1 Introduction

When Christian Hülsmeyer, in the very beginning of the twentieth century, had the idea of a technical device that uses the reflecting properties of electromagnetic waves to detect and locate distant metallic objects, his intention was to prevent ship collisions. This application was already laid out in the patent application of 1904 (see Figure 1.1), describing the first Radar system [Hül04a], [Hül04b]. Hülsmeyer called his invention "Tele-

Eigentum des Kaiserlichen Patentamts.
Eingefügt der Sammlung für Unterklasse ...
Gruppe Nr. ...

KAISERLICHES PATENTAMT.

AUSGEGEBEN DEN 21. NOVEMBER 1905.

PATENTSCHRIFT

— № 165546 —

KLASSE 74d.

CHR. HÜLSMEYER IN DÜSSELDORF.

Verfahren, um entfernte metallische Gegenstände mittels elektrischer Wellen einem Beobachter zu melden.

Patentiert im Deutschen Reiche vom 30. April 1904 ab.

Fig. 1.

B

A

Figure 1.1: Hülsmeyer's patent of the first radar, called "Telemobiloskop"

mobiloskop"(Greek: τηλε (tele) = far, Latin: mobilis = movable, Greek: σκοπειν (skopein) = to examine). At that time no industrial company was interested in the technology Hülsmeyer had invented [Swo86], which maybe was due to the fact that the nature of electromagnetic waves was known only since a few years. Theoretically described by James Clerk Maxwell in 1864 and experimentally proven by Heinrich Hertz in 1886 [Cum+04] the idea of invisible and unrecognizable waves must have appeared strange to most engineers, which emphasizes the achievement of Christian Hülsmeyer. Nevertheless, there was hardly any progress in radar technology before World War II, when radar became very important for all countries. And as a very powerful remote sensing technique, it is of great interest for military organizations to the present day. Due to its popularity in the military sector radar is said to be a very mature technology [Pee98]. However, there is a wide and still growing spectrum of civil applications, which show different requirements and, therefore, provide new interesting fields of research. As it was Hülsmeyer's initial idea to use radar as a traffic safety device, today it is indispensable in ship and air traffic control and becomes more and more important in road traffic safety. Most results of this work are applicable or adaptable for many other purposes like area surveillance [Möl12], [Sch13] or even oceanographic applications like ship tracking [Dzv+09] or tsunami detection [Dzv+11]. However, responding to the high and still growing interest in automotive radar and it's importance for our society, all system design examples as well as the line of argument will follow the application of road safety radar sensors.

Today most major car manufacturers already offer radar based Driver Assistance Systems (DAS). State of the art DAS are for example enhanced Adaptive Cruise Control (ACC) systems that adjust the desired speed as conventional ACCs and additionally maintain a save distance to the road user in front [Men99]. Another safety application is the Lane Change Assistant that gives a warning to the driver, who initiates a lane change while another road user is driving on that particular lane next to him.

These DAS are mainly designed for highway and rural road traffic scenarios. However, the great majority of accidents that cause injured persons happen in inner city traffic scenarios as the statistic of Figure 1.2 indicates. Consequently, the applications within the automotive section have

