ON RADAR POLARIMETRY IN FM-CW RADAR

Yoshio Yamaguchi†, Toru Nishikawa†, Wolfgang -M. Boerner††, Masakazu Sengoku†, and Hyo Joon Eom†††

† : Faculty of Engineering, Niigata University, Ikarashi 2-8050, Niigata-shi, 950-21, JAPAN
†† : Dept. of Electrical Engineering and Computer Science, University of Illinois at Chicago,
Chicago, IL, 60607-7018 USA
††† : Dept. of Electrical Engineering, Korea Advanced Institute of Science and Technology, 373-1 Kusong-Dong,
Yusong-gu, Teajon, 305-701 KOREA

Abstract - This paper attempts to apply the principle of radar polarimetry to wideband synthetic aperture FM-CW radar and presents a basic polarimetric detection result of a linear target in a laboratory measurement. Although the principle of radar polarimetry has well been established for the completely polarized wave and for the monostatic case, it still needs to be extended to wideband radar system. The FM-CW radar utilizes a wideband signal and the resultant beat signal whose frequency is proportional to range is different from the scattered wave in pulse radar. This paper points out that the Fourier transformed complex beat spectrum obtained by an synthetic aperture FM-CW radar acts like an element of the scattering matrix which plays the most important role in polarimetric imaging. The fact was verified by a polarimetric detection in a laboratory, demonstrating the validity of FM-CW radar polarimetry and indicating an establishment of a full polarimetric and synthetic aperture radar system.

1. Introduction

Radar polarimetry, i.e., the full utilization of vector nature of electromagnetic wave information, has become an indispensable tool in advanced radar systems. The principle of radar polarimetry for monochromatic (single frequency) wave has already been established by many investigators [1]-[7]. However, the wideband polarimetry is still in the developmental phase. Since we have been dealing with a wideband FM-CW radar [8], the problem is how to introduce the radar polarimetry into this radar system.

In this paper, we regarded the polarimetric target reflection coefficient obtained by a synthetic aperture FM-CW radar as the element of scattering matrix. Although the coefficient is derived from a wideband signal, it is a single complex value, and we thought it represents target scattering information, provided that the scattering characteristics are almost constant under the bandwidth. The polarimetric measurement provides full scattering matrix elements. If the replacement, i.e., target reflection coefficient = scattering matrix element, is possible, the polarization synthesis (optimal power reception) should work well in detection or imaging problems. Therefore, the main purpose of the paper is to confirm the validity of the replacement. If the validity is confirmed, it leads to an establishment of wideband and full polarimetric synthetic aperture radar system.

In the following, the principle of synthetic aperture FM-CW radar is given in Sec.2, a brief principle of polarimetric imaging by radar polarimetry is outlined in Sec.3. Sec.4 shows experimental verification. A radar system operative in the X-band was applied to the polarimetric detection of a metallic pipe of different orientations. It is shown that the polarimetry can be applied to the FM-CW radar.

2. Synthetic Aperture FM-CW Radar Signal

FM-CW radar basically measures a distance between antenna and an object by the beat frequency of a linearly swept transmitted signal and reflected signal from the object. If a target is located in the Fresnel region and if the target reflection coefficient given by

$$g = g(x_0, z_0), \qquad (1)$$

$$(x_0, z_0) : \text{coordinate of the object}$$

remains the same or at least does not change so much within the swept frequency bandwidth, the frequency domain beat spectrum due to the target is given by

$$U(x,z) = B\int_0^{\infty}\int_{\infty}^{\infty} f(z - z_o)\, g(x_o, z_o)\, h(x - x_o, z_o)\, dx_o\, dz_o \qquad (2)$$

where

$$f(z - z_o) = \frac{\sin[\alpha(z - z_o)]}{[\alpha(z - z_o)]}, \qquad \alpha = \frac{2\pi\Delta f}{c}$$

$$h(x - x_o, z_o) = \exp\left[-j\frac{4\pi f_0}{c}\left\{z_o + \frac{(x - x_o)^2}{2 z_o}\right\}\right] \qquad (3)$$

One can see that this expression is of the convolution integral form at $z = z_o$ and can consider it as one kind of Fresnel hologram. The object distribution function $g(x_0, z_0)$ can be recovered by an inverse convolution integral after multiplying the complex conjugated function h^* by U.

$$g(x_0, z_0) = \int_{-\frac{L}{2}}^{\frac{L}{2}} U(x, z_0)\, h^*(x_0 - x, z_0)\, dx \qquad (4)$$

L in eq(4) is the antenna-scan width in the azimuth direction. This equation is the basis for the synthetic aperture FM-CW radar principle. It should be noted that (4) gives a single complex value although it is derived from a wideband signal.

