EuMW 2015
FREEDOM THROUGH MICROWAVES

EUROPEAN MICROWAVE WEEK 2015

SIX DAYS • THREE CONFERENCES • ONE EXHIBITION

PALAIS DES CONGRÈS, PARIS, FRANCE
SEPTEMBER 6 - 11, 2015

Exhibition Opening Hours:
- Tuesday 8th September: 9.30 – 18.00
- Wednesday 9th September: 9:30 – 17.30
- Thursday 10th September: 9:30 – 16.30

Software Defined Radar

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WS12: EuMIC - *SiGe for mm-Wave and THz*

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Overview

- Introduction - Motivation
  - Radar Principles – Transmit signals
  - Radar Fundamentals – Ambiguity function
- A Software Defined Radar (SDR) Platform
  - Concept – Hardware – Performance
  - Exemplary Implemented Radar Principles:
    - Frequency division MIMO
    - Frequency division MIMO with BPSK und $\Delta\Sigma$-Mod.
    - Stacked OFDM
    - Phase Coded Continuous Wave (PCCW) MIMO Radar
- Radarbook Evaluation Platform

Motivation I

- State-of-the-art in automotive Radar
  – Linear frequency modulated continuous wave (LFMCW), slow ramp as well as fast chirped
- Pros
  – Deramping in hardware, i.e. even a large transmit bandwidth yields a small IF bandwidth
- Cons
  – Linear ramp generation, analog modulation

Motivation II

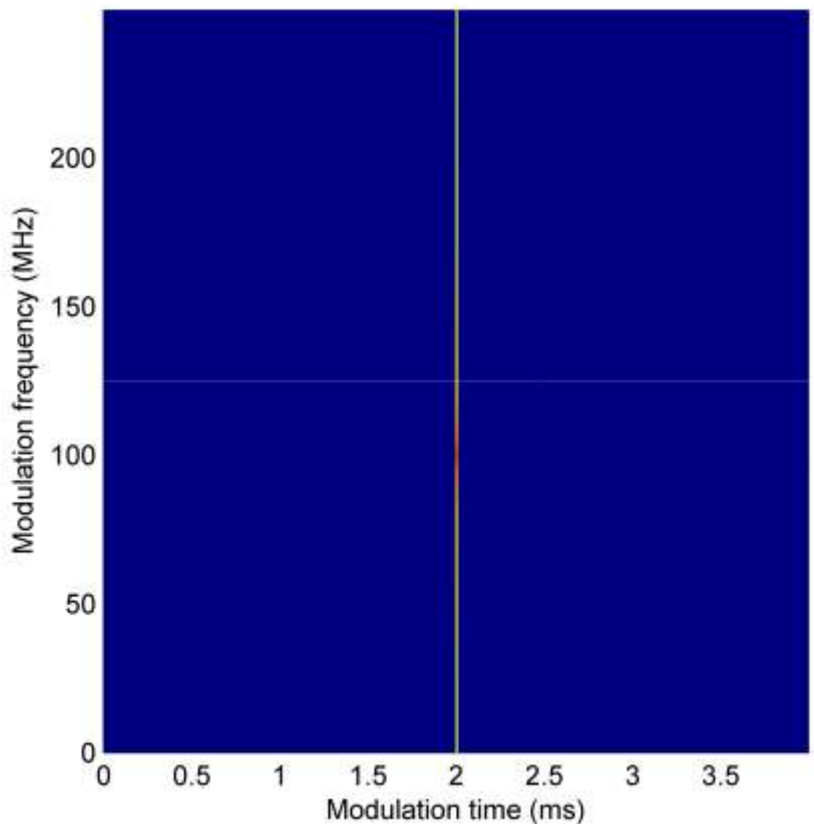
- Current discussion for automotive Radar
  – Silicon-Germanium vs. CMOS technology
- CMOS allows for / requires / goes for ...?
  – Higher integration levels – BB and radio?
  – Towards digitally centric designs – VHDL?
  – Alternative modulation schemes – PRN?
  – Integration vs. RF performance – technology node?
  – Automotive market volume high enough – costs?

Radar Principles

Pulse Radar

- Localization
  in “time”
- Time measurement
- Distance measurement
- Range profiles

Spectrogram

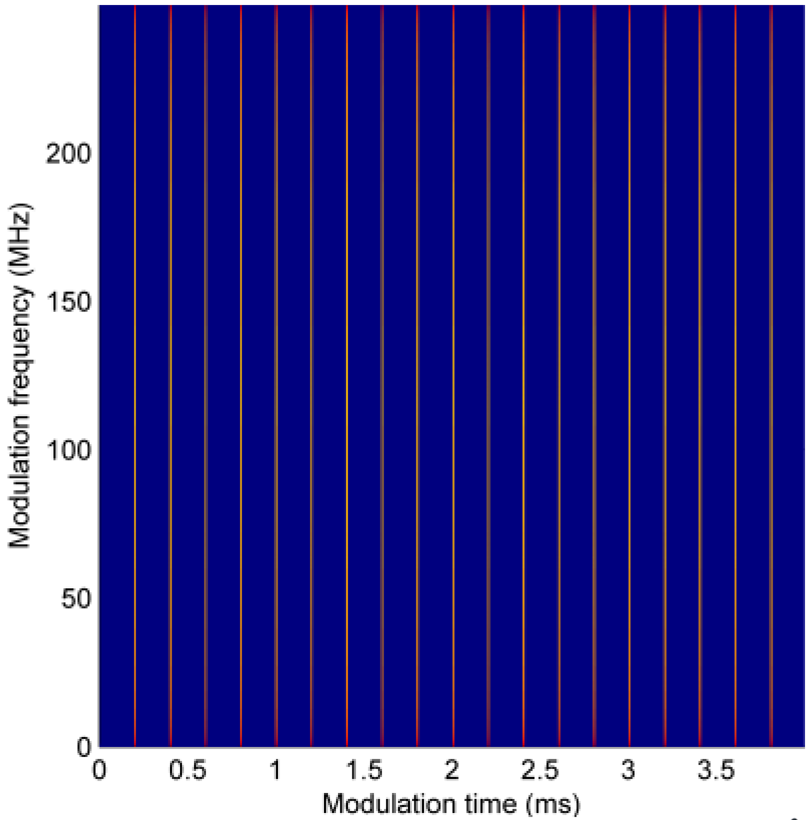


Radar Principles

Short Pulse Train

- Short pulses
- High peak power, difficult for integration
- Receiver variants
  - Fast sampling
  - Sequential Sampling (correlation receiver)

Spectrogram

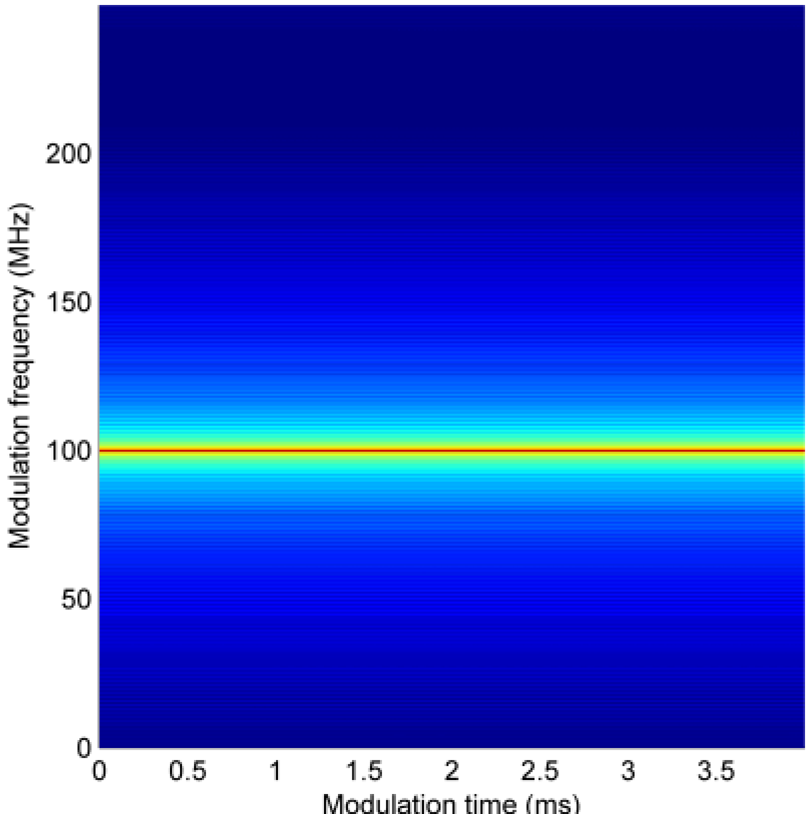


Radar Principles

Doppler Radar

- Localization in "frequency"
- Frequency measurement
- Velocity measurement
- Velocity profiles
- Simplest sensor
- Vehicle speed measurement

Spectrogram

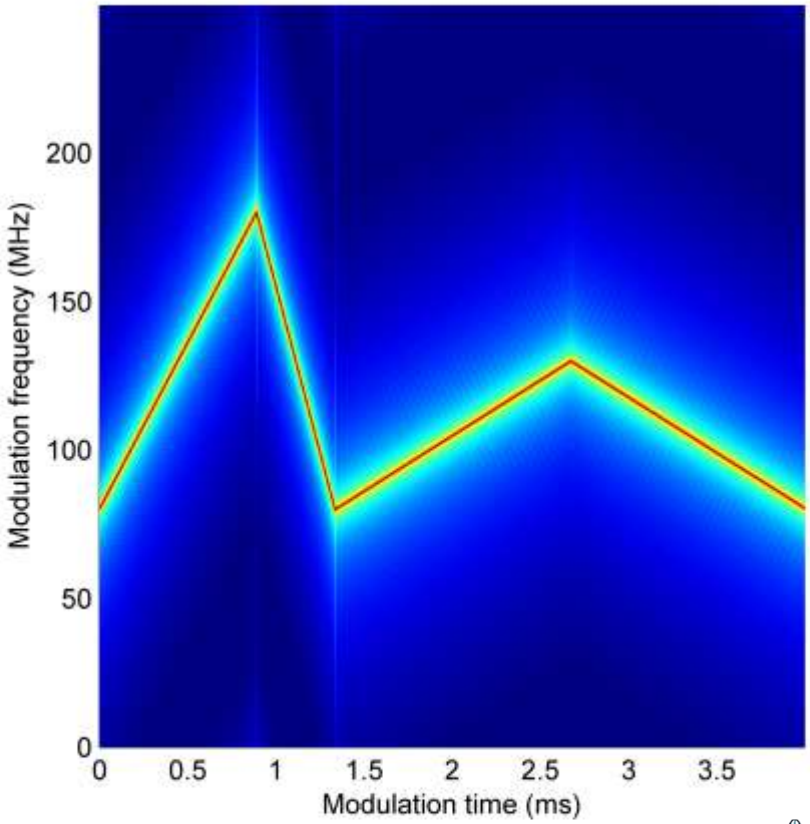


Radar Principles

Linear FMCW Radar

- Localization in "frequency"
- Localization in "time"
- Range-velocity coupling
- Multiple ramps to resolve range velocity coupling
- "Ghost" targets
- Most widely used

Spectrogram

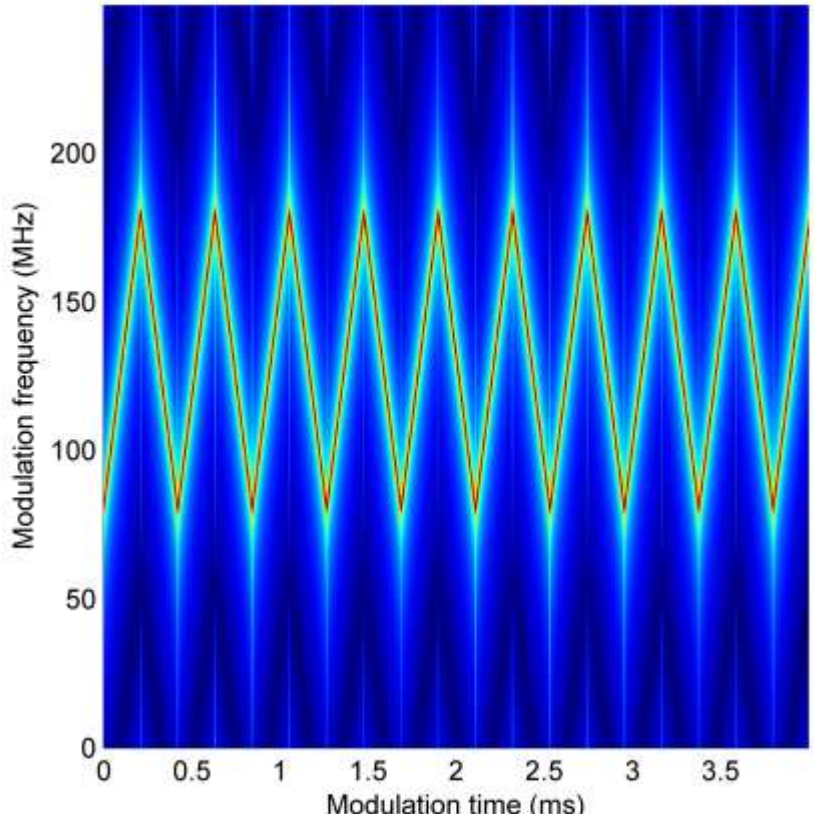


Radar Principles

Fast Chirped FMCW Radar

- Dominant localization in "time" per chirp
- Velocity via phase rotation of chirps
- Range velocity processing with 2D FFT
- State-of-the art for actual/upcoming radars
- Higher IF, higher IF data rate

