PAPER

Classification of Target Buried in the Underground by Radar Polarimetry

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SUMMARY This paper discusses the classification of targets buried in the underground by radar polarimetry. The subsurface radar is used for the detection of objects buried beneath the ground surface, such as gas pipes, cables and cavities, or in archeological exploration operation. In addition to target echo, the subsurface radar receives various other echoes, because the underground is inhomogeneous medium. Therefore, the subsurface radar needs to distinguish these echoes. In order to enhance the discrimination capability, we first applied the polarization anisotropy coefficient to distinguish echoes from isotropic targets (plate, sphere) versus anisotropic targets (wire, pipe). It is straightforward to find the man-made target buried in the underground using the polarization anisotropy coefficient. Second, we tried to classify targets using the polarimetric signature approach, in which the characteristic polarization state provides the orientation angle of an anisotropic target. All of these values contribute to the classification of a target. Field experiments using an ultra-wideband (250 MHz to 1 GHz) FM-CW polarimetric radar system were carried out to show the usefulness of radar polarimetry. In this paper, several detection and classification results are demonstrated. It is shown that these techniques improve the detection capability of buried target considerably.
key words: *radio applications, subsurface radar, FM-CW radar, scattering matrix, polarization anisotropy coefficient, power polarization signature*

1. Introduction

The subsurface radar is used for the detection of objects buried beneath the ground surface, such as gas pipes, cables and cavities or in archeological exploration [1]-[3]. However, the subsurface radar receives various echoes including desired target echo, because the underground is inhomogeneous medium. These echoes sometimes make the detection of desired target difficult. It is our purpose to distinguish the target from these clutters distinctively.

Radar polarimetry may serve this purpose [4], [5] and it has been applied to subsurface radar in which polarimetric filtering is useful for the reduction of surface clutter [6]. If a fully polarimetric measurement is conducted, a 2×2 coherent Sinclair scattering matrix is obtained. The scattering matrix which represents polarimetric scattering characteristics contains useful information for classification and recognition of a target. Several methods have been proposed to classify target, such as the polarization anisotropy coefficient [7] and the power polarization signature and decomposition [8]. Since the man-made target is usually composed of sphere, plate and cylinder which have specific polarimetric characteristics, these techniques may be applicable to classify target for the subsurface radar.

In this paper, we tried to classify underground target by radar polarimetry. We first measure scattering matrices by polarimetric FM-CW radar (Sect. 2), then use the polarization anisotropy coefficient to separate the isotropic versus the anisotropic target. Next, we utilize the power polarimetric signature approach. These principles are described in Sect. 3. The field experiment and classification results are presented in Sect. 4, where these combined techniques improve the detection capability cooperatively.

2. Polarimetric Synthetic Aperture FM-CW Radar

An FM-CW radar measures the distance from an antenna to an object by the beat frequency of the transmitted signal and the signal reflected from the object [4], [5]. The transmitted signal is linearly swept from $f_0 - \frac{\Delta f}{2}$ to $f_0 + \frac{\Delta f}{2}$ where f_0 is the center frequency and Δf is the bandwidth of the transmitted signal. If a target, whose reflection coefficient distribution function is given by $g(x_0, z_0)$, is located at distance r from the transmitted antenna in the Fresnel region as shown in Fig. 1, the beat spectrum at $z = z_0$ can be written as

$$U(x, z_0) = \int_{-\infty}^{\infty} g(x_0, z_0)\, h(x - x_0, z_0)\, dx_0 \qquad (1)$$

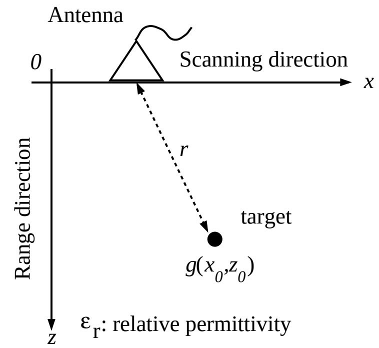

Fig. 1 Position of target in the Fresnel region.

