Advanced Polarimetric Subsurface FM-CW Radar

Toshifumi Moriyama, Hajime Kasahara,
Yoshio Yamaguchi, *Senior Member, IEEE*, and Hiroyoshi Yamada, *Member, IEEE*

***Abstract*—The subsurface radar suffers from two typical problems, i.e., strong clutter from surface and severe wave attenuation in the underground. This paper presents a unique countermeasure to these problems using a polarimetric FM-CW radar and an equivalent sensitivity time control (STC) technique. We apply the polarimetric filtering principle to suppress surface clutter either in the Co-pol channel or in the X-pol channel of synthetic aperture radar, yielding to polarimetric enhanced target image. This technique works when the surface clutter and target have different polarization properties. Moreover, we use an equivalent STC technique specially suited for FM-CW radar for a deep object sounding to compensate wave attenuation within the ground. These techniques contribute to a significant improvement of the radar performance and the detection image contrast, although the detection of the target is in general a much more complicated topic. The field experiments were carried out to show the usefulness of the method. Some detection results are presented.**

I. Introduction

SUBSURFACE radar has been attracting attention in diverse areas, such as archaeological exploration, detection of gas pipes, cables, and cavities [1]–[9]. There exist many kinds of radar systems, including impulse, chirp-pulse, coded-pulse, FM-CW, and stepped-frequency CW operation systems. Although the majority of commercial and experimental subsurface radars are impulse-based system [1], [2], [4], [5], the FM-CW radar has some advantages in obtaining a high-resolution image just by changing the transmitter frequency bandwidth with low transmission power using simple hardware [9].

In subsurface sensing, all radars suffer from two typical problems, i.e., strong clutter from surface and severe wave attenuation in the underground. The strong surface clutter sometimes masks the echo of the shallow target, even if the target is detectable to the radar. This is also relevant to power leakage from a transmitting antenna to a receiving antenna when two antennas are used near the surface. For reduction of this undesired signal, the cross-polarization antenna arrangement [2] or time-gated signal sampling [1] have been proposed in the pulse radar system. However, this time-gating approach is not applicable to CW radar systems, except for a gated stepped-frequency radar [10].

Manuscript received December 31, 1996; revised July 15, 1997. This work was supported in part by a Grant-in-Aid for Scientific Research from the Ministry of Education.

T. Moriyama, Y. Yamaguchi, and H. Yamada are with the Department of Information Engineering, Faculty of Engineering, Niigata University, Niigata-shi, 950-2181 Japan (e-mail: yamaguch@info.eng.niigata-u.ac.jp).

H. Kasahara is with NTT DoCoMo Company, Yokosuka, 239 Japan (e-mail: kasahara@yst2.nttdocomo.co.jp).

Publisher Item Identifier S 0196-2892(98)01127-9.

The wave attenuation in the underground is dependent on the conductivity of the medium and the frequency and is independent of radar types. For compensation of attenuation, the pulse radar can use the sensitivity time control (STC) system. On the other hand, there has been no solution to this problem for the CW radar systems, except for a hardware frequency-dependent amplification of the IF signal [11].

In this paper, we present a countermeasure to these problems for the FM-CW radar subsurface sensing. The principal purpose is to provide a method to suppress surface clutter [12] to detect deep objects. The first strategy for the surface clutter rejection is a polarimetric filtering approach, i.e., to use a null polarization state for the surface to null out the echo. By choosing the null polarization state of a typical surface scattering matrix, it is possible to synthesize or reconstruct a polarimetric power image in which the surface clutter is eliminated. The second strategy is to use an equivalent STC technique for a deep object to overcome the attenuation and to improve the resultant radar image contrast. This equivalent STC technique is based on the property of Fourier transform in the beat signal of FM-CW radar [13] and can be realized by simple software or hardware implementation. We propose the combined use of these two techniques for subsurface sensing applications. These principles are described in Sections II and III. Field experiments were carried out on the Niigata University campus. The detection result is presented in Section IV, indicating that the null polarization state imaging and the equivalent STC technique highly enhance the radar sounding capability.

