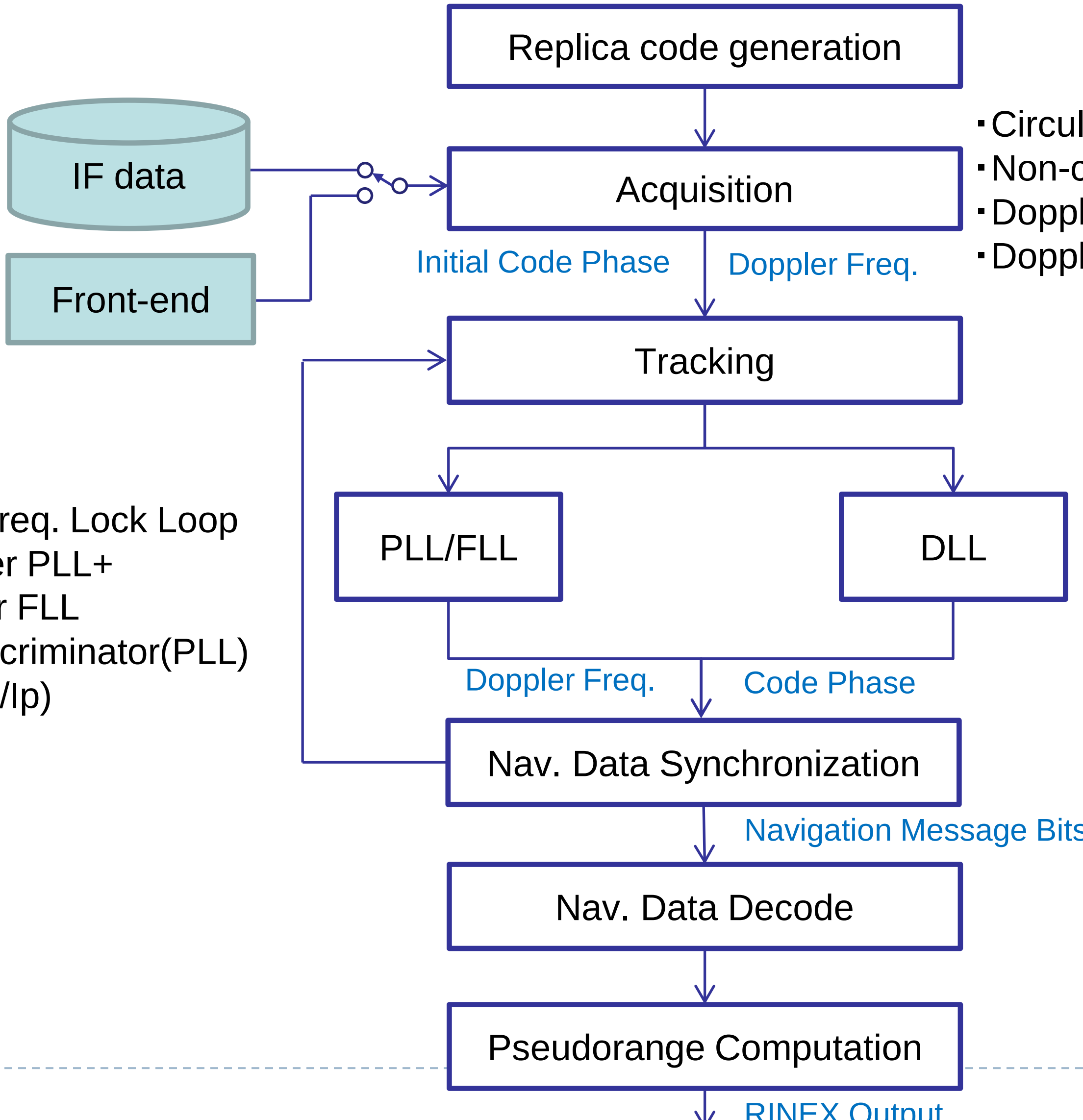
Feedback System

- Feedback system



- A Delay Lock Loop (DLL) tracks the code phase
- A Phase-Locked Loop (PLL) tracks the carrier phase
- A Frequency-Locked Loop (FLL) tracks the carrier frequency

GNSS Signal Processing



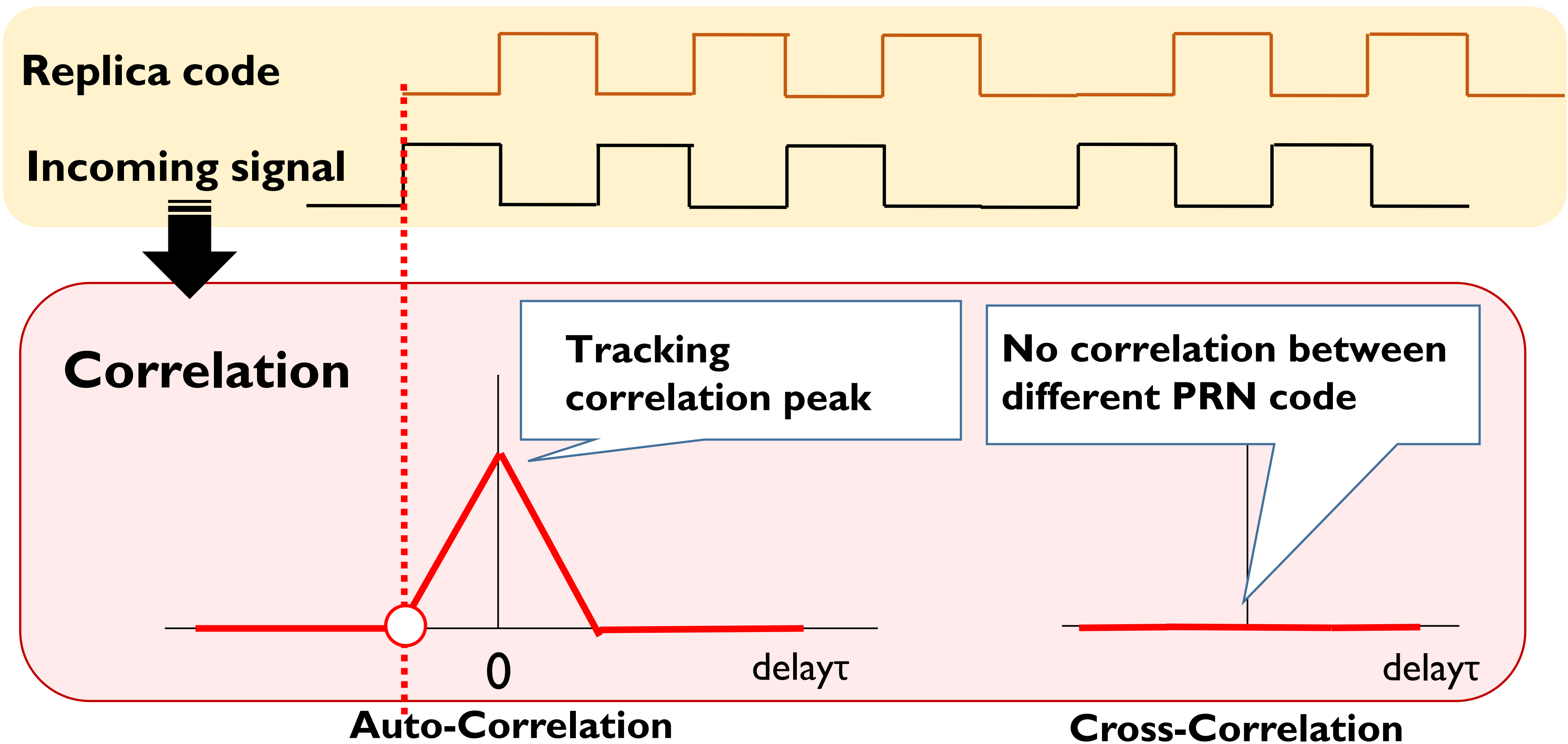
- Circular correlation by FFT
- Non-coherent integration
- Doppler search step: 200 Hz
- Doppler search range: -7~+7kHz

- Phase/Freq. Lock Loop
- 2nd order PLL+ 1st order FLL
- Error discriminator(PLL) atan(Qp/Ip)

- Delay Lock Loop
- Carrier aid 2nd order DLL
- Error discriminator (E-L)/(E+L)/2

