Radar Polarimetry Analysis Applied to Single-Hole Fully Polarimetric Borehole Radar

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***Abstract*—A fully polarimetric borehole radar system using four combinations of dipole and slot antennas was developed to acquire fully polarimetric data sets in drilled boreholes. First, to implement radar polarimetry analysis, a processing scheme suitable for analyzing a single-hole reflection data set acquired by the system is presented. This processing consists of antenna-characteristic compensation, migration for image reconstruction, and time–frequency analysis for single-frequency data set construction. Two polarimetric target decomposition methods, namely: 1) Pauli decomposition and 2) eigenvector-based decomposition, are applied to characterize the scattering problem of the subsurface fractures. The Pauli decomposition method provided important radar polarimetry information of fractures, and the eigenvector-based decomposition method made a significant contribution to understanding the scattering mechanisms from different fractures with different properties. Furthermore, information about fracture classification can be obtained by analysis of the H-alpha distribution provided by eigenvector-based decomposition of local radar image regions. The potential of polarimetric target decomposition techniques to fracture characterization is shown, which, in turn, provides valuable information about water permeabilities of fractures in hydrogeological studies.**

***Index Terms*—F-K migration, fracture characterization, fully polarimetric borehole radar, H-alpha decomposition, Pauli decomposition, radar polarimetry analysis, subsurface sensing.**

I. Introduction

BOREHOLE radar is a specialized application of ground-penetrating radar (GPR). As a new subsurface exploration technique, borehole radar has increasingly been employed in diverse fields. Typical applications include the estimation of fractures in hydraulic and geological research [1], the localization of metal pipes in civil engineering, and the detection of metal ores in geophysical exploration. At present, applications of borehole radar measurements are also involved in discerning oil-bearing and water-bearing layers in the petroleum industry [2] and in the estimation of water content of warm ice in polythermal glaciers in glaciological studies [3]. However, all applications of conventional borehole radar are primarily based on the level of "detection" of subsurface targets without using geologic, geophysical, or hydrological methods simultaneously. In general, to achieve a large penetration depth, most borehole radar systems are operated at frequencies ranging from 10 to 100 MHz, which is relatively low compared to GPR used on the ground surface. Usage of low frequencies results in poor radar range resolution, i.e., approximately 20 cm. In many engineering applications, characterization of subsurface fractures is an important issue. In particular, hydraulic researchers need to know the water permeability of each fracture. Conventional borehole radar systems, in this instance, have difficulties providing information about the physical properties of fractures, although they can be used to estimate their location and orientation.

Radar polarimetry analysis would be an alternative approach to obtain fracture characterization beyond radar resolution if a fully polarimetric data set were available. Therefore, we developed a fully polarimetric borehole radar system with combinations of dipole and axial slot antennas [4]–[6]. With this system, field measurements were carried out in several test sites, including Mirror Lake, U.S., Asse, Germany [7], [8], and Hirabayashi, Japan. We have shown that the newly developed borehole radar with an antenna-characteristic compensation algorithm [5] could be used to acquire high-quality fully polarimetric data sets [6], [8] and have clarified that a relationship exists between the polarimetric information of the borehole data set and fracture properties, such as surface roughness and water permeability [5], [8]. Nevertheless, effective radar polarimetry analysis for fracture characterization has remained inadequate.

In an earlier stage of the development of our radar system, Sato *et al.* [8] proposed a power-scattering matrix to evaluate the backscattered energy by subsurface fractures among different states of polarization. To obtain a power-scattering matrix for a specific fracture, the V-shaped train of its reflected signal is isolated by means of a frequency-wavenumber (F-K) filter. Integration of power is then done inside a slant window along the reflected signal for every polarization state [8]. This technique obtained useful information to evaluate the roughness of subsurface fractures and provided a method to classify fractures in terms of the energy distribution among different polarization states. However, due to poor radar resolution, the separation of a reflected signal corresponding to a fracture was not easy to implement. Moreover, the technique did not give a reasonable explanation of scattering mechanisms of different fractures with different properties.

