PROCEEDINGS OF ISAP '96, CHIBA, JAPAN

Rough Surface Anisotropy Estimation by Wideband Polarimetric Borehole Radar

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1. Introduction

Conventional borehole radars have only discussed the detection of an anomaly such as crack and geological structure by single polarization measurement. But recently the technology of radar polarimetry has been discussed and is applied to various purposes. We introduced the radar polarimetry into borehole radar measurement and showed that geological structure also have polarimetric feature. In this paper, we introduce an idea to evaluate surface characteristics with a scattering matrix obtained by polarimetric borehole radar.

2. Principal

We discuss a feature of a scattering matrix from flat plane, two-dimensional random surface and one-dimensional random surface. These scatters have different surface characteristics such as roughness and its orientation. As a method to extract these surface parameters from the scattering matrix, we apply transformation of the polarization basis of the scattering matrix. Generally, a polarization is parameterized with the tilt angle θ and the ellipticity angle ε. In this paper we apply the transform only to the tilt angle θ of polarization basis because it is effective for estimation of orientation of a linear object. We can obtain the transformed scattering matrix S' by the following equation with a rotation matrix $R(\theta)$ [1].

$$S'(\omega,\theta) = R(-\theta)\cdot S(\omega)\cdot R(\theta) = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} S_{HH}(\omega) & S_{HV}(\omega) \\ S_{VH}(\omega) & S_{VV}(\omega) \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \qquad (2)$$

3. FD-TD Simulation for Evaluation of Scattering Matrix

We simulated the polarization of reflected wave from a method of a geological structure by 3D FD-TD[2]. We used the FDTDA [3] for this simulation. Fig.1 shows the geometry of FD-TD simulation of reflection borehole radar measurements. The calculation size is 200*200*200 grid and 1 grid size is 5 cm. A dipole antenna and a slot antenna on a conducting cylinder are modeled as an electric dipole E_z and an magnetic dipole H_z, respectively. E_z or $\zeta_0 H_z$ (ζ_0:intrinsic impedance) component is induced at the exciting point for each transmitter. The excitation is a Gaussian pulse having pulse width of 30 grid. We can obtain the scattering matrices in reflection borehole radar measurement by sampling E_z or $\zeta_0 H_z$ component at a point above 30 grid from the exciting point.

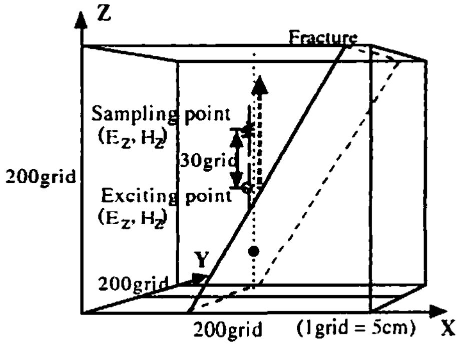

Fig.1 Geometry of FD-TD simulation

For modeling a subsurface fracture, we used a fractal model [4]. A spatial power spectrum of a cross section profile is defined as the following equation with wave number k.

$$P(k) = C \cdot k^{-\beta} \tag{1}$$

The inverse Fourier transformation gives a two-dimensional fractal rough surface by assuming a random phase. The dip of the fracture is 60 degree and the fracture width is 3 grid.

4 . Estimation of Rough Surface Anisotropy

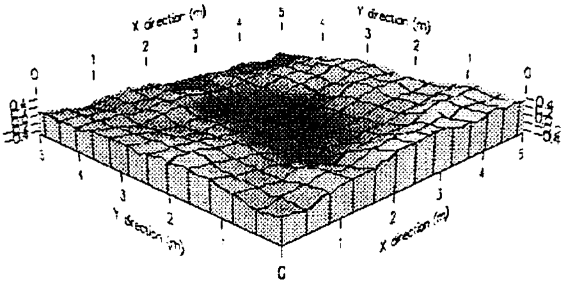

Fig.2 Example of random rough surface ($\beta = 3.4$, $\sigma = 5$ grid)

Fig.2 shows a example of a random rough surface ($\beta = 3.4$, RMS of the surface profile $\sigma = 5$ grid) and Fig.3 shows waveforms of the scattering matrix obtained by FD-TD simulation from the rough fracture. Fig.4 shows wavelength dependency of cross-polarization component of transformed scattering matrix S' against the rotation angle, which is deduced from Fig.3. The rotation angle, at which the cross-polarized component has minimum, can be observed systematically at 0° and 90° at the wavelength longer than 60 grid. Generally, a scattering matrix from a flat plane has zero cross-polarization component. Therefore, it means that this fracture acts as a flat plane at this wavelength. On the other hand, the rotation angle having minimum distributes randomly around the wavelength less than 40 grid. This feature is that of a fracture having isotropic rough surface.

