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Polarimetric Coupling in Phased Array Weather Radars: Requirements and Mitigation Techniques

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Abstract— The challenge of polarimetric coupling in phased array weather radars is explained, along with the resulting requirements. For the first time, state-of-the-art mitigation techniques on the system, hardware and software level are discussed together along with their achievements and shortcomings. An outlook is made toward future developments and applications, including integrated weather sensing and communications.

Keywords— Phased arrays, polarimetry, polarimetric coupling, weather radar, data quality.

I. INTRODUCTION

Meteorological observations demonstrate an increase in the frequency of extreme precipitation events in recent years [1]. Such extreme weather events highlight the need for advanced measurement systems that can forecast and improve our understanding of their developments. This can be achieved through deployment of polarimetric phased array weather radars due to their capability of continuous remote monitoring of atmosphere and retrieval of the precipitation, clouds and wind parameters. Polarimetry is a key feature as different types of rain, snow and hail particles have distinct shapes. This causes incoming electromagnetic waves with different orientations of the electric field to be scattered differently by them. Knowledge of the scattering behavior at two orthogonal polarizations then provides additional information that can be used to determine the type, size, and orientation of the hydrometeors, as shown in Fig. 1.

To support its research on atmospheric physics and climate change, Delft University of Technology operates a wide range of polarimetric instruments, such as the ones shown in Fig.

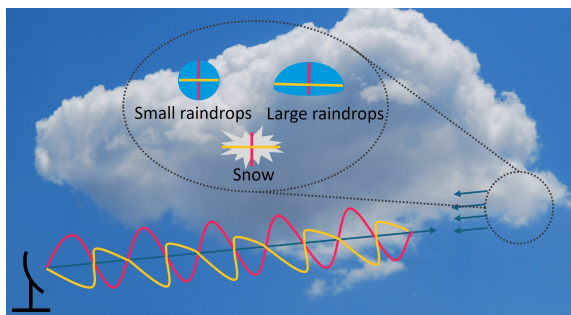


Fig. 1. System impression of dual-polarization radar working principle to identify shape, size and orientation of different hydrometeors.



Fig. 2. Photos of polarimetric weather radars: (a) MESEWI: X-band mechanically scanning radar operated by TU Delft. (b) HORUS PPAR by the Advanced Radar Research Center [2]. Licensed under CC BY 4.0.

2a. Recently, the use of phased array antennas (PAAs) has been introduced to weather radars. An example of such a polarimetric phased array radar (PPAR) is shown in Fig. 2b. As the beam can be scanned electronically, this provides an unprecedented level of flexibility [3]. Next to the benefit of an increase in the scanning speed, new applications are enabled. Examples include the use of multiple coherent beams to scan 3D volumes [4], the use of space-time adaptive processing [5] and the concept of a multi-function PPAR [6]. Although it brings many benefits and new opportunities, the use of dual-polarized PAAs comes with trade-offs. Reduction of orthogonality of the emitted polarizations with scanning is one of the fundamental challenges, which is the focus of this paper.

In weather radar, the return signal can be considered stochastic, and information is contained in the powers and correlations. The reduction of orthogonality causes such estimates to become biased [7], causing errors in applications like hydrometeor classification and quantitative precipitation estimation (QPE). In this paper, the state-of-the-art mitigation techniques on the system, hardware and software level are discussed along with their advantages and shortcomings. The remainder of the paper is structured as follows. Section II describes the cause of polarimetric coupling. Section III investigates what level of coupling can be tolerated in practical scenarios. Section IV explores the state-of-the-art polarimetric coupling mitigation methods for PAA weather radar to meet these requirements. Other problems associated with PPAR, such as cost and manufacturability, are outside the scope of this paper. Section V provides a brief overview of future research, including emerging applications in joint weather sensing and communications. Finally, Section VI concludes the paper.

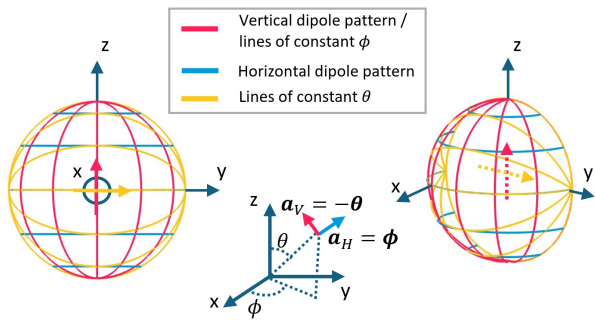


Fig. 3. Non-orthogonal emitted fields by two orthogonal dipoles. The coordinate system shows the convention commonly used for the weather radar.

