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Automotive Radar

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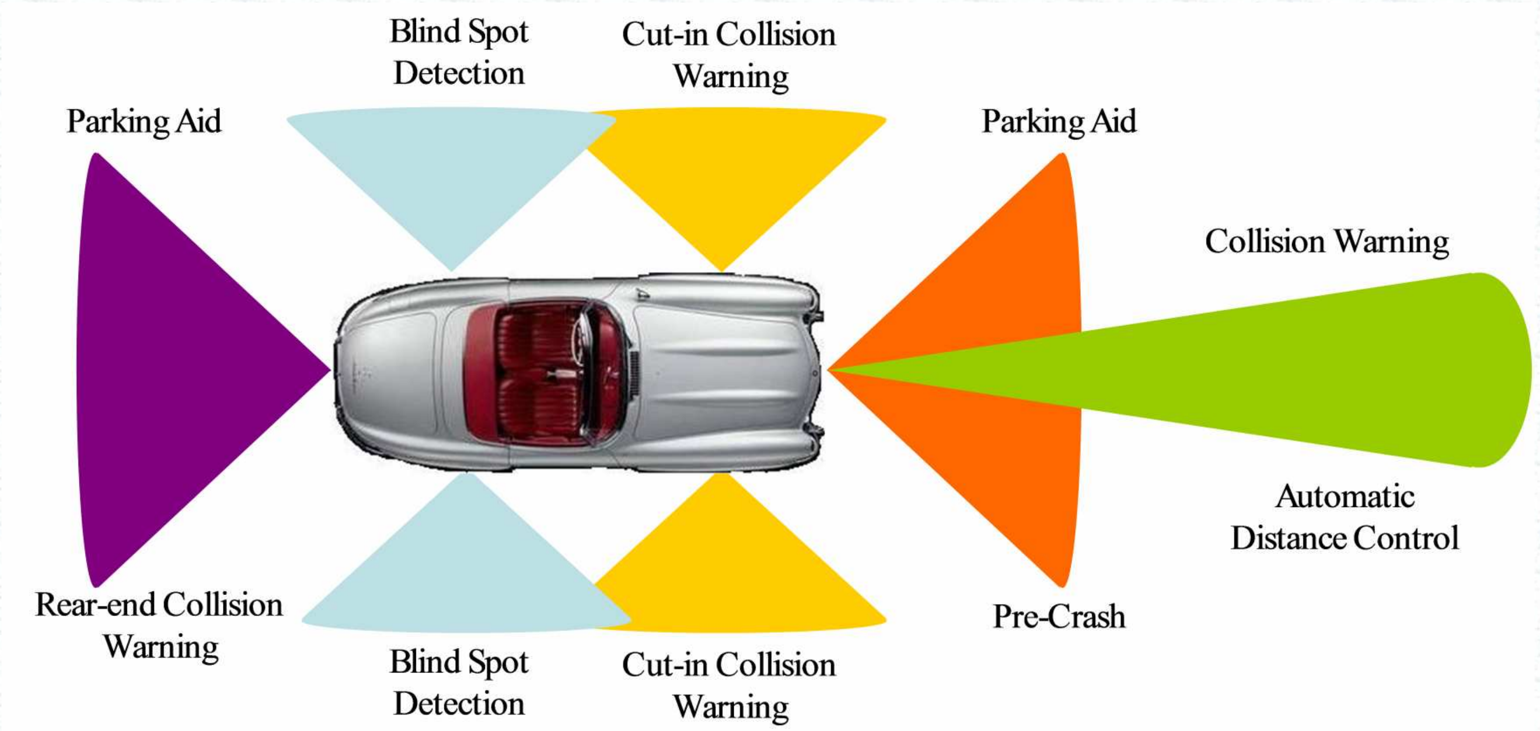
2012 IEEE Radar Conference, May 7-11, Atlanta

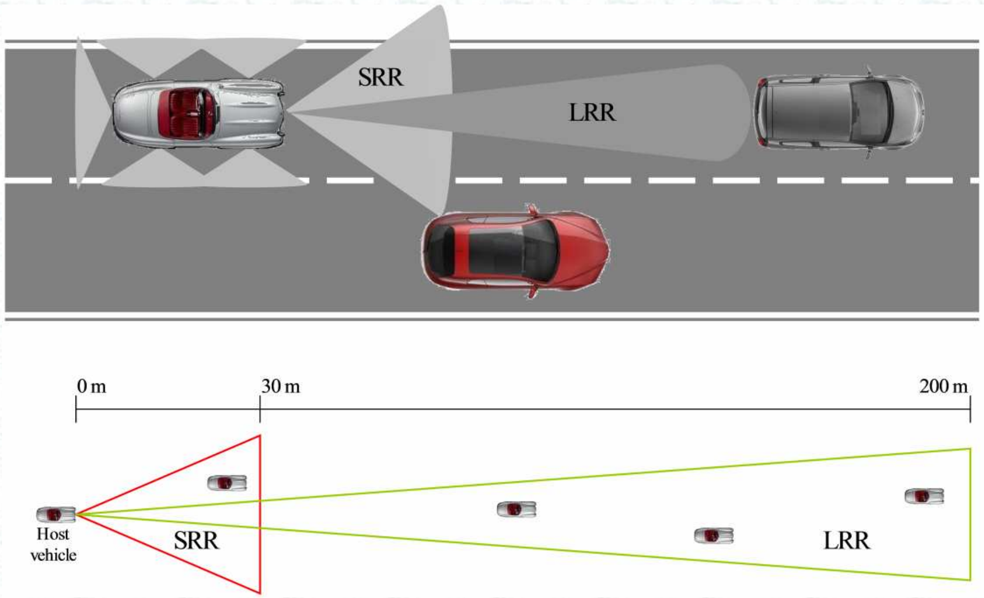
Automotive RADAR – Why?

- Automotive RADARs as core sensor (range, speed) of driver assistance systems: long range (LRR) for Adaptive Cruise Control, medium range (MRR) for cross traffic alert and lane change assist, short-range (SRR) for parking aid, obstacle/pedestrian detection



Automotive RADAR – Why?

