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# Polarimetric Calibration of an FMCW Doppler Radar with Dual-Orthogonal Signals

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***Abstract*—In this paper, the full calibration chain of FMCW radar with simultaneous transmission of two orthogonally polarized orthogonal waveforms is considered. Specifically for this type of polarimetric radar, compensation of signals' biases and equalization of the amplification gains of the parallel polarimetric channels in the receiver are jointly performed using the noise measurements. The calibrations of the absolute complex gains of the transmitter's polarimetric channels together with complex antenna gains are done using the model-based fit of the measurements of the rotating dihedral reflector. Phase relations between polarimetric channels are treated in the Doppler domain using the unfolded velocity of the target. The performed calibration results in high-accurate measurements of the radar targets' polarimetric scattering matrix (PSM) in the Doppler domain. All the proposed calibration steps are illustrated using real radar data.**

***Index Terms*—radar polarimetry, polarimetric calibration, polarization scattering matrix measurements**

## I. Introduction

Instant polarimetric properties of any object as a subject of radar observations can be fully described using the concept of Polarization Scattering Matrix (PSM), which relates the polarization state of the incident electromagnetic signal with the polarization state of the scattered signal in a specific direction. Polarimetric radars with the capability to measure the PSM have a long history and many applications. In the last one and a half decades, the novel concept of simultaneous radar polarimetry using FMCW signals with dual orthogonality (in polarimetric and waveform domains) [3], [5] has been implemented and intensively studied experimentally using the S-band FMCW polarimetric Doppler PARSAX radar [4]. Besides other advantages, the simultaneous polarimetry using signals with dual orthogonality at least two times improves the ambiguity in the Doppler frequency estimation.

The analysis of experimental data shows that multi-channel parallel measurements of the polarimetric signal, which are specific for this type of polarimetric radar, are strongly influenced by the non-ideality and non-equality of the radar signal transmission and reception channels. In this paper, we present the full calibration chain of the measured polarimetric signals processing that results in high-accurate measurements of the radar targets' PSM in the Doppler domain and illustrate the proposed calibration steps using real radar data.

The paper is organized as follows. Chapter II presents the mathematical model and processing algorithms of the polarimetric measurements using sensing signals with dual (polarization and waveform) orthogonality. The noise-based equalization of the signals in polarimetric channels with non-equal biases and amplifications is proposed and illustrated in Chapter III. Chapter IV describes the calibrations of the absolute complex gains of the transmitter's polarimetric channels together with complex antenna gains using the measurements of the rotating dihedral reflector. The proposed model-based fit of the measured polarimetric data takes into account the non-ideality of the radar and dihedral reflector's spatial arrangement. Chapter V describes the Doppler-domain-based compensation of the residual phase difference between the PSM columns that are measured using quasi-simultaneous polarimetric FMCW waveforms [6] and illustrates the results using the statistics of moving cars polarimetric observations. The final conclusions and recommendations for the proposed calibration chain usage are presented in Chapter VI.

## II. Model of the FMCW Polarimetric Sensing Waveforms with Dual Orthogonality and their Processing Algorithms

Instant polarimetric properties of any object as a subject of radar observations can be fully described using the concept of Polarization Scattering Matrix (PSM), which relates the polarization state of the incident electromagnetic signal with the polarization state of the scattered signal in a specific direction (see e.g., [1], [2]):

$$\dot{\mathbf{E}}_R(t) = \dot{\mathbf{S}} \cdot \dot{\mathbf{E}}_T(t) = \begin{Vmatrix} S_{11}e^{j\psi_{11}} & S_{12}e^{j\psi_{12}} \\ S_{21}e^{j\psi_{21}} & S_{22}e^{j\psi_{22}} \end{Vmatrix} \cdot \dot{\mathbf{E}}_T(t) \quad (1)$$

where $\dot{\mathbf{E}}_{T/R}(t) = \left\| \dot{E}_1^{T/R}(t), \dot{E}_2^{T/R}(t) \right\|^T$ are complex polarization vectors of the transmitted and received signals, $\dot{\mathbf{S}}$ - the PSM of an observed object. It is necessary to mention that all these polarization vectors and PSM have to be written at some but the same polarization basis (PB) $\{1, 2\}$. In general, the notation (1) can be used not only for the description of the polarization state of the transmit and received signals with normalized vectors $\dot{\mathbf{E}}$ but for the full description of

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signals propagation within the radar channel, including signal amplitudes and phases, and the noise instant values.

