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RÉSUMÉ

Cet exposé présente quelques résultats concernant les techniques de polarisation adaptatives pour la réjection du fouillis de sol. L'analyse se fonde sur les mesures effectuées au moyen d'un radar à faible résolution équipé d'un récepteur en diversité de polarisation. Un système spécialement conçu a été employé pour la saisie et l'enregistrement de données. On étudie tout d'abord le comportement polarimétrique des phénomènes du fouillis de sol enregistrés.

Étant donné les caractéristiques polarimétriques assez différentes des échos de la cible et du fouillis de sol, il est indiqué que certaines techniques de traitement polarimétriques peuvent être utilisées avec succès pour améliorer les propriétés de détection en présence d'un fouillis de sol qui masque la cible. Il est considéré deux types différents de filtres pour le fouillis qui sont en mesure de réjecter les signaux non voulus par l'enregistrement et la mise à jour — à chaque exploration — de la carte de polarisation de la couverture radar du système. Quelques résultats sont également décrits concernant l'évaluation d'efficacité des techniques de filtrage en question.

ABSTRACT

This paper reports some results on adaptive polarization techniques for rejection of ground clutter. The analysis is based on measurements carried out with a low resolution radar equipped with a diversity polarization receiver and recorded through a suitably designed acquisition system. The polarization behavior of the recorded ground clutter phenomena is first investigated.

Owing to the considerably different polarimetric features of target echoes and ground clutter, it is shown that some polarimetric processing techniques can successfully be applied to improving radar target detection performance in the presence of screening ground clutter. Two different types of ground clutter cancellers, which are able to reject undesired signals by recording and updating at each scan the polarization map of the system coverage, are considered. Some results relating to performance evaluation of such filtering techniques are reported.

I. INTRODUCTION

Conventional radar systems operate with fixed single-polarized antenna for transmission as well as for reception. Therefore, the received backscattered wave, which is completely described in terms of the related field vector, is converted to a scalar signal. In such a way some information is lost. To overcome this limitation, the entire information content of the backscattered wave has to be acquired by retaining its polarization through a vector measurement process. There are several reasons which make polarization diversity techniques potentially useful in radar systems. In some cases, it may occur that, due to radar system design constraints, the usual signal parameters (e.g. Doppler frequency, bearing, etc.) cannot be fully exploited to provide their inherent signal discrimination capabilities in the presence of interfering radar returns. In these cases, the use of polarization can still enhance radar discrimination capabilities. This information can also be usefully exploited to devise adaptive polarization cancellation of partially polarized disturbance.

Performance of these techniques is related to the actual polarization behavior of different radar objects. Available information based on radar measurements, mainly refers to the statistical parameters of polarization evaluated through long term averages and space independent observations. Conversely, the performance evaluation of adaptive polarization techniques requires a deeper knowledge of short-term polarization behavior, as during the dwell-time of a scanning antenna illuminating the target. In this paper some measurement results which describe the statistical polar-

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ization behavior of S-band, short-term, returns from ground clutter are presented. These results have been obtained through off-line analysis of recorded data obtained from measurements carried out with a low-resolution, fixed circular polarization transmission, ATC radar, suitably modified for double-polarization reception.

The measurements were carried out within spatial windows, pertaining to different radar scans. The observed results indicate frequent high stationarity polarization behaviors on the same window from one scan to another corresponding to high clutter/noise ratios. This result, together with the above recognition of both spatially narrow patterns on the polarization domain and a high polarization degree during dwell-time, reveals potentially useful adaptive ground clutter cancellation capability, especially with strong clutter.

Such a capability was pointed out by applying different types of polarization adaptive cancellers to radar signals, acquired within windows where a target was detected in the presence of clutter disturbance. Good performance was obtained when using a polarization map as a means to estimate polarization parameters of clutter, based upon its high stationary polarization features. This is due to the fact that it is possible to estimate the clutter polarization behavior at one scan, and to use that information to reject the clutter signals at the next scan, thus improving the signal/clutter ratio.

Some numerical results refer to experimental data relevant to different types of clutter and different target behaviors, processed through several alternative schemes for adaptive polarization cancellation of partially polarized disturbance. These results confirm the signal/clutter improvement obtainable by polarization-map based cancellers.

After a brief analytical introduction, section 3 reviews the main polarimetric features of ground clutter phenomena from a statistical point of view. Some adaptive polarimetric techniques along with the performance evaluation results, obtained by some simulations carried out with the above mentioned measurements data, are reported in section 4.

