PAPER

Reduction of Surface Clutter by a Polarimetric FM-CW Radar in Underground Target Detection

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SUMMARY This paper presents an experimental result of polarimetric detection of objects buried in a sandy ground by a synthetic aperture FM-CW radar. Emphasis is placed on the reduction of surface clutter by the polarimetric radar, which takes account of full polarimetric scattering characteristics. First, the principle of full polarimetric imaging methodology is outlined based on the characteristic polarization states for a specific target together with a polarimetric enhancement factor which discriminates desired and undesired target echo. Then, the polarimetric filtering technique which minimizes a surface reflection is applied to detect a thin metallic plate embedded in a sandy ground, demonstrating the potential capability of reducing surface clutter which leads to an improvement of underground radar performance, and validating the usefulness of FM-CW radar polarimetry.

key words: *radio applications, sub-surface radar, polarimetry, SAR*

1. Introduction

Sub-surface radar has been attracting interests in diverse areas [1]-[5] such as exploring archeological explorations, detecting gas pipes or electric cables in urban area in advance construction works, detecting defects of known underground objects, or exploring some natural resources. There exist many kinds of radar including pulse, FM-CW, coded pulse, etc. However, in an operation of any radar types, there arises a problem on surface clutter which degrades the radar performance. If a surface under a test site is wet or dense, the surface echo sometimes masks the desired target echo even though it exists, leading to the radar detection impossible. The reduction of surface clutter therefore is one of the important problems in sub-surface radar sensing [6].

Radar polarimetry, i. e., the full utilization of the vector nature of electromagnetic wave information, may serve this problem. Since we have been engaged in the development of FM-CW radar system aimed at detecting objects buried in lossy medium [7], [8], we examine in this paper how the radar polarimetry can apply to the detection problems and to the reduction of surface clutter. Since the principle of radar polarimetry [9], [10] can be incorporated into a wideband FM-CW radar system [11], the synthetic aperture FM-CW radar has become an advanced full polarimetric radar system suitable in the short range region. This paper applies the polarimetric filtering principle to actual detection problems by the FM-CW radar. The emphasis is placed on the reduction of surface clutter while enhancing the target contrast, taking account of full polarimetric scattering characteristics. Polarimetric enhancement factor, which is defined as a power ratio of two different targets, is employed as a discriminator which theoretically and conceptionally plays an important role in imaging a specific target in a complex featured imagery. It is shown that it is possible to eliminate one of the targets (surface) and at the same time to enhance another target (desired target) even in the underground by using a specific polarization state which optimizes the enhancement factor. Section 2 presents the methodology and Sect. 3 shows the polarimetric detection results of targets embedded in a sandy ground, demonstrating the potential capability of reducing surface clutter while enhancing the target which leads to an improvement of underground radar performance, and validating the usefulness of FM-CW radar polarimetry.

2. Polarimetric Enhancement

The synthetic aperture FM-CW radar can provide a high resolution two-dimensional SAR imagery which displays an interior information (depth and scanning directions) of an underground if the radar is scanned on the surface [7]. The image consists of thousands of pixels. If a polarimetric measurement is conducted, for example in the (HV) polarization basis, it is possible to obtain polarimetric imagery. The set of the polarimetric data provides a Sinclair scattering matrix pertaining to each pixel in the synthetic aperture FM-CW radar imagery [11]. In this case, each pixel has its own scattering matrix. If a scattering matrix is given, it is possible to synthesis any polarimetric channel power by using a specific polarization state. The optimization of the receiving power for a given target is well described in [9], [10].

In this section, we will consider the Co-pol channel case where the polarization state of the receiver is identical with that of the transmitter. The characteris-

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tic polarization state theory [10] shows that the Co-pol channel power of a monostatic radar is given by

$$P=A|\boldsymbol{h}^T[S(HV)]\boldsymbol{h}|^2$$
$$=A\left|\frac{[1\rho]}{1+\rho\rho^*}\begin{bmatrix}S_{HH} & S_{HV}\\ S_{VH} & S_{VV}\end{bmatrix}\begin{bmatrix}1\\ \rho\end{bmatrix}\right|^2, \quad (1)$$

provided a unit magnitude coherent wave is transmitted. In Eq. (1), A is a constant independent of polarization, $[S(HV)]$ is Sinclair scattering matrix representing target's polarimetric scattering characteristics measured in the (HV) polarization basis,

$$[S(HV)]=\begin{bmatrix}S_{HH} & S_{HV}\\ S_{VH} & S_{VV}\end{bmatrix}, \quad (2)$$

and $\boldsymbol{h}$ is the polarization state of a radar transmitter in terms of the polarization ratio ρ defined by Jones vector form

$$\boldsymbol{h}=\frac{1}{\sqrt{1+\rho\rho^*}}\begin{bmatrix}1\\ \rho\end{bmatrix}. \quad (3)$$

