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Polarimetric Optimization for Clutter Suppression in Spectral Polarimetric Weather Radar

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***Abstract*—For the polarimetric-Doppler weather radar, sometimes there are artifacts caused by unknown interference displaying in the radar plan position indicator (PPI). These artifacts are not confined to specific range bins and also they are non-stationary when observed in the Doppler domain. This paper puts forward a method to suppress such clutter by designing the generalized spectral linear depolarization ratio (GsLDR) filter. This filter combines the optimal polarization contrast enhancement (OPCE) technique and the double spectral linear depolarization ratio (DsLDR) filter. The success of this filter is mainly based on the polarimetric property difference between precipitation and clutter. The X-band polarimetric-Doppler IRCTR Drizzle Radar (IDRA) data are used to qualitatively and quantitatively verify the performance of the newly proposed filter for radar artifacts suppression.**

I. Introduction

Clutter which may lead to the atmospheric targets undetected or impose a bias on the real reflectivity, has aroused extensive attention in radar meteorology. The environment might be complicated because of different sources of clutter, such as ground clutter, radio frequency interference, insects and birds mitigation, and artifacts caused by unknown interference.

Most of the time, artifacts are speckles along the whole range bins in some azimuth directions in the plan position indicator (PPI). These artifacts are easily treated as precipitation in the radar PPI, resulting in a relatively high false alarm. Moreover, these speckles are not confined to some range bins and also they are non-stationary when observed in the Doppler domain. For example, radar artifacts have influenced the display of the polarimetric X-band radar IRCTR Drizzle Radar (IDRA) since its installation in 2007. Radar technicians and engineers have tried to deal with this problem; however, no practical solution is achieved until now.

Currently, the standard clutter suppression processing consists of a narrow notch filter centered around 0 ms^{-1} and the double spectral linear depolarization ratio (DsLDR) filter [1]. Further, removing the range bins whose reflectivity are less than the threshold which is set to 3 dB larger than the measured noise level, a noise clipping technique is implemented. DsLDR filter, is based on the different distribution of the spectral-polarimetric parameter — spectral linear depolarization ratio (sLDR) [2] of precipitation and clutter. However, its shortcoming lies in that the sLDR of precipitation and clutter overlap, making it impossible to distinguish them thoroughly. Additionally, it is not desirable that the narrow notch filter may suppress the precipitation whose radial velocity is around 0 ms^{-1} and the noise clipping may remove the weak precipitation.

Aiming at keeping the precipitation while suppressing as much clutter as possible, a method called generalized spectral linear depolarization ratio (GsLDR) filter based on optimal polarization contrast enhancement (OPCE) [3] is proposed here. OPCE, which is widely used in the area of SAR target detection, is mainly based on the polarimatic property difference of the two chosen objects, namely the precipitation and the artifacts in this paper. The time-domain process OPCE, which enhances the intensity of precipitation and suppresses that of clutter, can effectively select the precipitation while eliminating the clutter.

The detail of the newly-proposed clutter suppression method is introduced in the next section followed by real radar data verification. Finally, some conclusions are drawn.

II. Description of the Technique

To fully take advantage of the polarimetric information to mitigate the influence of clutter in polarimetric weather radar, a time-domain process OPCE is applied here. For general radar detection, it is not necessary to make an accurate measurement of radar echoes intensity. While for weather radar, it is important to obtain the quantitative precipitation estimation.

However, when we apply the OPCE process, it will add a non-linear weight on the intensity of precipitation and clutter, which is unfavorable because it biases the original reflectivity. Additionally, it will eliminate all the phase information which is necessary for the Doppler processing. Thus, the GsLDR filter used here is a pre-processing to design one selection mask whose function is to retain the precipitation and eliminate the clutter. It cannot independently be regarded as a way of clutter filtering, and it should combine with other filtering methods. Specifically, we apply GsLDR filtered result masking on the result of the DsLDR filter to get the final range-Doppler spectrogram.

