Paper

Doppler polarimetric ground clutter identification and suppression for atmospheric radars based on co-polar correlation

Dmitri Moisseev, Christine Unal, Herman Russchenberg, and Leo P. Ligthart

Abstract — A new clutter suppression technique that uses both Doppler and polarimetric information is presented. Polarimetric properties of the target and clutter are calculated per Doppler frequency cell and based on this information clutter suppression is performed. This new clutter suppression technique is demonstrated with radar measurements of precipitation made by the Delft atmospheric research radar (DARR).

Keywords — radar polarimetry, ground clutter suppression, Doppler radar, atmospheric radar remote sensing.

1. Introduction

The performance of a ground-based atmospheric radar is highly influenced by ground clutter. In order to remove this influence, clutter suppression techniques are used. The most common ground clutter suppression technique uses Doppler information, such as the mean Doppler velocity and spectrum width. Ground clutter has a zero mean Doppler velocity and narrow Doppler spectrum. Based on this, reflections that have velocities close to zero are suppressed. The problem of ground clutter suppression becomes more difficult to solve when atmospheric targets with low radial velocities are studied. Such targets as clouds have Doppler velocities close to zero and have narrow Doppler spectra. Therefore to preserve reflections from this kind of targets accurate knowledge of the ground clutter spectrum is required.

There are several methods of ground clutter identification by polarimetric radars reported in the literature. In 1997 by Hagen [1] the use of Ldr, which is the ratio of cross-polar reflection to the co-polar one expressed in the linear $v-h$ polarization basis, is discussed for ground clutter detection. It was noticed that Ldr for ground clutter is larger than for most of the meteorological targets. However, for the melting layer of precipitation Ldr can be rather high and comparable with the one of ground clutter. Another approach described by Ryzhkov [3] uses a cross-correlation coefficient $\rho_{hv}(0)$ between horizontal and vertical co-polar returns. It was reported that for weather echoes, values of the modulus of the cross-correlation coefficient are usually larger than 0.7 and are lower for areas contaminated with ground clutter. Note that even for the melting layer reflections $\rho_{hv}(0)$ is larger than 0.9 as it was presented by Bringi [3]. Therefore the cross-correlation coefficient gives a high contrast between ground and weather echoes and is well suited for ground clutter identification. However, the main disadvantage of this technique is that it rejects all range bins which are affected by the ground clutter and thus gives substantial loss of data.

In order to overcome drawbacks of the Doppler and polarimetric ground clutter suppression techniques it is useful to combine both of them. The use of polarimetry added to Doppler information will give an accurate classification of range-Doppler bins affected by clutter and will lead to the suppression of only a few Doppler cells instead of a complete range bin. In part 2 of this article the formulation of Doppler polarimetry is given. Based on this formulation the co-polar correlation coefficient in the spectral domain, the magnitude of which is the co-polar coherency spectrum, is introduced. The problem of spectral estimates based on actual radar data is also discussed in this part. In part 3 the co-polar coherency spectrum is used for the ground clutter suppression. This ground clutter suppression method is illustrated on precipitation measurements performed by DARR. Part 4 gives conclusions and recommendations for further studies.

2. Radar Doppler polarimetry: definition of the co-polar coherency spectrum

2.1. Theoretical formulation

To describe the time behavior of stationary (in statistical sense) radar targets the covariance matrix $\mathbf{C}(\tau)$ is used. We shall define it similarly to the wave coherency matrix given by Perina [4]. The covariance matrix expressed in an arbitrary polarization basis (x,y) is

$$\mathbf{C}(\tau) = \left\langle \vec{k}(t) \cdot \vec{k}(t+\tau) \right\rangle , \tag{1}$$

where $\vec{k}(t) = \begin{pmatrix} S_{xx}(t) & \sqrt{2}S_{xy}(t) & S_{yy}(t) \end{pmatrix}^T$ is the target vector obtained from the elements of the scattering matrix and $\langle\rangle$ denotes ensemble average. It should be noted that by radar target covariance matrix is commonly implied the matrix $\mathbf{C}(0)$, see for example [5]. Further, the spectral covariance matrix $\mathbf{F}(\omega)$ can be introduced. Its elements of which are related to the elements of the covariance matrix as follows:

$$F_{ij}(\omega) = 2\int_{-\infty}^{+\infty} C_{ij}(\tau)\exp(-i\omega\tau)d\tau$$

$$C_{ij}(\tau) = \frac{1}{4\pi}\int_{-\infty}^{\infty} F_{ij}(\omega)\exp(i\omega\tau)d\omega\,, \tag{2}$$

where $i, j = 1,2,3$.
Equation (2) represents the well known Wiener-Khinchin theorem, see for example Davenport and Root [6], which relates correlation functions to power (cross-) spectra.
Based on Eq. (2) the cross-correlation coefficient between horizontal and vertical co-polar returns can be related to power and cross spectra:

$$\rho_{hv}(0) = \frac{C_{13}(0)}{\sqrt{C_{11}(0)C_{33}(0)}} = \frac{\int_{-\infty}^{+\infty} F_{13}(\omega)d\omega}{\sqrt{\int_{-\infty}^{+\infty} F_{11}(\omega)d\omega\cdot\int_{-\infty}^{+\infty} F_{33}(\omega)d\omega}}\,. \tag{3}$$

Similar to the definition of the co-polar cross-correlation coefficient, which is given in Eq. (3), we can define a cross-correlation coefficient for every frequency ω. Remembering that $F_{ij}(\omega)d\omega$ gives the variance if $j = i$ and covariance if $j \neq i$ of the signal with the frequency ω, we can introduce the spectral co-polar correlation coefficient $w_{hv}(\omega)$

$$w_{hv}(\omega) = \frac{F_{13}(\omega)}{\sqrt{F_{11}(\omega)\cdot F_{33}(\omega)}}\,. \tag{4}$$

The graph of the modules of the co-polar correlation coefficient $w_{hv}(\omega)$ as a function of frequency is called co-polar coherency spectrum after Priestley [8]. The co-polar coherency spectrum $|w_{hv}(\omega)|$ shows the extent to which *hh* and *vv* elements of the scattering matrix are linearly related. The use of this spectrum for ground clutter suppression is further discussed in this article.

2.2. Estimation of co-polar coherency spectrum

The analysis and formulations which were introduced above were done based on infinitely long and continuous measurements. In the case of real radar measurements we deal with the estimation of spectral characteristics from finite measurement samples. In this case estimated Doppler spectrum $I_{ij}^N(\omega)$ is connected to the actual spectrum $F_{ij}(\omega)$ as follows [7, 8]:

$$I_{ij}^N(\omega) = \int_{-\frac{\pi}{T_s}}^{\frac{\pi}{T_s}} W_N(\theta-\omega)F_{ij}(\theta)d\theta\,, \tag{5}$$

where T_s is the sampling interval ($\frac{\pi}{T_s}$ is the maximum unambiguous Doppler frequency), $W_N(\omega)$ is the spectrum of the covariance lag window and N is the number of samples. If $N \to \infty$, $W_N(\omega)$ will behave like a δ-function and this will lead to

$$\lim_{N\to\infty} I_{ij}^N(\omega) = \int_{-\frac{\pi}{T_s}}^{\frac{\pi}{T_s}} \lim_{N\to\infty} W_N(\theta-\omega)F_{ij}(\theta)d\theta = F_{ij}(\omega)\,. \tag{6}$$

If N is so small that the spectral width of $W_N(\omega)$ is much larger than the one of $F_{ij}(\omega)$ then

$$I_{ij}^N(\omega) = W_N(0)\int_{-\sigma_w}^{\sigma_w} F_{ij}(\theta)d\theta = W_N(0)\cdot C_{ij}(0)\,. \tag{7}$$

Based on Eqs. (6) and (7) it can be concluded that if the number of samples is large enough that the spectrum width of the lag window will be much smaller than the width of $F_{ij}(\omega)$, then the estimated Doppler spectrum $I_{ij}^N(\omega)$ will coincide with the actual spectrum $F_{ij}(\omega)$. Moreover, if N is so small that the spectrum width of $W_N(\omega)$ is much larger than the width of $F_{ij}(\omega)$ then the estimated $I_{ij}^N(\omega)$ spectrum will be proportional to $C_{ij}(0)$ and the estimated co-polar coherency spectrum will coincide with the modulus of the correlation coefficient $|\rho_{hv}(0)|$.