In reality, the polarization state of the received radar signal is not defined as easily as presented in (1). The realistic model of the polarization vector of the transmitted wave has to include all non-ideality and non-equality of the transmission channels for signals with both orthogonal polarizations, non-equality of the transmit antenna gains on these polarizations, and the possible presence of the non-zero cross-polarization coupling. As a result, the measured signals at the output ports of the polarimetric received antenna can be written as

$$\dot{\mathbf{E}}_{\mathbf{R}}(t) = \frac{A}{r^2} e^{-2jkr} \cdot \dot{\mathbf{X}} \cdot \dot{\mathbf{E}}_{\mathbf{T}} + \dot{\mathbf{n}} \tag{2}$$

where the measured PSM $\dot{\mathbf{X}}$ of the whole radar channel can be defined as

$$\dot{\mathbf{X}} = \dot{\mathbf{R}} \cdot \dot{\mathbf{R}}_{\mathbf{A}} \cdot \dot{\mathbf{P}}_{-} \cdot \left(\dot{\mathbf{S}}_{\mathbf{0}} + \dot{\mathbf{C}}\right) \cdot \dot{\mathbf{P}}_{+} \cdot \dot{\mathbf{T}}_{\mathbf{A}} \cdot \dot{\mathbf{T}} \tag{3}$$

and its general amplitude is defined using the standard radar equation

$$A = \left(2\eta_0 P_t G_t G_r \lambda^2 / (4\pi)^2\right)^{1/2} \tag{4}$$

Here $\dot{\mathbf{S}}_{\mathbf{0}}$ is the actual PSM of the radar object of interest (target), $\dot{\mathbf{C}}$ is the PSM of clutter, $\dot{\mathbf{T}}$ is the $(2 \times 2)$ diagonal distortion matrix of the transmitter, $\dot{\mathbf{T}}_{\mathbf{A}}$ is the distortion matrix of the dual-polarized transmit antenna, $\dot{\mathbf{R}}_{\mathbf{A}}$ is the similar distortion matrix of the dual-polarized receiving antenna, $\dot{\mathbf{R}}$ - is the diagonal distortion matrix of the receiving antenna's output ports and input circuits of the receiver. $\dot{\mathbf{E}}_{\mathbf{T}}$ is the idealized polarization state vector of the transmitted signal. $\dot{\mathbf{P}}_{+}$ and $\dot{\mathbf{P}}_{-}$ are the distortion matrices of the propagation channel in both directions: from the radar to the target and back, respectively, $\dot{\mathbf{E}}_{\mathbf{T}}$ is the received polarimetric signal that has to be used to characterize the target with the "true" PSM $\dot{\mathbf{S}}_{\mathbf{0}}$. This equation also takes into account the initial amplitude of the transmitted wave (using the constant $A$ that is defined by the standard radar equation), the dependencies of received signal amplitude and phase from the range $r$ between radar and observed target, and the presence of the thermal white Gaussian noise $\dot{\mathbf{n}}$ in every measurement channel. In this equation, $k$ is the modulus of the propagation vector, $P_t$ - transmit power, $G_t$, $G_r$ - gains of the transmit and receive antennas, $\lambda$ - radar wavelength, and $\eta_0$ - intrinsic impedance of free space.

Using the normalization of every matrix and vector to one of arbitrarily selected elements (e.g., with indexes 11), it is possible within this equation to separate the general scalar relations between total amplitudes/powers/phases and vector/matrix relations that describe the dependencies between the polarization-orthogonal components of the received signals.

As follows from (1), for the measurements of all elements of the PSM, it is necessary to transmit such waveforms on orthogonal polarizations that, with signal processing in the receiver's channels, their amplitudes and phases can be correctly and independently estimated. Within this study, we use the definition of a polarimetric radar as a radar that is capable of measuring all elements of the PSM using sensing signals with dual orthogonality - in polarization and waveform spaces [3] [4], [5]. Such signals can be represented as a sum of two orthogonal polarization components, which form the polarization basis of the radar measurements, and which are modulated with some kind of orthogonal waveforms that can be separated during the reception with some type of matched processing.