At present, polarimetric synthetic aperture radar (PolSAR) has shown considerable advancement [9], [10], and polarimetric techniques have increasingly been developed. One of the main advantages of polarimetric techniques is the possibility to separate and understand scattering contributions of different nature [11]. This can be done by analyzing the scattering

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matrix with various techniques to extract information about a scattering process.

Pauli decomposition based on the coherent Sinclair scattering matrix is a rather simple decomposition [11], [12]. Yet, the technique yields much information. Three Pauli decomposition components correspond to sphere scattering, diplane scattering, and all other comprehensive scattering mechanisms apart from sphere and diplane scattering. Using Pauli decomposition, we can derive a three-color composite image of a fully polarimetric data set for visual classification purposes. However, the approach is not sufficient for the interpretation of all areas since it is only able to distinguish among three ideal scattering mechanisms and their combinations. Some ambiguous areas remain, which makes an interpretation of the data more difficult.

The polarimetric H-alpha decomposition method, or eigenvector-based decomposition method, has been increasingly employed to characterize the scattering properties of media [11]–[13]. Unlike Pauli decomposition, H-alpha decomposition is based on the Kennaugh matrix [13]. Two important physical features can be derived from this decomposition, namely: 1) polarimetric scattering entropy H, which is a global measure for the distribution of the components of a scattering process [11]–[13], and 2) alpha parameter, which is a continuous angle between 0° and 90° that can be used to represent a wide variety of different scattering mechanisms [11]–[13], therefore, providing a powerful extension to Pauli decomposition.

The purpose of this paper is to develop polarimetry analysis methods to further exploit the potential of this system, which may be thought of as equivalent to PolSAR (normally applied in air) for characterizing subsurface targets. We first describe a field experiment based on this radar system located at the Mirror Lake fractured-rock research site in New Hampshire. Here, we applied Pauli decomposition and eigenvector-based entropy decomposition methods, as an extension of the earlier approach with polarimetry analysis of the power-scattering matrix [8], to scattering mechanism recognition for subsurface fractures. Finally, we interpret the result of fracture characterization and implement a fracture classification system. The radar polarimetry analysis on the basis of polarimetric target decomposition methods provides a powerful tool for subsurface fracture characterization and classification. In the following sections, a processing scheme will be explained mainly for quantitative determination of the scattering matrix, isolation of the fractures as research subjects, and single-frequency data set construction. Emphasis is placed on the implementation of polarimetric target decomposition methods, i.e., Pauli decomposition and eigenvector-based entropy decomposition, for fracture characterization.

II. Field Measurements

Since 1990, the Toxic Substances Hydrology Program of the U.S. Geological Survey (USGS) has been supporting investigations of bedrock in the Mirror Lake watershed in Grafton County, NH. The aim is to address the nation's need for accurate and efficient methods for evaluating groundwater resources in fractured rock. The joint research group of Tohoku University and USGS carried out field measurements at the Mirror Lake site. Field measurements involved a borehole cluster of FSE-1, -2, -3, and -4, which form a square [7].

According to USGS geological data, the host rock at Mirror Lake is granite and is quite homogeneous except for fractures. The dielectric constant of the host rock is about 8, and the conductivity is less than 0.001 S/m. To accurately determine the velocity of the medium, we calculated a velocity tomogram by using cross-hole measurement with dipole–dipole antenna combination [14], [15]. The velocity tomography result based on an algebraic reconstruction method [15] gave an average velocity of 0.13 m/ns. The velocity will be used in later constant velocity F-K migration processing. Notice also that the dielectric constant in the velocity tomogram is slightly lower than 8.

Using our fully polarimetric borehole radar system [6], single-hole reflection measurements and cross-hole transmission measurements were carried out at this test site. The single-hole reflection measurements were conducted at FSE-3 and FSE-1, with an antenna separation of 1.6 m in all antenna arrangements. The cross-hole measurement was carried out between FSE-1 and FSE-3 for all combinations of dipole and slot antennas. The separation of the FSE-1 and FSE-3 was 9 m. In all the measurements, frequency-domain data were acquired between 2 and 402 MHz with a 2-MHz frequency interval. For the radar polarimetry analysis included in this paper, we only used the single-hole fully polarimetric data set acquired at FSE-1.