- W.r.t. to other sensing technology RADAR is robust in harsh environments (bad light, bad weather, extreme temperatures)
- Multiple RADAR channels required for additional angular information
- Data fusion in the digital domain with other on-board sensors

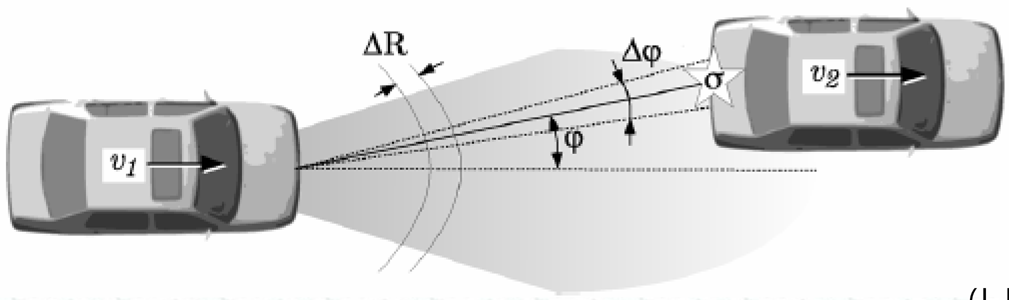


Automotive RADAR –a bit of Story

- First tentative for mm-wave automotive RADAR since 70's (but integrated-unfriendly technologies lead to large size, high cost)
- Since 1998-1999 first generation of radar sensors (Daimler, Toyota)
- Last generation based on 180/130 nm SiGe chipset and advanced packaging with integrated antenna commercially available (e.g. Bosch)
- High RADAR frequency (small λ) allows small size and weight, highly integration with SiGe and future CMOS tech. will reduce assembly and testing costs and hence final user cost much below US$1000
- Market expanding at 40%/year and is expected increasing with all premium/middle cars having a RADAR in next years (7% of all vehicles sold world-wide, mainly in Europe, Japan and US, will have RADARs)

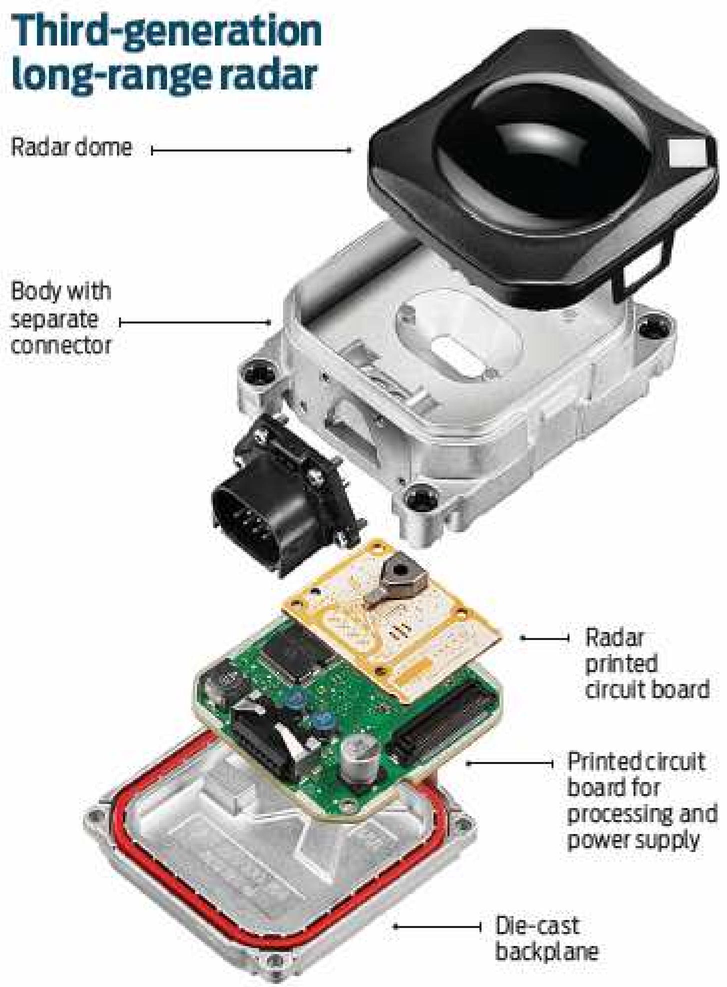
Automotive RADAR – Technical spec

Type	LRR	MRR	SRR
Maximum transmit power (EIRP)	55 dBm	-9 dBm/MHz	-9 dBm/MHz
Frequency band	76-77 GHz	77-81 GHz	77-81 GHz
Bandwidth	600 MHz	600 MHz	4 GHz
Distance range $R_{\min}...R_{\max}$	10-250 m	1-100 m	0.15-30 m
Distance resolution ΔR	0.5 m	0.5 m	0.1 m
Distance accuracy δR	0.1 m	0.1 m	0.02 m
Velocity resolution Δv	0.6 m/s	0.6 m/s	0.6 m/s
Velocity accuracy δv	0.1 m/s	0.1 m/s	0.1 m/s
Angular accuracy $\delta\varphi$	0.1°	0.5°	1°
3 dB beamwidth in azimuth $\pm\varphi_{\max}$	±15°	±40°	±80°
3 dB beamwidth in elevation $\pm\vartheta_{\max}$	±5°	±5°	±10°



(J. Hasch et al., IEEE
Tran. Micr Theory Tech, 2012)

Automotive RADAR with SiGe mm-Wave T/R

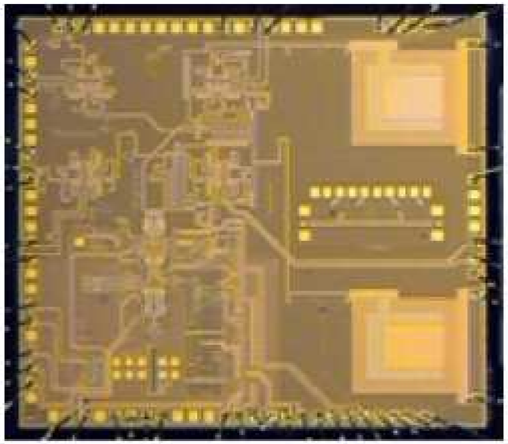


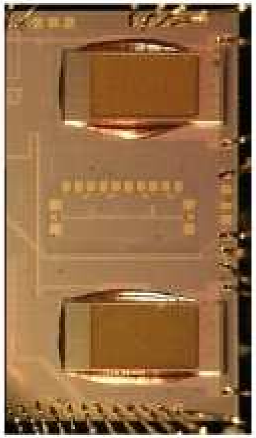
B. Fleming, IEEE Vehicular Tech. Mag. 2012

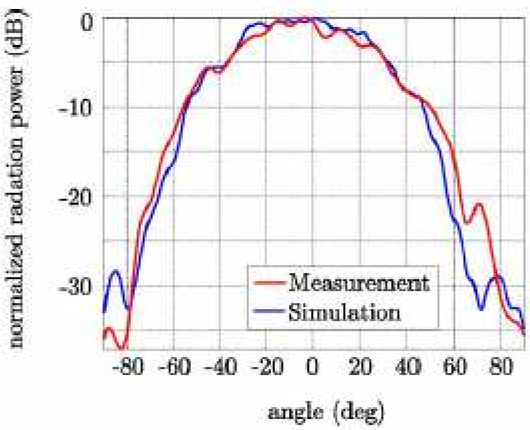
- Commercially available from Bosch based on SiGe Infineon Chipset
- 2 PCB boards
- FCMW modulation
- LRR 7dBm Pout, 4 channels (2 TX/RX, 2 RX only), dielectric lens antenna provides high gain for Rmax 250m
- Alternative versions with PCB or on-chip Integrated antennas