II. ANALYTICAL REMARKS

The e.m. wave backscattered by radar obstacles or targets is intrinsically non-stationary polarized during antenna dwell time. Thus the wave is called partially polarized [1].

In a right handed cartesian H-V-Z coordinate system, the electric field vector of a plane harmonic partially polarized wave propagating along the z-axis (positive sense), can be represented by a complex vector given by :

$$\underline{E}(z,t) = [E_H(z,t), E_V(z,t)]^T = \underline{E}(t)\exp[j(\omega t - kz)]$$

where the labels H and V denote the horizontal and vertical components respectively, the upper label « T » means vector transposition and $\underline{E}(t) = [E_H(t), E_V(t)]^T$ is the electric field vector whose components are the complex envelopes of the horizontal and vertical field components.

Given the four parameters a = « amplitude », α = « absolute phase angle », ϕ = « polarization orientation angle » and τ = « ellipticity polarization angle », they completely describe the vector $\underline{E}(t)$ according to the following expressions :

$$\underline{E}(t) = a\exp(j\alpha)\,\underline{h}(t) = \\ = a\exp(j\alpha)\begin{bmatrix}\cos\phi & -\sin\phi\\ \sin\phi & \cos\phi\end{bmatrix}\begin{bmatrix}\cos\tau\\ j\sin\tau\end{bmatrix}$$

with ϕ and τ representing the wave polarization vector $\underline{h}(t) = [h_H(t), h_V(t)]^T$. In the right side of this expression the time dependence is not reported, even if it still holds.

The Poincaré sphere representation [2] can be used for representing the wave polarization state $\underline{h}(t)$ at time t : in such a representation the vector $\underline{h}(t)$ is considered as normalized with respect to the amplitude parameter. Thus the Poincaré representation utilizes only two parameters, ϕ and τ, so that each polarization state vector is represented on a sphere surface (Poincaré sphere) by a point P with spherical coordinates (1, 2 ϕ, 2 τ). Another useful representation is the so-called polarization chart, which is the orthogonal projection of the sphere surface on the equatorial plane (figs. 1 and 2), in which different symbols are used for polarization states pertaining to different Poincaré hemispheres. The polarization state at different times is thus univocally represented by different points on the polarization chart. As a consequence the representative

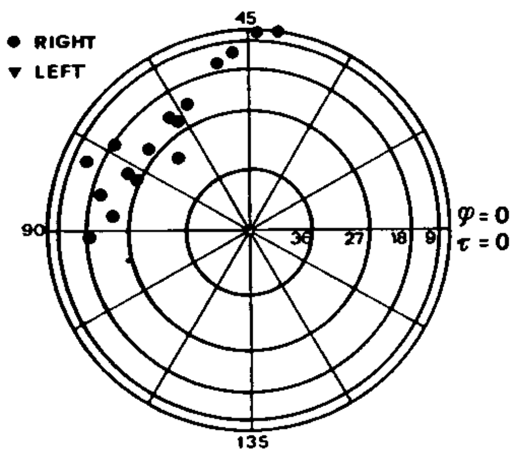

Fig. 1. Polar representation of extended ground clutter during dwell time.

where the standard deviation σ_ϕ represents the statistical parameter evaluated for the distributed ground clutter phenomenon ;

2) with reference to the point clutter phenomenon, we define a spreading angle $\Delta\tau = \tau_i + 45°$ of the i-th sample, with respect to the mean polarization $\tau_m = -45°$ of the analyzed window. In such a case, the selected statistical parameter is the standard deviation σ_τ :

$$\sigma_\tau = \left[\frac{1}{N}\sum_{i=1}^{N}(\tau_i - \tau_m)^2\right]^{1/2}.$$

Moreover this parameter roughly expresses — in the case of distributed clutter — the standard deviation of the samples along the prevalent (average) radius corresponding to the angle ϕ_m. Figure 3 concisely describes these parameters, in connection with a typical window relevant to a distributed clutter phenomenon (plots P_i represent the polarization of each echo sample during dwell-time).

