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Array Design, Calibration and Target Feature Extraction Concepts

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Overview of Polarimetry in Application to Automotive Radar: Array Design, Calibration and Target Feature Extraction Concepts

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***Abstract*—An overview of polarimetric sensing and its growing application in automotive radar systems is presented. While polarimetric techniques are extensively used in fields like weather monitoring and target imaging, their integration into automotive radar presents unique challenges, particularly in calibration and measurement accuracy across wide scanning angles. This paper reviews key polarimetric principles and their use in different applications, with a focus on current automotive radar implementations, and the calibration challenges posed by off-broadside measurements. Future research directions for improving polarimetric accuracy in dynamic automotive environments are also discussed.**

***Index Terms*—wave polarimetry, MIMO radar, FMCW radar, calibration, target recognition, target classification.**

I. INTRODUCTION

Polarimetry, which refers to the measurement of the polarization of electromagnetic waves, is increasingly being applied in various radar systems, including automotive radar [1]–[6], weather monitoring [7]–[9], synthetic aperture radar (SAR) imaging [10], [11], defence [12]–[14] and radio astronomy receivers [15], [16]. Polarimetric radar systems can measure the scattering matrix of a target, allowing for a more detailed characterization of its properties, such as size, shape, and material composition [17]–[19].

Since the 1970s, polarimetric radar has been used in weather monitoring to model wave attenuation in rain, detect hail, and estimate rain rates [20]. Polarimetric measurements can observe changes in raindrop shape (Fig. 1) based on size [9], providing insights into rain density. PARSAX, shown in Fig. 2, is a mechanically steered polarimetric radar at Delft University that allows simultaneous measurement of all backscattering matrix elements [21]. In recent years, phased array radars (PAR) have increasingly replaced traditional radar systems, combining fast data updates with polarimetric measurement capabilities. Polarimetric phased array radars (PPARs), such as Skyler [22] (Fig. 3 (a)) and the Horus [23] (Fig. 3 (b)), support dual-polarization and advanced weather monitoring.

Polarimetric measurements are widely used beyond weather monitoring, notably in SAR to distinguish materials, surface textures, and structures by analyzing different polarization states (Fig. 4). In radio astronomy, they help characterize the polarization of interstellar radio waves [15], [16]. For defense, polarimetric radars are employed to classify unmanned aerial vehicles [12], [13] and detect small weapons through walls [14]. Recently, they have also shown potential for detecting small floating objects on the sea surface [24], useful for water security and emergency scenarios.

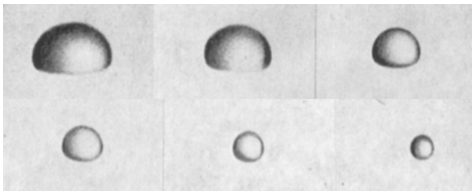

Fig. 1. Shape of large drops falling at terminal velocity having equivalent spherical diameters of D=8.00, 7.35, 5.80, 5.30, 3.45, and 2.70 mm [9].

Fig. 2. S- / X-band high-resolution Doppler polarimetric FMCW radar [21].

(a) (b)

Fig. 3. PPAR for weather applications: (a) Skyler X-band PPAR [22], (b) Horus S-band PPAR [23].

In automotive applications, mm-Wave technology has enabled the integration of PARs due to their compact size (Fig. 5 (a)). There is growing interest in incorporating polarimetric

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TABLE I
KEY FEATURES IN POLARIMETRY FOR VARIOUS APPLICATIONS

	Weather Radar	**Automotive Radar**	**SAR Radar**	**Radio Telescope**
Center freq.	2 GHz to 10 GHz	77 GHz	1 GHz to 8 GHz	100 MHz to 1 THz
Radar type	Pulse/ FMCW	MIMO FMCW	Pulse from moving platform	Parabolic receiver
Tx and Rx design	Co-located/ bistatic Tx&Rx	Spread TXs and RXs	Co-located/ bistatic Tx&Rx	Receiver only
Measurement focus	Polarimetric variables for hydrometeors detection (ZDR, KDP, etc.)	Target scattering matrix measurement.	Measurements of the scattering properties of targets across different polarization states.	Characterize the electromagnetic properties of celestial bodies.
Calibration focus	Mismatches between polarization beams.	Synchronization between polarization channels across all Txs and Rxs.	Account for radar movements and varying geometries.	Low power of received signals, long-range signal propagation.