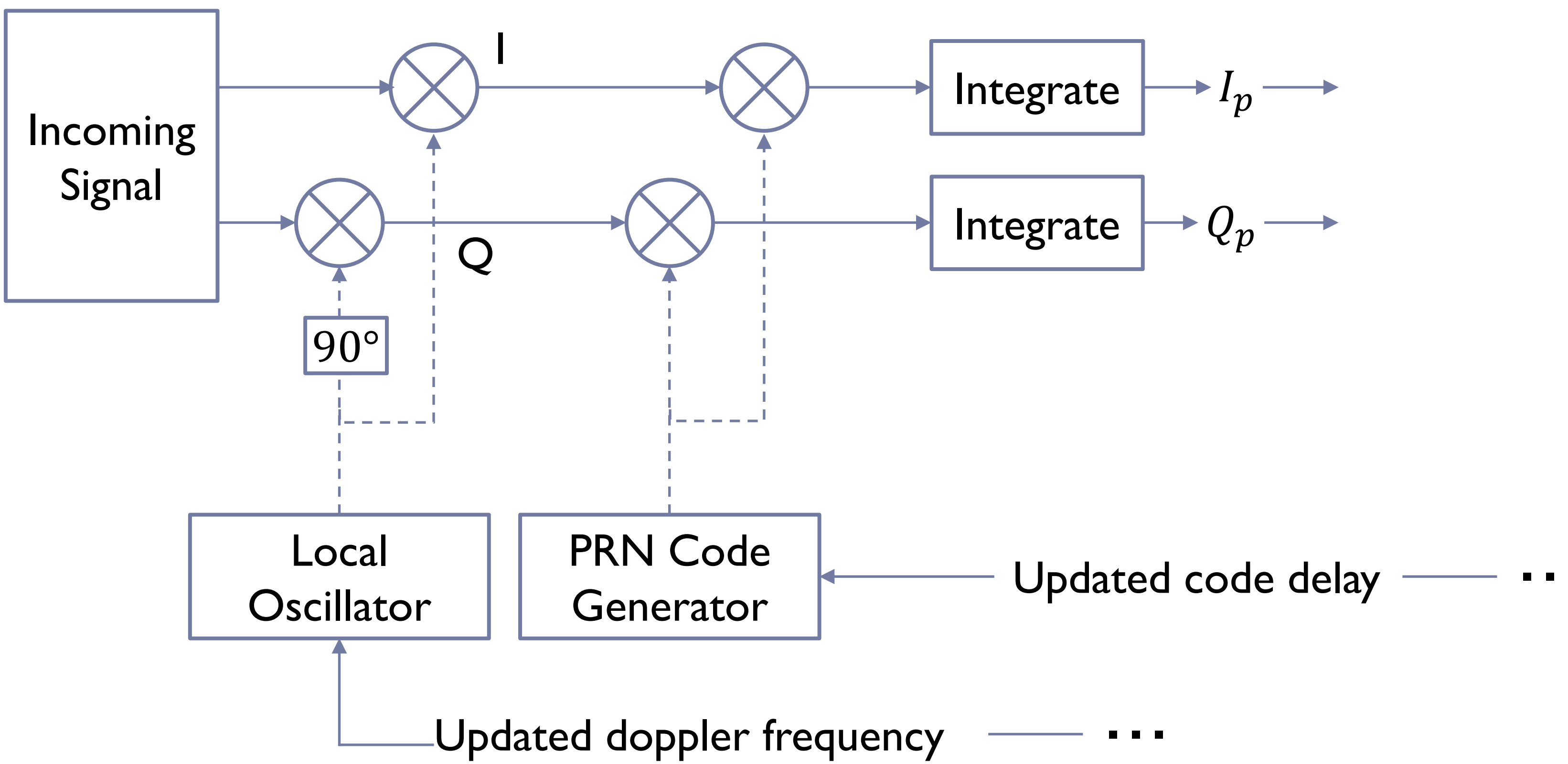
GNSS Signal Correlation

① Replica PRN code generation
② Correlation between replica code and incoming signal



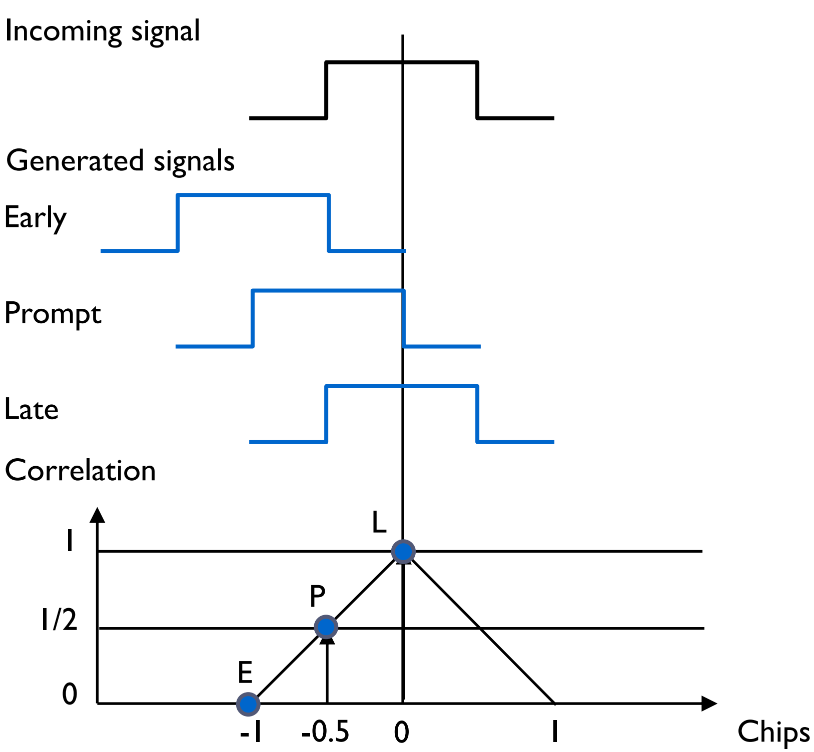
Correlation in Time-Domain

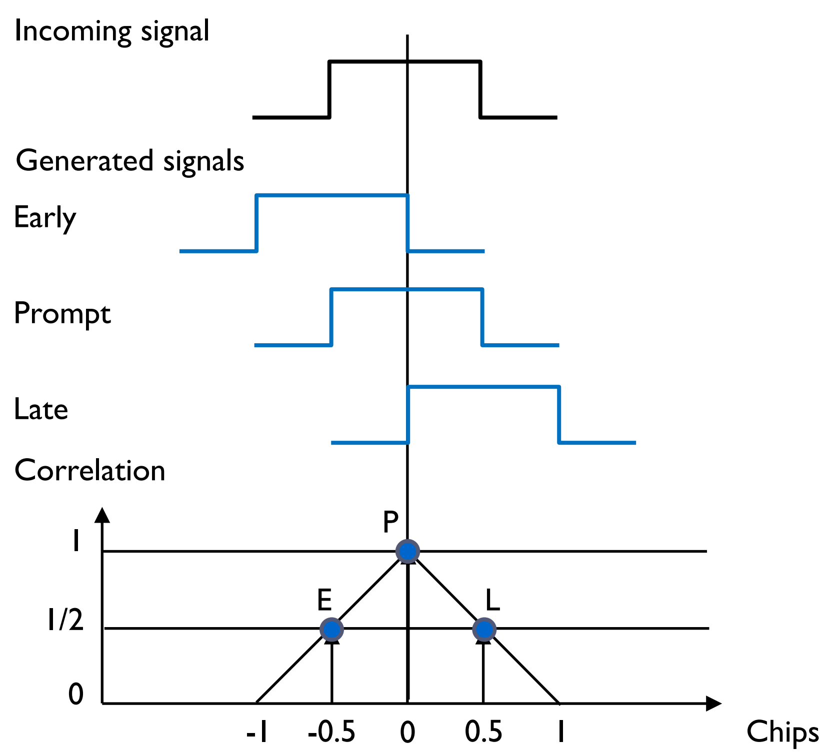
- Remove carrier phase
- Correlation with local replicas



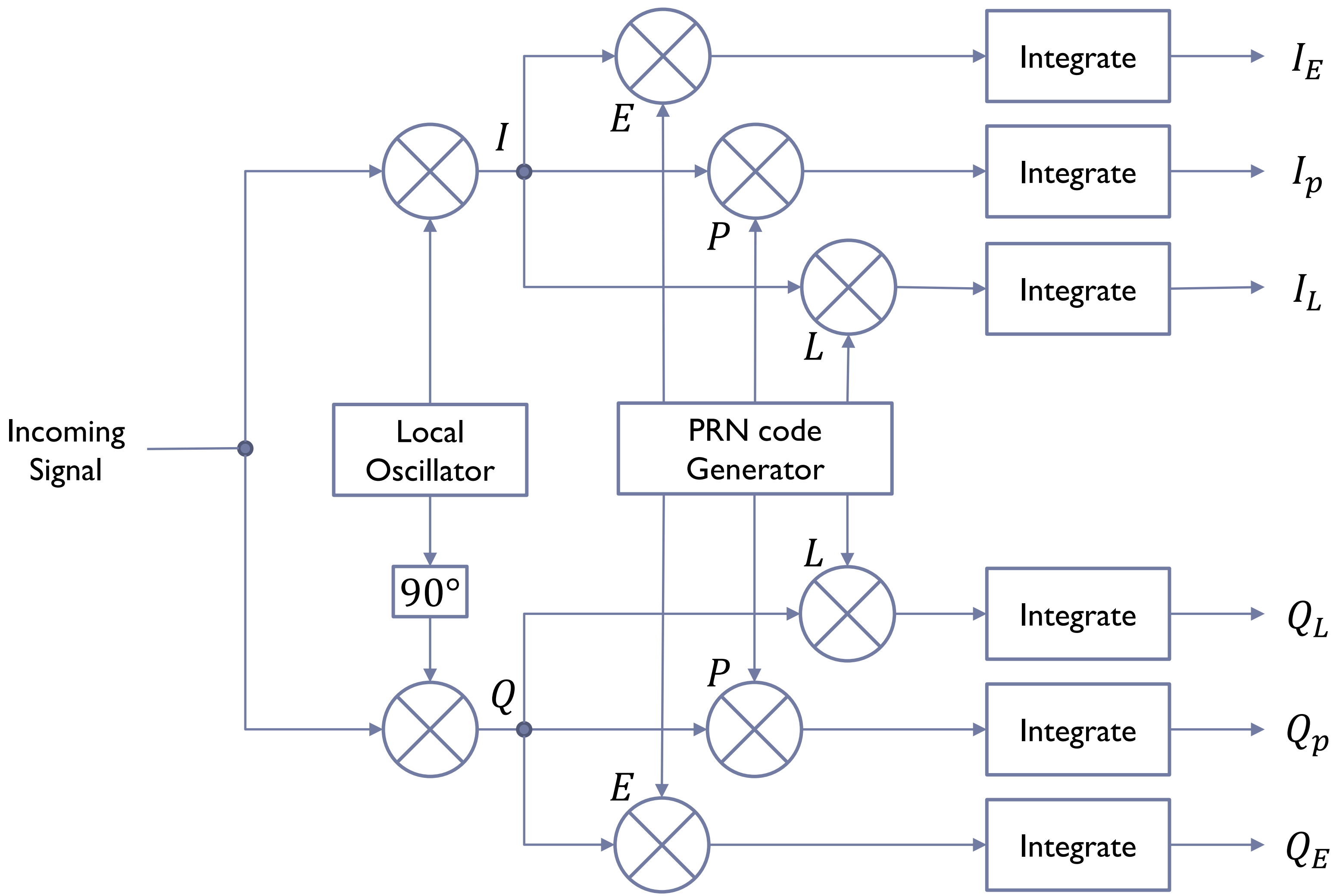
E-P-L Correlator (1)

