PAPER

Optimal Problem for Contrast Enhancement in Polarimetric Radar Remote Sensing

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SUMMARY This paper proposes two numerical methods to solve the optimal problem of contrast enhancement in the cross-pol and co-pol channels. For the cross-pol channel case, the contrast (power ratio) is expressed in a homogeneous form, which leads the polarimetric contrast optimization to a distinctive eigenvalue problem. For the co-pol channel case, this paper proposes a cross iterative method for optimization, based on the formula used in the matched-pol channel. Both these numerical methods can be proved as convergent algorithms, and they are effective for obtaining the optimum polarization state. Besides, one of the proposed methods is applied to solve the optimal problem of contrast enhancement for the time-independent targets case. To verify the proposed methods, this paper provides two numerical examples. The results of calculation are completely identical with other authors', showing the validity of the proposed methods.

key words: *radar polarimetry, remote sensing, scattering matrix, polarization, optimization*

1. Introduction

The problem on the polarimetric contrast optimization or enhancement has been attracting attention in the polarimetric radar remote sensing [1]-[12], because the contrast enhancement enables us to classify targets or distinguish the desired target from background or undesired target. The basic concept of polarimetric contrast enhancement or optimization is illustrated in Fig. 1, where the desired target is enhanced against the clutter by changing the polarization states of the transmitter and receiver. This technique can be used to any polarimetric Synthetic Aperture Radar (SAR) imagery in which each pixel corresponds to a scattering matrix or an equivalent Mueller matrix or Stokes matrix, depending on the data storage format. Boerner's group (Kostinski, et al. [1], [2], Boerner, et al. [3], [4], and Tanaka, et al. [5]) has founded the polarimetric-filtering principle for both coherent and incoherent cases, based on the polarization ratio and the Stokes vector formulations. The CAL-TECH/JPL (NASA) group (Van Zyl, et al. [6]-[8]) applied the principle to the SAR data acquired at NASA JPL. Touzi, et al. [9] proposed a filtering technique to optimize the partially polarized wave scattering from an object and applied their method to SAR images. Yamaguchi, et al. [10] applied the principle to SAR image sets in three radar channels (the co-pol channel, the cross-pol channel and the matched channel) and gave some significant conclusions by comparing the resultant imagery.

For the coherent case, it is easy to obtain the optimum polarization states for contrast enhancement in three radar channels. In the cases of the co-pol channel and the cross-pol channel, for example, the optimum contrast polarization states are the Co-pol Nulls and Cross-pol (X-pol) Nulls of undesired target, respectively. Based on the polarization ratio, the Co-pol Nulls and X-pol Nulls can be obtained easily [11]. For the incoherent case, on the other hand, the optimum contrast polarization states are different from the Co-pol Nulls or X-pol Nulls. Obviously, it is a tedious task to obtain the optimum polarization state in the co-pol or cross-pol channel by the Lagrangian multiplier method [4] because both the numerator and denominator of the power ratio are quadratic functions of the transmitting Stokes vector. So, some authors [10] calculated the values of the power ratio (as a function of the transmitting polarization state, tilt angle and ellipticity angle) at many points, then compared these values for obtaining the optimum polarization state. This method is very easy for

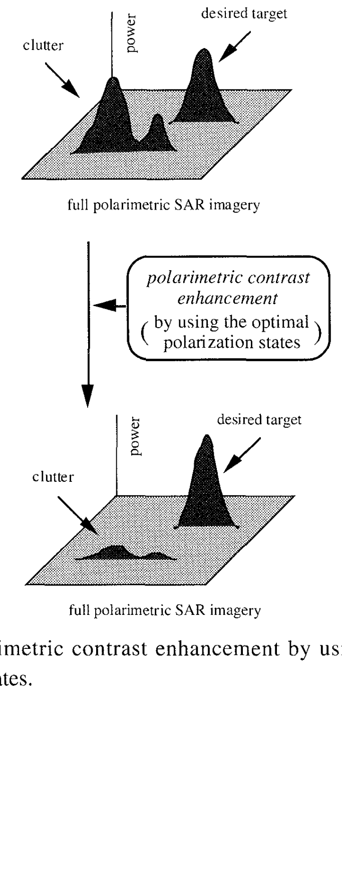

Fig. 1 Polarimetric contrast enhancement by using the optimal polarization states.

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programming, but needs many multiplications and divisions.

In this paper, we present two methods to solve the problem on the polarimetric contrast enhancement in the co-pol and cross-pol channels for the incoherent case, respectively. For the cross-pol channel case, the problem of the polarimetric contrast enhancement is transformed into an eigenvalue problem, which can be solved easily. For the co-pol channel case, this paper proposes a cross iterative method for obtaining the optimum polarization state, based on the result of [12]. This numerical method can be proved as a convergent algorithm, and can be used for obtaining the optimum contrast polarization state rapidly. To verify the presented methods, this paper provides a numerical example for contrast optimization in the cross-pol and co-pol channels. The results are completely identical with [10]. Finally, we apply one of the proposed methods to the time-dependent targets case by using an example and also obtain the same result as [5], showing the validity of the proposed methods.

2. Case of the Matched-Pol Channel

In this section, we first give the formula of the optimum polarization state for contrast enhancement in the matched-pol channel because the result will be used in Sect. 4.

Let us consider the following model [1]

$$maximize \left(\frac{\vec{e}^H [G_1] \vec{e}}{\vec{e}^H [G_2] \vec{e}} \right), \tag{1}$$

where $[G_1]$ and $[G_2]$ denote the Graves matrices [14] of the desired target and undesired target, respectively. The vector $\vec{e}$ denotes the transmitting polarization state, and superscript H denotes conjugate transpose.

Without loss of generality, we assume that the amplitude of $\vec{e}$ equals 1 ($\| \vec{e} \| = 1$) in this paper.