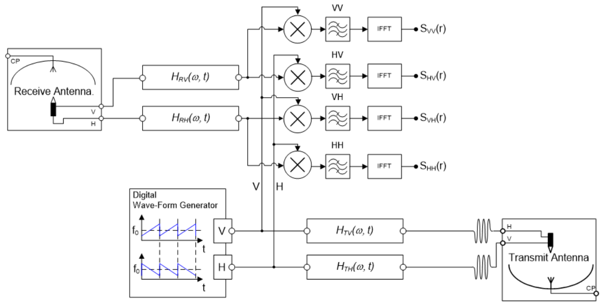


Fig. 1. The simplified block diagram of the TU Delft PARSAX radar - polarimetric FMCW radar with dual-orthogonal sensing signals

The simplest for the received signal processing implementation and, as a result, most widely used in existing polarimetric radar systems are time-multiplexed polarimetric waveforms when transmission and reception of the orthogonally polarized components are separated in time. The main disadvantages of this technique are that the columns of the PSM are not measured simultaneously, and the full PSM is measured with two-times reduction of the operational pulse/sweep/waveform repetition frequency. The first factor degrades the measurement accuracy for fast-moving/changing targets. The second is even more critical as it reduces two times the ambiguity in Doppler velocity estimation.

An alternative approach is formulated in [3] - to transmit and receive the signals simultaneously with orthogonally-polarized components that are modulated with orthogonal waveforms, i.e., waveforms that follow the orthogonality conditions:

$$\begin{aligned} U_{ij}^{T} &= \int \dot{E}_i^T(t) \cdot \dot{E}_j^{T*}(t) \cdot dt \equiv 0 \\ U_{ij}^{R}(\tau, \omega_d) &= \int \dot{E}_i^T(t) \cdot \dot{E}_j^{R*}(t - \tau, \omega_d) \cdot dt \cong 0 \end{aligned} \tag{5}$$

where indexes $i, j = 1, 2$, $i \neq j$ relate to the orthogonally-polarized components, and $T, R$ are related to transmitted and received signals, respectively. The joint matching processing of these waveforms gives the possibility to simultaneously measure all elements of the PSM. Different types of the LFM-based polarimetric signals for the FMCW radars have been proposed in [3] [4], [5], [7] and implemented within the TU Delft PARSAX radar. The block diagram of this radar is presented in Fig. 1, and the optimal for deramping processing FMCW waveforms with dual-orthogonality [6] that were used for measurements within this study are presented in Fig. 2.

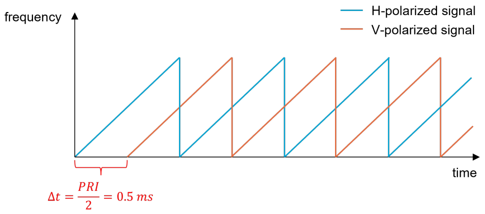


Fig. 2. Dual-orthogonal polarimetric waveform for the quasi-simultaneous measurements of the PSM elements in an FMCW polarimetric radar

The main specific feature of such polarimetric radar is the simultaneous measurements of signals at the output of four parallel polarimetric receiver channels. These signals are proportional to all elements of measured PSM $\dot{\mathbf{X}}$, defined with equation (3). More specifically, the range- and time-dependent polarimetric signal at every output of the FMCW radar deramping receiver's four parallel polarimetric channels can be written as a sum of the signal $x_{i,j}(r,t)$, which is scattered by external objects, with the thermal noise:

$$y_{i,j}(r,t) = x_{i,j}(r,t) + n_{i,j}(r,t) \tag{6}$$

where $r$ is the range coordinate after the beat signal range compression, $t$ is the discrete slow time that is equal to the integer number of the sweep repetition interval ($SRI$), $x$ is the slow-time-dependent range profile of the complex scattered signals, $n$ is the complex white Gaussian noise with zero mean and the variance $\sigma^2_{i,j}$. Indexes $i,j$ are related to two transmitted and two received polarization channels (e.g., horizontal $H$ and vertical $V$), respectively.

