Abstract

RADAR SENSORS are one of the most crucial sensor types in the field of advanced driver assistance systems due to their robust measurement principle compared to optical systems. They achieve high range, angle, and Doppler resolutions, all with high measurement dynamics, while being cost-efficient. Although more and more of these sensors are finding their way into vehicles, the level of their cooperation is often limited to sensor data fusion at the object level. Therefore, the advantages of distributed radar systems, such as evaluating the angle-dependent radar cross-section, the velocity vector of the target, and the increase in spatial resolution, remain unused.

This work, therefore, presents methods based on the bistatic scattering behavior of radar targets for distributed radar systems. In addition to introducing different classes of distributed radars, different levels of synchronization are discussed, and measurements are presented for a quasi-coherent system. The system uses trilateration and high signal bandwidths to spatially separate targets. This equivalent resolution is then compared to the angular resolution achieved with conventional monostatic multi-antenna systems. A fully automated measurement system for the direct determination of the velocity vector of a target is also presented. Basic radar targets and various vehicles are examined concerning their bistatic radar cross section (RCS) and categorized into different scattering classes. Also, the far-field boundary is experimentally investigated for retroreflective and isotropic radar targets.

Based on the preceding findings, a new dielectric radar target is presented. Due to its mixed specular and retroreflective response, the dielectric corner reflector combines two of the scattering classes and makes an ideal calibration target for distributed radar systems. The design and fabrication aspects, as well as the modeling of this target, are presented. Anti-reflective coatings that circumvent the specular response are introduced. Finally, the analysis of its bistatic RCS, as well as the impact of anti-reflective coatings, concludes this work.

Kurzfassung

RADARSENSOREN zählen, aufgrund ihrer robusten Messweise, neben optischen Systemen zu den wichtigsten Sensoren im Bereich moderner Fahrerassistenzsysteme. Sie zeichnen sich durch eine hohe Entfernungs-, Winkel- sowie Doppleraufösung bei gleichzeitig hoher Messdynamik aus und sind zudem kostengünstig. Obwohl immer mehr Radarsensoren in Fahrzeugen verbaut werden, beschränkt sich die gesamtheitliche Messmethodik oft auf eine Sensordatenfusion auf der Objektebene. Damit bleiben wesentliche Vorteile verteilter Radarsysteme, wie beispielsweise die Auswertung winkelabhängiger Radarquerschnitte, die Möglichkeit zur direkten Ermittlung des Geschwindigkeitsvektors eines Ziels, sowie eine allgemeine Verbesserung der räumlichen Auflösung, ungenutzt.

In dieser Arbeit werden daher verschiedene Aspekte und Methoden vorgestellt, wie diese Vorteile basierend auf dem bistatischen Streuverhalten von Radarzielen genutzt werden können. Neben der Beschreibung verschiedener Klassen von verteilten Radarsystemen, wird vor allem die Synchronisation zwischen vernetzten Sensoren erläutert, sowie zugehörige Messungen eines quasi-kohärenten Systems vorgestellt. Dieses System nutzt Trilateration und hohe Signalbandbreiten, um Ziele räumlich aufzulösen. Diese sogenannte äquivalente Auflösung wird darauffolgend mit der monostatischen Winkelauflösung von Antennengruppen verglichen. Außerdem wird ein vollautomatisiertes Messsystem zur direkten Bestimmung des Geschwindigkeitsvektors vorgestellt. Des Weiteren werden klassische Radarziele und verschiedene Fahrzeuge hinsichtlich ihres bistatischen Radarquerschnitts (RCS, engl.: radar cross section) untersucht und in verschiedene Reflexionsklassen eingeteilt. Ferner wird die Fernfeldgrenzbedingung für retroreflektive und isotrope Radarziele experimentell ermittelt.

