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Performance Effect of Unintended Polarization on Clutter Attenuation

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ABSTRACT

Various parameters can affect the ground moving target indicator (GMTI) radar performance. One such parameter that may often be overlooked is that of the unintended polarization of the antenna, e.g., the cross-polarization response. This paper discusses the issue of cross-polarization on clutter attenuation performance for GMTI radars.

Keywords: radar; clutter attenuation; polarization; ground moving target indicator, GMTI.

1 INTRODUCTION

Ground moving target indicator (GMTI) radar systems require careful attention to radar system characteristics for optimal performance. For GMTI systems which use clutter attenuation, we desire that the channels are equal such that any differences in the signals is only a result of differences caused by the moving targets. One issue that is known in literature, but sometimes forgotten by GMTI systems engineers is that of polarization differences between channels. This paper discusses GMTI performance issues related to polarization mismatches between channels. To simplify, we will consider the case of a two-channel monopulse system as an example.

2 Unintended polarization problem

Radar system antennas are generally designed to operate with a specific polarization. It is known that real antenna systems allow some unintended polarization along with the desired polarization. This polarization mismatch is an issue in radar detection and signal processing. An additional issue arises in ground moving target indicator (GMTI) radar systems which use multiple subapertures to cancel clutter if there is a polarization mismatch between the subarrays. The mismatch allows different levels of unintended polarization into the radar channels which cause errors in the assumptions in the signal processing. Worse, the signals observed by each channel from the clutter and the target are dependent upon their characteristics, which are not known a priori. Therefore, additional signal processing cannot be used to remove the problem.

For the purposes of this paper, we will assume that desired antenna is a specific polarization, such as vertical, or horizonal, and the unintended polarization is the opposite polarization. Therefore, a target with a cross-polarized response can excite the unintended polarization in the subarrays differently. Typically the antenna designer works to limit the polarization issues in one of the channels or the combination of all channels, but due to other constraints may not be able to match the polarization response for all of the channels. This may be due to asymmetry from size constraints, or mutual coupling, or multipath. If the antenna does not filter the cross-pol response adequately then the cross-pol response will affect the clutter attenuation performance.

The issue of unintended polarization affecting angle-of-arrival systems is not new, but it may sometimes be neglected in system design considerations. A good description of unintended polarization consequences for monopulse radar

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systems is given in [1-2], and more recently in [3]. We repeat from [1]: "Antennas are designed to respond to input waves having a particular polarization (e.g., vertical), and there is always one orthogonal polarization (or cross-polarization) for the antenna (e.g., horizontal). The antenna patterns for the cross-polarization will differ from those for the intended polarization, and targets which scatter both polarizations will generate spurious responses at the antenna output." For example, it is not unusual for a monopulse antenna to have a nice peak response at the center of the beam in the sum channel for the intended polarization and a null-like response for the unintended polarization in the sum channel at this same angle location. However, the opposite can be true in the difference channel in this same case. In other words, the difference channel will have null response at the center angle for the intended polarization, but it can have a peak response in the unintended polarization (cross-pol) at this same location. Obviously, a target that excites only the unintended polarization at this angle will cause a serious error in the estimated angle-of-arrival. In fact the unintended polarization is used as an electronic attack signal in "cross polarized jamming" [3].

We mentioned the fact that channels may have different responses which are dependent upon the target polarization. Since this is the case we are unable to correct for the polarization differences which leads to loss in clutter rejection performance. Targets that have modest cross-pol return will not be properly processed. If the antenna does not filter out this return, the unintended polarization results in a signal that behaves as a "multiplicative noise". Its behavior is "multiplicative" because it increases with increasing transmitter power. Its behavior is "noise"-like because it is known that for monostatic radars the cross-pol response from uniform clutter is generally uncorrelated with respect to the co-pol response [4,5]. Therefore, the unintended polarization is not cancelled properly resulting in a potential limit to the apparent noise floor.

3 Analysis

In this section we present a model for our discussion. To simplify the discussion we will assume a two subarray radar where one subarray transmits and receives a pure intended polarization; whereas, the other subarray has a slight polarization rotation in both transmit and receive. We will also assume that the polarization differences in returns from clutter and targets caused by the spatial offsets between the channels are negligible. In other words, the only polarization differences we will consider those due to antenna design/implementation issues.

Let us assume that intended polarization for each channel is vertical and the unintended polarization is horizontal. The received signal for a monostatic radar system for the first subarray number is given by the following:

$$\begin{bmatrix} r_{hh,1} & r_{hv,1} \\ r_{vh,1} & r_{vv,1} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} t_{hh} & t_{hv} \\ t_{vh} & t_{vv} \end{bmatrix} \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \tag{1}$$

where $r_{ij,1}$ is the received signal field for the i transmit polarization and the j receive polarization; and t_{ij} is the target scattering matrix for the i incident polarization, and j scatter polarization. The first matrix on the right-hand-side is the receive antenna polarization response. The last matrix on the right-hand-side is the transmit polarization response.