Spectrogram

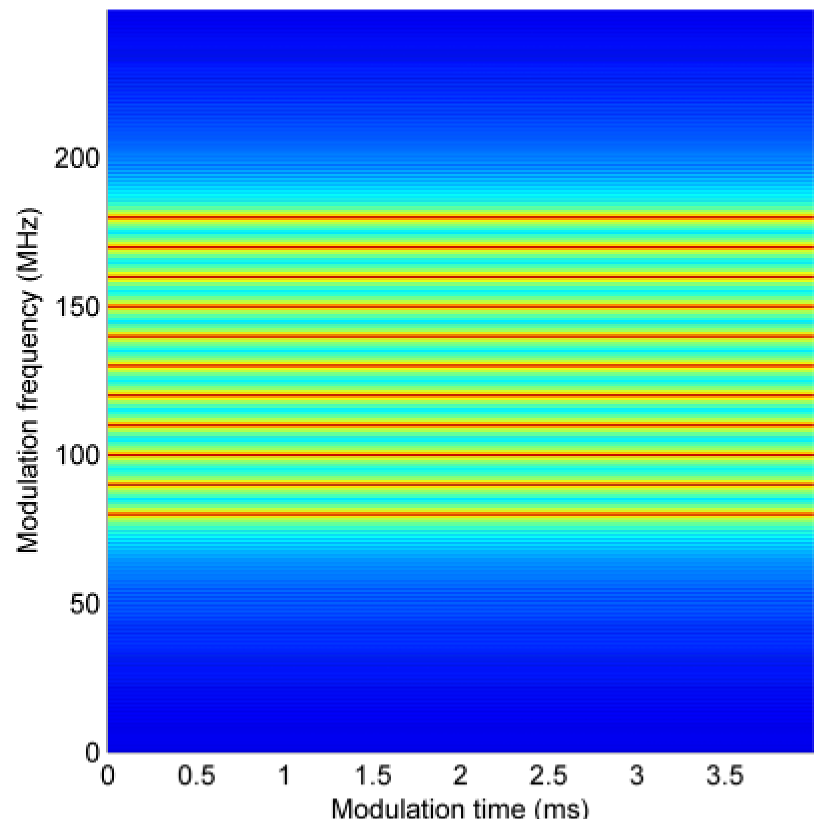


Radar Principles

OFDM Radar

- Orthogonal Sub-carriers
- Instantaneous “FSCW“
- High bandwidth and linear ADC
- Lots of knowledge from communications
- Lots of ongoing research

Spectrogram

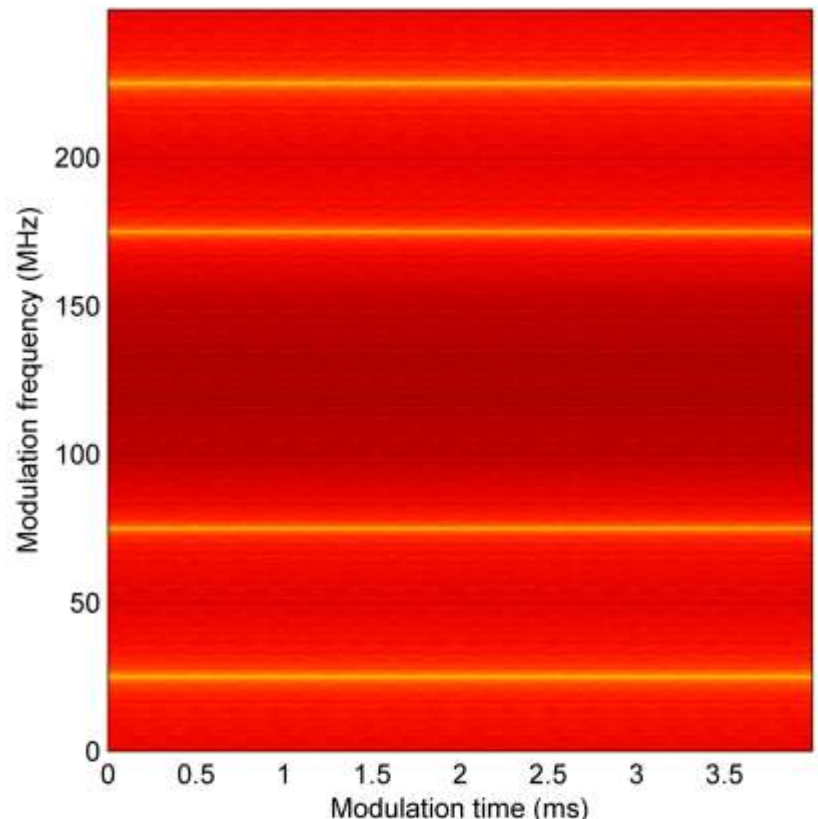


Radar Principles

CW PRN Coded Radar

- High instantaneous bandwidth (unlimited)
- CW, moderate power
- PRN controlled phase mod.
- Receiver
  - High BW
  - Subsampling
  - Hardware correlators
  - Parallel correlation
- Fully digital, CMOS?

Spectrogram



Radar Fundamentals I

- Transmit signal $s(t)$
- Amplitude factor, loss, target scattering $a(t)$
- Round-trip delay time (RTDT) $\tau_0 = \frac{2d_0}{c}$
- Doppler frequency $\omega_0 = 2\pi f_\mathrm{c} \frac{2v_0}{c}$
- Noise $n(t)$
- Receive signal $r(t) = a(t)\, s(t - \tau_0) e^{-\mathrm{j}\omega_0 t} + n(t)$

Radar Fundamentals II

- Correlate receive signal with Doppler shifted transmit signal

$$c(\tau,\omega) = \int_{-\infty}^{\infty} r^*(t)s(t+\tau)\,\mathrm{d}t$$

$$c(\tau,\omega) = \int_{-\infty}^{\infty} a(t)\,s^*(t-\tau_0)e^{+\mathrm{j}\omega_0 t}\,s(t+\tau)e^{-\mathrm{j}\omega t}\,\mathrm{d}t + \mathrm{noise}$$

- Considering $\tau_0 = 0$, $\omega_0 = 0$ and $a(t) = 1$ leads to the Ambiguity Function (AF)

$$A(\tau,\omega) = \int_{-\infty}^{\infty} s^*(t)\,s(t+\tau)\,e^{-\mathrm{j}\omega t}\,\mathrm{d}t$$

Radar Fundamentals III

- Typically, short range radars (SRR) work with periodic sequences, thus also the correlation function is periodic, and the calculation of the ambiguity function must be adapted.

- Ambiguity Function for periodic sequences with a bunch of sequences for Doppler proc.

$$A_{\mathrm{seq}}(\tau,\omega) = \int_{-\frac{T_{\mathrm{seq}}}{2}}^{\frac{T_{\mathrm{seq}}}{2}} s_p^*(t)\, s_p(t+\tau)\, e^{-\mathrm{j}\omega t}\,\mathrm{d}t$$

Radar Fundamentals V

- Symmetry of the ambiguity function

$$A(\tau,\omega) = A^*(-\tau,-\omega)$$

- Along the zero-Doppler axis ($\omega = 0$) the ambiguity function is the autocorrelation function of the waveform

$$A(\tau,0) = \int_{-\frac{T_{\mathrm{seq}}}{2}}^{\frac{T_{\mathrm{seq}}}{2}} s_p^*(t)s_p(t+\tau)\,\mathrm{d}t = R_{ss}(\tau)$$

Radar Fundamentals VI

- Maximum of ambiguity function

$$|A(\tau,\omega)| \leq |A(0,0)| = \int_{-\infty}^{\infty} |s(t)|^2 \, \mathrm{d}t$$

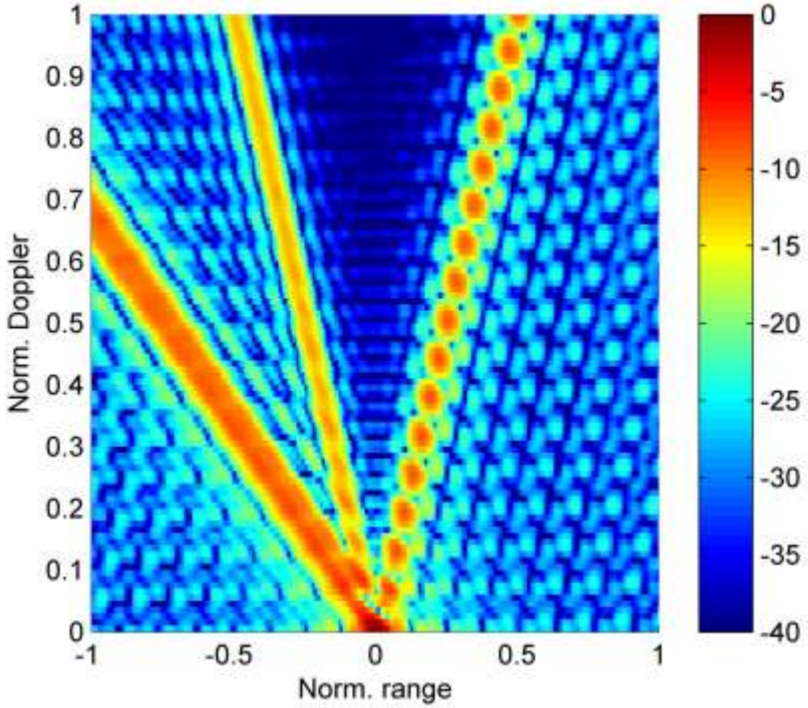
- Moyal's Identity

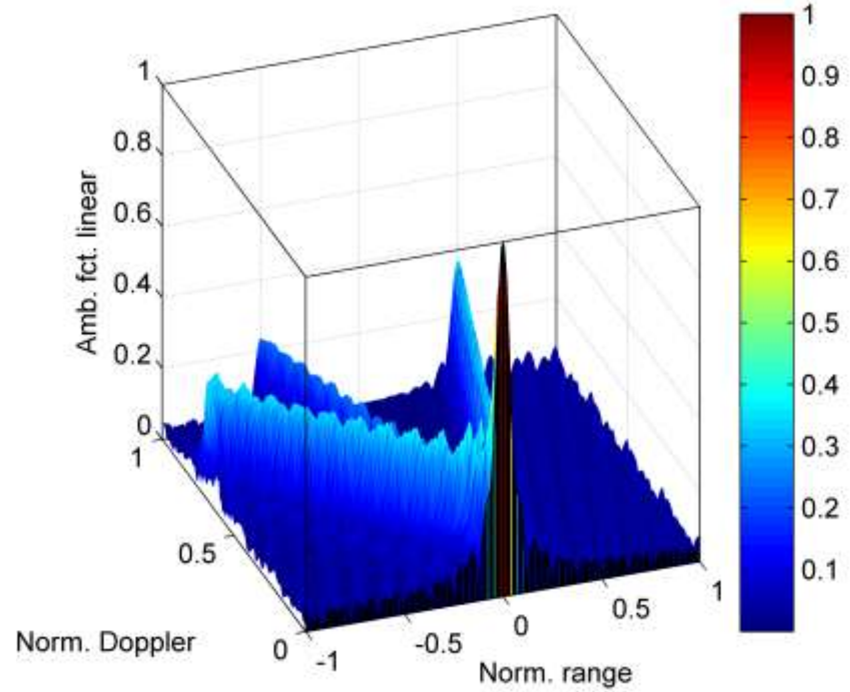
$$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |A(\tau,\omega)|^2 \, \mathrm{d}\tau \, \mathrm{d}\omega = |A(0,0)|^2$$

➔ A reduction of the ambiguity function in one place, forces a heightening somewhere else!

Ambiguity Function I

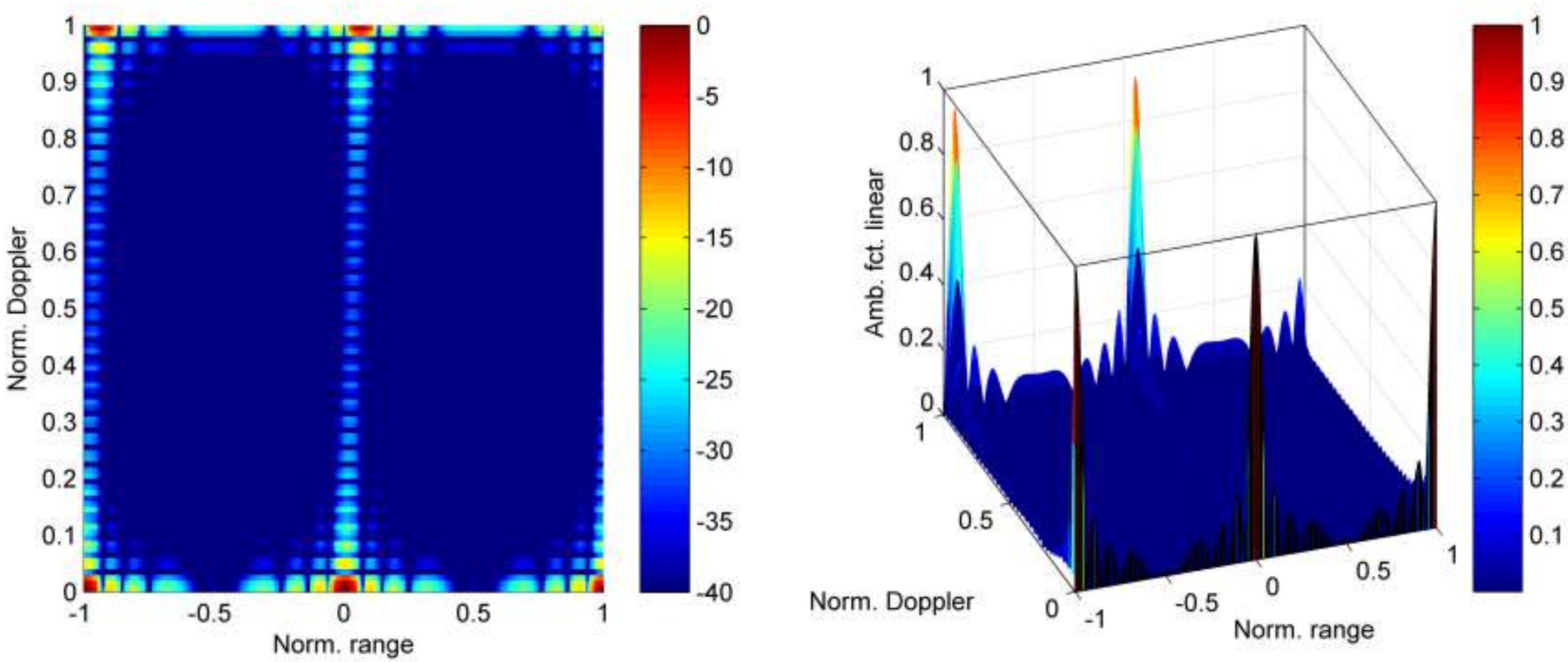
- Linear FMCW Radar (3 ramps)