II. DEFINITION OF POLARIMETRIC COUPLING

Ideally, the emitted polarizations should be perfectly orthogonal everywhere. If this is not the case, the returned signal from one polarization consists in part of the desired return signal from the scatterers, and in part of the leaked signal from the other polarization. However, in practice, achieving this orthogonality has proven to be difficult. Fig. 3 illustrates an example in which the radiation patterns for the two polarizations are formed by employing two ideal crossed dipole antennas. It can be seen that even in this idealized scenario, orthogonality of the fields is not achieved except for the principal planes. Although the vertically oriented dipole has a component only along the ϕ direction, the horizontally oriented dipole will have components along both ϕ and θ . In reality, mutual coupling and environmental effects will result in imperfect orthogonality even on the principal planes. The reduction of orthogonality as we move further away from the principal planes is also present in practical polarimetric arrays.

III. POLARIMETRIC PERFORMANCE REQUIREMENTS

The requirements on the polarimetric coupling depend on the application. As previously mentioned, the information in the weather radar signals is extracted through estimates of their powers and correlations. These are then transferred, using the appropriate proportionality constants, into the derived polarimetric variables, like horizontal reflectivity (Z_H), differential reflectivity (Z_{DR}), co-polar correlation coefficient (ρ_{HV}), linear depolarization ratio (LDR) and specific differential phase (K_{DP}). One of their main applications is QPE, whose performance is often used to derive the requirements. Generally the limit is an accuracy of 1 dB for Z_H and 0.1 dB for Z_{DR} [8], which would cause a 10% increase in the RMS error of commonly used rainfall estimation algorithms. Similar requirements can be derived for the other polarimetric variables. Although requirements on the accuracy of polarimetric variables have been extensively described, the way these translate into system requirements remains an open question due to their complex dependency of numerous factors. One factor that is particularly important is the measurement mode used by the radar. The three most studied measurement modes are as follows: the alternate transmission mode (AHV: emit one

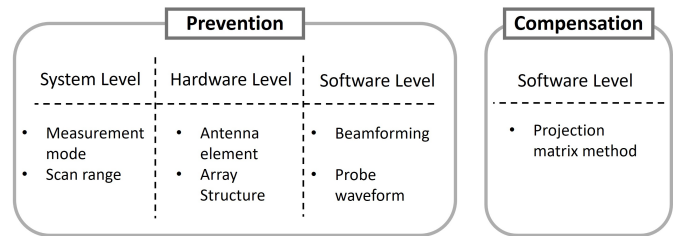


Fig. 4. Overview of the different mitigation methods for polarimetric coupling.

polarization at a time, alternating between two orthogonal ones), simultaneous transmission mode (SHV: emit two orthogonal polarizations at the same time) and the 3-Pol1D mode (emit 3 different polarizations alternately, which are not orthogonal [9]). Simultaneous reception of two polarizations is implied in all modes. A recent study has quantified the isolation requirements between two polarizations, described in terms of cross-polar discrimination (XPD), which expresses the ratio of the co-to cross-polar patterns [10]. This study found a required XPD ranging from 22.5 dB for the AHV mode to 51 dB for the SHV mode. For the 3Pol1D method, a requirement of 22 dB was derived [9]. The isolation of the antenna front-end was not taken into account, and a uniform weather scenario was assumed. It should be noted that the different measurement modes have their own applications, advantages and disadvantages [11].

IV. MITIGATION OF POLARIMETRIC COUPLING

Fig. 4 provides an overview of the methods discussed in this section. The mitigation of polarimetric coupling starts with the choices made on the system level. The cross-coupling increases off the principal planes, and different measurement modes have different cross-coupling tolerances. Next to these system-level choices, which need to take into account the intended application, there are three main approaches to mitigate the polarimetric coupling: (1) reducing coupling through hardware; (2) reducing coupling through the emitted signals; (3) mitigating biases induced by polarimetric coupling through signal processing methods.

A. Reducing coupling through hardware

The first approach has resulted in a plethora of different antenna elements [12]–[18]. A review of different causes of cross-polarization (X-Pol) in antenna elements can be found in [12]. Some recurring elements can be derived from these references. Firstly, the focus of antennas for PPAR is on patch or dipole elements. Secondly, though excellent X-Pol levels have been achieved in the principal planes, performance in the diagonal planes remains either lackluster or not mentioned. Lastly, there is a shortage of literature on the effects of the front-end isolation. Further, research has also been carried out on different array architectures, such as the cylindrical polarimetric phased array. Due to rotational symmetry, the scanned beam is always in the principal planes, reducing cross-polarization effects [13]. Other methods, such as the use of optimally polarized elements across the array in hybrid

Table 1. Main advantages and disadvantages of mitigation methods from Section IV.