Likewise, the received signal for the second channel is given by:

$$\begin{bmatrix} r_{hh,2} & r_{hv,2} \\ r_{vh,2} & r_{vv,2} \end{bmatrix} = \begin{bmatrix} 0 & \delta \\ \delta & 1 \end{bmatrix} \begin{bmatrix} t_{hh} & t_{hv} \\ t_{vh} & t_{vv} \end{bmatrix} \begin{bmatrix} 0 & \delta \\ \delta & 1 \end{bmatrix} \tag{2}$$

The rotation/distortion that creates the unintended polarization in this channel is in the factor, δ, which we assume is small.

The resulting receive signal for the first channel is given by:

$$r_{vv,1} = t_{vv} \quad (3)$$

and for the second channel:

$$r_{vv,2} = t_{vv} + 2\delta t_{vh} + \delta^2 t_{hh} \quad (4)$$

where we make use of the reciprocity condition $t_{vh} = t_{hv}$.

We desire that the polarization response of the antenna for both channels would be purely the intended polarization, i.e., $\delta = 0$. At the very least we want that the two channels to be matched. Since they are mismatched, applying a simple clutter attenuation procedure, such as displaced phase center antenna (DPCA). by subtracting the two receive channels (in the absence of a target), the result is:

$$r_{vv,2} - r_{vv,1} = 2\delta t_{vh} + \delta^2 t_{hh} \quad (5)$$

whereas, we would desire this result would be zero.

The impact of the non-zero value of equation (5) on attenuation is examined now. Start by considering the last term first. Note that since δ is small, then δ^2 is very small. However, for clutter and targets, typically t_{hh} is larger than t_{vh} by a significant amount. By noting that often t_{hh} is correlated with t_{vv} and by assuming that the clutter region remains homogeneous over a large enough region then we should be able to adapt to this issue and further attenuate this term. Therefore we will only consider the first term in equation (5) for the rest of this document:

$$r_{vv,2} - r_{vv,1} \approx 2\delta t_{vh} \quad (6)$$

Define the ratio of the backscatter coefficient of the unintended polarization, $\sigma_{0,u}$, to the backscatter of the intended polarization, $\sigma_{o,i}$, as the depolarization ratio $DR = 10\log_{10}\left|\sigma_{0,u}/\sigma_{0,i}\right|$, in deciBels. Values of this ratio for uniform clutter range from -3 dB to -10 dB, and as high as 0 dB for trees [6]. A typical value reported in [2] is -6 dB.

Before we analyze the performance impact, we will recall that for random clutter t_{vh} is almost always uncorrelated with respect to the co-pol, t_{vv}. Therefore, the term on the right-hand-side of equation (6) behaves as a noise term that is proportional the transmitted power. In other words, it behaves like a multiplicative noise. If we do not manage the unintended polarization term in our antenna system design, it is possible for this multiplicative noise term will dominate the thermal noise and limit clutter attenuation performance.

Loosely following the discussion from [7] we can write:

$$sinr = \frac{P_{avg} T_{cpi} \left(A_{SA,eff}/\lambda\right)^2 \sigma_t}{(4\pi) R^4 \left[\left(kTF_N\right) + N_u/2\right]} G_p L_{rad} = \frac{P_{avg} T_{cpi} \left(A_{SA,eff}/\lambda\right)^2 \sigma_t}{(4\pi) R^4 \left(kTF_N\right) \left[1 + \dfrac{N_u}{2\left(kTF_N\right)}\right]} G_p L_{rad} \quad (7)$$

here $sinr$ is the signal-to-interference-plus-noise ratio, P_{avg} is the average transmitter power during the coherent processing interval, T_{cpi} is the coherent processing interval time, $A_{SA,eff}$ is the effective area of each subarray, G_p is the GMTI (DPCA) processing gain for the target for two channels, σ_t is the RCS of the target, L_{rad} is the combination of the radar loss terms, R is the range to the target, k is Boltzman's constant, T is the nominal noise temperature, F_N is the noise figure for the radar, λ is the wavelength of the radar, and N_u is the new "noise" term caused by the unintended polarization. The N_u in equation (7) has a factor of one-half because we have used the simplifying assumption that only one of the subarrays has the unintended polarization.