Assume under the back scatter alignment (BSA), the received power can be expressed as

$$P = \frac{1}{2} K \cdot g \cdot h \tag{1}$$

where K is the Kennaugh matrix (short for K matrix), g and h are the Stokes vectors of the transmitter and the receiver, respectively. For the OPCE problem, the optimal polarization

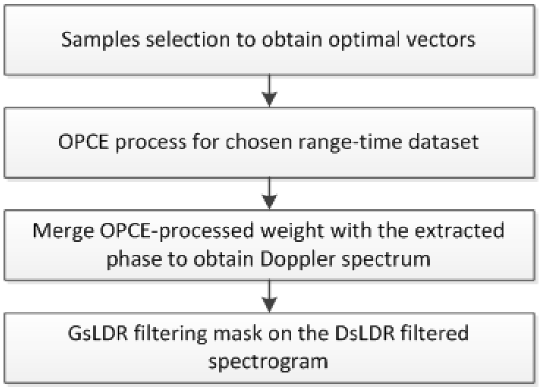


Fig. 1: Flow chart of OPCE-based clutter suppression method.

states $g = \begin{pmatrix}1 & g_1 & g_2 & g_3\end{pmatrix}^t$ (here t denotes the transpose) and $h = \begin{pmatrix}1 & h_1 & h_2 & h_3\end{pmatrix}^t$ are required for maximizing the power ratio of the signal and the clutter whose average K matrix are denoted as K_S and K_C [3]

$$\begin{aligned} \text{maximize} \quad & \frac{K_S}{K_C} \\ \text{subject to} \quad & g_1^2 + g_2^2 + g_3^2 = 1. \\ & h_1^2 + h_2^2 + h_3^2 = 1. \end{aligned} \tag{2}$$

From (2), the optimal polarization vectors (g_m, h_m) which act as the weighted function of the chosen signal and clutter can be obtained. When applying (g_m, h_m) to other signal samples, the more similar the matrix is with K_S, the better performance OPCE will achieve. The similarity can be quantified by the contrast power ratio (CPR) between the two chosen objects expressed as

$$CPR = \frac{g_m^t \cdot K_S \cdot h_m}{g_m^t \cdot K_C \cdot h_m} \tag{3}$$

OPCE, enhancing the K_S when compared with K_C, means the larger value of CPR the better contrast performance OPCE achieves.

The flow chart of the newly-proposed clutter suppression method based on the OPCE process is shown in Fig. 1. It mainly divides into four steps.

(a) Firstly, samples of radar data containing precipitation and clutter should be selected separately as the training samples to obtain the optimal vectors for OPCE. For Doppler weather radar, the Fourier transform can be applied to the range-time data to check its Doppler velocity which may indicate precipitation in certain range bins. Those whose spectrum distribution is continuous and non-zero can be regarded as precipitation, otherwise environment clutter. By choosing precipitation and clutter of different sizes and areas, a series of (g_m, h_m) can be obtained. One set of the optimal vectors whose corresponding CPR is the largest can be selected as the optimal polarization vectors for further OPCE process.

(b) Secondly, use the chosen optimal vectors to conduct OPCE for other range-time datasets. When applying OPCE in one range-time dataset, the three original polarization channels HH, VH and VV which consist of the polarization scattering matrix should be firstly combined to form the K matrix. Then the precipitation-enhanced and clutter-suppressed power intensity can be expressed as

$$G = h_m^t \cdot K \cdot g_m \tag{4}$$

Then it is possible to design a weight to merge with the extracted phase to further produce the OPCE-processed spectrogram. The weight W is a function of G, expressed as

$$W = f(G) \tag{5}$$

The optimal design of the weight W is to separate the precipitation and the artifacts in the GsLDR domain, which will be illustrated in step (d). After some statistical tests, $W = G$ is chosen in this paper as an empirical relation.