II. FM-CW Radar

A. Equivalent STC Technique

The FM-CW radar measures a distance from an antenna to an object by the beat signal of the transmitted signal and reflected signal from the object. The transmitted signal is linearly swept from $f_0 - \Delta f/2$ to $f_0 + \Delta f/2$, where f_0 is the center frequency. Fig. 1 shows the relation of frequency and time in the FM-CW radar. If the object is located at distance r_b from the antenna in a medium of permittivity ε_r, the beat signal can be usually expressed as a function of time as follows:

$$s_b(t) = gA(r_b)\,\mathrm{Re}[\exp\{j2\pi(f_b t + \theta)\}] \qquad (1)$$

where

g reflection coefficient;
$A(r_b)$ amplitude factor;
$f_b = M\tau = \frac{\Delta f}{\Delta t}\frac{2\sqrt{\varepsilon_r}}{c}r_b$ beat frequency;

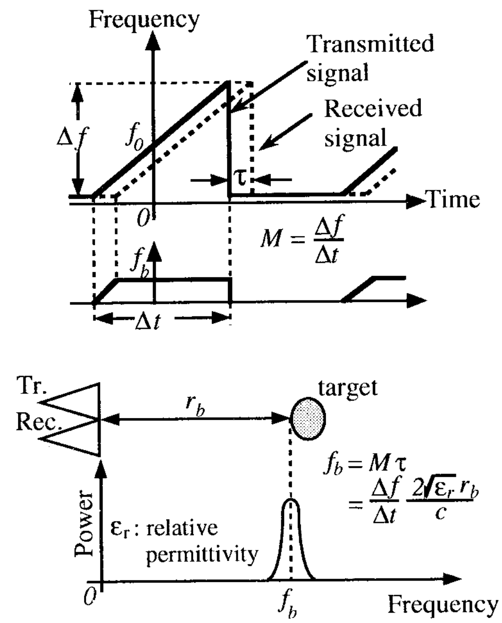

Fig. 1. Principle of FM-CW radar.

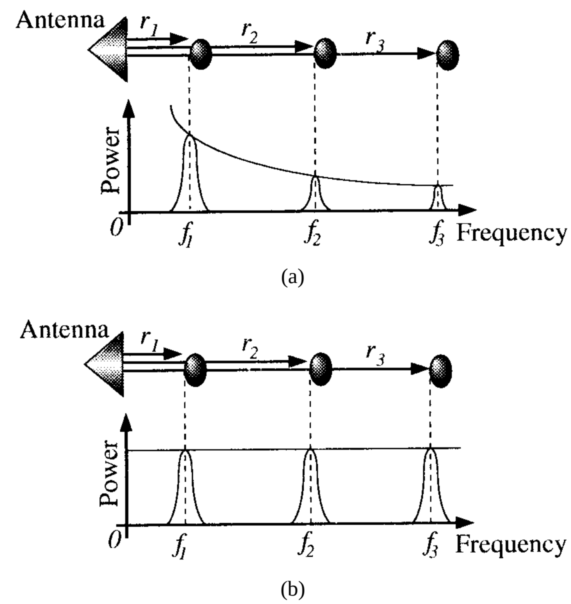

Fig. 2. Compensation of attenuation: (a) before compensation and (b) after compensation.

$M = \frac{\Delta f}{\Delta t}$	modulation rate;
Δf	sweep frequency width;
Δt	sweep time;
θ	phase.

Re[·] means the real part of the argument. f_b is the beat frequency proportional to the distance r_b. g is a reflection coefficient, which for the subsurface radar case, includes the effect of inhomogeneity within the medium. $A(r)$ is an amplitude factor due to the path length. In the free-space case, the attenuation factor is proportional to r_b^{-2}. This amplitude factor decreases rapidly with increasing r_b, as shown Fig. 2(a). In order to enhance the deep sounding capability, it is necessary to compensate the amplitude factor.

Since the beat frequency f_b in the FM-CW radar system can be obtained by the Fourier transform to (1), we may go back to (1) and use the property of Fourier transform as follows:

$$\text{FT}[s_b(t)] = \frac{1}{2} g A(r_b) \delta(f - f_b) \exp(j2\pi\theta), \quad f \geq 0 \quad (2)$$

$$\text{FT}\left[\frac{d^n}{dt^n} s_b(t)\right] = \frac{1}{2}(j2\pi f_b)^n g A(r_b) \delta(f - f_b) \exp(j2\pi\theta), \quad f \geq 0 \quad (3)$$

where FT denotes Fourier transform. It should be noted in (3) that the attenuation term $A(r_b)$ is multiplied with $(j2\pi f_b)^n$. This means the factor is amplified with f_b, which is proportional to the target distance. This multiplication would compensate the attenuation due to path length, as shown Fig. 2(b). We use the term $(j2\pi f_b)^n g A(r_b)$ as a whole, instead of $gA(r_b)$ in the signal analysis. This technique is similar to the STC concept used in pulse radar systems. The degree of the compensation rate is dependent on the number of differentiation, with respect to time for the beat signal (1).

In the subsurface case, the attenuation factor is multiplied with the additional term $e^{-\alpha r_b}$, due to lossy medium, where α is a function of the conductivity, permittivity, and frequency. This term $e^{-\alpha r_b}$ cannot be removed by the compensation method. Therefore, this technique contributes only to compensation of the attenuation, with respect to r_b^{-n}. On the other hand, there arises phase error due to inhomogeneity in the underground. This inhomogeneity factor is included in g in our radar system. We regard g as a total target reflection coefficient, which includes inhomogeneity in the medium, since the radar cannot measure the inhomogeneity from the surface.