Let $\vec{g}$ denote the Stokes vector of $\vec{e}$, and let $[G] = \begin{bmatrix} \sigma_1 & \sigma_2 \\ \sigma_3 & \sigma_4 \end{bmatrix}$, then we have [12]

$$\vec{e}^H [G] \vec{e} = \frac{1}{2}(\sigma_1 + \sigma_4) + \frac{1}{2}(\sigma_1 - \sigma_4) g_1 + \frac{1}{2}(\sigma_2 + \sigma_3) g_2 + i\frac{1}{2}(\sigma_2 - \sigma_3) g_3, \tag{2}$$

where $g_1^2 + g_2^2 + g_3^2 = 1$. So, we can rewrite (1) as the following form

$$maximize \left(\frac{A_0 + A_1 g_1 + A_2 g_2 + A_3 g_3}{B_0 + B_1 g_1 + B_2 g_2 + B_3 g_3} \right), \tag{3}$$

where A_i and B_i can be obtained from (2). For the problem (3), we know from [12] that the optimum polarization state is

$$g_i = \frac{A_i - C_m B_i}{\sqrt{\sum_{i=1}^{3} (A_i - C_m B_i)^2}} \quad (i = 1, 2, 3), \tag{4}$$

where

$$C_m = \frac{z_{12} + \sqrt{z_{12}^2 - z_1 z_2}}{z_2},$$

$$z_1 = A_0^2 - A_1^2 - A_2^2 - A_3^2,$$

$$z_2 = B_0^2 - B_1^2 - B_2^2 - B_3^2,$$

$$z_{12} = A_0 B_0 - A_1 B_1 - A_2 B_2 - A_3 B_3.$$

Note that the above formula (4) will play an important role in Sect. 4.

3. Case of the Cross-Pol Channel

Let $[M] = (m_{ij})_{4\times4}$ denote a Mueller matrix of a radar target, and let $\vec{g}$ denote the polarization state of the transmitting antenna. Then the received power in the cross-pol channel is

$$P_x = \frac{1}{2} \vec{g}' [K_x] \vec{g}$$

$$= \frac{1}{2} [1, g_1, g_2, g_3] \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{10} & m_{11} & m_{12} & m_{13} \\ m_{20} & m_{21} & m_{22} & m_{23} \\ m_{30} & m_{31} & m_{32} & m_{33} \end{bmatrix} \begin{bmatrix} 1 \\ g_1 \\ g_2 \\ g_3 \end{bmatrix}$$

$$= -\frac{1}{2} [g_1, g_2, g_3] \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{12} & m_{22} & m_{23} \\ m_{13} & m_{23} & -m_{33} \end{bmatrix} \begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix} + \frac{1}{2} m_{00}, \tag{5a}$$

where superscript $'$ denotes transpose. Note that under the assumption $g_1^2 + g_2^2 + g_3^2 = 1$, m_{00} can be written as

$$m_{00} = [g_1, g_2, g_3] \begin{bmatrix} m_{00} & 0 & 0 \\ 0 & m_{00} & 0 \\ 0 & 0 & m_{00} \end{bmatrix} \begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix}.$$

Therefore, the received power in the cross-pol channel can also be expressed as

$$P_x = \frac{1}{2} [g_1, g_2, g_3] \begin{bmatrix} m_{00} - m_{11} & -m_{12} & -m_{13} \\ -m_{12} & m_{00} - m_{22} & -m_{23} \\ -m_{13} & -m_{23} & m_{00} + m_{33} \end{bmatrix} \begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix}$$

$$= \frac{1}{2} \vec{x}' [\bar{M}] \vec{x}. \tag{5b}$$

where

$$\vec{x} = (g_1, g_2, g_3)',$$

$$[\bar{M}] = \begin{bmatrix} m_{00} - m_{11} & -m_{12} & -m_{13} \\ -m_{12} & m_{00} - m_{22} & -m_{23} \\ -m_{13} & -m_{23} & m_{00} + m_{33} \end{bmatrix}.$$

It should be noted that (5b) is a homogeneous form which is convenient for optimization.

Now let us consider the problem of the contrast enhancement optimization in the cross-pol channel. Denote $[M_a]$ and $[M_b]$ as the Mueller matrices of the desired target and the clutter (undesired target), respectively. Then the power ratio between the desired target and the clutter is

$$C_x = \frac{\vec{g}^t [K_x^a] \vec{g}}{\vec{g}^t [K_x^b] \vec{g}} . \tag{6}$$

By use of expression (5b), we can rewrite (6) as

$$C_x = \frac{\vec{x}^t [\bar{M}_a] \vec{x}}{\vec{x}^t [\bar{M}_b] \vec{x}} . \tag{7}$$

Our purpose is to find the $\vec{x}$ such that C_x is maximum. According to algebra theory [13], we can know that the following unit eigenvectors associated with the maximum eigenvalue are the desired solutions.

$$[\bar{M}_a] \vec{x} = \lambda [\bar{M}_b] \vec{x} . \tag{8}$$

Obviously, there are two optimum solutions, which have the following form

$$\vec{x}_{\pm} = (\pm g_1, \pm g_2, \pm g_3)^t . \tag{9}$$

Since we only need to find one eigenvector corresponding to the maximum eigenvalue of (8), it is unnecessary to obtain all eigenvectors of (8). For obtaining this desired eigenvector, it is better to use the following method (**Method X**), which has been proved as an effective method by the theory of numerical algebra [13].

Step 1 Calculate $[W] = [\bar{M}_b^{-1}] [\bar{M}_a]$.

Step 2 Select $\vec{x}_0$ as a starting vector.

Step 3 After $\vec{x}_k$ has been obtained, we let

$$\vec{x}_{k+1} = \frac{[W] \vec{x}_k}{\| [W] \vec{x}_k \|_2} .$$

Step 4 If $\| \vec{x}_{k+1} - \vec{x}_k \|_1 \le \varepsilon$, we can regard $\vec{x}_{k+1}$ as the desired eigenvector.

(For $\vec{q} = (q_1, q_2, q_3)^t$ in this paper, we define

$\| \vec{q} \|_p = (|q_1^p| + |q_2^p| + |q_3^p|)^{\frac{1}{p}}$.)