- How to estimate tracking error?
- Early-Prompt-Late (E-P-L) correlator



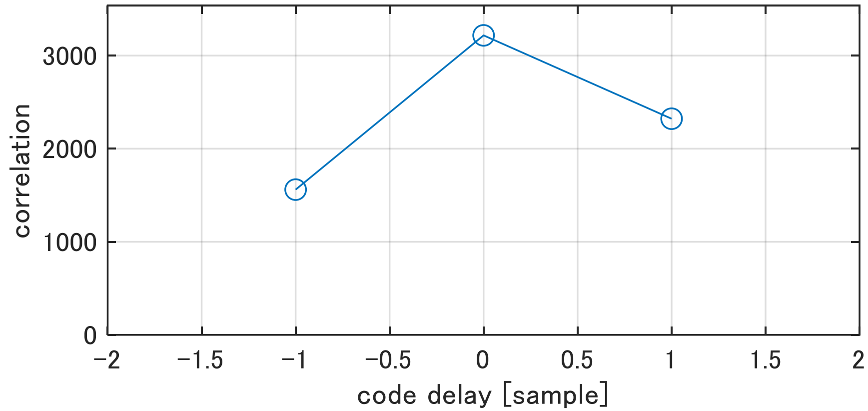


E-P-L Correlator (2)



Exercise 1: E-P-L Correlator

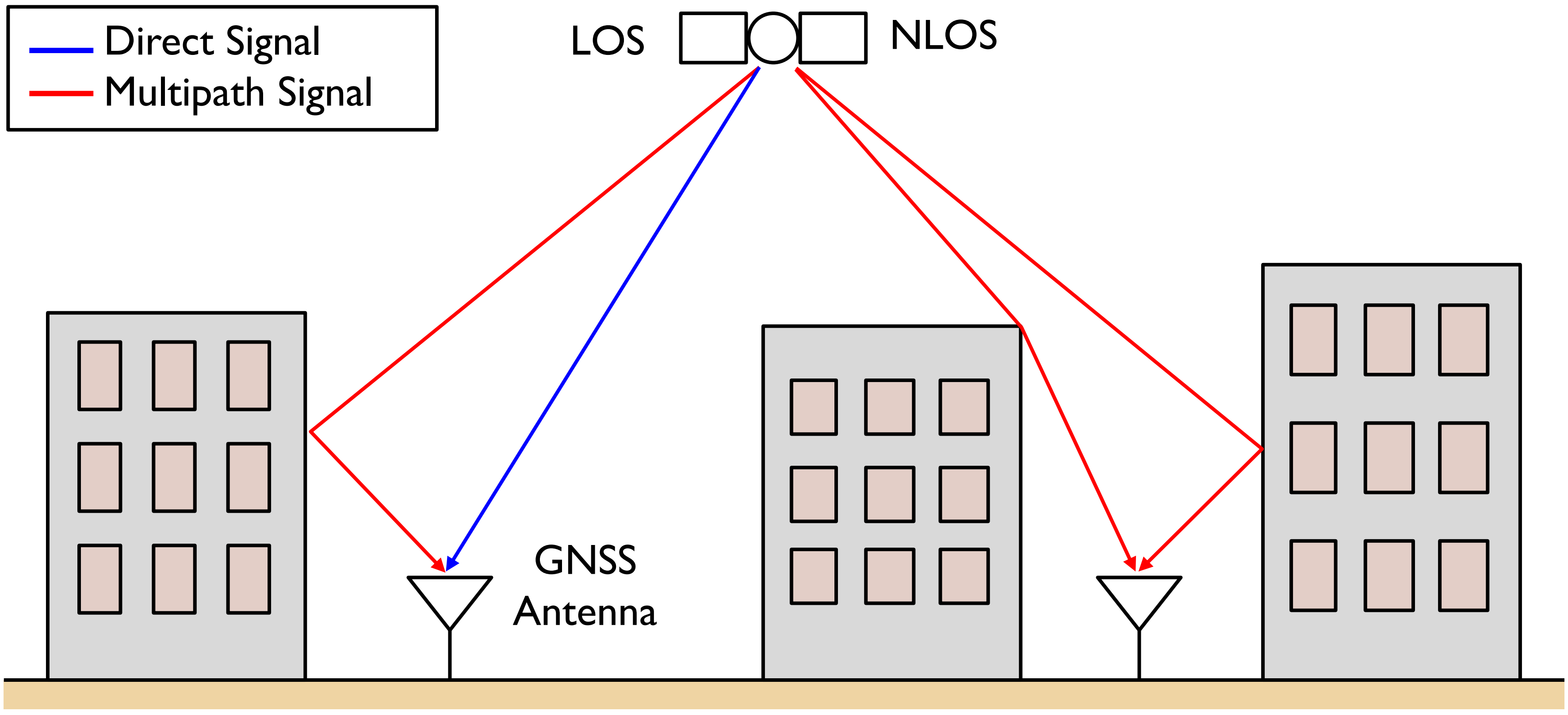
- MATLAB
  - /08_Signal_Tracking/matlab/Ex1_run_EPL_correlation.m
  - Using code phase and Doppler frequency estimated by signal acquisition



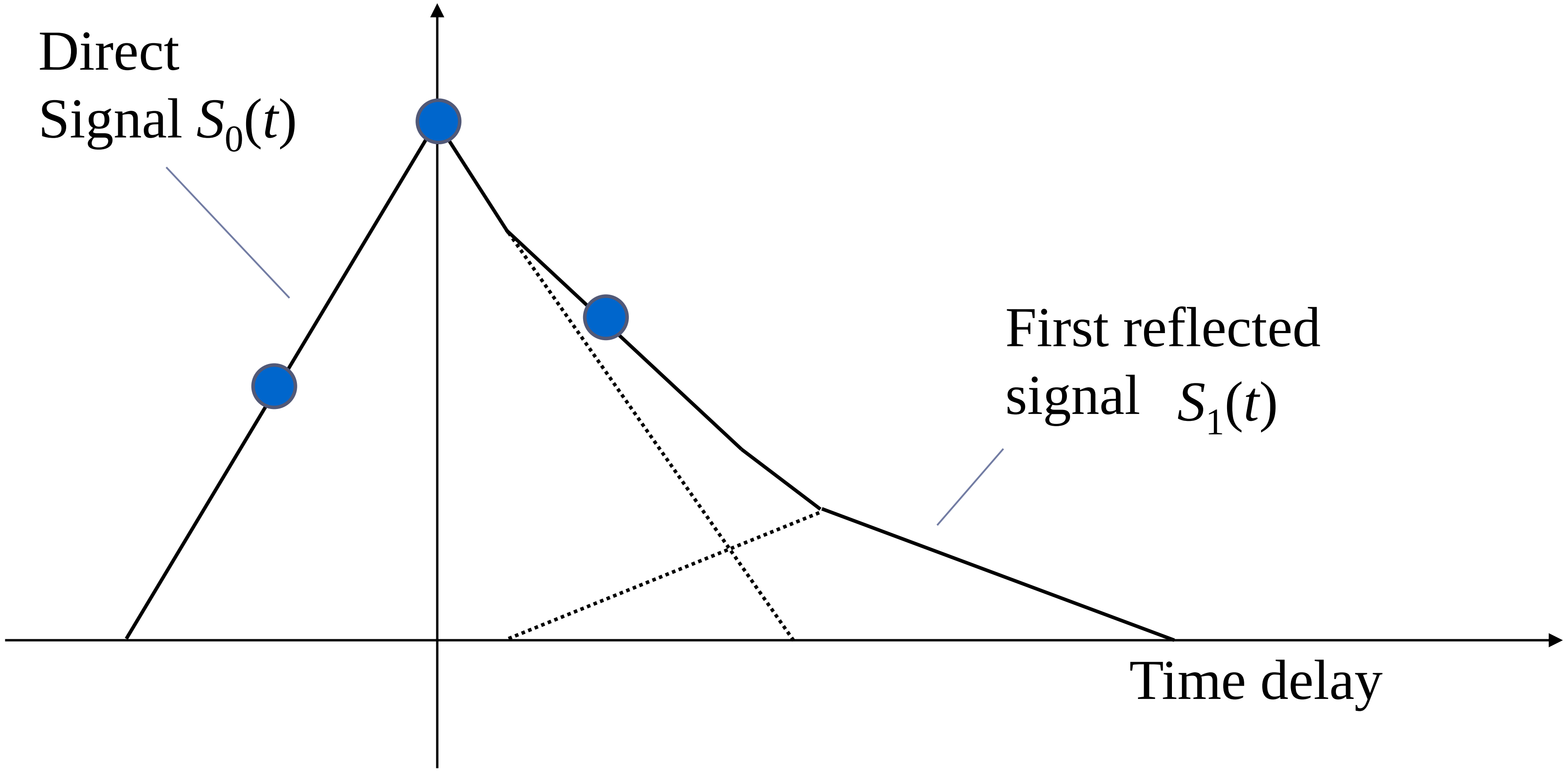
- Advanced challenge:
  - Try for different satellites
  - Add very-early and very late correlators

Effect of Multipath on Correlation (1)

- LOS and NLOS multipath

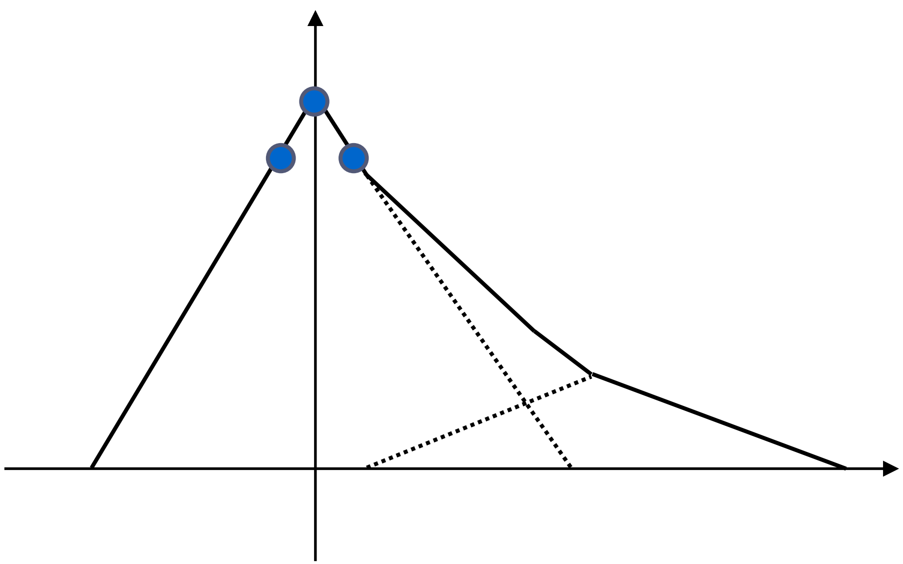


Effect of Multipath on Correlation (2)