The value of N_u is given by:

$$\begin{aligned} N_u &= \frac{P_{avg}T_{cpi}\left(A_{SA,eff}/\lambda\right)^2 4\delta^2\sigma_{0,u}\rho_a\rho_r/\cos\psi}{(4\pi)R^4}L_{rad} \\ &= \frac{P_{avg}T_{cpi}\left(A_{SA,eff}/\lambda\right)^2 4\delta^2 10^{(DR/10)}\sigma_{0,i}\rho_a\rho_r/\cos\psi}{(4\pi)R^4}L_{rad} \end{aligned} \tag{8}$$

The point of equation (8) is to show that increasing the transmitted power in equation (7) does little to improve the SINR if the unintended polarization leakage term is significant. A side note is that equation (8) does not include the processing gain, G_p , because we have assume that only one of the two channels has the unintended polarization.

Therefore, we can rewrite equation (7) as:

$$sinr = G_p snr_0 \left[\frac{1}{1+(\beta/2)\cdot 10^{(DR/10)}cnr_{0,i}}\right] \tag{9}$$

where snr_0 is the signal-to-noise ratio per channel for the target including only the thermal noise, i.e., the term not inside the brackets in equation (7); and $cnr_{0,i}$ is the clutter-to-noise ratio per channel for the intended polarization including only thermal noise. Also, we have let $\beta = 4\delta^2$. This makes β the ratio of the subarray gain of the unintended polarization to the intended polarization.

In order to limit the effect of the unintended polarization on the system performance we desire:

$$(\beta/2)\cdot 10^{(DR/10)}cnr_{0,i} \ll 1 \tag{10}$$

4 Example

This section presents an example to illustrate the issue. Assume that the backscatter coefficient of the intended polarization is -15 dBsm/m^2, the depolarization ratio of the clutter is the nominal -6 dB mentioned above. Assume also that the value of β is -10 dB. Plugging this into equation (10) says that the clutter-to-noise ratio needs to be less than 19 dB in order to limit the effects of the unintended polarization on the SINR performance. Another way to say this, is if this unintended polarization is present, the best we could do in clutter attenuation is drive the clutter down by 19 dB.

If the range and azimuth resolution of the radar were 10 m in both directions and we were operating at a relatively shallow elevation angle, then the clutter level would be approximately 5 dBsm. This would mean that after cancellation processing, the clutter level would be -14 dBsm. This might be adequate for a 0 dBsm target, however, we would generally prefer better. If we could improve β to -20 dB, then we could drive the clutter down by 29 dB and we would drive the clutter level down to -24 dBsm which is much more comfortable for detecting a 0 dBsm target.

Note that the "noise" from the unintended polarization and the thermal noise add together, so that if they were equal the apparent "noise" floor would increase by 3 dB. Figure 1 shows that we wish to keep the unintended polarization term well below the thermal noise floor.

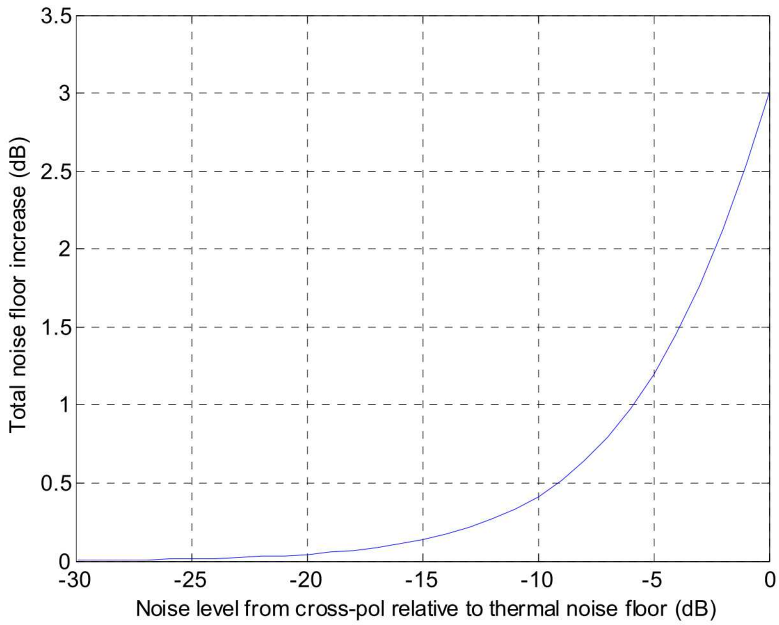

Figure 1: Total apparent noise floor increase due to the addition of the unintended polarization "noise"

5 Other notes

Although we do not consider it here, angle-of-arrival is also affected by the unintended polarization issue, e.g. [2,3]. Note that not only does it add a multiplicative noise term as discussed above, but can also introduce an additional phase offset if the unintended polarization is strong enough relative to the intended polarization.

6 SUMMARY & CONCLUSIONS

This paper shows that the radar system designer needs to consider the polarization characteristics of the antenna carefully as part of the overall GMTI system design. As with monopulse, the effect of the unintended polarization is to limit the apparent null depth. It is highly desirable that the unintended polarization be at least 20 dB lower than the intended polarization, with a goal 30 dB lower.

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