Example on-chip integrated antenna for 77 GHz automotive RADAR

- On-chip antenna elements based on shorted λ/4 microstrip lines, formed by the top and bottom metal layers of the chip backend
- Quartz glass resonators are positioned above the on-chip patch antenna elements to improve efficiency and bandwidth. The antennas are spaced at a distance to allow direction of arrival (DOA) estimation of a target or provide separate beams illuminating a dielectric lens







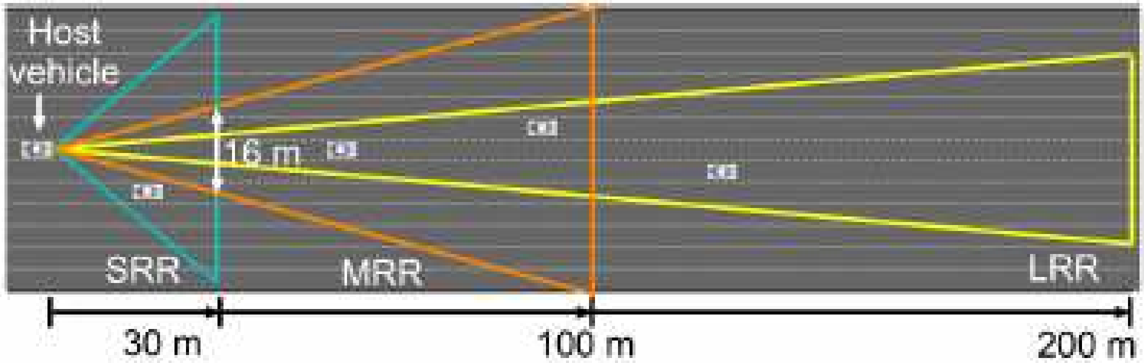
(J. Hasch et al., IEEE Tran. Micr Theory Tech, 2012)

Main signal processing functions in automotive RADARs:

- Range estimation
- Doppler frequency estimation
- CFAR techniques
- Direction of arrival (DOA) estimation
- Tracking

Long Range Radar (LRR)

Observation area



Parameter	Value
Velocity resolution	$\Delta v_r = 2.25$ km/h
Range resolution	$\Delta R = 1$ m
Unambiguous radial velocity	$v_{max} = 250$ km/h
Maximum range	$R_{max} = 200$ m
Short measurement time	$T_{CPI} = 10$ ms

Requirements for LRR RADAR

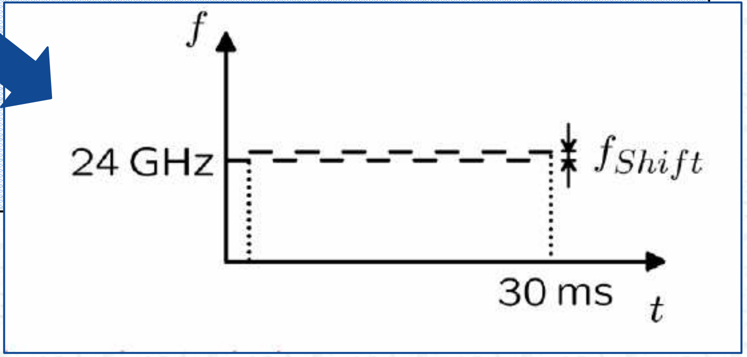
Functionalities: Autonomous Cruise Control (ACC)
Collision warning

LRR for vehicular applications

Transmitted signals

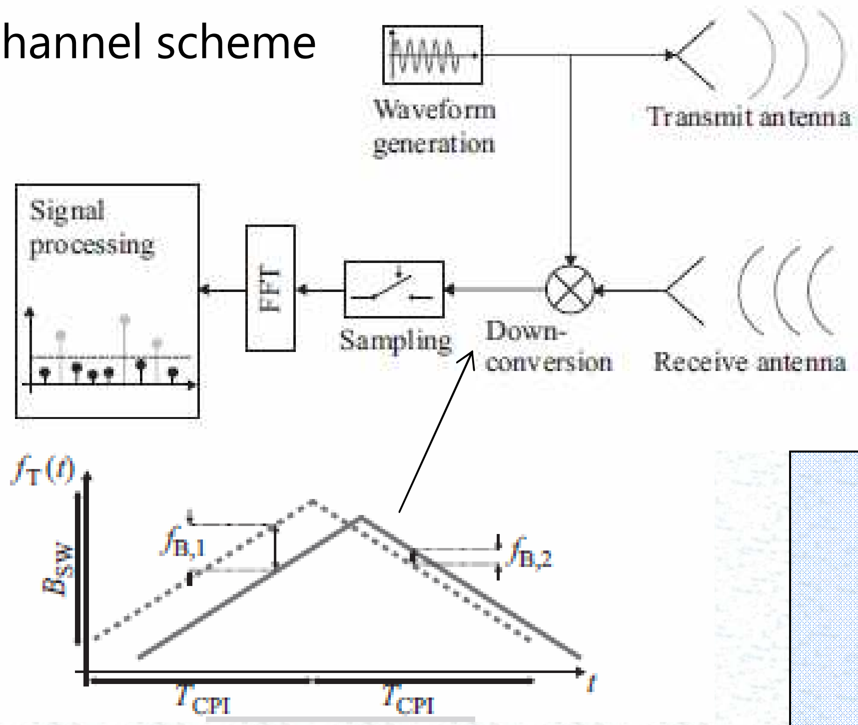
Some special waveforms must be used to fulfill the requirements of simultaneous range and radial velocity measurement:

- Pulse Doppler
- FMCW with (at least) up- and down-chirp signals
- Frequency Shift Keying (FSK) CW
- MFSK CW



LRR for vehicular applications

Single channel scheme



$$s_T(t) = \cos\left[2\pi\left(f_T t \pm \frac{B_{sw}}{T_{CPI}}\frac{t^2}{2}\right)\right]$$

$$s_R(t) = s_T\left[t - \tau(t)\right]$$

$$f_{B,1} = f_D + f_\tau = -\frac{2}{\lambda}v_r - \frac{2B_{sw}}{cT_{CPI}}R$$

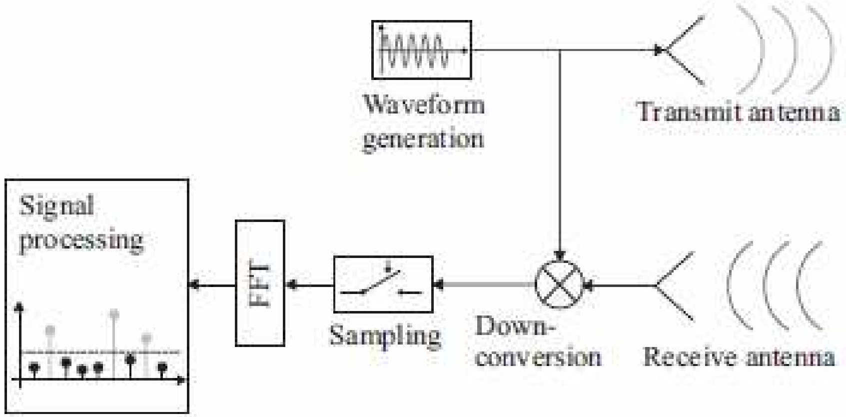
$$f_{B,2} = f_D - f_\tau = -\frac{2}{\lambda}v_r + \frac{2B_{sw}}{cT_{CPI}}R$$