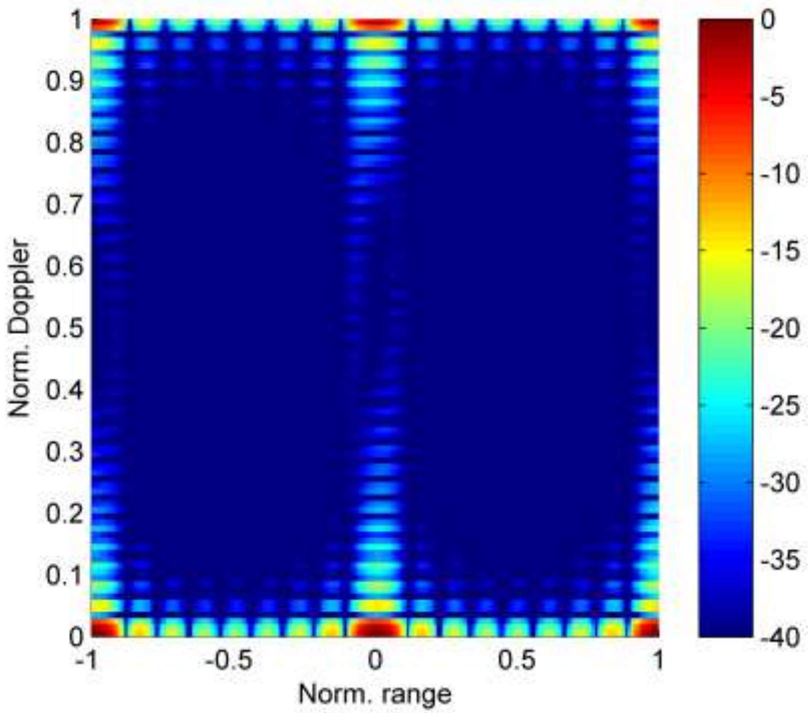
Ambiguity Function II

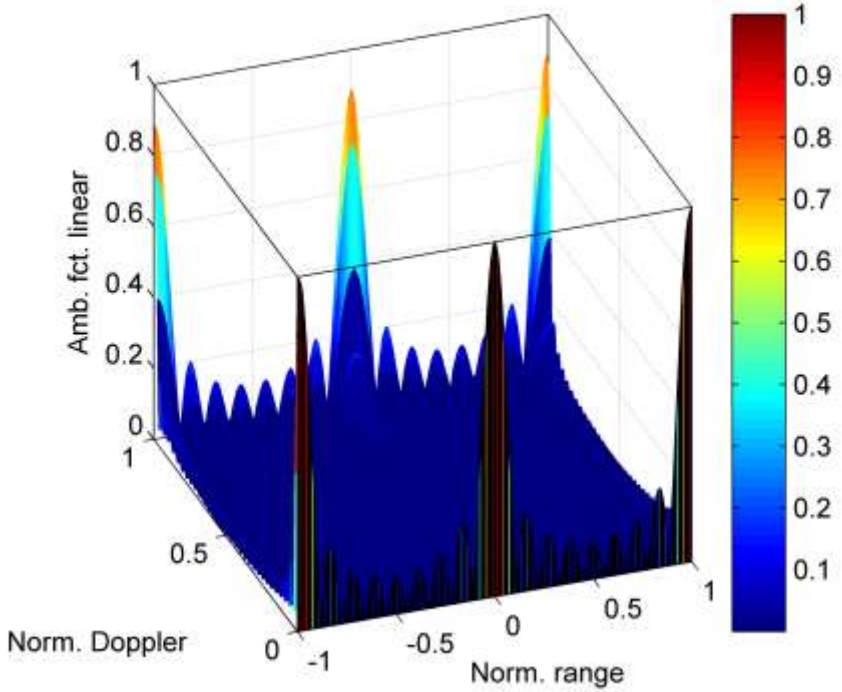
- Fast Chirped FMCW Radar



Ambiguity Function III

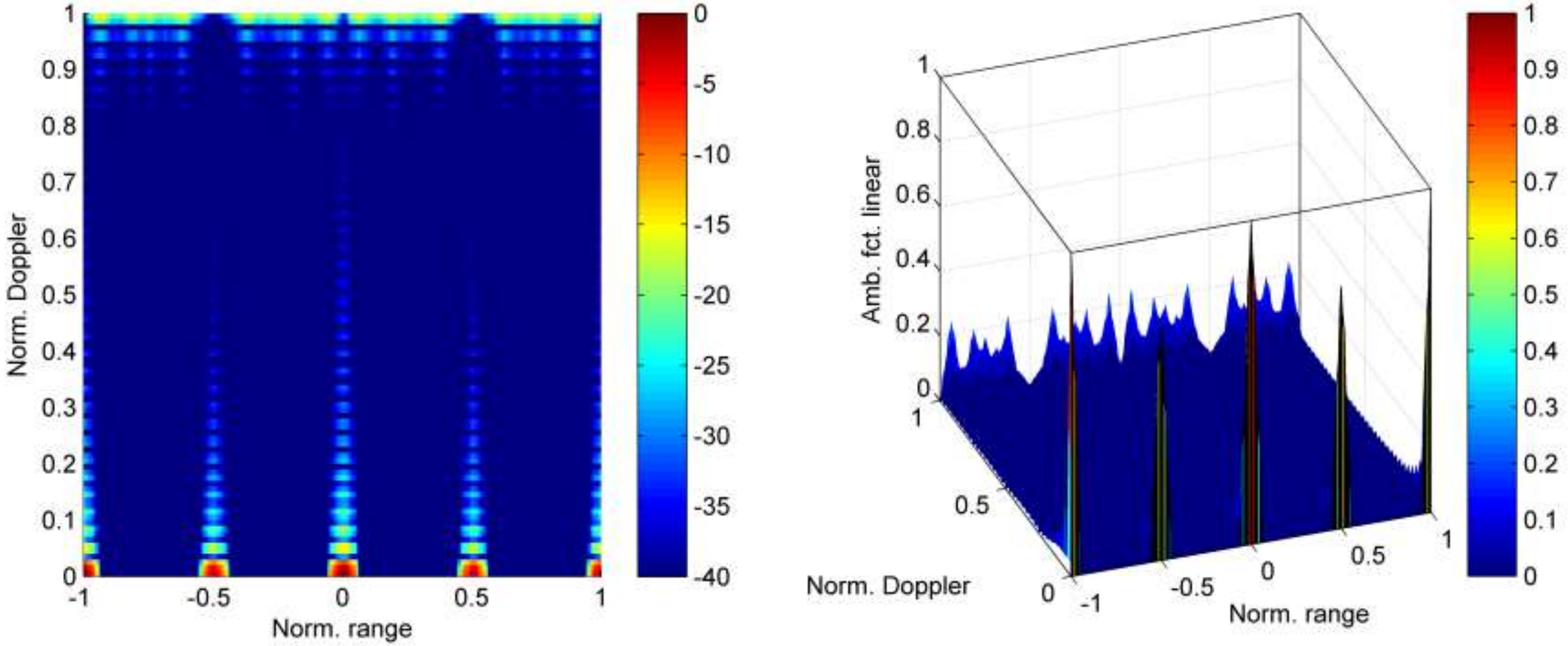
- OFDM Radar





Ambiguity Function IV

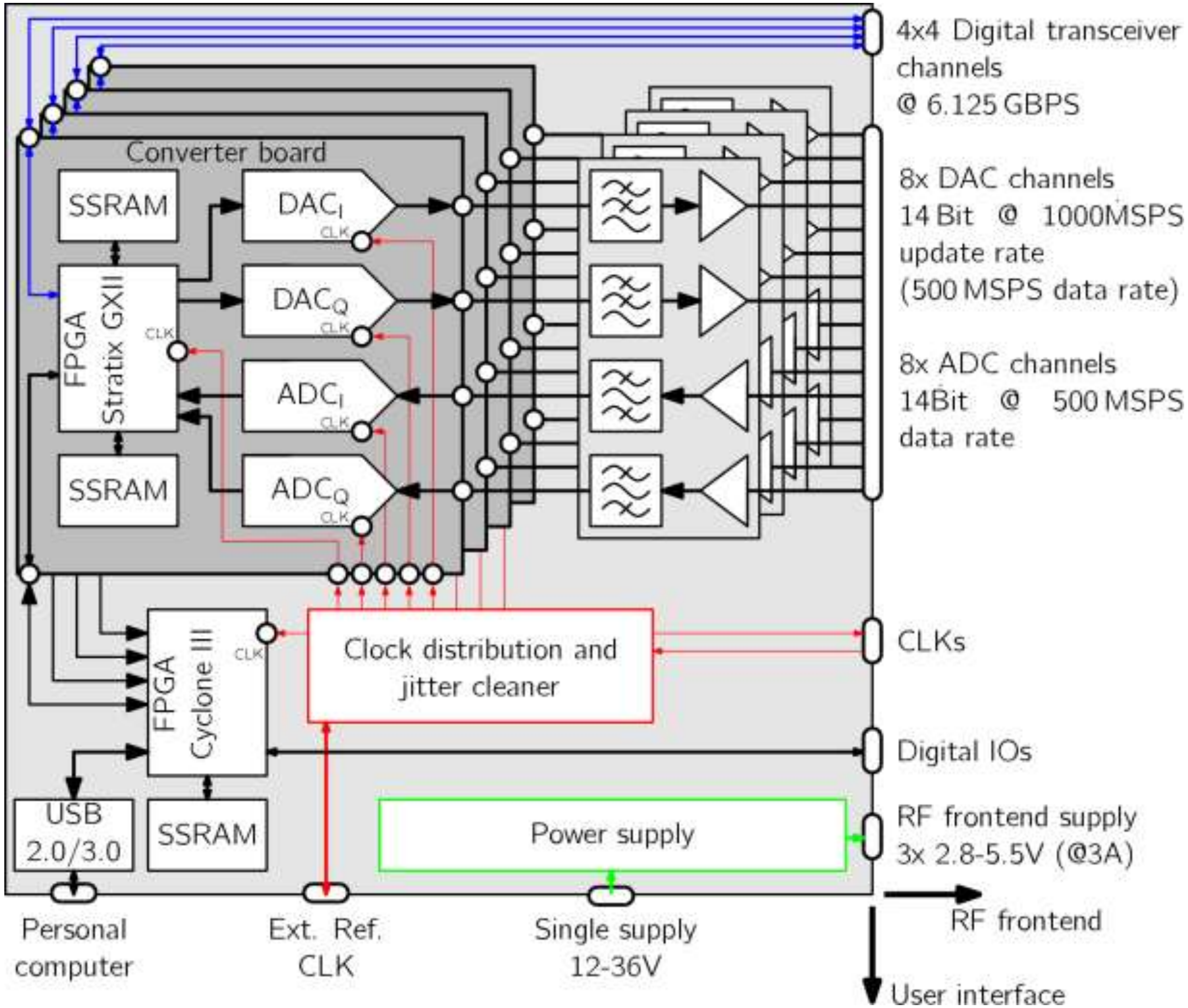
- PCCW with Almost Perfect Autocorrelation Sequence (APAS)



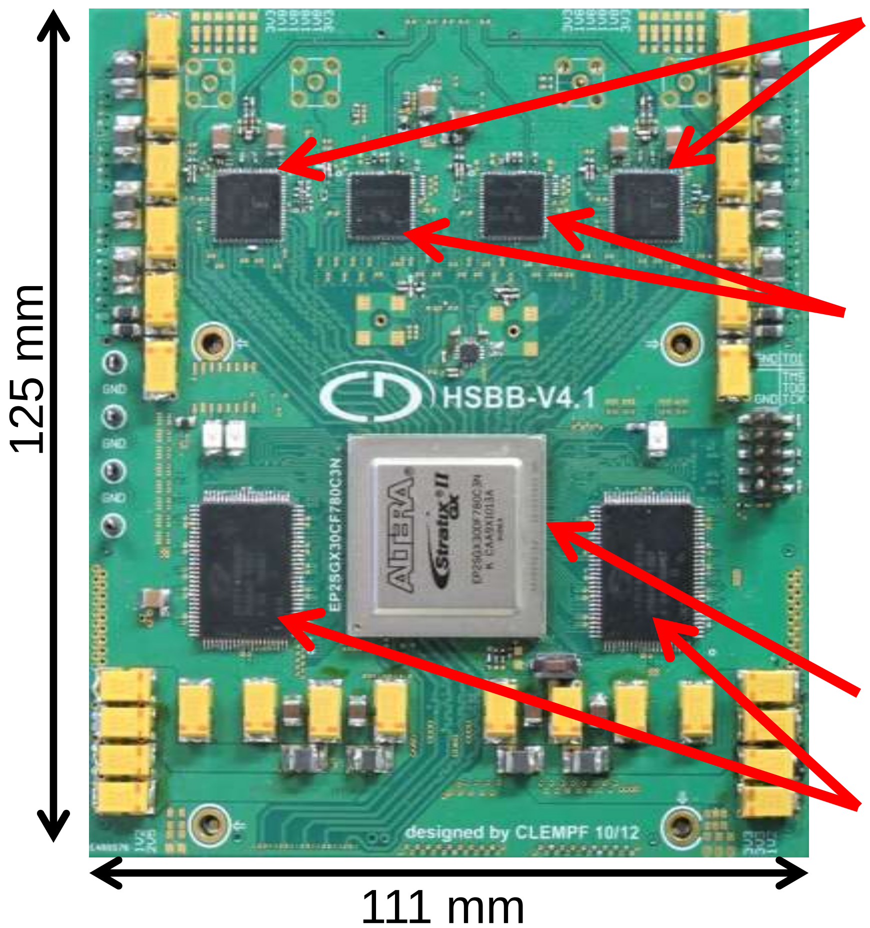
Software Defined Radar (SDR)

- Development of a Software Defined Radar (SDR) platform for application with 77-GHz SiGe-based multi-channel frontends.
- Technical Data:
  - 4 converter boards with 2 ADCs and 2 DACs, 500 MS/s, 14 bit each.
- Goal
  - Demonstration and verification of concepts and algorithms on real 77-GHz frontend hardware

