Modeling and Validation of Automotive RADAR MMIC Impairments by using the Standardized Interfaces for Closed-Loop Simulation

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MMIC: Monolithic Microwave Integrated Circuit

Overview

01 Introduction

02 Physical RADAR Sensor Model

03 Modeling of MMIC Impairments

04 Conclusion and Outlook

Automotive Sensors

- Advanced driver assistance systems (ADAS) sensors and example applications

Adaptive Cruise Control

https://www.bosch-mobility-solutions.com/

Camera

https://www.kostal-automobil-elektrik.com/

LiDAR

https://www.blickfeld.com/

Automated Emergency Braking

https://www.openpr.com/

Ultrasonic Sensors

https://www.bosch-mobility-solutions.com/

RADAR

https://www.everythingrf.com/News/details

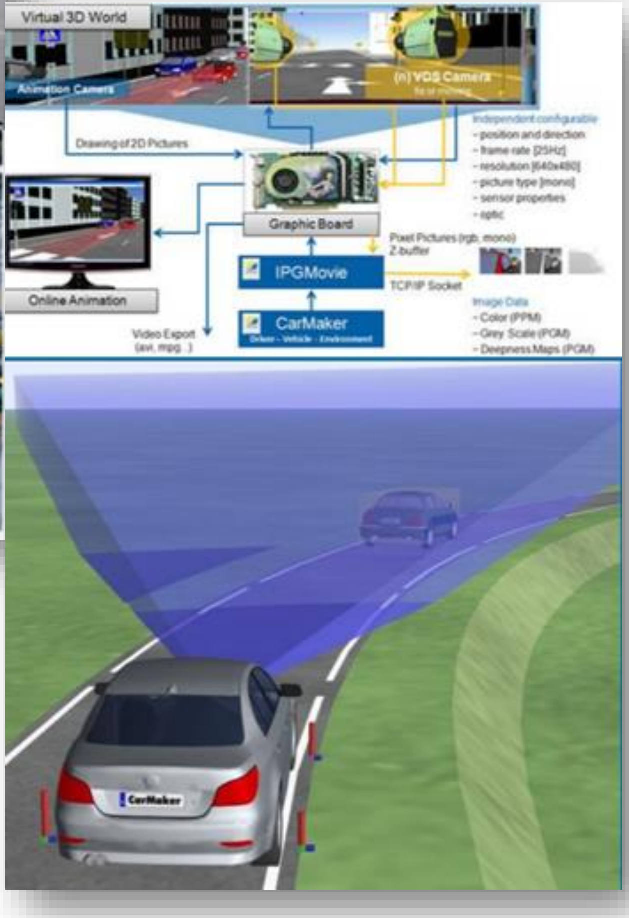
Problem Statement

- Validation of these systems is done with real test drives which are expensive, time consuming, safety critical

- ADAS Safety functions require a proof distance of about 240 million km*

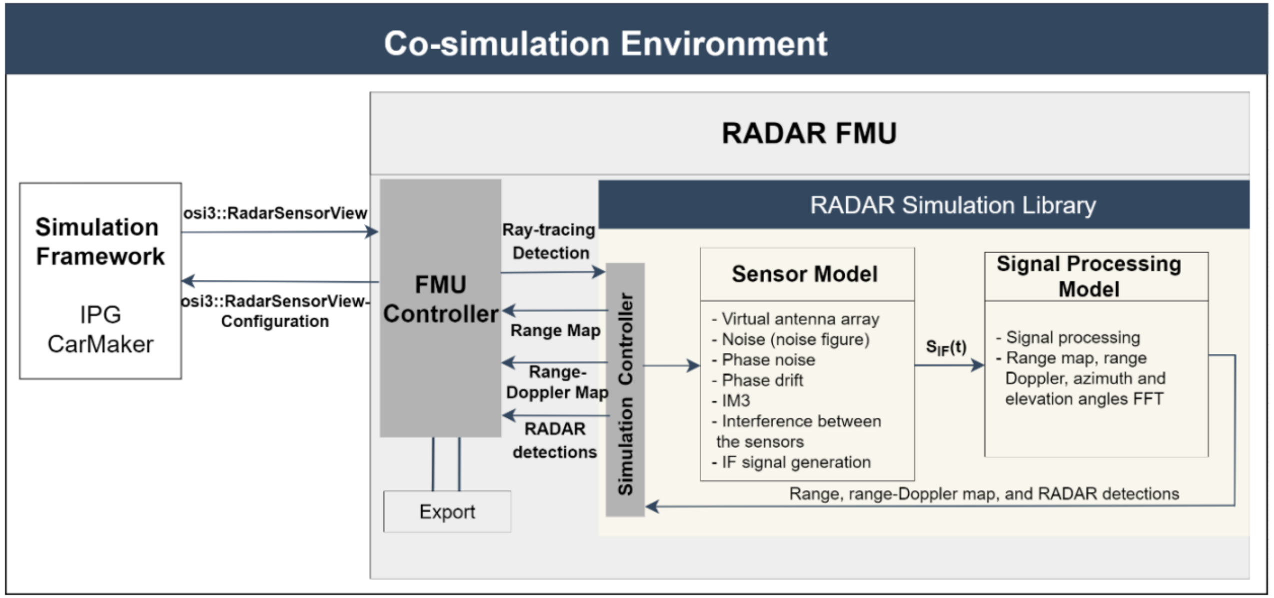
- Methods for ADAS Validation
  - Prototypes and road trials
  - Model-in-the-Loop Testing (driving simulator)
  - Hardware-in-the-Loop Testing (senor test benches)
  - **Combination of simulation & real-world test: hybrid strategy**

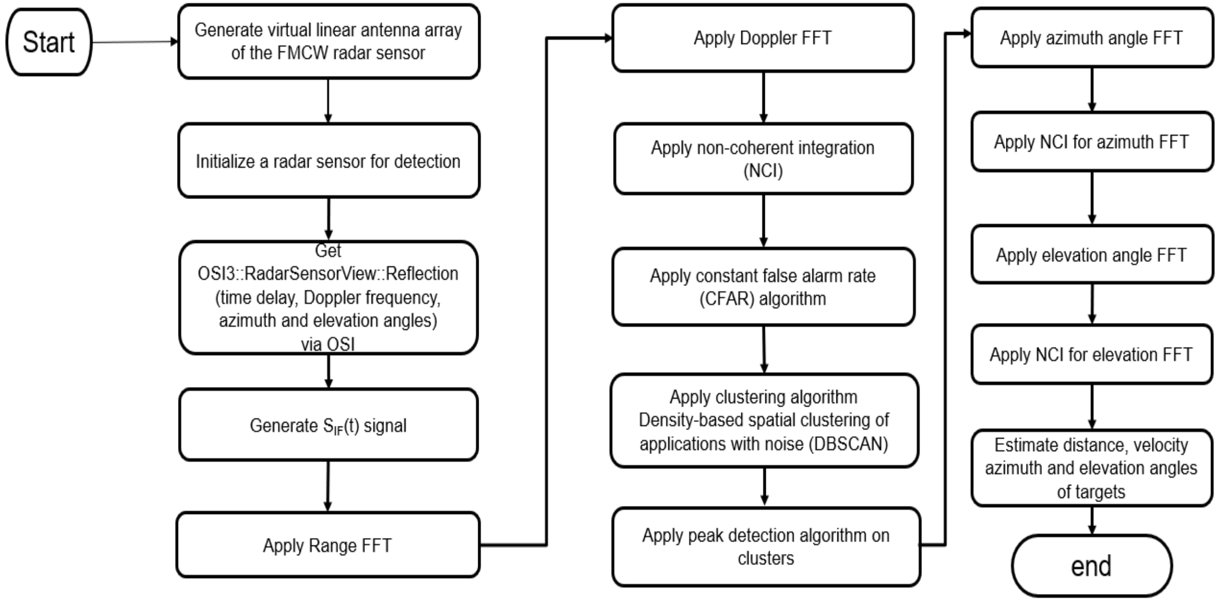
- **Required:** Development and validation of physical ADAS sensor models



Sources:
- *MAGNA Steyr, IPG, Toyota, FTG*
- **Handbook of Driver Assistance Systems, Editors: Winner, H., Hakuli, S., Lotz, F., Singer, C.*

