CHARACTERIZATION OF DEPOLARIZING BEHAVIOR OF RADAR TARGETS; INTRODUCTION OF THE DEGREE OF DOPPLER POLARIMETRIC COUPLING

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ABSTRACT

Recent advances in the radar system design have allowed us to perform Doppler and polarimetric measurements simultaneously. This new measurement technique enables the study of the relation between Doppler and polarimetric properties of radar targets. To characterize this interrelation we introduce the degree of Doppler polarimetric coupling. We show that this new parameter gives extra information about polarimetric behavior of radar targets and can be used to describe the depolarization properties of radar targets.

RADAR DOPPLER POLARIMETRY

Since we would like to describe the behavior of all elements of a target scattering matrix together, it is convenient to consider them as a multivariate random process. Generally, a multivariate process can be characterized by its covariance matrix [1], where every element is auto- (cross-) correlation function of the involved elementary random processes. In our case these elementary random processes are elements of a target scattering matrix. Now, if we assume that the elements of the scattering matrix are jointly stationary processes then the target covariance matrix expressed in an arbitrary polarization basis (x, y) will be

$$\mathbf{C}(\tau) = \left\langle \overrightarrow{k(t)} \otimes \overrightarrow{k(t+\tau)}^{+} \right\rangle, \quad (1)$$

where $\overrightarrow{k(t)}$ is the target scattering vector. Further, we can define the spectral covariance matrix $\mathbf{F}(\omega)$, the elements of which are related to the elements of the covariance matrix by the Wiener-Khinchin theorem as follows:

$$F_{ij}(\omega) = 2\int_{-\infty}^{+\infty} C_{ij}(\tau)\exp(-i\omega\tau)d\tau \text{ and } C_{ij}(\tau) = \frac{1}{4\pi}\cdot\int_{-\infty}^{+\infty} F_{ij}(\omega)\exp(i\omega\tau)d\omega \quad (2)$$

where $i, j = 1, 2, 3$. It can be shown that the spectral covariance matrix $\mathbf{F}(\omega)$ is Hermitian semi-positive definite matrix for all frequencies ω, while the covariance matrix $\mathbf{C}(\tau)$ is Hermitian only for zero time lag.

Let us consider the main difference between proposed and conventional polarimetric techniques. We can easily see from (1) and (2) that if the time delays τ involved in (1) are restricted to $|\tau| \ll 1/\Delta\omega$, where $\Delta\omega$ is the maximum spectrum width of the $\mathbf{F}(\omega)$, then definition (1) converges to $\mathbf{C}(0)$, which is commonly used in radar polarimetry. Thus it can be seen that the conventional polarimetric target description fully characterizes radar objects only for short observation times.

The standard Doppler processing, on the other hand, allows one to obtain Doppler power spectra $F_{ii}(\omega)$ for every element of the scattering matrix and as a result describes the time behavior of a target, but does not show the interrelations between polarimetric measures.

DOPPLER POLARIMETRIC COUPLING

Changes in polarimetric properties of radar targets will result in changes in the radar signal. Moreover, it can also result in different signal spectral properties for measurements with different polarization setups. To characterize this effect of coupling between Doppler and polarimetric properties of radar targets, let us introduce a parameter which can be used to quantify the dependence of polarimetric target properties on Doppler characteristics of the target.

In order to derive this parameter we shall consider the spectra widths for all elements of the covariance matrix $\mathbf{C}(\tau)$. It is convenient to define the spectra widths σ_{ij} $(i, j = 1..3)$ as [1]:

$$\sigma_{ij} = 0.5\left(\int_{-\infty}^{+\infty} |F_{ij}(\omega)|\, d\omega\right) / \max_{\omega}(|F_{ij}(\omega)|) \quad (3)$$

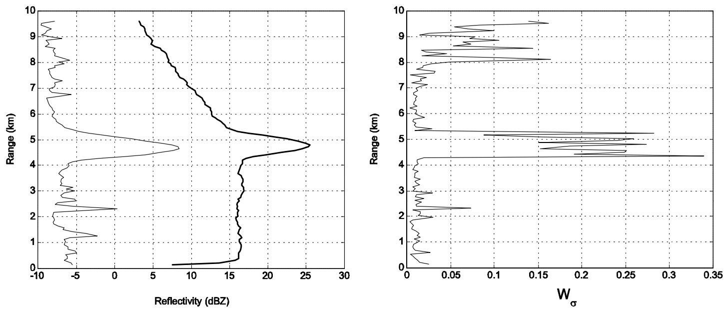

Figure 1: The slant profile of precipitation. The elevation angle is 20 degrees. The left figure shows the reflectivity profile. The thick solid line represents the hh measurement and the thin line shows the hv profile. The right figure gives the profile of the degree of Doppler polarimetric coupling of this event.