Parameter	Value
Carrier frequency	$f_T = 24$ GHz
Time on target	$T_{CPI} = 10$ ms
Sweep bandwidth	$B_{sw} = 150$ MHz
Velocity resolution	$\Delta v_r = 2.25$ km/h
Range resolution	$\Delta R = 1$ m
Unambiguous radial velocity	$v_{max} = 250$ km/h
Unambiguous range	$R_{max} = 200$ m
Base band bandwidth	$f_{B,max} = 31.2$ kHz

Parameters for an LRR radars
24 GHz or 77 GHz

H. Rohling, Automotive Radar tutorial, 2008

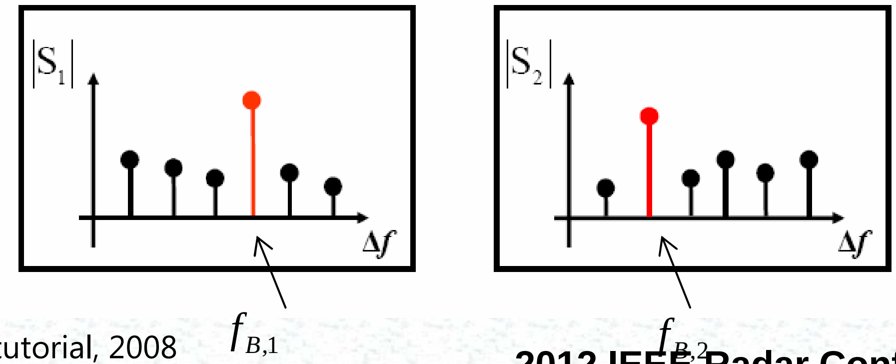
LRR for vehicular applications



FFT: applied on each segment (up and down chirp)

frequency and range estimation accuracy depends on the number of FFT points. Typical values: 128-4096 points

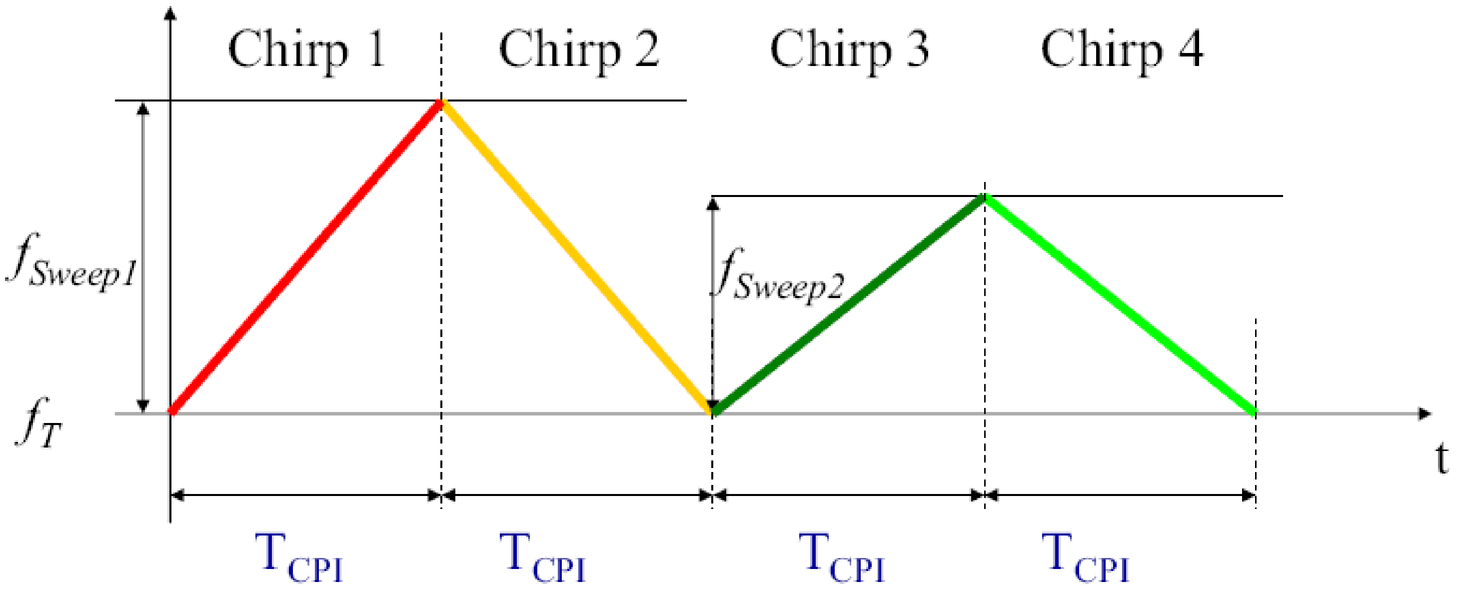
up chirp



down chirp

H. Rohling, Automotive Radar tutorial, 2008

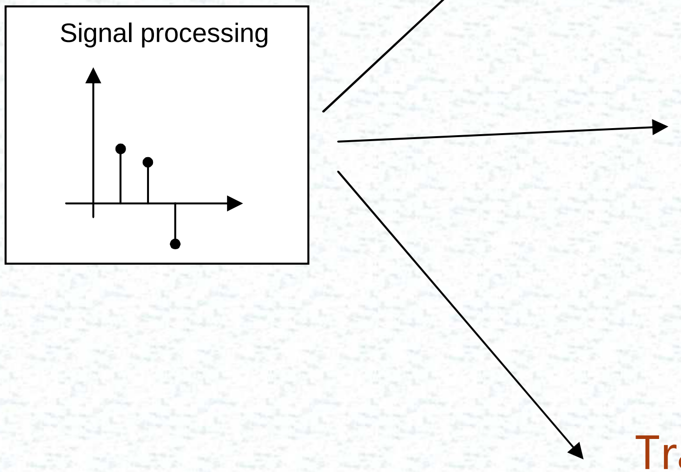
LRR for vehicular applications



With only one up and down chirp , two targets are ambiguous. With four chirps two targets can be easily resolved

H. Rohling, Automotive Radar tutorial, 2008

LRR for vehicular applications



CFAR techniques for detection
Most common: 1D-CA-CFAR applied on FFT output (frequency domain)