RADAR FMU Model Block Diagram

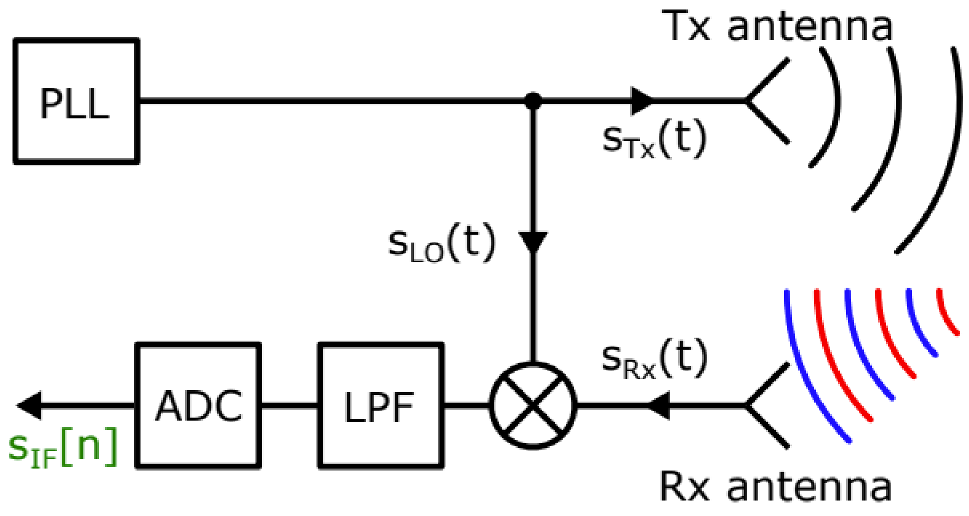




- “Radar_FMU“ model is developed that retrieved the raytracing data via OSI
- The input of the “Radar_FMU“ model is OSI3::SensorView->OSI::RadarSensorView::Reflection
- “Radar_FMU“ also output distance, velocity, azimuth and elevation angle for each reflection/target
- Implemneted RADAR MMIC impairments: Phase noise, **third order intermodulation**

IF: intermediate frequency

Phase Noise



- Phase Noise (PN) are random fluctuations in the phase of a signal due to non-idealities of the oscillators and phase-locked loop (PLL)
- **PN limits received SNR:** Weak object signal is buried under the PN of an adjacent strong object; it also has a strong impact on the velocity domain
- Spur in PN generate the ghost objects

Simulate Decorrelated Phase Noise (DPN) in IF level

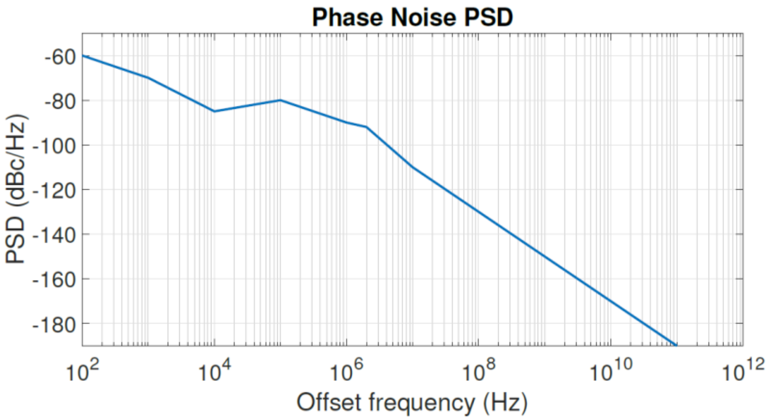
- Phase noise after mixer is referred as decorrelated phase noise (DPN)

Phase Noise Measurements (PSD)

Compute PSD of DPN

Generate samples of DPN Using its PSD

Add samples of DPN to the phase of IF signal



- **It is common to assume that PN is a zero-mean, wide-sense stationary (WSS) process and thus PN can be represented by its power spectral density (PSD)**

Mathematical Model for PN In IF Level

- Transmit signal can be written as $\boldsymbol{S_{Tx}(t) = A_{Tx}\,cos\left(2\pi f_0 t + \pi k t^2 + \varphi(t)\right)}$

  Where $\boldsymbol{k}$ is the slope of the chips calculated as $\boldsymbol{k} = \frac{\boldsymbol{B}}{\boldsymbol{T}}$ where B is the bandwidth of the transmit signal and $\varphi(t)$ is the Phase Noise (PN)

- The received signal $\boldsymbol{S_{Rx}(t) = A_{Tx}\,cos\left(2\pi f_0 (t - \tau) + \pi k (t - \tau)^2 + \varphi(t - \tau)\right)}$

  Where τ is round trip delay time (RTDT) of target

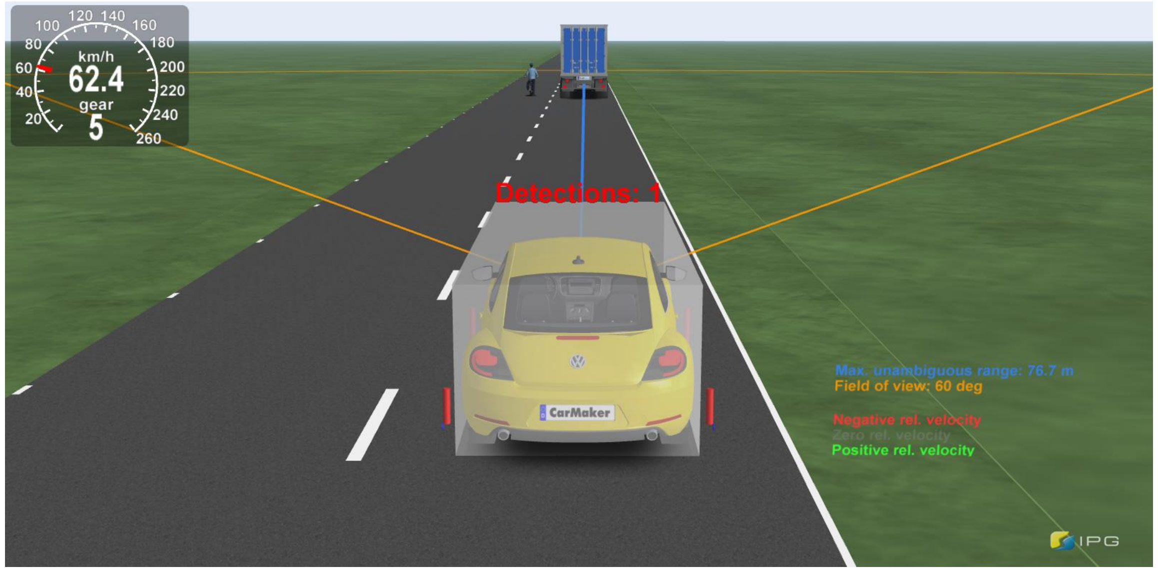
- IF signal $\boldsymbol{S_{IF}(t) = [S_{Tx}(t).S_{Rx}(t)] * h_{LPF}(t)}$

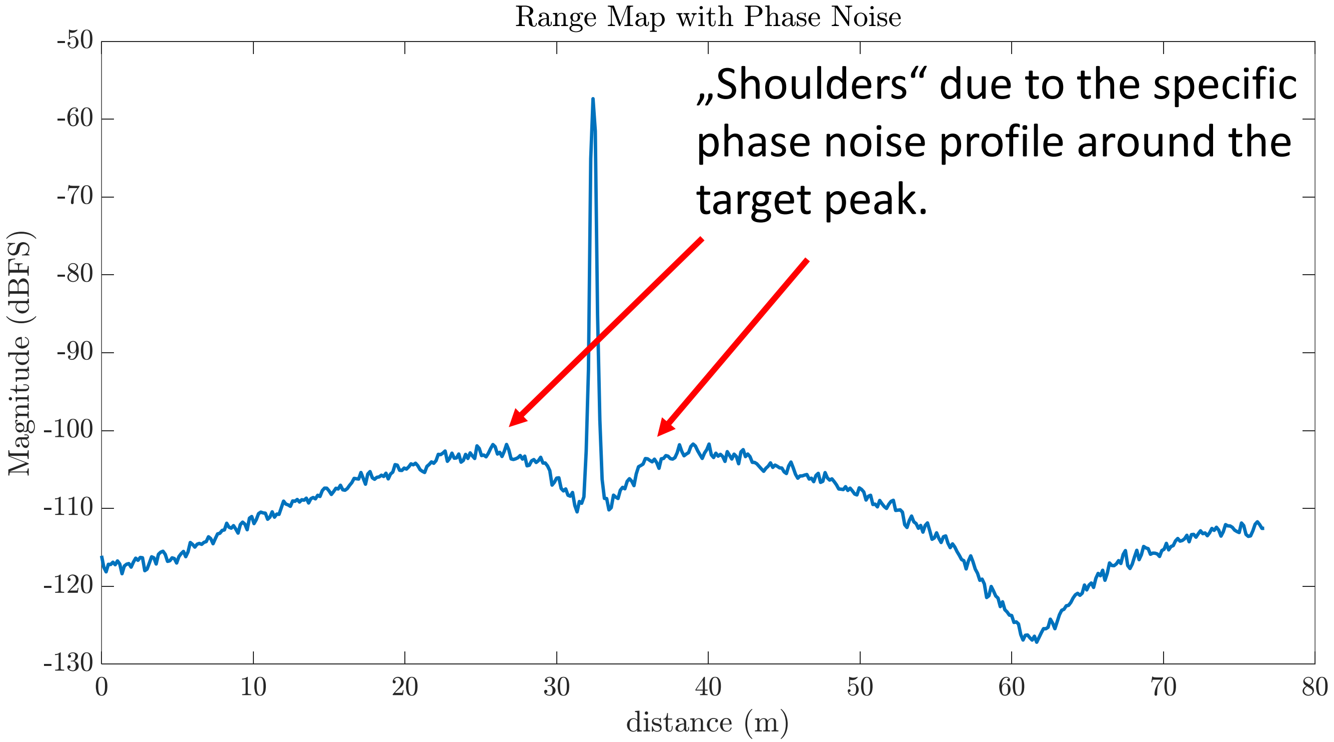
$$\boldsymbol{S_{IF}(t) = \left[\frac{A_{Tx}^2 \alpha}{2} cos\left(2\pi f_B t + \Phi + \Delta\varphi(t)\right)\right] * h_{LPF}(t)}$$

where $\boldsymbol{f_B = k\tau}$ is the IF beat frequency and $\Phi = 2\pi f_0 \tau - \pi k \tau^2$ is a constant phase term and $\Delta\varphi(t) = \varphi(t) - \varphi(t - \tau)$ is decorrelated phase noise (DPN)