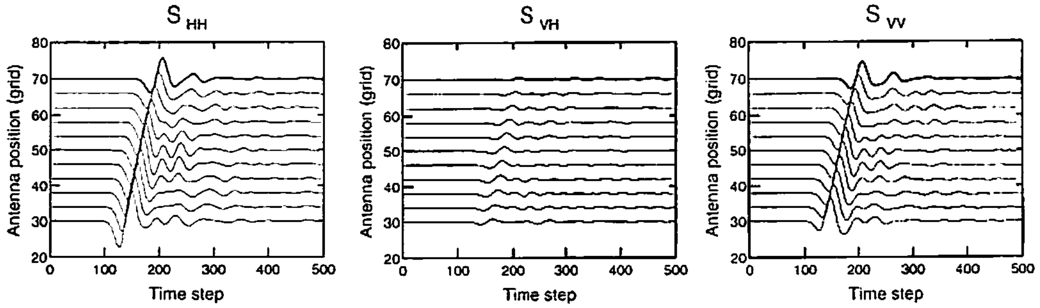

Fig.3 Waveforms of the scattering matrix obtained by FD-TD in random rough fracture

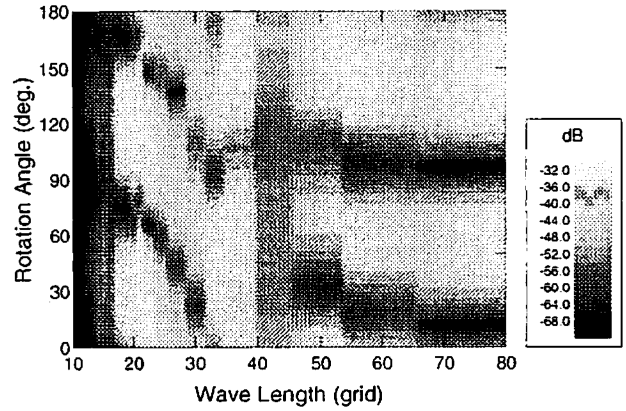

Fig.4 Wavelength dependency of cross-polarization component of transformed scattering matrix S' against the rotation angle.

Next, we discuss the case of anisotropic rough surface. Here, we modeled an anisotropic rough surface as a plane having one dimensional roughness oriented to 60° . Fig.5 shows an example of the modeled anisotropic surface ($\beta = 1.0$, $\sigma = 6$ grid). Fig.6 shows wavelength dependency of the cross-polarization component of the scattering matrix S' transformed from scattering matrix of the anisotropic fracture . The systematic rotation angle which give the minimum of the cross-polarization component can be found at 60° for the wavelength less than 30 grid. This means that rotation of the polarization basis reveals the orientation of the anisotropy of a distributed scatter.

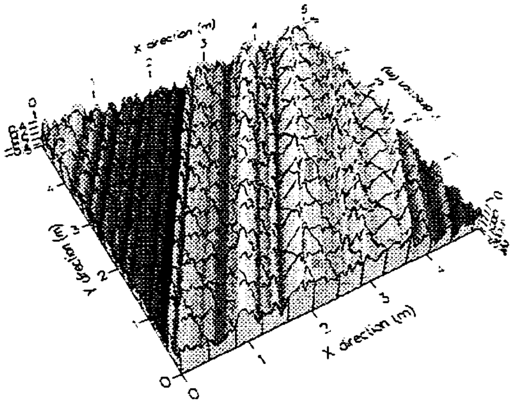

Fig.5 Example of modeled anisotropic surface ($\beta = 1.0$, $\sigma = 6$ grid)