As soon as the reception channels are real independent electronic devices, their characteristics are not ideal or identical. The final measured signal at the output of every receiver channel can be represented as

$$V_{i,j}(r,t) = a_{i,j}(r) \cdot y_{i,j}(r,t) + b_{i,j}(r) \tag{7}$$

where $a_{i,j}(r)$ and $b_{i,j}(r)$ are channel-specific amplification and bias of the output signal, respectively. In general, both parameters can be functions of the range, and their short-term temporal dependency is not expected.

The presented model of the polarimetric radar, which uses signals with dual orthogonality for the simultaneous measurements of all elements of the PSM, helps to develop a set of calibration algorithms that will convert the measured complex range profiles $V_{i,j}(r,t)$ into the best estimation of true PSM of target and clutter $\hat{\dot{\mathbf{S}}}_\mathbf{0} + \hat{\dot{\mathbf{C}}}$. These data, which describe the true polarimetric characteristics of the target and clutter in the best possible way, can be processed further to solve classical radar's tasks for target reliable detection, classification, and identification.

In this paper, we propose to start with the noise-based polarimetric channels equalization algorithm for the vector $\dot{\mathbf{Y}}(r,t)$ estimation, which will be presented and illustrated in Chapter III. After such a noise-based equalization of polarimetric channels, it is possible to make an external calibration of the radar. This calibration provides the necessary data for the estimation of the matrix $\dot{\mathbf{S}}_\mathbf{0} + \dot{\mathbf{C}}$ using signals $y_{i,j}(r,t)$.

As in most standard/usual scenarios, the propagation channels can be regarded as non-depolarized channels, the matrices $\dot{\mathbf{P}}_+$ and $\dot{\mathbf{P}}_-$ are diagonal and can be neglected from the consideration. In most practical cases using the mentioned above normalizations, the diagonal distortion matrix of the transmitter $\dot{\mathbf{T}}$ and the distortion matrix of the dual-polarized transmit antenna $\dot{\mathbf{T}}_\mathbf{A}$ can be combined into the distortion matrix of the polarimetric transmitter and denoted as the same notation $\dot{\mathbf{T}}_\mathbf{A}$. A similar operation can be done by combining the distortion matrix of the dual-polarized receiving antenna $\dot{\mathbf{R}}_\mathbf{A}$ with the diagonal distortion matrix of the receiving antenna's output ports and input circuits of the receiver $\dot{\mathbf{R}}$.

Finally, the estimation of the true polarization scattering matrices at the specific radar resolution volume at a distance $r$ from the sensor will still be affected by thermal noise $\hat{\dot{\mathbf{N}}}$ and can be written as

$$\hat{\dot{\mathbf{S}}}_\mathbf{0} + \hat{\dot{\mathbf{C}}} + \hat{\dot{\mathbf{N}}} = \left(\dot{\mathbf{R}}_\mathbf{A}\right)^{-1} \cdot \dot{\mathbf{Y}} \cdot \left(\dot{\mathbf{T}}_\mathbf{A}\right)^{-1} \tag{8}$$

The matrices $\dot{\mathbf{T}}_\mathbf{A}$ and $\dot{\mathbf{R}}_\mathbf{A}$ can be estimated through an external radar calibration using, for example, the observation of the rotated dihedral reflector [10], [11]. An example of such calibration will be given in Chapter IV.

All such corrections, calibration, and equalizations have to be done within the specific measurement polarization basis, which is defined by the polarizations of the transmit and receive antennas. After the estimation of the PSM using (8), the results can be converted to any suitable polarization basis for further analysis. In the case of the PARSAX radar, such a conversion is required due to the specific construction of the antenna steering system. The linearly-polarized measurement polarization basis changes its orientation angle in relation to the elevation angle. Finally, the PSM estimation in standard polarization basis $\{H,V\}$ has to be calculated as

$$\begin{aligned} \hat{\dot{\mathbf{S}}}_\mathbf{0HV} \quad &+ \quad \hat{\dot{\mathbf{C}}}_\mathbf{HV} + \hat{\dot{\mathbf{N}}}_\mathbf{HV} = \\ &= \mathbf{Q}^\mathbf{T}(\alpha) \cdot \left(\dot{\mathbf{R}}_\mathbf{A}\right)^{-1} \cdot \dot{\mathbf{Y}} \cdot \left(\dot{\mathbf{T}}_\mathbf{A}\right)^{-1} \cdot \mathbf{Q}(\alpha) \end{aligned} \tag{9}$$

where $\mathbf{Q}(\alpha)$ is the polarization basis rotation matrix for the angle $\alpha$ that defined by the elevation angle for analyzed measurements.