Range Map With Phase Noise Profile

- $f_0 = 77\ \mathrm{GHz}$
- $B = 1\ \mathrm{GHz}$
- Max. range $= 74.94\ \mathrm{m}$
- $T_{\mathrm{sw}} = 40.96\ \mu\mathrm{s}$
- $f_s = 25\ \mathrm{MHz}$
- Static Target at 30 m distance
- Azimuth angle: 0 deg
- 32 virtual receive antennas
- RX antenna spacing: $\frac{\lambda}{2}$
- RCS = 70 dBm^2

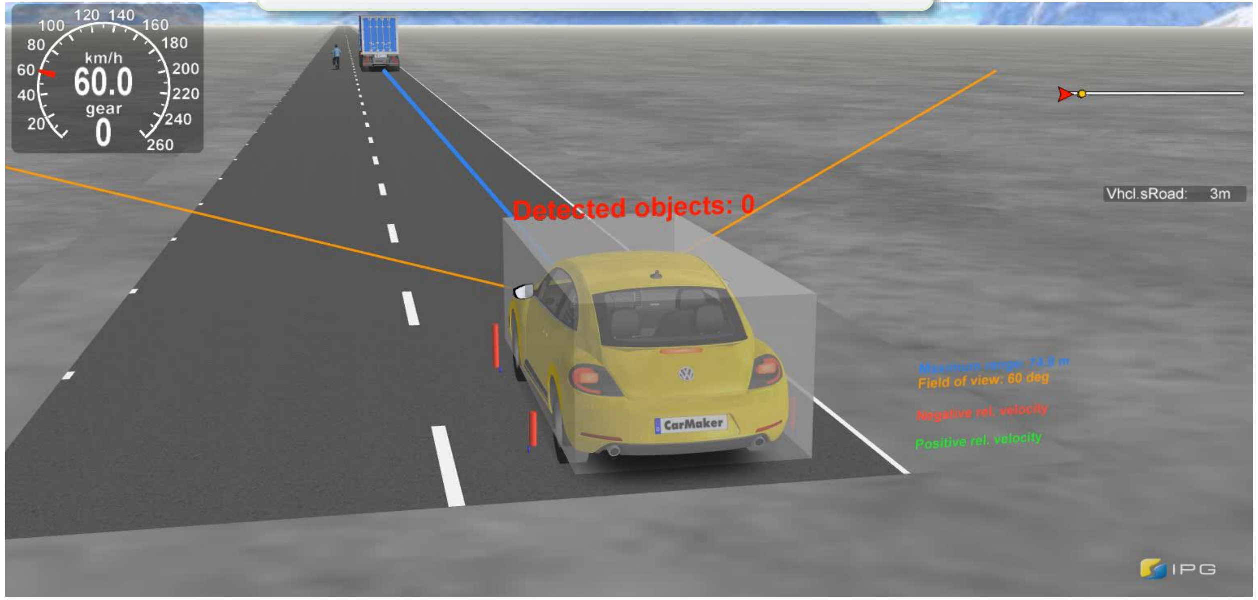




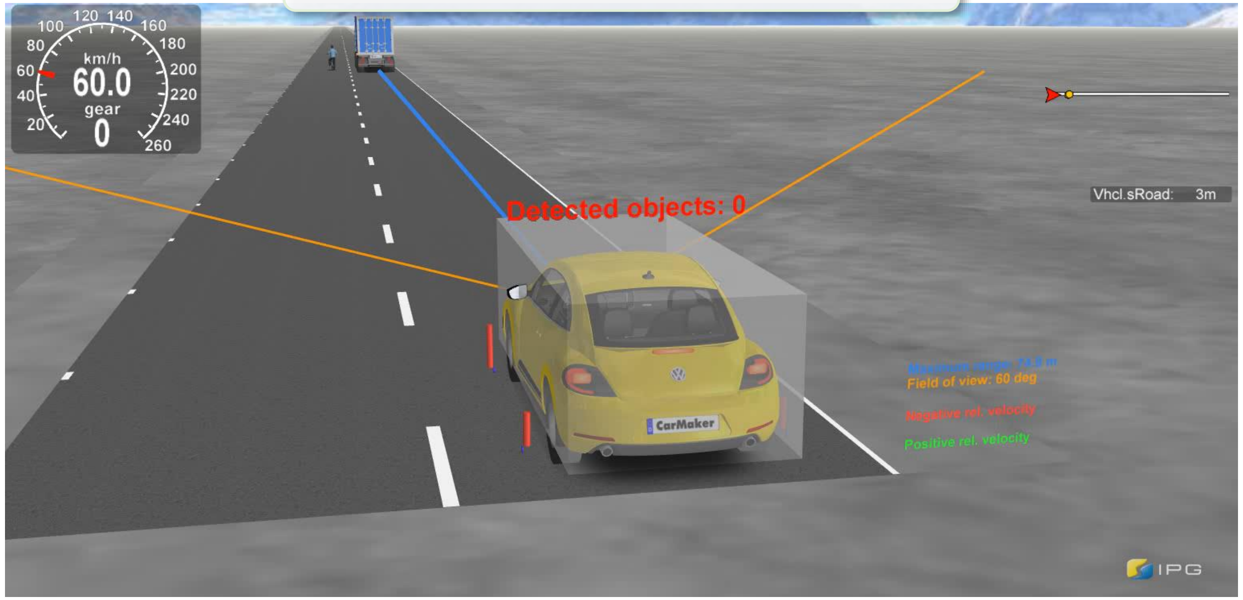
„Shoulders“ due to the specific phase noise profile around the target peak.