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$$h(x-x_0, z_0) = \exp\left[j \frac{4\pi\sqrt{\varepsilon_r}\, f_0}{c} \left\{ z_0 + \frac{(x-x_0)^2}{2 z_0} \right\} \right] \tag{2}$$

where $h(x-x_0, z_0)$ is a propagation function, and $U(x, z_0)$ is the measured signal and can be interpreted as a Fresnel hologram. Therefore, the reflection distribution function of target can be obtained by an inverse Fresnel transform.

$$g(x_0, z_0) = \int_{-\frac{L}{2}}^{\frac{L}{2}} U(x, z_0)\, h^*(x_0 - x, z_0)\, dx \tag{3}$$

where L is the antenna scan width. We call this method the synthetic aperture processing for the FM-CW radar.

3. Radar Polarimetry [4]

In the polarimetric FM-CW radar, if the polarimetric measurement is conducted in the *AB* polarization basis, the set of polarimetric monostatic complex field cross-section (S_{AA}, $S_{AB} = S_{BA}$, S_{BB}) provides a scattering matrix $[S(AB)]$. It is possible to synthesize the co-pol radar channel power P_{co} and the cross-pol power P_x at any polarization state if the scattering matrix $[S]$ is given. Now, let $\boldsymbol{E}_t$ be the transmitted wave from the radar, and $\boldsymbol{E}_s$ be the scattered wave from the target. In general, the transmitted field $\boldsymbol{E}(AB)$ is defined by the Jones vector

$$\boldsymbol{E}(AB) = \frac{1}{\sqrt{1+\rho\rho^*}} \begin{bmatrix} 1 \\ \rho \end{bmatrix} \tag{4}$$

where ρ is the polarization ratio. The polarization ratio is defined by the ratio of two orthogonal components of $\boldsymbol{E}$ in the *AB* basis as

$$\rho = \frac{E_B}{E_A} = \left| \frac{E_B}{E_A} \right| e^{j(\phi_B - \phi_A)} = |\rho|\, e^{j\phi} = \tan\gamma\, e^{j\phi}. \tag{5}$$

The parameters of γ and $\phi = \phi_B - \phi_A$ are related to the geometric parameters of polarization ellipse as

$$\tan 2\tau = \tan 2\gamma \cos\phi \tag{6}$$

$$\sin 2\varepsilon = \sin 2\gamma \sin\phi \tag{7}$$

where ε and τ are the ellipticity and the tilt angles, respectively.

The scattered wave $\boldsymbol{E}_s$ can be related to the transmitted wave $\boldsymbol{E}_t$ via the scattering matrix $[S]$ by

$$\boldsymbol{E}_s(AB) = [S(AB)]\, \boldsymbol{E}_t(AB) \tag{8}$$

$$[S(AB)] = \begin{bmatrix} S_{AA} & S_{AB} \\ S_{BA} & S_{BB} \end{bmatrix}, \quad S_{AB} = S_{BA} \tag{9}$$

(for monostatic case)

where $[S(AB)]$ represents the target's polarimetric scattering characteristics in the *AB* basis. In FM-CW radar case, if the polarimetric measurement is carried out in the *AB* polarization basis, we regard each polarimetric target reflection coefficient g as the scattering matrix elements as [5]

$$\begin{bmatrix} S_{AA} & S_{AB} \\ S_{BA} & S_{BB} \end{bmatrix} = \begin{bmatrix} g_{AA} & g_{AB} \\ g_{BA} & g_{BB} \end{bmatrix}. \tag{10}$$

The scattering characteristics contain useful information for classification and recognition of targets. In order to classify the target buried in the underground, we use two techniques, i.e., the power polarization anisotropy coefficient and the polarimetric signature.

3.1 Power Polarization Anisotropy Coefficient

The scattering matrix has two invariants regardless of the polarization basis which can be related to its eigenvalue λ_1 and λ_2. The first invariant is the span, i.e., the sum of the square of scattering matrix elements

$$Span[S(AB)] = |S_{AA}|^2 + 2|S_{AB}|^2 + |S_{BB}|^2 = |\lambda_1|^2 + |\lambda_2|^2. \tag{11}$$

The second invariant is the determinant of scattering matrix

$$\left| Det[S(AB)] \right| = \left| S_{AA} S_{BB} - S_{AB}^2 \right| = |\lambda_1 \lambda_2|. \tag{12}$$

The power polarization anisotropy coefficient μ is defined in terms of these two invariants as follows [7],

$$\mu = \sqrt{1 - 4\left| \frac{Det[S]}{Sapn[S]} \right|^2} = \frac{|\lambda_1|^2 - |\lambda_2|^2}{|\lambda_1|^2 + |\lambda_2|^2}, \quad |\lambda_1| \geq |\lambda_2|,\ 0 \leq \mu \leq 1 \tag{13}$$

If the power polarization anisotropy coefficient μ is equal to 0, the target is isotropic target (such as sphere or plate). On the other hand, if this coefficient is close to 1, the target is anisotropic target (such as a straight wire or a helical target) or any other polarimetrically sensitive target.

