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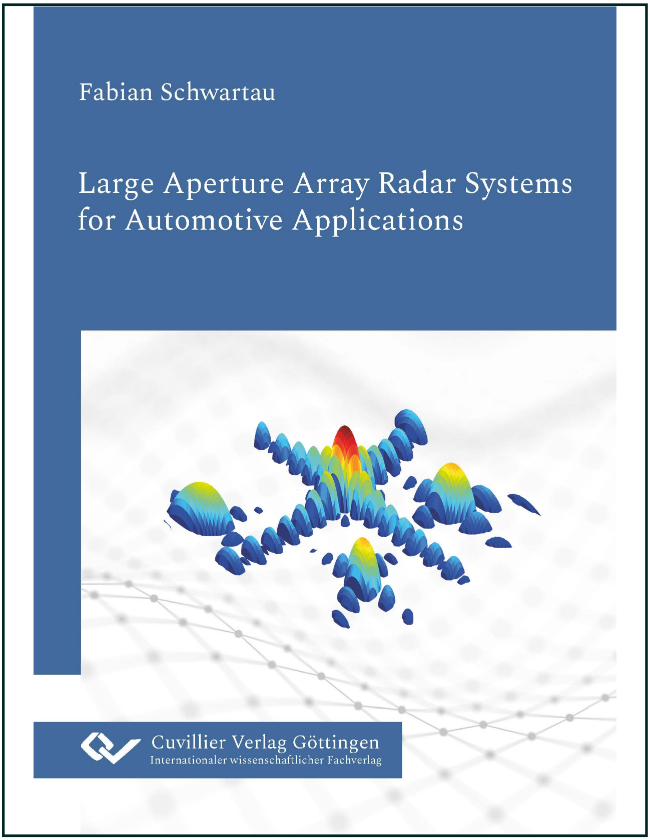
Large Aperture Array Radar Systems for Automotive Applications



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1 Introduction

The term radar stands for *radio detection and ranging* and describes the general method of measuring parameters of a target like its distance or velocity with electromagnetic waves. According to the Radio Regulations Articles of the ITU, Electromagnetic waves are located in the radio frequency range, defined as "frequencies arbitrarily lower than 3000 GHz, propagated in space without artificial guide" [1]. The foundation of radar was laid in 1887 by Heinrich Hertz, who experimentally proved that electromagnetic waves are reflected from metal surfaces [2]. The first experiments for locating objects were carried out by Christian Hülsmeyer, who registered a patent in 1904 for a radar to detect ships [3].

A radar system transmits a radio wave signal and receives the echoes from all objects' reflections in range. The radar then analyzes the received echo, for example, by measuring the delay between the transmission of the signal and reception of the echo. This allows the distance estimation to the object because an electromagnetic wave always travels with the speed of light in vacuum.

To measure the delay of a signal, it needs to be modulated. The simplest form of modulation is to use a short pulse at a specific center frequency. A plot of the returned energy over time gives a simple view of the reflections as a function of their distance. A non-modulated (i.e., continuous wave (CW)) radar cannot measure the distance to an object. As the signal is periodical, it is impossible to distinguish between the different periods. However, if the target moves, it changes the reflected signal frequency. This effect is known as the Doppler effect, which allows an estimation of the targets' velocity based on the observed frequency shift. More sophisticated radar systems are capable of measuring both distance and velocity with a more complex modulation scheme. Commonly used are, for example, frequency ramps or noise modulation.

The radar becomes even more sophisticated when it can create a radio frequency beam and point it in multiple directions. Such a radar can determine the direction of the object, allowing a location in three-dimensional space. Simple radar systems use large antennas or antenna arrays with a narrow beam, which are steered mechanically. Although a robust and straightforward design, the steering is relatively slow. The next step is to use an antenna array and steer the beam electronically using, for example, phase shifters in each path [4, pp. 1]. By choosing the correct phase of each antenna element, which compensates the path difference in a specific direction, the beam's direction can be controlled. The signal is then added and fed to the receiver. In the case of an electronically steered transmitter, the signal is split, phase-shifted, and fed to each antenna element of the transmit array. Although the steering is much faster with this concept, the larger amount of electronic components makes it much more complex and potentially more expensive.