SDR Evaluation Platform



Single Converter Board



ADCs

- 500 MSPS (Data rate)
- 14 Bit

DACs

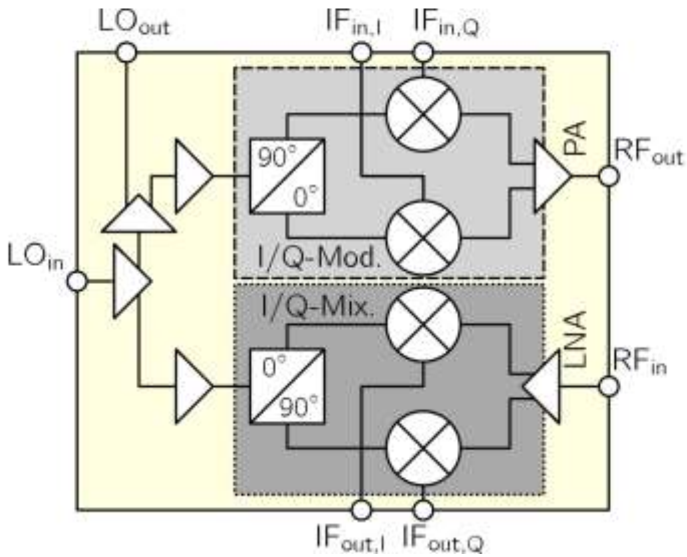
- 500 MSPS (Data rate)
- 1 GSPS (Update rate)
- 14 Bit

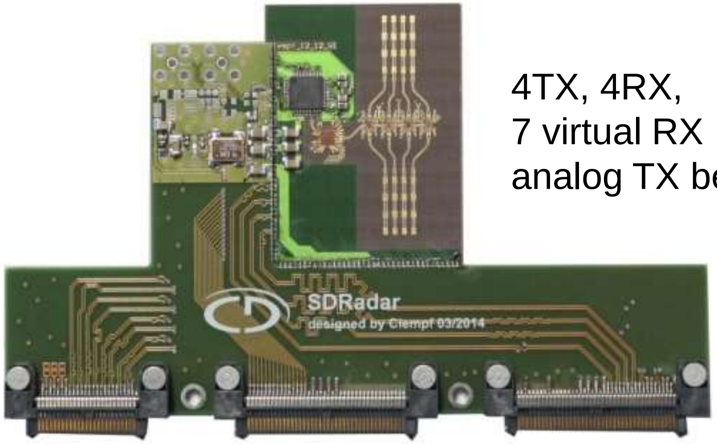
FPGA

Memory

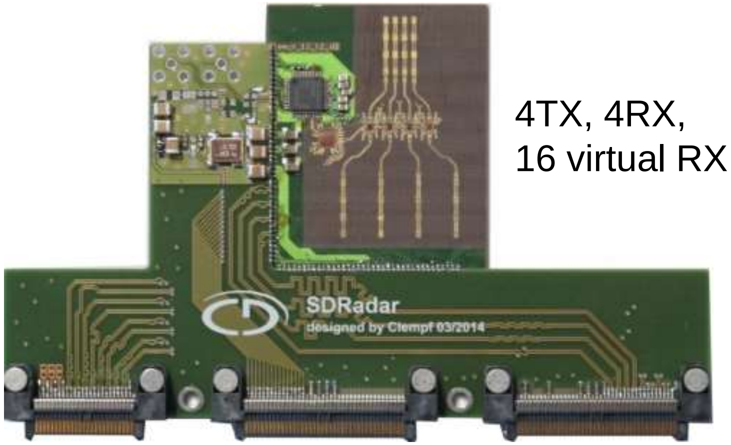
RF-Frontends

B7HF200 SiGe:C
Bipolar technology from Infineon
Vcc = 3.3 V
Idc = 131 mA
1428 x 1028 µm²





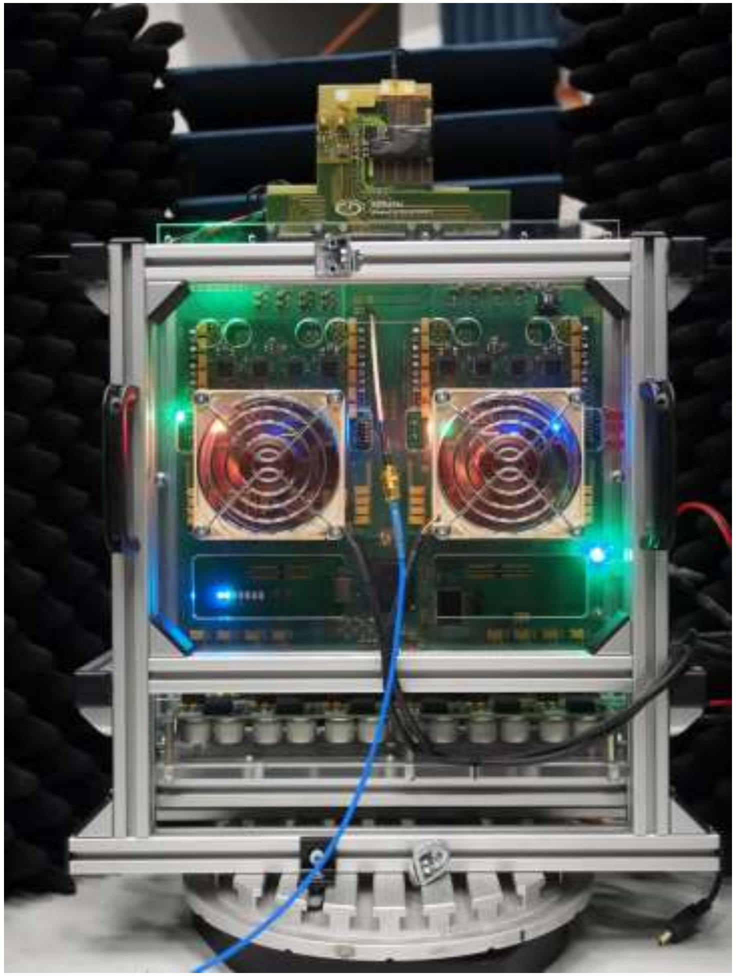
4TX, 4RX,
7 virtual RX MIMO +
analog TX beamforming



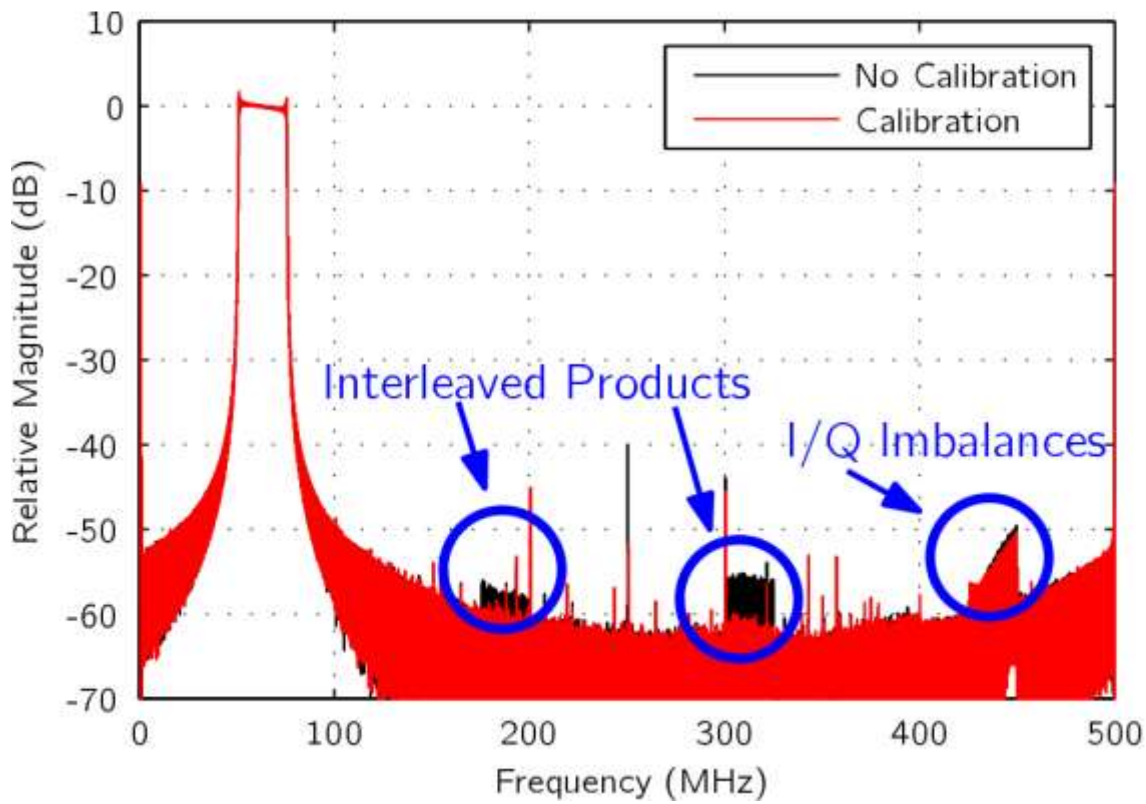
4TX, 4RX,
16 virtual RX MIMO

SDR Platform

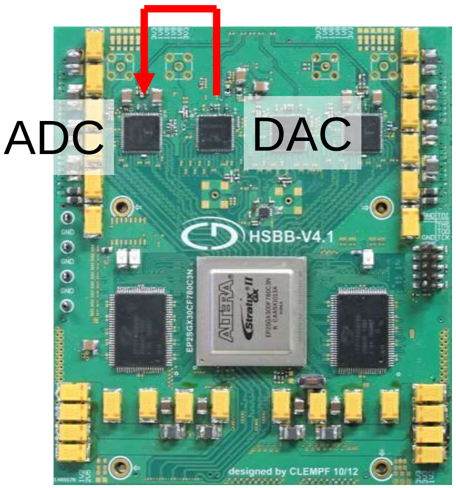
- 4 TX and 4 RX channels
- Large bandwith up to 4 GHz (tuned VCO)
  - TDM
  - FDM
  - SOFDM (Stacked OFDM)
- Bandwidth up to 400 MHz (SDR with fixed VCO-frequency)
  - TDM
  - FDM
  - OFDM
  - PRN

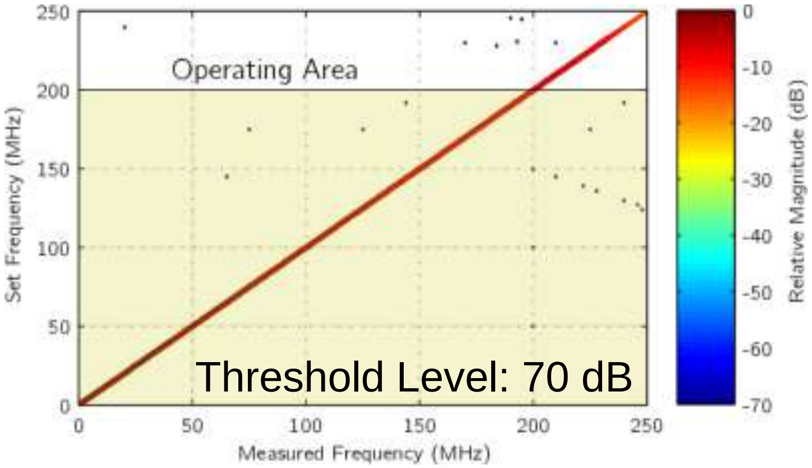


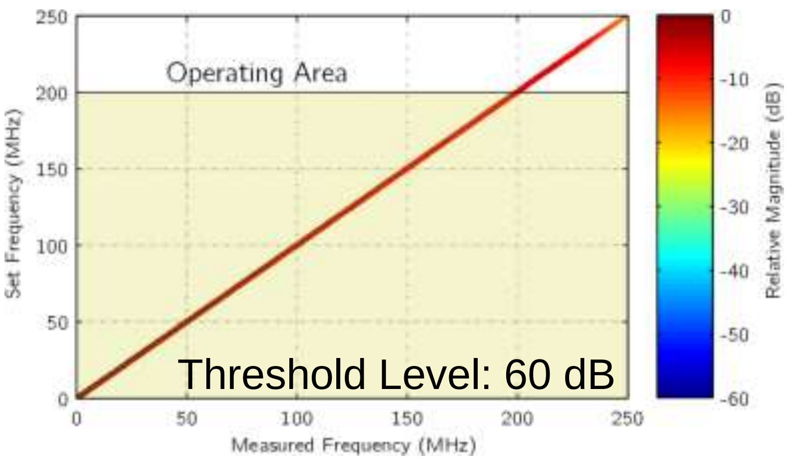
Performance of ADC/DAC (Calibration ADC)

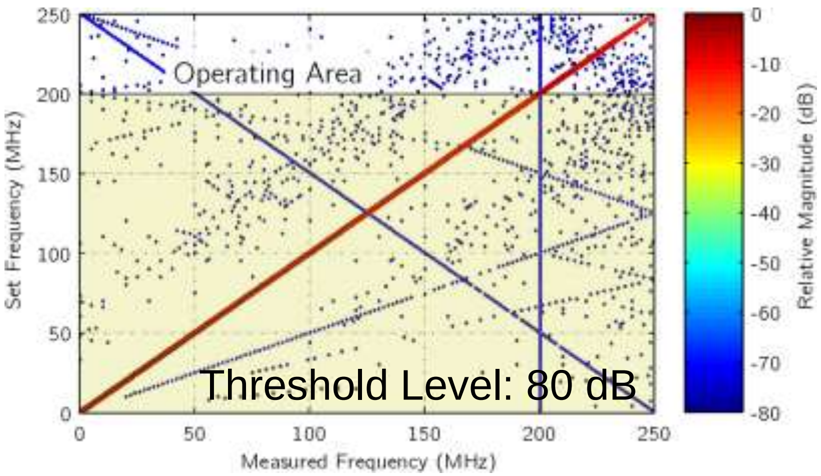


Performance of ADC/DAC (Spurs)