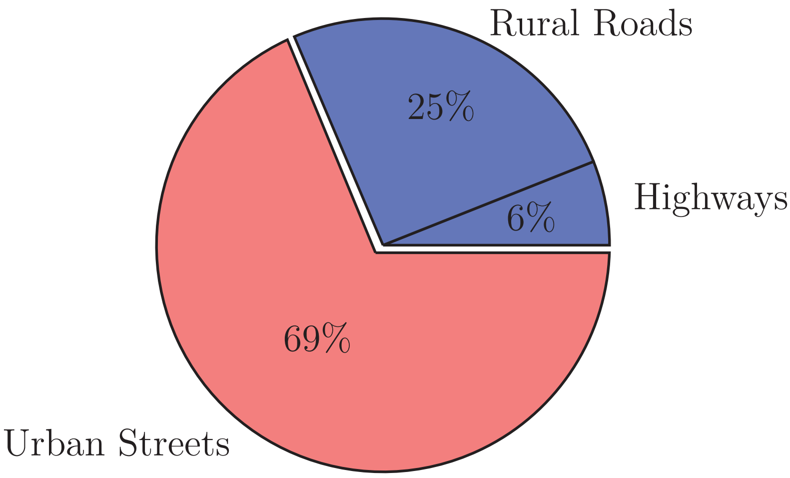

Figure 1.2: Accidents causing personal injuries by accident location [Ger]

to be expanded from ACC systems for highway applications to inner city applications with special focus on pedestrian protection [RR07],[Rit13]. Therefore, the requirements on such sensors will expand as well. From the radar sensor point of view, the urban environment is completely different from that of the highway. While in a highway scenario the possible maneuvers for vehicles and the directions of movements are limited, an inner city traffic scenario is much more diverse and complex (see Figure 1.3). In addition to vehicles moving in any direction with sudden maneuvers, pedestrians are a completely new type of radar target. The echo signal of a pedestrian, in contrast to vehicles and other objects, shows a characteristic spectrum of different radial velocities originated from the movement of the different body parts i.e. arms, legs and the torso.

Therefore, safety applications for urban traffic scenarios require a high performance remote sensing technology. Radar suits this requirements in a perfect way because it provides the ability to measure target range and

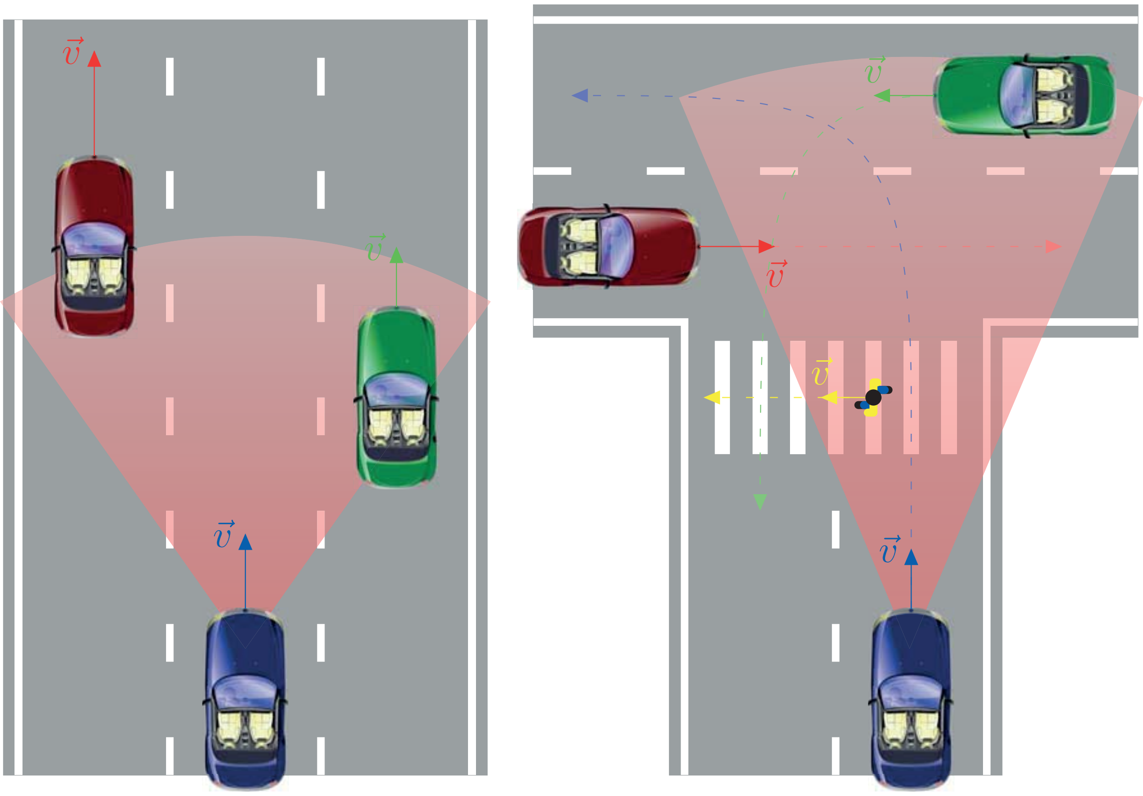

Figure 1.3: Highway (left) and inner city traffic scenario (right)