Phase Noise Visualisation in CarMaker

Simulation without phase noise



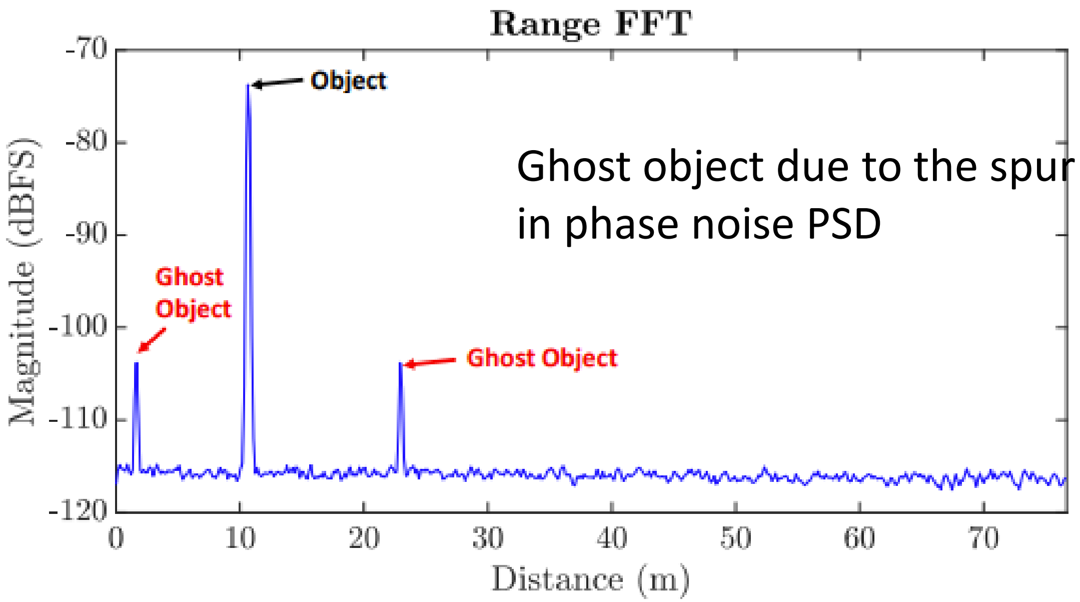
Simulation with phase noise



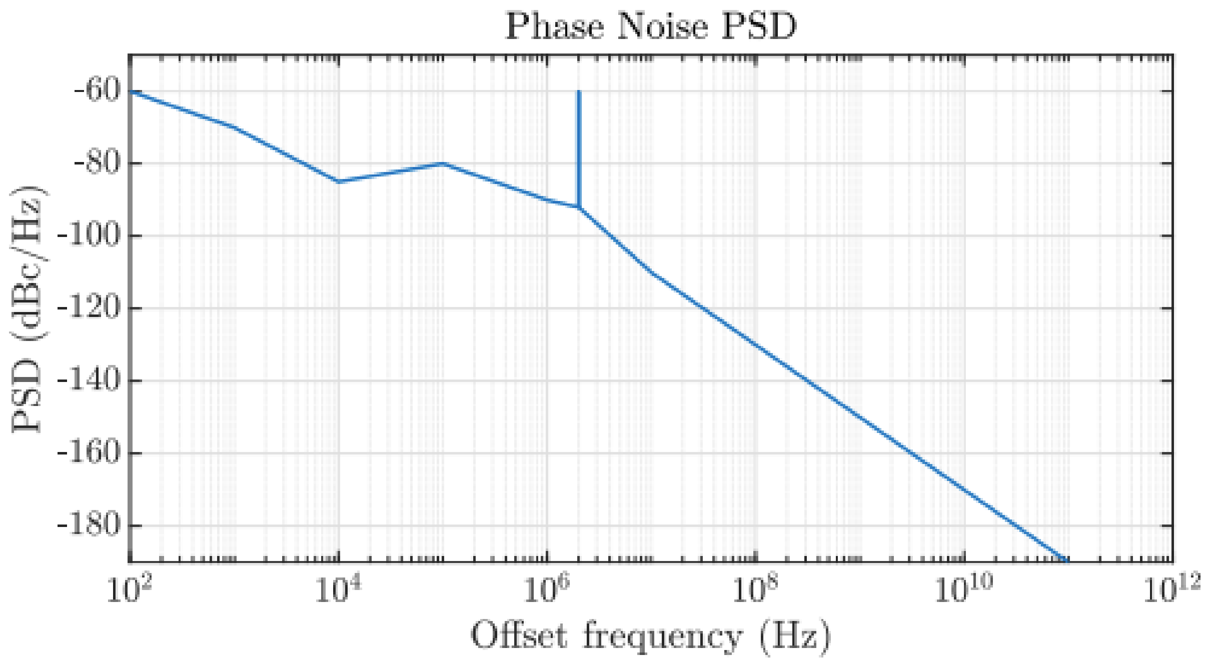
- Radar FMU simulation with thermal noise and without any other impairments
- Targets get detected as soon as they come into the field of view and the maximum detectable range
- RCS of truck: $70\ \mathrm{dBm}^2$, RCS of bicycle: $7\ \mathrm{dBm}^2$

- Same scenario, but with phase noise
- RCS of truck: $70\ \mathrm{dBm}^2$, RCS of bicycle: $7\ \mathrm{dBm}^2$
- Bicycle gets detected only at very close distance, at larger distances it gets masked by the truck.

Ghost Objects Due to Phase Noise



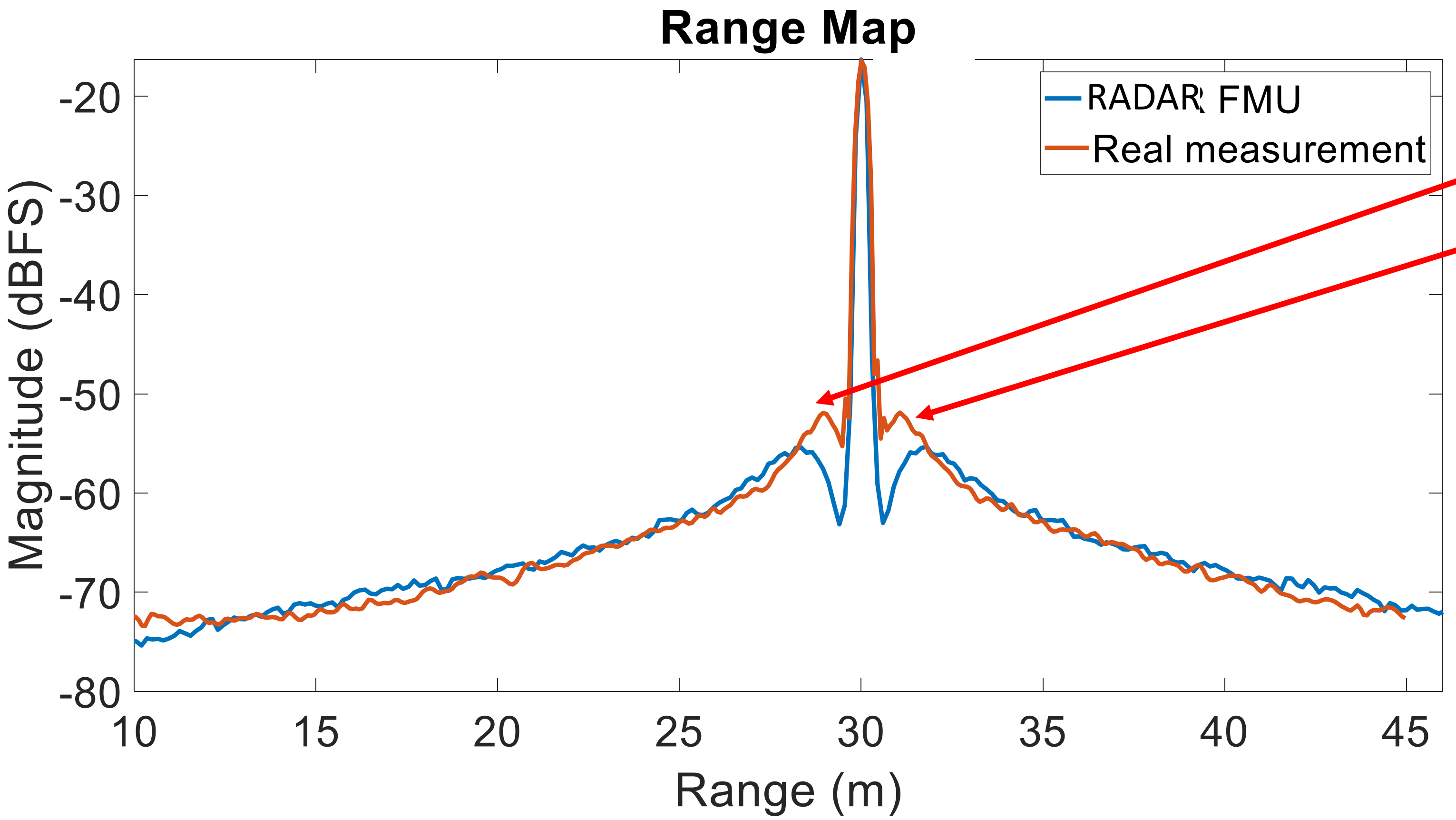
Ghost object due to the spur in phase noise PSD



- $f_{Ghost\ 1,2} = f_{spur} \pm f_B$

f_{spur} is the frequency of phase noise spur and f_B is the beat frequency of target

RADAR FMU Model: Validation of Phase Noise



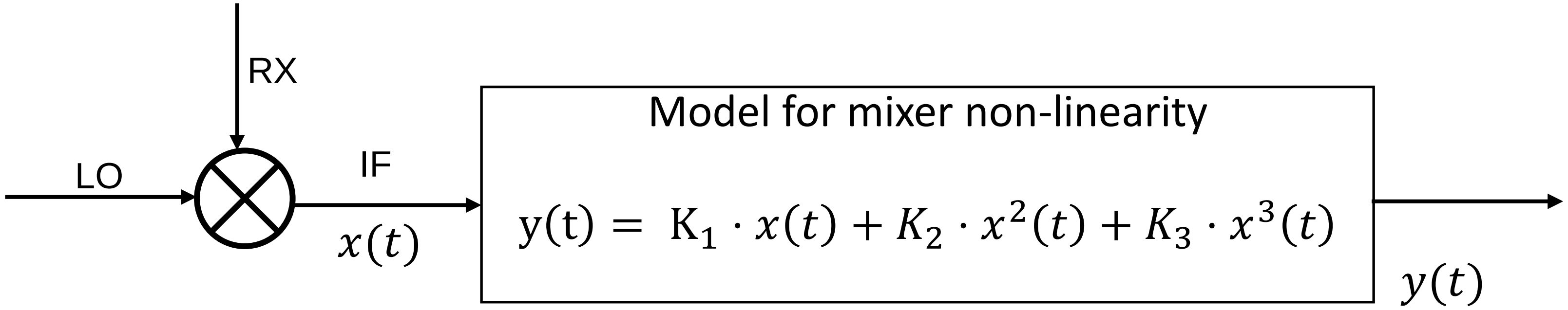
„Shoulders“ due to the specific phase noise profile around the target peak.