The downside of both of these steering types is that the radar can look only in a single direction at any given time. An even more complex system is used to solve this issue, which is becoming more and more popular in recent years. It is called digital beamforming and is essentially the same as an electronically steered antenna. The vital difference is that the steering of the beam is carried out digitally on a computer. It can be applied to transmitters and receivers by using one transmitter or receiver unit per antenna element. In the receiver's case, all signals are recorded simultaneously, and the steering can be implemented in software, which allows to point the radar's beam in multiple directions at the same time. Transmit beamforming allows to digitally steer the beam into a specific direction, like in a phased array, but the illumination of multiple directions is also possible. This is also implemented by changing the phase values or delays for each transmitted signal to compensate for the path difference for the desired angle.

If the transmitters use orthogonal signals, which do not form a beam in a particular direction, it is possible to separate the different transmitters in each received signal. This type is called a multiple input multiple output (MIMO) radar and increases the spatial resolution by measuring each combination of transmitter and receiver [3]. The beamforming is carried out subsequently on a computer, allowing to steer both transmitter and receiver after the measurements are carried out. The downside of the beamforming and MIMO approaches is the even higher system complexity and cost as it requires a complete transmitter or receiver for each antenna.

With beamsteering or beamforming, it is possible to build a three-dimensional representation of the surrounding scenario. When including the Doppler information, such a radar can distinguish targets in four dimensions, and the time may be considered the fifth dimension. To get a more and more precise representation of the radar's scenario, a higher resolution is required. This primarily refers to the angular and range resolution. As will be discussed later, a higher range resolution requires a higher bandwidth of the transmitted signal, while higher angular resolution requires a larger aperture of the antenna array (relative to the wavelength). To achieve both while keeping a compact form factor, radar systems have been pushing to higher frequencies. Higher frequencies and the demand for cheaper solutions lead to increased integration of such systems, turning fully integrated radar solution into a mass product.

Especially the automotive industry has been pushing the integration of radar systems in the past years. The goal of assisted and even autonomously driving cars has led to increased demand for reliable and cheap radar solutions. Also, the demands in terms of the resolution are continuously increasing as the car's precise knowledge of its surroundings is a key component for assisted and autonomous driving. Although such cars are additionally equipped with lidar[1] and camera systems, radar systems are considered more reliable and cheaper [5, 6]. Lidar and camera systems are, for example, heavily susceptible to dirt, ice or snow on the sensor itself or in the air. Table 1.1, taken from [6], summaries the different aspects of the three technologies.

The three systems, radar, lidar, and vision, are based on the concept of detecting electromagnetic waves and estimating their angle of arrival (AoA). The two differences are that radar and lidar emit their own coherent electromagnetic wave, while the vision-based system uses incoherent illuminators of opportunity, and radar is working at a much lower frequency compared to lidar and vision and has, therefore, a much lower bandwidth.

Besides the angular resolution, the lack of color and contrast is the only other negative point of a radar system. The collection of information, like the color or contrast of a target in a visual system, is used to classify the target further. Although a radar cannot measure any color or contrast information, modern systems are capable of measuring other object parameters that help to classify the object. There has been much research regarding radar systems capable of measuring reflections of different polarizations. A target's amplitude and

[1] Light detection and ranging, similar to a radar system, but it uses lasers instead of radio waves to measure the distance to a target.

Table 1.1: Comparision of different automotive sensing systems, taken from [6]

Sensor	Radar	Lidar	Vision
Range	++	+	++
Range resolution	+	++	o
Angular resolution	o	++	+
Works in bad weather	++	o	-
Works in dark	++	++	- -
Works in bright	++	+	+
Color/contrast	- -	- -	++
Radial velocity	++	o	-

polarization properties can be used for further classification, providing similar information like color or contrast [7, 8], compensating the system's drawbacks.

Compared to the other systems, the only major drawback of a radar is the low angular resolution. This is the starting point of this thesis, and the goal is to provide additional insight on how to overcome the issue of limited angular resolution in automotive radar applications.