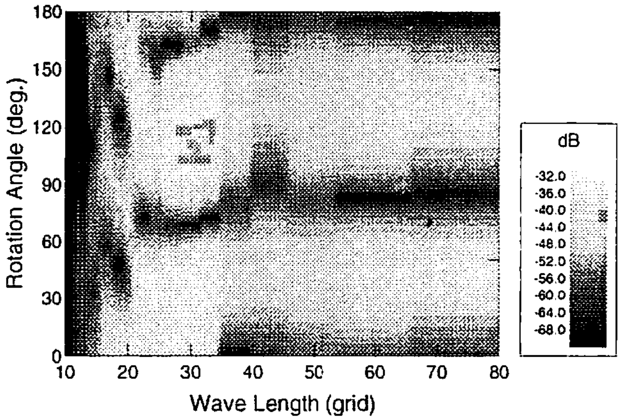

Fig.6 Wavelength dependency of cross-polarization component of transformed scattering matrix S' against the rotation angle (60° anisotropic rough surface case)

5 . Application to Field Data

We conducted scattering matrix mesurement in Kamaishi mine with a wideband polarimetric borehole radar system [5] which can measure full components of a scattering matrix by use of a dipole antenna and a slot antenna on a conducting cylinder as either a transmitter or a receiver.

Rotation of a polarization basis can similarly be applied to a time-domain scattering matrix. Fig.7 shows rotation angle dependency of cross-polarization component of scattering matrices obtained in the polarimetric borehole radar measurement. We find that the matrix component for the fracture around the depth of 6m are invisible at 0° and at 90° and have maximum at 45° . On the other hand , the fracture around the depth of 2m or 9m is visible independently on rotation angle. But, we can not observe a fracture having the feature of one-dimensional random rough surface.

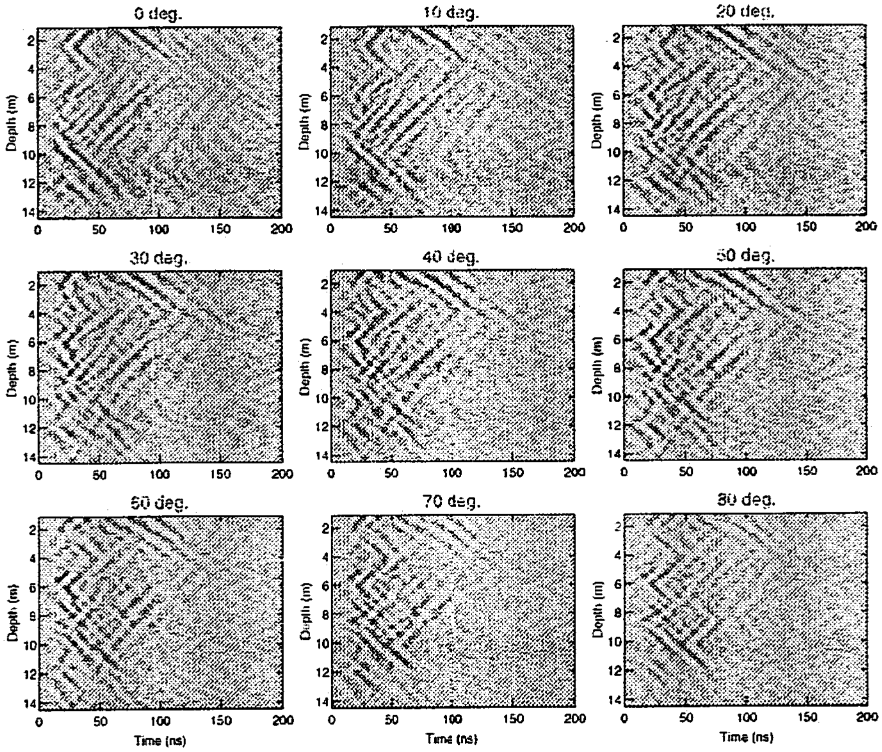

Fig.7 Rotation angle dependency of cross-polarization component transformed with scattering matrices obtained in polarimetric borehole radar measurement

6 . Summary

We have discussed classification of surface characteristics by rotation of polarization basis of scattering matrix from distributed scatters. As a result of FD-TD simulation, we found the rotation angle minimizing cross-polarization component for flat plane. isotropic rough surface and anisotropic rough surface. Moreover, in field experiment result, we can observe fractures having characteristics of a flat plane and a random rough surface. This method is also appricable to estimate the wind direction in a sea rough surface.

Acknowledgement

This works was supported by TEPCO Research Foundation and Grant-in-aid of Japan Ministry of Education, Science and Culture.

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