1 Introduction

The invention of the radar dates back to the early twentieth century, when Christian Hülsmeyer developed his so-called Telemobiloskop [1]. A device, tested at the river Rhein in Cologne, which generated a sound when a ship passed by. At first, no practical applications of such a system were pursued [2], and the invention was neglected. It was not until the Second World War that the research on radar was intensified, as it promised advantages over present location and detection methods, like binoculars and acoustic mirrors [3]. After the war, the developments continued, and civilian applications, e.g., air traffic control, weather radar, automotive radar, and satellite-based radar for earth observation, were introduced.

About twenty years before the invention of radar, Carl Benz was the first to file a patent on a vehicle with a gas engine [4] in 1886, which is considered the birth of the modern automobile. With increasing developments and declining prices, the popularity of automobiles has risen over the years. It can be imagined that the number of accidents involving automobiles was also growing. Manufacturers and legislators have tried to increase the safety of motor-driven vehicles by technical and regulatory means. For example, higher passenger safety is achieved by implementing safety belts and airbags, and interactions between road users are regulated by laws. However, these remedies are not sufficient to prevent accidents in the first place. With the ongoing developments, the dream of automotive driving, presumably as old as humankind itself, is getting tangible. Nevertheless, it took until the 1960s that the first ideas of connecting automobiles and radars came up [5]. The frequencies were around 15 GHz at first, so the systems had considerably large apertures. With continuing development, higher frequencies were possible. The first commercial automotive radar for adaptive cruise control (ACC) at 76 GHz was available 1998/99 [5]. Nowadays, highly integrated circuits, advanced materials, and further developments allow comparably cheap radars with multiple channels for beamforming. All these developments in traffic safety led to a reduction of the road traffic fatality rate per $100,000$ population by 16% in the years from 2010 to 2021 [6]. Currently, the developments are heading towards partly-automated and automated vehicles.

Six stages of automotive driving (AD) are differentiated [7] as shown in Figure 1.1. Level 0 describes driving without automation. However, some simple assistance, like emergency brake assistance, is also listed under level 0. When single assistance, like ACC or lane assist, is available, it is called level 1. Combining these two, level 2 is reached. The first three levels have in common that the driver must be attentive and keep their

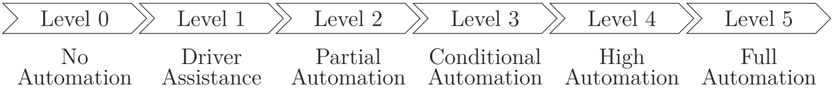

Figure 1.1: Levels of automated driving [9].

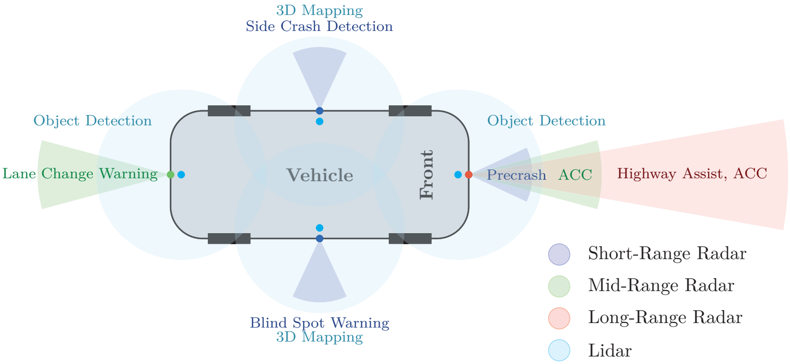

Figure 1.2: Radar and lidar based automotive driving functions [10].

hands on the steering wheel. Level 3 allows full automated driving in highly limited scenarios, e.g., traffic jam pilot, where the driver must intervene in complex situations. The next step would be driverless taxis, which can operate in a local environment for level 4 and fully automated driving without any restrictions in level 5. These three levels have in common that the manufacturer is responsible for incidents while the vehicle drives autonomously. Currently, automotive driving at level 2 is widely available, while some manufacturers recently got authorization to roll out level 3 [8].

To enable AD, complete knowledge about the environment, other traffic participants, and the vehicle itself is necessary. Therefore, multiple sensors, like cameras, lidars, and radars [11] are installed on automated vehicles. Additionally, some approaches use inter-vehicle communication to transfer information between vehicles [12]. However, all these sensors have strengths and weaknesses, which means that only the fusion of all of them leads to optimal results. For example, cameras don't work well in bad weather and illumination conditions, but are perfect for object classifications and color reception. Lidars typically have high performance in object detection. Still, they can not directly evaluate velocities. Radars, on the other hand, are suitable for measuring the velocity of other traffic participants but cannot easily classify objects. A detailed overview of the sensors and their performance is provided in [10] and [11]. Different AD functions around the vehicle and their corresponding sensors are displayed in Figure 1.2. Integrating this many sensors into a vehicle can be challenging, as a compromise between making the sensors as invisible as possible and their performance has to be found [13].

For this work, mainly long-range radars are relevant, as they have to provide a high angular resolution to distinguish between objects in up to 250 m distance [14]. However, as the lower range boundary of the setup is given by the compact test range (CTR) size and the signal processing speed of the radar target simulator (RTS), short-range sensors can also be tested.