This differentiation can be realized easily either by simple hardware or software. If a differential circuit in the audio frequency region is added for the hardware implementation (see Fig. 3), the strong and close (lower frequency in beat spectrum) surface clutter, relative to far (high frequency) target echo, can be suppressed in real time. This method is similar to [11]. Therefore, this circuit widens the dynamic range for the deep target signal. In the software implementation case, the differentiation can be performed by finite difference (center, forward, and backward difference) of the A/D-converted beat signal imitating the hardware scheme, or simply the multiplication of $(j2\pi f_b)^n$ to the right hand of (2) to yield (3) in the frequency domain.

In addition to this simple compensation method, this technique conserves the relative phase information of (2) because of the multiplication factor $(j2\pi f_b)^n$. Therefore, the attenuation compensated beat signal can be applied to radar polarimetry and synthetic aperture processing, where the phase information plays a decisive role.

B. Synthetic Aperture Processing

If a target whose reflection-coefficient distribution function, given by $g(x_0, z_0)$, is located at distance r from the transmitting antenna in the Fresnel region, as shown Fig. 4, the beat

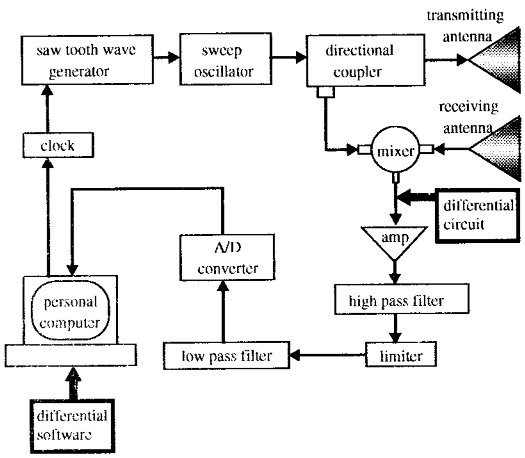

Fig. 3. Block diagram of FM-CW radar.

spectrum at $z = z_0$ can be written as [9], [14]

$$U(x, z_0) = \int_{-\infty}^{\infty} g(x_0, z_0) h(x - x_0, z_0)\, dx_0 \tag{4}$$

$$h(x - x_0, z_0) = \exp\left[j \frac{4\pi\sqrt{\varepsilon_r} f_0}{c} \left\{ z_0 + \frac{(x - x_0)^2}{2z_0} \right\} \right] \tag{5}$$

where h is a propagation function and $U(x, z_0)$ is the measured signal and can be interpreted as a Fresnel hologram. Therefore, the reflection function of target can be obtained by an inverse Fresnel transform for the case of (2)

$$g(x_0, z_0) = \int_{-L/2}^{L/2} U(x, z_0) h^*(x_0 - x, z_0)\, dx \tag{6}$$

where L is the antenna scan width. The symbol $*$ denotes complex conjugation. The equivalent STC technique multiplies (2) by the factor $(j2\pi f_b)^n$ and yields

$$g(x_0, z_0) = (j2\pi f_b)^n \int_{-L/2}^{L/2} U(x, z_0) h^*(x_0 - x, z_0)\, dx. \tag{7}$$

Therefore, this technique conserves the phase information and can be used for the synthetic aperture processing.

III. Polarimetric Suppression of Clutter

If a polarimetric measurement is conducted in the HV polarization basis, the FM-CW radar provides a scattering matrix. It is possible to synthesize a radar channel power at any polarization state from a scattering matrix [14]. Now, let $\mathbf{E}_t$ be the transmitted wave from the radar and $\mathbf{E}_s$ be the scattered wave from the target. The $\mathbf{E}_t$ is defined by the Jones vector form

$$\mathbf{E}_t = \frac{1}{\sqrt{1 + \rho\rho^*}} \begin{bmatrix} 1 \\ \rho \end{bmatrix} \tag{8}$$

where ρ is the polarization ratio. The scattered wave can be related to the transmitted wave via the scattering matrix $[S]$

$$\mathbf{E}_s(HV) = [S(HV)]\mathbf{E}_t(HV) \tag{9}$$

$$[S(HV)] = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \approx \begin{bmatrix} g_{HH} & g_{HV} \\ g_{VH} & g_{VV} \end{bmatrix} \tag{10}$$

