A Comparison of Polarimetric Schemes to detect small Maritime Targets

Hartmut Schimpf, Hans-Hellmuth Fuchs

FGAN Forschungsinstitut für Hochfrequenzphysik und Radartechnik (FHR)
Neuenahrer Straße 20, D-53343 Wachtberg – Werthhoven, GERMANY

Abstract *On the basis of fully polarimetric 35 GHz data, several detection schemes for the discrimination of small maritime targets against sea clutter were implemented and compared to each other. Single channel detection performance is compared to that of the "optimal polarimetric detector" and the "polarimetric matched filter", the advantage of using polarimetry is demonstrated. These well-known polarimetric schemes are compared to the concept of "polarimetric persistence", i.e. the temporal behaviour of the polarimetric state of a dominant scatterer. It is found that the polarimetric persistence of man-made objects differs strongly from that of natural sea clutter and lends itself to a powerful discrimination between the two classes.*

Introduction

Small maritime targets like jet skis, water scooters, different types of small boats, and even swimmers are recognised as an increasing threat to civilian or military ships in scenarios of asymmetric warfare and terrorist attacks. Under these circumstances it is of paramount importance to detect suspicious objects as early as possible in order to be able to perform a classification or even identification, and to react timely and appropriately. Meanwhile, it is widely accepted that polarimetric methods due to their high potential of increased detection performance may add a valuable contribution. In this paper, several polarimetric detectors like the "optimal polarimetric detector", the "polarimetric matched filter" and the "span detector" will be compared to the classic single channel detector, and the detection gain will be quantified which received a more in-depth analysis in former work [4]. The more recent concept of "polarimetric persistence" is introduced and its competitiveness to traditional methods demonstrated.

The paper is organized as follows. First, the MEMPHIS radar is introduced , together with a description of the measurement scenario and the data that were used for the analysis. Next, the results of more traditional polarimetric detectors are summarised and compared to the classical single channel detection. The main part will be dedicated to the concept of "polarimetric persistence". Several ways to implement "polarimetric persistence" in a detection scheme are proposed and their performance compared to that of other polarimetric detectors.

The measurements

The MEMPHIS radar [6] is fully polarimetric at 35 GHz, i.e. the transmit polarization is switched from pulse to pulse between horizontal (H) and vertical (V), both H and V are received simultaneously thus providing the full scattering matrix. In order to avoid any artifacts, a careful polarimetric calibration was performed to remove effects like cross-talk and channel imbalance. This was achieved using the concept of „distortion matrices" [1] on transmit and receive. A moderate range resolution of 0,75m is obtained by means of a 200 MHz chirp. The effective PRF taking into accout the pulse-to-pulse switching of the transmit polarization was $20s^{-1}$.

In order to measure the backscatter behaviour of sea clutter and embedded targets, the radar had been installed on top of a cliff at a height of 19 meters above sea level. The distances to the objects measured were between 700 meters and 2500 meters, consequently the look-down angles were between 2° and close to 0.5°. The measurements were performed in a staring configuration with real beam resolution in cross-range. This means that the target-to-clutter contrast is range dependent, and that care has to be taken when generalizing performance results that are obtained at a certain fixed range.

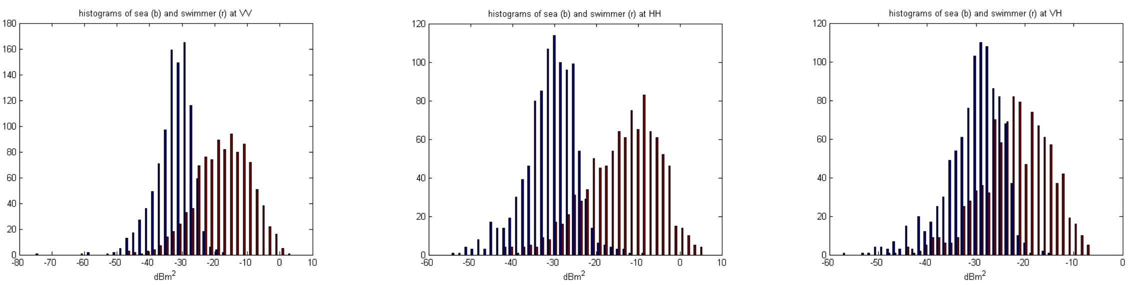
Several scenes were analysed that contain a swimmer and a nearby small boat in relatively benign sea conditions. In order to be able to evaluate the reflectivity statistics of swimmer, boat and sea clutter, these entities had to be separated from each other and extracted independently. As one can see from fig.1 both swimmer and boat created well visible tracks in the range-time plots.