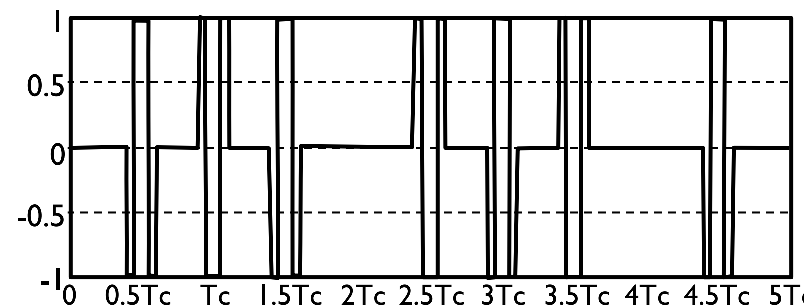
Correlator Type

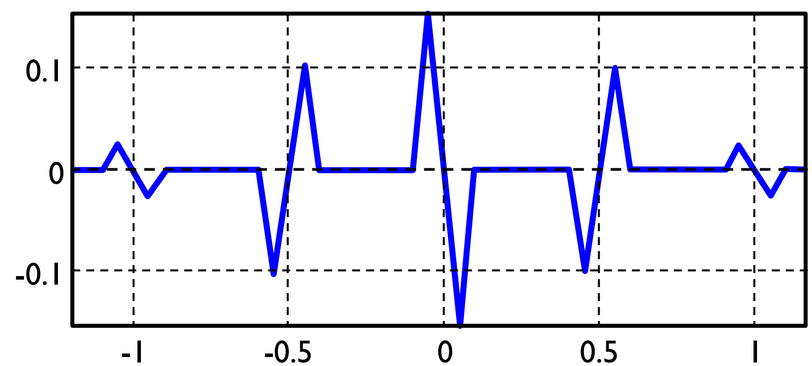
- Narrow correlator



- Narrow the width of the Early and Late correlation points
- Requires wide bandwidth

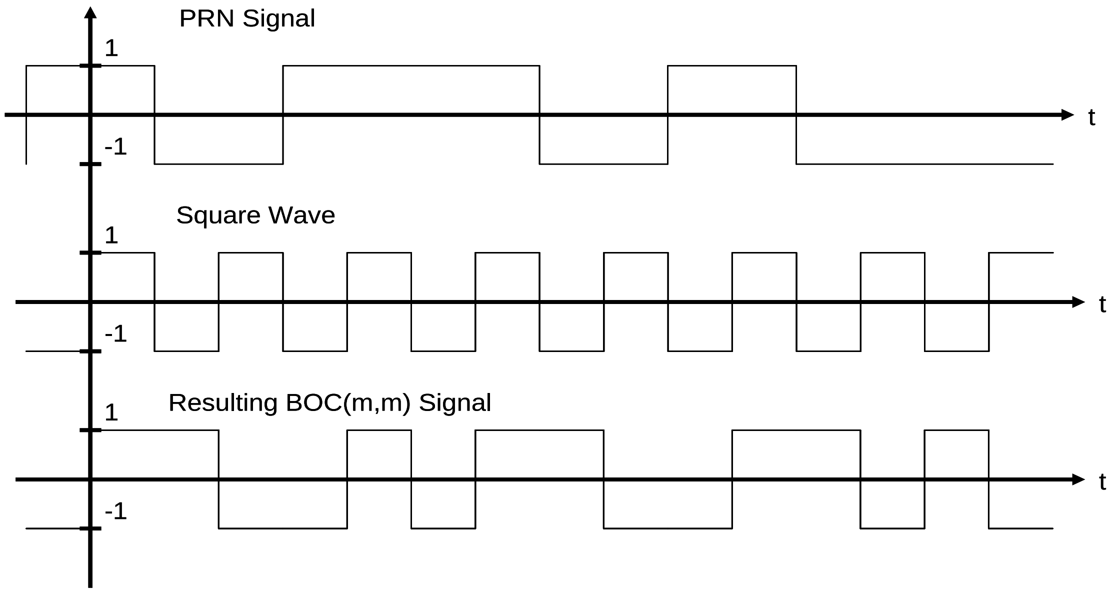
- Double-delta correlator
  - strobe correlator

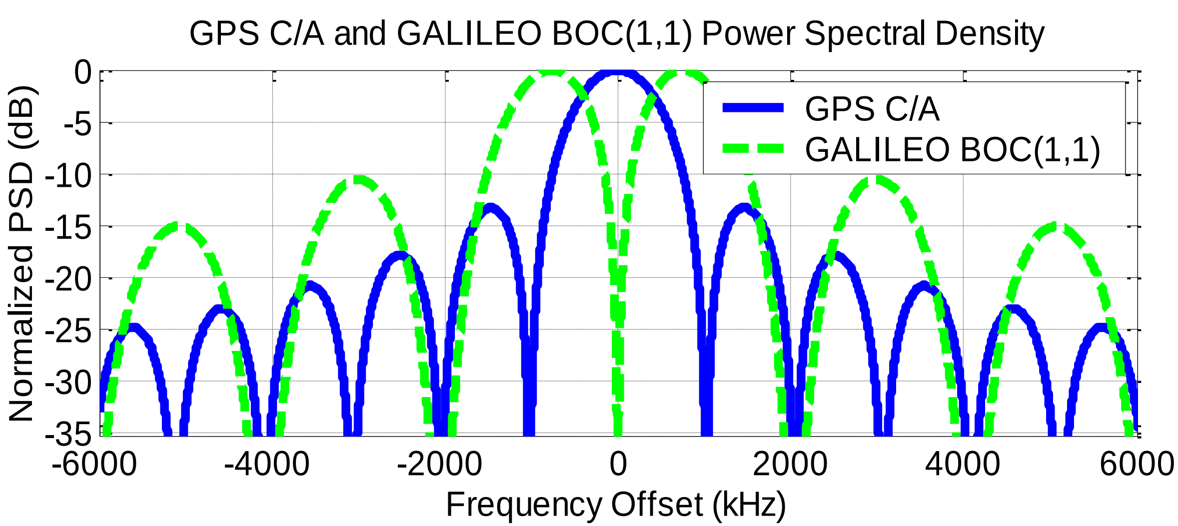




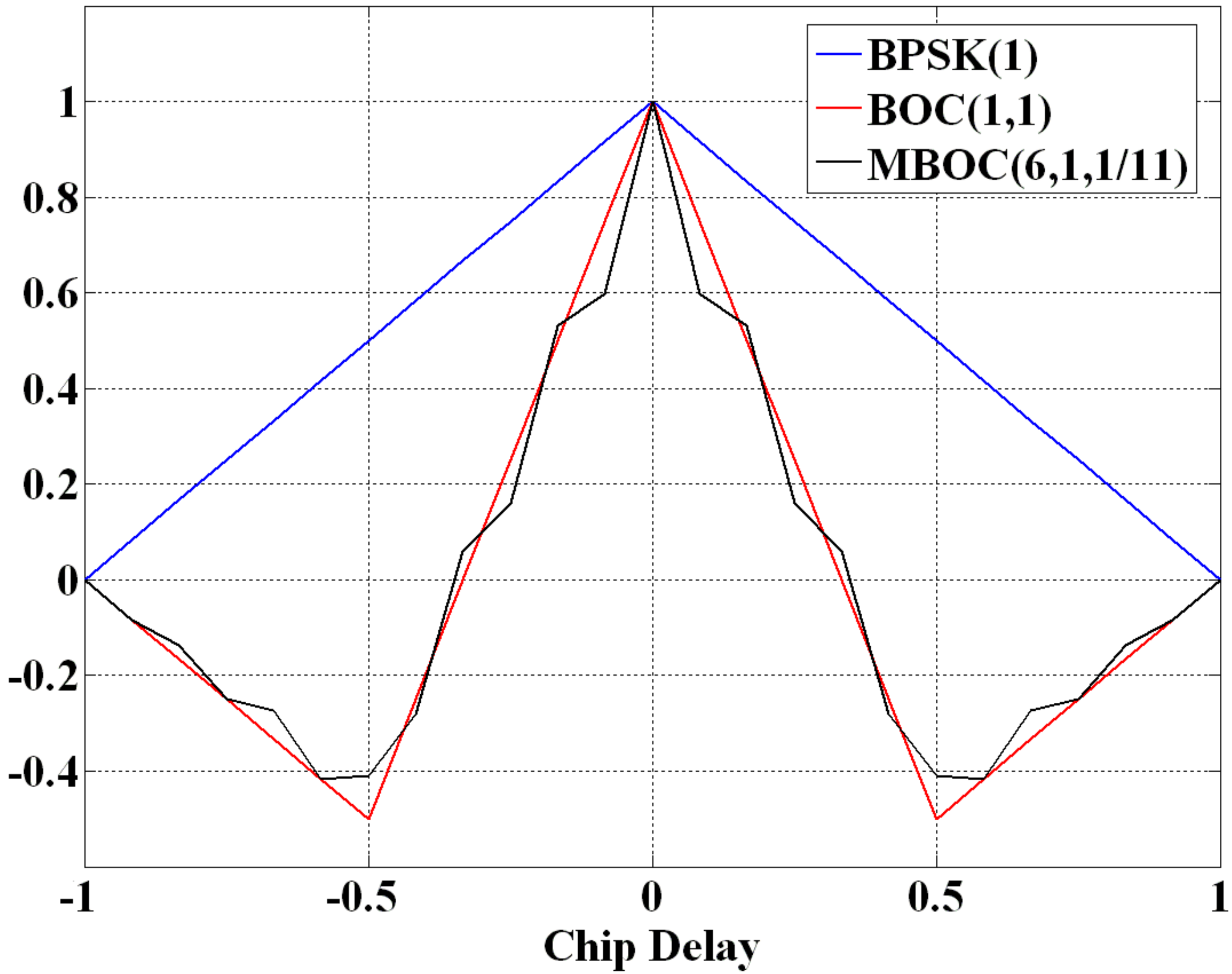
- Correlate only at the edges of the replica code

BPSK vs. BOC (1)


PRN Signal
1
-1
t
Square Wave
1
-1
t
Resulting BOC(m,m) Signal
1
-1
t


GPS C/A and GALILEO BOC(1,1) Power Spectral Density
Normalized PSD (dB)
0
-5
-10
-15
-20
-25
-30
-35
-6000
-4000
-2000
0
2000
4000
6000
Frequency Offset (kHz)
GPS C/A
GALILEO BOC(1,1)