Since Eqs.(11)-(13) are independent of polarimetric basis, this method reduces the polarimetric constraints for subsurface radar antenna design. It is difficult to realize a pure circular polarization radar antenna over wide band frequencies if we try to use the circular polarization basis. However, it is easier to realize a linear polarization antenna system in the same frequency band. The important factor for antenna characteristics is the polarization orthogonality. The requirement for the antenna polarization is not necessarily pure linear, nor pure circular, which makes the radar system design easier. The method provides directly the polarization anisotropy coefficient μ from scattering matrix not only in the linear polarization basis but also in other polarization basis. We can construct radar system by various antennas which have orthogonal polarization property. In that sense, this method provides a robust technique for polarimetric system.

3.2 Polarimetric Signature

Provided the scattering matrix $\left[\ S\ \right]$ has been recovered from measurement, then, it is possible to synthesize the radar channel power at any polarization state on the Poincaré polarization sphere. For the co-pol channel case (the polarization state of receiver is identical with that of the transmitter), the received power is obtained from

$$P_{co} = \left| \boldsymbol{E}_t^T\,(HV) \left[\ S\ \right] \boldsymbol{E}_t\,(HV) \right|^2 . \tag{14}$$

The superscript T denotes transpose. The variation of the received power with respect to the polarization state illustrates the polarimetric scattering behavior of a target. Moreover, the maximum power of (14) is obtained by the co-pol max polarization state as

$$\rho_{cm} = \frac{-A \pm \sqrt{B^2 - 4AC}}{2A} \tag{15}$$

where

$$A = S_{HH}^* S_{HV} + S_{HV}^* S_{VV}, \quad B = \left| S_{HH} \right|^2 - \left| S_{VV} \right|^2 ,$$
$$C = -A^* .$$

It is possible to derive orientation and tilt angles of maximum polarization state which is related to the target.

4. Experimental Result

In order to confirm how these two techniques contribute the classification of buried targets, we carried out an experiment on target detection and classification in the underground at the Niigata University Campus. The experimental procedure is summarized in Table 1. The antenna was a single ridged horn operative from 250 MHz to 1.0 GHz. 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 polarization orthogonal to H. The polarimetric synthetic aperture FM-CW radar provides the images according to (3) consisting of 64×150 pixels.

4.1 Experiment 1

The measurement situation is shown in Fig. 2. The target was a metallic plate, 25 cm wide and 25 cm long, which was buried at the depth of 50 cm in a sandy medium. Three fixed polarization radar images (HH, HV, VV) after applying the synthetic aperture processing are shown in Fig. 3(a)-(c). At the depth of 50 cm, the target echo appears in the co-pol

Table 1 Measurement specifications.

Radar system	FM-CW
Antenna	Single ridged horn
Sweep time	5.1 msec
Sweep interval	2.0 cm
Scanning point	64
Target	Metallic plate (W: 25 cm× L: 25 cm)
	Metallic pipe (ϕ : 10 cm× L: 85 cm)

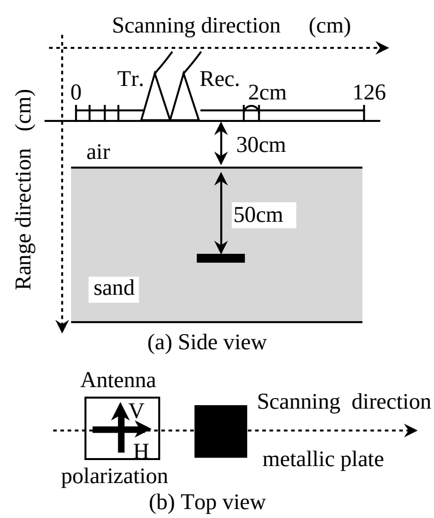

Fig. 2 Measurement situation.