DOA estimation
Most common: Monopulse with two antennas

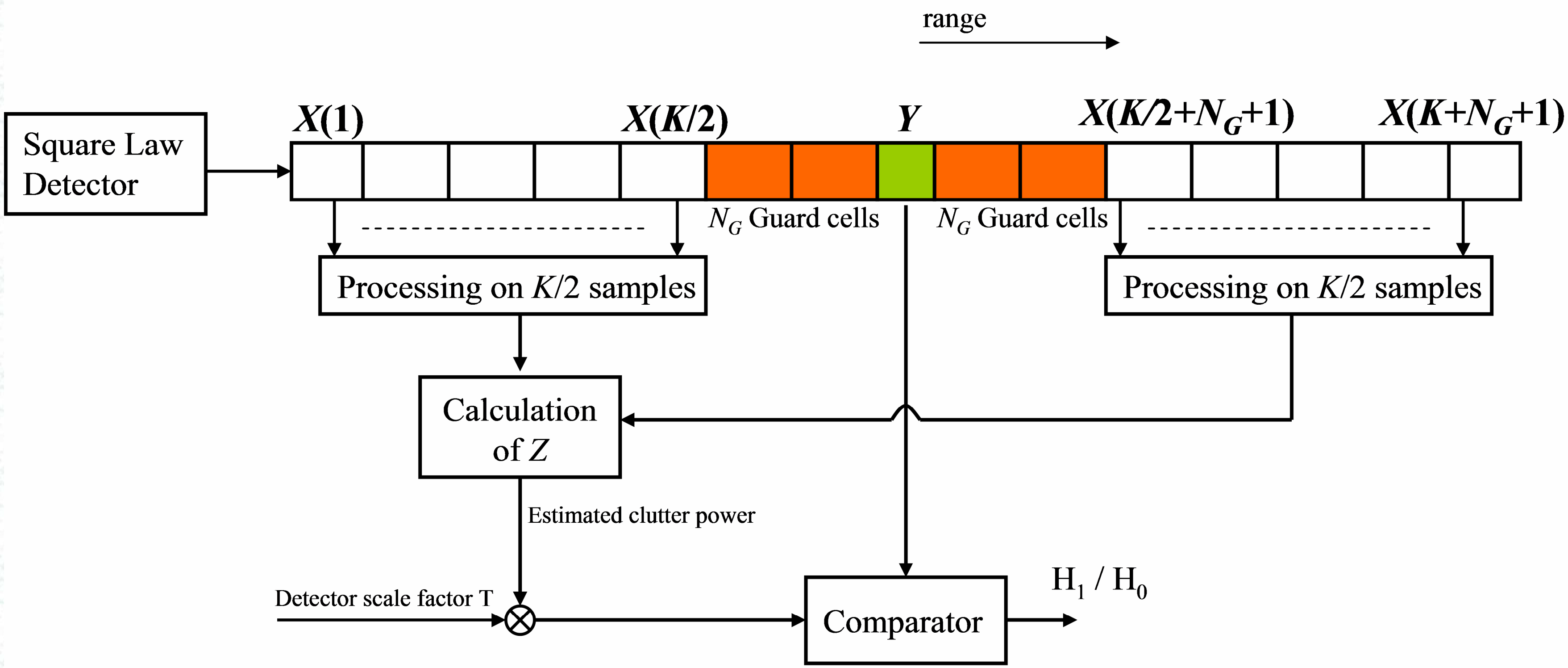
Tracking techniques after detection
Most common: linear KF

Incoherent CFAR detectors

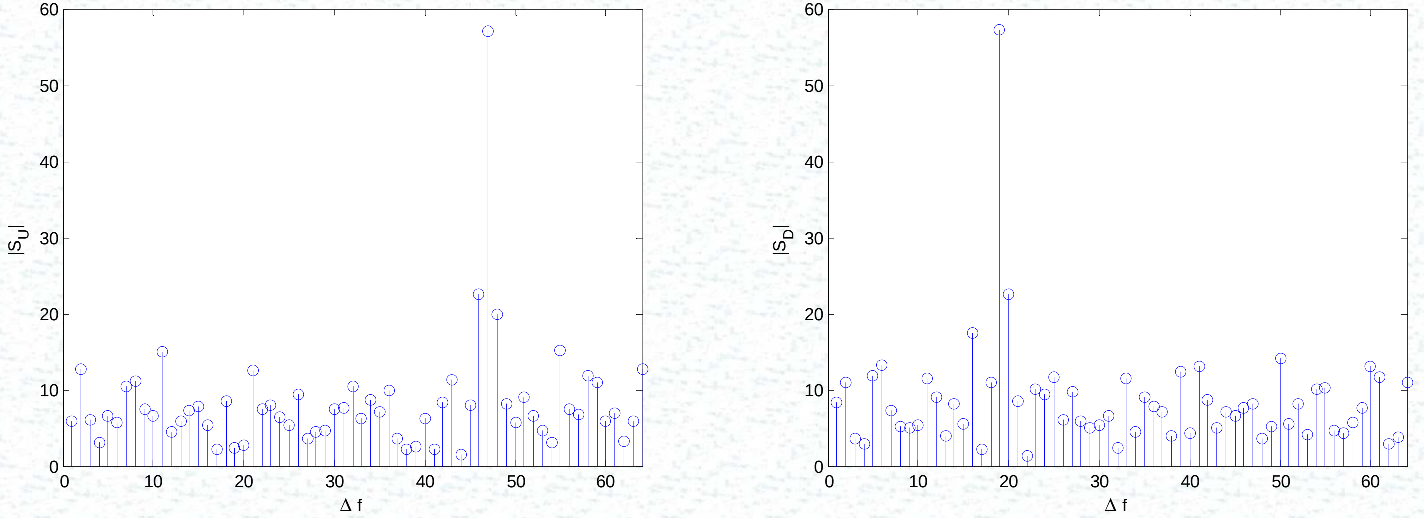
Depending on the adaptive threshold Z we have different CFAR techniques

- CA-CFAR : $Z = \mathrm{mean}(X_1, X_2, \ldots X_N)$
- GO-CFAR: $Z_1 = \mathrm{mean}(X_1, X_2, \ldots X_{N/2})$
  $Z_2 = \mathrm{mean}(X_{N/2+1}, X_{N/2+2}, \ldots X_N)$
  $Z = \max(Z_1, Z_2)$
- SO-CFAR: $Z_1 = \mathrm{mean}(X_1, X_2, \ldots X_{N/2})$
  $Z_2 = \mathrm{mean}(X_{N/2+1}, X_{N/2+2}, \ldots X_N)$
  $Z = \min(Z_1, Z_2)$
- OS-CFAR: $\boldsymbol{Y} = \mathrm{sort}(X_1, X_2, \ldots X_N)$
  $Z = Y_K$