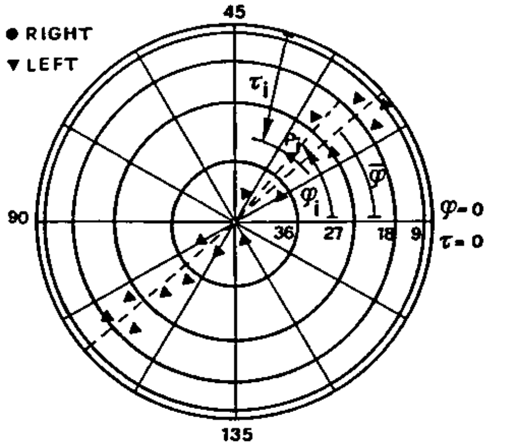

Fig. 3. Statistical polarization parameters defined through the polarization chart.

The statistical parameters previously described were evaluated for set of windows extracted from acquired data. It was found that the window sample alignement along the prevalent direction increases as the C/N ratio increases : this effect is emphasized by the correspondent decrease of the σ_ϕ parameter distribution. Similar behavior, but less evident, is shown by the σ_τ parameter, which denotes a joint decrease in the extent of the sample distribution along the prevalent direction ϕ_m.

Another statistical analysis which is relevant to the distribution of values of the polarization degree p evaluated for all 16 sample windows extracted from the entire acquired data set was carried out. A sample

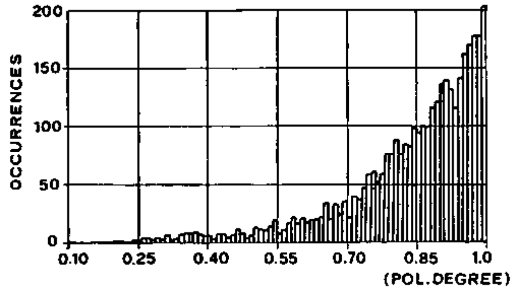

Fig. 4. Hystogram of the degree of polarization p.

hystogram thus obtained is shown in figure 4. We can observe a distribution clustered on high values of the degree of polarization.

An additional investigation concerning the scan-to-scan stationarity of the polarization state of each analyzed window was accomplished. The observed results indicate frequent high stationary polarization behaviors on the same window from one scan to another, corresponding to high C/N ratios. This result, together with the above recognition of both spatially narrow patterns on the polarization domain and a high polarization degree during dwell-time, point out potential ground clutter cancellation capabilities through adaptive polarization techniques, especially with strong clutter.

IV. ADAPTIVE REJECTION OF GROUND CLUTTER

In the preceding section the main polarimetric features of ground clutter have been highlighted. A considerably different polarization behavior is shown by aircraft targets, which present a noticeably high degree of polarization during dwell time but a high non-stationarity from scan to scan [4].

Such different behaviors make adaptive polarization filtering on reception profitable to improve the signal to ground clutter ratio. This improvement can be achieved by resorting to polarization map filtering techniques. In this paper the results referring to simulation of two types of such cancellers are reported.

The first filter operates by acquiring the needed polarization parameters of each radar coverage cell during a scan (polarization map). The stored polarization parameters are then used to adapt the polarization on reception at the successive scans in order to filter out ground clutter at each specified coverage cell. The polarization map is successively periodically updated, after a given number of scans. Different types of adaptive polarization cancellers can be used [1] in order to attenuate the clutter power at each radar coverage

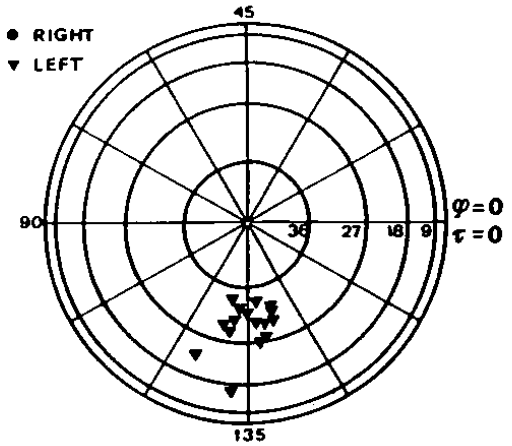

Fig. 2. Polar representation of point ground clutter during dwell time.

point of the polarization state of a partially polarized wave moves on the polarization chart as a function of time.

A useful description of such a polarization state is also expressed by the second order statistics, which define the so-called Stokes vector $\underline{g}$, as :

$$\underline{g} = \begin{bmatrix} g_0 \\ g_1 \\ g_2 \\ g_3 \end{bmatrix} = \begin{bmatrix} \langle h_H h_H^* \rangle + \langle h_V h_V^* \rangle \\ \langle h_H h_H^* \rangle - \langle h_V h_V^* \rangle \\ 2 \langle \mathrm{Re}\,(h_H^* h_V) \rangle \\ 2 \langle \mathrm{Im}\,(h_H^* h_V) \rangle \end{bmatrix}$$

where $\langle \cdot \rangle$ denotes time average.