III. Processing for Further Polarimetry Analysis

A crucial issue of fully polarimetric borehole radar measurement is how to successfully apply methodologies of polarimetric analysis, the use of which has matured in the field of PolSAR. To achieve this goal, several procedures have to be carried out, in which antenna-characteristic compensation, migration processing for subsurface image reconstruction, and time–frequency analysis for constructing single-frequency data sets are indispensable to further polarimetric analysis and should be implemented sequentially [5], [16]–[18].

Using a stepped-frequency acquisition system, a fully polarimetric data set was acquired in the frequency domain. We then selected optimized zero-phase bandpass filters and obtained profiles in the time domain after performing an inverse fast Fourier transform (IFFT). In time-domain profiles, only limited reflection information from omnidirectional subsurface targets could be observed due to strong direct antenna coupling. To recover the real reflections obscured by antenna coupling, an averaged signal at adjoining depths was subtracted from the original signal at each depth for every polarization state. The transfer functions of the dipole and slot antennas in this system were noticeably distinct from each other [4], [5]. To solve this problem, Miwa *et al.* [5] proposed a useful antenna-characteristic compensation algorithm for quantitative determination of the scattering matrix, which is required for further polarimetry analysis. The antenna-characteristic compensation with a cross-hole calibration method was successfully applied to the radar profiles after removal of antenna coupling [5], [19]. Performing IFFT again, we could observe typical radar reflection from subsurface fractures in the profiles shown in Fig. 1. The radar resolution depends on frequency bandwidth

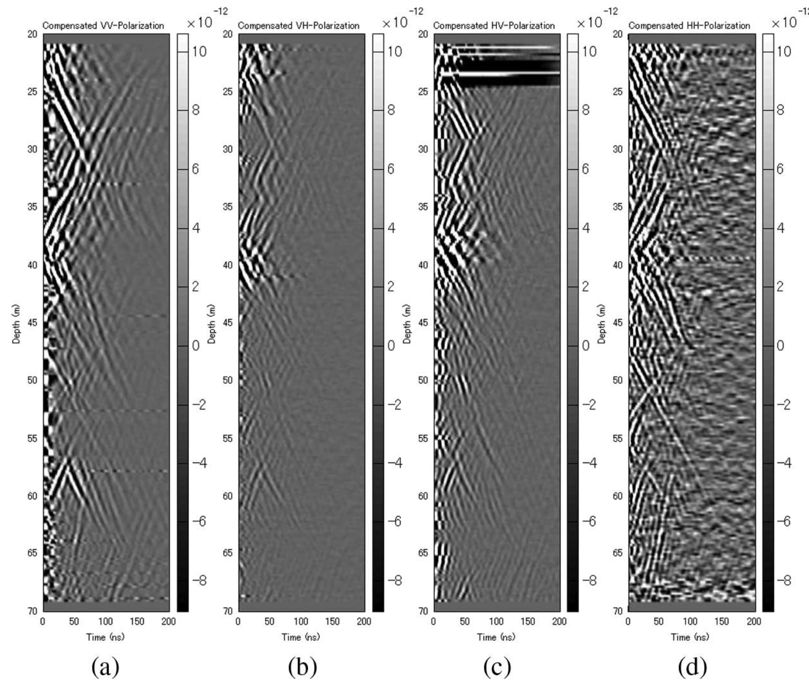


Fig. 1. Fully polarimetric borehole radar profiles after antenna-characteristic compensation. (a) VV, (b) VH, (c) HV, and (d) HH polarization states (separation of Tx and Rx: 1.6 m; survey depth: 20–70 m; measurement interval: 20 cm; FSE-1, Mirror Lake, NH). Note also that the frequency components are equalized and the signal amplitudes are comparable among all polarization states after antenna-characteristic compensation.