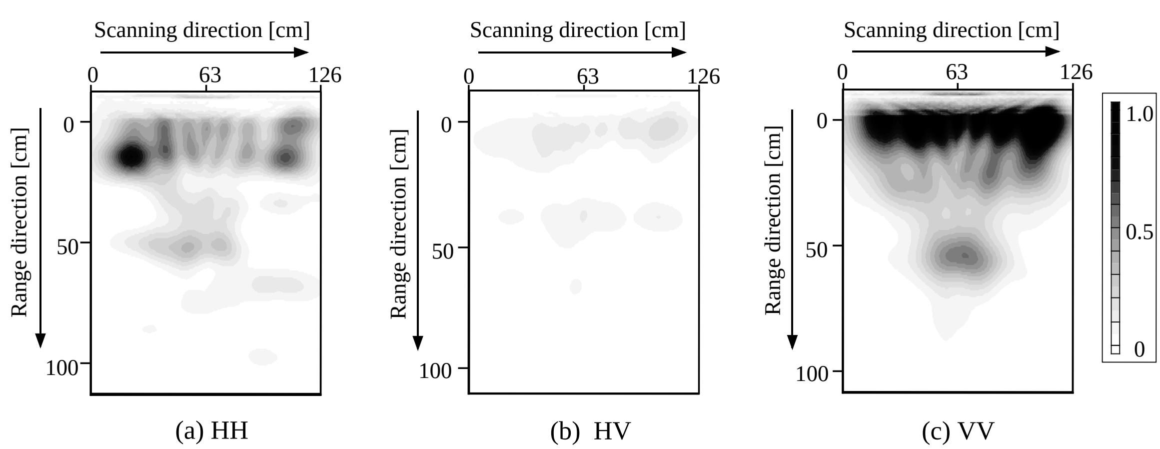

Fig. 3 Fixed polarization images.

channel (*HH* and *VV*) images, whereas the x-pol channel image (*HV*) does not show the target echo, because we were dealing with a plate target.

Figure 4 shows the power polarization anisotropy coefficient μ image of the measured scattering matrices. This image varies from the blue to the red according to the value of the power polarization anisotropy coefficient μ ($0 \le \mu \le 1$). At the depth of 50 cm, there is blue area (isotropic). In order to examine the polarimetric characteristics of this area, we derived the histogram of the power polarization anisotropy coefficient μ in the neighborhood of the target (5×11 pixels). It is found in Fig. 5 that the average power polarization anisotropy coefficient μ of target area is 0.21. This value indicates that the target is a polarimetric insensitive target. Therefore, in this case, we recognize that this target consists mainly of plate component.

The polarimetric power signature of the associated target of $[S_1]$ is displayed in Fig. 6. The received power becomes large at linear polarization state. On the other hand, the circular polarization state reduces the received power compared to linear polarization. The shape is similar to that of a plate in linearly polarized *HV* basis [9]. Therefore, the result indicates that the polarimetric nature of target is close to a flat target.

Thus, it is possible to recognize that the target is a plate target from inspection of these two methods.

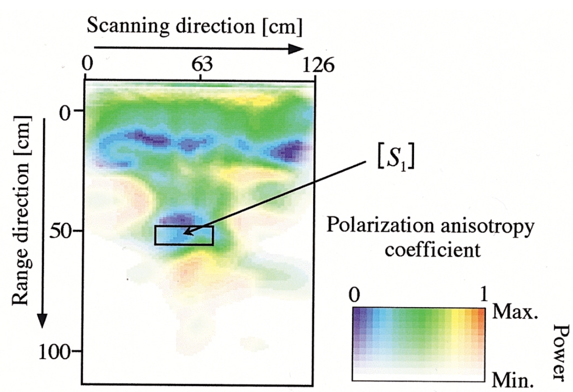

Fig. 4 Power polarization anisotropy coefficient. (The box in the image indicates the target area.)

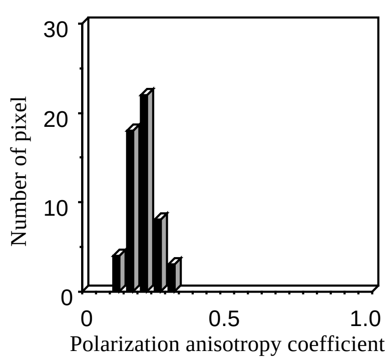

Fig. 5 Distribution of power polarization anisotropy coefficient.