Data samples for the sea clutter were extracted in a region far enough away from the swimmer and the boat to avoid any interaction, but close enough to warrant equal sea conditions and measurement geometry

Fig.1 *a swimmer (left track in the range-time-plot) and a small boat (right track) under benign sea conditions*

Single channel detection

The data that were extracted for the three classes “sea clutter”, “boat” and “swimmer” were transformed into reflectivity histograms for the three polarimetric channels HH, VV, and HV=VH (the cross-polarization returns are identical in the backscatter case due to the reciprocity theorem [2] p.313) as shown in fig.2 for the swimmer:



VV **HH** **VH=HV**

Fig.2 *reflectivity statistics for sea clutter (left, blue) and swimmer*

As one sees the histograms are fairly well separated for the VV and HH channels (parallel polarization) whereas for the cross-polarization there is considerable overlap. These histograms can now be used to construct ROC curves (probability of detection Pd vs. probability of false alarm Pfa) as shown in fig.3 for both swimmer (left) and boat.

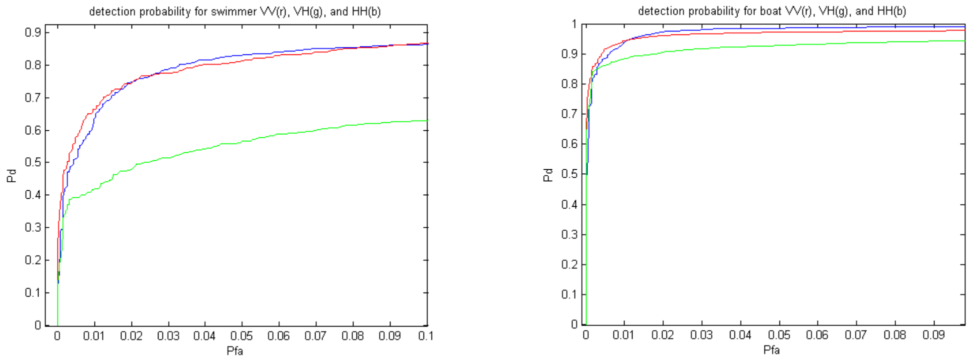


Fig.3 *single channel ROC curves (P_d vs.P_{fa}) for swimmer (left) and boat, polarizations VV(red), HH(blue) and VH(green)*

As one sees the single channel detection performance for HH and VV is almost identical in both cases which means that they obviously carry about the same amount of independent information. For VH, the performance is worse, especially for the swimmer.

Optimal polarimetric detector

The optimal polarimetric detector (OPD) was first introduced by Novak et al. in 1989 [7]. If the resolution cell is large enough, targets as well as the sea surface can be treated as multi-scatterers. In that case they can be described by means of a multidimensional complex Gaussian probability density function (pdf):

$$f(\vec{X}) = \frac{1}{\pi^3 |\Sigma|} \exp\left\{-\vec{X}^{T*}\Sigma^{-1}\vec{X}\right\} \quad \text{where} \quad \vec{X} = \begin{bmatrix} HH \\ HV \\ VV \end{bmatrix} = \begin{bmatrix} HH_I + i \cdot HH_Q \\ HV_I + i \cdot HV_Q \\ VV_I + i \cdot VV_Q \end{bmatrix} \quad \text{and} \quad \Sigma = E\left\{\vec{X}\vec{X}^{T*}\right\}$$

(Σ is the covariance matrix) In the ideal case, the pdf's of clutter and target (plus clutter) are known from former experience. Then both classes

ω_{T+C} : target plus clutter

ω_C : clutter only

can be separated by means of their „likelihood-ratio“This corresponds to a quadratic detector. The

$$\frac{f(\vec{X} \mid \omega_{T+C})}{f(\vec{X} \mid \omega_C)} > T_D$$

resulting ROC curve for the OPD is shown in fig.4 comparing boat and swimmer. Obviously, the combination of several polarimetric channels carrying independent information has led to a considerable increase in detection performance (about 8% at P_{fa}=0.01 for both the swimmer and the boat).