(c) Thirdly, merge OPCE-processed weight with the extracted phase to further obtain the Doppler spectrum. The phase information can be acquired by normalizing all the data with the absolute amplitude of the corresponding point in the range-time domain in HH channel. Then multiplying the OPCE-processed weight W and the obtained phase as

$$S^{OPCE} = W \cdot \frac{S_{hh}}{|S_{hh}|} = W \cdot exp\left(j\Phi_{hh}\right) \tag{6}$$

where S_{hh} is the original range-time HH scattering matrix element and Φ_{hh} is the related phase. Further through the Fourier transform, the range-Doppler spectrogram can be obtained. Then to keep the consistence of the data value interval for better comparison, the processed data are scaled by using the following equation:

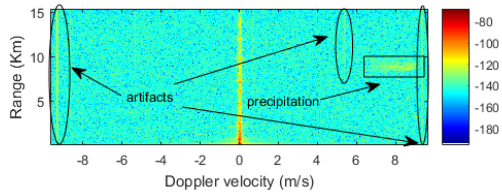
$$P^{OPCE}(v) = P^{OPCE}(v) - (P^{OPCE}_{max}(v) - P_{max}(v)) \tag{7}$$

where $P^{OPCE}(v)$ is the Doppler power spectrum of the OPCE-processed data S^{OPCE}, $P^{OPCE}_{max}(v)$ is the maximum of $P^{OPCE}(v)$ and $P_{max}(v)$ is the maximum of the original Doppler spectrum data.

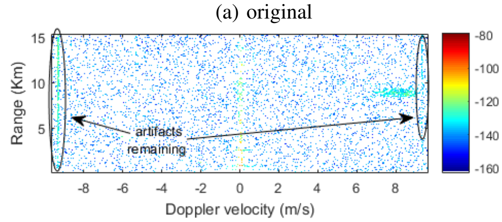
(d) Finally, applying the GsLDR filtered spectrogram as a mask on the result of the DsLDR filter. The distribution of sLDR of precipitation is in a specific range while that of clutter tends to be more random and always larger [1], which can act as a property to distinguish precipitation from clutter. Similarly, a new parameter called the generalized spectral linear depolarization ratio (GsLDR) is defined as

$$GsLDR(v) = P_{vh}(v) - P^{OPCE}(v) \tag{8}$$

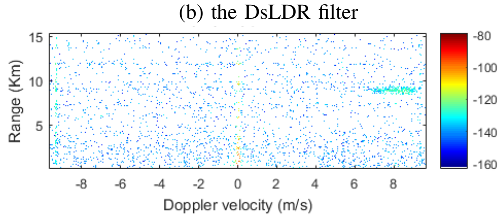
where $P_{vh}(v)$ is the original cross polarization Doppler spectrum. By setting a proper threshold of GsLDR, it is possible to keep precipitation while removing environment clutter. However, the OPCE process is a non-linear process — destroying the original Doppler spectrum



(a) original



(b) the DsLDR filter



(c) the GsLDR filtering mask on the DsLDR filter

Fig. 2: Spectrogram comparison between different filters.

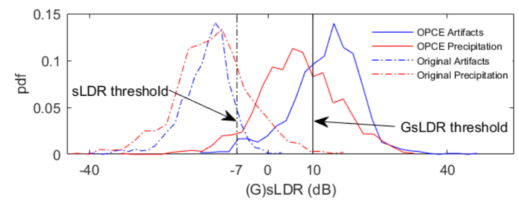
width and spectrum intensity of precipitation, which is unfavorable for further signal processing. Even though it has such a drawback, it has a desirable performance on environment clutter suppression, and it can act as a mask on the result of the DsLDR filter. For the DsLDR filter, the threshold is set to keep as much precipitation as possible. As for the OPCE process, it will enhance the whole Doppler spectrum of these range bins with precipitation, so its threshold GsLDR should be better set to eliminate as much clutter as possible. The way how to set the threshold will be discussed later combining with the real radar data.

The contents above discussed the detail steps on how to implement the newly-proposed clutter suppression method. To quantify the performance of the clutter suppression method, the reflectivity comparison between the true reflectivity, the DsLDR filtered reflectivity and the GsLDR filtered reflectivity is necessary, which will be illustrated in the next section.