1.1 Organization of the Thesis

This thesis covers a wide range of topics surrounding the theoretical description, the design, the simulation, the construction, and the evaluation of an automotive radar system. This introduction additionally describes the contributions of this work, followed by the notation used throughout it.

The second chapter introduces the required fundamentals for this thesis. It contains descriptions for frequency modulated continuous wave (FMCW) and chirp sequence (CS) radars, the definition of far-field conditions, algorithms for beamforming in the near- and farfield, description of array parameters, the concept of synthetic and virtual apertures, calculation of radar resolution parameters, the constant false alarm rate (CFAR) algorithm for detection of targets within the digital domain, and a few other things.

The third chapter introduces the concept of a modular radar system for automotive applications. The state-of-the-art in current systems is summarized, followed by defining goals for future radar systems. The remainder of the chapter primarily deals with the antenna array design using modified genetic algorithms for the optimization of antenna element positions and weights within the array. The proposed array is analyzed in terms of angular resolution, directivity, and an exemplary application is used to estimate the expected performance in terms of maximum range.

Three aspects of the prosed radar system are then analyzed in the fourth chapter. These aspects are the general concept of a radar system with high angular and range resolution, the usage of individual and flexible modules, and the coherent synchronization of such modules. These goals are analyzed by the design, construction, and evaluation of a demonstrator radar system. The chapter deals with the concept, the involved hardware, the calibration, the software, and the signal processing of the demonstrator. Simulations and measurements showcase the capabilities of the system.

The fifth chapter describes a second demonstrator's construction, which uses the antenna array proposed in the third chapter. It utilizes a virtual and synthetic aperture to keep the system complexity and cost low, thus having only a single transmitter and receiver yet providing the same results as the fully populated antenna array. The second demonstrator is used to capture a more realistic automotive scenario and provides a three-dimensional image.

Chapter six analyzes potential sources of manufacturing tolerances and other effects that influence the antennas' position within the array. The magnitude of the identified causes is estimated, and the effect on the array is analyzed. Subsequently, an algorithm is introduced and evaluated to measure and compensate for the displacement of individual modules of the systems.

A conclusion of the work with a summary of the results presented in the previous chapters is given in chapter seven. Additionally, it contains an outlook of the next steps towards the next generation of high-resolution radar systems. Chapter eight contains appendices.

1.2 Contributions

This thesis contributes the following additional knowledge, techniques, and analysis to the current state of the art:

- **Fundamentals for Signal Processing and Analysis of Radar Systems**
  The second chapter provides a comprehensive overview of the mathematical fundamentals required for the analysis of and signal processing for radar systems. This overview focuses on large aperture radar systems utilizing FMCW or CS modulation, but most of it is also applicable to other systems.
- **Generation Algorithm for Large Aperture Arrays**
  Two customized genetic algorithms are proposed in Chapter 3, which are capable of optimizing the positions and weights of antenna elements in a large aperture MIMO array. The algorithms additionally allow to group transmitters and receivers into modules, limiting the potential positions they can be placed at. The algorithms provide multiple parameters to optimize for different aspects of the array, like the side lobe level or the main lobe's shape.
- **Modular, Optically Synchronized, and Large Aperture Radar**
  Two radar demonstrators are developed and analyzed in Chapter 4 and 5. Together the two demonstrators showcase a future automotive radar system, which is based on a modular design with high angular resolution. The modules operate fully coherently due to the synchronization with a radio over fiber system.
- **Antenna Position Displacement Compensation**
  Chapter 6 proposes a novel algorithm capable of compensating the displacement of antenna modules within a coherent radar system during operation. All common changes in antenna positions during operation or tolerances during production can be measured and subsequently compensated.

1.3 Notation

There are a couple of notations used throughout the following work. In general, scalars are light letters, like a or A, vectors, and matrices are represented as bold letters, like $\boldsymbol{a}$ or $\boldsymbol{A}$. The indexes x, y, and z added to a vector represent the three elements of it, pointing into the three Cartesian axes.