Basierend auf diesen Ergebnissen wird ein neuartiges dielektrisches Radarziel vorgestellt. Aufgrund seiner gemischten Reflexionseigenschaften, die sowohl spiegelnd als auch retroreflektiv sind, stellt sich der dielektrische Winkelreflektor als ideales Kalibrierobjekt für verteilte Radarsysteme heraus. Der dielektrische Winkelreflektor wird hinsichtlich seiner Entwurfs- und Herstellungsaspekte vorgestellt und modelliert. Antireflexbeschichtungen werden erörtert, die die spiegelnden Reflexionen mindern. Die Arbeit schließt mit der Analyse des bistatischen RCS und des Einflusses seiner Antireflexbeschichtungen ab.

1 | Introduction

Gedenket dankbar des Heeres namenloser Techniker, welche die Instrumente des Radioverkehres so vereinfachten und der Massenfabrikation anpassten, dass sie jedermann zugänglich geworden sind.

Albert Einstein, 7. Große Deutsche Funkaustellung und Phonoschau
Berlin, 22. August 1930

The ability to accurately sense and navigate the environment is crucial for almost every evolved organism. One way of enabling this is *echolocation*, a concept widespread among some species. Bats are probably the best-known representatives of echolocation. By emitting chirps of high-frequency sounds and analyzing the returning echoes, they can evaluate the distance and direction of objects as well as the respective relative velocity, size, and shape. This ability is not exclusive to bats as it is also found in other species like toothed whales, certain kinds of birds, and various insectivores, showing how animals utilize echolocation in diverse ways [1].

Interestingly, parallels can be drawn between the echolocation abilities of these animals and the capabilities that come from binaural hearing in humans. With our two ears located on opposite sides of the head, we are also able to accurately determine the direction of a sound source [2]. This ability is thought to be based on cross-correlation techniques inherent to our brain that detect interaural time and intensity differences [3]. This *bistatic* sound localization is also very robust to interferers, leading to the ability of direction finding even in very noisy environments, known as the *cocktail party effect* [4]. This skill set aids spatial awareness and navigation, much like echolocation for bats. Some blind people also use noises generated by themselves to find their way around, just one of the many aspects that show the skillfulness of humans [5].

The ingenuity of researchers and technicians alike drove the invention of locating systems, trying to replicate these phenomena of nature. Christian Hülsmeyer stands at the forefront of this technological advance by describing the initial concept of what we know today as radar, which he called *Telemobiloskop* at the dawn of the 20th century [6]. Since then, radar technology has evolved drastically and penetrated a wide range of technical disciplines. However, its foundational principles echo the fundamental techniques of echolocation found in nature.

Just as in binaural hearing or echolocation, there are four general measurands that a radar system can gather. The basis of range estimation lies in the evaluation of time differences; velocities are estimated via Doppler frequency shifts or object tracking, objects can be classified via the evaluation of the respective received intensity, and angles are estimated via correlation to analyze phase differences. Multistatic systems, however, can enhance those measurement values. While many of the first radars were bistatic systems, their design was not to use the benefits of their distribution but to avoid self-interference. Only later were the advantages of multistatic systems used to leverage their multiple transmitter and receiver locations to improve detection and accuracy [7]. These multistatic techniques include trilateration, which uses the ranges of a target to determine its precise location, and triangulation, which utilizes angles between points for position determination. Moreover, not only the radial Doppler velocities but the actual velocity vector of a target can be estimated. The separation of measurement nodes also diversifies the received intensities of targets with varying cross sections depending on their orientation and helps to enhance detection capabilities and object classification.

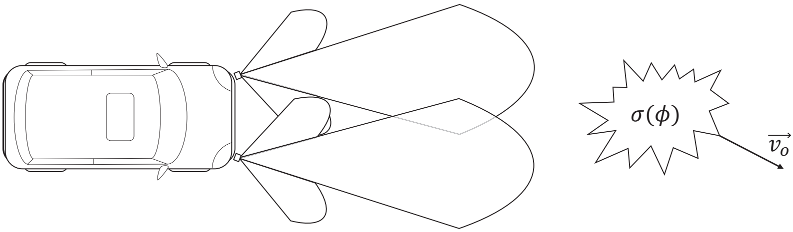

Figure 1.1: Sketch of a car with a bistatic radar setup as an example of a distributed sensing system for automotive applications. As the target on the right is illuminated from different aspect angles in contrast to a monostatic system, the angle-dependent radar cross-section and the velocity vector can be estimated.