4. Case of the Co-Pol Channel

4.1 Theorems

Before showing a method to obtain the optimum contrast polarization state in the co-pol channel, let us present three theorems which ensure the convergence of the proposed method. The proofs of these theorems are given in Appendix 1.

Theorem 1: Let

$$[K_c] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{10} & m_{11} & m_{12} & m_{13} \\ m_{20} & m_{21} & m_{22} & m_{23} \\ m_{30} & m_{31} & m_{32} & m_{33} \end{bmatrix}$$

$$= \begin{bmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{01} & m_{11} & m_{12} & m_{13} \\ m_{02} & m_{12} & m_{22} & m_{23} \\ m_{03} & m_{13} & m_{23} & -m_{33} \end{bmatrix}$$

denote a Kennaugh matrix of a radar target in co-pol channel. Then for any $\theta \in [0, 1]$, we have that

$$[A] = \begin{bmatrix} m_{11}+m_{00} & \theta m_{12} & \theta m_{13} \\ \theta m_{12} & m_{22}+m_{00} & \theta m_{23} \\ \theta m_{13} & \theta m_{23} & -m_{33}+m_{00} \end{bmatrix}$$

is a nonnegative definite matrix (positive semi-definite matrix) and

$$[B] = \begin{bmatrix} m_{11}-m_{00} & \theta m_{12} & \theta m_{13} \\ \theta m_{12} & m_{22}-m_{00} & \theta m_{23} \\ \theta m_{13} & \theta m_{23} & -m_{33}-m_{00} \end{bmatrix}$$

is a nonpositive definite matrix (negative semi-definite matrix).

Theorem 2: $[A]$ is a 3×3 nonnegative definite matrix and $[B]$ is a 3×3 nonpositive definite matrix. $\vec{a}$ and $\vec{b}$ are 3-dimensional vectors. c_a and c_b are constants. If $\vec{X}_m$ is the optimum solution of the problem

$$maximize \left(\frac{\vec{x}^t [A] \vec{x} + 2\vec{a}^t \vec{x} + c_a}{\vec{x}^t [B] \vec{x} + 2\vec{b}^t \vec{x} + c_b} \right), \tag{10}$$

then the optimum solution of the problem

$$maximize \left(\frac{\vec{x}^t [A] \vec{y} + \vec{a}^t \vec{x} + \vec{a}^t \vec{y} + c_a}{\vec{x}^t [B] \vec{y} + \vec{b}^t \vec{x} + \vec{b}^t \vec{y} + c_b} \right) \tag{11}$$

is $(\vec{X}_m, \vec{Y}_m)$, where $\vec{Y}_m = \vec{X}_m$.

Theorem 3: $[A]$ and $[B]$ are nonnegative definite and nonpositive definite matrices, respectively. If a starting point $\vec{x}_0$ is close to the optimum solution $\vec{X}_m$ of (10), then $\vec{x}_n$ converges to $\vec{X}_m$ by the following iteration:

Select $\vec{x}_0$ as a starting vector. After $\vec{x}_n$ has been known, consider the following problem

$$maximize \left(\frac{(\vec{x}_n)^t [A] \vec{x} + \vec{a}^t \vec{x}_n + \vec{a}^t \vec{x} + c_a}{(\vec{x}_n)^t [B] \vec{x} + \vec{b}^t \vec{x}_n + \vec{b}^t \vec{x} + c_b} \right). \tag{12}$$

Its solution $\vec{x}_{n+1}$ can be obtained by (4).

4.2 Method

Now let us consider the problem of the optimum polarization state for contrast enhancement in the co-pol channel. The received power in the co-pol channel can be expressed as

$$P_c = \frac{1}{2} \vec{g}^t [K_c] \vec{g} , \tag{13}$$

where

$$[K_c]=\begin{bmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{01} & m_{11} & m_{12} & m_{13} \\ m_{02} & m_{12} & m_{22} & m_{23} \\ m_{03} & m_{13} & m_{23} & -m_{33} \end{bmatrix}.$$

So the ratio of the received powers in the co-pol channel between the desired target and the clutter is

$$C_c=\frac{\vec{g}^t\,[K_c^a]\,\vec{g}}{\vec{g}^t\,[K_c^b]\,\vec{g}}. \tag{14}$$

Our purpose is to find the $\vec{x}$ such that C_c is maximum. This problem can be solved by the following steps (**Method C**).

Step 1 Find two optimum solutions of

$$maximize\left(\frac{\vec{x}^t\left[D(K_c^a)\right]\vec{x}}{\vec{x}^t\left[D(K_c^b)\right]\vec{x}}\right)$$

by solving the problem

$$[D(K_c^a)]\,\vec{x}=\lambda\,[D(K_c^b)]\,\vec{x}\,, \tag{15}$$

where

$$[D(K_c)]=\begin{bmatrix} m_{11}+m_{00} & 0 & 0 \\ 0 & m_{22}+m_{00} & 0 \\ 0 & 0 & -m_{33}+m_{00} \end{bmatrix}.$$

Because both matrices in (15) are diagonal, the eigenvectors can be obtained very easily.

Step 2 Select one optimum solution of

$$maximize\left(\frac{\vec{x}^t\left[D(K_c^a)\right]\vec{x}}{\vec{x}^t\left[D(K_c^b)\right]\vec{x}}\right)$$

as a starting point, denoted as $\vec{x}_0$.