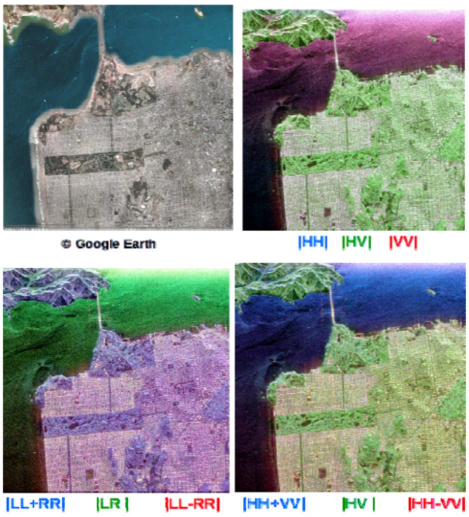
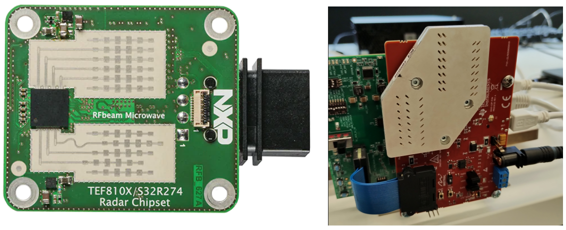


Fig. 4. Polarimetric measurement in SAR imaging [11].



(a) (b)

Fig. 5. Automotive radars: (a) 77 GHz single-polarized radar transceiver developed by NXP [28], (b) 77 GHz $\pm 45^o$ fully-polarized radar developed by Huber&Suhner [27].

measurements into automotive radars, allowing more detailed target characterization, including material properties, size, shape, and orientation [5]. Studies have shown polarimetric radar's usefulness for road user detection, direction of arrival (DOA) estimation, and road surface modeling [1], [2], [25]. In 2019, a groundbreaking analysis of polarimetric millimeter-wave radars for automotive use was conducted [26]. Recently, a 77 GHz ±45° PPAR (Fig. 5 (b)) developed by Huber&Suhner was delivered to Delft University for further testing [1], [27].

A summary and comparison of key features while applying polarimetry in design and processing for various applications is provided in Table I. Despite the significant progress in the domain, the ambitious performance requirements and emerging applications such as automotive radars make the use of polarimetry still scientifically and practically challenging.

This paper aims to provide a comprehensive overview of polarimetric techniques, address the scientific challenges related to polarimetric measurement, and identify open areas for future exploration. The rest of the paper is organized as follows. Section II discusses the scientific challenges in polarimetric measurement and calibration, specifically for weather and automotive applications. Section III provides a review of the existing research on polarimetric array design, polarimetric calibration and feature extraction in automotive radar applications. Section IV presents the conclusions and highlights the open areas for future research.

II. MAJOR CHALLENGES IN POLARIMETRY

A. Increment of the cross-polarization level of the radiation pattern in off-broadside measurement

Calibration in fully-polarimetric radar systems is more complex than in single-polarized systems, especially for off-broadside targets. When scanning off-broadside, the polarization basis of the backscattered wave becomes non-orthogonal as shown in Fig. 6, introducing cross-polarized components [8], [17]. Additionally, phased array scanning alters the radiation pattern, affecting amplitude and phase. Therefore, radiation pattern calibration is crucial for accurate measurements in electrically scanned PPARs.

B. Varying antenna phase centers in MIMO polarimetric radar

In polarimetric radar, phase information from received signals is crucial for extracting the target's scattering matrix. Accurate measurement of polarimetric phase information requires consideration of the antenna phase center, defined as the point where the phase remains essentially constant over a radiation sphere. Any inconsistency in the phase center between polarizations can lead to measurement errors.

In polarimetric weather pulse radars (Fig. 3), transmitters and receivers are co-located, avoiding phase center variation. However, in most frequency-modulated continuous wave (FMCW) radars, often used in automotive applications

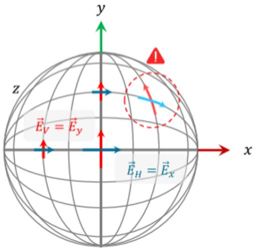


Fig. 6. Change of polarization basis when scanning [29].

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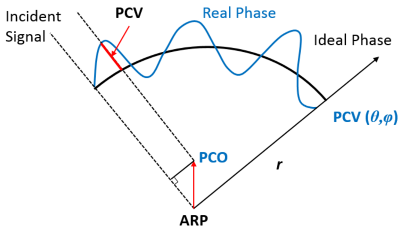

Fig. 7. PCV and PCO model [31].

(Fig. 5), they are separated, causing different phase center locations. This issue is further complicated in multi-input multi-output (MIMO) systems, where antennas are spread over a larger area. The phase center is not fixed and can vary with frequency and observation angle. As shown in Fig. 7, the phase center offset (PCO) does not coincide with the antenna reference point (ARP), necessitating corrections to ensure precise measurements [30]. Additionally, actual phase variations deviate from the ideal spherical model, leading to phase center variation (PCV).