1.1 State of the Art

Testing is an essential step in specifying the capabilities of a radar sensor. Simple tests can be performed by presenting a single target with a known spatial position and radar cross section (RCS) for the radar. However, such a setup is rather inflexible when it comes to moving targets and angular resolution testing. This led to the development of RTS. These devices receive the transmitted signal of the radar, allow a manipulation of the signal in the base band, and retransmit the signal back to the radar. Therefore, applying a Doppler frequency for velocity, delaying the signal for distance, and amplifying or attenuating the signal to change the RCS is possible [15]. This section gives an overview of different methods and systems to enable radar target generation.

Overall, RTS can be divided into two categories according to the type of signal processing, analog and digital. While digital RTS have advantages when it comes to the signal processing itself, as it can easily be done with software, analog RTS have advantages when it comes to bandwidth and minimum simulation distance, as no latency due to signal processing is necessary [15]. However, the signal manipulation does not allow for a full spatial simulation. This must be enabled by multi-antenna systems or by moving the antenna around.

In the last few years, many different systems have been reported. For example, a pure analog system from [15] offers a simulation of range, velocity, and RCS in the 77/79 GHz radar band. [16] reports a system with movable antennas to enable additional spatial simulation. They apply multiple antennas on a semicircular positioning system, allowing movement along azimuth, elevation, and pitching of the antennas. Systems using an antenna array for spatial simulation are reported by [17] and [18]. Hereby, the target angle can be altered by transmitting from a specific antenna or superimposing signals from multiple antennas. Additionally, commercial systems are provided, like the dynRTS from Perisens [19], which is a fully analog RTS. Other systems are the AREG from Rohde & Schwarz [20], the DARTS 9030-M from dSpace [21], or the E8707A from Keysight [22].

However, these systems are limited due to the increasing radar apertures for high angular resolution measurements, as large free-space ranges are necessary to achieve plane wave conditions over the aperture. To allow such measurements in laboratories, usually CTRs, as reported by [23] are used. Therefore, approaches combining such systems with a CTR to allow angular target generation must be analyzed to determine their suitability for such test ranges.

1.2 Goals and Content of this Work

This work presents different approaches to combine a compact test range with a radar target simulator in order to enable angular resolution testing. The first setup is the most intuitive one, as it applies two antennas placed at an offset to the focal point of the CTR. This method allows flexible angular measurements. Another approach is minimal invasive to the compact range, as a simple biprism is placed between the radar and reflector. It is a practical application of the Fresnel biprism experiment. However, due to its characteristics, it is a rather inflexible method as it does not allow dynamic changes in the angle. The third setup can be divided into two subsets. It is an application of the Fresnel mirror experiment, where two mirrors are slightly tilted to each other. For this work, the CTR reflector is split vertically in half. Both possible setups, tilting around vertical axes, called yawing, and around a horizontal axis, called pitching, are analyzed.

The work is organized as follows. At first, in section 2, the physical and technical fundamentals are provided. This includes basic information about electro magnetic (EM) waves, together with the reflection and refraction of an incidence field on material interfaces, compact test range design and considerations, fundamentals of radar systems with the focus on frequency modulated continuous wave (FMCW) radar, angular resolution, and a short section about RTS. Afterwards, a brief introduction to permittivity and some essential terms in measurement is given. Section 3 provides information about the simulation setup, the final CTR reflector with calibration measurements and results, and the radar systems used in the measurements. The following parts are about the three setups, with section 4 for the two-antenna setup, section 5 for the Fresnel biprism setup, and section 6, divided into two parts for both Fresnel mirror setups. These sections provide information about the structure, estimation, calculation, simulation, measurements, and occurring errors and inaccuracies of the specific setup. The work is concluded with a comparative summary of the results from the three setups and an outlook on future work.

2 Fundamentals

This chapter is intended to provide an overview of the main principles on which this work is based. However, it is not possible to cover all topics in detail, which is why some points that seem important must be neglected here. Nevertheless, if it is necessary to introduce them for a better understanding of the work, this will be done by making reference to them. In the following, a short outline of the structure of this chapter is given. Section 2.1 provides the basics of EM waves in general, followed by the near and far-field conditions and polarization in sections 2.1.1 and 2.1.2. Additionally, the incidence on a reflective and dielectric boundary area is explained in section 2.1.3. The following section 2.2 provides information about the operation principle and edge design of compact measurement ranges. Afterwards, the principles of radar systems, in particular FMCW Radar, automotive and multiple input multiple output (MIMO) radar, are introduced in section 2.3. The chapter concludes with remarks on material parameters in section 2.4 and the explanation of general terms for measurement used in this work in section 2.5.

2.1 Electromagnetic Waves

The first observations of electromagnetic interactions were found early in history. Experiments by Galvani and Faraday showed the presence of field appearances but could not further explain the occurring behavior. In the 1860s, James Clerk Maxwell was the first scientist to predict the existence of electromagnetic waves. He provided a theory and an equation system to calculate the connection between electric and magnetic waves and their environmental interactions [24, 25]. However, it took about 20 years until Heinrich Hertz could prove the existence of electromagnetic waves experimentally [26].

Generally, EM waves appear when an electric charge is accelerated. This will cause a change in the electric field and, subsequently, in the magnetic field. The generated EM wave can propagate independently of its source, depending on the environment. The behavior of the fields is described by the Maxwell equations. Similar to acoustic waves, EM waves carry momentum and energy. However, they do not necessarily need matter to propagate, as they can travel through a vacuum [27]. EM waves are characterized by frequency, propagation direction, amplitude, and polarization. Most of them are also properties of other physical waves, with the exception of polarization, which is only present for EM waves [28]. The spectrum of EM waves reaches from low frequencies,