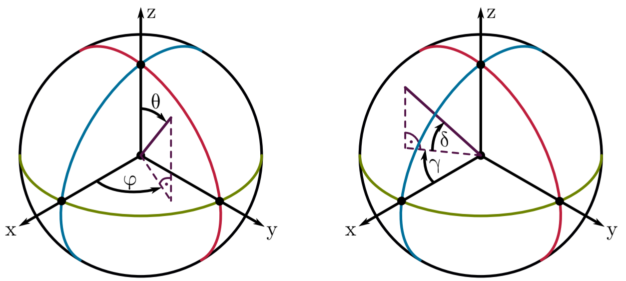
Figure 1.1(a) shows the standard polar coordinates used throughout this work. θ is defined as the angle downward from the z-axis, φ is the angle from the positive x-axis towards the positive y-axis. Figure 1.1(b) shows a polar coordinate system based on azimuth (γ) and elevation (δ). The azimuth is defined as the angle from the positive x-axis towards the negative y-axis. The elevation is the angle pointing upwards from the xy-plane. The x-axis is the boresight axis of the radar system; antenna elements are thus placed in the yz-plane. The y-axis points to the left when looking from behind the radar, and z is oriented upwards.

Antenna arrays can be expressed in several ways. One way is to describe the weights $\boldsymbol{w}$ in square brackets, like [1,1,1,0,1]. This expression represents an array with equidistant elements. In the example, only the first three and the last one are populated. Weights can also be used to express weights for a taper. Especially for large arrays, it is more convenient to describe the distances between two elements, while an exponent can indicate the repetition of a certain distance. Curly brackets surround this type. For example, $\{1^2,2\}$ represents the same array as the one before. A distance of 1 usually translates to $\lambda/2$, if not otherwise noted.

The following operators are used:

$\lVert \cdot \rVert$	2-norm of a vector
$\lvert \cdot \rvert$	Absolute value of a scalar, vector or matrix
$\cdot^*$	Conjugate complex of scalar, vector, or matrix
$\cdot^{\mathrm{T}}$	Non-conjugate transpose of a vector or matrix
$\cdot * \cdot$	Convolution of two signals
$\Re\{\cdot\}$	Real value
$\mathfrak{F}_l\{\cdot\}$	Discrete Fourier transformation on axis l
$\angle\cdot$	Phase angle of complex number
$\max\{\cdot\}$	Maximum of a vector
$\min\{\cdot\}$	Minimum of a vector
$\mathrm{count}\{\cdot\}$	Number of elements in a vector or matrix. In case of a matrix the columns are treated as elements.
$\mathrm{unique}\{\cdot\}$	Unique number of elements in a vector or matrix. In case of a matrix the columns are treated as elements.
$\mathrm{mean}_l\{\cdot\}$	Mean value of a scalar, vector or matrix on axis l

All symbols used throughout this work are listed and described in the "List of Symbols" starting on page 123.



(a) (b)

Figure 1.1: Coordinate systems in polar coordinates (a) and azimuth/elevation (b)

2 Fundamentals

This chapter contains all fundamental concepts and equations which are used throughout this work. This includes the signal representation in section 2.1, general considerations of radar systems from Section 2.2 to 2.7, beamforming and movement compensation in Sections 2.8 and 2.9, description and calculation of array parameters from Section 2.10 to 2.14, and the CFAR algorithm in Section 2.15.

2.1 Signal Representation

Signals in the time domain may be expressed as complex baseband signals [9, p. 8]. This is possible because any bandpass limited and real-valued signal $s(t)$ can be expressed by

$$s_{\mathrm{comp}}(t) = \left[s(t)e^{-j2\pi f_{\mathrm{c}} t}\right] * h_{\mathrm{LP}}(t), \tag{2.1}$$

without loosing any information, where f_{c} is the chosen center frequency (usually the center of a bandpass signal), and $h_{\mathrm{LP}}(t)$ is the impulse response of an ideal low pass filter covering the complete bandpass-bandwidth of the signal. This notation simplifies the representation of signals which are modulated to a certain carrier frequency and allows the more obvious representation of signal phase values.