Incoherent CFAR detectors

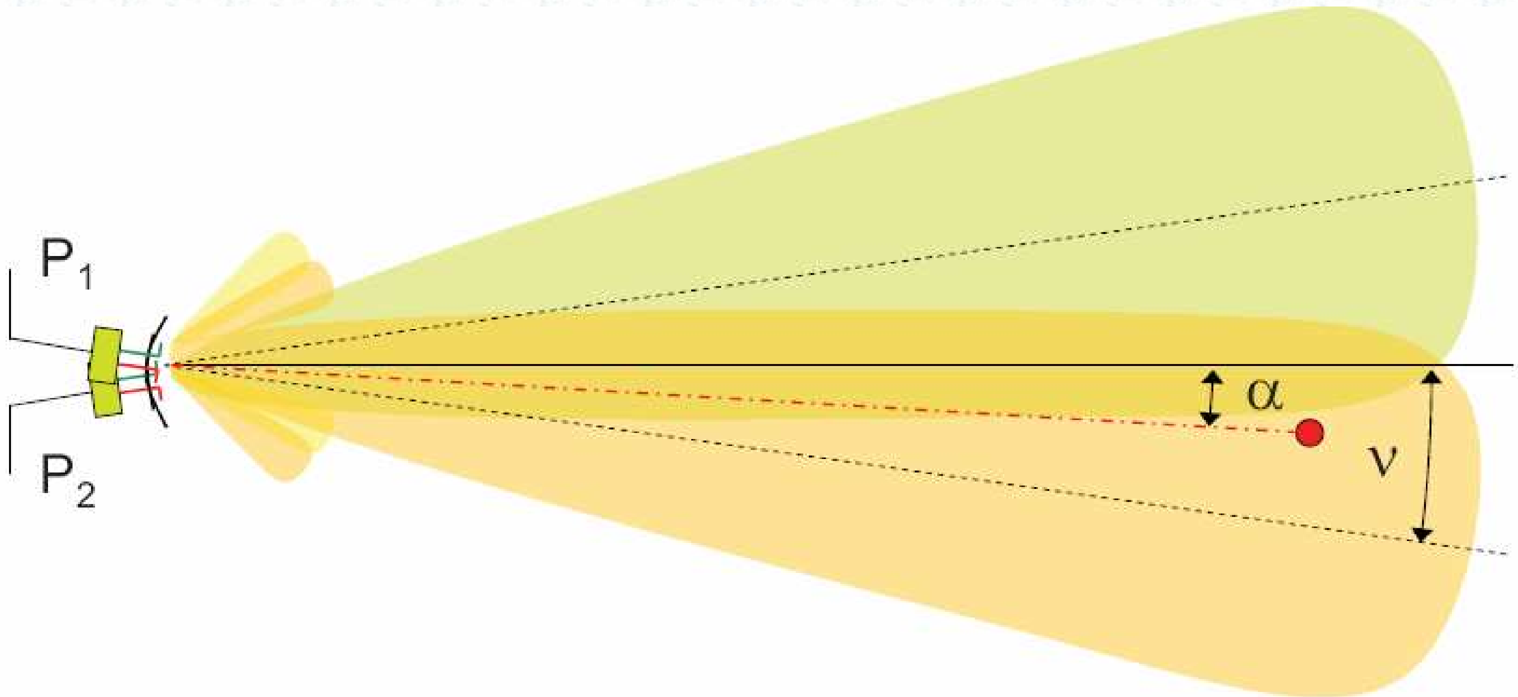


Incoherent CFAR detectors



Plot of the absolute value of the FFT for
up- and down-chirp

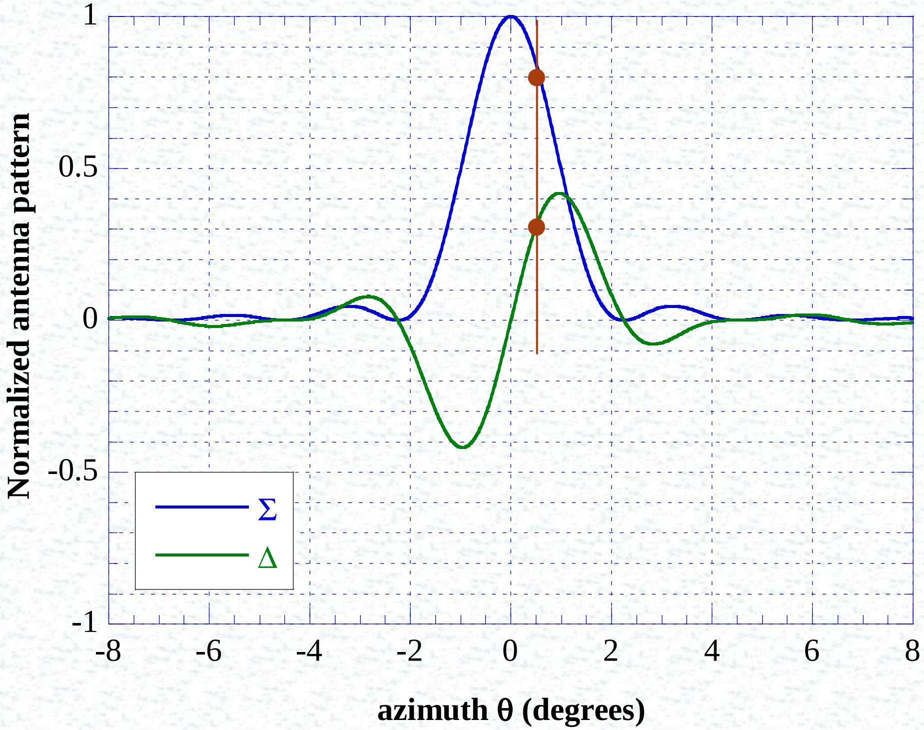
DOA estimation - Monopulse



- It needs two beams for each angular coordinate
- Sum and difference patterns are used
- It can use single or multiple pulses