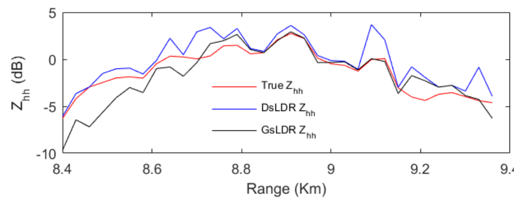
III. Application to Radar Data

In this section, the IDRA data is used to verify the performance of the newly proposed filter. The data occurred at 02:00 UTC in 1st July 2011 and Ray 67 is used to act as the original spectrogram taken from HH channel shown in Fig. 2a.

Some artifacts locate along the whole range bins, and their Doppler velocity are nonzero. Moreover, the intensity of the precipitation is weaker compared with the artifacts and the ground clutter. After integrating the whole Doppler bins resulting in one reflectivity, the true reflectivity of precipitation will be biased by the artifacts and the ground clutter. Additionally,



(a) (G)sLDR distribution of precipitation and artifacts



(b) Reflectivity comparison between different filters

Fig. 3: Clutter suppression performance analysis.

it will be a relatively high false alarm in the radar PPI with the artifacts and the ground clutter. The result of the DsLDR filter and the GsLDR filter are shown in Fig. 2b and Fig. 2c, respectively. The performance of the DsLDR filter is not ideal because the majority of the artifacts remains and the removal of the ground clutter is not complete. Compared with Fig. 2b, the artifacts in Fig. 2c are removed but at the loss of some precipitation marginal in the Doppler-range domain.

The artifacts and precipitation are extracted, and their sLDR and GsLDR are calculated as shown in Fig. 3a. The legend ”OPCE Artifacts” means the GsLDR of the artifacts after the OPCE process, while the ”Original Artifacts” means the original sLDR value of the artifacts. From Fig. 3a, the sLDR distribution of the precipitation is [-40 dB, 18 dB] while that of the artifacts is [-30 dB, 0 dB], so it is impossible to remove the artifacts when the threshold shown as the black dash line is set to -7 dB. When the OPCE process is applied to the spectrogram, the GsLDR of the precipitation and the artifacts deviate from each other as shown in Fig. 3a, making it possible to remove artifacts at the loss of some precipitation. When the threshold is set to 10 dB as the black line, the majority of the artifacts disappears.

Fig. 2 has qualitatively illustrated the performance of the DsLDR filter and the GsLDR filter in clutter suppression. Then it is also necessary to quantify this clutter suppression performance. For the Doppler radar, the reflectivity in specific range bin is the integral of the whole spectrum. The ground clutter and artifacts will bias the true value of reflectivity. For this case, the true Z_{hh} is calculated by selecting only the precipitation area labeled by the square window in Fig. 2a, locating in 8.4-9.36 Km. The result is shown in Fig. 3b. From Fig. 3b, the GsLDR filter has a more accurate estimation of Z_{hh} than the DsLDR filter when the true Z_{hh} is larger than -2 dBZ. In this case, the DsLDR filter is biased by artifacts and ground clutter, while the GsLDR filter is only biased by ground clutter but to a smaller extent, which can be seen in the comparison between the Fig. 2b and the Fig. 2c. The GsLDR filter has good performance in artifacts suppression at the loss of the weak signal whose true value is smaller than -2 dBZ.

When we apply the method discussed above to every spectrogram of one PPI and integrate all the Doppler spectra to get the reflectivity to form a final clutter-suppressed PPI. The original PPI, the PPI after the DsLDR filter, the PPI after the standard processing and the PPI after the GsLDR filter are presented in Fig 4.

From Fig. 4b, it is hard to position the precipitation accurately because of the echo intensity related to the radar artifacts and ground clutter. This clutter results in high false alarm in radar PPI display. The current standard IDRA clutter suppression processing consists of a narrow notch filter, the DsLDR filter and the noise clipping, and the result is shown in Fig. 4c. Large amount of clutter is reduced, however, it is still undesirable because of the artifacts caused by unknown interference. Finally, as shown in Fig. 4d, it is apparent that the newly proposed method has better performance in the ground clutter and radar artifacts suppression than the DsLDR filter. However, it will lose the weak signal whose true values are as small as -2 dBZ.