The component g_0 represents the total average power of the wave and meets the relation :

$$g_0^2 \geq g_1^2 + g_2^2 + g_3^2 .$$

In the preceding expression the equality holds when the wave is completely polarized, that is its polarization state is time invariant. In such a case the coordinates of the representative fixed point P on the Poincaré sphere can be expressed in terms of Stokes parameters by :

$$P = (g_1/g_0, g_2/g_0, g_3/g_0) .$$

The Stokes vector of a partially polarized wave can be decomposed as :

$$\underline{g} = [g_{0p}, g_1, g_2, g_3]^T + [g_0 - g_{0p}, 0, 0, 0]^T ,$$

where $g_{0p} = (g_1^2 + g_2^2 + g_3^2)^{1/2}$ is the power of the completely polarized wave component, while $(g_0 - g_{0p})$ is the power of the unpolarized wave component. The degree of polarization p can thus be defined as : $p \triangleq g_{0p}/g_0$.

III. POLARIZATION BEHAVIOR OF GROUND CLUTTER

As mentioned earlier, the employed radar system was a low resolution primary radar, designed for Air Traffic Control (ATC), operating in S band [3]. It was properly modified to acquire with a double channel receiver : during measurements the transmitted signal was RC polarized through a circular polarizer, while on reception two orthogonally polarized channels (RC and LC) were able to decompose the received signal in two components, so the polarization information could be retained by a vector processing of the signal.

Data acquisition was performed through a system whose general features are reported in [3]. The data thus collected were processed through properly developed software packages.

The submitted statistics were obtained by processing the acquired data, pertaining to the polarization state of several radar bins, which were gathered in spatial windows of 16 sweeps * 1 range bin, corresponding to the dwell-time on point targets. With reference to the polarization chart representation of such a sequence of samples, two main features have been observed : the first (fig. 1), corresponding to extended ground clutter phenomena, shows that the polarization state of samples lines up along a preferred direction ; the other (fig. 2), pertaining to point clutter phenomena, exhibits quite a clustered distribution of the polarization state of the samples around their polarization mean state on the Poincaré sphere. Such phenomena become more evident as the average power g_0 of the window increases. In order to evaluate the above-mentioned features statistically, a linear translation of the polarization state of the samples pertaining to each analyzed window was performed on the polarization chart, so as to map the mean polarization pertaining to each observed data sequence on the circularly left-handed polarization point ($\tau = -45°$, center point of the polarization chart). As a consequence, straightforward expressions for some parameters, which statistically express the above-mentioned features, can be defined. Precisely :

1) with reference to the distributed clutter phenomenon, we define an angular orientation offset $\Delta\phi \triangleq (\phi_i - \phi_m)$ for the i-th sample with respect to a leading (average) orientation angle ϕ_m of the analyzed data sequence ; the computation of parameter ϕ_m is a minimum problem for the function :

$$\sigma_\phi = \left[\frac{1}{N} \sum_{i=1}^{N} (\phi_i - \phi_m)^2 \right]^{1/2}$$

window. The simplest device is a linear polarization filter, which linearly combines the input orthogonally polarized signals $s_1(t)$ and $s_2(t)$ as follows :

$$s(t) = s_1(t)\, w_1 + s_2(t)\, w_2 .$$

The weights, w_1 and w_2, are estimated in accordance with the polarization map parameters. The output $s(t)$ is thus minimized when the polarization at successive scans equals that at the sample scan.

A block diagram of the first type of canceller considered for its application with the polarization map is shown in figure 5.

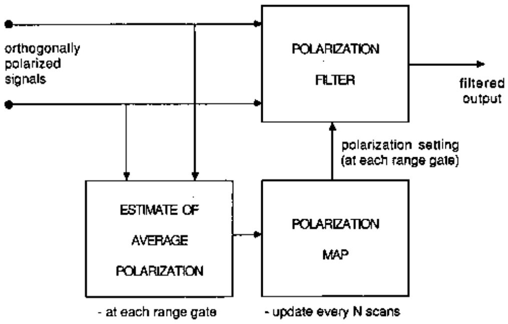

Fig. 5. Block diagram of the adaptive polarization filtering device which utilizes the polarization map for ground clutter rejection.