H. Rohling, Automotive Radar tutorial, 2008

DOA estimation - Monopulse

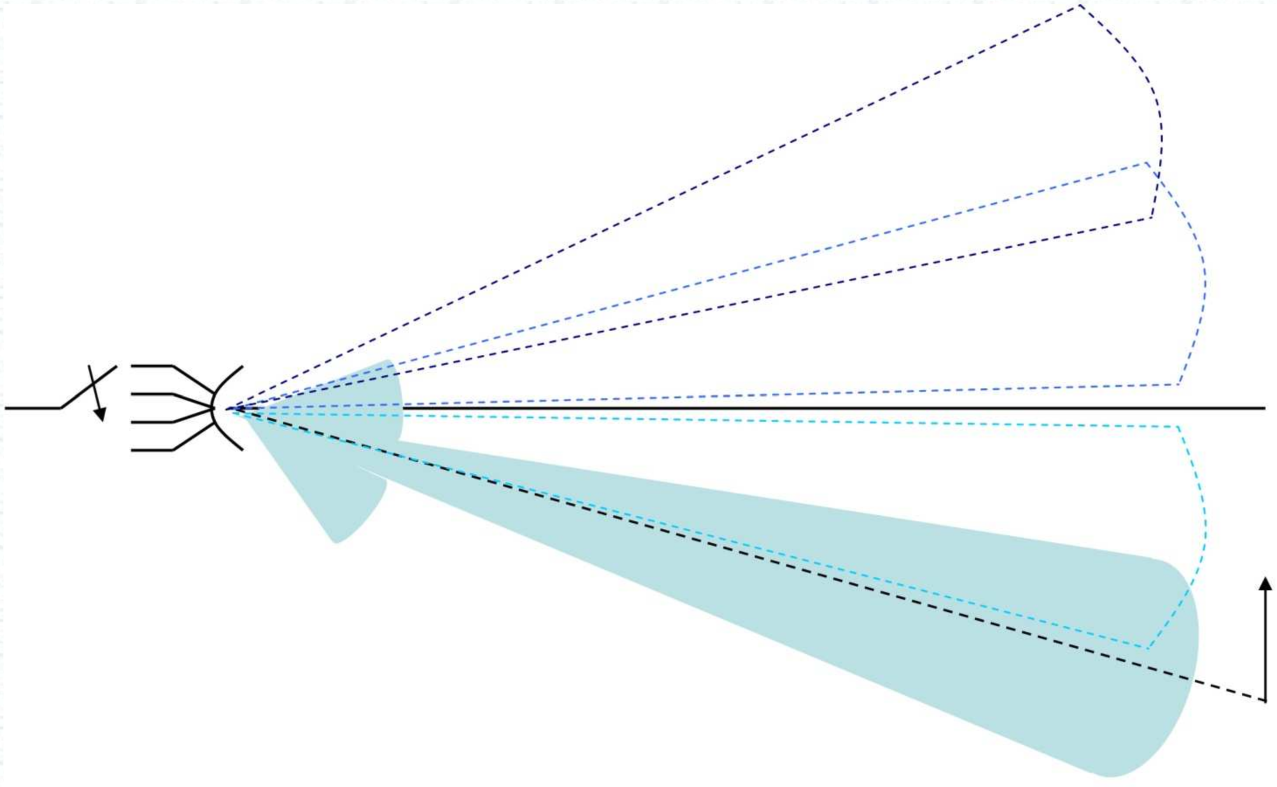


Example, with Gaussian antenna pattern and -3dB beamwidth=3°

Ideally, without noise

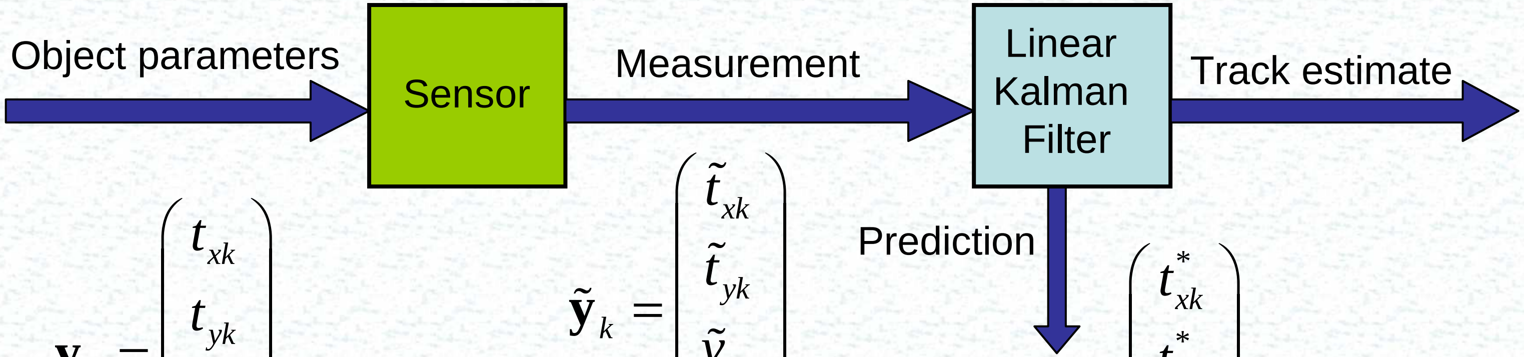
$$\alpha \simeq \frac{\Delta}{\Sigma}$$

DOA estimation – Sequential lobing



Tracking - Linear Kalman filter

$$K_k = P_k^* \left(P_k^* + R\right)^{-1}$$



$$\mathbf{y}_k = \begin{pmatrix} t_{xk} \\ t_{yk} \\ v_{xk} \\ v_{yk} \end{pmatrix} \qquad \tilde{\mathbf{y}}_k = \begin{pmatrix} \tilde{t}_{xk} \\ \tilde{t}_{yk} \\ \tilde{v}_{xk} \\ \tilde{v}_{yk} \end{pmatrix} \qquad \mathbf{y}_k = \begin{pmatrix} t^*_{xk} \\ t^*_{yk} \\ v^*_{xk} \\ v^*_{yk} \end{pmatrix} \qquad \hat{\mathbf{y}}_k = \begin{pmatrix} \hat{t}_{xk} \\ \hat{t}_{yk} \\ \hat{v}_{xk} \\ \hat{v}_{yk} \end{pmatrix}$$

Linear model

$$\begin{pmatrix} t_{x_k} \\ t_{y_k} \\ v_{x_k} \\ v_{y_k} \end{pmatrix} = \begin{pmatrix} 1 & 0 & \Delta T & 0 \\ 0 & 1 & 0 & \Delta T \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} t_{x_{k-1}} \\ t_{y_{k-1}} \\ v_{x_{k-1}} \\ v_{y_{k-1}} \end{pmatrix} \qquad \mathbf{y}_k = \mathbf{A}\mathbf{y}_{k-1}$$

H. Rohling, Automotive Radar tutorial, 2008

Linear Kalman filter

Prediction step:

- Prediction estimation based on Process matrix A:

$$\hat{\mathbf{y}}_k^* = \mathbf{A}\hat{\mathbf{y}}_{k-1}$$

- Track estimation:

$$\mathbf{P}_k^* = \mathbf{A}\mathbf{P}_{k-1}\mathbf{A}^T + \mathbf{Q}$$

Track estimation step

- Prediction accuracy estimation based on tracking accuracy and process noise:

$$\hat{y}_k = \hat{y}_k^* + K_k\left(\tilde{y}_k + \hat{y}_k^*\right)$$

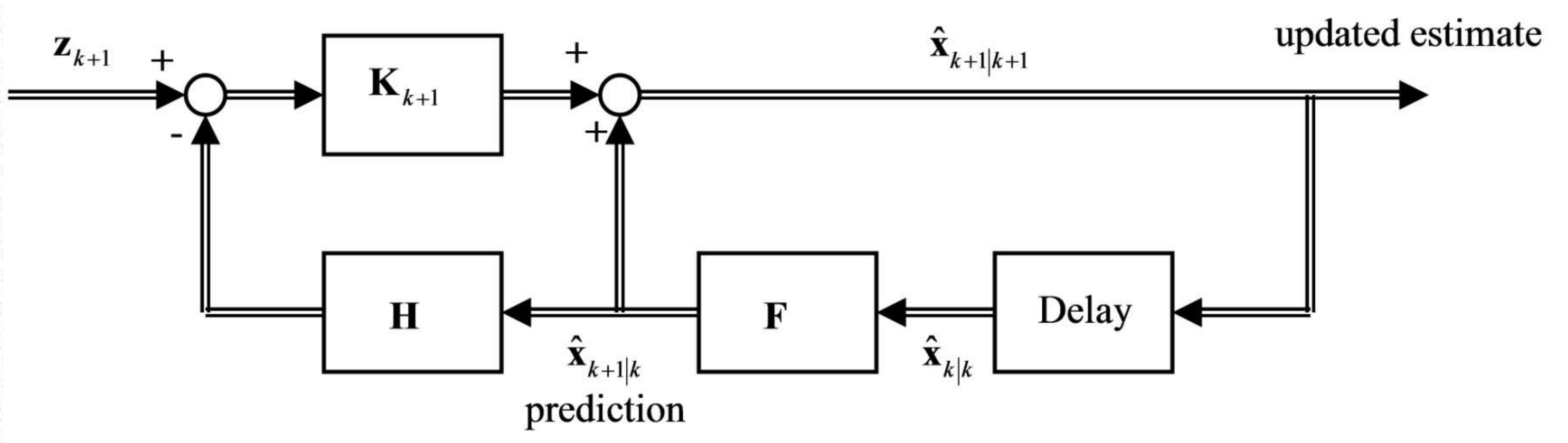
- Tracking accuracy estimation:

$$P_k = \left(I + K_k\right)P_k^*$$

Kalman gain based prediction accuracy and measurement noise

$$K_k = P_k^*\left(P_k^* + R\right)^{-1}$$

Linear Kalman filter



UWB radars

Chacteristics:

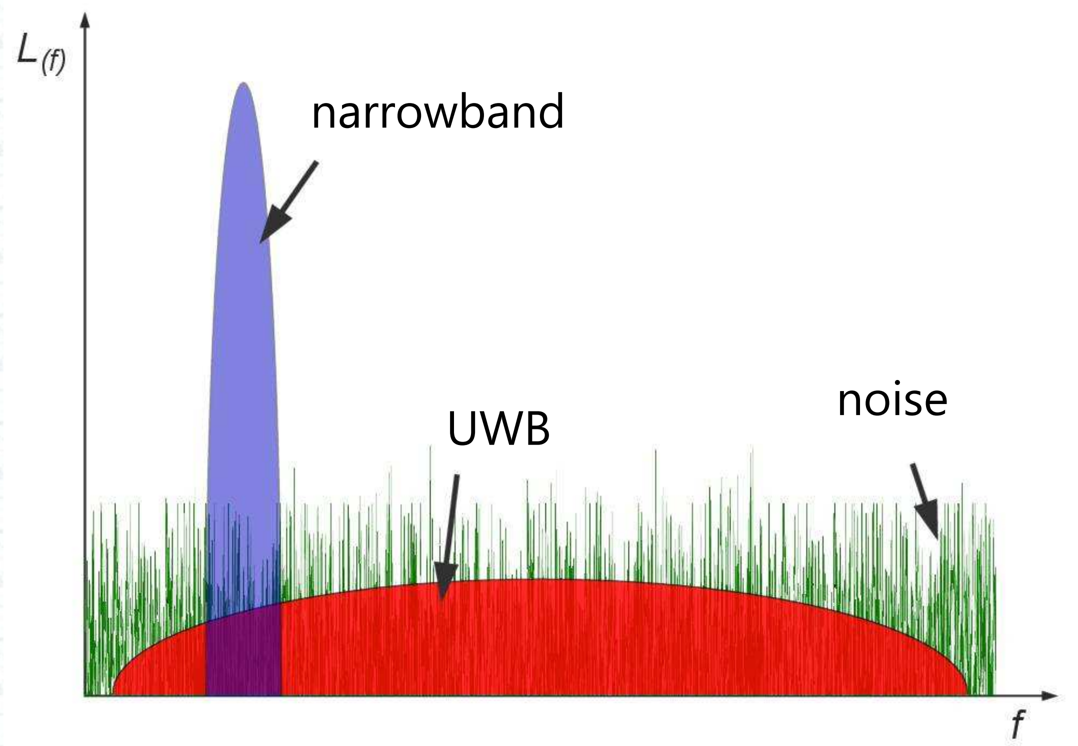
- Low power consumption
- Low cost circuitry
- Low probability of detection
- Different materials and environments distort pulses differently

Applications:

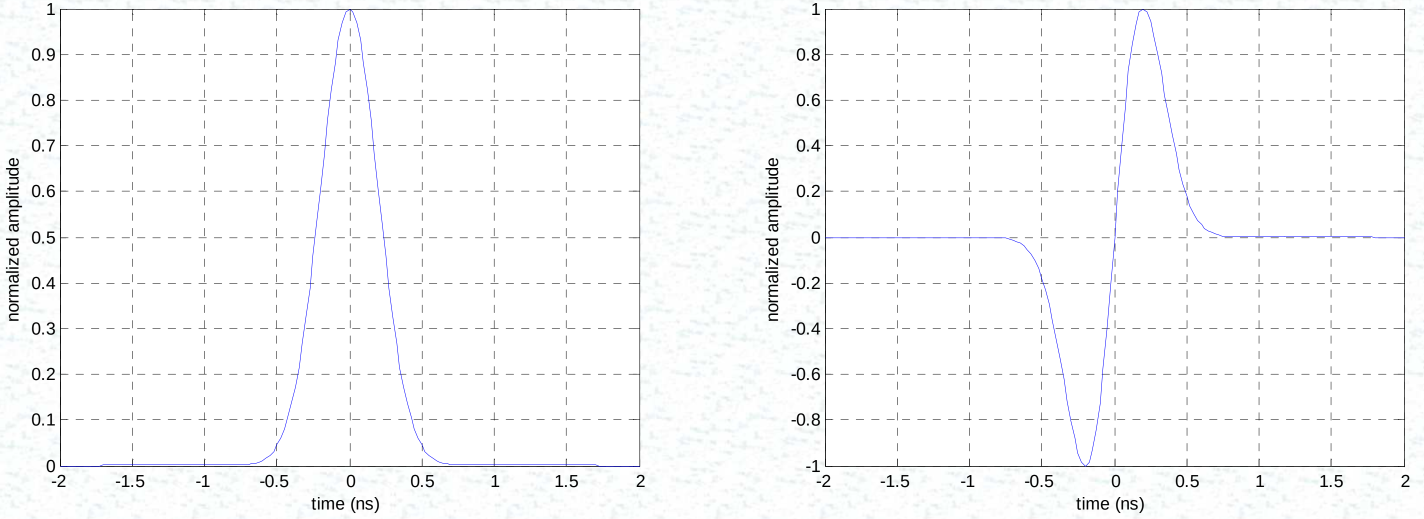
- Vehicular radar (Short range)
- Ground Penetrating Radar (GPR)
- Trough-the-wall imaging
- Medical radars

UWB RADAR definition

The amount of spectrum occupied by a signal transmitted by a UWB-radar (i.e. the bandwidth of the UWB signal) is at least 25% of the center frequency. Thus, a UWB signal centered at 2 GHz would have a minimum bandwidth of 500 MHz and the minimum bandwidth of a UWB signal centered at 4 GHz would be 1 GHz. Often the absolute bandwidth is bigger than 1 GHz.



UWB RADAR



Waveform of UWB SRR, Gaussian pulse and Gaussian doublet