BPSK vs. BOC (2)

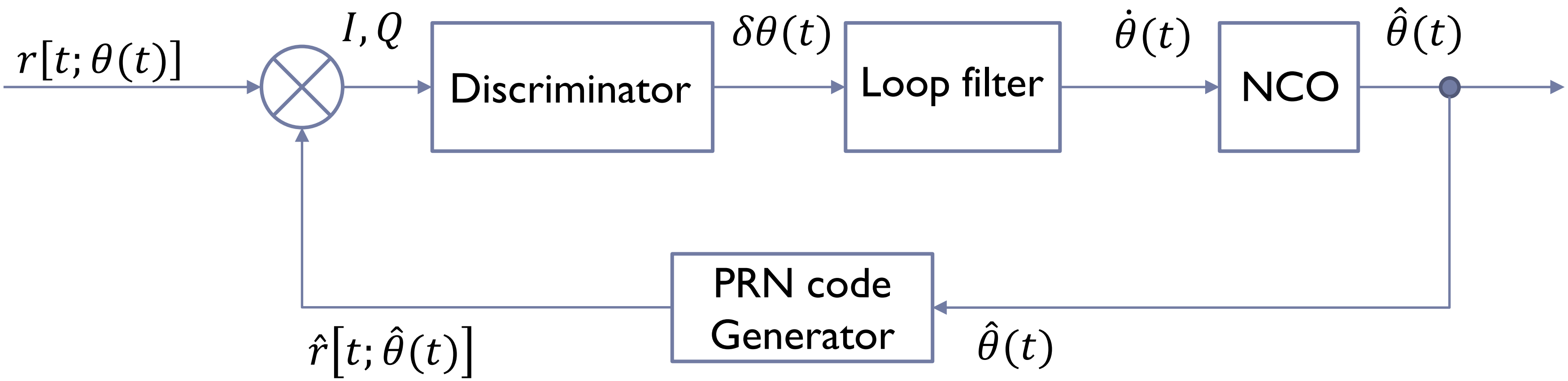


DLL vs. PLL vs. FLL

- **Delay Lock Loop**
  - **Purpose**: Compute pseudorange for user position calculation
  - **Operation**: Generates a replica of the PRN code transmitted by the satellite and maintains synchronization with the received code
- **Phase Lock Loop**
  - **Purpose**: Demodulation of navigation data
  - Measurement of pseudorange change rate for user speed calculation
  - Calculation of carrier phase for RTK, etc.
  - **Operation**: Adjusts the frequency and phase of the replica sine wave to synchronize with the phase of the input carrier wave
- **Frequency Lock Loop**
  - **Purpose**: Frequency trapping between signal acquisition and PLL start
  - Rough tracking in poor reception conditions
  - **Operation**: The frequency difference between the replica signal and the received signal is detected by the discriminator, and the replica signal oscillator is controlled to set the frequency difference to zero

Delay Lock Loop (1)

Time domain



$r[t;\theta(t)]$: received code

$\hat{r}[t;\hat{\theta}(t)]$: local code

$\delta\theta(t)$: code phase error

$\dot{\theta}(t)$: code phase rate

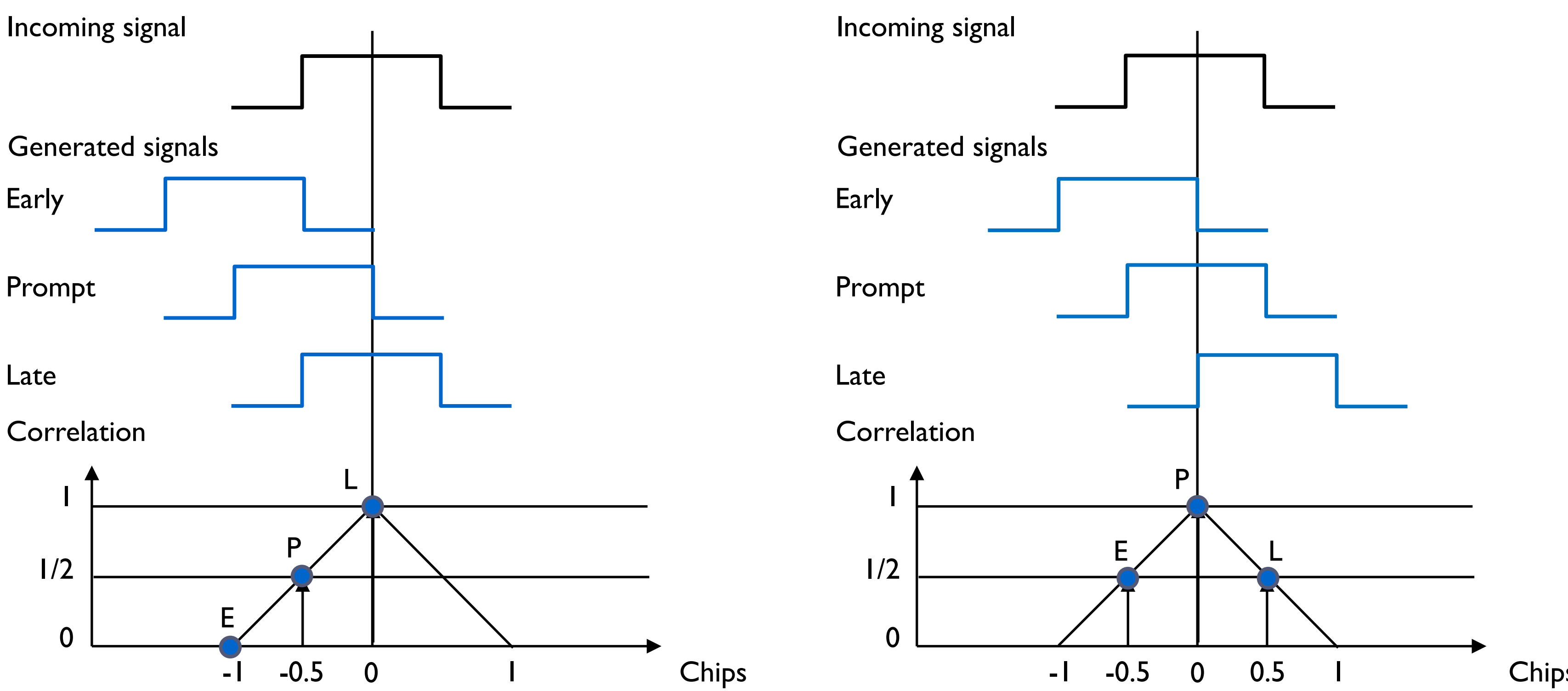
$\hat{\theta}(t)$: estimated code phase

Delay Lock Loop (2)

- Error discriminator

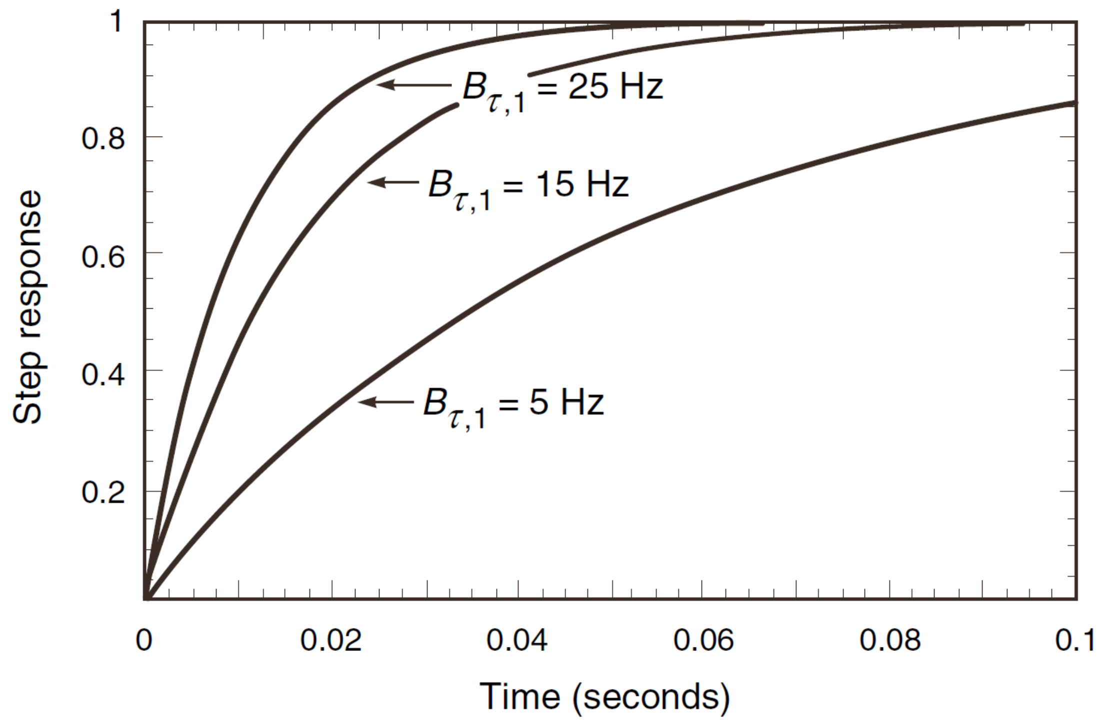
$$\frac{1}{2}\frac{(E-L)}{E+L}$$

- $E = \sqrt{I_E^2 + Q_E^2}$ is the Early correlation power.
- $L = \sqrt{I_L^2 + Q_L^2}$ is the Late correlation power.