The performance of this type of canceller was estimated by a simulation based on the processing of the experimental data : the experienced improvement of signal to clutter ratio was up 15 dB with strong ground clutter. It must be noted that the performance are strongly related to the use of a circular polarization in transmission, because a better discrimination among the different phenomena can be obtained than in the case of transmission of a linearly polarized wave, due to the scattering properties of the different radar objects [5].

The second type of ground clutter polarization filtering can be applied by resorting to a non-linear polariz-

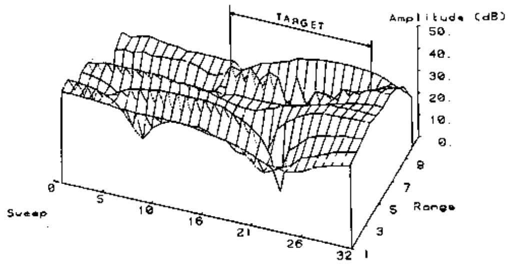

Fig. 6 a. Signals present at the input channels of the non-linear polarization filter : channel 1.

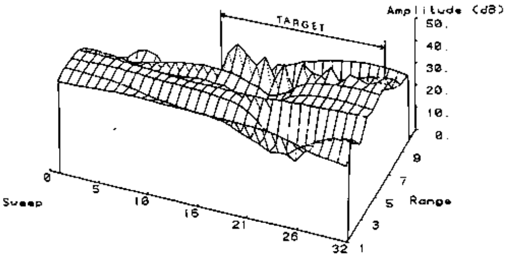

Fig. 6 b. Signals present at the input channels of the non-linear polarization filter : channel 2.

ation filter [5]. The non-linear polarization filtering is used to enhance the suppression of partially polarized disturbance because it attenuates the disturbance echoes, which representative polarization points are present in a large area of the Poincaré sphere surface : the suppression area dimension can be set according with the estimated spread of the ground clutter echoes around their mean polarization.

Indeed the second polarization map filtering device estimates an extended set of ground clutter polarization parameters acquired in the polarization map (i.e. average polarization, polarization state preferred direction of sample alignment, polarization distribution around the mean direction). Such a filter adapts its parameters for each vector signal sample so the input signals at successive scans can be attenuated when their suppression polarization area is placed optimally on the Poincaré sphere, according to the ground clutter behavior estimated through the polarization map.

A polarization filter capable of such a processing was simulated and applied to experimental data sequences. Its block diagram is composed of three blocks : the estimation section, the non-linear-PVT transformation block, the so-called non-linear polarization filter. The second block is realized by means of a « PVT transformation operator » [6], which can modify the polarization of the input data samples by translation of the related representative points over the Poincaré surface : the corresponding output samples exhibit representative polarization points which are moved towards or away

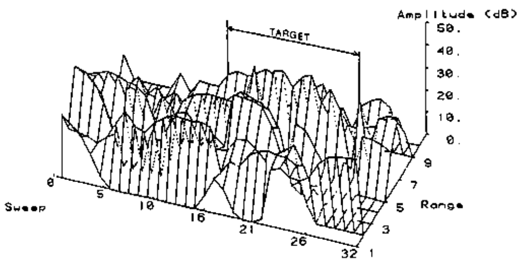

Fig. 7. Response of the non-linear polarization filter, which utilizes the polarization map.

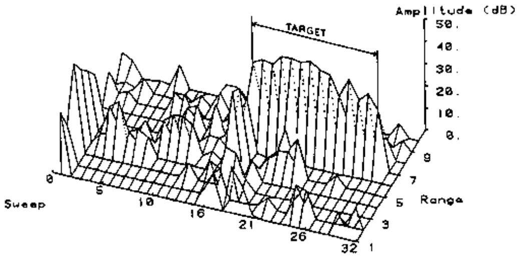

Fig. 8. Response of the non-linear polarization filter with MTI pre-processing.

from a characteristic mean polarization, the null polarization of the non-linear polarization filter, corresponding to the maximum attenuation performance.

Figures 6 and 7 illustrate the performance of such a filter. The first figure refers to the signals present on the two input channels, while the second refers to the output signal after adaptive non linear polarization filtering. The signal representation is three-dimensional : on the vertical axis the signal amplitude is reported at each cell of the processed range/cross-range window. The above adaptive polarization techniques are compatible with Doppler frequency filtering : some elaborations were carried out which show a large signal to clutter ratio improvement when MTI pre-processing of the input signals is separately performed on the two receiving channels. The MTI outputs are then used as inputs to the last polarization filtering device (fig. 8).

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