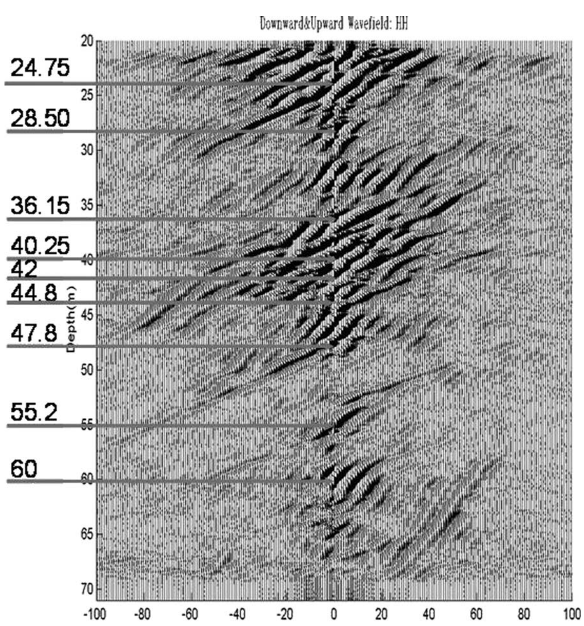


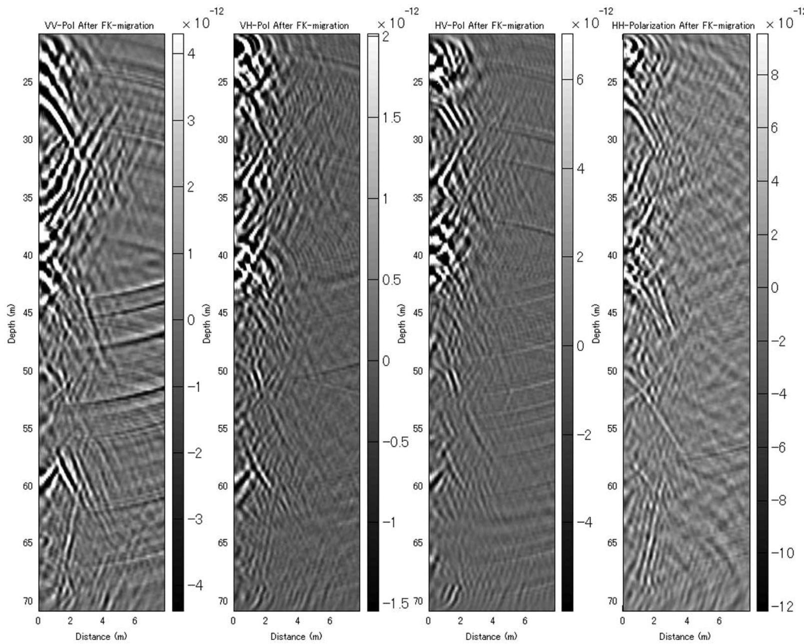
Fig. 2. Wavefield separation of a copolarized HH component.

of the measured signals. By using a wavefield separation technique and rearranging the downward wavefield along the negative time axis, we could determine the borehole intersection depths for the main fractures. Fig. 2 shows the upward and downward wavefield of HH polarization component [21]. We selected nine fractures shown in Table I as research subjects for evaluating the suitability of applying radar polarimetry to fracture characterization. The same fractures could also be determined by a directional borehole radar system in a previous USGS research project [20].

TABLE I
FRACTURES FOR RADAR POLARIMETRY ANALYSIS

Fracture Number	Borehole intersection below top of casing (m)	H-Alpha parameters	Surface roughness
1	24.75	Medium entropy medium alpha	Medium roughness
2	28.50	Low entropy low alpha	Smooth
3	36.15	Low entropy low alpha	Smooth
4	40.25	Medium entropy high alpha	Rough
5	42.00	Medium entropy high alpha	Rough
6	44.80	Low entropy low alpha	Smooth
7	47.80	Medium entropy high alpha	Rough
8	55.20	Medium entropy medium alpha	Medium roughness
9	60.00	Low entropy low alpha	Smooth