Step 3 Let $h=\frac{1}{q}$, after obtaining the solution $\vec{x}_k$ of the problem

$$maximize\left(\frac{(\vec{x})^t\left(\left[D(K_c^a)\right]+k\,h\left[O(K_c^a)\right]\right)\vec{x}+2\,k\,h\,\vec{m}_a^t\,\vec{x}}{(\vec{x})^t\left(\left[\bar{D}(K_c^b)\right]+k\,h\left[O(K_c^b)\right]\right)\vec{x}+2\,k\,h\,\vec{m}_b^t\,\vec{x}+2\,m_{00}^b}\right), \tag{16a}$$

consider the problem

$$maximize\left(\frac{(\vec{x})^t\left(\left[D(K_c^a)\right]+(k+1)\,h\left[O(K_c^a)\right]\right)\vec{x}+2\,(k+1)\,h\,\vec{m}_a^t\,\vec{x}}{(\vec{x})^t\left(\left[\bar{D}(K_c^b)\right]+(k+1)\,h\left[O(K_c^b)\right]\right)\vec{x}+2\,(k+1)\,h\,\vec{m}_b^t\,\vec{x}+2\,m_{00}^b}\right) \tag{16b}$$

Its solution $\vec{x}_{k+1}$ can be obtained by Step 4. In the above equations,

$$[\bar{D}(K_c^b)]=\begin{bmatrix} m_{11}^b-m_{00}^b & 0 & 0 \\ 0 & m_{22}^b-m_{00}^b & 0 \\ 0 & 0 & -m_{33}^b-m_{00}^b \end{bmatrix},$$

$$[O(K_c)]=\begin{bmatrix} 0 & m_{12} & m_{13} \\ m_{12} & 0 & m_{23} \\ m_{13} & m_{23} & 0 \end{bmatrix}$$

and

$$\vec{m}=(\,m_{01}\,,m_{02}\,,m_{03}\,)^t\,.$$

Step 4 Select $\vec{x}_{k+1}^0=\vec{x}_k$ as a starting vector. After $\vec{x}_{k+1}^n$ has been known, $\vec{x}_{k+1}^{n+1}$ can be obtained by solving the problem

$$maximize\left(\frac{(\vec{x}_{k+1}^n)^t\left(\left[D(K_c^a)\right]+(k+1)\,h\left[O(K_c^a)\right]\right)\vec{x}+(k+1)\,h\,\vec{m}_a^t\,\vec{x}_{k+1}^n+(k+1)\,h\,\vec{m}_a^t\,\vec{x}}{(\vec{x}_{k+1}^n)^t\left(\left[\bar{D}(K_c^b)\right]+(k+1)\,h\left[O(K_c^b)\right]\right)\vec{x}+(k+1)\,h\,\vec{m}_b^t\,\vec{x}_{k+1}^n+(k+1)\,h\,\vec{m}_b^t\,\vec{x}+2\,m_{00}^b}\right). \tag{17}$$

Since (17) and (3) have the same form, $\vec{x}_{k+1}^{n+1}$ can be obtained easily by the formula (4). If $\|\,\vec{x}_{k+1}^{n+1}-\vec{x}_{k+1}^{n}\,\|_1\leq\varepsilon_{k+1}$, we can regard $\vec{x}_{k+1}^{n+1}$ as the possible solution of (16b), denoted as $\vec{x}_{k+1}$. Obviously, $\vec{x}_q$ can be regard as the possible solution of (14), denoted as $\vec{x}_+$.

Step 5 Select $-\vec{x}_0$ as a starting point, we can also obtain another possible solution $\vec{x}_-$ of (14) by the above steps. Substituting these two possible solution $\vec{x}_+$ and $\vec{x}_-$ into (14), we can decide either $\vec{x}_+$ or $\vec{x}_-$ is optimum solution.

Figure 2 shows the procedure for the Method C.

Some Notes

Note 1: Theorem 1 tells us that in (16b) the matrix $[D(K_c^a)]+(k+1)\,h\,[O(K_c^a)]$ is nonnegative definite and the matrix $[\bar{D}(K_c^b)]+(k+1)\,h\,[O(K_c^b)]$ is nonpositive definite. Therefore, the condition of Theorem 2 and Theorem 3 is satisfied. Then applying Theorem 2 and Theorem 3 to (16b) and (17), we can know that $\vec{x}_{k+1}^{n+1}$ is convergent to the solution of (16b). In the iteration of the Step 4, the formula (4) is used for obtaining the solution of (17). Executing this process repeatedly, we can obtain the solution of (16b) finally.

Note 2: Because there is only small difference between (16a) and (16b), the optimal solutions of (16a) are close to the optimal solutions of (16b). According to the Theorem 3, one can know that the optimal solution of (16b) can be obtained by letting the optimal solution of (16a) as the starting point and using the iteration of the Step 4. Therefore one can obtain the optimum solution of (14) by the above steps, which means that the Method C is a convergent algorithm.

Note 3: In Step 3 of the Method C, it is unnecessary to obtain very accurate solutions $\vec{x}_k$ $(k = 1, 2, \ldots, q-1)$. So, it is better to let $\varepsilon_1, \varepsilon_2, \cdots, \varepsilon_{q-1} = J\,\varepsilon_q$ (e.g. $J = 100$ or 1000) for reducing the number of iterations.

Note 4: The optimum solution of (7) can also be solved by the above iteration. But the Method X is simpler than the Method C.

Note 5: Obviously, for the asymmetric scattering matrix case (which is corresponding to the general bistatic case or monostatic non-reciprocal case), the Method C can also be used to obtain the optimum polarization state in the co-pol channel or cross-pol channel.

For helping readers to comprehend this method, we present the basic idea of the Method C shown in Fig. 3.

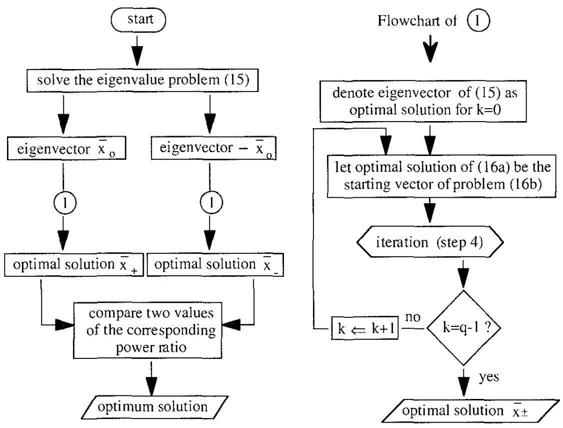

Fig. 2 The procedure for the Method C.