## III. Noise-Based Polarimetric Channels Equalization

Usually, it is possible in most FMCW radars to measure only the noise signals in polarimetric channels using the capability to blank the transmitters' power amplifier. As soon as all parallel channels of the polarimetric radar receiver have the same electronic design and are physically located in the same environment with the same system temperature, the true power of noise signals in all channels must be the same. This assumption can be used for estimating the specific amplification $a_{i,j}(r)$ and bias $b_{i,j}(r)$ in equations (6) and (7) for every polarimetric receiver's channel. In the case

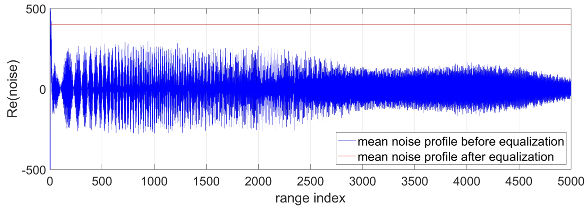


Fig. 3. Average range profiles of the real part of the PARSAX radar noise data - the initial signal that is strongly influenced by the range compression (blue line represents the voltage in ADC units ) and the signal after application of the proposed algorithm (red line represents the voltage in noise std units, shifted from zero value up for 400 unis for better visibility)

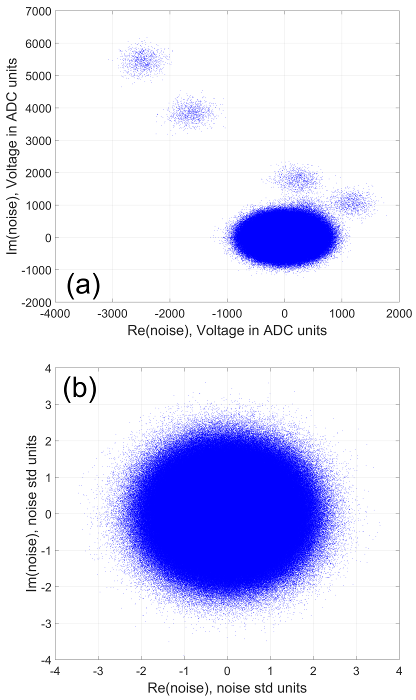


Fig. 4. Clouds of the samples from the noise range profile at the IQ plane: (a) a multimodal distribution of the measured data, (b) Gaussian distribution after application of the proposed algorithm (skewness $10^{-7}$, kurtosis 3.147 for both real and imaginary parts of the signal).

of noise-only measurements, the channel-specific measured signals will look like:

$$\dot{N}_{i,j}(r) = a_{i,j}(r) \cdot \dot{n} + b_{i,j}(r) \tag{10}$$

where $N_{i,j}(r,t)$ is the measured noise range profile at the output of the FMCW receive channel $(i,j)$, and $n$ is the true noise signal that is expected to be time-, range- and channel-independent white Gaussian noise with zero mean and the system temperature-dependent variance $\sigma_0^2$. If these assumptions are correct, then

$$\begin{aligned} mean(N_{i,j}(r)) &= b_{i,j}(r) \\ var(N_{i,j}(r)) &= [a_{i,j}(r)]^2 \cdot \sigma_0^2 \end{aligned} \tag{11}$$

As soon as the range profiles of these noise signal's moments are estimated, it is possible to equalize/calibrate signals in all