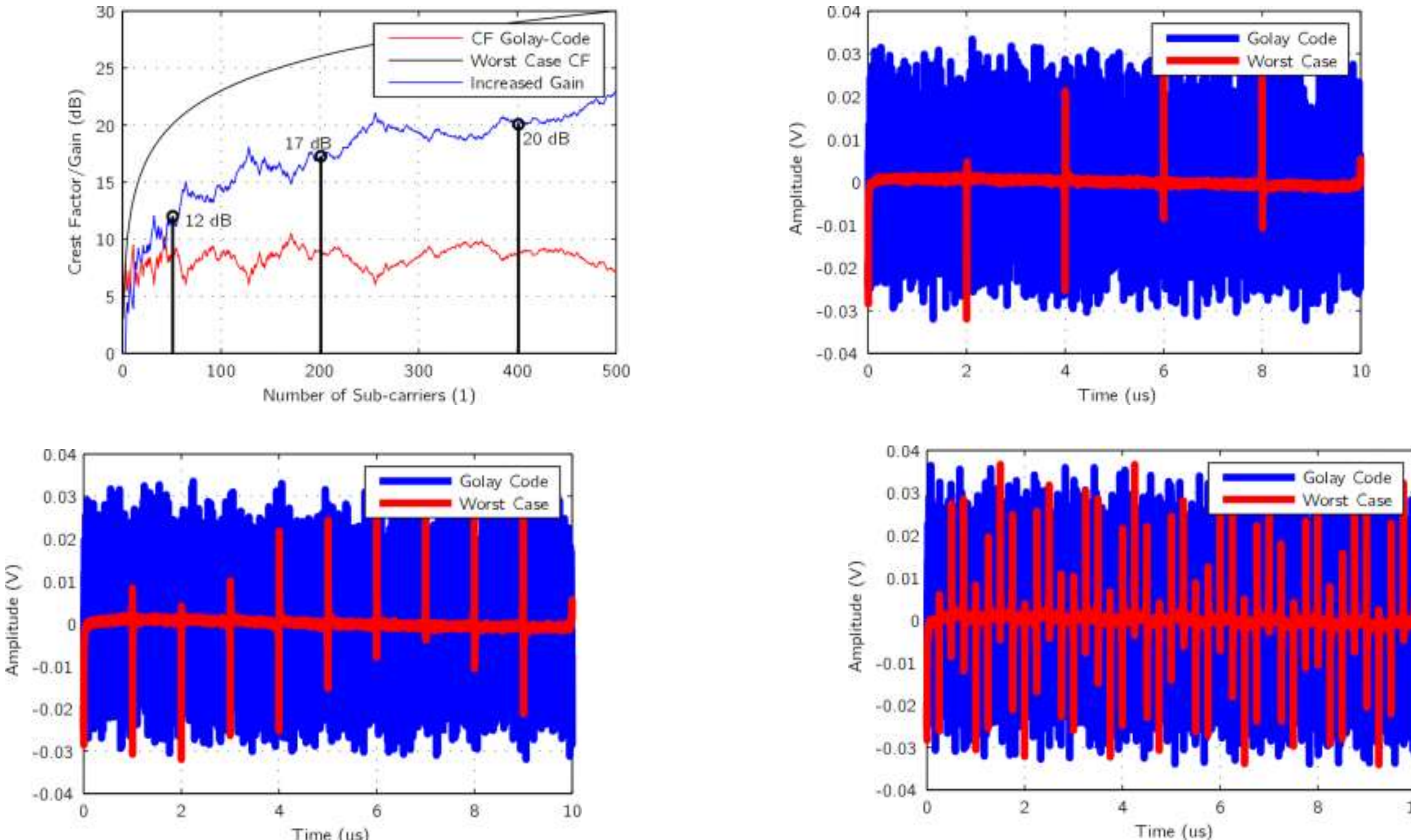








Crest Factor – Time Signals (Golay Phase Values vs. Worst Case)

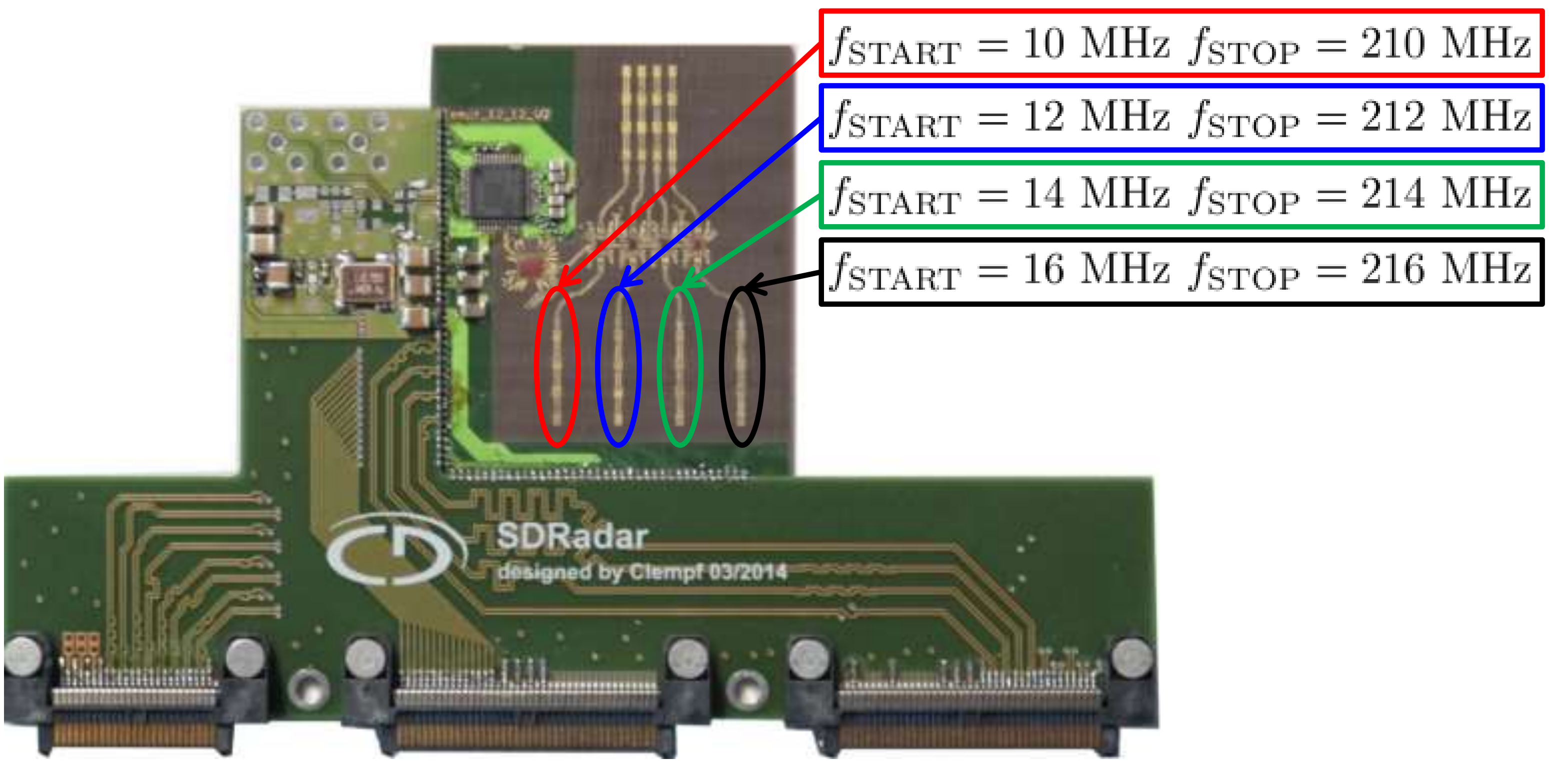


WS12: EUMIC - SiGe for mm-Wave and THz

Andreas Stelzer

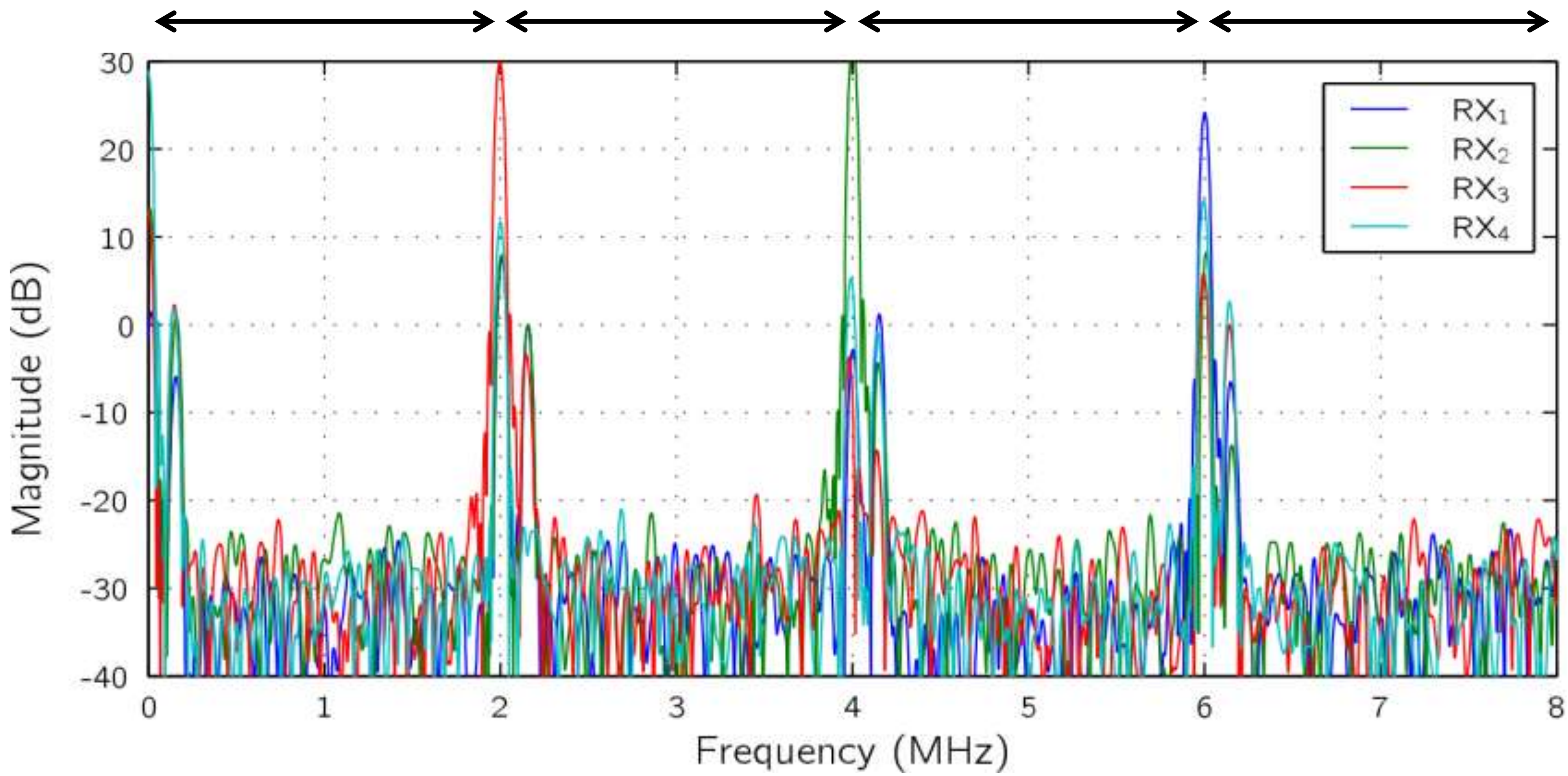
FDM MIMO Mode, 16 virt. RX

- MIMO Operation (FDM mode, single ramp) and DBF (16 virt. RX antennas) with: $T_{\mathrm{SW}}=40\,\mu\mathrm{s}$, $B_{\mathrm{SW}}=200\,\mathrm{MHz}$