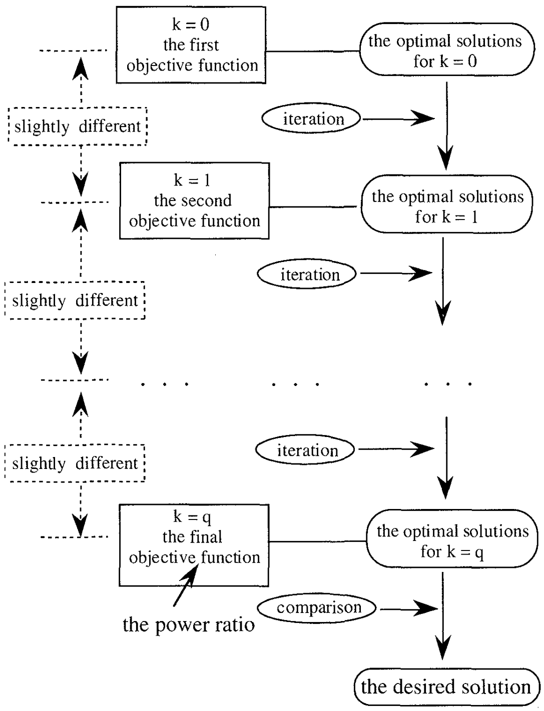

Fig. 3 The basic idea of the Method C.

5. Examples

Example 1: In this example, we use the following averaged Mueller matrices [10] for the purpose of comparison:

$$[M_a] = \begin{bmatrix} 2.5903 & 0.3716 & 0.0391 & 0.0060 \\ 0.3716 & 2.0150 & 0.0426 & -0.0274 \\ 0.0391 & 0.0426 & -0.9294 & -0.1669 \\ -0.0060 & 0.0274 & 0.1669 & -1.5047 \end{bmatrix}$$

and

$$[M_b] = \begin{bmatrix} 1.2749 & 0.3539 & -0.0614 & -0.0298 \\ 0.3539 & 1.0870 & -0.0007 & 0.0010 \\ -0.0614 & -0.0007 & 0.3154 & 0.7949 \\ 0.0298 & -0.0010 & -0.7949 & 0.1276 \end{bmatrix}.$$

Select $\vec{x}_0 = (1, 0, 0)^t$ as a starting vector and let $\varepsilon = 0.00001$, after 17 iterations by the Method X, we can obtain one optimum polarization state for contrast enhancement in the cross-pol channel

$$\vec{x}_{\max}(x-pol) = (0.02265,\ -0.84094,\ -0.54065)^t.$$

According to symmetry of (7), we know the other solution is $-\vec{x}_{\max}(x-pol)$. The corresponding maximum power ratio is 8.09068. Table 1 gives the numbers of iterations and the calculation results with different starting vectors, showing the validity of the Method X.

Using the Method C and letting $h = 0.1$ $(q = 10)$, $\varepsilon_1, \varepsilon_2, \cdots, \varepsilon_9 = 0.1$ and $\varepsilon_{10} = 0.00001$, we can obtain after 54 iterations that the optimum polarization state for contrast enhancement in the co-pol channel is

Table 1 Numbers of iterations and the calculation results with different starting vectors.

starting vector	number of iterations	result of calculation (optimum polarization states)	power ratio
$\bar{x}_o = (\pm 1,\ 0,\ 0)^t$	17	$\bar{x}_m = \pm\,(0.02265, -0.84094, -0.54065)^t$	8.09068
$\bar{x}_o = (0,\ \pm 1,\ 0)^t$	9	$\bar{x}_m = \mp\,(0.02265, -0.84094, -0.54065)^t$	8.09068
$\bar{x}_o = (0,\ 0, \pm 1)^t$	12	$\bar{x}_m = \mp\,(0.02265, -0.84094, -0.54065)^t$	8.09068

Table 2 Numbers of the main operations by different methods.

method	precision	case	number of multiplications	number of divisions	number of used square roots	number of used sine functions or cosine functions
other authors' method [10]	0.00175	co-pol	5.184×10^7	1.62×10^6	0	1.8×10^3
		x-pol	4.212×10^7	1.62×10^6	0	1.8×10^3
proposed methods	0.00001	co-pol	2816	221	108	0
		x-pol	264	69	17	0

$$\vec{x}_{\max}(co-pol)=(-0.17712, 0.55983, -0.80946)^t,$$

and that the corresponding power ratio is 7.38601.

The above results of calculation by the presented methods are completely identical with [10], showing the validity of the presented methods. The numbers of main operations by the method [10] and our methods are shown in Table 2. From the numbers of various operations, one can know that the proposed methods are very effective.

Example 2: Let $[M_a]=(m^a_{ij})_{4\times4}$ and $[M_b]=(m^b_{ij})_{4\times4}$ are time-averaged Mueller matrices for a target and a clutter, and let $\vec{g}$ is the completely polarization state of the transmitting antenna. Then the $[M_a]\,\vec{g}$ and $[M_b]\,\vec{g}$ can usually be regarded as "partially polarized waves." In general, a partially polarized wave can be decomposed into its completely polarized component and unpolarized component. Tanaka et al. [5] presented the following model: to find the transmitting polarization state such that the ratio of completely polarized components of "the reflected waves" (due to the target and clutter) is maximum

$$maximize\ \sqrt{\frac{\vec{g}^t\,[\tilde{M}_a]^t\,[\tilde{M}_a]\,\vec{g}}{\vec{g}^t\,[\tilde{M}_b]^t\,[\tilde{M}_b]\,\vec{g}}},$$

where $[\tilde{M}_a]=(m^a_{ij})_{3\times4}$ and $[\tilde{M}_b]=(m^b_{ij})_{3\times4}$ $(i=1,2,3,\ j=0,1,2,3)$ are the submatrices of the matrices $[M_a]$ and $[M_b]$, respectively. This problem was solved by use of the differentiation [5].