3. Application of Radar Polarimetry

Let $\mathbf{E}_t$ be the transmitted wave from a radar, and $\mathbf{E}_s$ be the scattered wave from a target arriving at the receiver. The scattered wave can be related to the transmitted wave via scattering matrix [S]

$$\mathbf{E}_s(AB) = \begin{bmatrix} E_s^A \\ E_s^B \end{bmatrix} = \begin{bmatrix} S_{AA} & S_{AB} \\ S_{BA} & S_{BB} \end{bmatrix}\begin{bmatrix} E_t^A \\ E_t^B \end{bmatrix} = [S(AB)]\,\mathbf{E}_t(AB) \qquad (5)$$

where (AB) denotes the polarization basis. The amplitude factor due to path length is omitted in this expression because we are interested in polarimetric information. It is understood in (5) that the target can be regarded as the polarization transformer. The voltage at the receiving antenna is obtained from

$$V = \mathbf{h}^T \mathbf{E}_s = \mathbf{h}(AB)^T [S(AB)]\,\mathbf{E}_t(AB) \qquad (6)$$

where **h** is the polarization state of the receiver when it acts as a transmitter and the subscript T denotes transpose. It should be noted that the voltage does not depend on the polarization basis, i.e., the voltage remains the same no matter how the basis is. This invariance leads to the transformation of scattering matrix under the change of polarization basis as follows: Since the basis transformation matrix [T] using the polarization ratio ρ from the basis (HV) to the new basis (AB) is given by

$$[T] = \frac{1}{\sqrt{1+\rho\rho^*}}\begin{bmatrix} e^{j\phi_1} & \rho^* e^{j\phi_2} \\ \rho e^{j\phi_1} & -e^{j\phi_2} \end{bmatrix}, \tag{7}$$

the vector transformation is carried out as

$$\mathbf{E}(AB) = [T]^{-1}\mathbf{E}(HV), \text{ or } \mathbf{E}(HV) = [T]\mathbf{E}(AB), \tag{8}$$

which leads to

$$\begin{aligned} V(HV) &= \mathbf{E}_r^T(HV)\,[S(HV)]\,\mathbf{E}_t(HV) \\ &= \mathbf{E}_r(AB)^T\left([T]^T[S(HV)][T]\right)\mathbf{E}_t(AB) \\ &= V(AB). \end{aligned} \tag{9}$$

Therefore the scattering matrix is transformed from the basis (HV) to the basis (AB) as

$$[S(AB)] = [T]^T[S(HV)][T] = \begin{bmatrix} S_{AA} & S_{AB} \\ S_{BA} & S_{BB} \end{bmatrix} \tag{10}$$

This transformation indicates that the scattering matrix in any polarization basis can be obtained, provided that the scattering matrix elements in the conventional HV basis are given.

Now, we regard the signal given by (4) as the element of the scattering matrix [S] because it is a complex value and represents target scattering characteristics. The polarimetric measurement provides full scattering matrix elements

$$[S(HV)] = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} = \begin{bmatrix} g_{HH} & g_{HV} \\ g_{VH} & g_{VV} \end{bmatrix} \tag{11}$$

where the first subscript indicates the polarization state of transmitter, and the second subscript represents the receiver polarization. If this (11) is valid, the polarimetric theory holds for the FM-CW radar. The receiving power for the monostatic case is given as

$$\begin{aligned} P = |V|^2 = \left|\mathbf{h}^T\mathbf{E}_s\right|^2 &= \left|\mathbf{h}(HV)^T[S(HV)]\mathbf{E}_t(HV)\right|^2 \\ &= \left|\mathbf{h}(AB)^T[S(AB)]\mathbf{E}_t(AB)\right|^2 \end{aligned} \tag{12}$$

It is known in the characteristic polarization state theory [4] that the polarization ratio which diagonalizes the scattering matrix gives Co-Pol maximum power. Also there exists a polarization ratio which gives Co-Pol null power. The details are given in [4] and [7]. Based on the polarimetric theory, we carried out a fundamental experiment to confirm the validity of the replacement (11).

4. Fundamental Polarimetric Detection

A laboratory experiment was carried out to detect a linear target of different orientations with respect to the polarization direction. The target is a metallic pipe of 0.6 cmϕ × 100 cm. The block diagram of an FM-CW radar system is shown in Fig.1. In this configuration, both transmitting and receiving antennas are separated, which allows one to carry out dual orthogonal channel polarimetric measurement. The antennas used are standard rectangular horns of precisely the same type operative at 8.2 - 9.2 GHz. The aperture size is 15.8 cm × 11.8 cm. The polarization combination is a set of HH, HV, VH, and VV, where H stands for polarization direction being parallel to the scanning direction (Fig.2) and V for orthogonal. The first letter H or V is for the transmitter polarization and the second letter is for the receiver.