The real-valued signal can be restored with

$$s(t) = 2\Re\left\{s_{\mathrm{comp}}(t)e^{+j2\pi f_{\mathrm{c}} t}\right\}. \tag{2.2}$$

As the low pass filter in (2.1) and the real part operation in (2.2) each half the resulting signal power, an additional factor of two is required in (2.2).

2.2 FMCW Radar

The FMCW radar, more precisely linear FMCW radar, in this case, modulates the frequency of the transmitted signal in linear dependency of the time. The received signal is mixed[1] with the currently transmitted signal yielding the baseband signal, which contains information about the targets it reflected on. FMCW radars can utilize up and down sweeps or a combination of both. Sawtooth modulation is a common waveform, as it allows easy calculation of range and Doppler and, thus, is used in the following description. The following equations to describe an FMCW radar are taken from [10, p. 39].

[1] A single mixer and not an IQ-mixer is assumed in the following. This leads to always positive frequencies in the baseband signal.

The delay in the received signal compared to the transmitted signal is proportional to the distance

$$\tau = \frac{2d}{c_0}, \tag{2.3}$$

d being the distance of a particular target and c_0 the speed of light.

Looking at a single sweep, the received signal has a slightly different frequency compared to the currently transmitted signal. The frequency difference, called beat-frequency f_b, depends on the distance of the target and the slope s of the frequency ramp according to

$$f_\mathrm{b} = s\frac{2d}{c_0}. \tag{2.4}$$

The slope is defined as

$$s = \frac{B}{t_\mathrm{s}}, \tag{2.5}$$

with the bandwidth B and the ramp duration t_s. Rearranging (2.4) and inserting the result into (2.5) gives the final equation for the target distance:

$$d = \frac{f_\mathrm{b} t_\mathrm{s} c_0}{2B}. \tag{2.6}$$

The observed frequency difference between the signals only corresponds directly to the beat frequency f_b if the target is not moving. If the target is moving with a radial velocity of v_r, an additional Doppler shift of

$$f_\mathrm{d} = \frac{2v_\mathrm{r}}{\lambda} \tag{2.7}$$

is observed. λ is the wavelength, defined as

$$\lambda = \frac{c_0}{f_\mathrm{c}}, \tag{2.8}$$

where c_0 is the speed of light and f_c is the center frequency of the radar. The actual measured frequency is the sum or difference of those two frequencies. If the ramp is an up sweep, the measured frequency is

$$f_\mathrm{bu} = f_\mathrm{b} - f_\mathrm{d}, \tag{2.9}$$

or

$$f_\mathrm{bd} = f_\mathrm{b} + f_\mathrm{d} \tag{2.10}$$

in case of a down sweep.

When both up and down sweep are measured, it is possible to calculate range and Doppler. Therefore, the equations above can be rearranged to calculate the range d and radial velocity v_r of the target:

$$d = \frac{c_0 t_\mathrm{s}}{4B}(f_\mathrm{bd} + f_\mathrm{bu}), \tag{2.11}$$

$$v_\mathrm{r} = \frac{\lambda}{4}(f_\mathrm{bd} - f_\mathrm{bu}). \tag{2.12}$$

The maximum unambiguity range is given in [10, p. 50] as

$$d_\mathrm{max} = \frac{c_0 N_\mathrm{ft}}{4B}, \tag{2.13}$$

where N_{ft} is the number of samples for a single chirp (i.e., ramp or fast-time axis).

To extract the frequency information from the received baseband signal, a Fourier transformation along the time axis is commonly applied.

Figure 2.1 shows a qualitative plot of the transmitted and received FMCW radar signals in case of a single target with a positive Doppler shift, indicating a target moving towards the radar. In this case f_{bd} is higher than f_{bu}, which results in a positive radial velocity according to (2.11).