The above problem can also be solved simply by the Method C. For example, let

$$[M_a]=\begin{bmatrix}0.915 & 0.028 & 0.061 & -0.040\\ -0.701 & 0.737 & -0.403 & -0.583\\ 0.135 & -0.339 & 0.808 & -0.665\\ -0.214 & 0.547 & -0.220 & -0.819\end{bmatrix}$$

and

$$[M_b]=\begin{bmatrix}0.824 & -0.015 & 0.003 & -0.062\\ 0.158 & -0.621 & 0.256 & -0.147\\ -0.530 & 0.303 & -0.698 & 0.386\\ 0.461 & -0.289 & 0.512 & -0.702\end{bmatrix}$$

be the time-averaged "Mueller matrices" of a target and a clutter [5], respectively. Using the Method C, we can obtain that the optimum polarization state is

$$\vec{x}_m=(-0.24127, -0.97005, 0.02825)^t.$$

This result is identical with [5], showing the validity of the Method C.

6. Conclusion

In this paper, we presented two effective methods to obtain the optimum polarization states for contrast enhancement in the co-pol channel and cross-pol channel, respectively. In the case of the cross-pol channel, we turned the problem of the polarimetric contrast optimization into an eigenvalue problem, which can be solved very easily. In the case of the co-pol channel, we presented a numerical method for solving the problem of the polarimetric contrast optimization, based on the formula of the optimum contrast polarization state in the matched-pol channel [12]. This numerical method was proved as a convergent algorithm and can be used to obtain the optimum contrast polarization state rapidly. To verify the proposed methods, we gave two numerical examples in Sect. 5. The results are completely identical with [10] and [5], respectively, showing the validity of the proposed methods. From the numbers of various operations shown in Table 2, one can know that the proposed methods are very effective. Besides, we have calculated some other examples by the presented methods. There was no example which required more than 200 iterations.

There have existed two simple methods to obtain the optimum contrast polarization state in the matched-pol channel [1], [12]. In this paper, two effective methods to obtain the optimum contrast states in the co-pol channel and cross-pol channel were proposed. So the problem to obtain the optimum contrast polarization states in three radar channels has been solved completely.

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Appendix 1: The Proofs of the Theorems

1. The Proof of Theorem 1

(i) For an arbitrary vector $\vec{x}$ (without loss of generality, we assume that $\|\vec{x}\|_2 = 1$), the received powers in the co-pol channel satisfy

$$2P_c(\vec{x}) = m_{00} + 2\vec{m}\cdot\vec{x} + \vec{x}^t \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{12} & m_{22} & m_{23} \\ m_{13} & m_{23} & -m_{33} \end{bmatrix} \vec{x} \geq 0,$$

$$2P_c(-\vec{x}) = m_{00} - 2\vec{m}\cdot\vec{x} + \vec{x}^t \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{12} & m_{22} & m_{23} \\ m_{13} & m_{23} & -m_{33} \end{bmatrix} \vec{x} \geq 0,$$

where $\vec{m} = (m_{01}, m_{02}, m_{03})^t$. Adding the above two inequalities together, we can obtain

$$m_{00} + \vec{x}^t \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{12} & m_{22} & m_{23} \\ m_{13} & m_{23} & -m_{33} \end{bmatrix} \vec{x} = \vec{x}^t \begin{bmatrix} m_{00}+m_{11} & m_{12} & m_{13} \\ m_{12} & m_{00}+m_{22} & m_{23} \\ m_{13} & m_{23} & m_{00}-m_{33} \end{bmatrix} \vec{x} \geq 0.$$

So

$$\vec{x}^t A \vec{x} = \vec{x}^t \begin{bmatrix} m_{00}+m_{11} & \theta m_{12} & \theta m_{13} \\ \theta m_{12} & m_{00}+m_{22} & \theta m_{23} \\ \theta m_{13} & \theta m_{23} & m_{00}-m_{33} \end{bmatrix} \vec{x}$$

$$= \vec{x}^t \theta \begin{bmatrix} m_{00}+m_{11} & m_{12} & m_{13} \\ m_{12} & m_{00}+m_{22} & m_{23} \\ m_{13} & m_{23} & m_{00}-m_{33} \end{bmatrix} \vec{x}$$

$$+ \vec{x}^t (1-\theta) \begin{bmatrix} m_{00}+m_{11} & 0 & 0 \\ 0 & m_{00}+m_{22} & 0 \\ 0 & 0 & m_{00}-m_{33} \end{bmatrix} \vec{x}$$

$$\geq 0,$$

which means that $[A]$ is a nonnegative definite matrix. In the above inequality, it was used that $m_{ii} + m_{00} \geq 0$ ($i = 1, 2$) and $m_{00} - m_{33} \geq 0$, which can be proved as follows:

Let $\overrightarrow{x(1)} = (1, 0, 0)^t$, then

$$2P_c(\overrightarrow{x(1)}) = m_{00} + 2\vec{m}\cdot\overrightarrow{x(1)} + m_{11} \geq 0$$

and

$$2P_c(-\overrightarrow{x(1)}) = m_{00} - 2\vec{m}\cdot\overrightarrow{x(1)} + m_{11} \geq 0.$$

Adding both inequalities together, we have $m_{00} + m_{11} \geq 0$.

Similarly, we can prove that $m_{00} + m_{22} \geq 0$ and $m_{00} - m_{33} \geq 0$.

(ii) For an arbitrary vector $\vec{x}$ ($\|\vec{x}\|_2 = 1$), the received power in the cross-pol channel satisfies

$$2P_x(\vec{x}) = m_{00} - \vec{x}^t \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{12} & m_{22} & m_{23} \\ m_{13} & m_{23} & -m_{33} \end{bmatrix} \vec{x}$$

$$= -\vec{x}^t \begin{bmatrix} m_{11}-m_{00} & m_{12} & m_{13} \\ m_{12} & m_{22}-m_{00} & m_{23} \\ m_{13} & m_{23} & -m_{33}-m_{00} \end{bmatrix} \vec{x} \geq 0.$$

Note that $m_{11} - m_{00} \leq 0$, $m_{22} - m_{00} \leq 0$ and $-m_{33} - m_{00} \leq 0$ which can be proved by letting $\vec{x}$ be special vectors and using the inequality of $P_x(\vec{x}) \geq 0$. For example, using the notation $\overrightarrow{x(3)} = (0, 0, 1)'$, we have

$$2 P_x(\overrightarrow{x(3)}) = m_{00} + m_{33} \geq 0 .$$

Therefore, $-m_{33} - m_{00} \leq 0$.