4.2 Experiment 2

The measurement situation is shown in Fig. 7. The target was a metallic pipe of 10 cm in diameter and 100 cm long which was buried at the depth of 80 cm in the ground. This pipe was oriented 135 degrees with respect to the scanning direction. Figure 8 shows three fixed polarization radar images, *HH*, *HV* and *VV*. The desired target echo appears at a depth of 80 cm deep in Fig. 8(a)-(c). However, other echoes (clutter) exist in the co-pol images (*HH* and *VV*).

The power polarization anisotropy coefficient μ and the polarimetric power signature of $[S_2]$ show that this target is close to a straight wire (see Fig. 9 and Fig. 11). The average power polarization anisotropy coefficient μ is 0.88 in the neighborhood of the target (5×5 pixels) in Fig. 10(a). Figure 10(b) shows the histogram of the power polarization anisotropy coefficient μ in clutter area (5×9 pixels). The polarization anisotropy coefficient μ of clutter is more uniformly distributed than that of target. This parameter can be used to discriminate the target and clutter. The shape of

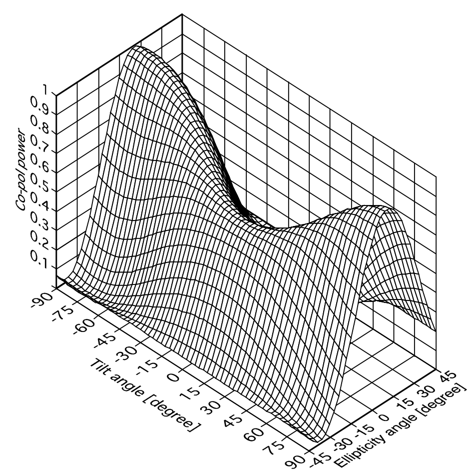

Fig. 6 Polarimetric signature.

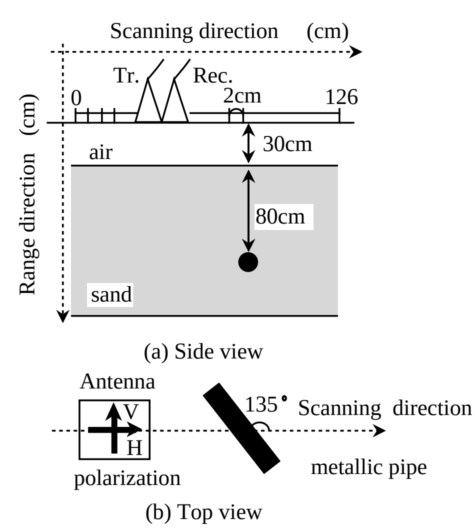

Fig. 7 Measurement situation.

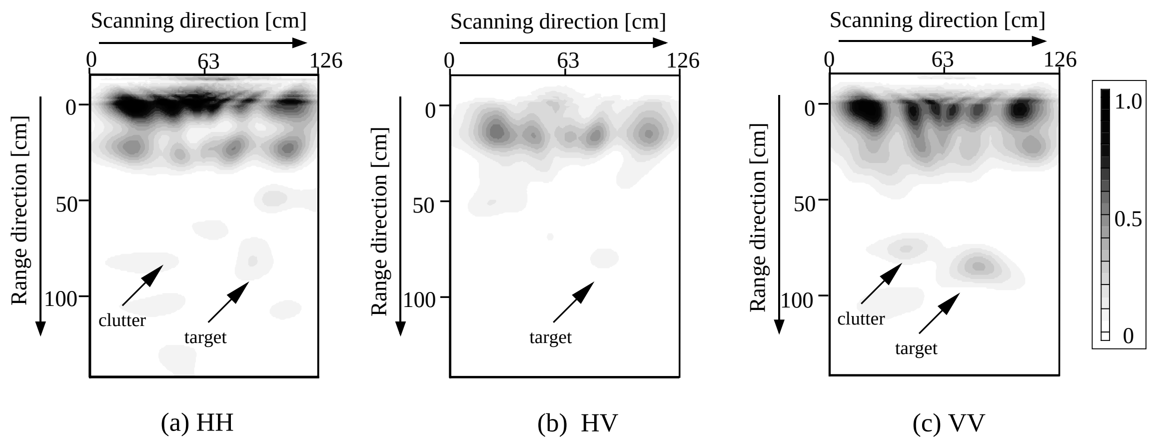

Fig. 8 Fixed polarization images.