RCS = $\mathbf{70\ dBm^2}$

- Peak shape, noise level are matching well
- The difference in shoulder height appears because simulation and real measured phase noise profile are different

Mixer Non-Linearity: third-order intermodulation (IM3)

- Two-tone sinusoidal test signal with frequencies $\omega_{IF,1}$ and $\omega_{IF,2}$ is applied to the input of the non-ideal mixer will output (generally undesired) third-order intermodulation (IM3) components with frequencies $2\omega_{IF,1} \pm \omega_{IF,2}$ and $2\omega_{IF,2} \pm \omega_{IF,1}$



Model for mixer non-linearity

$$\mathrm{y(t)} = \mathrm{K}_1 \cdot x(t) + K_2 \cdot x^2(t) + K_3 \cdot x^3(t)$$

- K_1: mixer voltage gain
- Only the IM3 products $2\omega_{IF,1} - \omega_{IF,2}$ and $2\omega_{IF,2} - \omega_{IF,1}$ are modelled
- Local oscillator (LO) leakage is not modeled here

Mixer Non-Linearity: third-order intermodulation (IM3)

- Conversion of mixer power gain to linear coefficient:

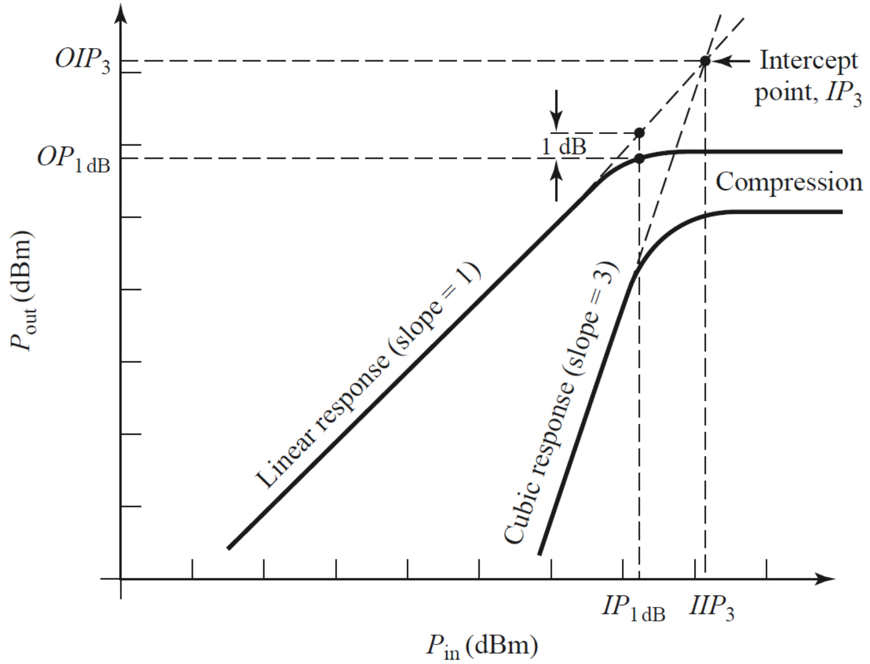
$$K_1 = 10^{\frac{G}{20}}$$

- All IF signals are scaled with K_1, because the linear part of $y(t)$ models the ideal mixer operation
- K_3 can be computed from the third-order

  intercept point (IIP3):

$$IIP3 = 20 \cdot \log_{10}\left(\frac{\sqrt{4 \cdot K_1}}{\sqrt{3 \cdot K_3}}\right)$$

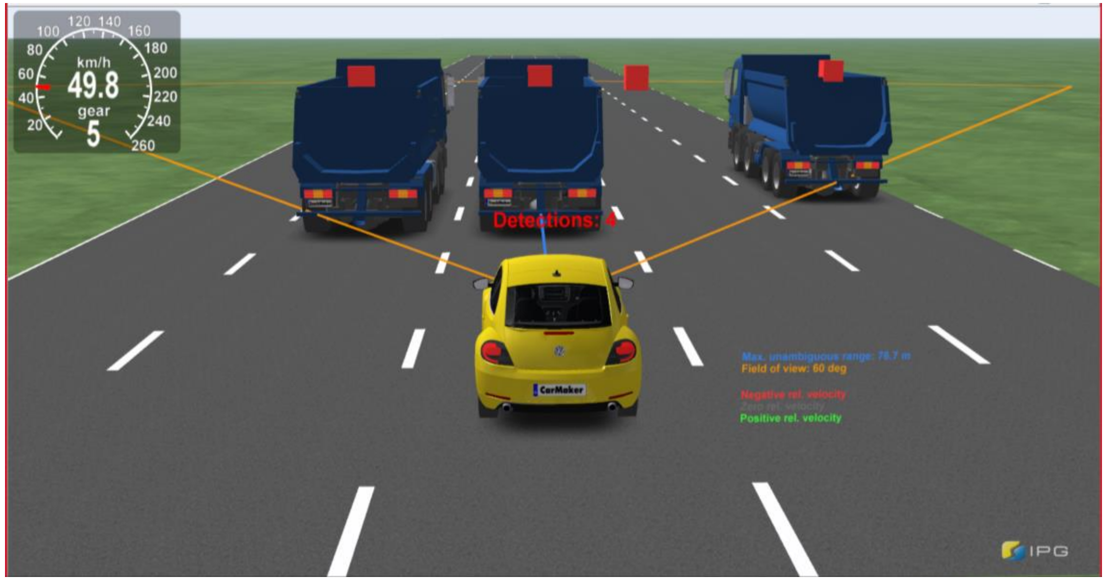
$$K_3 = \frac{4 \cdot K_1}{3 \cdot 10^{\frac{IIP3}{10}}}$$

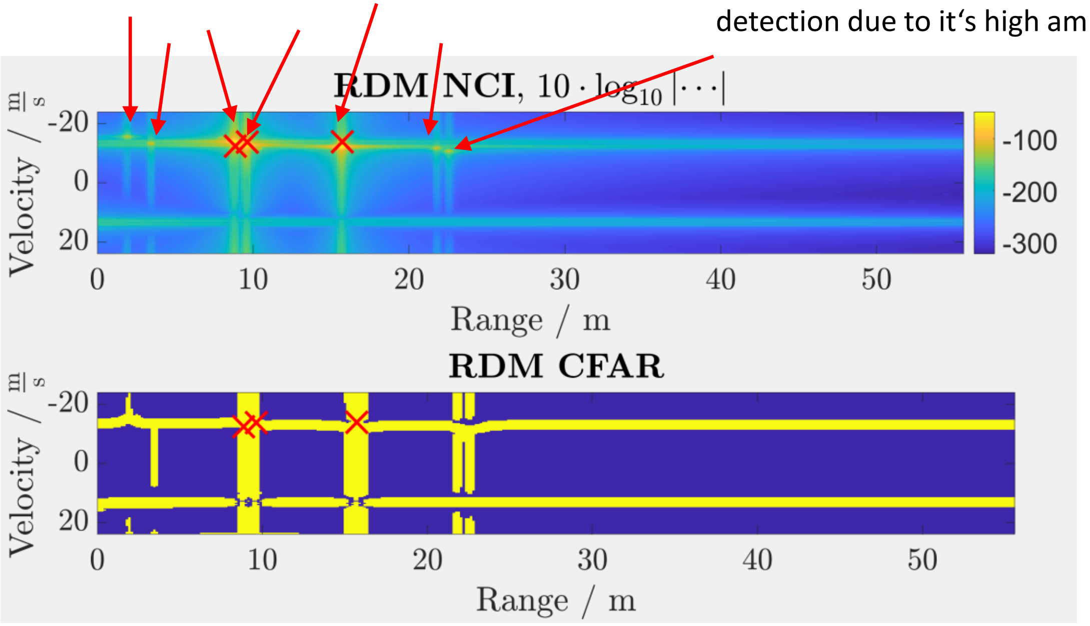


Mixer Non-Linearity: third-order intermodulation (IM3)

- In this scenario 3 trucks are placed at a distance of $8.9\ m$, $9.7\ m$ and $15.8\ m$