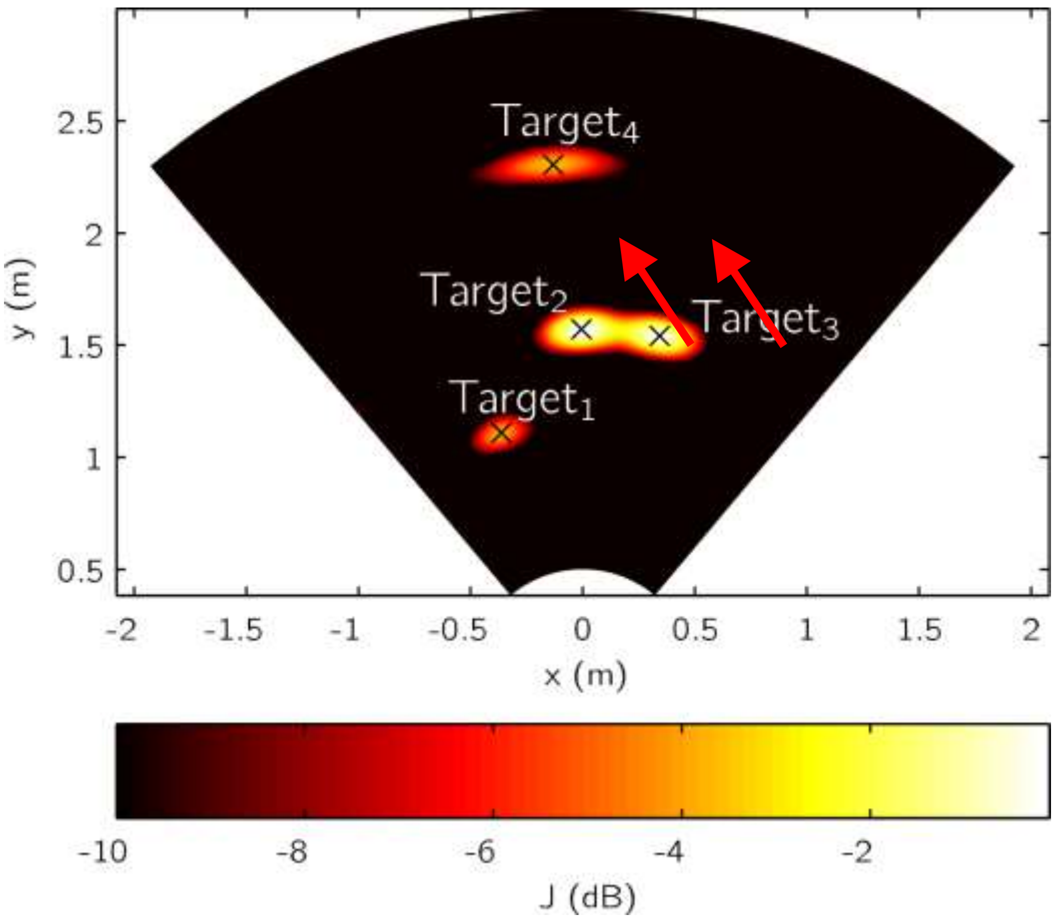
Measurements FDM MIMO

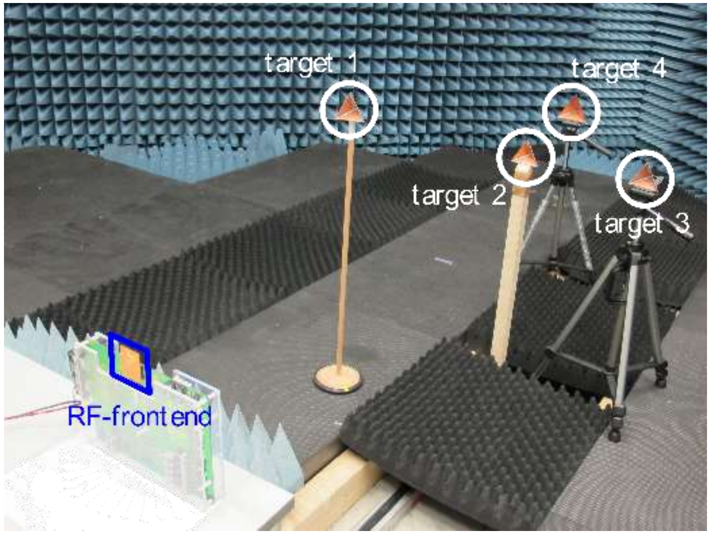
Max. unambiguous range: 60 m



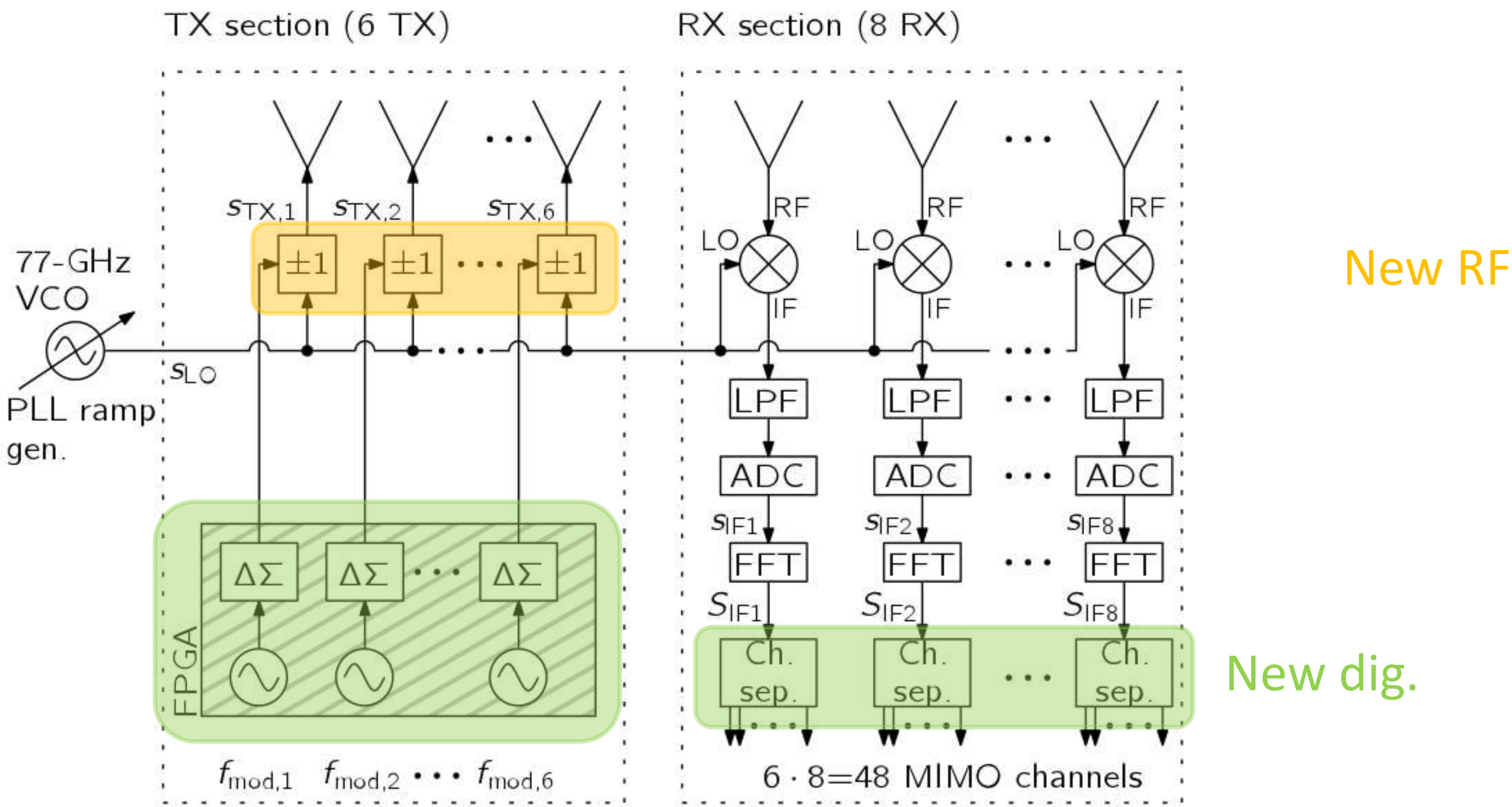
Measurement Results – FDMA MIMO

- Digital beamforming result with FDMA MIMO
- No motion compensation required



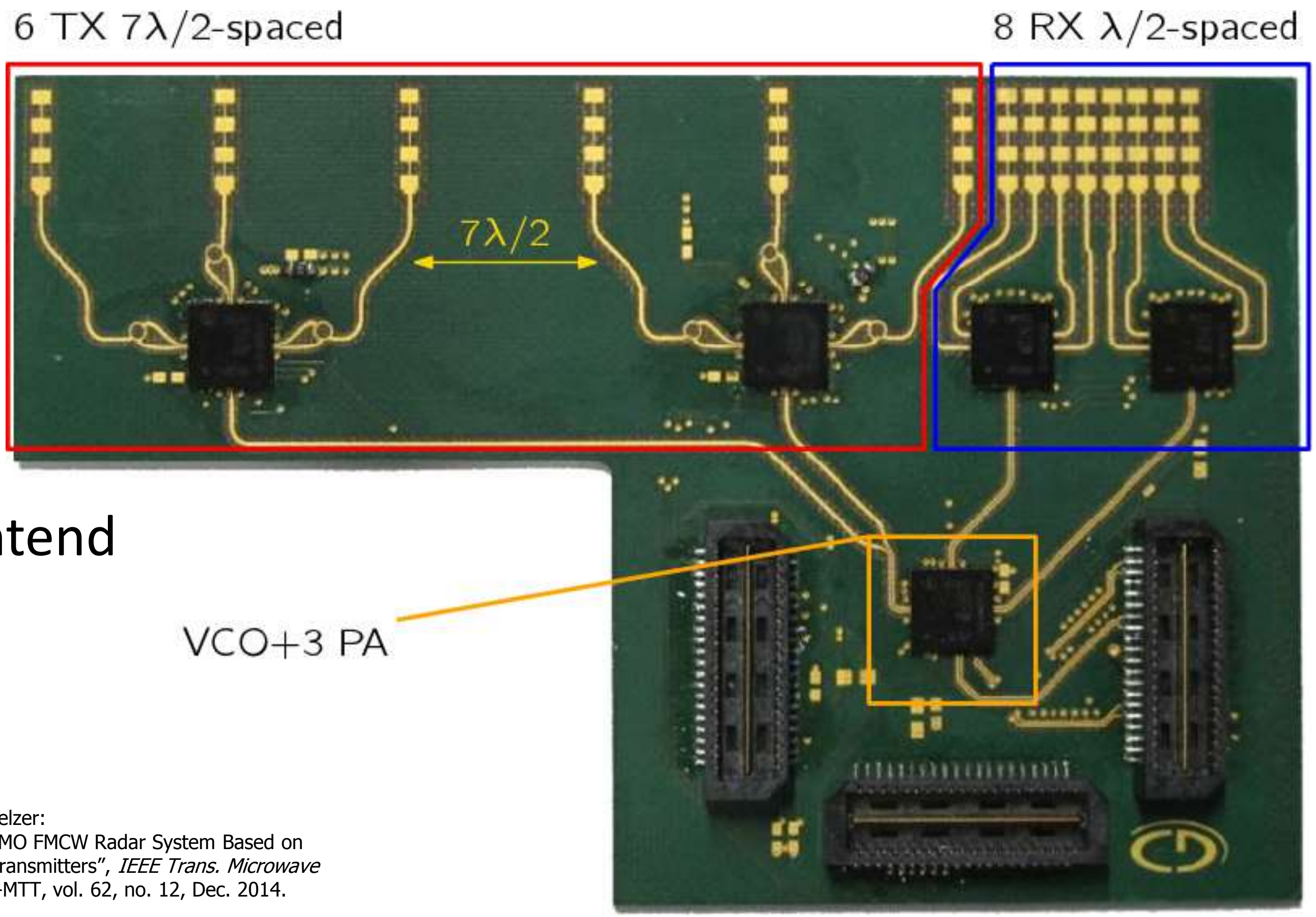


ΔΣ-TX FDM MIMO with 6 TX and 8 RX



R. Feger, C. Pfeffer, A. Stelzer:
"A Frequency-Division MIMO FMCW Radar System Using Delta-Sigma-Based Modulators"
IEEE MTT-S International Microwave Symposium, 2014, Tampa

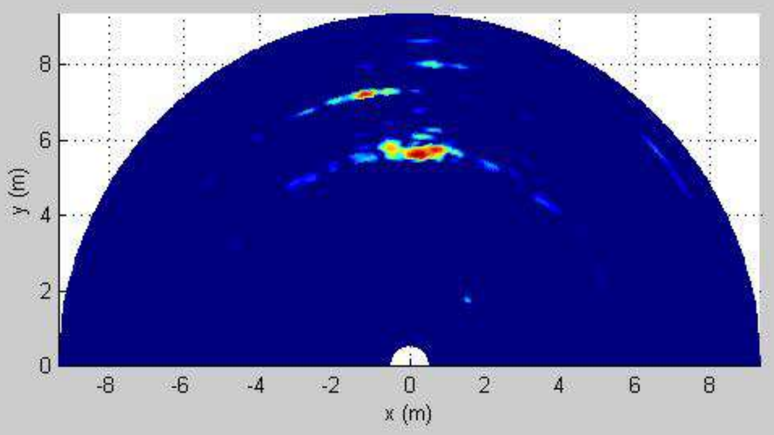
ΔΣ-TX FDM MIMO with 6 TX and 8 RX



RF Frontend

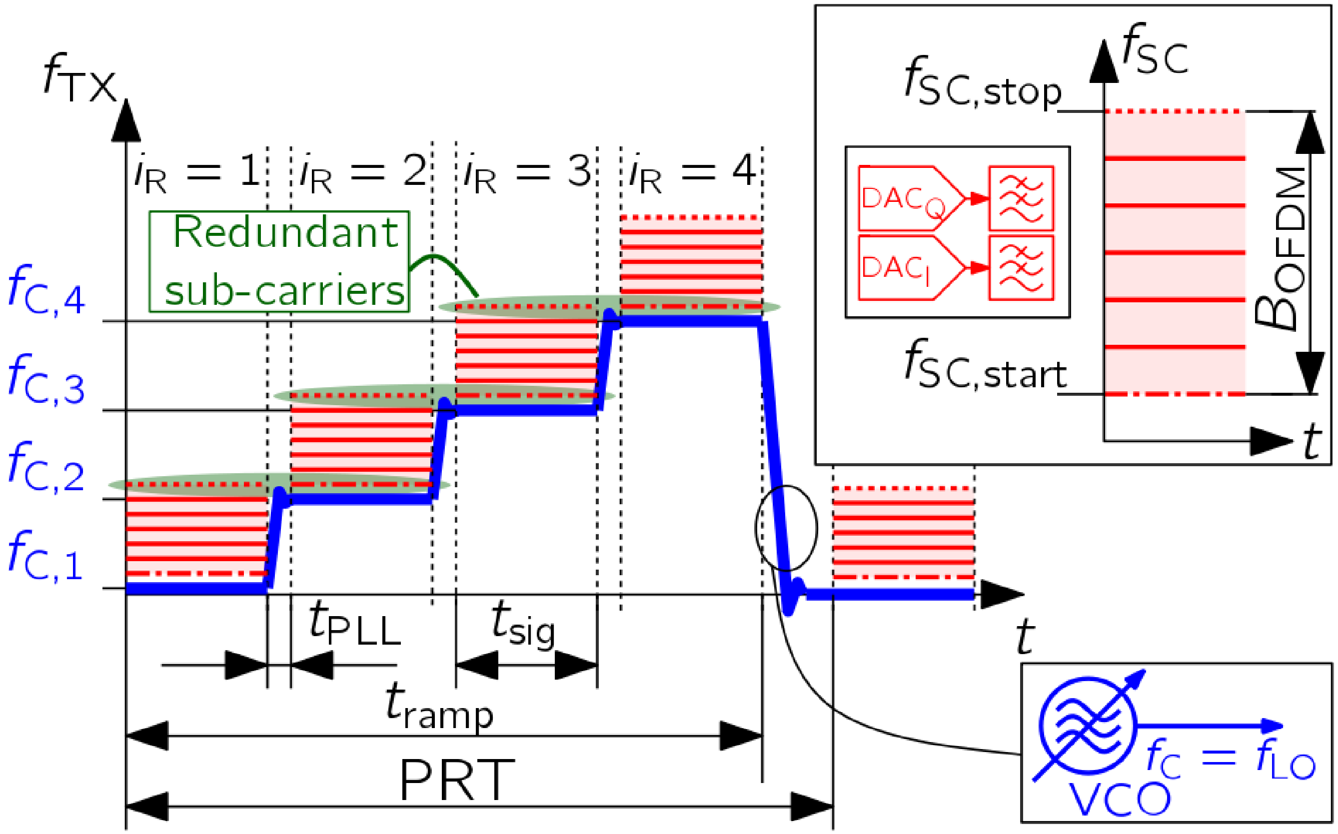
R. Feger, C. Pfeffer, A. Stelzer:
"A Frequency-Division MIMO FMCW Radar System Based on Delta-Sigma Modulated Transmitters", *IEEE Trans. Microwave Theory and Techn.,* IEEE-MTT, vol. 62, no. 12, Dec. 2014.