C. *Complexity of polarimetric radar calibration*

Polarimetric radars are used in various applications, each with specific measurement focuses. Weather radars aim to accurately estimate key polarimetric variables such as differential reflectivity (ZDR), specific differential phase (KDP), and copolar correlation coefficient (ρhv), which are essential for quantifying rainfall and hail [8]. In SAR systems, the emphasis is on accurately measuring scattering properties across horizontal and vertical polarizations to differentiate surface types [11]. Radio astronomy uses polarimetry to characterize celestial bodies' electromagnetic properties [15]. Automotive applications leverage polarimetric information for target detection and classification [2].

The differences in polarimetric calibration approaches arise not only from varying goals and operational environments but also from the types of polarimetric radars used. For instance, pulse PPARs in weather applications have co-located transmitters and receivers, simplifying the calibration process by allowing easier alignment of horizontal and vertical (H and V) channels. The calibration is then focused on ensuring that the H and V beams are well-aligned and have minimal cross-polarization [32]. In contrast, automotive polarimetric MIMO radars feature transmitters and receivers at separate locations, requiring calibration techniques that address phase and amplitude imbalances across the array while synchronizing polarizations to minimize cross-talk. Meanwhile, radio astronomy receivers typically focus on calibration for long distances and weak signals from celestial targets.

These distinct needs complicate the integration of calibration methods across applications. For instance, techniques designed for co-located systems, like those in weather radar, may not adapt well to the distributed setups of automotive and MIMO radars. Similarly, real-time calibration methods in automotive applications may not apply to the precise static calibration required in radio astronomy. Table I shows that for each application specialized calibration techniques are developed to address unique challenges, but the diversity in system architectures, operational environments, and calibration goals makes creating a unified approach difficult.

D. *Lack of comprehensive system model for joint development of antennas and calibration strategies*

As discussed, significant challenges remain in polarimetric radar calibration. To address these issues, a system model is needed that integrates radar antenna design (e.g., radiation element type, MIMO topology) with calibration strategies (e.g., reference targets, algorithms). Currently, research on such a comprehensive system model is lacking. Therefore, it is necessary to develop a low-complexity model that combines antenna design and calibration strategies, facilitating an integrated analysis of how antenna characteristics affect calibration accuracy and performance.

III. REVIEW OF EXISTING RESEARCH ON POLARIMETRY FOR AUTOMOTIVE RADARS

A. *Antenna array design*

Series-fed subarray design enhances polarimetric MIMO antenna systems by improving polarization diversity and target discrimination. One design approach uses separate single-polarized subarrays for each polarization state, while the other uses dual-polarized subarrays, which handle two orthogonal polarizations simultaneously. Although dual-polarization offers compactness, it increases design complexity, especially in multi-layer structures. Implementing dual-polarization on a single layer can reduce this complexity, as shown in recent studies [33]–[35]. Table II shows some existing designs of automotive polarimetric antennas.

Beamforming techniques in series-fed subarrays aim to improve the resolution. Wide horizontal beamwidth is crucial for automotive radars to monitor the environment effectively. In [40], a beamwidth enhancement technique using a coupled-mode patch antenna was proposed, broadening horizontal coverage and improving radar awareness.

MIMO topology design focuses on optimizing the spatial arrangement of transmitters and receivers. By designing the MIMO topology to achieve specific phase relationships between virtual array elements, polarimetric calibration becomes more accurate, enhancing target discrimination. Aligning phase relationships simplifies the calibration process, as demonstrated in designs like [36]. Placing the same polarized channels on the same side of the board [37] further minimizes phase discrepancies, streamlining the calibration procedure.

TABLE II
KEY LITERATURE ON AUTOMOTIVE POLARIMETRIC ANTENNA DESIGNS

Ref.	**Freq. [GHz]**	**Port isol. [dB]**	**BW [MHz]**	**Radiation ele.**	**Size**	**Pol. type**
[36]	77	30	/	Horn	6Tx/8Rx	H/V linear
[35]	77	15.9	5000	wave-guide	1x1	R/L circle
[37]	79	18	3000	microstrip-line	12Tx/16Rx	$\pm 45^o$
[38]	77	17.5	3900	ridge-gap-waveguide slot	8x18	R/L cricle
[39]	76-81	30	5000	sectoral horn	12Tx/16Rx	H/V linear
[33]	77	35	3000	Patch	1x10	$\pm 45^o$

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B. Polarimetric calibration in MIMO automotive radar

The usage of MIMO FMCW radars in automotive sensing allows high-precision DOA estimation. Moreover, fully polarimetric radars in automotive applications can obtain the scattering matrix of the objects, which can be used for target classification or identification. In the mm-wave band (77 GHz), the measurement of amplitude and phase become extremely sensitive to the outer or inner interference. Thus, calibration is necessary before data collection.