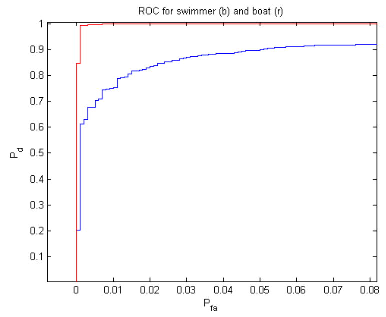


Fig.4 *OPD detection performance for the boat (red) and the swimmer (blue)*

Polarimetric matched filter

Based on a formalism proposed by Cadzow [3], Novak et al. [7] also discussed the "polarimetric matched filter" (PMF). The idea behind it is to find an optimal linear combination $y=h^{T*}X$ of the measured data channels such that the „target-to-clutter ratio" offered to the detector is maximized.

$$\left(\frac{T}{C}\right)_{out} = \frac{\vec{h}^{T*}\Sigma_T\vec{h}}{\vec{h}^{T*}\Sigma_C\vec{h}}$$

Here again, the covariance matrices defined above are needed. The optimal weight vector $\mathbf{h_o}$ is obtained

$$\Sigma_T\vec{h}_o = \lambda_{\max}\Sigma_C\vec{h}_o$$

as the solution to the generalized eigenvalue problem

where $\mathbf{h_o}$ is the eigenvector corresponding to the maximum eigenvalue λ_{max}. The results for the detection performance of the PMF are shown in fig. 5 (blue curve) for the swimmer. The results are less convincing than those of the OPD, and only slightly better than those for single channel detection.

Polarimetric span detector

For comparison fig.5 (black curve) also shows the results for the "polarimetric span detector" (PSD) which physically is the "total power" detector where the backscatter powers from all polarimetric channels are summed up with equal weighting:

$$Y = |HH|^2 + 2\,|HV|^2 + |VV|^2$$

Mathematically spoken, the PSD is a suboptimal detector because the linear combination of channels is not done using optimized weighting factors. Therefore, it is not quite clear why it performs better than the PMF with the given data. One reason one might think of is that the estimators for the covariance matrices Σ_T and Σ_C that dominate the eigenvalue problem are not fully representative.

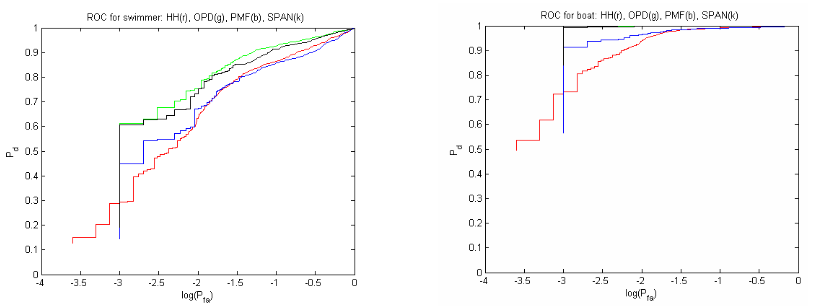


Fig.5 *comparison of detection performance for swimmer(left) and boat: single channel HH (red), OPD (green), PMF (blue) and PSD (black)*

Fig.5 summarizes the above results by showing a direct comparison between all four detectors (single channel HH, OPD, PMF and span) for the case of the swimmer (left) and the boat (right). This time the abscissa is given in logarithmic scale in order to allow a more detailed look at low P_{fa} values between 10^{-3} and 10^{-2} where the P_d differences are most pronounced. It is quite obvious that all three polarimetric schemes perform better than the ordinary single channel detector. The OPD is clearly the best, but the span detector performs almost as well. The PMF, on the other hand, is rather disappointing and hardly better than the single channel detector.

Polarimetric persistence

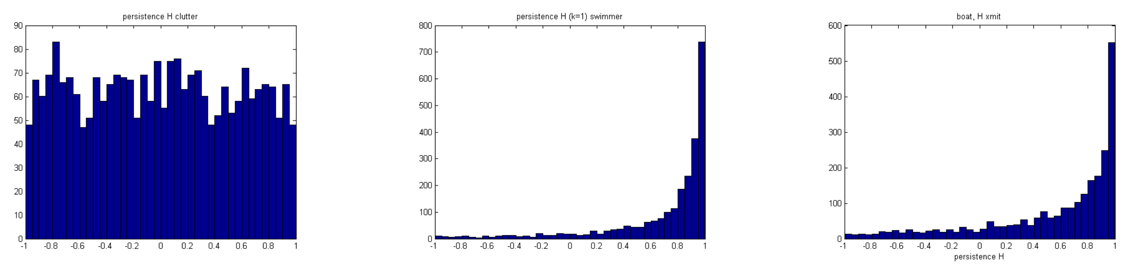
By “polarimetric persistence” we denote the similarity of consecutive polarimetric states within each individual range cell. Polarimetric states are characterized by their Stokes vector ([2], p.155) which stands for a certain position on the Poincaré sphere. The Stokes vector depends on the transmit polarization and is computed either from HH, HV together with their phases, or from VV, VH with their phases:

$$I = |HH|^2 + |HV|^2$$
$$Q = |HH|^2 - |HV|^2$$
$$U = 2\cdot\mathrm{Re}\{HH \cdot HV^*\}$$
$$V = 2\cdot\mathrm{Im}\{HH \cdot HV^*\}$$