It is known that there exist four characteristic polarization states (maximum, extremum, and two nulls) for a single target in this polarimetric channel. The maximum power is achieved by selecting one of the following polarization ratios

$$\rho_{m1,2}=\frac{-B\pm\sqrt{B^2-4AC}}{2A}, \quad (4)$$

where $A=S_{HH}^*S_{HV}+S_{HV}^*S_{VV}$, $B=|S_{HH}|^2-|S_{VV}|^2$, $C=-A^*$. The other gives the extremum (saddle point) power.

Now, let's define a contrast enhancement factor by the power ratio which seems useful for target detection in a complex featured subsurface SAR imagery,

$$C=\frac{P_1}{P_2}=\left|\frac{S_{1,HH}+2\rho S_{1,HV}+\rho^2 S_{1,VV}}{S_{2,HH}+2\rho S_{2,HV}+\rho^2 S_{2,VV}}\right|^2, \quad (5)$$

where the subscript 1 corresponds to a pixel within a target for which we wish to enhance and the subscript 2 corresponds to the other pixel of a different target to be eliminated. This quantity defines the degree to which contrast of a special target versus another is enhanced quantitatively in a complex featured imagery. This definition is based on the power rather than the voltage because the dynamic range of the power is doubled, which will contribute to high contrast target detection. The problem becomes to find a polarization state (i. e., polarization ratio ρ) which maximizes the contrast factor (5) in a lossy inhomogeneous medium. The maximum of (5) and hence the corresponding polarization state may be easily found from

$$C=\infty \Rightarrow S_{2,HH}+2\rho S_{2,HV}+\rho^2 S_{2,VV}=0. \quad (6)$$

The specific polarization states are given by

$$\rho_n=\frac{-S_{2,HV}\pm\sqrt{S_{2,HV}^2-S_{2,HH}S_{2,VV}}}{S_{2,VV}}. \quad (7)$$

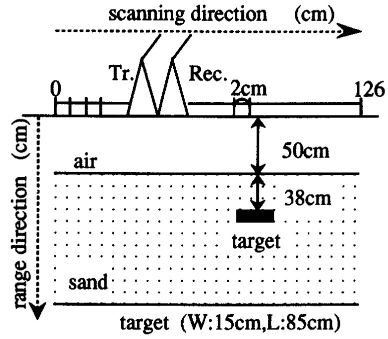
These polarization states are identical with Co-pol nulls for target 2. Hence the maximization problem of the polarimetric contrast enhancement factor reduces to find the null polarization states of undesired target. It is possible to calculate the channel power in all pixels of a SAR imagery using the optimal polarization states (4) or (7) so that the target is maximized or eliminated. This is the characteristic polarimetric filtering technique for a specific target in a SAR imagery.

It should be noted that this optimization is based on the scattering matrix only no matter how the propagation medium is. In other words, this method uses a final scattering matrix obtained by a radar, even if the target is buried in lossy inhomogeneous medium. This optimization also assumes the scattering characteristics of target 1 and 2 are dissimilar, i. e., the scattering matrices of $[S_1]$ and $[S_2]$ are different in the elements. If they are similar, the optimization procedure becomes different [12]. However in such a case, the power ratio formulation would fail to discriminate two targets because the contrast factor is close to unity.

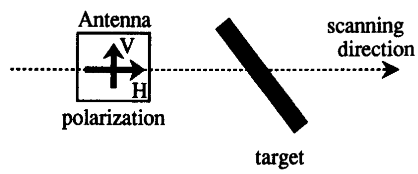
A similar theory may apply to the Cross-pol channel imagery and the Matched-pol channel imagery.

3. Polarimetric Detection in Sandy Ground

Next, an experiment of polarimetric object detection was carried out to confirm the methodology for the reduction of surface clutter. This measurement was carried out in Niigata University Campus where the