- Ego vehicle approaching the targets with the velocity of $50\ km/h$



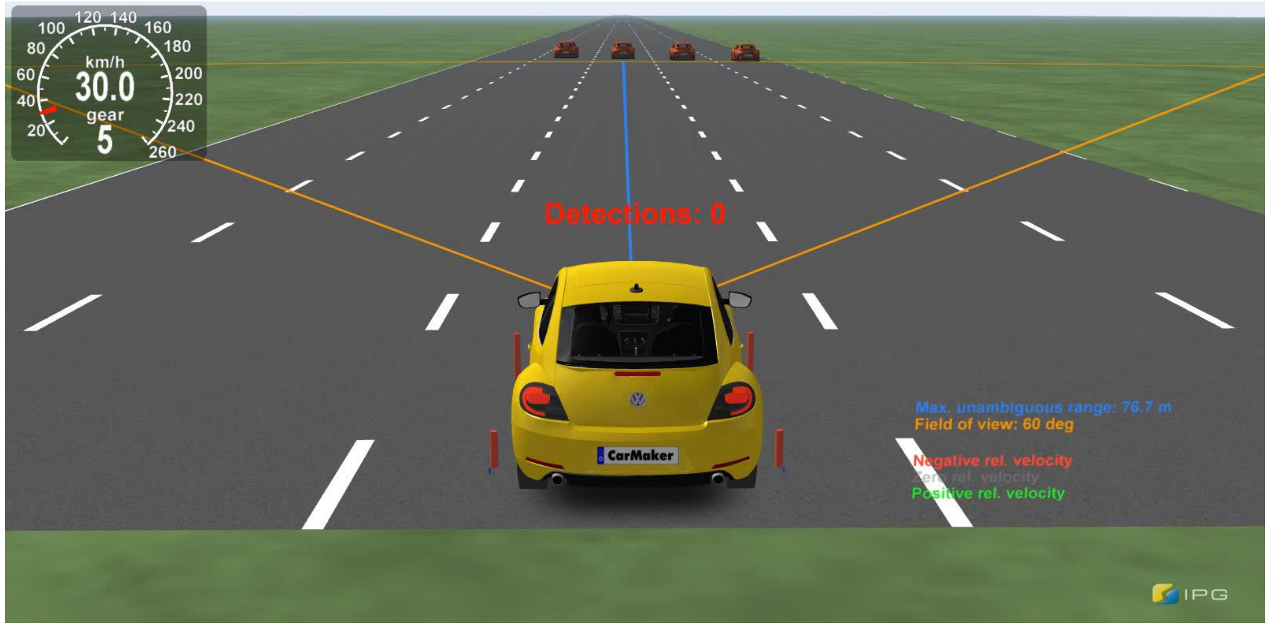


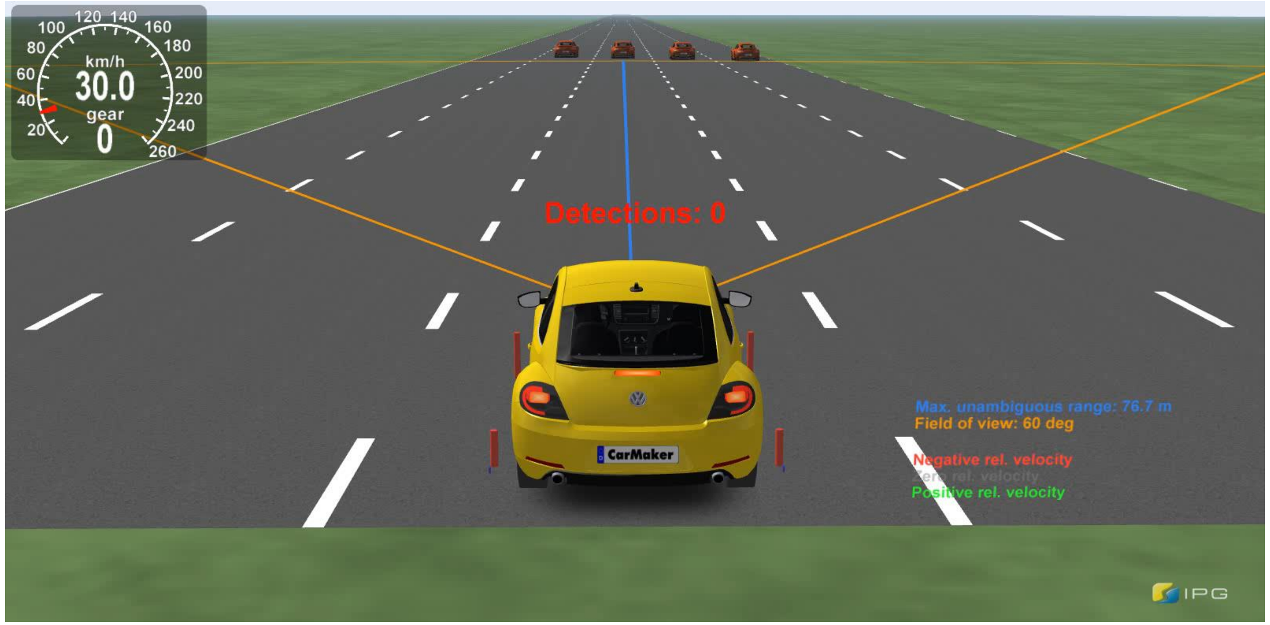
This IM3 signal detected as flase detection due to it‘s high amplitude

- $2 \cdot R_1 - R_2 = 7.65\ m$ (overlapped in RDM by R1 peak), $2 \cdot R_2 - R_1 = 10.62\ m$ (overlapping with target peak R2)
- $2 \cdot R_1 - R_3 = 1.55\ m$ (visible in RDM), $2 \cdot R_3 - R_2 = 22.82\ m$ (visible in RDM)
- $2 \cdot R_2 - R_3 = 3.53\ m$ (visible in RDM), $2 \cdot R_3 - R_2 = 21.83\ m$ (visible in RDM)
- Red crosses indicate VGT values

Mixer Non-Linearity: third-order intermodulation (IM3)

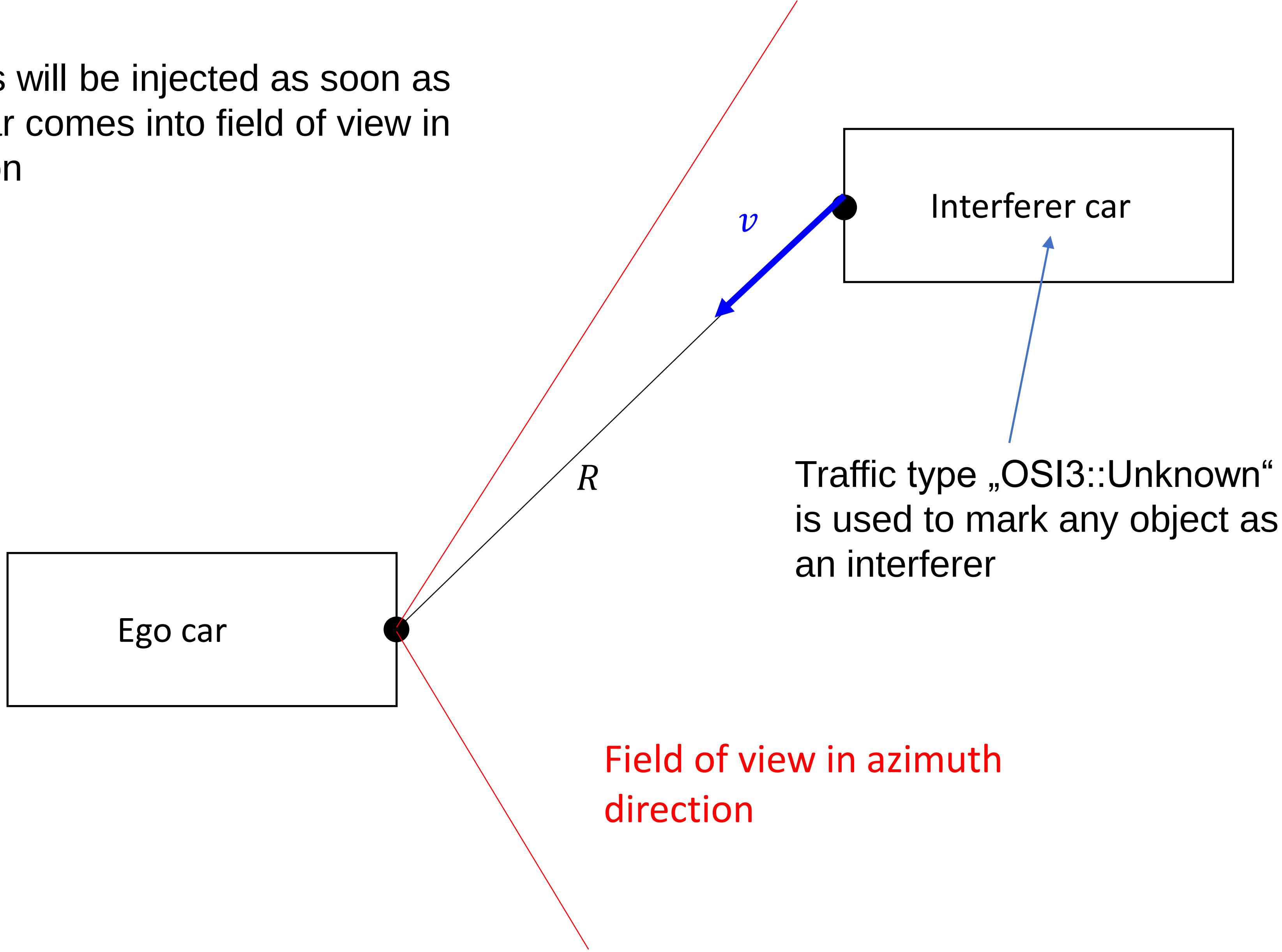
- Ego vehicle is approaching the targets with $30\ km/h$





Interference from other RADAR sensors

- Interferer ramps will be injected as soon as the interferer car comes into field of view in azimuth direction