It can be shown that for the case of no Doppler polarimetric coupling σ_{ij} will be the same for all i and j. Moreover, if the spectra width for the different elements of the covariance matrix $\mathbf{C}(\tau)$ are different, the Doppler and polarimetric properties of a target are related. Using (3) we can introduce the degree of the Doppler polarimetric coupling, W_σ, for a radar target as:

$$W_\sigma = (\max_{i,j} \sigma_{ij} - \min_{i,j} \sigma_{ij})/(\max_{i,j} \sigma_{ij} + \min_{i,j} \sigma_{ij}) \quad (4)$$

The degree of Doppler polarimetric coupling gives a quantitative measure of the dependence between Doppler and polarimetric properties of radar targets. It lies in the interval from 0 to 1. The zero value of W_σ corresponds to no Doppler polarimetric coupling and if W_σ is equal to unity, it corresponds to the case where the Doppler and polarimetric target properties have a one-to-one relation.

DOPPLER POLARIMETRIC PROPERTIES OF PRECIPITATION

A good example to illustrate the effect of Doppler polarimetric coupling is polarimetric measurements of a stratiform precipitation. It was shown by [2] and by [3] that the polarimetric properties of a stratiform rain can considered to be deterministic, which results in near singular covariance matrix $\mathbf{C}(0)$. The polarimetric signatures of the melting layer of the precipitation, where precipitating snow melts into rain, on the other hand, are less deterministic [3], hence all eigenvalues of the covariance matrix for the melting layer measurements are different from zero.

In Fig. 1 a). the slant profile of stratiform precipitation is shown. This measurement was carried out by DARR at a 20 degree elevation angle with a 75 m range resolution. The polarization switching was performed every 1.25 ms, which resulted in the set of hh, hv and vv measurements for every 3.75 ms.

For this measurement the degree of Doppler polarimetric coupling was calculated for all range cells and it is shown in Fig. 1 b). Since for the rain and cloud measurements the observed cross-polar power measurements are strongly predetermined by the imperfection of the antenna, all cross-polar measurements whose power was more than 20 dB lower than that of a co-polar channel were discarded. This thresholding explains the sharp increase in W_σ in the area of the melting layer. The increase of the degree of Doppler polarimetric coupling for ranges further than 8 km is determined by a poor signal-to-noise ratio.

It can be seen from Fig. 1 b) that in the area of rain and cloud the degree of Doppler polarimetric coupling is close to zero, which can be explained by the nearly deterministic behavior of light rain. It should be pointed out that the deterministic behavior of rain and cloud polarimetric signatures is not the result of the processing; on the contrary, the use of the thresholding on the measured cross-polar signal is the result of this deterministic behavior. The melting layer, on the other hand, has a non-zero cross-polar signal and as a result its polarimetric signature has more variability. It can be seen that W_σ varies from 0.1 till almost 0.35 for the melting layer. The signal-to-noise ratio for the cross-polar measurements in the melting-layer region is better than 20 dB.

Let us look in more detail at what causes these relatively high values of W_σ. In (5) the following relative Doppler widths for the elements of the covariance matrix $\mathbf{C}(\tau)$ are given for the range of 4.5 km. This range gate corresponds to

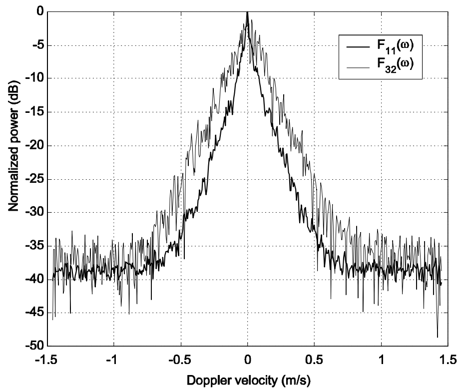

Figure 2: The Doppler spectra of park area measurements. The thick solid line corresponds to the co-polar Doppler power spectrum and the thin line corresponds to the $vv - hv$ cross spectrum.

the bottom of the melting layer where the highest Ldr value, a ratio of $\left\langle |S_{hv}|^2 \right\rangle$ to $\left\langle |S_{vv}|^2 \right\rangle$, is achieved.

$$[\sigma_{ij}] = \begin{pmatrix} 1.00 & 1.04 & 0.95 \\ 1.04 & 1.59 & 1.00 \\ 0.95 & 1.00 & 0.96 \end{pmatrix} \quad (5)$$

Also at this range gate the degree of Doppler polarimetric coupling is equal to 0.25. It can also be seen that the cross-polar signal has the widest spectrum $F_{22}(\omega)$. This result can be explained by the physical processes which take place in the melting layer. Due to the melting of snow flakes the particle shape changes. Moreover, the melting process leads to the exchange of the energy between the melting layer and the surrounding air, which results in an increase in turbulence in the area of the melting layer. The turbulent air causes variation in the orientation of the particles. Since the cross-polar measurements are more sensitive to changes in the shape and orientation of hydrometeors than the co-polar measurements, the broadening of the spectrum due to changes in polarimetric properties of particles will be more apparent in $F_{22}(\omega)$. This example illustrates the possibility of using Doppler polarimetry to retrieve the microphysical properties of precipitation.