This multitude of measurement capabilities is the reason why radar applications have found a strong foothold in the automotive industry. Modern vehicles, in their attempt to enhance the safety of passengers and other road users alike, rely heavily on accurate sensing and detection systems. The wish for more autonomy via advanced driver systems and fully autonomous driving has also propelled the development of radar technology, making it a robust and cost-efficient alternative to other sensing technologies like ultrasonic sensors and optical-based systems like cameras and lidar [8].

The FCC [9], ETSI [10], and the Bundesnetzagentur [11] all approved the opening of a part of the W-Band at $76 - 81\,\text{GHz}$ for radar sensing, enabling a multitude of various benefits, like higher angular resolutions or the improvement of the range resolution capabilities, by employing higher signal bandwidths. This led to rapid changes in the availability and types of automotive radar systems on the market. Current devices of the fourth and fifth generation [12, 13] have been developed and presented within short periods of time and, with each development step, have significantly improved performance. However, these monostatic systems have inherent limitations as distributed approaches are yet to come to automotive radar and have yet to prove their advantages in the automotive sector [14].

1.1 State of the Art

Current research specifically dedicated to automotive applications explores distributed systems to unlock the benefits mentioned above. In this context, especially frequency-modulated continous wave (FMCW) radar systems are often studied and generally involve multiple-input multiple-output (MIMO) techniques to increase the angular resolution [15, 16]. Besides presenting the MIMO capabilities of his distributed radar system, Gottinger describes in great detail the intricacies of distributed radar systems by focusing on synthesizing synchronicity between radar nodes in his Ph.D. dissertation [17]. These techniques often rely on special calibration techniques, e.g., by employing known signal paths or reference objects to achieve various degrees of synchronicity. In [18], various levels of synchronicity are compared. This research also reaches even higher frequency bands with the first so-called sub-THz systems, e.g., working at 150 GHz, often categorized as *imaging* radars, as they make it possible to achieve even higher resolutions while maintaining the same aperture. Other modular systems achieve synchronicity by employing optical transmission lines to distribute clock signals [19].

Distributed systems also allow direct direction of movement estimation without the use of tracking algorithms [20]. Target motion estimation in cooperative systems was presented in [21] and [22], both using a 77 GHz FMCW radar system with two sensing nodes and active reference targets for calibration to achieve precise measurement of the target velocity vector.

Another advantage that comes with spatially distributed radars is the possibility to trilaterate target locations. In a previous work that dealt with incoherent sensing nodes, trilateration-based localization methods were investigated, but the available bandwidths at 24 GHz limited target localization [23].

Large-scale automotive-focused research explored the challenges of real road traffic in several small-scale studies in the EU-funded MOSARIM project [24]. The issue of mutual interference played a significant role here, with approaches to solutions focusing on enhancing old modulation schemes or exploring completely new ones. The findings of these interference studies are also a basis for co-located cooperative sensing nodes, especially for simultaneous operation.

In addition to the benefits mentioned before, distributed radar systems can give more insight into object types through the knowledge of bistatic radar cross section (RCS) and statistical classification. Research in these systems primarily targets subjects like debris [25], vulnerable road users [26], and various vehicles, but are often limited to synthetic aperture radar (SAR) applications [27] or limited by data on the object layer [28]. Other studies are confined to near-field measurements, leaving far-field conditions less examined [29].

Finally, as all the aforementioned radar systems rely heavily on correct calibration, the analysis of calibration targets is crucial for the correct operation of a distributed radar system. Literature often presents corner reflectors as ideal calibration targets, especially for SAR and polarimetric applications [30, 31]. Some research and analyses about dielectric-based retroreflectors were yet only conceptual or based in the optical region [32, 33].