The antennas are scanned one-dimensionally at 1 cm incremental interval from 0 up to 179 cm in the azimuth direction. Fig.3 shows the synthetic aperture images for each polarization at 60 degrees. The power is calculated according to (12), the range is measured from the antenna aperture, and the azimuth direction indicates the scanned width. It is seen that the image with VV pol produces the largest power.

The scattering matrix for this case was found to be

$$[S] = \begin{bmatrix} -0.284 + j\,0.339 & -0.046 + j\,0.439 \\ -0.046 + j\,0.439 & -0.417 + j\,0.422 \end{bmatrix}$$

From this scattering matrix, the Co-pol channel power can be calculated as a function of geometric parameters of polarization ellipse, which is called "polarimetric signature". The polarimetric response is illustrated in Fig.4. The Co-Pol Max. is given for the polarization ratio of $\rho = 1.53 - j\,0.14$, which is equivalent to the tilt angle of $\tau = 57.0°$ and the ellipticity angle of $\varepsilon = -2.4°$. This tilt angle is close to the orientation angle of the target (60°) and the ellipticity angle indicates the polarization state is almost linear. This fact coincides with the physical experimental situation. On the other hand, Co-Pol null is given by $\rho = -0.45 - j\,0.502$. The polarimetric images using these polarization ratios are illustrated in Fig. 5. It is seen that the Co-Pol max image provides the largest power, and that the Co-Pol null image eliminates the target. The result shows the polarimetric imaging based on the synthetic aperture FM-CW radar coefficient is possible.

5. Conclusion

In this paper, we have demonstrated the fundamental result of radar polarimetry applied to the synthetic aperture FM-CW radar. Since the target reflection coefficient obtained by FM-CW radar is complex signal, we regarded it as the scattering matrix element. It is possible to obtain complete scattering matrix element by the polarimetric measurement, which leads to an establishment of full polarimetric FM-CW radar system. The validity was confirmed by a fundamental experiment using a linear target. The experimental results show that the FM-CW radar polarimetry works well. This polarimetric FM-CW radar seems to have a potential ability in imaging because we can choose any polarization state.

Acknowledgement

This work was supported in part by Grant-in-Aid for Scientific Research of Ministry of Education, Japan.

References

[1] A. B. Kostinski and W. -M. Boerner, "On foundation of radar polarimetry", *IEEE Trans. Antennas Propag.* vol.AP-34, pp.1395-1404, 1986.

[2] D. Giuli, "Polarization diversity in radar", *Proc. of the IEEE*, vol.74, pp.245-269, 1986.

[3] J. vanZyl, C.H. Papas, and C. Elach, " On the optimum polarization of incoherently reflected waves", *IEEE Trans. Antennas Propag.* vol.35, no.7, pp.818-825, 1987

[4] W. -M. Boerner, W. L. Yan, A. Q. Xi, and Y. Yamaguchi, "On the basic principles of radar polarimetry: the target characteristic polarization state theory of Kennaugh, Huynen's polarization fork concept, and its extension to the partially polarized case," *Proc. of the IEEE*, vol.79, no.10, pp.1538-1550, Oct. 1991.

[5] A. B. Kostinski, B. D. James, W.-M. Boerner, "Polarimetric matched filter for coherent imaging," *Can. J. Phys.* 66, pp.871-877, 1988.

[6] Y. Yamaguchi, W. -M. Boerner, H. J. Eom, M. Sengoku, S. Motooka, and T. Abe, "On the characteristic polarization states in the cross-polarized radar channel," *IEEE Trans. Geoscience Remote Sensing*, vol.30, no.5, pp.1078-1080, Sept. 1992.

[7] W. -M. Boerner et al ed., *Direct and Inverse Methods in Radar Polarimetry*, Part 1 and 2, Netherlands, Kluwer Academic Publishers, 1992.

[8] Y. Yamaguchi, A. Kawakami, M. Mitsumoto, M. Sengoku, and T. Abe, "Synthetic aperture FM-CW radar applied to detection of objects," *IEICE Trans.* vol. B-II, no.7, pp.413-420, 1991.

[9] Y. Yamaguchi, T. Nishikawa, M. Sengoku, W.- M. Boerner, and H. J. Eom, "On the fundamental study of radar polarimetry in FM-CW radar", *Spring National Convention Record of IEICE*, SB-1-4, 1993.

[10] T. Nishikawa, Y. Yamaguchi, and M. Sengoku, "Polarimetric and synthetic aperture FM-CW radar imaging", *Technical Report of IEICE*, AP92-98, Nov. 1992.