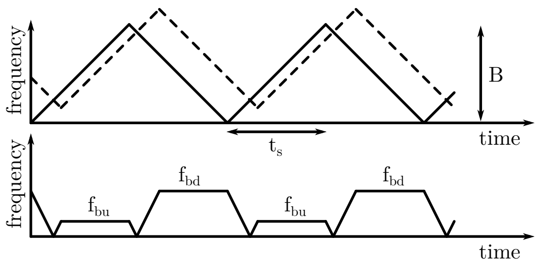


Figure 2.1: Qualitative plot of the signals in an FMCW radar, according to [10, p. 40]. The top figure shows the transmitted (solid) and received (dashed) signal. The received signal has an additional positive Doppler shift, indicating a target moving towards the radar.

Although the FMCW radar is theoretically capable of measuring range and Doppler for a target, practical implementation is hard to accomplish. To calculate both values, two measurements with an up and down sweep have to be performed. If multiple targets have been detected, they have to be matched between the two measurements. False matching will lead to false detections. This problem is why a chirp sequence radar is often preferred in applications where range and Doppler are required.

2.3 Chirp Sequence Radar

The chirp sequence modulation is very similar to the FMCW modulation but overcomes the problem of having to match two targets from two measurements to be able to calculate range and Doppler. CS also uses linear FMCW ramps, called chirps, but they are usually much shorter, multiple of them are transmitted consecutively in short order, and only up or down sweeps, but not both, are utilized. The assumption is that the target does not move more than $\lambda/4$ between two chirps.[2] It is then possible to analyze the phase change of the target over time. This is done with a Fourier transformation of a single distance over time and results in the target's radial Doppler frequency.

In practice, the measured data is put into a matrix. Each chirp fills one row of the matrix. Like in FMCW radar signal processing, a Fourier transformation along each row (called fast time axis) transforms the axis into the range axis. Every column then represents the same range over time. A second Fourier transformation along each column transforms the

[2] The additional delay between two measurements should be less than $\lambda/2$. As the wave travels to the target and back, the target may not move more than $\lambda/4$ to measure a delay of less than $\lambda/2$.

so-called slow time axis into the Doppler axis. The matrix then represents the amplitudes in dependence of range and Doppler and is called range-Doppler matrix.

The range calculation is the same as for FMCW, when based on the parameters of a single chirp, see (2.6). The same holds for the Doppler calculation from (2.7), which is applied to the slow time axis of the matrix.

A few important system parameters resulting from the chosen waveform parameters are given in [10, p. 50]. The maximum Doppler frequency is

$$f_{\mathrm{d,max}} = \frac{1}{2T_{\mathrm{s}}}, \tag{2.14}$$

with T_{s} being the period of the chirps, which is usually different to the length of the chirps t_{s}, as shown in Figure 2.2 If the Doppler frequency of a target is higher than this value, aliasing will occur and the radial velocity has a wrong value.

The maximum Doppler frequency can be converted to the maximum velocity with (2.7), yielding

$$v_{\mathrm{r,max}} = \frac{\lambda}{4T_{\mathrm{s}}}. \tag{2.15}$$

Figure 2.2 shows the qualitative plot of the transmitted and received signals in a CS radar. It is important to note that the time of a single chirp t_{s} describes the measurement's length. The transmitted chirp usually starts shortly before the first sample is taken. This ensures that the signal had enough time to return from all targets, and the sweep is stable.

When looking at a target at a distance of 150 m, the delay is already 1 µs for the return signal. In this case the chirps would typically be 2 µs to 10 µs in length. The additional delay between the start of transmission and the start of sampling is therefore important. An FMCW radar with its much longer chirps is usually not affected that much.

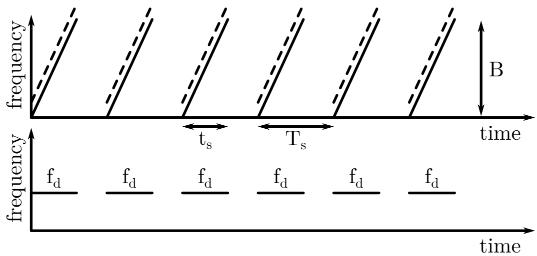


Figure 2.2: Qualitative plot of the signals in a CS radar. The top figure shows the transmitted (solid) and received (dashed) signal frequency over time. The bottom figure depicts the frequency difference between transmitted and received signal.