1.2 Objectives and Research Contributions

Based on the aforementioned state-of-the-art and current research, the main objective of this thesis is to combine the findings of the topics of distributed radar sensing, which comes with the challenge of synchronization of sensor nodes and a necessity for suitable calibration targets, especially in an automotive context, where baselines are relatively small, and targets are often not present in the far-field. Therefore, building upon an experimental bistatic FMCW radar system that enables direct velocity vector estimation, the implications of near-range measurements concerning the RCS of targets are thoroughly analyzed. Also, the aspects of bistatic scattering of basic targets are presented and used to identify the bistatic scattering characteristics of automobiles. These findings then establish a basis to assess a novel dielectric retroreflector as a suitable calibration and reference target for distributed radar systems.

The main research contributions of this thesis, therefore, include the following:

I Finding a simple solution to establish coherence between sensing nodes via data correction using an over-the-air calibration approach for direct velocity vector estimation

IIa Evaluating the far-field condition for basic scatterers with respect to their analytical RCS

IIb Analyzing the bistatic scattering behavior of basic target types to classify automobiles in addition to statistical means

III Establishing, deriving models for, and experimentally analyzing a novel calibration target suitable for near-range measurements that combines scattering mechanics

1.3 Scope and Outline

Based on the fundamentals of distributed radar systems in automotive applications, the topics and methodologies of different research areas are summarized in order to provide a holistic picture of the properties of radar targets in distributed radar systems. In addition to a general overview of the topic, theoretical models are given, enhanced, and validated experimentally. The experimental results are limited to the frequency band of current automotive radar sensors, i.e., the $76 - 81$ GHz range in the W-Band. Nevertheless, the theoretical models that are mainly based on quasi-optical methods are valid for all problems with equivalent electrical dimensions.

Starting with Chapter 2, the underlying system concept of the most common automotive radar system, the FMCW radar, is given. The different measurement dimensions of range, velocity, angle, and power are introduced. Furthermore, the general structure of different classes of distributed radars is presented, highlighting the issue of synchronicity of cooperative radar networks. In accordance to research contribution I, a simple data correction method is shown that enables a quasi-coherent system. Subsequently, the principle of direct measurement of the velocity vector of a target without the use of tracking algorithms is introduced. Finally, the advantages and limitations of trilateration-based target separation are given by the concept of equivalent angular resolution.

Chapter 3 gives insights into validation and experimental results on trilateration-based measurements and direct velocity vector estimation. For this, a bistatic quasi-coherent experimental radar system with a direct line-of-sight for calibration is presented. An automated measurement setup is used to evaluate the accuracy of the velocity vector estimation. This exploration underlines the benefits of over-the-air calibration and data correction of bistatic measurements highlighted in Chapter 2, central to research contribution I.

The work further illuminates the fundamental bistatic radar scattering characteristics in Chapter 4. Besides giving a fundamental insight into various basic radar targets, the RCS as a far-field quantity is analyzed concerning generally accepted far-field conditions. The far-field boundary for radar scatterers is then verified experimentally and specifically addresses contribution IIa. Given these far-field conditions, the highly variable RCS of automobiles as complex radar scatterers are simulated, analyzed, and statistically categorized. A bistatic RCS analysis of both canonical targets and automobiles concludes the chapter and, in all, fulfills research contribution IIb.

Finally, in Chapter 5, a novel target for radar applications is introduced — the dielectric corner reflector (DCR). Based on optical approaches, its working principles are combined with the RCS models of dielectric scatterers. Various manufacturing processes and their influence on the performance and material properties are described and measured. The unique properties of the DCR are further highlighted, starting with RCS measurements, as well as analyses and modeling of the interference effects caused by the specular response for perpendicular incidence. In addition, the design of optimal DCRs is evaluated based on lossy material properties. Anti-reflective coatings are introduced, especially for materials with high permittivity, which reduce the specular reflection. The bistatic scattering behavior of the DCR concerning these anti-reflective coatings is then demonstrated simulatively. Finally, the DCR is compared and evaluated against the conventional metal corner reflector. Through the introduction and comprehensive analysis of the DCR, this final chapter addresses research contribution III by establishing a novel radar target.

The citations throughout this work will follow the convention of the IEEE of a numbered reference style, i.e., literature will be referred to as [#], except for citations referring to the author's work that are marked by [Pub#].