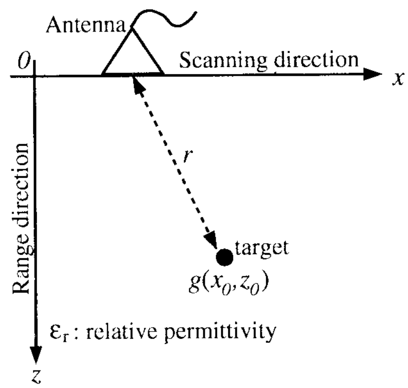

Fig. 4. Position of target in the Fresnel region.

where $[S(HV)]$ represents the target's polarimetric scattering characteristics in the HV basis. The Co-pol and the X-pol power are obtained from

$$P_c = \left| \mathbf{E}_t^T(HV)[S(HV)]\mathbf{E}_t(HV) \right|^2 \tag{11}$$

$$P_x = \left| \mathbf{E}_{\perp,t}^T(HV)[S(HV)]\mathbf{E}_t(HV) \right|^2 \tag{12}$$

where the subscript $\perp$ denotes the orthogonal and the superscript T denotes the transpose. We define a contrast enhancement factor by the power ratio as

Co-pol channel

$$C_c = \frac{P_{c,1}(\text{Power of target 1})}{P_{c,2}(\text{Power of target 2})} = \frac{\left| \mathbf{E}_t^T(HV)[S_1(HV)]\mathbf{E}_t(HV) \right|^2}{\left| \mathbf{E}_t^T(HV)[S_2(HV)]\mathbf{E}_t(HV) \right|^2} \tag{13}$$

X-pol channel

$$C_x = \frac{P_{x,1}}{P_{x,2}} = \frac{\left| \mathbf{E}_{\perp,t}^T(HV)[S_1(HV)]\mathbf{E}_t(HV) \right|^2}{\left| \mathbf{E}_{\perp,t}^T(HV)[S_2(HV)]\mathbf{E}_t(HV) \right|^2}. \tag{14}$$

The subscript 1 corresponds to the desired target to be enhanced, and the subscript 2 corresponds to the undesired target to be eliminated. The problem becomes to find a polarization state that maximizes the contrast factor of the desired target. The answer is to choose the null polarization of the undesired target. This is analytically derived from

$$C_c \Rightarrow \infty, \quad P_{c,2} = \left| \mathbf{E}_t^T(HV)[S_2(HV)]\mathbf{E}_t(HV) \right|^2 = 0 \tag{15}$$

$$C_x \Rightarrow \infty, \quad P_{x,2} = \left| \mathbf{E}_{\perp,t}^T(HV)[S_2(HV)]\mathbf{E}_t(HV) \right|^2 = 0. \tag{16}$$

If the radar system is assumed monostatic $(S_{HV} = S_{VH})$, the null polarization states are given by, for the Co-pol channel,

$$\rho_{cn\,1,2} = \frac{-S_{2,HV} \pm \sqrt{S_{2,HV}^2 - S_{2,HH}S_{2,VV}}}{S_{2,VV}} \tag{17}$$

TABLE I
MEASUREMENT SPECIFICATIONS

Radar system	:FM-CW
RF power	:18dBm
Antenna	:single ridge horn
Sweep frequency	:250MHz~1.0GHz
Sweep time	:5.1mesc
Scanning interval	:2.0cm
Scanning point	:64
Target	:metallic plate (W:20cm×L:85cm)

and for the X-pol channel

$$\rho_{xn\,1,2} = \frac{-B_2 \pm \sqrt{B_2^2 - 4A_2C_2}}{2A_2} \tag{18}$$

$$A_2 = S_{2,HH}^* S_{2,HV} + S_{2,HV}^* S_{2,VV}$$
$$B_2 = |S_{2,HH}|^2 - |S_{2,VV}|^2$$
$$C_2 = -A_2^*.$$

Since the null polarization states are obtained, it is possible to determine the corresponding Jones vector (8). The channel power in all pixels of SAR imagery can be recalculated according to (11) and (12). This polarimetric imaging suppresses surface echo, while it enhances the desired target. Although the power for the desired target may be somewhat reduced by this polarimetric filtering, the contrast enhancement becomes large.

The polarimetric filtering works for targets whose polarization properties are different from each other. If the scattering matrix $[S_1]$ is similar to $[S_2]$, the contrast enhancement factor is close to unity. This does not enhance the target. However, in the subsurface radar case, we take target 1 as the desired target and target 2 as undesired target. Target 2 is, for example, surface clutter, which generally has different polarimetric properties from the target. In addition, we know from the outset the location of the surface from the radar. This information is important in the subsurface sensing because we do not know where the desired target is located within the underground. Therefore, just by choosing a null polarization state of surface for polarimetric imaging, the radar would enhance the desired target versus the surface.