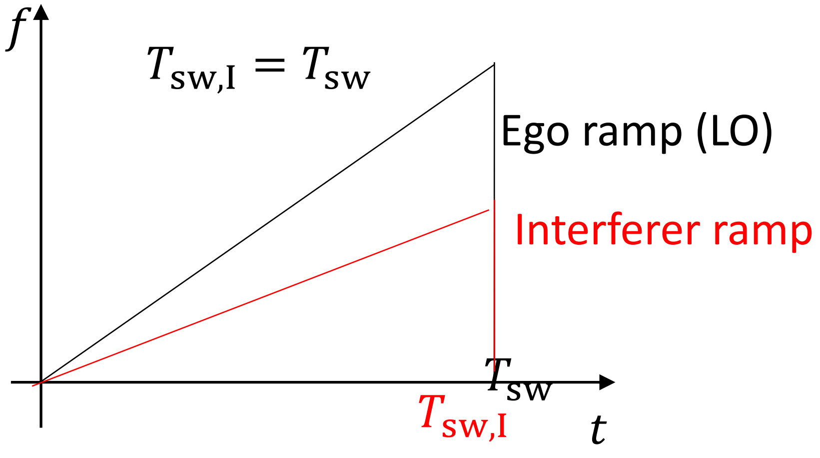


Traffic type „OSI3::Unknown“ is used to mark any object as an interferer

Field of view in azimuth direction

Interference from other RADAR sensors

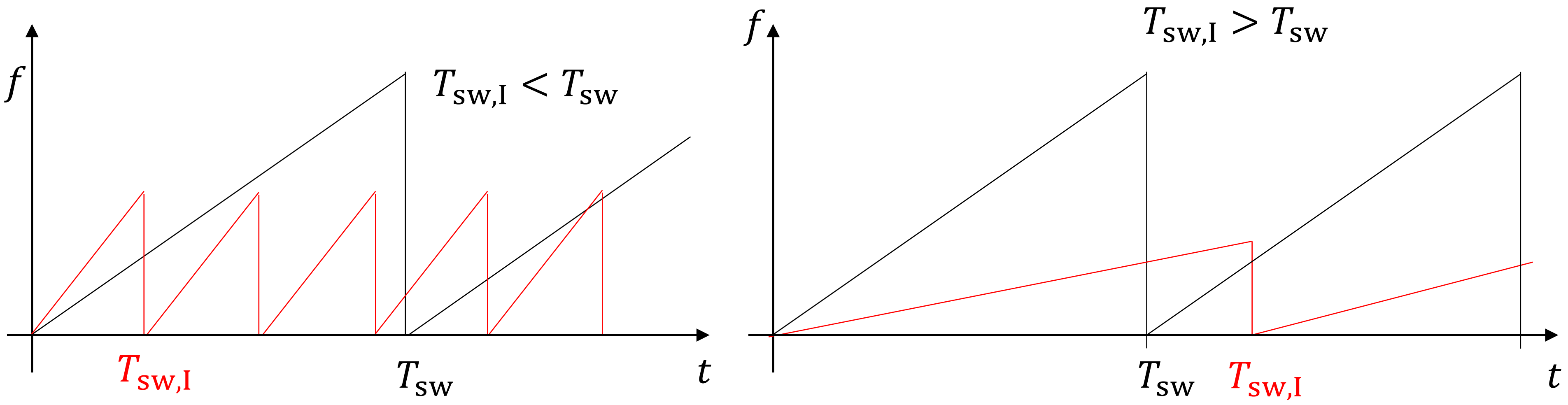
Same ramp duration for interferer and ego sensor



- $y_{\mathrm{IF}}(t) = \frac{1}{2} A_{\mathrm{TX}} A_{\mathrm{RX}} \cdot \cos\left[2\pi(f_0 - f_{\mathrm{I}}) \cdot t + \pi(k - k_{\mathrm{I}}) \cdot t^2 + 2\pi f_{\mathrm{I}} \tau_{\mathrm{I}} + 2\pi k_{\mathrm{I}} t \tau_{\mathrm{I}} - \pi k_{\mathrm{I}} \tau_{\mathrm{I}}^2\right]$
- $\tau_{\mathrm{I}} = \tau_{0,\mathrm{I}} + \frac{v}{c} \cdot (i \cdot T_{\mathrm{s}} + l \cdot T_{\mathrm{sw}}) = \tau_{0,\mathrm{I}} + \frac{v \cdot \Delta t}{c} = \tau_{0,\mathrm{I}} + \frac{\Delta x}{c} = \tau_{0,\mathrm{I}} + \Delta\tau$
- $\tau_{0,\mathrm{I}} = \frac{R'_{n,m}}{c}$: time delay from interferer to ego car (one way)
- $i = 0,1,\ldots$: current sample in ego ramp, $l = 0,1,\ldots$: current ego ramp
- Instantaneous frequency: $f_{\mathrm{inst}}(t) = \frac{1}{2\pi} \varphi_{\mathrm{I}}'(t) = (f_0 - f_{\mathrm{I}}) + (k - k_{\mathrm{I}}) \cdot t + k_{\mathrm{I}} \tau_{\mathrm{I}}$
- Low pass filter: set samples of $y_{\mathrm{I}}(t) \equiv 0$ if $f(t) \notin \left[-\frac{f_{\mathrm{S}}}{2}, \frac{f_{\mathrm{S}}}{2}\right]$, f_{s} : sample rate

Interference from other RADAR sensors

Different ramp duration for interferer and ego sensor



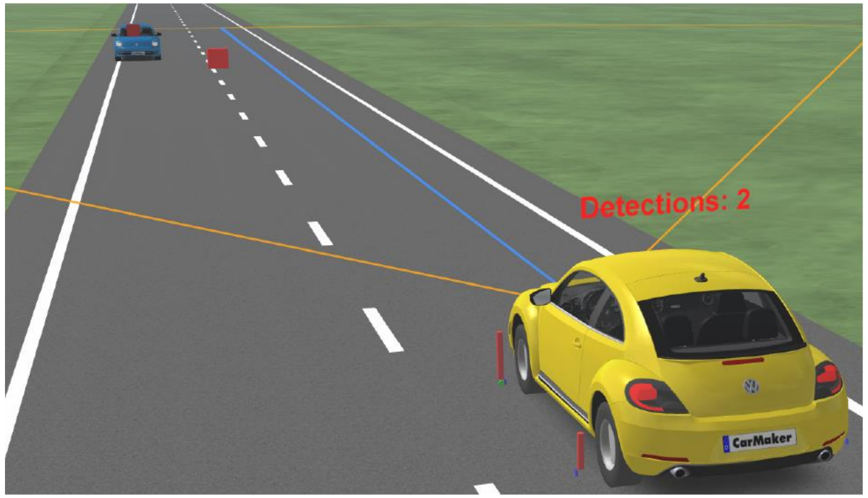
Ego ramp (LO) Interferer ramp

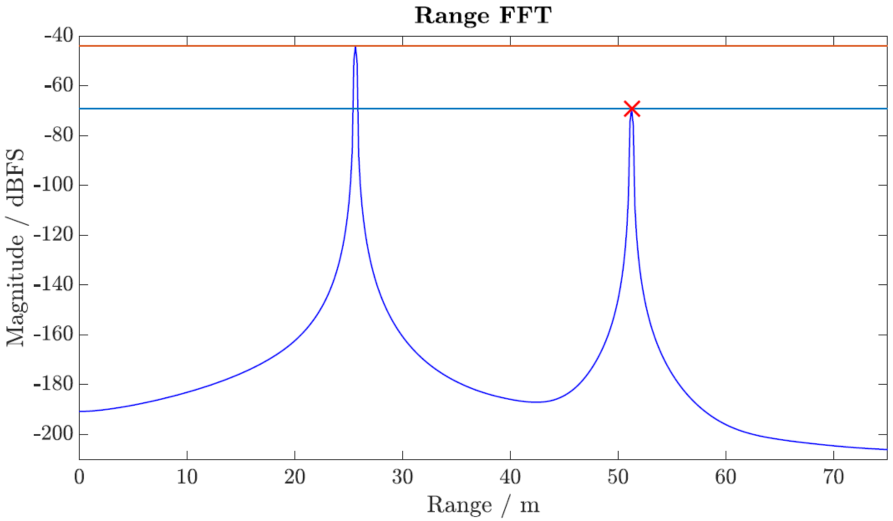
- Ego ramp (LO): $\varphi(t) = 2\pi f_0 \cdot t + \pi k \cdot t^2, \;\; 0 \leq t \leq T_{\mathrm{sw}}, \;\; t = i \cdot T_{\mathrm{s}}$ i: current sample ego ramp $i = 0,1,\ldots,N_{\mathrm{samples,ramp}} - 1$
- Interferer: $\varphi_{\mathrm{I}}(t' - \tau) = 2\pi f_{\mathrm{I}} \cdot (t' - \tau) + \pi k_{\mathrm{I}} \cdot (t' - \tau)^2, \;\; 0 \leq t' \leq T_{\mathrm{sw,I}}$ $t' =$

$$(t + l \cdot T_{\mathrm{sw}}) \bmod T_{\mathrm{sw,I}} \equiv t + l \cdot T_{\mathrm{sw}} - \left\lfloor \frac{t + l \cdot T_{\mathrm{sw}}}{T_{\mathrm{sw,I}}} \right\rfloor \cdot T_{\mathrm{sw,I}},$$ l: current ego ramp

