# Generalized Optimization of Polarimetric Contrast Enhancement

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***Abstract*—A generalized optimization of polarimetric contrast enhancement (GOPCE) is proposed in this letter. For this problem, it is not only necessary to find the optimal polarization states such that the received power ratio of a desired target and clutter is maximal, but also necessary to find three optimal coefficients such that the ratio of two factors associated with the desired target and clutter is maximal, where both the factors consist of three parameters, i.e., the Cloude entropy and two special similarity parameters. The optimal coefficients of the GOPCE are obtained by solving an eigenvalue problem. Using an example, we demonstrate that the GOPCE can be employed for detecting roads in a forest area by using polarimetric synthetic aperture radar data.**

***Index Terms*—Detection, optimization, radar polarimetry, synthetic aperture radar (SAR).**

## I. Introduction

THE OPTIMIZATION of polarimetric contrast enhancement (OPCE) is one of important problems in radar polarimetry. The traditional OPCE is to choose optimal polarization states for enhancing a desired target versus an undesired target/clutter [1]–[5]. For target detection in a polarimetric synthetic aperture radar (SAR) image, the contrast enhancement enables us to discriminate or distinguish the desired target from background by a power image. For obtaining better contrast enhancement, however, it is unnecessary to use the power image only. If incidence angles are lower than 60°, for example, Touzi *et al.* [9] concluded that the polarization entropy is very effective for ship detection. Therefore, we need to find a function or transform such that a desired target can be clearly discriminated from background in a new image composing of the functional values of all pixels. This function not only includes the received power, but also includes more polarimetric information of the desired and undesired targets. The generalized OPCE (GOPCE) is to find an optimal function including the optimal polarization states. However, it is impossible to know what the optimal function form is. Therefore, it is necessary to give an assumption on the function form.

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In this letter, a GOPCE is proposed. The function form is assumed to be the product of the received power and the square of a linear combination of the Cloude entropy [6] and two special similarity parameters [7], [8]. Then, a method is proposed for obtaining the optimal function of the GOPCE. As an application, the GOPCE is employed for detecting roads in a forest area.

## II. Similarity Parameter

In this section, we present two special similarity parameters which will be used in Section III.

For the problems of target classification and target recognition in radar polarimetry, one problem is how to extract characteristics of a radar target. The similarity parameter [7] may be employed for charactering single-reflected and double-reflected contributions of a target. Let

$$[S] = \begin{bmatrix} S_{\mathrm{HH}} & S_{\mathrm{HV}} \\ S_{\mathrm{VH}} & S_{\mathrm{VV}} \end{bmatrix} \tag{1}$$

denote a target scattering matrix in a linear horizontal (H) and vertical (V) polarization base, and let $\psi$ denote the orientation angle of the target, which is easily obtained due to Huynen's decomposition. We may rotate the target to a special position, where its orientation angle equals zero

$$[S^0] = [J(-\psi)] \cdot [S] \cdot [J(\psi)] = \begin{bmatrix} S^0_{\mathrm{HH}} & S^0_{\mathrm{HV}} \\ S^0_{\mathrm{VH}} & S^0_{\mathrm{HH}} \end{bmatrix} \tag{2}$$

where $[J(\psi)]$ is a rotation matrix [7], [10]–[13].

According to the definition of the similarity parameter [7], one easily calculates two typical similarity parameters as follows.

1) The similarity parameter between an arbitrary scattering matrix [S] and a plane is given by

$$r_1 = r([S], \mathrm{diag}(1,1)) = \frac{\left|S^0_{\mathrm{HH}} + S^0_{\mathrm{VV}}\right|^2}{2\left(\left|S^0_{\mathrm{HH}}\right|^2 + \left|S^0_{\mathrm{VV}}\right|^2 + 2\left|S^0_{\mathrm{HV}}\right|^2\right)}. \tag{3}$$

This parameter is related to the measurement of single reflections from a target. For a smooth ground area or a waveless sea area, $r_1$ is large in general.