IV. EXPERIMENTAL RESULT

In order to confirm the method of combined use of the polarimetric suppression and the equivalent time sensitivity technique, we carried out an experiment for target detection in the underground at Niigata University. The experimental condition is shown in Table I. The dynamic range of our system is approximately 40 dB. The maximum RF power was 18 dBm, which did not cause saturation of the receiver. The antenna was a single-ridge horn antenna that was swept from 250 MHz to 1.0 GHz. The target was a metallic plate of 20-cm wide and 85-cm long, which was buried at the depth of 125 cm in a sandy ground. 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. The measurement situation is shown in Fig. 5. The target was oriented 135°, with respect to the scanning direction. We obtained three fixed $(HH, HV,$ and $VV)$ polarization radar images in Fig. 6 after the synthetic aperture processing. The target echo appears at the depth of 125 cm in the Co-pol channel (VV and HH) images. On the other hand, the surface clutter exists in all fixed polarization images. This clutter is larger than other echoes and especially surpasses the target echo in the X-pol channel (HV) image. Therefore, it is difficult to detect the target in the HV image because of surface clutter.

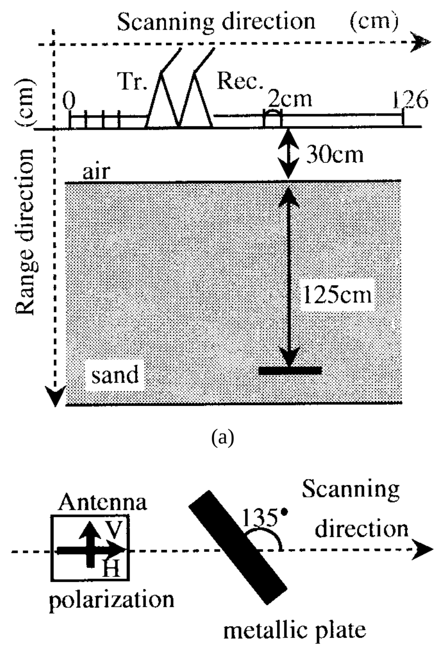

Fig. 5. Measurement situation: (a) side view and (b) top view.

A. Combined Use of Two Techniques

For the suppression of the surface clutter, we choose the null states (17) and (18) of the surface. Fig. 7 shows the Co-pol null and the X-pol null images. It is seen that the surface echo is suppressed. However, the metallic plate echo is weak, and another clutter above the plate becomes strong, especially in the Co-pol channel. Therefore, the X-pol channel is useful to reduce the clutter of underground, except for the surface clutter in this case. However, this advantage depends on polarization property of ground inhomogeneity. The weak target echo is due to severe attenuation of wave in the underground. In order to compensate the attenuation, the equivalent STC technique was applied to Fig. 7. Fig. 8 shows the same polarization image using the equivalent STC technique (the first-order differentiation). We used the backward difference in the computer for the differentiation. It is seen that the metallic pipe echo becomes strong and that surface echo is suppressed. Moreover,