DOPPLER POLARIMETRIC PROPERTIES OF GROUND TARGETS

Another important class of radar targets is ground-based objects. The characterization of the scattered waves from these objects is important for many radar remote sensing applications such as for the retrieval of bio-physical properties of vegetation and for ground-clutter suppression. In order to illustrate the use of Doppler polarimetry two measurements were carried out with DARR.

The first measurement concerned the park area in Delft known as the ”Delftse Hout”. The measurement was performed with a -2 degrees elevation angle, and the radar distance to the park was about 2 km. The same polarization switching scheme as discussed earlier was employed. And the calculated widths give the following results

$$[\sigma_{ij}] = \begin{pmatrix} 1.00 & 0.61 & 0.77 \\ 0.61 & 1.45 & 2.02 \\ 0.77 & 2.02 & 1.12 \end{pmatrix} \quad (6)$$

As can be seen from (6) this measurement shows a completely different relation between Doppler and polarimetric properties than the precipitation measurement. The degree of Doppler polarimetric coupling for the park area was found to be 0.54 and as can be seen in (6) the minimum spectrum width is associated with the covariance between S_{hh} and S_{vh}, while the maximum spectrum width is found for the covariance between S_{vv} and S_{hv}. These cross spectra are shown in Fig. 2. This result can be associated with the dynamic properties of ground clutter.

The second measurement which was carried out to illustrate the coupling between Doppler and depolarization properties of radar targets is the measurement of the highway. This highway connects The Hague and Rotterdam. The speed limit on this highway is 120 km/hr for cars and of 80 km/hr for road-transport vehicles. The radar specifications for this measurement are similar to the previously discussed park measurement. For this measurement the calculated spectrum widths are:

$$[\sigma_{ij}] = \begin{pmatrix} 1.00 & 0.59 & 0.70 \\ 0.59 & 1.21 & 0.56 \\ 0.70 & 0.56 & 1.21 \end{pmatrix} \quad (7)$$

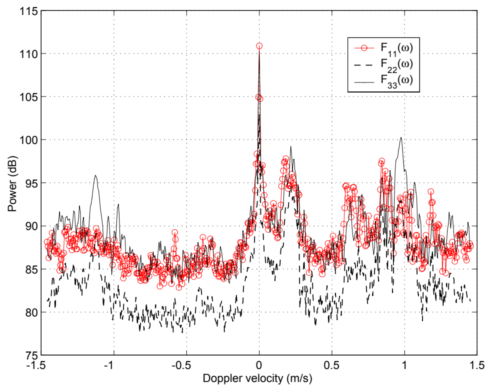

Figure 3: Doppler power spectra of the highway measurements. The solid line with circles represents the Doppler power spectrum of S_{hh}. The dashed line corresponds to the Doppler power spectrum of S_{hv} and the solid line corresponds to the power spectrum of S_{vv}.

In Fig.3 Doppler power spectra of the co-polar elements $F_{11}(\omega), F_{33}(\omega)$ and the cross-polar element $F_{22}(\omega)$ of the scattering matrix are shown. It can be seen that there are four clear peaks at -1.2, 0.2, 0.7 and 1 m/s, which correspond to the reflections from vehicles and a peak around 0 m/s, which corresponds to the reflections from the ground. These observed vehicle velocities are not real Doppler velocities of cars, since the true velocities are much higher than the maximum unambiguous Doppler velocity for this measurement setup. The noise like signal at 85 dB for co-polar spectra and at 80 dB for the cross-polar spectrum is caused by the decorrelation of the measured signals due to continuous changes of targets in the radar volume. Because, the measurement time used to obtain one Doppler spectrum is 7.68 s and in total averaging is performed over 30 spectra in order to reduce the variance of the spectra estimate. Because of the different polarimetric properties of the vehicles the resulting Doppler power spectra are also different for different polarizations, as can clearly be seen in Fig. 3. The values of the spectrum width for different elements of the covariance matrix are given in (7) and the obtained value of the Doppler polarimetric coupling is 0.37. This example shows that a compound target consisting of several scattering centers with different Doppler and polarimetric properties will have a rather high value of the degree of Doppler polarimetric coupling.

CONCLUSIONS

In this paper a new polarimetric formulation Doppler polarimetry was introduced. It was shown that this formulation is more general than the common polarimetric one. It was also shown that the Doppler polarimetric target characterization converges to the polarimetric one for short observation times. Moreover, it was shown that Doppler and polarimetric properties of depolarizing radar targets are interrelated. To characterize this interrelation we introduced the degree of Doppler polarimetric coupling. It was shown that this new parameter gives extra information about polarimetric behavior of radar targets and can be used to describe the depolarization properties of radar targets better. These conclusions were illustrated by Doppler polarimetric measurements of precipitation and ground-based objects.

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