Delay Lock Loop (3)

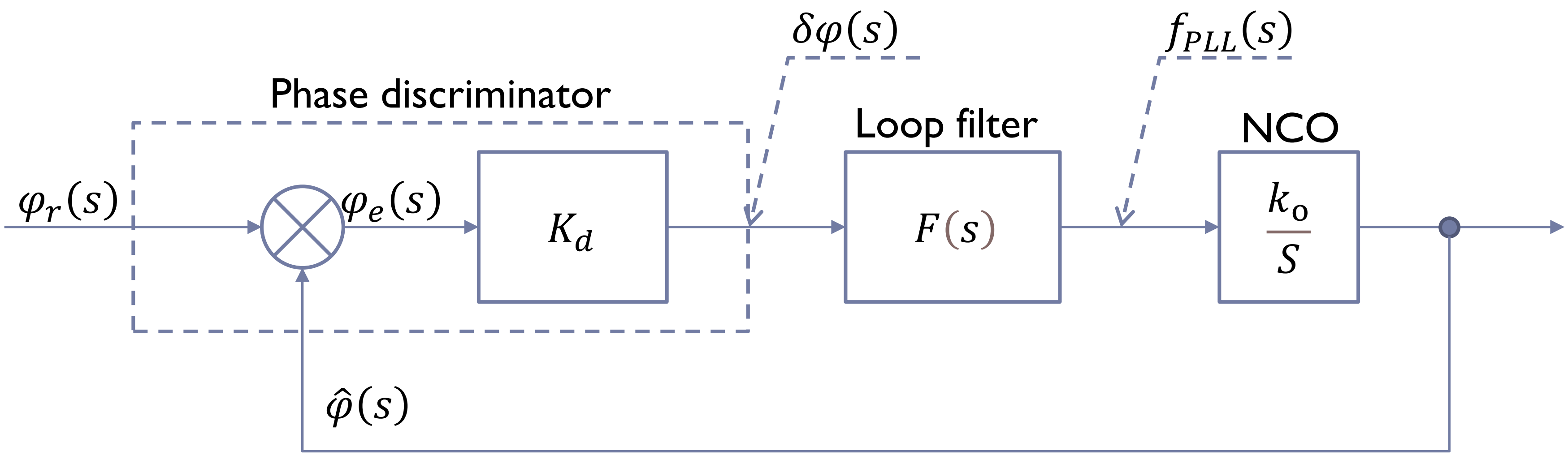
- Typically modeled as first order system



- Large loop bandwidth tracks target value quickly
- Smaller loop bandwidth reduces noise

Phase Lock Loop (1)

Frequency domain



$\varphi_r(s)$: received carrier phase
$\hat{\varphi}(s)$: local carrier phase
$\varphi_e(s)$: phase error

$\delta\varphi(s)$: magnified phase error
$f_{PLL}(s)$: frequency tracked by PLL
K_d, K_o : the gain of PD and NCO

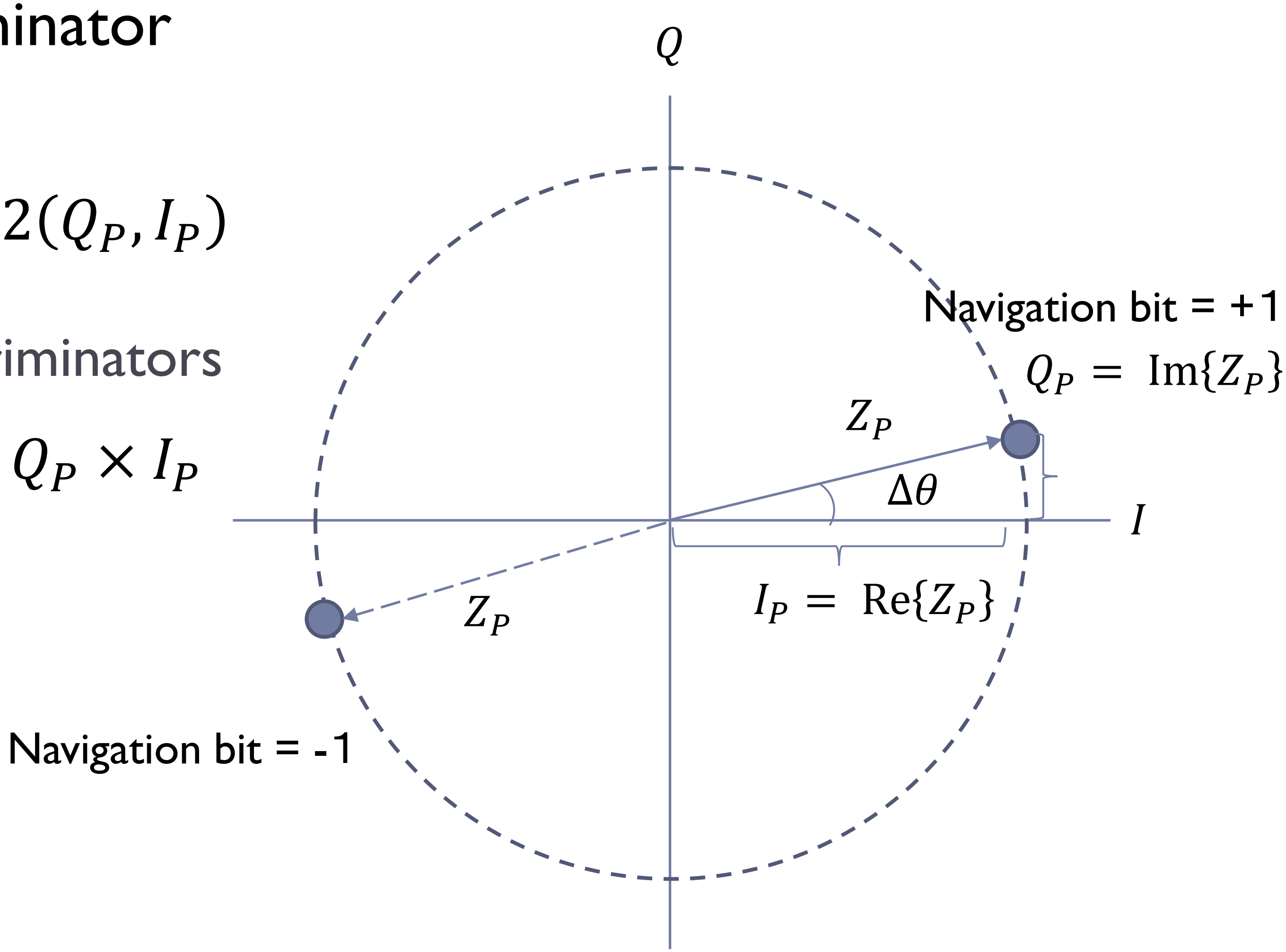
Phase Lock Loop (2)

- Error discriminator
  - Coherent

$$\Phi_e = ATAN2(Q_P, I_P)$$

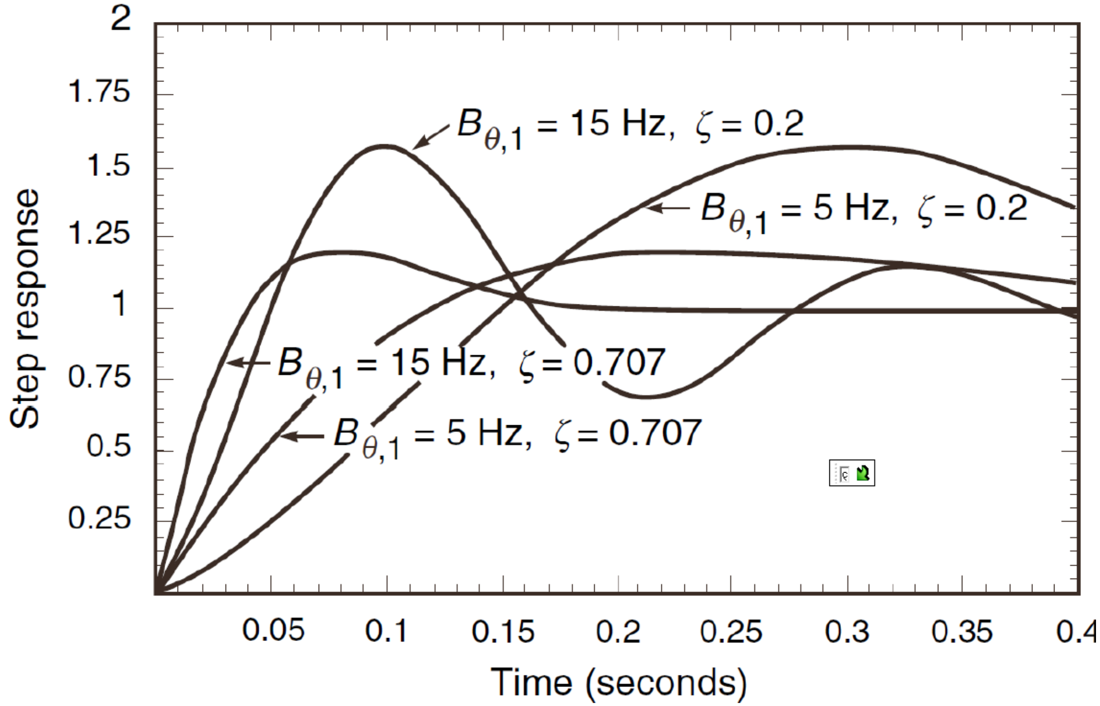
  - Costas discriminators

$$\sin(2\Phi_e) = Q_P \times I_P$$



Phase Lock Loop (3)