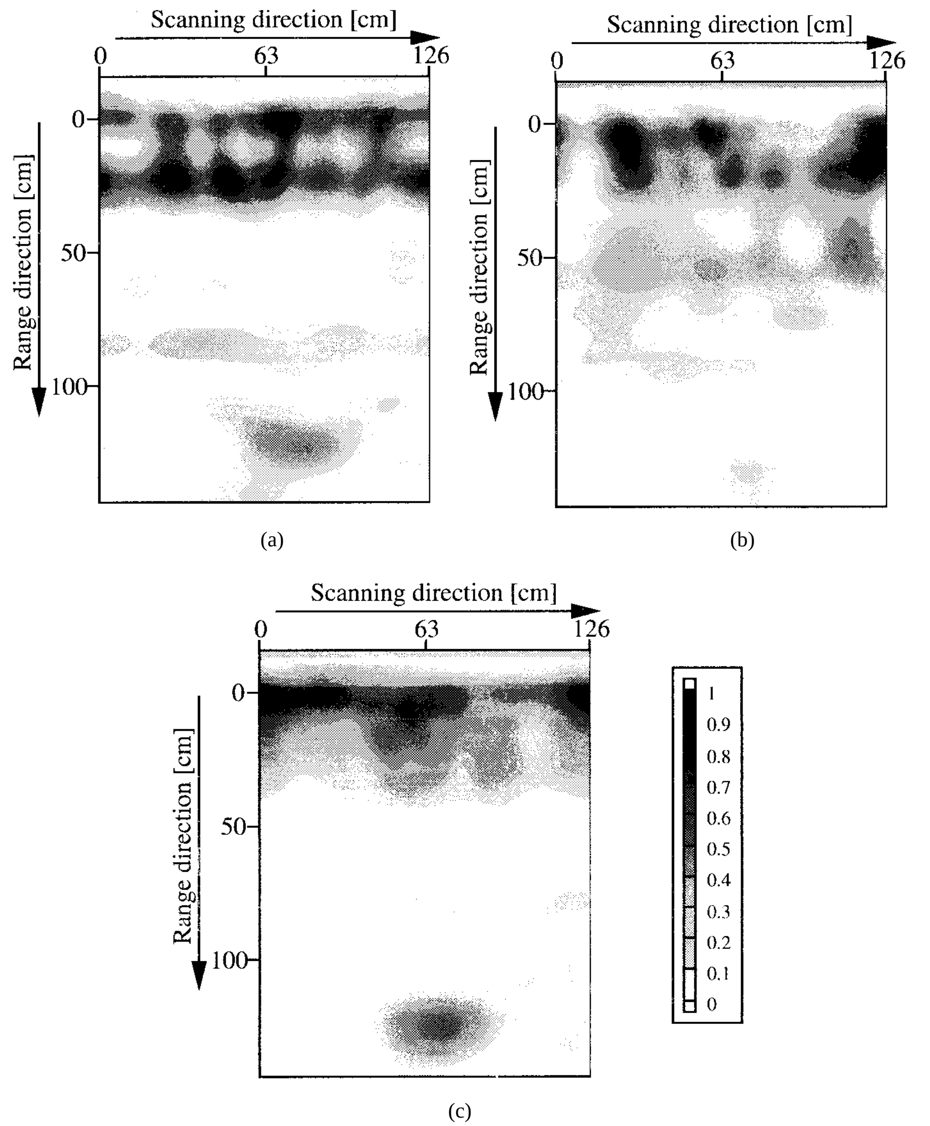

Fig. 6. Detection results after synthetic aperture processing: (a) HH, (b) HV, and (c) VV.

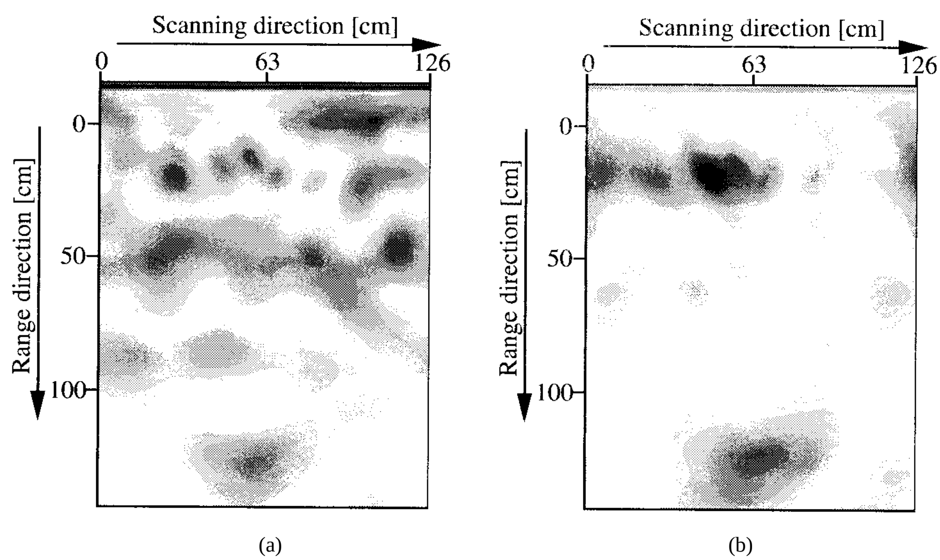

Fig. 7. Null polarization state images of surface: (a) Co-pol case and (b) X-pol case.