Interference from other RADAR sensors

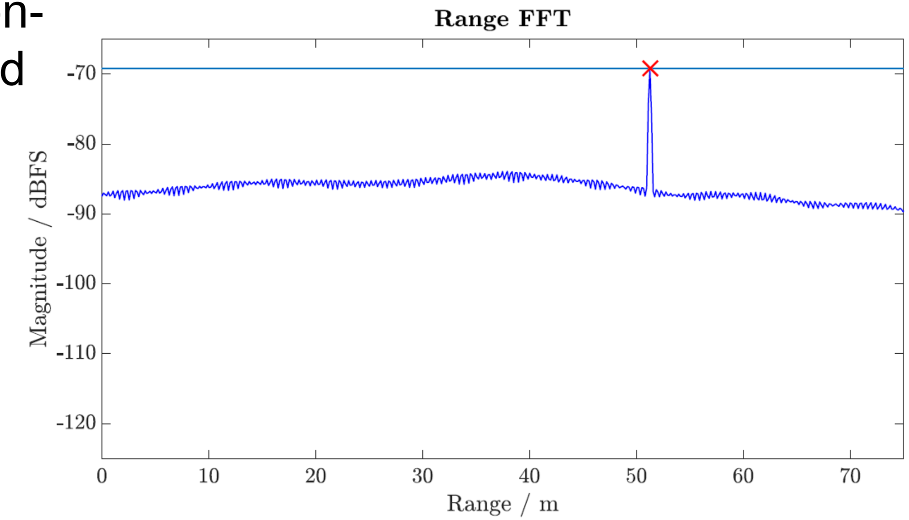
Same ramp duration for interferer and ego sensor





- **Same ramp duration:** ghost target is created at half the distance
- Red cross marks VGT distance of actual target
- Ghost object magnitude is higher since the power decays only with $1/R^2$ instead of $1/R^4$
- **Different ramp duration:** Non-uniform „noise“ floor is created

Different ramp duration for interferer and ego sensor



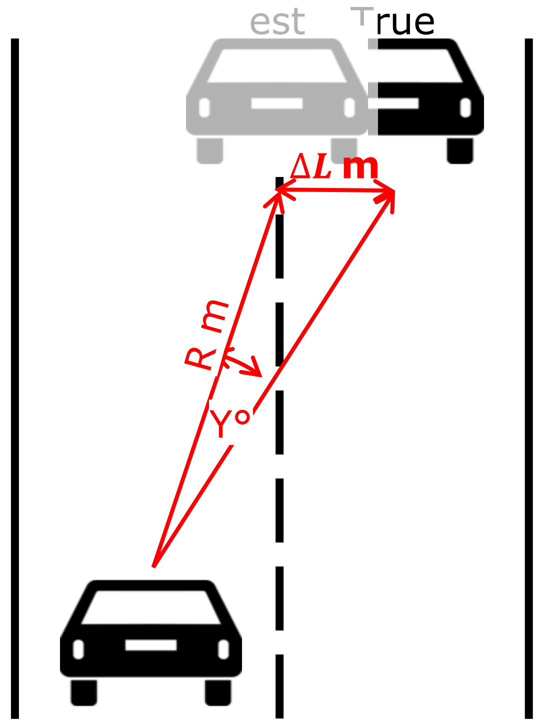
Phase Drift of TX and RX Channels

- **Phase Drift:** describes the change of the output phase of one TX channel (affecting also the phase balance), mainly over temperature

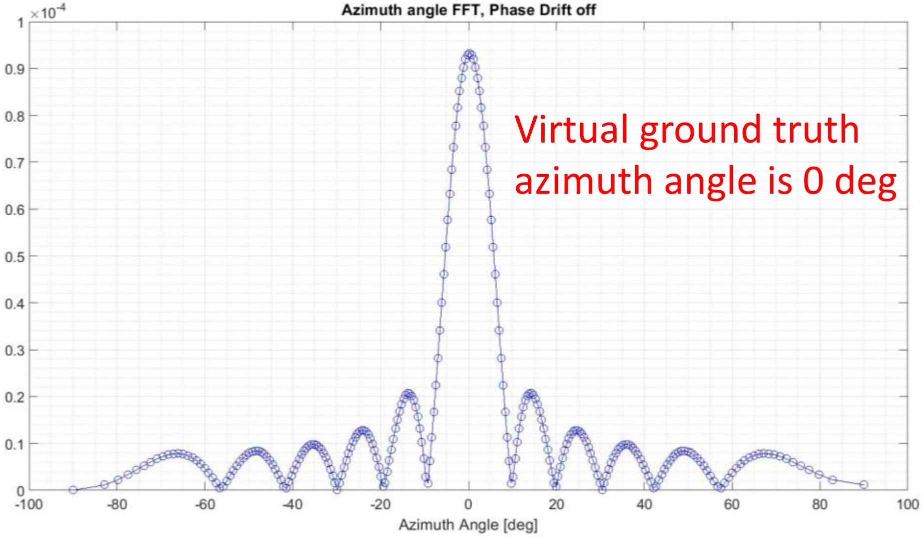
- **Phase balance** is the phase difference between the phases of two TX channels

- **Phase Drift Causes**
  - Angular estimation error,
  - **Sensitivity / SNR degradation in angular domain**

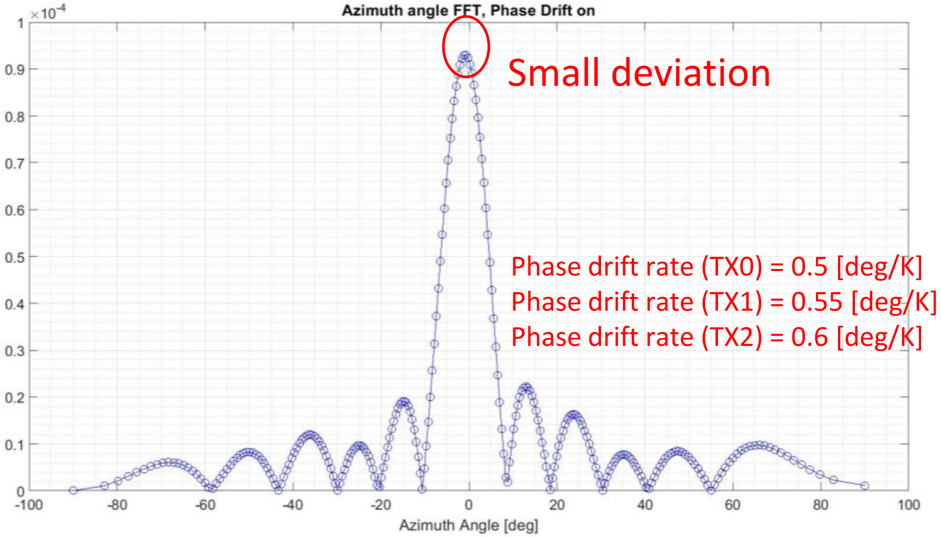
  (increased sidelobe level)



Phase Drift of TX and RX Channels

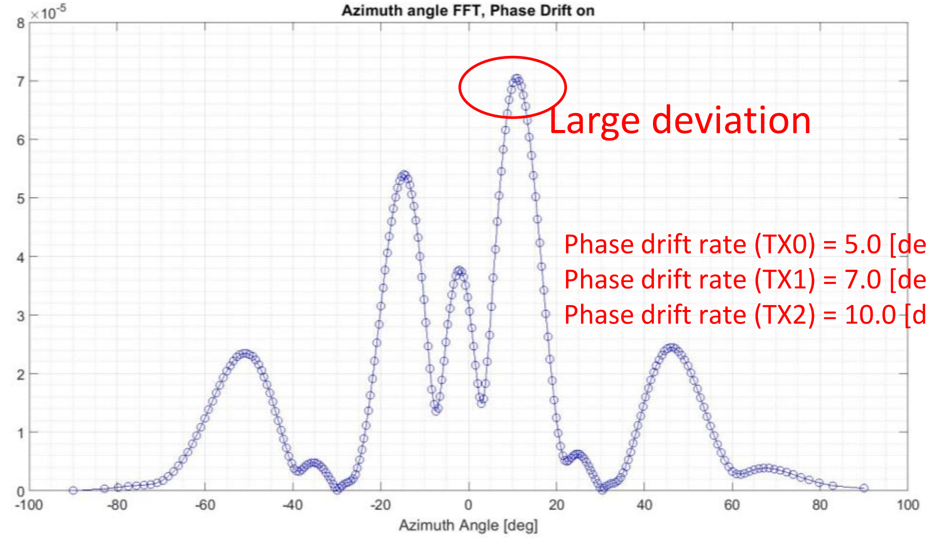

Azimuth angle FFT, Phase Drift off

Virtual ground truth azimuth angle is 0 deg


Azimuth angle FFT, Phase Drift on

Small deviation

Phase drift rate (TX0) = 0.5 [deg/K]
Phase drift rate (TX1) = 0.55 [deg/K]
Phase drift rate (TX2) = 0.6 [deg/K]


Azimuth angle FFT, Phase Drift on

Large deviation

Phase drift rate (TX0) = 5.0 [deg/K]
Phase drift rate (TX1) = 7.0 [deg/K]
Phase drift rate (TX2) = 10.0 [deg/K]

- $s_{IF}(t) = A_{IF}\cos(2\pi k\tau t + 2\pi f_c\tau - \pi k\tau^2\ -)$
- Typical values of phase drift rate: 2.5°, 1.5°, 0.5°
- Typical values of initial phase imbalance: $\Delta\varphi_{initial,TX1-TX2}$: 3°, 5°, 10°

Conclusion

- The ray tracing-based RADAR sensor model is developed by using standardized interfaces OSI and FMI
- The sensor model includes the RADAR MMIC impairments, including phase noise, IM3, sensor interference, and phase drift
- These effects need to be considered to obtain realistic sensor model output
- The modeling of these impairments on the IF level makes simulation faster