IV. Conclusion

This paper puts forward a method that combines optimal polarization contrast enhancement technique and the double spectral linear depolarization ratio filter for clutter suppression in spectral polarimetric weather radar.

With proper selection of the training samples in the specific radar environment, it is possible to find precipitation and the most unwanted clutter. Then with the extraction of the Kennaugh matrix, the optimal receiving and transmitting vectors which act as the weighted functions can be obtained. Further by combing the precipitation-enhanced and clutter-suppressed weight with the extracted Doppler velocity, OPCE-processed spectrogram without loss of Doppler information can be acquired. Finally, with a proper set of threshold of GsLDR, spectrogram with almost all precipitation kept and clutter mostly suppressed is obtained, which further will act as the mask for the result of the DsLDR filter.

Compared with the traditional clutter suppression method — the DsLDR filter, the newly proposed method improves the suppression ratio of the clutter while keeping almost all the precipitation. The effectiveness of this method is proved by the verification of IDRA radar data.

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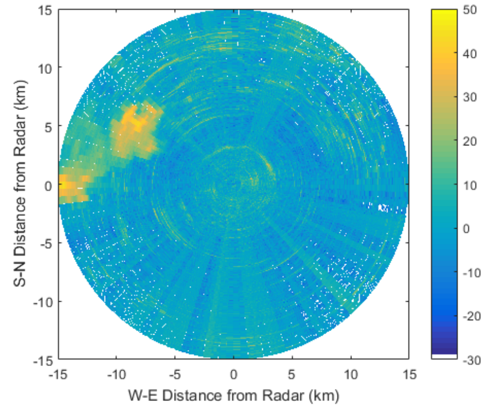
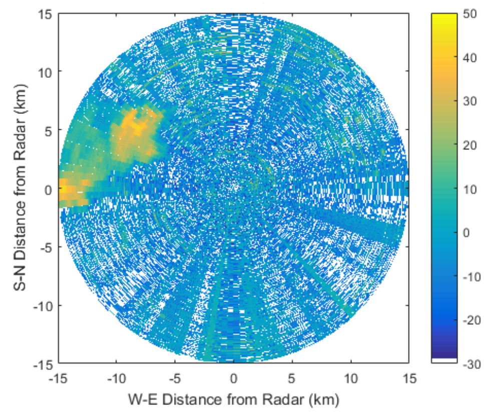
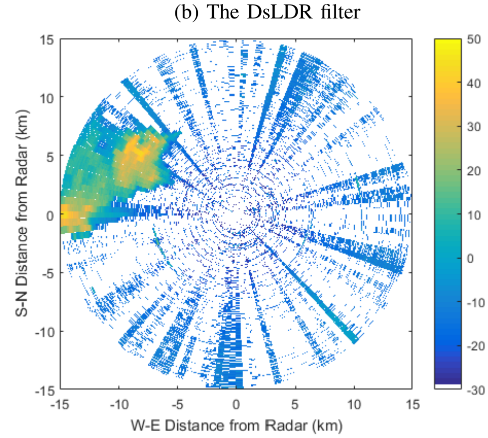


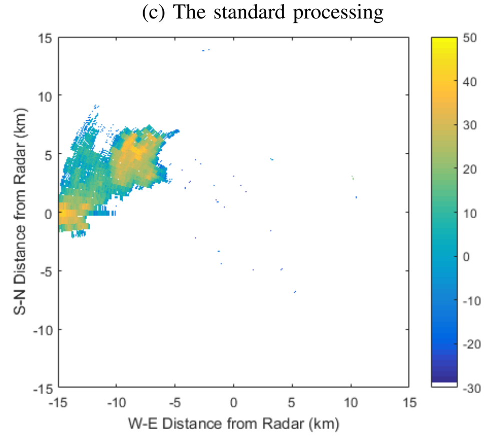
(a) Original



(b) The DsLDR filter



(c) The standard processing



(d) The GsLDR filter

Fig. 4: Radar PPI after different processing.