TABLE I
AMPLITUDES OF THE ELEMENTS OF THE COVARIANCE MATRICES OF THE POLARIMETRIC NOISE BEFORE AND AFTER EQUALIZATION

| before | HH | HV | VH | VV |
|---|---|---|---|---|
| HH | 1.3300 | 0.0156 | 0.0122 | 0.0125 |
| HV | 0.0156 | 5.4700 | 0.0267 | 0.0254 |
| VH | 0.0122 | 0.0267 | 2.3200 | 0.0270 |
| VV | 0.0125 | 0.0254 | 0.0270 | 4.9600 |
| after | HH | HV | VH | VV |
| HH | 1.0000 | 0.0058 | 0.0070 | 0.0048 |
| HV | 0.0058 | 1.0000 | 0.0076 | 0.0049 |
| VH | 0.0070 | 0.0076 | 1.0000 | 0.0079 |
| VV | 0.0048 | 0.0049 | 0.0079 | 1.0000 |

polarimetric channels:

$$\begin{aligned} y'_{i,j}(r,t) &= \frac{V_{i,j}(r,t) - mean(N_{i,j}(r))}{\sqrt{var(N_{i,j}(r))}} \\ &= x'_{i,j}(r,t) + n'_{i,j}(r,t) \end{aligned} \tag{12}$$

After such an equalization/calibration, the variance of the residual noise $n'_{i,j}(r,t)$ is equal to 1, and the amplitude of the informative component $x'_{i,j}(r,t)$ equals to the $\sqrt{SNR}$ - the square root from the signal to noise ratio in this specific polarimetric channel.

The proposed algorithm applying to the real PARSAX radar polarimetric data shows that such normalization of the measured polarimetric signals using the independently measured noise signals provides the capability to remove some artifacts of the bit signal processing and range compression in FMCW radar. These artifacts result in the signal amplitude modulation along the range axis (see Fig. 3) and multi-modal shape of the noise signal distribution (Fig. 4a). The proposed algorithm completely removes any unexpected range dependence of the noise characteristics (strictly linear red line in Fig. 3) and improves the noise normality (Fig. 4b) in every channel. Using the estimation of the noise polarimetric $4 \times 4$ covariance matrix before and after correction (12), it was demonstrated that not only the channel amplitudes are equalized but also the channels' independence is improved (cross-channel covariance coefficients become closer to zero) (see Table I). In this table, the amplitudes of the covariance matrix elements estimated before equalization have been normalized with the general multiplier $10^6$ for compactness. The analysis also shows that, in agreement with (12), the phases of the covariance matrix elements have not been influenced by this equalization algorithm.

The equality of the noise variance in range and in between polarimetric channels, together with the representation of signals' amplitude in terms of SNR simplifies not only the comparative analysis of the PSM elements' amplitudes but also the range dependency analysis of any element of the PSM.

## IV. Polarimetric Calibration using a Rotating Dihedral Corner Reflector

The external calibration of a polarimetric radar provides a possibility to estimate the distortion matrices $\dot{\mathbf{T}}_\mathbf{A}$ and $\dot{\mathbf{R}}_\mathbf{A}$ together with the absolute complex gains of the transmitter, receiver, and antennas polarimetric channels [8], [9]. These characteristics are necessary for the equation (8) implementation to estimate the true PSM of a radar target and can be represented using similar forms without losing generality:

$$\dot{\mathbf{T}}_\mathbf{A} = T_{HH}\begin{bmatrix} 1 & \dot{\delta}_1^T \\ \dot{\delta}_2^T & \dot{f}^T \end{bmatrix}, \; \dot{\mathbf{R}}_\mathbf{A} = R_{HH}\begin{bmatrix} 1 & \dot{\delta}_1^R \\ \dot{\delta}_2^R & \dot{f}^R \end{bmatrix} \quad (13)$$

where for both antennas $\delta_1$ and $\delta_2$ are crosstalk terms, and $f$ represents the one-way co-polarized channel imbalance in amplitude and phase. One of the possible approaches to the external calibration of polarimetric radars that minimize the number of necessary calibration targets with different PSM is to use the dihedral corner reflector, which is rotated around the line of sight [10], [11]. The PSM of this reflector that rotates through an angle $\alpha$ in the plane $(h, v)$ can be written in this coordinate system as follows

$$S(\alpha) = \sqrt{\frac{\sigma}{4\pi}}\begin{bmatrix} -\cos 2\alpha & \sin 2\alpha \\ \sin 2\alpha & \cos 2\alpha \end{bmatrix} \quad (14)$$

The sizes $a$ and $b$ of such reflector have to be selected using the equation of the maximum radar cross section (RCS) $\sigma = 8\pi a^2 b^2/\lambda^2$ that has to be big enough to provide high values for signal-to-noise and signal-to-clutter ratios.