Approach	Techniques	Limitations	References
Coupling reduction through hardware	Design of antenna elements and array topologies, feeding networks and front-end integration	Performance for large scan ranges in the diagonal planes remains inadequate	[12]–[18]
Coupling reduction through software	Beamforming, phase coding, orthogonal waveforms, XPC	Computational complexity, reduction of other data quality aspects	[19]–[22]
Coupling compensation	Projection matrix method	Assumptions of perfect pattern knowledge and uniform weather	[23]–[27]

beamforming [14], have been proposed, having attractive trade-offs between the polarimetric pattern gains and the cost.

B. Reducing coupling through software

Polarimetric coupling reduction in software can be done either through the emitted waveforms, or through the beamforming. With regards to the waveform, aspects, such as the range-Doppler trade-off, the suppression of second-trip echoes, and the blind range of the radar, need to be taken into account. When it comes to polarimetric coupling, however, the waveform must always be considered together with the intended measurement mode. For the AHV or 3Pol1D measurement methods, the only relevant aspect of the waveform is its bandwidth, as the coupling is frequency dependent. For the SHV mode, however, the returns from the two polarizations can be made orthogonal by emitting different waveforms from each of the two polarizations. Next to reducing the polarimetric coupling, this allows for retrieval of additional polarimetric parameters. The topic of waveform orthogonality has been well researched, and although many different methods exist, there is always a trade-off. In the pulse-to-pulse phase coding technique [19] for example, the Doppler domain is effectively split in half, which causes issues when observing phenomena with high velocities. Recently the designation of some array elements as ‘canceller elements’ that emit an out-of-phase waveform to cancel the X-Pol emitted by the majority of the elements has been introduced [20]. Further, beamforming can be used to reduce polarimetric coupling. In [21], the beamforming problem was formulated as an optimization problem using the sidelobe and X-Pol level as constraints. An important constraint missing when applying this to PPAR is the matching of the beams emitted by different polarizations. This was taken into account in [22]. Nonetheless, such optimisation algorithms are computationally complex, hindering their implementation in real-time applications.

C. Compensation of polarimetric bias

An alternative to reducing the polarimetric coupling is compensating it in the received signals. After all, if the co-and cross-polar patterns are perfectly known, and a point target is assumed, the effects of the antenna patterns can simply be inverted in signal processing. This method is known as the projection method. It was first proposed for point targets using dipole antennas, and later extended to other types of antennas [23] and distributed targets [25], and tested at low elevation angles [27]. It remains to be seen whether the assumption of

uniform weather as well as perfect pattern knowledge limit the applicability of this method in practical scenarios where in-field array calibration will play an important role [28].

V. OUTLOOK

Most of the current operational PPAR systems comprise electronic scanning in elevation and mechanical in azimuth as in [29]. To the authors knowledge, the only radars capable of full electronic scanning are reported in [2], [27]. These projects have demonstrated that interdisciplinary teams consisting of both application-oriented atmospheric scientists, as well as technological radar-and antenna specialists are necessary. Often, research focuses on a single aspect of the system, as described in Section IV. The different approaches use their own figures of merit. Future research by the authors will focus on a system model to combine these individual metrics into a complete system performance, enabling the analysis of their joint effects. Such a novel system model should be an extension of current PPAR simulators [30], [31], including effects of both the hardware, software and compensation methods into a single model.

Another promising future prospect is the advent of 6G networks. One of the aspects of 6G is the integration of sensing techniques into such networks is expected [32]. As communication systems can also use dual-polarized phased arrays, developments from PPAR may be carried over to allow opportunistic sensing by the network. The integration of communication links, traditional weather radars and other sensing measures can provide a dense grid of high-quality weather estimates [33], which in turn could be used to provide channel information to the communication network. There are some remaining obstacles for this integration, including the unsolved problem of resource (e.g. time, frequency, power, gain) sharing between communication and sensing tasks.

VI. CONCLUSION

The use of PPAR provides new levels of flexibility and opportunities. One of the major remaining challenges is the polarimetric coupling resulting from the emitted electric fields being non-orthogonal. Different mitigation methods were discussed on the hardware and software level for the first time. As for the former, hardware can provide adequate isolation in the principal planes at the cost of added complexity, but no sufficient isolation over a wide scan range in the diagonal planes has been achieved. Regarding the software, beamforming algorithms have resulted in adequate coupling

mitigation in simulations but remain too computationally heavy for real-time use. Tuning the waveforms can provide additional mitigation in certain measurement modes, at the cost of exacerbating other data quality issues. Another class of mitigation methods is the projection matrix compensation method. In simulations, assuming full pattern knowledge and uniform weather, this method solves the coupling issue. It remains to be seen whether it can provide this performance in real applications with practical integrated phased arrays. In general, the polarimetric coupling problem can thus be considered solved in the principal planes. Outside of those, different methods, each having their own downsides, were proposed, but have not been sufficiently demonstrated yet under real-life conditions.

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