radial velocity simultaneously with high accuracy and unambiguously even in multi target situations. The most important capability of radar is the clear separation of multiple targets by their different ranges and/or radial velocities.

However, these outstanding features depend on a sophisticated waveform design. In recent decades, researchers have developed many different waveforms for continuous wave radars in the automotive section [RK12]. In that respect, the Multiple Frequency Shift Keying (MFSK) waveform invented by [RM01] marks one very important milestone. This waveform runs on highly integrated and commercially successful sensors for DAS [Sau+09]. It serves perfectly the needs of highway traffic safety applications.

For the more diverse urban traffic environment the class of chirp sequence waveforms [Gri90], [Sto92] is more appropriate because it provides a two-dimensional resolution i.e. separation of targets, so that the multi target capability is improved. However, the classic chirp sequence waveform may lead to ambiguities in the radial velocity measurement, which is a major limitation. The main contribution of this thesis is the design of enhanced chirp sequence waveforms for the resolution of radial velocity ambiguities. Furthermore, a radar detector has been designed for the two-dimensional measurement result, obtained using chirp sequence waveforms. This detector is designed to be efficient in terms of detection performance and computation power.

2

Radar Measurement

Radar is a remote sensing technique. The name itself is an acronym and stands for **Ra**dio **D**etection **a**nd **R**anging. The measurement principle is to transmit *radio* waves (i.e. electromagnetic waves) and to evaluate the received echo signals. According to the name, the two objectives of a radar system are to *detect* distant objects, called *targets*, and to estimate the *range* R_0 between the radar location and the target.
Furthermore, a radar system is capable of measuring the radial velocity v_r of a target. Since the radial velocity v_r is the change of target range R_0 over time, the velocity measurement fits into the terminology under the aspect of ranging.
A third target parameter that can be measured using radar is the angle of incident α in azimuth or elevation direction.

With target range R_0 and azimuth angle α the target's position relative to the radar location is known. In addition to that, the radial velocity v_r provides useful information about the target. These target parameters are illustrated in Figure 2.1.

2.1 Range Measurement

The distance between the radar's transmit/receive antennas and the target is desired to know. In a mono-static radar, where transmit and receive antenna are at the same location, this range R_0 is through the speed of