(a) Cross-sectional view

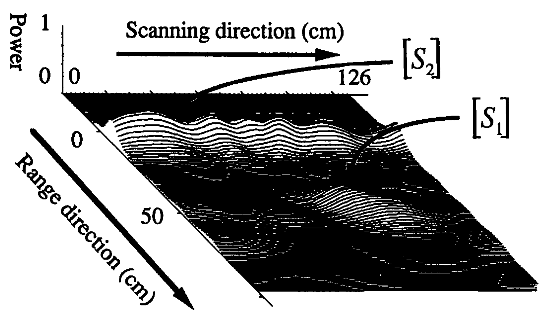


(b) Top view

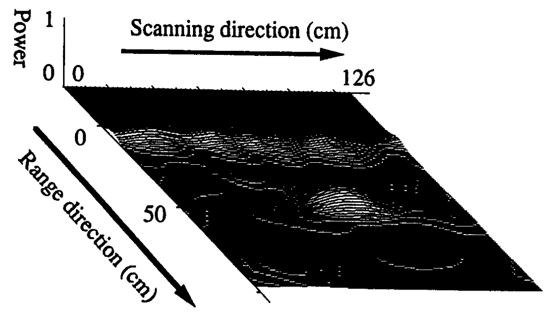
Fig. 1 Experimental scheme.

ground is essentially made of sand. The radar system employed is identical with that described in [7]. First, we determined the permittivity of the ground by comparing the radar detection range and the actual range. The average permittivity was found to be 4.68, which is typical value for dry sand [13].

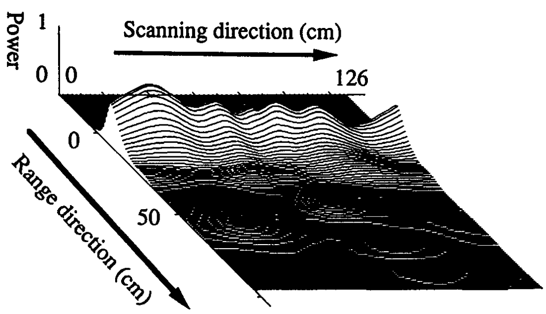
The target was a metallic plate of 15×85 cm which was buried at the depth of 38 cm horizontally in a sandy ground. It is oriented −45 degrees with respect to the scanning direction. The experimental scheme is shown in Fig. 1. The polarimetric detection was conducted in the conventional linearly polarized (HV) basis. In this measurement, H stands for the polarization being parallel to the scanning direction and V for the orthogonal polarization to H. It is possible to obtain fixed polarization radar image as shown in Fig. 2 by scanning antenna horizontally over the surface. These images are obtained by a synthetic aperture processing. The range (depth) is calibrated according to the measured permittivity. It is seen that surface clutter exists in all fixed polarization images and that surface clutter surpasses the target echo in the VV image (c) which makes the target detection impossible. The reason of the difference in the target echo strengths of Figs. 2 (a) and (c) is due to the difference in directivities of antenna combinations with respect to the aperture size and alignment in the near field polarimetric measurement and due to a small mis-alignment of the target with respect to the horizontal scanning direction (i.e., the horizontal target might not be placed precisely, even though we tried to place it horizontally).



(a) HH



(b) HV



(c) VV

Fig. 2 Synthetic aperture images in the (HV) polarization basis.

4. Clutter Reduction with Polarimetric Enhanced Image

The image consists of many pixels (in this case, 64× 128). Each pixel has its own scattering matrix. For the full polarimetric imaging, let's choose two targets for which we wish to maximize and minimize, or to obtain maximum contrast enhancement. We took a pixel within a surface layer which represents typical polarimetric scattering characteristics statistically. The method to choose the pixel or equivalently the polarization state is depicted in Fig. 3 where the Co-pol null plot of the surface pixels is shown as a function of ellipticity and tilt angles. Since the Co-pol nulls are located in a concentrated region, we took the center position pertaining to a surface pixel. This pixel is denoted as the undesired target 2. A pixel which resides within the metallic plate and produces the maximum power was chosen as the desired target 1. These two pixels are found to have scattering matrices as:

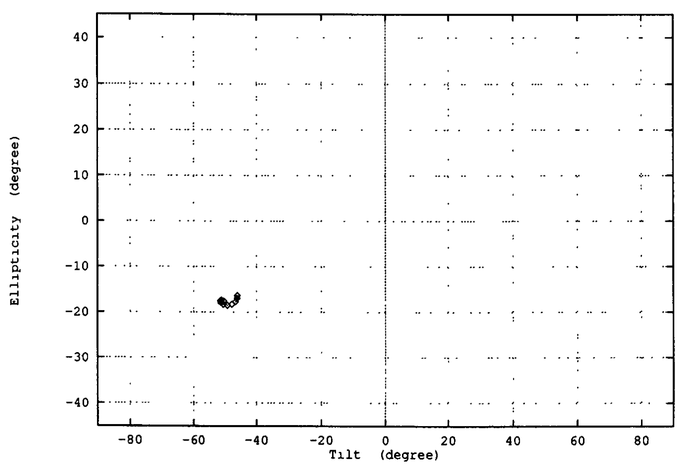


Fig. 3 Co-pol null plot of surface pixels.