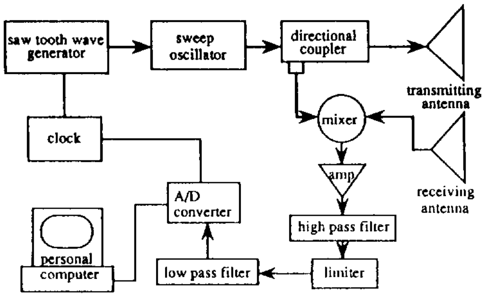


Fig.1 Block diagram of FM-CW radar

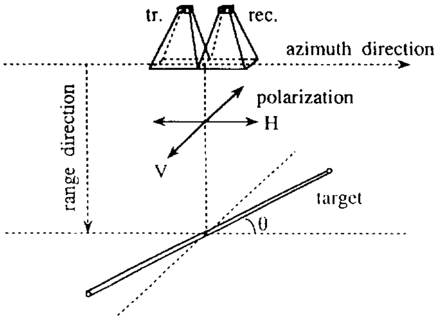
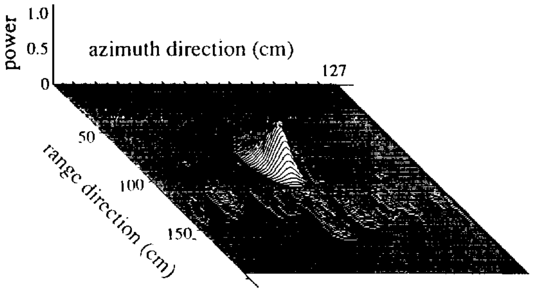
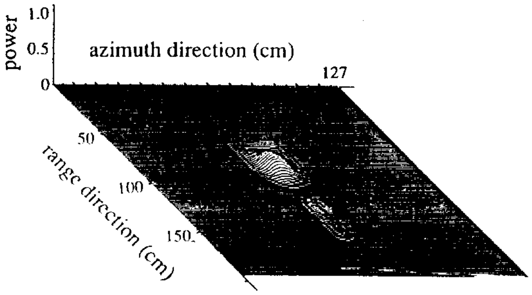


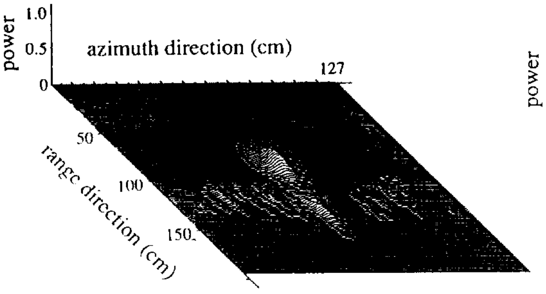
Fig.2 Measurement scheme



(a) VV



(b) VH



(c) HH

Fig.3 Image based on HV polarization basis

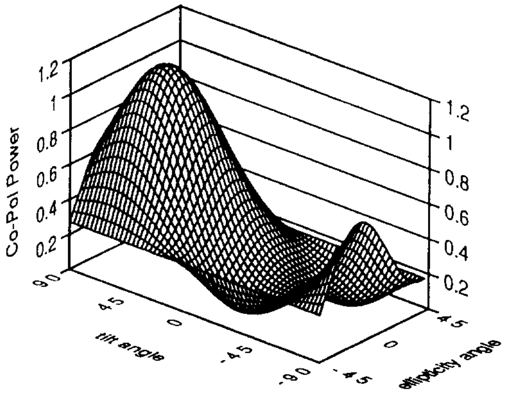
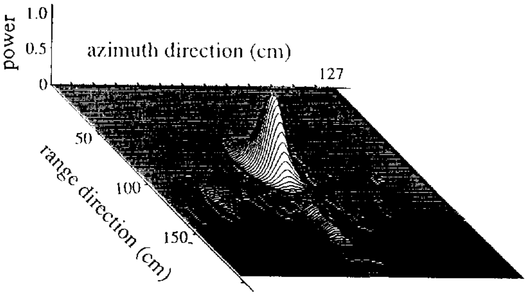
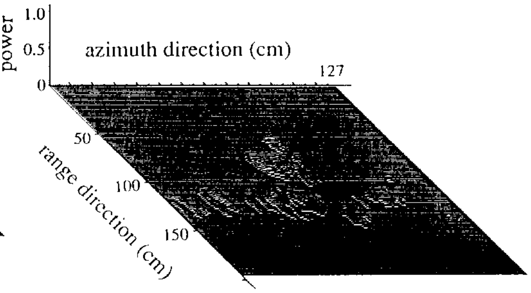


Fig.4 Power as a function of polarization state



(a) Co-POL max



(b) Co-POL null

Fig.5 Optimal polarization image