2) The similarity parameter between an arbitrary scattering matrix [S] and a dihedral is given by

$$r_2 = r([S], \mathrm{diag}(1,-1)) = \frac{\left|S^0_{\mathrm{HH}} - S^0_{\mathrm{VV}}\right|^2}{2\left(\left|S^0_{\mathrm{HH}}\right|^2 + \left|S^0_{\mathrm{VV}}\right|^2 + 2\left|S^0_{\mathrm{HV}}\right|^2\right)}. \quad (4)$$

This parameter is related to the measurement of double reflections from a target. For a smooth ground area or a waveless sea area, $r_2$ is small in general but it is large in an urban area.

For two different kinds of targets, e.g., a forested area and a no-trees area, single reflections and double reflections may be quite different. In addition, since the polarization entropy [6] is very good for measuring randomness of targets, we employ the above similarity parameters $r_1$ and $r_2$ as well as the entropy for measuring the differences between two kind of targets.

## III. Generalized OPCE

Let TA and TB denote two kinds of targets, and let $[\bar{K}(\mathrm{TA})]$ and $[\bar{K}(\mathrm{TB})]$ be the average Kennaugh matrices of TA and TB, respectively. For the traditional OPCE problem, we need to find the optimal polarization states $\mathbf{g} = (1, g_1, g_2, g_3)^t$ (here $t$ denotes the transpose) and $\mathbf{h} = (1, h_1, h_2, h_3)^t$ for maximizing the power ratio of TA and TB, i.e.,

$$\begin{aligned} \text{maximize} \quad & \frac{\mathbf{h}^t[\bar{K}(\mathrm{TA})]\mathbf{g}}{\mathbf{h}^t[\bar{K}(\mathrm{TB})]\mathbf{g}} \\ \text{subject to} \quad & g_1^2 + g_2^2 + g_3^2 = 1 \\ & h_1^2 + h_2^2 + h_3^2 = 1. \end{aligned} \quad (5)$$

Using an iteration algorithm [5], one easily obtains the optimal polarization states $\mathbf{g}_m$ and $\mathbf{h}_m$ for the above problem. As shown in Section IV, the traditional OPCE can be utilized for contrast enhancement by a polarimetric SAR image composing of the received powers of all pixels. That is to say, if a function $P = \mathbf{h}^t_m[K]\mathbf{g}_m$ is selected, then a polarimetric SAR image is obtained by the function values of all pixels.

For a generalized OPCE (GOPCE), we need to find an optimal function containing the received power. In general, however, it is impossible to know what the optimal function form is. Therefore, it is necessary to give an assumption on the optimal function form. For convenience, we assume that the function form consists of two factors. One factor is associated with target scattering characteristics and the other is the received power. For simplicity, we assume in this letter that the function form has the following form:

$$\mathrm{GP} = \left[\sum_{i=1}^{3} x_i r_i\right]^2 \times \mathbf{h}^t_m [K] \mathbf{g}_m \quad (6)$$

where $r_1$ and $r_2$ are defined by (3) and (4), respectively. $r_3 = H$ denotes the polarization entropy [6]. For an arbitrary pixel, the corresponding entropy $r_3 = H$ is obtained by decomposing the average covariance matrix of an adjacent 3 × 3 window. In (6), $x_1, x_2$, and $x_3$ are three coefficients which will be obtained by solving an optimal problem.

In general, two different targets, e.g., TA and TB, should have different scattering characteristics. In this letter, $\mathbf{r} = (r_1, r_2, r_3)^t$ is employed for measuring the difference between TA and TB. Note that (6) includes the scalar product of the characteristic vector $\mathbf{r}$ and the coefficient vector $\mathbf{x} = (x_1, x_2, x_3)^t$. If most of the characteristic vectors of TA are close to a main direction, and if the direction of the coefficient vector $\mathbf{x}$ is the same as the total sum of the characteristic vectors of TA, then $[\sum_{i=1}^3 x_i r_i]^2$ becomes larger for all pixels of TA on the average. Similarly, if most of the characteristic vectors of TB are close to another main direction, and if $\mathbf{x}$ is perpendicular to the total sum of the characteristic vectors of TB, then $[\sum_{i=1}^3 x_i r_i]^2$ becomes smaller for all pixels of TB on the average. Therefore, the optimal coefficient vector $\mathbf{x}_m$ may maximize the difference of the characteristics between TA and TB. In this way, we use both the factors $[\sum_{i=1}^3 x_i r_i]^2$ and $\mathbf{h}^t_m[K]\mathbf{g}_m$ for enhancing the desired target TA versus the undesired target TB.