- Typically modeled as second order system



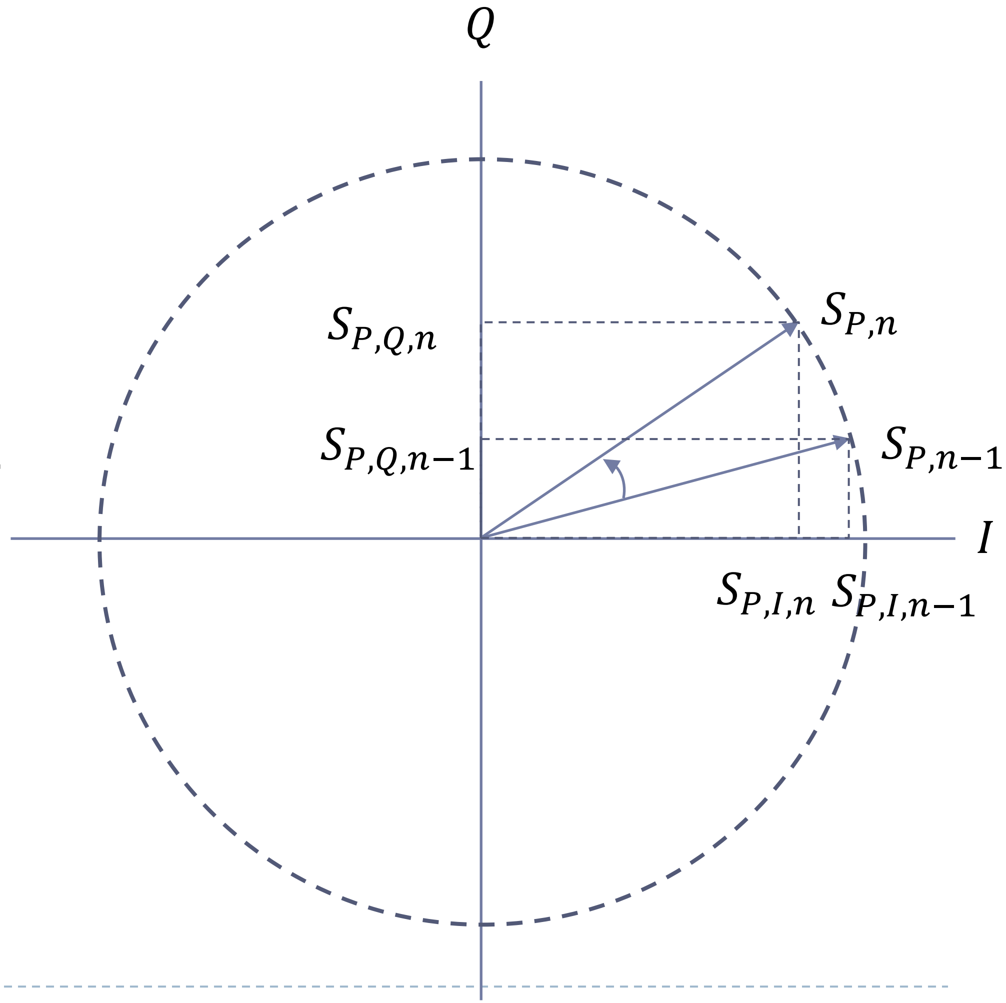
- Large loop bandwidth tracks target value quickly
- Smaller loop bandwidth reduces noise

Frequency Lock Loop

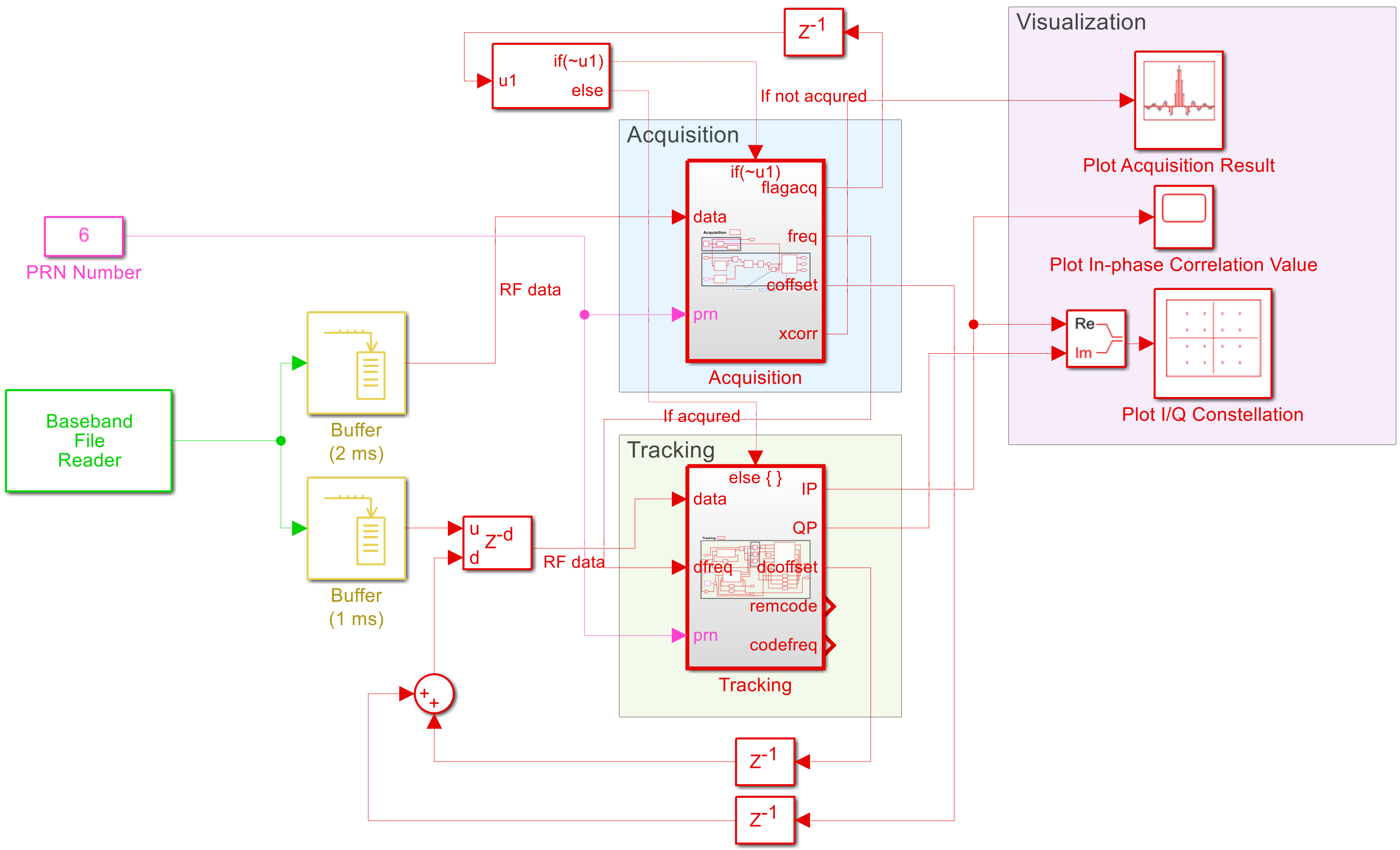
- If the frequency is shifted, the correlation value vector is rotated
- Error discriminator

$S_{P,I,n-1}\, S_{P,Q,n} - S_{P,I,n}\, S_{P,Q,n-1}$

Approximate frequency shift = angular velocity as an outer product

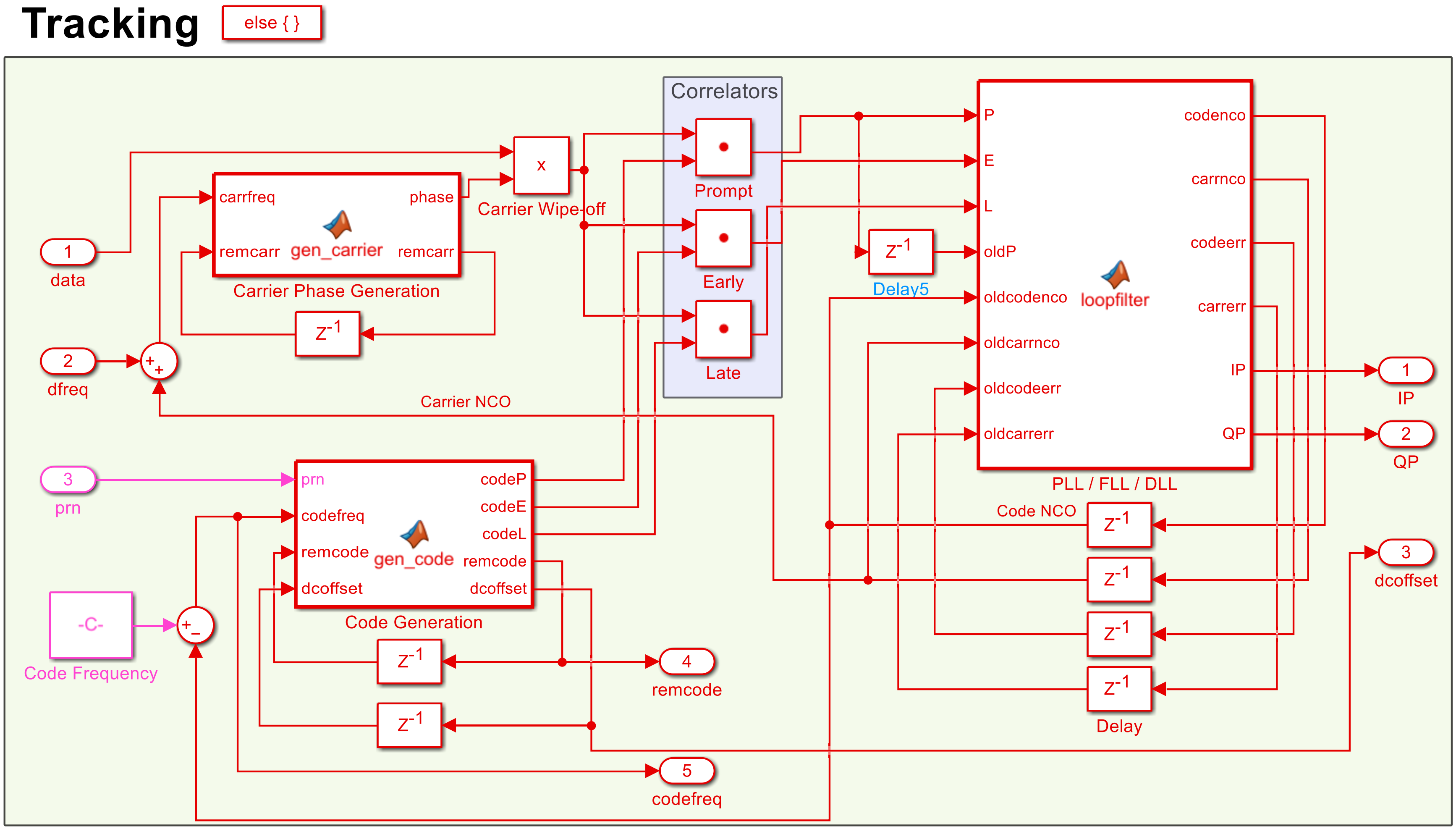


Simulink Implementation (1)