We applied an F-K migration technique to the antenna-characteristic compensated fully polarimetric radar profiles in the time domain for subsurface image reconstruction by inversely tracing the wave propagation process [16], [17]. An assumption of constant velocity is necessary for this migration technique. The velocity value 0.13 m/ns obtained by velocity tomography was used for migration processing. Fig. 3 shows the fully polarimetric profiles after antenna-characteristic compensation and F-K migration. We can observe that the frequency components are equalized, and the signal amplitudes are now comparable among all polarization states. Although some artifacts can be observed far from the borehole axis in Fig. 3, which are caused by the overestimation or underestimation of



(a) (b) (c) (d)

Fig. 3. Fully polarimetric borehole radar profiles after antenna-characteristic compensation and F-K migration. (a) VV, (b) VH, (c) HV, and (d) HH polarization states (separation of Tx and Rx: 1.6 m; survey depth: 20–70 m; measurement interval: 20 cm; FSE-1, Mirror Lake, NH).

true velocity in the process of F-K migration, we believe that the antenna-characteristic compensation was successful and the migrated image was acceptable. Hence, further radar polarimetry analysis can be made based on the profiles shown in Fig. 3.

A short-time Fourier transform (STFT) [18] was applied to the profiles shown in Fig. 3 for single-frequency data set construction. This transform is defined as

$$X(f,\tau) = \int_{-\infty}^{+\infty} x(t)\gamma(t-\tau)e^{-j2\pi ft}dt. \tag{1}$$

In STFT, the input signal is analyzed section by section. A localized time window function $\gamma(t-\tau)$ is applied over the signal, and Fourier analysis is performed on the signal segment in the window. Thus, STFT provides information on both time locality and frequency spectra. In this paper, a window function was empirically constructed as

$$\gamma(t) = \begin{cases} \exp\left[-\left(\frac{t-4.8828}{0.9766}\right)^2\right], & t \le 4.8828 \text{ ns} \\ \exp\left[-\left(\frac{t-39.0624}{0.9766}\right)^2\right], & 39.0624 \text{ ns} \le t \le 43.94 \text{ ns} \\ 1, & \text{else.} \end{cases} \tag{2}$$

We applied STFT to one sample signal, which was made by summing up the signals at all depths and calculating their average in the case of dipole–dipole antenna combination. By analyzing the time–frequency distribution of this sample signal, it became evident that the frequency bandwidth of reflected signals from subsurface fractures mainly ranged from about 20 to 110 MHz. This bandwidth was utilized in our later polarimetry analysis.

IV. Polarimetric Analysis

A. *Pauli Decomposition*

Following the procedures described in the earlier sections, Pauli decomposition was implemented in the frequency domain after antenna-characteristic compensation was applied, and then by means of IFFT, three Pauli decomposition components were obtained in the time domain. Fig. 4 shows the Pauli decomposition result. In the figure, colors red, green, and blue represent the three Pauli decomposition components $\mathrm{HH} - \mathrm{VV}$, $(\mathrm{VH} + \mathrm{HV})/2$, and $\mathrm{HH} + \mathrm{VV}$. By analyzing the color dominance among red, green, and blue in Fig. 4, we identified differences among different Pauli decomposition components, which, in turn, reflect that the fractures in question have different scattering mechanisms. Typically, we found that the fractures at the depth of about 25 and 60 m have a dominant red component, whereas a dominance of green can be observed in the zone surrounding the fracture at about 40 m and in the fracture at about 47 m. As we will also discuss in eigenvector-based decomposition analysis later, these fractures have quite different properties. A reasonable explanation is that cross-polarized scattering is susceptible to fractures with large roughness and fracture zones with severely cracked rock, whereas strong copolarized scattering tends to occur at fractures with smooth surfaces. As a result, water-bearing features can be inferred for the fracture zones at about 40 and 47 m; on the other hand, fractures at about 25 and 60 m have low water permeability. We think that the sole employment of Pauli decomposition can provide valuable information about fracture characterization and classification. Nevertheless, low radar resolution results in a poor resolution of Pauli decomposition in a color-coded red–green–blue display, and as a result, effective Pauli decomposition information cannot be obtained for other typical fractures.