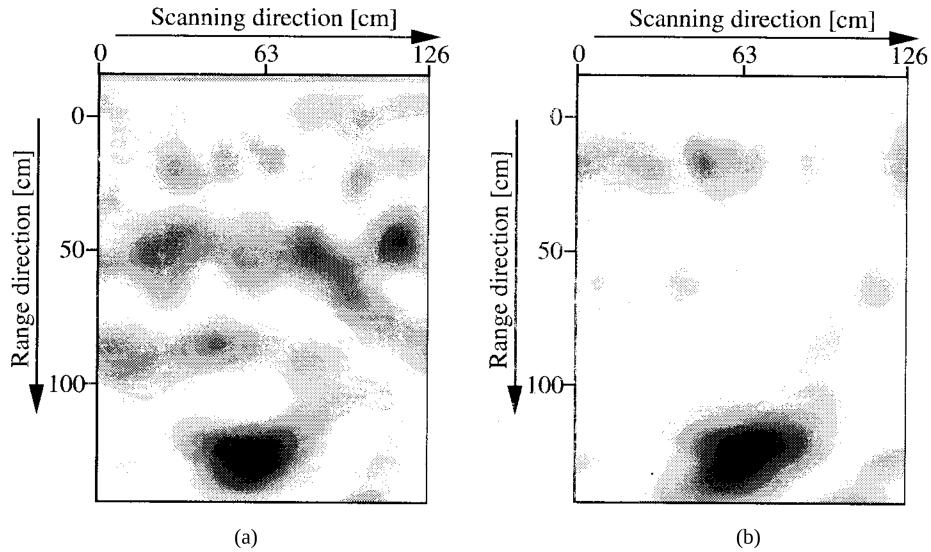

Fig. 8. Null polarization state images of surface using the equivalent STC technique (the first-order differentiation): (a) Co-pol case and (b) X-pol case.

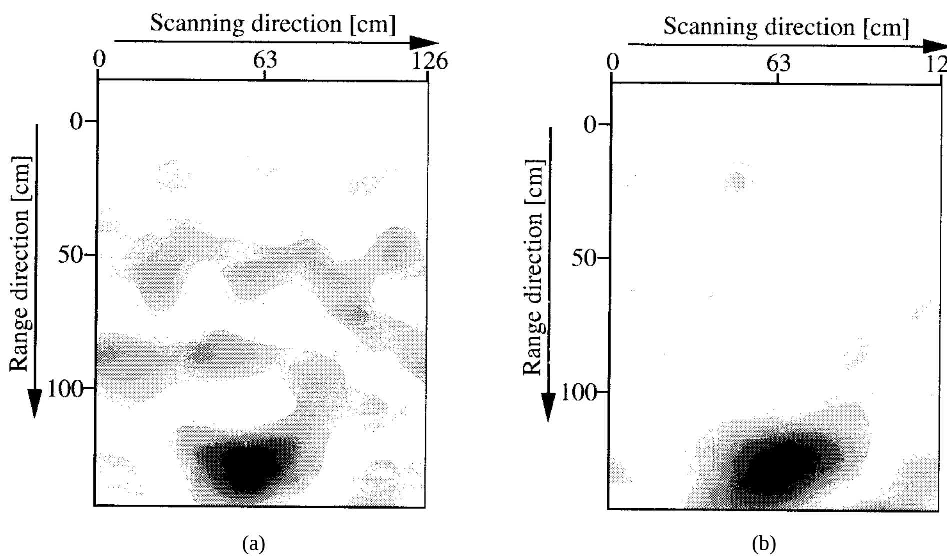

Fig. 9. Null polarization state images of surface using the equivalent STC technique (the second-order differentiation): (a) Co-pol case and (b) X-pol case.

Fig. 9 is the null polarization images using the second-order differentiation. The metallic pipe is clearly detected versus those in Fig. 8. Therefore, the combined use of these two techniques enhances the detection capability.

If the polarization properties of two targets are different, it is always possible to suppress one target. For the subsurface radar case, the suppression of surface clutter enhances the desired target buried in the underground. However, target enhancement becomes difficult when multiple targets exist and in a heavily inhomogeneous medium that may include the same polarization property of desired target. In this experiment, the present technique yielded a satisfactory result, since the polarization property of the desired target was different from the other.

V. Conclusion

We proposed a method of combined use of the polarimetric filtering and the equivalent STC technique for the subsurface FM-CW radar. Radar polarimetry suppresses clutter, and the equivalent STC technique compensates the attenuation of wave, with respect to the distance. The equivalent STC technique conserves the phase information of beat signal, which is necessary information for radar polarimetry. As a consequence, the FM-CW radar can combine the two techniques. In order to confirm the validity of the combined use of these two techniques, we carried out the experiment. It was possible to clearly detect the metallic pipe buried at the depth of 125 cm in the sandy ground. This combined method is effective for detection of deep targets and enhances the FM-CW radar performance.

References

[1] I. Arai and T. Suzuki, "An underground radar system," *Trans. IEICE*, vol. J66-B, pp. 289–294, June 1983.

[2] L. Peters, Jr., J. J. Daniels, and J. D. Young, "Ground penetrating radar as a subsurface environmental sensing tool," *Proc. IEEE*, vol. 82, pp. 1802–1822, Dec. 1994.