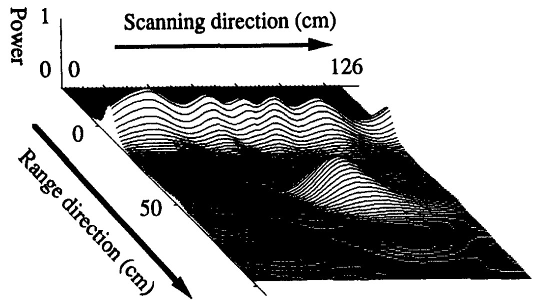


Fig. 4 Co-pol maximum image for the plate.

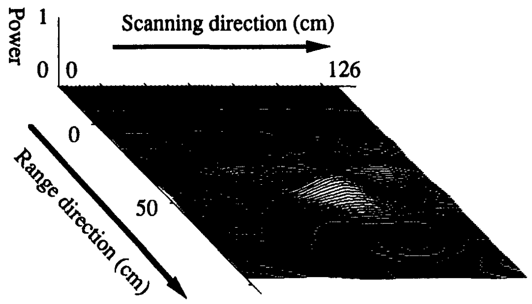


Fig. 5 Clutter reduced (Co-pol null for surface) image.

Target 1 (plate)

$$[S_1]=\begin{bmatrix} 0.192+j0.445 & -0.083-j0.405 \\ -0.083-j0.405 & -0.064-j0.148 \end{bmatrix},$$

Target 2 (surface)

$$[S_2]=\begin{bmatrix} -0.047-j0.497 & -0.166+j0.265 \\ -0.166+j0.265 & 0.393+j0.633 \end{bmatrix}.$$

Figure 4 shows a Co-pol maximum image for the plate (target 1) based on the optimization of (4). Although the plate is maximized, the surface clutter appears somewhat strong. This image is similar to an ordinal fixed polarization image of Fig.2 in the sense that the surface clutter exists.

For the reduction of surface clutter, we re-calculated all other pixel values in the entire scene again using the polarization state of (7). Figure 5 shows a resultant image. It is seen that the surface echo above the target is suppressed considerably and that we still have strong target contrast. Although the main purpose here is to minimize the surface, the echo from the desired target appears strong. This is a great advantage for detection problems.

The scattering matrices above are scaled with a certain value so that the Span of $[S_2]$ becomes unity. This scaling by a constant factor does not affect any problem in polarimetric analysis. It is interesting to note that $Span\{[S_1]\}=0.602$ and $Span[\{S_2]\}=1$. This fact shows that the power by the surface is stronger than that of the target. Indeed, the maximum powers attainable for these two pixels are $P_{1\max}=0.477$, and $P_{2\max}=0.841$, depending upon polarization state. If the polarimetric scattering characteristics of the surface are different from that of the target, as usually is, the power ratio (5) of the target and the surface becomes infinity. This means that the target is enhanced while surface clutter is suppressed.

It should be noted that no special signal processing was attempted to enhance the target in Fig. 5. The present method uses the scattering matrix only obtained by the synthetic aperture FM-CW radar. Although the polarimetric calibration in an underground is difficult to carry out, the final scattering matrix obtained by the polarimetric FM-CW radar serves an efficient target detection.

In a sub-surface sensing, in general, we do know the surface position and roughness, and we do not know a desired target information in the underground including position, size, orientation angle, medium property, etc. In such a case, all we have is the surface information. The present method proposes to use Co-pol null polarization state for the surface in the detection problems as well as in SAR imagery. Then a full-polarimetric radar will play an important role in advanced and efficient sub-surface detection sensing.

In addition to this advantage, the polarization state which maximizes/minimizes a specific target may be useful for the target classification and identification provided the polarimetric calibration is performed in the ground, which will be treated in a near future.

5. Conclusion

This paper demonstrated the polarimetric filtering principle to detect a target buried in sandy ground. The polarimetric enhancement factor was used as a discriminator even for targets embedded in a lossy inhomogeneous medium. In a sub-surface sensing, all we have is the information on the surface. The present method uses Co-pol null polarization state in the sensing. By using the Co-pol null polarization state which minimizes the surface, or equivalently maximizes the enhancement factor, it was possible to enhance the targets in a radar image while reducing surface clutter. Although the propagation medium is inhomogeneous, this methodology can be applied to target discrimination, provided the scattering characteristics of two targets are different. This full-polarimetric FM-CW radar will play an important role in advanced and efficient sub-surface sensing. The polarization state which optimizes a specific target may be useful for obtaining target information and identification, which still needs further investigation.

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