If one takes the normalized Stokes vector $S=(s_1, s_2, s_3) = (Q/I, U/I, V/I)$ then the scalar product $\gamma = S(t_n) \bullet S(t_{n+1})$ is called “polarimetric persistence” [5]:

$$\gamma_n = \vec{s}(t_n)\cdot\vec{s}(t_{n+1}) = \sum_{i=1}^{3} s_i(t_n)s_i(t_{n+1})$$

Its value is the closer to “1” the more similar to each other both polarization states are, i.e. the more “persistent” the polarization state is [5]. By definition, γ can take values between –1 and +1. If one computes γ for a sample of 1000 temporal values from one individual range cell, then sea clutter yields an almost homogeneous distribution. This means that there is no regularity from one pulse to the next (fig.6, left). Also, looking at Q, U and V, one sees that they evenly cover the whole Poincaré sphere. The man-made objects, on the other hand, show a strong concentration of γ near +1 which means that their polarimetric state changes more steadily than that of sea clutter.



sea clutter **swimmer** **boat**

Fig.6 *histograms of persistence γ from 2500 consecutive temporal values for sea clutter, swimmer and boat*

By definition, because γ is computed on the basis of normalized Stokes vectors, the persistence does not depend on the amplitude of the receive signal. However, it is clear that γ physically describes the behaviour of one or several dominant scatterers within the resolution cell. A scatterer is dominant only as long as there are only negligible contributions from competing scatterers located within the same resolution cell. From this it becomes clear that a certain minimum T/C is required for γ to yield good detection performance.

Influence of T/C on the polarimetric persistence

In order to analyze the influence of T/C on auf γ, real sea clutter from the first 50 range cells was added coherently with a varying weighting coefficient “k” to those areas where the boat and the swimmer were located. The conservation of energy was observed by applying an appropriate normalization. For the complex signal, the following ansatz was made:

$$V_{T+C} = (V_T + k{*}V_C) / (1+k)$$

Accordingly one gets the following expression for T/C:

$$\frac{T}{C}(k) = \frac{T}{C}(k=0)\left|\frac{1+kV_C/V_T}{1+k}\right|^2$$

As expected, the γ histograms of the man-made objects begin to show a less pronounced concentration around +1 for increasing “k”. This in turn has consequences for the ROC curves as can be seen in fig.7.

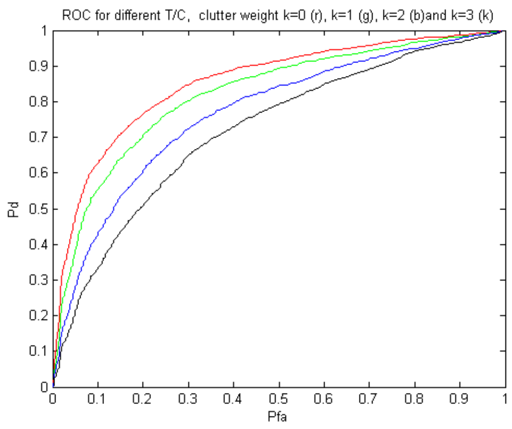


Fig.7 ***decrease of the γ-based detection performance for the swimmer as a function of T/C. The cases k=0/1/2/3 correspond to T/C=20.9dB / 15.1dB / 11.8dB und 9.6dB***