Using a similar method to the proof (i), we can prove that $[B]$ is a nonpositive definite matrix.

2. The Proof of Theorem 2

Denote the maximum value of $\dfrac{\vec{x}'[A]\vec{x} + 2\vec{a}'\vec{x} + c_a}{\vec{x}'[B]\vec{x} + 2\vec{b}'\vec{x} + c_b}$ be $\max\left(\dfrac{\vec{x}'[A]\vec{x} + 2\vec{a}'\vec{x} + c_a}{\vec{x}'[B]\vec{x} + 2\vec{b}'\vec{x} + c_b}\right)$. Since $[A]$ is a nonnegative definite matrix, we can assume that $[A] = [U'][A_0][U]$, where $[U]$ is a real nonsingular matrix, $[A_0] = \mathrm{diag}(\lambda_1^a, \lambda_2^a, \lambda_3^a)$, λ_1^a, λ_2^a and λ_3^a are nonnegative number. Let

$$[U]\vec{x} = (u_1(x), u_2(x), u_3(x))',$$

then

$$\vec{x}'[A]\vec{x} + 2\vec{a}'\vec{x} + c_a$$
$$= \lambda_1^a u_1^2(x) + \lambda_2^a u_2^2(x) + \lambda_3^a u_3^2(x) + 2\vec{a}'\vec{x} + c_a .$$

$$\vec{x}'[A]\vec{y} + \vec{a}'\vec{x} + \vec{a}'\vec{y} + c_a$$
$$= \lambda_1^a u_1(x)u_1(y) + \lambda_2^a u_2(x)u_2(y) + \lambda_3^a u_3(x)u_3(y) + \vec{a}'\vec{x} + \vec{a}'\vec{y} + c_a$$
$$\leq \frac{1}{2}(\lambda_1^a u_1^2(x) + \lambda_2^a u_2^2(x) + \lambda_3^a u_3^2(x) + 2\vec{a}'\vec{x} + c_a) + \frac{1}{2}(\lambda_1^a u_1^2(y) + \lambda_2^a u_2^2(y) + \lambda_3^a u_3^2(y) + 2\vec{a}'\vec{y} + c_a)$$
$$= \frac{1}{2}(\vec{x}'[A]\vec{x} + 2\vec{a}'\vec{x} + c_a) + \frac{1}{2}(\vec{y}'[A]\vec{y} + 2\vec{a}'\vec{y} + c_a) . \tag{A·1}$$

Similarly, by use of the condition that $[B]$ is a nonpositive definite matrix, we can prove

$$\vec{x}'[B]\vec{y} + \vec{b}'\vec{x} + \vec{b}'\vec{y} + c_b$$
$$\geq \frac{1}{2}(\vec{x}'[B]\vec{x} + 2\vec{b}'\vec{x} + c_b) + \frac{1}{2}(\vec{y}'[B]\vec{y} + 2\vec{b}'\vec{y} + c_b) . \tag{A·2}$$

According (A·1) and (A·2), we have

$$\max\left(\frac{(\vec{x})'[A]\vec{y} + \vec{a}'\vec{x} + \vec{a}'\vec{y} + c_a}{(\vec{x})'[B]\vec{y} + \vec{b}'\vec{x} + \vec{b}'\vec{y} + c_b}\right)$$
$$\leq \max\left(\frac{\vec{x}'[A]\vec{x} + 2\vec{a}'\vec{x} + c_a + \vec{y}'[A]\vec{y} + 2\vec{a}'\vec{y} + c_a}{\vec{x}'[B]\vec{x} + 2\vec{b}'\vec{x} + c_b + \vec{y}'[B]\vec{y} + 2\vec{b}'\vec{y} + c_b}\right)$$
$$\leq \max\left(\frac{\vec{x}'A\vec{x} + 2\vec{a}'\vec{x} + c_a}{\vec{x}'B\vec{x} + 2\vec{b}'\vec{x} + c_b}\right) .$$

Therefore, if $\vec{X}_m$ is the optimum solution of the problem (10), then the optimum solution of the problem (11) is $(\vec{X}_m, \vec{Y}_m)$, where $\vec{Y}_m = \vec{X}_m$.

3. The Outline of the Proof of Theorem 3

Here, we only give the outline of the proof of Theorem 3 because the proof is very complicated.

First, let us consider the following algorithm for solving the problem

$$maximize\left(\frac{\vec{x}'[A]\vec{y} + \vec{a}'\vec{x} + \vec{a}'\vec{y} + c_a}{\vec{x}'[B]\vec{y} + \vec{b}'\vec{x} + \vec{b}'\vec{y} + c_b}\right) \tag{A·3}$$

subject to: $x_1^2 + x_2^2 + x_3^2 = 1$,

$y_1^2 + y_2^2 + y_3^2 = 1$.

I Select a vector $\vec{x}_0$ as a starting point.

II After $\vec{x}_n$ is obtained, consider the problem

$$maximize\left(\frac{\vec{x}_n'[A]\vec{y} + \vec{a}'\vec{x}_n + \vec{a}'\vec{y} + c_a}{\vec{x}_n'[B]\vec{y} + \vec{b}'\vec{x}_n + \vec{b}'\vec{y} + c_b}\right). \tag{A·4}$$

Note that (A·4) and (3) have the same form, so the optimal solution $\vec{y}_{n+1}$ can be obtained easily by the formula (4).