For the above function form (6), the mathematical model of the GOPCE is to find $\mathbf{x} = (x_1, x_2, x_3)^t, \mathbf{g}$ and $\mathbf{h}$ from the following optimization:

$$\begin{aligned} \text{maximize} \quad & \frac{\frac{1}{M}\sum_{\mathrm{TA}}\left[\sum_{i=1}^3 x_i r_i(\mathrm{TA})\right]^2}{\frac{1}{N}\sum_{\mathrm{TB}}\left[\sum_{i=1}^3 x_i r_i(\mathrm{TB})\right]^2} \times \frac{\mathbf{h}^t[\bar{K}(\mathrm{TA})]\mathbf{g}}{\mathbf{h}^t[\bar{K}(\mathrm{TB})]\mathbf{g}} \\ \text{subject to} \quad & g_1^2 + g_2^2 + g_3^2 = 1 \\ & h_1^2 + h_2^2 + h_3^2 = 1 \\ & x_1^2 + x_2^2 + x_3^2 = 1 \end{aligned} \quad (7)$$

where $M$ and $N$ denote the selected pixel numbers of TA and TB, respectively. For the above GOPCE problem (7), the optimal polarization states $\mathbf{g}_m$ and $\mathbf{h}_m$ are the same as those of the traditional OPCE problem (5) which can easily be obtained by the method in [5]. Now we only need to find the optimal coefficients $x_i (i = 1, 2, 3)$. Obviously, these coefficients can be obtained by solving the following eigenvalue problem:

$$\frac{1}{M}\sum_{\mathrm{TA}}[R(\mathrm{TA})]\mathbf{x} = \lambda \frac{1}{N}\sum_{\mathrm{TB}}[R(\mathrm{TB})]\mathbf{x} \quad (8)$$

where $[R(\mathrm{TA})] = [r_i(\mathrm{TA})r_j(\mathrm{TA})]_{3\times3}$ and $[R(\mathrm{TB})] = [r_i(\mathrm{TB})r_j(\mathrm{TB})]_{3\times3}$. It is easy to prove that the eigenvector associated with the maximum eigenvalue is the optimal coefficient vector $\mathbf{x}_m = (x_1, x_2, x_3)^t$ of (7).

A possible generalization of the proposed optimization is the extension of the linear combination $r_i$ in (6) to a quadratic form. One easily gives the corresponding GOPCE model and obtains its optimal solution.

In addition, we may consider the GOPCE for the cases of three special channels, i.e., the copolarized, cross-polarized, and matched-polarized channels. Obviously, if $\mathbf{g}$ and $\mathbf{h}$ are independent, the power ratio associated with two optimal polarizations is larger in general than those in the three special channel cases because the independent variable of the OPCE for the three special channels is $\mathbf{g}$ only [5].

## IV. Application and Conclusion

As an application, the GOPCE can be employed for detecting roads in a forest. Here, we use a National Aeronautics and Space Administration SIR-C/X-SAR L-band image of a forest

Fig. 1. Span image of a forest area, Tian Shan, China.

TABLE I
DIFFERENCE OF SCATTERING CHARACTERISTICS BETWEEN TA AND TB

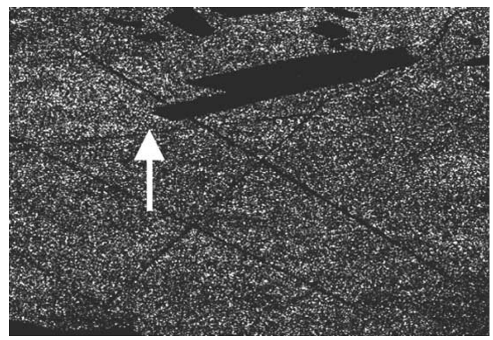
| | TA (forest area) | TB (no trees area) |
|---|---|---|
| $r_1$ on avg. | 0.31 | 0.59 |
| $r_2$ on avg. | 0.37 | 0.22 |
| $r_3$ on avg. | 0.49 | 0.33 |
| first principal component | $0.431r_1 + 0.547r_2 + 0.718r_3$ | $0.864r_1 + 0.222r_2 + 0.452r_3$ |