3. Ground clutter identification and suppression

In most cases of atmospheric remote sensing the ground clutter has narrow Doppler spectrum and according to Eq. (7) $|w_{hv}(\omega)|$ is roughly equal to $\rho_{hv}(0)$. Since the almost isotropic nature of weather objects their coherency spectrum will be close to unity and not depended on spectrum resolution. Thus, the co-polar coherency spectrum can be used to identify areas of the Doppler spectrum, which are affected by clutter.
To test this new clutter suppression technique, slant profile measurements of precipitation were performed. The elevation angle of the radar was 20 degrees; thus all the clutter reflections are measured by the side lobes of the antennas. Since it is very difficult to predict the polarization state of the side lobes and it is not the topic of this article we will perform all calculations as if the polarization of the side lobes coincide with the polarization of the main lobe.
Measurements of the scattering matrix are performed with three consecutive sweeps of alternating linear polarizations on the receiving and transmitting channels. This cycle takes 3.75 ms. For this particular example about one minute

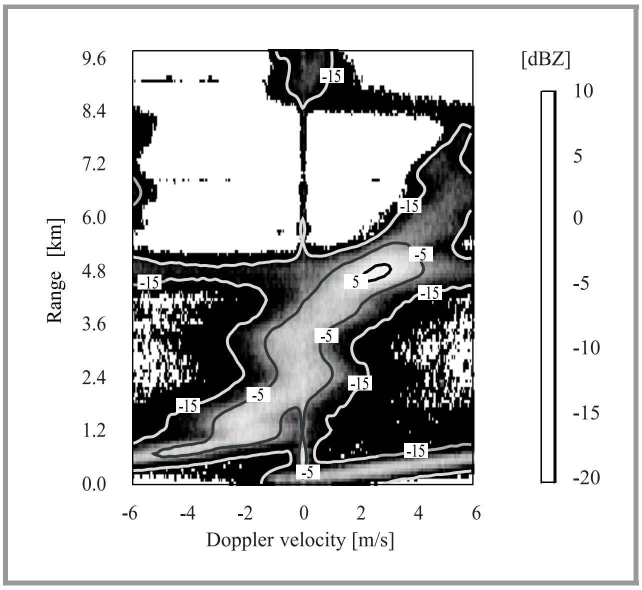

Fig. 1. Doppler spectrum of the precipitation event (HH-polarization). High reflectivity at 4.8 km corresponds to the melting layer. Reflections below the melting layer come from rain. Ice crystals falling out of the cloud cause reflections above the melting layer.

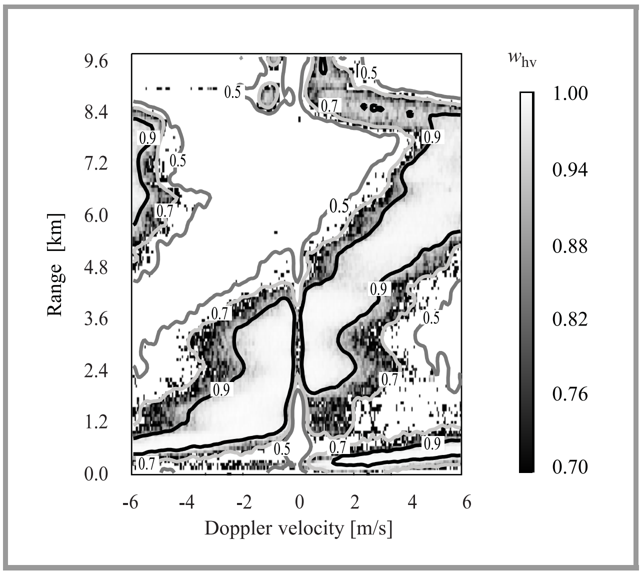

Fig. 2. Co-polar coherency spectrum $|w_{hv}(\omega)|$. The contours represent $|w_{hv}(\omega)|$ values between 0.5 and 1. The gray scaling shows values of between 0.7 and 1. As expected the values of $|w_{hv}(\omega)|$ for weather echoes are larger than 0.7 and for areas affected by ground clutter they are less than 0.7.