III After $\vec{y}_{n+1}$ is obtained, consider the problem

$$maximize\left(\frac{\vec{x}'[A]\vec{y}_{n+1} + \vec{a}'\vec{x} + \vec{a}'\vec{y}_{n+1} + c_a}{\vec{x}'[B]\vec{y}_{n+1} + \vec{b}'\vec{x} + \vec{b}'\vec{y}_{n+1} + c_b}\right), \tag{A·5}$$

its solution $\vec{x}_{n+1}$ can be obtained easily by the formula (4).

IV If $\| \vec{x}_{n+1} - \vec{x}_n \|_1 \leq \varepsilon$ and $\| \vec{y}_{n+1} - \vec{y}_n \|_1 \leq \varepsilon$, we can regard $\vec{x}_{n+1}$ and $\vec{y}_{n+1}$ as the optimal solution of the problem (A·3).

Then, we can prove the following lemma by using Largrangian multiplier method and two mathematical theorems: (a) a monotone increasing bounded sequence must be convergent; (b) a bounded sequence must contain a convergent subsequence.

Lemma $\dfrac{\vec{x}'[A]\vec{y} + \vec{a}'\vec{x} + \vec{a}'\vec{y} + c_a}{\vec{x}'[B]\vec{y} + \vec{b}'\vec{x} + \vec{b}'\vec{y} + c_b}$ has a maximum at

$(\vec{x}_{\max}, \vec{y}_{\max})$. Suppose that $\dfrac{\vec{x}'[A]\vec{y}+\vec{a}'\vec{x}+\vec{a}'\vec{y}+c_a}{\vec{x}'[B]\vec{y}+\vec{b}'\vec{x}+\vec{b}'\vec{y}+c_b}$ has only finite maximums. If a starting vector $\vec{x}_0$ be very close to $\vec{x}_{\max}$, then $\vec{x}_n$ converges to $\vec{x}_{\max}$ and $\vec{y}_n$ converges to $\vec{y}_{\max}$ by the above algorithm.

Finally, using the above lemma and Theorem 2, we can know that the proposed algorithm (Method C) is convergent. Therefore, Theorem 3 holds.

Appendix 2: Graves Matrix, Mueller Matrix and Kennaugh Matrix

There are several matrices representing polarimetric information. The basic matrix is the Sinclair scattering matrix $[S]$, which relates the transmitted electric field to the scattered electric field as

$$\vec{E}_s = [S]\vec{E}_t ,$$

$$[S] = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix},$$

where $\vec{E}_t$ and $\vec{E}_s$ denote the polarization states of the transmitted wave and the reflected wave, respectively. The power density of the reflected wave can be expressed as

$$P_s = \| \vec{E}_s \|^2 = \vec{E}_t^H \; [S]^H [S] \vec{E}_t \; = \vec{E}_t^H [G] \vec{E}_t$$

where $[G]$ is called the Graves matrix, defined as

$$[G] = [S]^H [S] \; = \begin{bmatrix} |s_{11}|^2 + |s_{21}|^2 & s_{11}^* s_{12} + s_{21}^* s_{22} \\ s_{11} s_{12}^* + s_{21} s_{22}^* & |s_{12}|^2 + |s_{22}|^2 \end{bmatrix}$$

This matrix is used for expressing the power density of the reflected wave, so it is also called as power matrix or power density matrix.

Now let $\vec{g}_t$ and $\vec{g}_s$ denote the Stokes vectors of $\vec{E}_t$ and $\vec{E}_s$, respectively, then we have

$$\vec{g}_s = [M]\vec{g}_t$$

where $[M]$ is called the Mueller matrix. The relation between the scattering matrix and the Mueller matrix is given by

$$[M] = \frac{1}{2}[V_c][Q][W][Q]' ,$$

where

$$[V_c] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix},$$

$$[W] = \begin{bmatrix} |s_{11}|^2 & s_{12}^* s_{11} & s_{11}^* s_{12} & |s_{12}|^2 \\ s_{21}^* s_{11} & s_{22}^* s_{11} & s_{21}^* s_{12} & s_{22}^* s_{12} \\ s_{11}^* s_{21} & s_{12}^* s_{21} & s_{11}^* s_{22} & s_{12}^* s_{22} \\ |s_{21}|^2 & s_{22}^* s_{21} & s_{21}^* s_{22} & |s_{22}|^2 \end{bmatrix},$$

$$[Q] = \begin{bmatrix} 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & -i & i & 0 \end{bmatrix}.$$

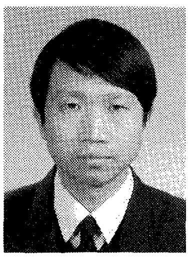
It should be pointed out that in polarimetric radar remote sensing, the Mueller matrix is often given in the average form. In this case, there is no scattering matrix which can be used to express the Mueller matrix in the above form. Next, let us consider the received power in two special polarized channels for a monostatic radar. In the co-pol channel, the received power is given by

$$P_c = \frac{1}{2}[V_c][M]\vec{g}_t \circ \vec{g}_t \; = [K_c]\vec{g}_t \circ \vec{g}_t ,$$

where $\circ$ denotes the dot product. For the monostatic radar case, the scattering matrix is symmetric. Therefore $[K_c]$ is also symmetric. In the cross-pol channel, the received power is given by

$$P_x = \frac{1}{2}[V_x][M]\vec{g}_t \circ \vec{g}_t \; = [K_x]\vec{g}_t \circ \vec{g}_t ,$$

where $[V_x] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$. In the above equations, $[K_c]$ $(= [V_c][M])$ and $[K_x]$ $(= [V_x][M])$ are called as the Kennaugh matrices corresponding to the co-pol channel and the cross-pol channel, respectively. Note that the origin of the coordinate system is usually placed in radar for Kennaugh matrices, whereas in the Mueller matrices case, the origin is of the coordinate system is in a target.



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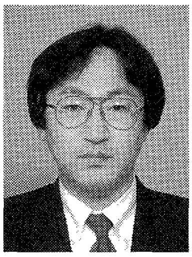

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