[3] N. Osumi and K. Ueno, "Microwave holographic imaging of underground objects," *IEEE Trans. Antennas Propagat.*, vol. AP-33, pp. 152–159, Feb. 1985.
[4] Y. Michiguchi, K. Hiramoto, M. Nishi, T. Ootaka, and M. Okada, "Advanced subsurface radar system for imaging buried pipes," *IEEE Trans. Geosci. Remote Sensing*, vol. 26, pp. 733–740, Nov. 1988.
[5] Y. Nishimura, "Introductions: The Tagajo site, the development of GPR surveying in Japanese archaeology," in *Proc. 6th Int. Conf. Ground Penetrating Radar*, Sendai, Japan, Sept. 1996, pp. 15–17.
[6] K. Iizuka and A. P. Freundorfer, "Detection of nonmetallic buried objects by a step frequency radar," *Proc. IEEE*, vol. 71, pp. 276–279, Feb. 1983.
[7] T. Suzuki, I. Arai, and D. Xiao, "Subsurface radar using coded pulse," IEICE Tech. Rep. SANE87-1, Jan. 1987.
[8] D. A. Noon, I. D. Longstaff, and R. J. Yelf, "Advances in the development of step frequency ground penetrating radar," in *Proc. 5th Int. Conf. Ground Penetrating Radar*, Ont., Canada, June 1994, pp. 117–132.
[9] Y. Yamaguchi and M. Sengoku, "Detection of objects buried in sandy ground by a synthetic aperture FM-CW radar," *IEICE Trans. Commun.*, vol. E76-B, pp. 1297–1304, Oct. 1993.
[10] G. F. Stickley, D. A. Noon, M. Cherniakov, and I. D. Longstaff, "Current development status of a gated stepped-frequency GPR," in *Proc. 6th Int. Conf. Ground Penetrating Radar*, Sendai, Japan, Sept. 1996, pp. 311–315.
[11] L. P. Lighthart and L. R. Nieuwkerk, "F.M.-C.W. delft atmospheric research radar," *Inst. Elect. Eng. Proc. F, Commun.*, vol. 127, pp. 421–426, Dec. 1980.
[12] T. Moriyama, Y. Yamaguchi, H. Yamada, and M. Sengoku, "Reduction of surface clutter by a polarimetric FM-CW radar in underground target detection," *IEICE Trans. Commun.*, vol. E78-B, pp. 625–629, Apr. 1995.
[13] H. Kasahara, T. Moriyama, Y. Yamaguchi, and H. Yamada, "On an equivalent sensitivity time control circuit for FM-CW radar," *Trans. IEICE*, vol. J79-B-II, pp. 583–588, Sept. 1996.
[14] Y. Yamaguchi, T. Nishikawa, M. Sengoku, and W.-M. Boerner, "Fundamental study on synthetic aperture FM-CW radar polarimetry," *IEICE Trans. Commun.*, vol. E77-B, pp. 73–80, Jan. 1994.

Toshifumi Moriyama was born in Fukui Prefecture, Japan, on January 1, 1972. He received the B.E. and M.E. degrees in information engineering from Niigata University, Niigata-shi, Japan, in 1994 and 1995, respectively. He is now pursuing the Ph.D. degree from Niigata University, where he is researching radar polarimetry and polarimetric radar sensing of buried objects.

Mr. Moriyama is a Research Fellow of the Japan Society for the Promotion of Science and a Student Member of the Institute of Electronic, Information, and Communication Engineers (IEICE) of Japan.

Hajime Kasahara received the B.E. and M.E. degrees in information engineering from Niigata University, Niigata-shi, Japan, in 1995 and 1997, respectively.

He is now with NTT DoCoMo Company, Yokosuka, Japan. His research interests include subsurface radar systems and radar signal processing.

Mr. Kasahara is a member of the Institute of Electronic, Information, and Communication Engineers (IEICE) of Japan.

Yoshio Yamaguchi (M'83–SM'94) was born in Niigata, Japan, on March 12, 1954. He received the B.E. degree in electronics engineering from Niigata University, Niigata-shi, Japan, in 1976 and the M.E. and Dr.Eng. degrees from Tokyo Institute of Technology, Tokyo, Japan, in 1978 and 1983, respectively.

He has been a Professor with the Faculty of Engineering, Niigata University, since 1978. From 1988 to 1989, he was a Research Associate at the University of Illinois, Chicago. His interests are in the field of propagation characteristics of electromagnetic waves in lossy medium, radar polarimetry, microwave remote sensing, and imaging.

Dr. Yamaguchi is a member of Institute of Electronic, Information, and Communication Engineers (IEICE) of Japan and the Japan Society for Snow Engineering.

Hiroyoshi Yamada (M'93) was born in Hokkaido, Japan, on November 2, 1965. He received the B.S., M.S., and Ph.D. degrees from Hokkaido University, Sapporo, Japan, in 1988, 1990, and 1993, respectively, all in electronic engineering.

He has been an Associate Professor with Niigata University, Niigata-shi, Japan, since 1993. His current research involves superresolution techniques, time-frequency analysis, electromagnetic wave measurements, and radar signal processing.

Dr. Yamada is member of the Institute of Electronic, Information, and Communication Engineers (IEICE) of Japan.