ΔΣ-TX FDM MIMO 6 TX, 8 RX Results



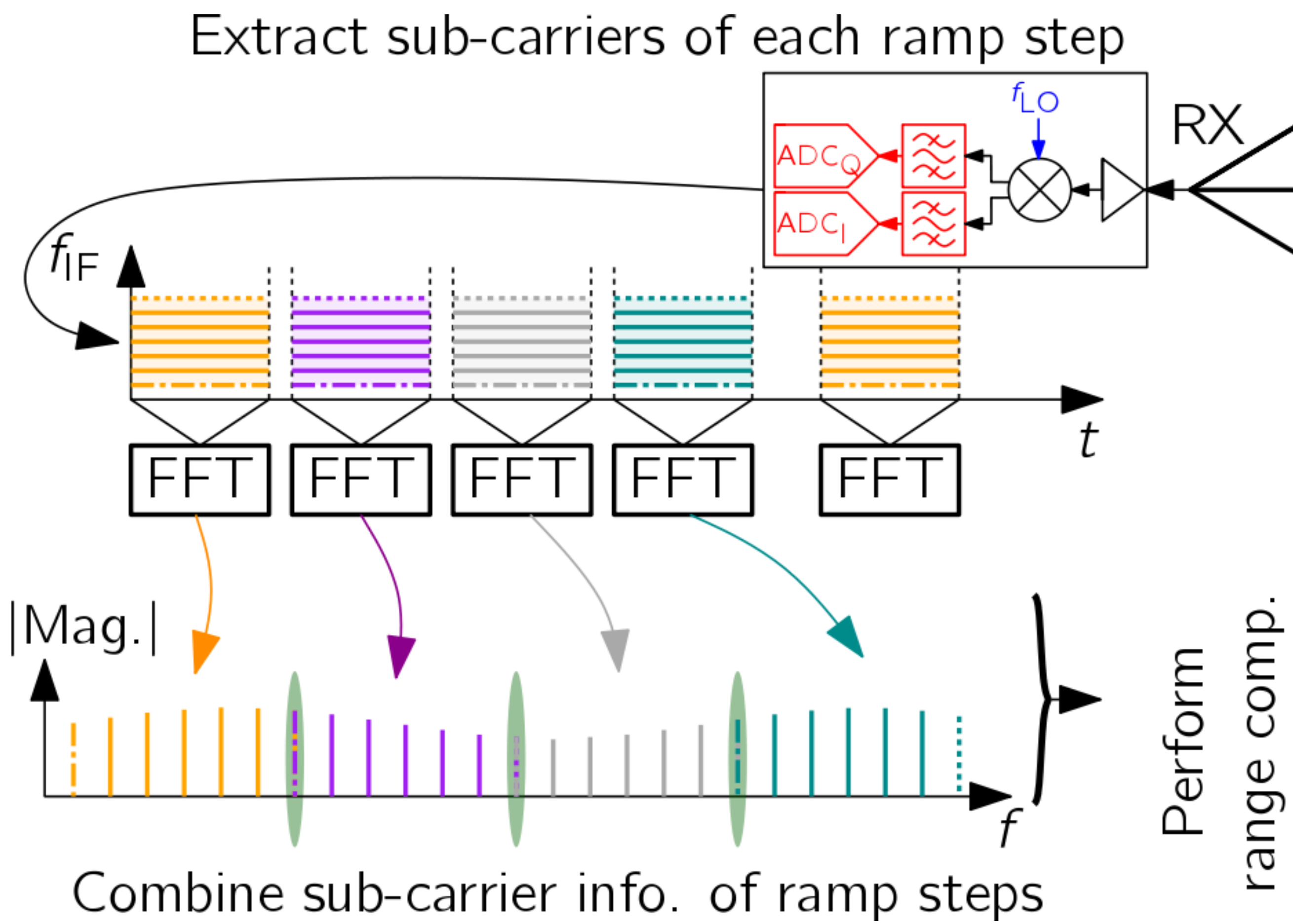
SOFDM – Principle (Transmit)

Transmit signal generation

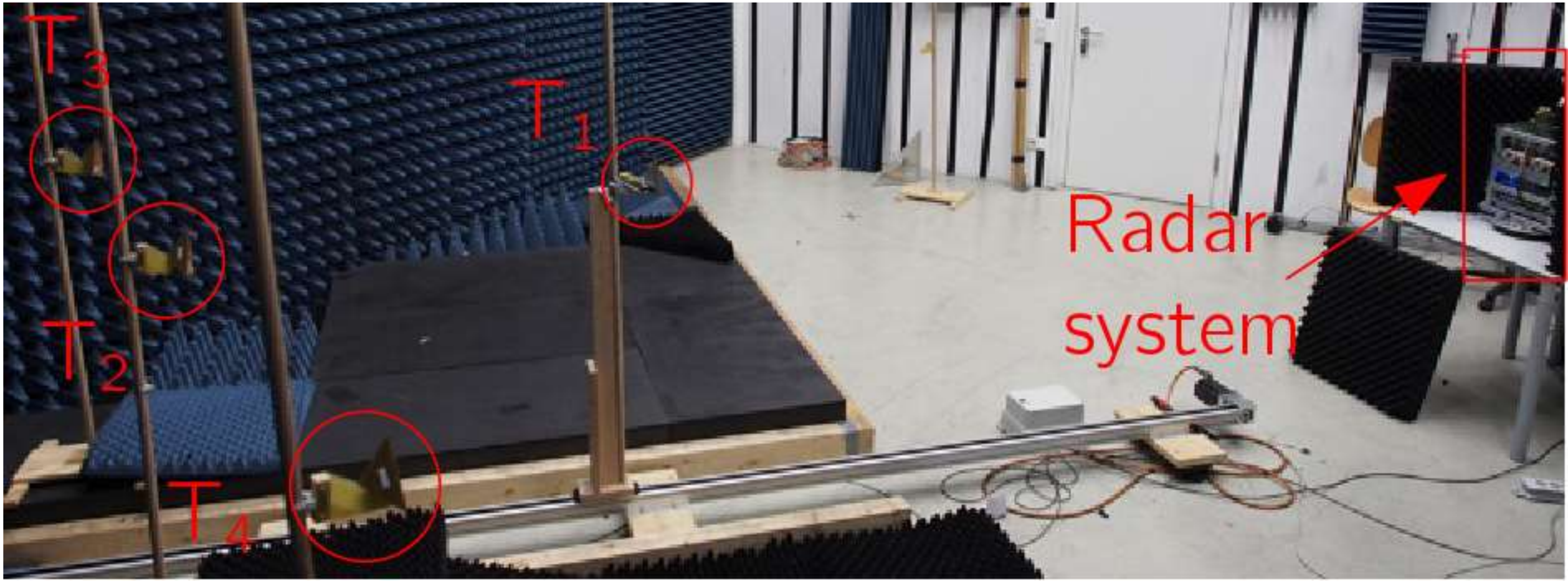


C. Pfeffer, R. Feger, and A. Stelzer,
„A Stacked RF-Carrier 77-GHz OFDM MIMO Radar System with 4 GHz Bandwidth,"
12th European Radar Conference (EuRAD), Paris, France, Sept. 2015.

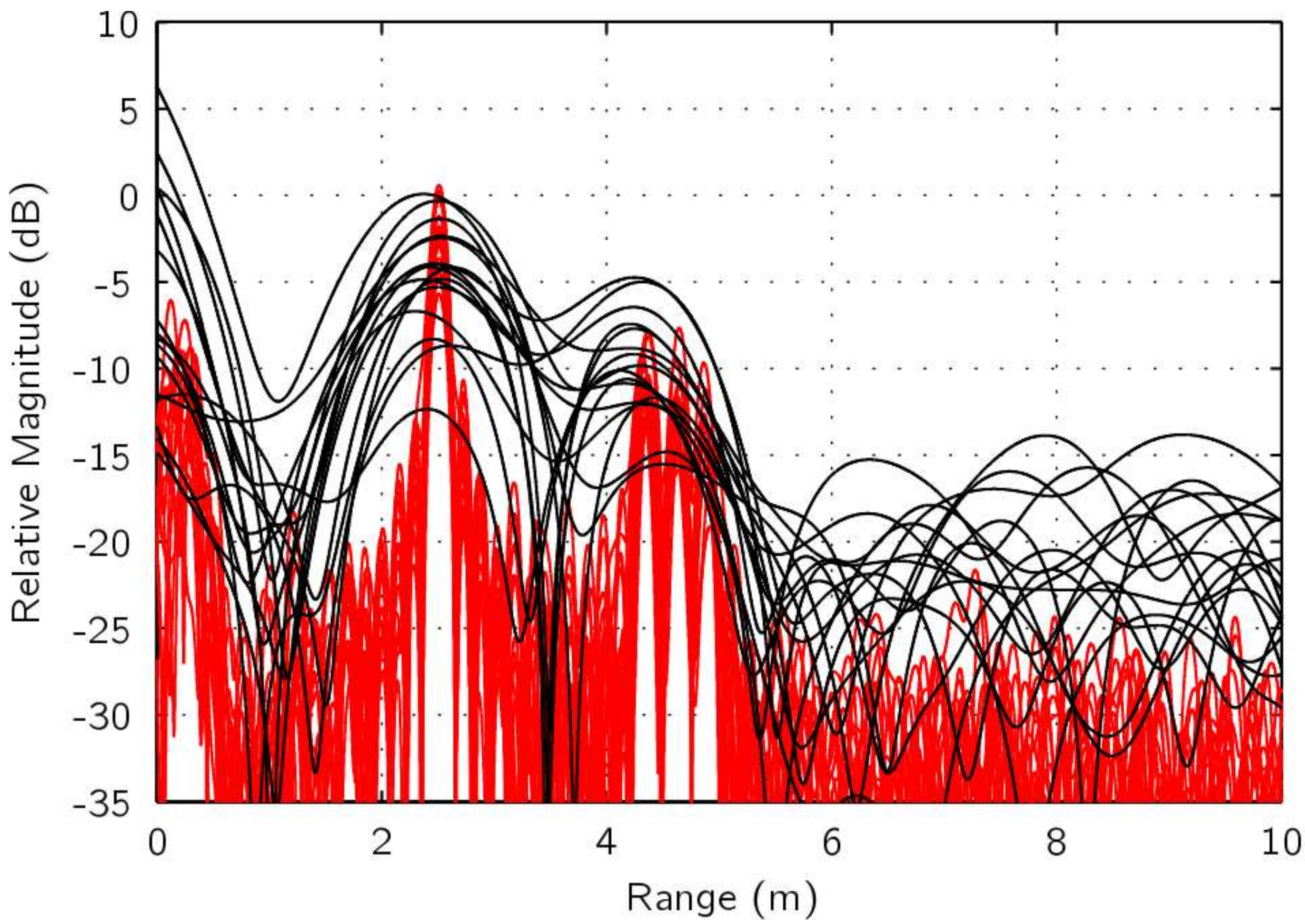
SOFDM – Principle (Receive+DSP)



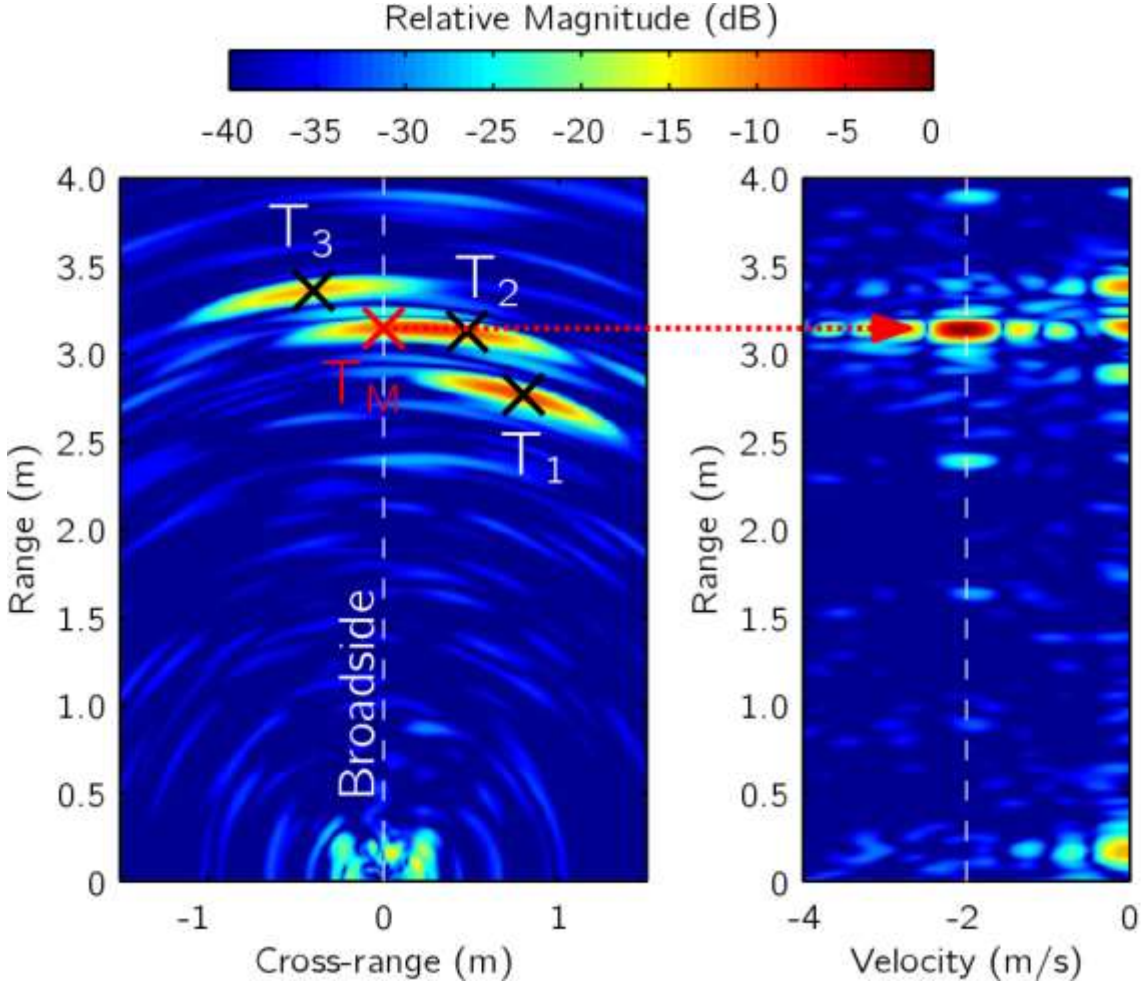
Measurement Setup



SOFDM 10 steps (BW=2GHz)