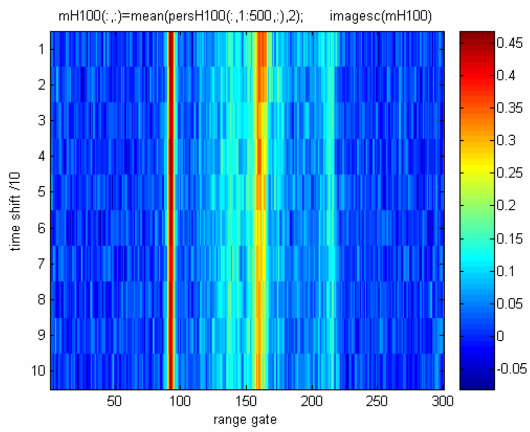


Fig.8 ***persistence γ as a function of the time step for 300 range gates***

Influence of the time step on the polarimetric persistence

Fig.8 shows γ as a function of the time step ("revisit time") between the two Stokes vectors that are multiplied. The time step was varied between the 10-fold and the 100-fold of the original value, i.e. between 0.5sec and 5sec. This time interval also encompasses the revisit times of usual rotating ship radars. In order to provide a more stable estimate, the γ values were averaged over 500 profiles during which time both objects (the swimmer in range gate 91, the boat in gate 161) did not leave their respective range cell. As one can see from fig.8 even for long revisit times the mean γ values reach values near 0.45.

Detection based on the polarimetric persistence

If one looks at all values γ for all times and all range cells (range-time-diagramme in fig.9) there occurs a striking difference between natural clutter and man-made objects. The concentration of persistence values close to γ=+1, as already shown in the histograms of fig.6, leads to well visible tracks of "man-made" objects which are very much distinct from the surrounding sea clutter.

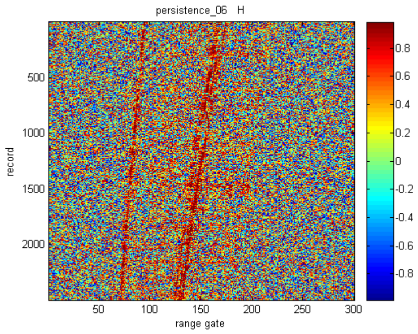


Fig.9 *range-time plot of persistence γ for H xmit polarization*

The most straightforward way to use γ for detection is to use the empirical probability density functions that are shown in fig.6 for sea clutter and the desired target object (boat, swimmer). A certain required false alarm rate leads to a corresponding threshold value which in turn determines the pertaining probability of detection. Fig.7 shows the ROC curves that consist of all possible pairs of P_d vs. P_{fa} if one chooses the swimmer seen under horizontal transmit polarization as an example. If one compares the detection performance of fig.7 with that of former results (fig.5) this does not not seem competitive. However, the results of fig.7 are based on only one fixed transmit polarization (H) whereas those from fig.5 make use of the full Sinclair matrix. If one carries this over to the case of the polarimetric persistence one gets two values γ_H and γ_V which belong to H and V transmit polarization, respectively. These two values γ_H and γ_V are almost independent of each other. If one computes the cross correlation coefficient between γ_H and γ_V one gets -0.004 for sea clutter, 0.218 for the swimmer, and 0.152 for the boat (based on 2500 values each). Therefore they carry independent information usable for detection.

The question is how to combine γ_H and γ_V appropriately to make optimal use of their independent information. If one looks at typical scatter plots in the γ_H vs. γ_V plane (fig.10) one sees that the sea clutter shows a homogeneous distribution whereas the man-made objects, as expected, are concentrated toward the point (+1, +1).

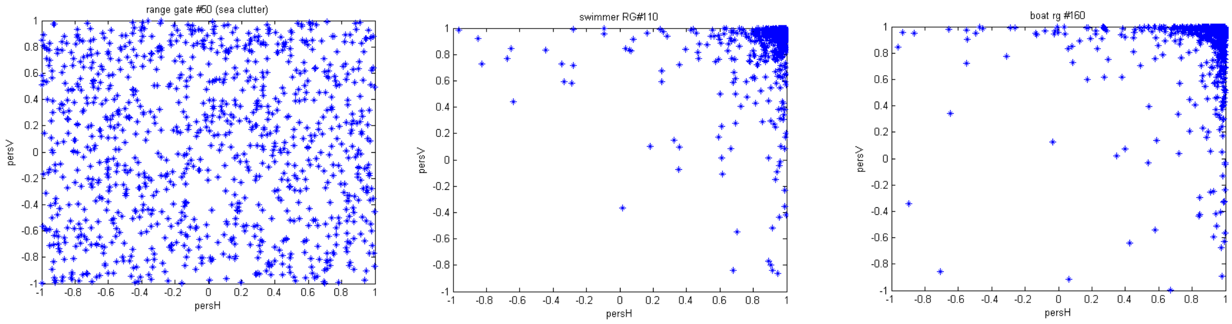


Fig.10 *scatter plots of γ_V vs. γ_H for sea clutter, swimmer and boat (from left to right)*