area in Tian Shan (China) for validating the effectiveness of the GOPCE. Fig. 1 shows the span image of the forest. In black areas, trees have been felled. Select two areas consisting of trees and four areas where there are no trees as TA and TB, respectively. TA and TB have not only different span but also different scattering characteristics, e.g., the single reflections, double reflections, and randomness. These characteristics are related to two similarity parameters (i.e., $r_1$ and $r_2$) and the polarization entropy (i.e., $r_3$), respectively. Table I shows the average values of every parameter and the first component factors of TA and TB. The first component factors of TA and TB are $0.431r_1 + 0.547r_2 + 0.718r_3$ and $0.864r_1 + 0.222r_2 + 0.452r_3$, respectively. From the largest coefficients of both the factors, we straightforwardly conclude that a forest area has large randomness and that single reflections is dominating in the no-trees areas TB. Solving (8), we obtain the optimal coefficient vector $\mathbf{x}_m = (-0.400, 0.208, 0.892)^t$. Using the first factor in (6) loading these optimal coefficients, we may enhance 3.594 times of the contrast ratio of TA to TB.

From Table I, one easily finds that (on average) $r_2$ and $r_3$ of TA are larger than those of TB, respectively, but $r_1$ of TA is smaller than that of TB. It indicates that double reflections and randomness of the forested areas TA are larger than those of the no-trees areas TB, and that single reflections from TA are in general smaller than those from TB. This conclusion is easy to understand. If we apply a special coefficient vector $\mathbf{x} = (0, 0, 1)^t$ to (7), i.e., if only the entropy $r_3$ is used, the corresponding first ratio factor of (7) equals 1.93. Similarly, if $\mathbf{x} = (0, 1, 0)^t$, i.e., if only $r_2$ is used, the corresponding first ratio factor of (7) equals 2.11. Since $r_1$ of TA is smaller than that of TB, the corresponding first ratio factor of (7) is 0.37 if $\mathbf{x} = (1, 0, 0)^t$. All these ratios are smaller than the first ratio factor of (7) with loading the optimal coefficient vector $\mathbf{x}_m$.

TABLE II
OPTIMAL POLARIZATION STATES AND CONTRAST RATIOS FOR THE OPCE AND THE GOPCE

| | optimal polarization state(s) | power ratio corresponding to the OPCE | ratio corresponding to the GOPCE |
|---|---|---|---|
| the co-pol channel case | $\mathbf{g}_{mc} = (1, -0.024, 0.065, -0.998)^t$ | 112.203 | 403.258 |
| the cross-pol channel case | $\mathbf{g}_{mx} = (1, -0.275, -0.961, -0.035)^t$ | 123.395 | 443.482 |
| the matched-pol channel case | $\mathbf{g}_{mm} = (1, 0.994, 0.105, 0.000)^t$ | 19.218 | 69.069 |
| case of two indepedent polarisations | $\mathbf{g}_m = (1, -0.281, -0.952, -0.121)^t$ $\mathbf{h}_m = (1, 0.265, 0.963, -0.049)^t$ | 123.654 | 444.412 |

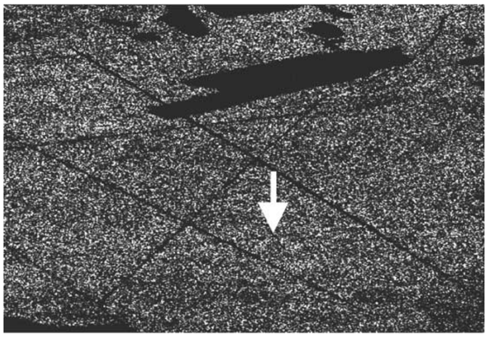


(a)

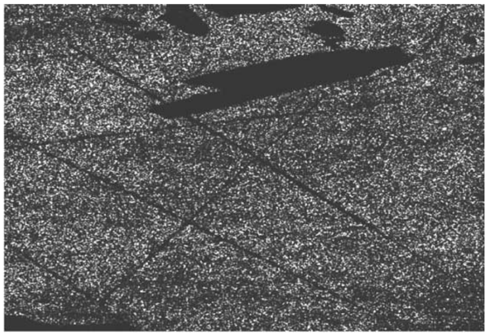
(b)