The timeline of the measured signal in the case of the rotated dihedral corner reflector (which can even be rotated manually) has to be converted in the angular dependency using the signal's minimum on co-polarised channels at orientations $\pm 45°, \pm n \cdot 90°$ and on cross-polarized channels at orientations $\pm n \cdot 90°$, where $n$ is the integer number of rotation. The resulting angular dependency of multi-channel measured data can be used for the estimation of parameters $\delta_1$, $\delta_2$, and $f$ using the best fit to the simulated model data methods.

Figure 5a represents the fitted to the angular grid and measured with the PARSAX radar polarimetric data of 16 continuous slow rotations of the dihedral corner reflector with sizes of $1.05 \times 1.5$ m at a distance of $1.3$ km. As can be seen from the zoomed part within the picture, the variability of the signal from rotation to rotation in the area of maximum does not exceed 0.1-0.2 dB for all channels. The observing theoretically unexpected difference of about 5 dB between co-polarized channels and $\approx 3$ dB between cross-polar channels originated from the receiver channels inequality. As can be seen from Fig. 5b, this inequality of signals in polarimetric channels was removed after the application of the described above noise-based equalization to the raw data. The application of the model-based distortion matrices (13) estimation algorithm to the data after the noise-based equalization shows the good quality of the PARSAX radar hardware design: for both antennas, the amplitudes of the crosstalk terms $\delta_1$ and $\delta_2$ are better than $0.005$, and the co-polarized channel imbalance $|f| > 0.95$ (better than 0.25 dB).

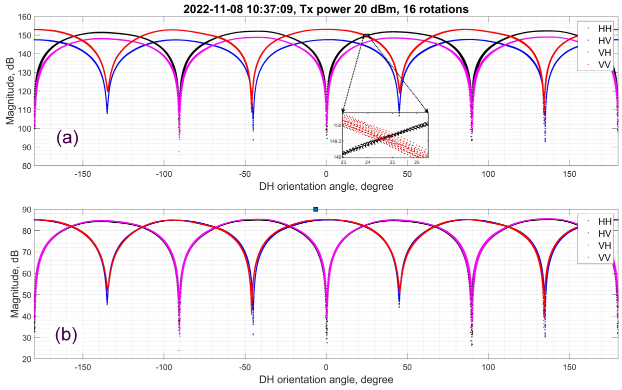


Fig. 5. The PSM elements' amplitudes of the dihedral corner reflector that is slowly rotating around the line of sight as functions of the rotation angle. The plot represents 16 sequential rotations, which were synchronized using the HH channel minima. (a) raw data, (b) data after the noise-based channels equalization.

## V. Polarimetric Phases Correction in the Doppler Domain

In the FMCW polarimetric radar with quasi-simultaneous dual-orthogonal signals (Fig. 2), a time shift between the transmitted H- and V-polarized signals for the case of moving targets would lead to an additional phase difference between the columns of the PSM. This phase difference is proportional to the target's velocity $\Delta\phi(v) = 2\pi(2v\Delta t)/\lambda$ and can be easily compensated in the Doppler domain for the case of the target's motion with the non-ambiguous Doppler velocity. Such compensation has been demonstrated in [12] for classical polarimetric waveforms with the polarization orthogonal components transmission with the time-shift of one sweep repetition interval $\Delta t = SRI = 1/PRF$. The polarimetric waveforms with dual orthogonality that are used in this study provide a possibility to coherently process every polarimetric channel with the original sweep repetition frequency, without Doppler ambiguity degradation. In this case the time-shift is two times smaller: $\Delta t = 0.5 \cdot SRI = 1/(2 \cdot PRF)$, but also results in the additional phase shift between the columns of the PSM, which can be related to the maximum unambiguous velocity $v_{max}$: $\Delta\phi(v) = \pi \cdot v/(2 \cdot v_{max})$. For the real measured polarimetric calibrated data, this effect is demonstrated in Fig. 6 using the phase difference between cross-polarized components $HV$ and $VH$, which is expected to be zero. This range-Doppler plane represents the collection data for moving cars that were measured within the street-way case when all these cars moved with the velocity below the Doppler ambiguity.