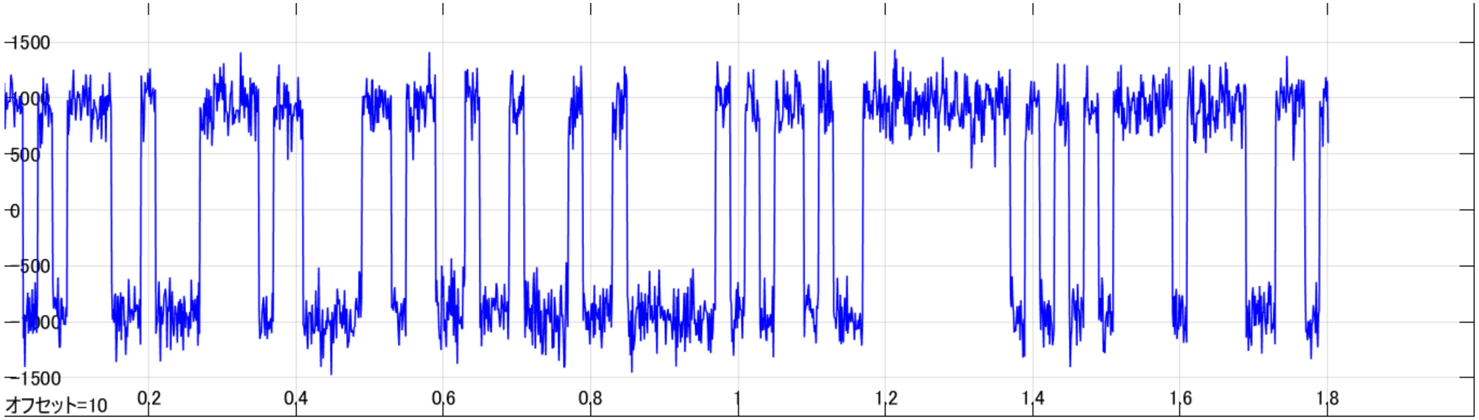
Simulink Implementation (2)

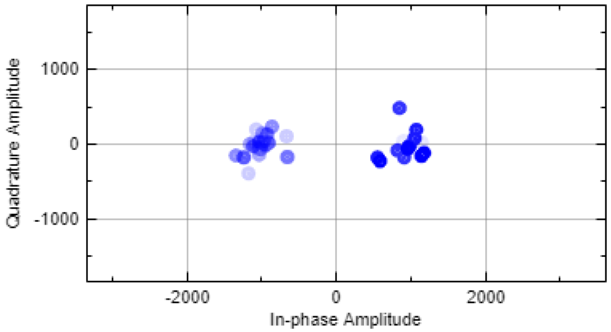
Tracking



Exercise 2-1: Signal Tracking

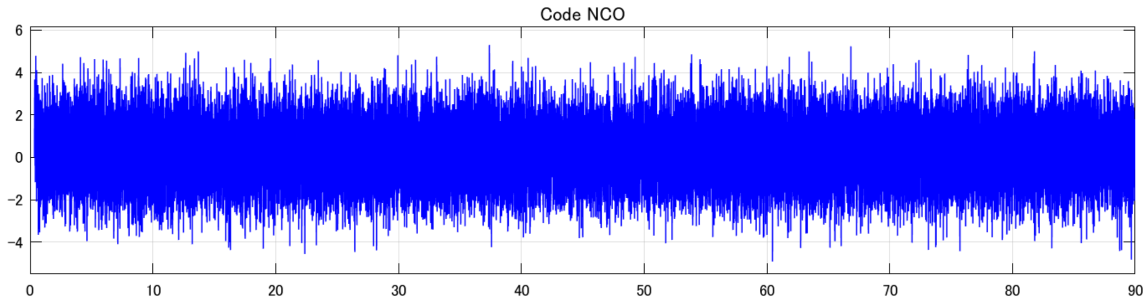
- Simulink
  - /08_Signal_Tracking/simulink/Ex2/tracking_1ch.slx

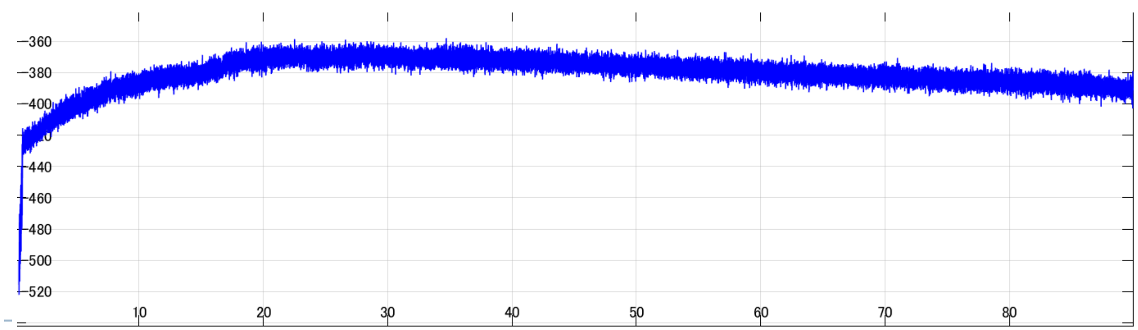


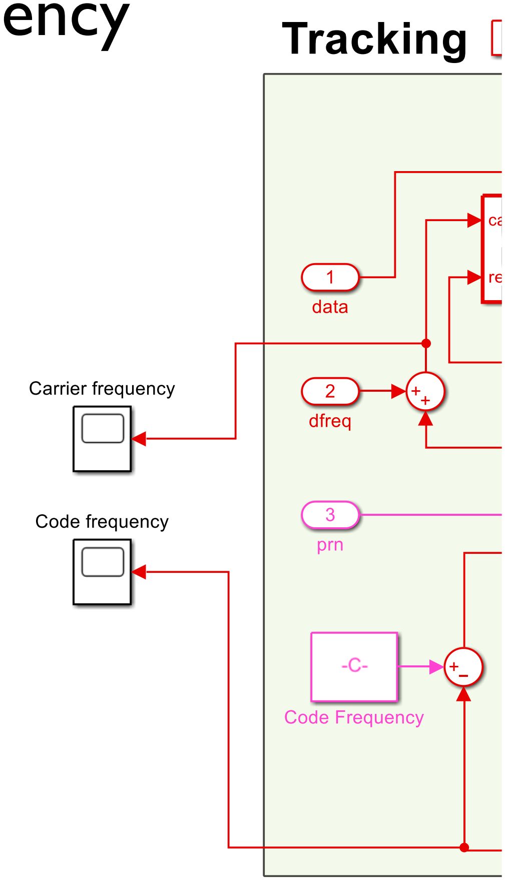


Exercise 2-2: Signal Tracking

- Simulink
  - /08_Signal_Tracking/simulink/Ex2/tracking_1ch.slx
- Plot tracked code frequency/carrier frequency
  - Using Scope







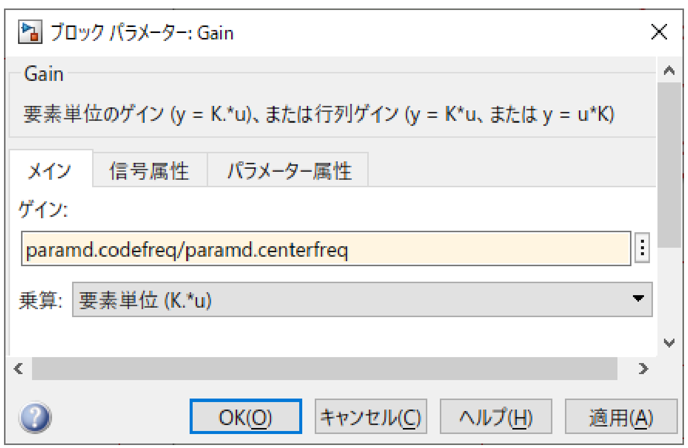
Exercise 2-3: Signal Tracking

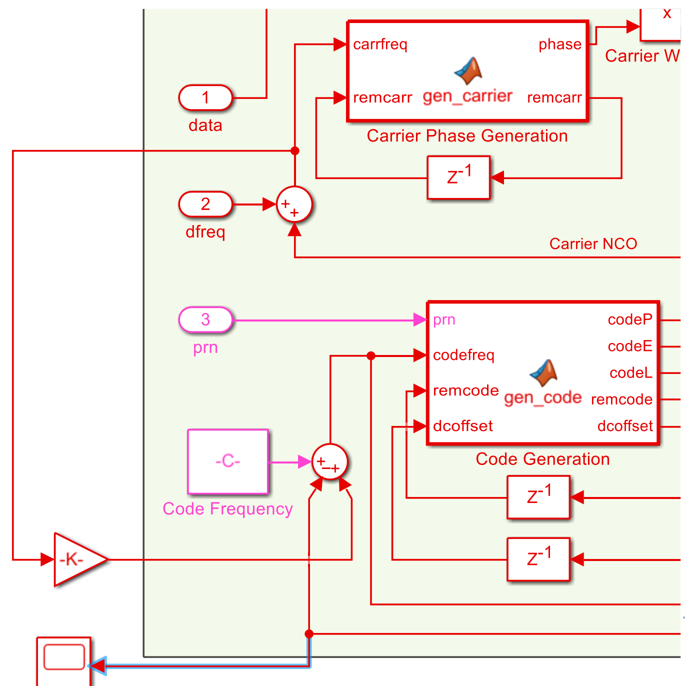
- Simulink
  - /08_Signal_Tracking/simulink/Ex2/tracking_1ch.slx
- Change DLL/PLL bandwidth
  - Check signal tracking results

```
%% Tracking

% ccorrelation space
paramd.corrspace = 1; % sample

% DLL noise bandwidth [Hz]
paramd.trk.dllB = 2;

% PLL noise bandwidth [Hz]
paramd.trk.pllB = 30;

% FLL noise bandwidth [Hz]
paramd.trk.fllB = 250;

paramd.trk.dllw2 = (paramd.trk.dllB/0.53)^2; % factor of DLL
paramd.trk.dllaw = 1.414*(paramd.trk.dllB/0.53); % factor of DLL
paramd.trk.pllw2 = (paramd.trk.pllB/0.53)^2; % factor of PLL
paramd.trk.pllaw = 1.414*(paramd.trk.pllB/0.53); % factor of PLL
paramd.trk.fllw = paramd.trk.fllB/0.25; % factor of FLL

```

Exercise 2-4 : Signal Tracking

- PLL aided DLL
  - The estimated frequency change of PLL is sufficiently accurate
  - DLL measurements are intended to remove long-time bias in the estimated frequency of the carrier tracking loop
  - The PLL assist reduces the noise bandwidth sufficiently to reduce noise





Exercise 3: Real-time Signal Tracking

- Simulink
  - /08_Signal_Tracking/simulink/Ex3/tracking_1ch_realtime.slx
- Real-time Signal Tracking
  - Connect RTL-SDR
    - Turn of Bias-T
  - Use of RTL-SDR Receiver