Fig. 2. (a) Received power image $\mathbf{h}_m^t[K]\mathbf{g}_m$ with the optimal polarization states $\mathbf{g}_m = (1, -0.281, -0.952, -0.121)^t$ and $\mathbf{h}_m = (1, 0.265, 0.963, -0.049)^t$. (b) The received power image $\mathbf{g}_{mc}^t[K]\mathbf{g}_{mc}$ with the optimal polarization state $\mathbf{g}_{mc} = (1, -0.024, 0.065, -0.998)^t$.

Using the iteration algorithm in [5], we obtain the optimal polarization states of the traditional OPCE problem as $\mathbf{g}_m = (1, -0.281, -0.952, -0.121)^t$ and $\mathbf{h}_m = (1, 0.265, 0.963, -0.049)^t$, and the corresponding power ratio (5) is 123.654. For comparison, we also present the calculation results of the OPCE with three special channel cases in Table II. One easily finds that the power ratio associated with two independent optimal polarizations is the largest in all other cases. Fig. 2(a) shows the received power image associated with the optimal polarization states $\mathbf{g}_m$ and $\mathbf{h}_m$. From this image, one easily finds a road below the largest black area, whereas it is not clear in Fig. 1. Fig. 2(b) shows the received power image (in the copolarized channel case) associated with the optimal



(a)



(b)

Fig. 3. (a) Image of GP $= [\sum_{i=1}^{3} x_i r_i]^2 \times \mathbf{h}_m^t[K]\mathbf{g}_m$. (b) The image of GP$_c = [\sum_{i=1}^{3} x_i r_i]^2 \times \mathbf{g}_{mc}^t[K]\mathbf{g}_{mc}$.

polarization state $\mathbf{g}_{mc} = (1, -0.024, 0.065, -0.998)^t$. It is difficult to find roads in Fig. 2(b), demonstrating that the OPCE for the case of two independent polarization states is better for road detection than that for the copolarized channel case.

Combining the optimal polarization states $\mathbf{g}_m$ and $\mathbf{h}_m$ with the optimal coefficient vector $\mathbf{x}_m$, we obtain that the corresponding total ratio (7) equals 444.488. It is larger than the maximal power ratio of the traditional OPCE problem (5).

After $\mathbf{x}_m, \mathbf{g}_m$, and $\mathbf{h}_m$ are obtained, we calculate GP $= [\sum_{i=1}^{3} x_i r_i]^2 \times \mathbf{h}_m^t[K]\mathbf{g}_m$ for all pixels to form an image, shown in Fig. 3(a). In this image, all roads detected before becomes clearer. In addition, one can find a new road from the left side to the right side. Although this new detected road is not so clear in Fig. 3(a), it is hardly found from Fig. 2(a). Therefore, the GOPCE is more effective than the traditional OPCE.

For the GOPCE problem in the copolarized channel case, after calculating GP$_c = [\sum_{i=1}^{3} x_i r_i]^2 \times \mathbf{g}_{mc}^t[K]\mathbf{g}_{mc}$ for all pixels, we also obtain an image shown in Fig. 3(b), where $\mathbf{g}_{mc}$ is the optimal polarization state in the copolarized channel case. Comparing Fig. 3(b) with Fig. 2(b), we conclude that the GOPCE is better than the standard OPCE for the copolarized channel case.

Since the calculation results of the OPCE and the GOPCE for two independent polarization states are almost the same as those for the cross-polarized channel case (as shown in Table II), we do not present the corresponding images.

In this letter, we have proposed a generalized OPCE. It is not only necessary to employ the received power ratio of a desired target and clutter for contrast enhancement, but also necessary to utilize the differences of target scattering characteristics between the desired target and clutter for enhancement. If there are differences of single reflections, double reflections, and randomness between two kinds of targets, the proposed GOPCE is effective. Theoretical analyses and calculation results have indicated that the GOPCE can be employed for detecting roads in a forest area and that it is more effective than the traditional OPCE.

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