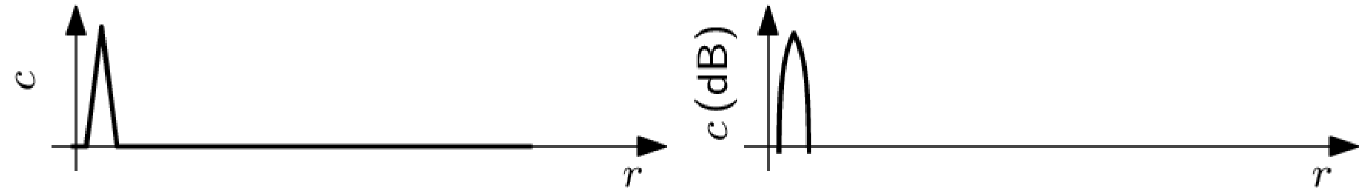


SOFDM Range/Doppler Measurements (2 m/s)



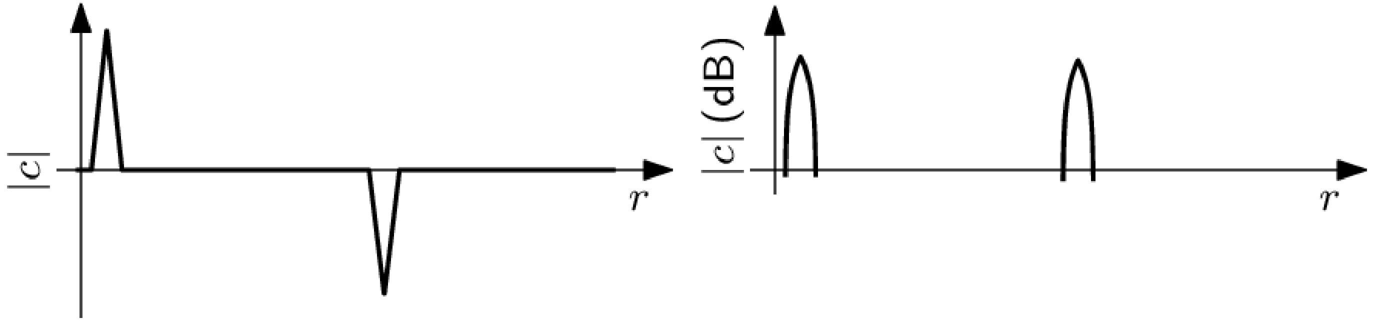
Phase-Coded CW Radar

- Perfect code's autocorrelation

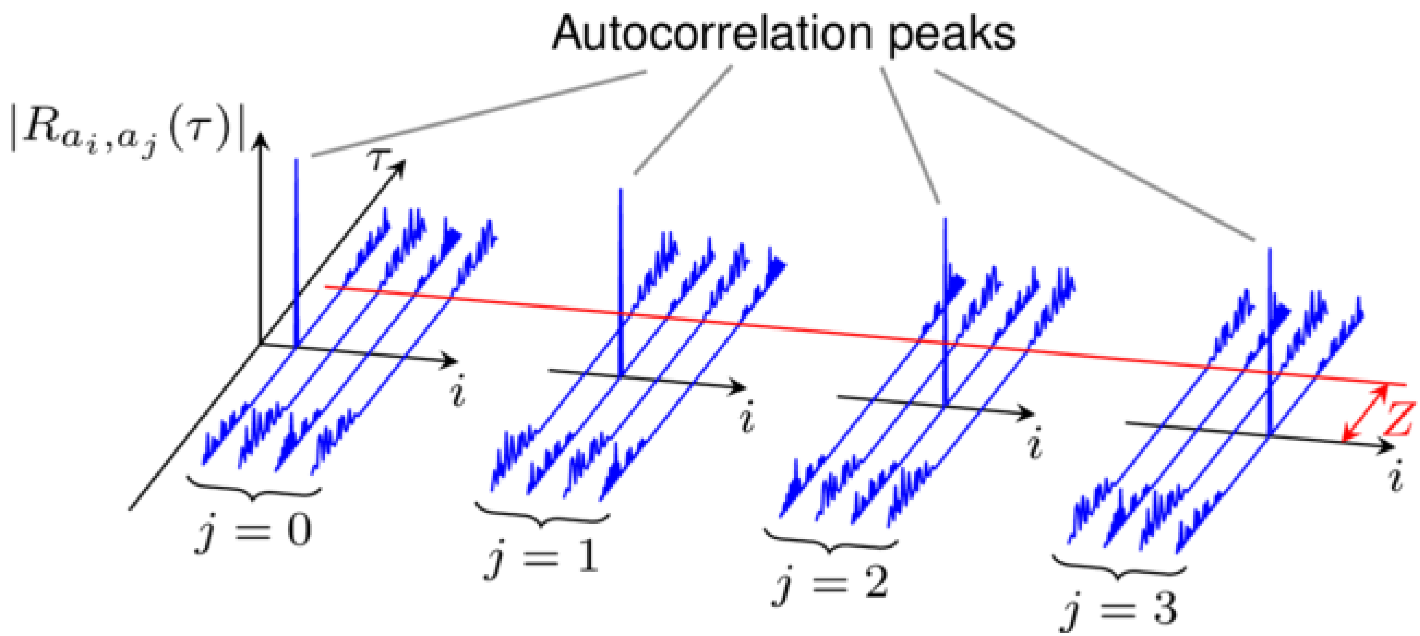


does **not** exist for purely binary phase-shift keying!

- Almost perfect autocorrelation sequence (APAS)

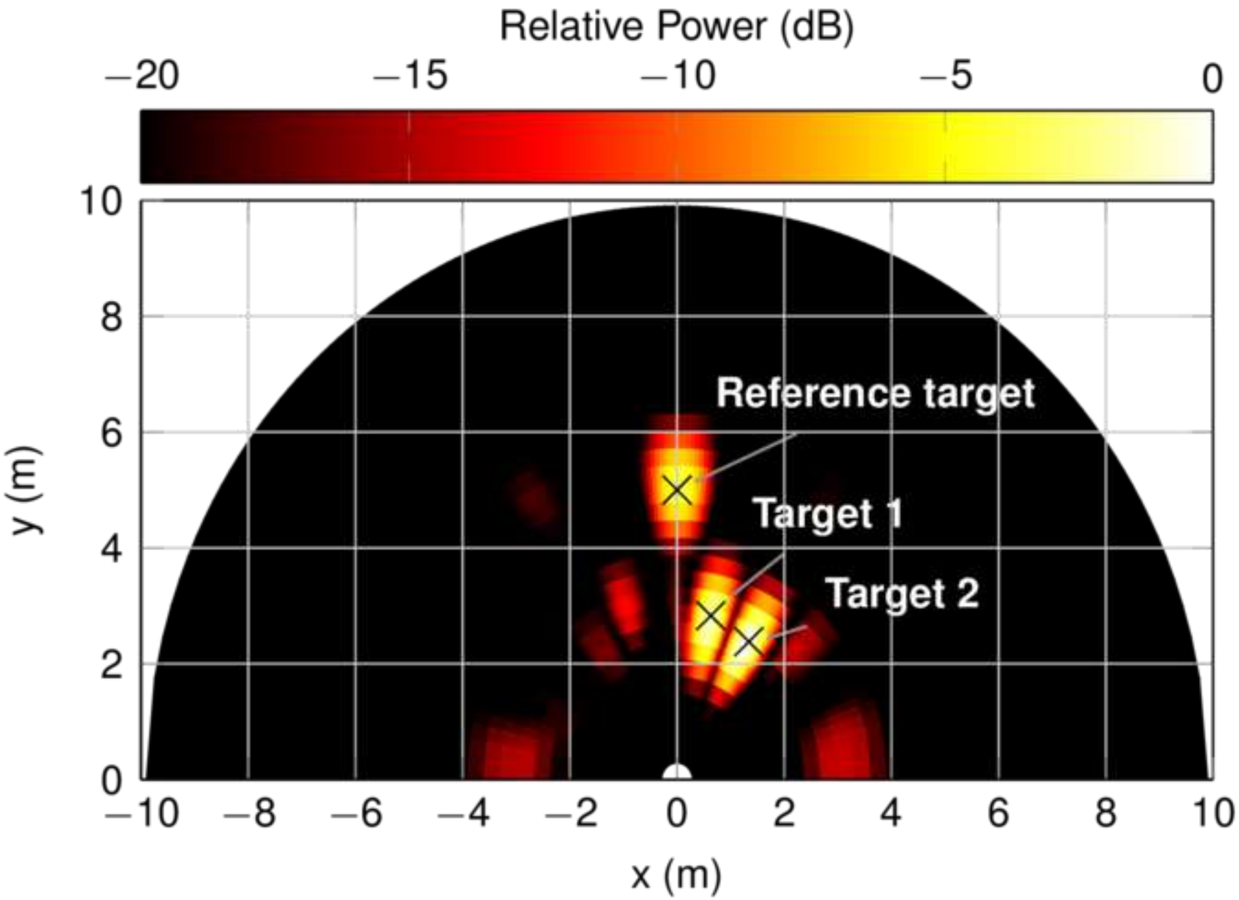


Zero Correlation Zone Sequence Sets



H. Haderer, R. Feger, C. Pfeffer, and A. Stelzer,
„Millimeter-Wave Phase-Coded CW MIMO Radar Using Zero-Correlation-Zone Sequence Sets,"
IEEE MTT-S Int. Microw. Symp. Dig., Phoenix, AZ, USA, May 2015.

PCCW-MIMO Meas. 4TX, 4RX

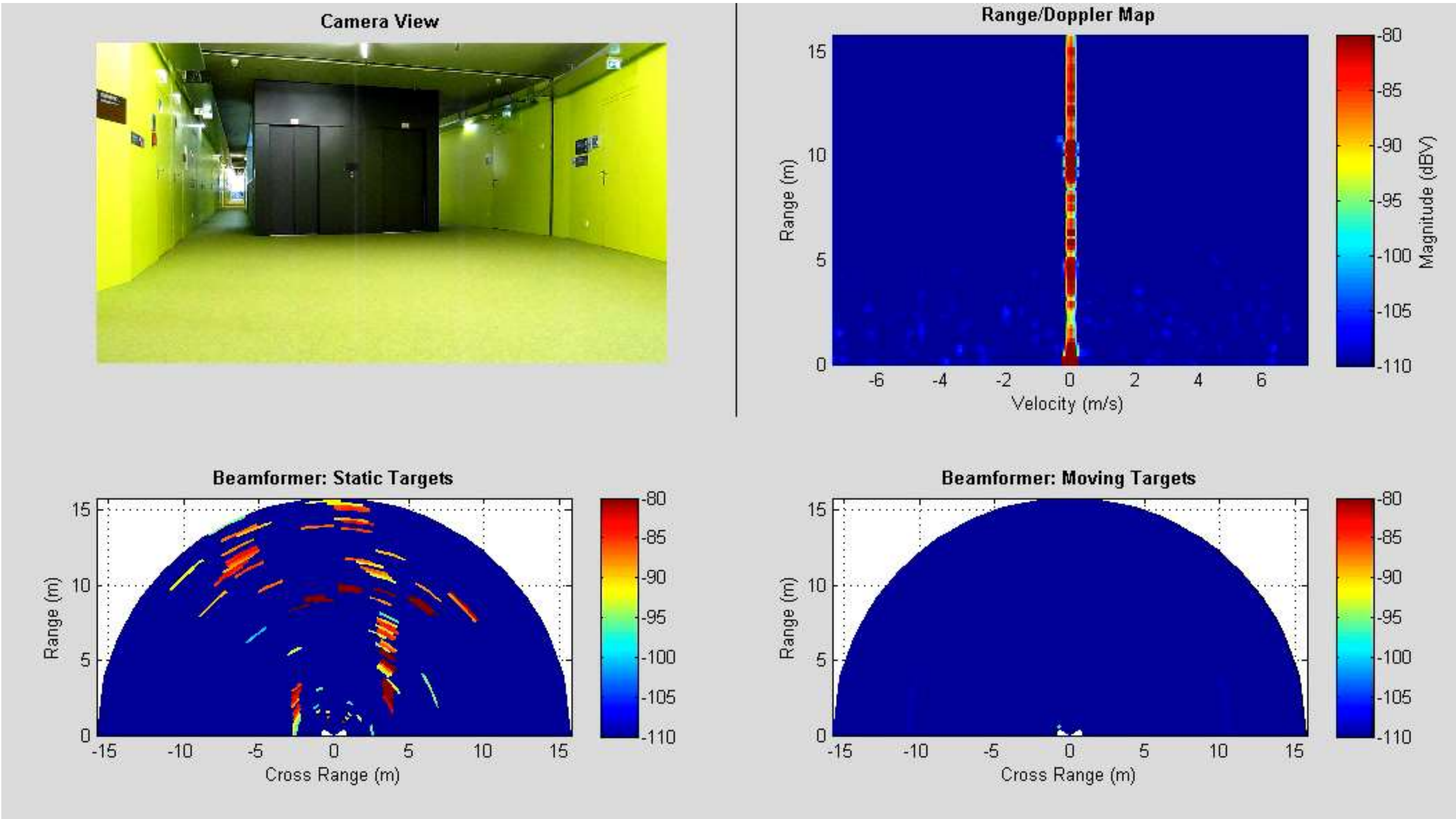


H. Haderer, R. Feger, C. Pfeffer, and A. Stelzer,
„Millimeter-Wave Phase-Coded CW MIMO Radar Using Zero-Correlation-Zone Sequence Sets,"
IEEE MTT-S Int. Microw. Symp. Dig., Phoenix, AZ, USA, May 2015.

SDR Platform and Radarbook

- SDR platform for complex scenarios and modulation.
- Radarbook for simple testing
  - Evaluation platform for research, development and teaching.
- Out-of-the-box measurements of Doppler, FMCW, MIMO, Range-Doppler
- Example Tracking of a UAV (offline)

UAV Tracking with Radarbook



Conclusion

- SDR Platform allows development of novel modulation schemes with real measurements
- (L)FMCW and (PRN) PCCW radar behave similar under similar assumptions
- Digital centric sensor design can be largely shifted towards VHDL based hardware design
- With CMOS the radar principle must be reassessed with respect to more digitally oriented approaches
- Technology node is also a question of topology, high RF-performance vs. high-digital performance

Acknowledgment

- Institute for Communications Engineering and RF-Systems
- Johannes Kepler University Linz
- Danube Integrated Circuit Engineering
- Infineon Technologies AG
- Linz Center of Mechatronics