Unlike the PPAR for weather applications, which uses full-digital beamforming to scan the beam in arbitrary directions, polarimetric radars for automotive applications usually require a wide array pattern in the azimuth plane and a narrow pattern in the elevation plane. Therefore, in polarimetric automotive radar, the measurement in different azimuth angles is done at the same time through a wide radiation pattern in azimuth instead of making the beam do the actual scanning process. Three basic methods to perform calibration in automotive radar were already studied in the 20th century [36]: 1) the isolated antenna calibration technique (IACT) [41], 2) the general calibration technique (GCT) [42] and 3) the single reference general calibration technique (SRGCT) [43]. Among these methods, the IACT method is the simplest yet most accurate calibration method [41]. The IACT method was applied to calibrate a fully polarimetric 8x8 MIMO FMCW radar system for automotive applications in [36], providing promising laboratory measurement results of several canonical objects at varying locations. However, the dependency on the different azimuth angles or the relative velocity to the scatterer is not considered in [36]. The calibration and processing techniques that provide stable polarimetric information of the same scatterer over the complete space of a target's range, angle, and velocity are studied in [44]. Until recently, the polarimetric calibration method using a single reference target was proposed [39]. In [39], a MIMO automotive PPAR is calibrated using a rotatory dihedral corner reflector. The calibration was separated into two steps: 1) calibrating the imbalances among virtual RXs within individual virtual subarrays, 2) calibrating across different subarrays.

C. Feature extraction in automotive applications

In DOA estimation, polarimetric radars help separate multipath from direct paths if the target is known. This is achieved using coherent Pauli decomposition and multipath reflection measurements [45]. Targets at the same radial distance but different DOAs can be distinguished through angular-dependent polarimetric scattering. Joint DOA and polarization estimation also enable the separation of adjacent targets located in the same direction but at different radial distances [6]. In addition, polarimetric extensions of sparse methods can be used to address challenges in DOA estimation when one polarization's signal power is weak or absent. In signal processing, sparse methods leverage the fact that only a few sources contribute to the observed data. Building on this concept, polarimetric extended sparse techniques like Polarimetric Sparse Learning via Iterative Minimization (POL-SLIM) and Polarimetric Sparse Iterative Covariance-Based Estimation (POL-SPICE) were developed for DOA estimation [25]. Fig. 8 clearly shows that the POL-SLIM provides a higher probability of detection (P_d) compared with other single-polarized SLIM-based methods, especially in low SNR regions.

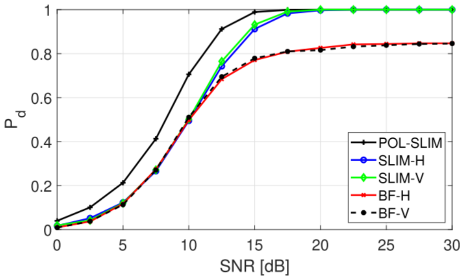

Fig. 8. P_d vs SNR of SLIM-based procedures [25].

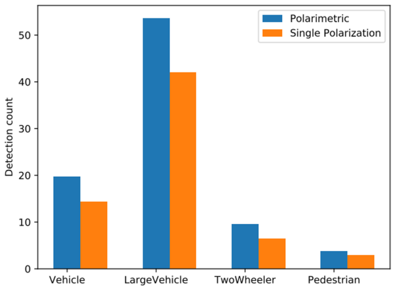

Fig. 9. Road user detection using polarimetric data [3].

For vehicle self-localization, polarimetric MIMO radar is crucial, especially in GNSS-denied environments like tunnels. Polarimetric data aid in distinguishing landmarks based on their scattering mechanisms, which is valuable for creating a gridmap for self-localization [4]. In road targets detection application, polarimetric information can be added to radar point clouds, which improves the segmentation performance of the deep learning model, mainly through phase information from scattering processes, resulting in an 11.2% F1 score improvement [46] and increase the detection count per class as shown in Fig. 9 [3]. Moreover, polarimetric data is also useful for road surface recognition [1]. Using statistical methods based on coherence matrix decomposition, attributes like target entropy and pedestal can be estimated, which are essential for characterizing road conditions like asphalt [1].

IV. CONCLUSION

Polarimetric sensing is emerging as a valuable tool in automotive radar systems, offering enhanced target discrimination and environmental awareness for safety. This overview covers the use of polarimetry in various applications (including weather radars, SAR and radio astronomy receivers) and highlights the unique requirements of automotive applications. The array design, calibration and feature extraction approaches are critically reviewed. The need for further research into MIMO array topologies and calibration methods is motivated, particularly in off-broadside scenarios due to the variation of polarimetric information with the target orientation and scattering angle.

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