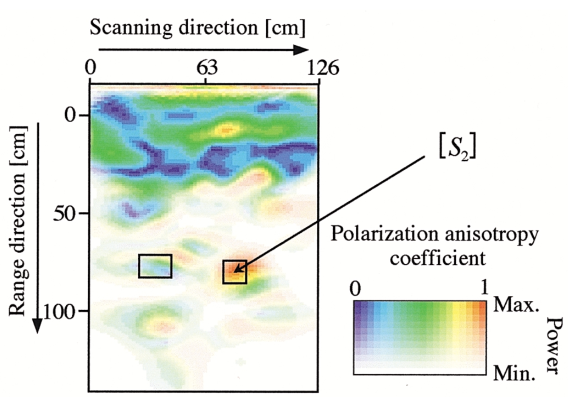

Fig. 9 Power polarization anisotropy coefficient. (The box in the image indicates the target area.)

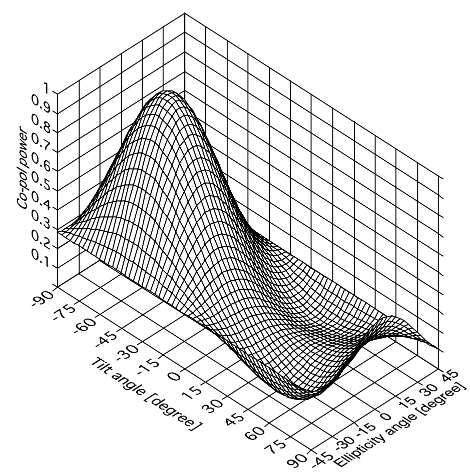

Fig. 11 Polarimetric signature.

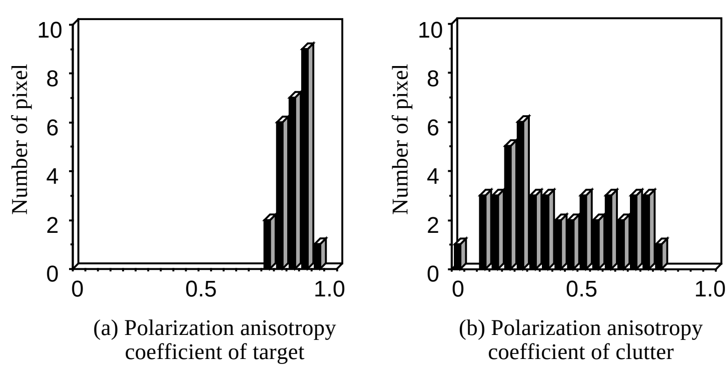

Fig. 10 Distribution of power polarization anisotropy coefficient.

polarization signature in Fig. 11 is similar to that of a wire in [9]. Therefore, this target is classified to be an anisotropic target (straight wire) by two methods. The polarization anisotropy coefficient is useful to find the polarimetric sensitive target in the measured result. The polarization ratio of the co-pol maximum is found to be

$$\rho_{cm} = 1.158 - j\,0.236$$

which corresponds to the characteristic polarization states of $\tau = -49.9°, \varepsilon = -5.7°$ for this target. We note that the tilt angle of the co-pol maximum polarization state is close to the actual target orientation. This may be caused by the fact that the sandy ground was rather homogenous.

In this way, these two methods work cooperatively for the classification of buried targets.

5. Conclusion

We examined the classification of a target buried in the underground by the broadband FM-CW radar polarimetry. In order to obtain the information for classification, we used the two techniques; (i) the power polarization anisotropy coefficient, and (ii) the polarimetric signature. The power polarization anisotropy coefficient μ changed significantly with target type (isotropic versus anisotropic). Although this approach is a robust one, it is straightforward to find the buried man-made target (both polarimetric sensitive and insensitive target). Moreover, the polarimetric signature presents the information of target in detail. The tilt angle of the co-pol maximum polarization state corresponded to the actual orientation angle of the buried straight wire target in the measurement. These two methods worked cooperatively for the classification of buried targets. Therefore, radar polarimetry improves the detection capability of buried targets considerably.

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