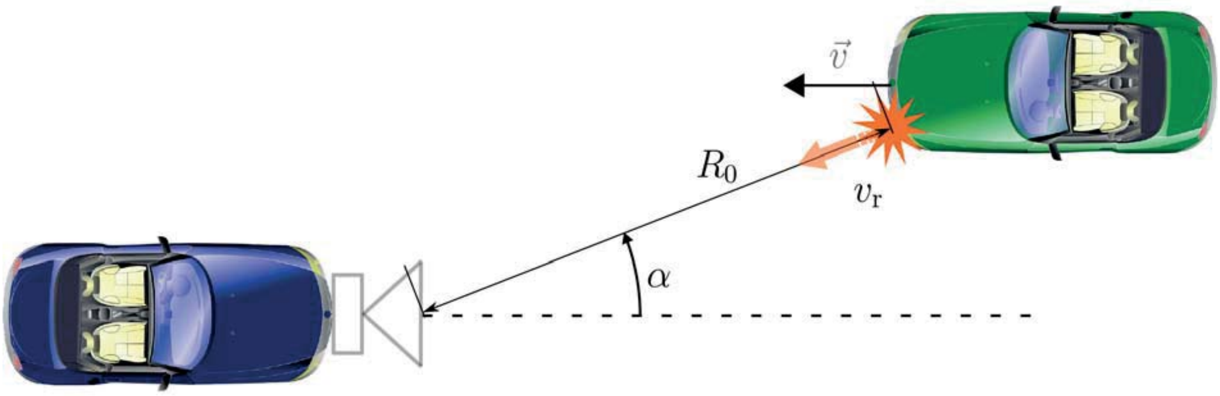

Figure 2.1: Measured target parameters R_0, v_r and α

light $c = 3 \times 10^8$ m/s directly proportional to half of the propagation delay τ, that takes the electromagnetic wave to travel from the radar transmit antenna to the reflecting object and back to the radar receive antenna [Sko80]:

$$R_0 = c \cdot \frac{\tau}{2}. \quad (2.1)$$

Therefore, the range measurement of a radar system is accomplished by the measurement of the propagation delay τ.

2.2 Radial Velocity Measurement

If a moving target is observed, the distance between radar and target changes over time with the radial component v_r of the target's velocity $\vec{v}$:

$$R(t) = R_0 + v_r \cdot t. \quad (2.2)$$

Due to the target movement in radial direction within the measurement interval a change in the echo signal's frequency relative to the transmit frequency is observed. From Physics this effect is known as the *Doppler-Effect* named after Christian Doppler (1803 - 1853), the Austrian physicist who first described this effect [Cum+04].

2.3 Angular Measurement

For the angular measurement there are two possible measurement principles available. The azimuth angle can be estimated by using either a mechanically rotating antenna configuration or an array consisting of several different antennas.
Using a mechanically rotating antenna setup, the angle α corresponds to the viewing direction, in which the maximum echo signal amplitude occurs. This technique is well known from the large air traffic control radars at airports.
Since mechanically rotating antennas are not appropriate for automotive radar systems in particular as well as not convenient in general, today a different angular measurement method, based on antenna arrays, is usually applied [ZR12], [ZKR13]. In this case, the angle α is determined from the path difference the receive signals show after traveling from one transmit antenna to multiple spatially distributed receive antennas and/or from multiple transmit antennas to one receive antenna.
The monopulse-technique uses a single transmit antenna and two receive antennas. The phase difference of the receive signals from a single transmit signal at both receive antennas depends directly on the angle of incidence [Pee98]. Because of the small size of the monopulse setup and because of it's cost effectiveness, the monopulse technique has become widely used in automotive radar [Men09].

2.4 Quality of a Radar Measurement

For each of the measured target parameters, range R_0, radial velocity v_r and azimuth angle α, there are three important figures that indicate the quality of the measurement and that are, therefore, critical for the radar waveform design:

- **Accuracy:** Considering a single radar target, the accuracy describes, in a statistical way, how close a measured value is to the true value. The accuracy depends on the Signal to Noise Ratio (SNR) and on the physical figure the measurement is based on. In the considered continuous wave radars this can be either a measured frequency, which provides an accurate measurement or it can be a measured phase difference, which provides limited accuracy for the same SNR.

- **Resolution:** In a two target situation the resolution describes the minimum distance, in terms of target range R_0, radial velocity v_r or azimuth angle α, both targets may have so that they are still recognized as two distinct targets by the radar system, assuming the same echo signal magnitude for both targets.
  A range resolution of $\Delta R = 1\,\mathrm{m}$ for example means that two otherwise equal targets have to be positioned at least $1\,\mathrm{m}$ apart from each other in radial direction, so that the radar recognizes them as two distinct targets.
  Especially for automotive radar systems the capability to distinguish between different targets is one key-requirement, so that a high resolution is an important objective in the system design.

- **Maximum unambiguous interval:** For each of the three target parameters range R_0, radial velocity v_r and azimuth angle α the measurement domain is limited to a certain maximum unambiguous interval.