Further analysis shows that in quite practical case of one-time folded target velocity, an extra phase shift of $\pi$ has to be added:

$$\Delta\phi = \begin{cases} \dfrac{\pi v}{2v_{max}} & v = v_{true} \\ \dfrac{\pi v}{2v_{max}} + \pi & v = v_{folded} \end{cases} \quad (15)$$

The resulting corrected elements of the PSM with compensated phases have to be calculated as

$$\dot{S}'_{VH} = \dot{S}_{VH} \cdot e^{j\Delta\phi}, \quad \dot{S}'_{VV} = \dot{S}_{VV} \cdot e^{j\Delta\phi}$$

where $\dot{S}'_{VH}$ and $\dot{S}'_{VH}$ are the compensated data.

The results of such compensation are demonstrated in Fig. 7a, where most targets have equal phases of $HV$ and $VH$ elements of the PSM. The reason why not all phase differences between cross-polar components in this plot are close to zero is demonstrated in Fig. 7b. In this figure, the phase difference is presented as a function of the signal amplitude. The inverse proportionality of the distribution width of the residual phase difference from the target's signal amplitude can be clearly seen from this picture as a result of the stronger noise influence on the phase characteristics of weaker targets.

## VI. Conclusions

This paper introduces the full calibration chain for signal processing in FMCW radar with simultaneous transmission of two orthogonally polarized orthogonal waveforms and echo signals parallel reception in the 4-channel receiver for simultaneous measurements of all elements of the PSM. The noise-based algorithm for equalization of polarimetric channels has been proposed and illustrated using measurements of the noise and slowly rotated dihedral corner reflector. The high performance of the proposed algorithm is demonstrated for polarimetric channel equalizations and the removal of some specific artifacts for the FMCW radar processing. Phase relations between polarimetric channels are treated in the Doppler domain, extending existing approaches to new classes of signals and cases with the Doppler velocity ambiguity. The performed calibration results in high-accurate measurements of the radar targets' polarimetric scattering matrix (PSM) in the Doppler domain. All the proposed calibration steps are illustrated using real radar data.

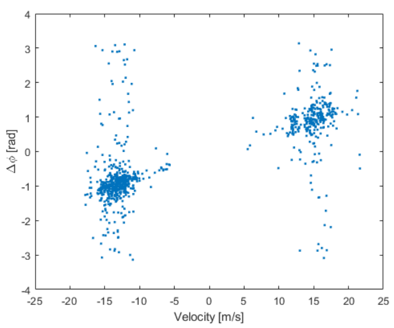


Fig. 6. Phase difference between the PSM elements $S_{HV}$ and $S_{VH}$ of multiple moving cars that shows a linear dependence on the Doppler velocity.

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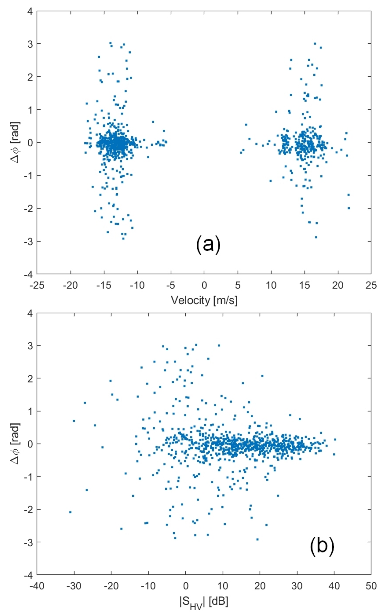


Fig. 7. Compensation results on the phase difference between the PSM elements $S_{HV}$ and $S_{VH}$ in case of unambiguous Doppler velocity: (a) the compensated phase difference; (b) the compensated phase difference w.r.t. signal amplitude