of data is collected. Prior to the Doppler processing averaged values of the scattering matrix elements are subtracted from the corresponding time series of scattering matrix elements. This average is performed on the complete data set. This subtraction is identical to suppression of the stable ground clutter.

To obtain Doppler spectra 256 sweeps are used. More details about the Doppler processing are discussed by

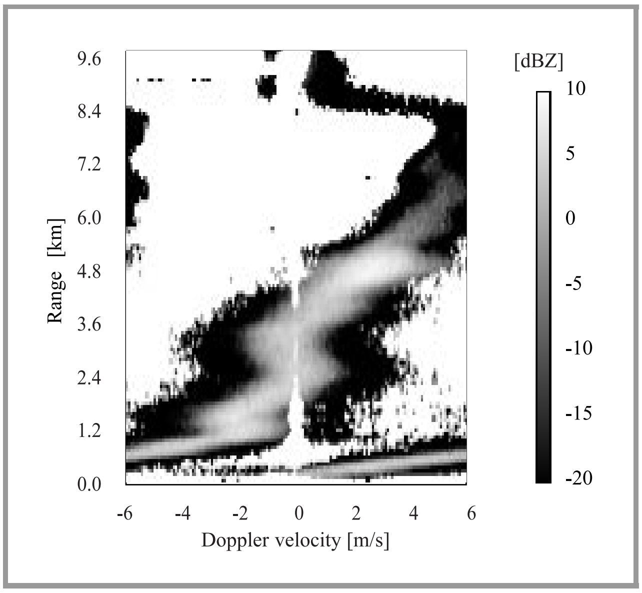

Fig. 3. Doppler spectrum of the precipitation event after clutter suppression. The reflections that have $|w_{hv}(\omega)|$ values below 0.7 are clipped away. This new clutter suppression method shows good performance. It is interesting to note that this suppression has also removed spectral leakage.

Unal [9]. A total of 40 spectra are obtained for each element of the scattering matrix. Based on these spectra the spectral covariance matrix $\mathbf{F}(\omega)$ is obtained and the co-polar coherency spectrum is estimated. In Fig. 1 the Doppler power spectrum for HH-polarization (element of the spectral covariance matrix) is shown. Figure 2 presents the modulus of the co-polar coherency spectrum $w_{hv}(\omega)$. A clear contrast can be seen between ground clutter and atmospheric targets. Therefore in order to suppress ground clutter, areas that have a cross-correlation coefficient below 0.7 are suppressed. The result is shown in Fig. 3.

4. Conclusions

It was shown that Doppler and polarimetric radar signal information can be effectively combined to improve ground clutter suppression. Based on this combination a new ground clutter suppression technique is introduced. This clutter suppression shows high performance especially in the case when ground clutter and target are occupying the same Doppler spectrum area. Moreover, the formulation of Doppler polarimetry is introduced. It is also expected that the further use of Doppler polarimetry will be an important tool for radar targets description.

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Leo P. Ligthart was born in Rotterdam, the Netherlands, on September 15, 1946. He received an Engineer's degree (*cum laude*) and a Doctor of Technology degree from Delft University of Technology in 1969 and 1985, respectively. He received Doctorates (*honoris causa*) at Moscow State Technical University of Civil Aviation in 1999 and Tomsk State University of Control Systems and Radioelectronics in 2001. Since 1992, he has held the chair of Microwave Transmission, Radar and Remote Sensing in the Department of Information Technology and Systems, Delft University of Technology. In 1994, he became director of the International Research Center for Telecommunications-transmission and Radar. Prof. Ligthart's principal areas of specialisation include antennas and propagation, radar and remote sensing, but he has also been active in satellite, mobile and radio communications.

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