Based on this beaviour, one can think of the following possible combinations of γ_H and γ_V to create one common variable Γ:

$\Gamma = \gamma_H * \gamma_V$
$\Gamma = \gamma_H + \gamma_V$
$\Gamma = \min(\gamma_H, \gamma_V)$
$\Gamma = \mathrm{sqrt}((\gamma_H + 1)^2 + (\gamma_V + 1)^2)$

(the second case corresponds to a rotation of the coordinate system by 45° so that Γ varies along the line that connects (-1, -1) to (+1, +1), in the fourth case Γ measures the distance to the "antipode" (-1, -1)). All four cases are represented by means of their ROC curves in fig.11. For comparison, also the case are shown when γ_H alone or γ_V alone are used. One clearly recognizes the increase in detection performance by combining γ_H and γ_V with each other. One reaches values of $P_d \approx 0.8$ for $P_{fa}=0.01$ what is equal if not slightly better then the OPD result.

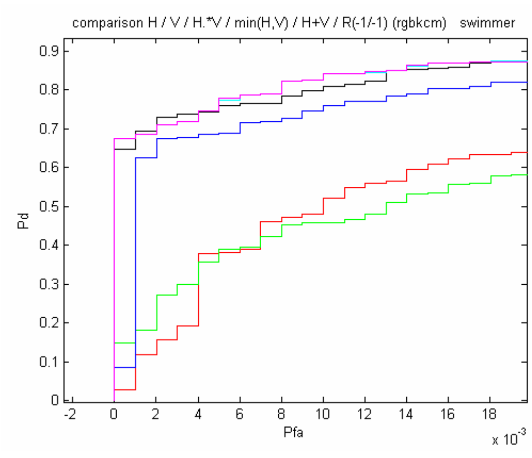


Fig.11 *P_d vs. P_{fa} for the six cases γ_H, γ_V, $\gamma_H * \gamma_V$, $\min(\gamma_H, \gamma_V)$, $\gamma_H + \gamma_V$ and $\mathrm{sqrt}((\gamma_H + 1)^2 + (\gamma_V + 1)^2)$ (red, green, blue, black, cyan, magenta)*

Summary and conclusions

It has been shown that polarimetric detection schemes like the OPD, the PMF or the „span detector" outperform the usual single channel schemes so that even small objects like swimmers or small boats can be extracted from the sea clutter background. Another physical phenomenon that shows very promising detection performance is the "polarimetric persistence". Based on the distinction between short-lived natural scatterers and the more persistent behaviour of strong scatterers located on artificial bodies, this approach is well suited to discriminate man-made objects from the sea clutter background. The discrimination performance can even be enhanced further by switching the transmit polarization from pulse to pulse. This yields two more or less independent persistence values that can be combined appropriately.

The detection performance that can be obtained by combining the more or less independent values of γ_H and γ_V is equal if not slightly better then the OPD result. Moreover, using the polarimetric persistence instead of the OPD leads to a much reduced mathematical complexity because no matrix operations are required.

It has to be pointed out, however, that the measurements used here were made under rather benign sea conditions, and these conditions varied only very little over the measurement period. Therefore, in order to be usable in practice for ship self protection, further analysis is necessary to assess the dependence of the ROC curves on sea state and wind conditions. Also, parameters like PRF, revisit time, decorrelation time and integration time have to be optimized depending on whether the ship is at rest or moving.

References

[1] Barnes, R.M., « Polarimetric Calibration using in-scene Reflectors », Lincoln Laboratory Project Report TT-65, MIT 1986

[2] Mott, H., « Antennas for Radar and Communications », Wiley 1992

[3] Cadzow, J., « Generalized digital matched filtering », Proc. 12th Southeastern Symposium on System Theory, VA, May 1980, pp.307-312

[4] Schimpf, H., Fuchs, H.-H., « Polarimetric Detection of Small Maritime Targets », Proc.IRS 2007, pp.379-384, Köln, September 2007

[5] Schimpf, H., « Polarimetric Target/Clutter Discrimination », Proc. 3rd Int'l Workshop on Radar Polarimetry, p.402, Nantes 1995

[6] Schimpf, H. et al., « MEMPHIS – a fully polarimetric experimental Radar » , Proc.IGARSS, pp.1714-1716, Toronto, 2002

[7] L.Novak et al., « Studies of target detection algorithms that use polarimetric radar data », AES-25, pp.150-165, 1989