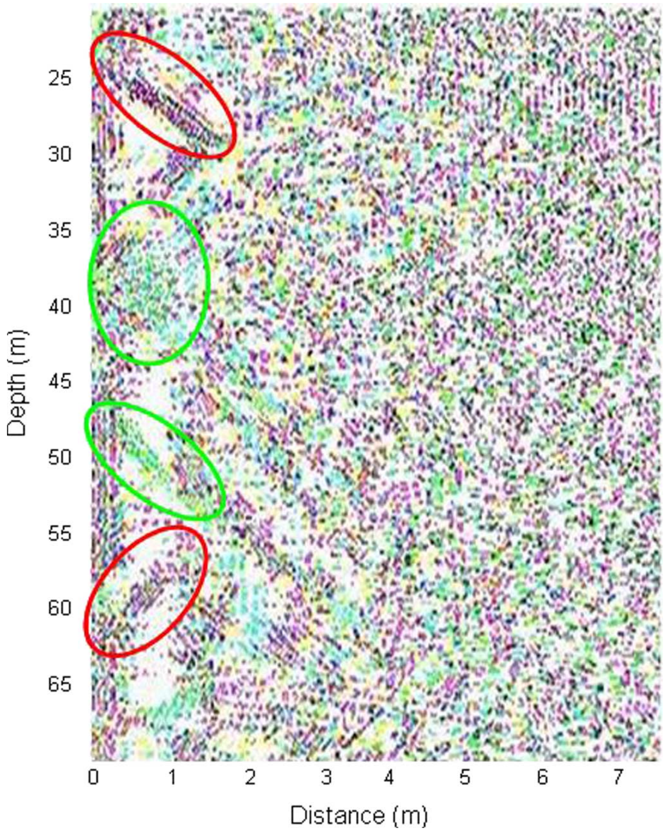


Fig. 4. Pauli decomposition of fully polarimetric borehole radar data set in the time domain. (a) Blue: sphere scattering (HH + VV). (b) Red: diplane scattering (HH–VV). (c) Green: other scattering $(\mathrm{VH}+\mathrm{HV})/2$.

B. Eigenvector-Based Decomposition

Eigenvector-based decomposition is an alternative method to extract further information for fracture characterization. With this polarimetric analysis, the entropy H and alpha $\overline{\alpha}$ introduced earlier in this paper can form a two-dimensional feature space, where each pixel can be assigned to a certain scattering behavior. H and $\overline{\alpha}$ represent the number of involved scattering mechanisms and the type of scattering, respectively [13]. Fig. 5 shows the classical H-alpha plane for random media scattering problems as described by Cloude and Pottier [13]. The nine zones correspond to different physical scattering characteristics [13]. In hydrological studies, subsurface fractures are characterized by their water permeability, surface roughness, fracture extent, and aperture width, which are closely related to the H-alpha distribution. In this paper, we used entropy decomposition analysis to characterize fractures. H-alpha distribution results at single frequencies 30, 50, 80, and 100 MHz are shown in Fig. 6. In these H-alpha distribution results, the definition of colors indicating nine different physical scattering mechanism zones is consistent with that used in Fig. 5.

As shown in Fig. 6, we found that the H-alpha distribution became unstable at high frequencies. For example, at the single-frequency 100 MHz, the scattering mechanism relative to zone 4 was overwhelmingly dominant. Hence, the delineation ability of H-alpha parameters to characterize subsurface fractures was decreasing. One reasonable explanation for this phenomenon is that high-frequency components are much more sensitive to small structures so that the depolarization effects get stronger compared to those observed with low-frequency components. On the other hand, we also found that the H-alpha distribution results showed consistency with one another at frequency components lower than 60 MHz. Here, we applied H-alpha distribution analysis to local regions using data from a single frequency (30 MHz) for all the fractures marked in Fig. 2. The local region for H-alpha analysis was chosen to be a 2 m $\times$ 1.5 m rectangle around each fracture. The borehole and fractures intersect precisely at the midpoint of the long side of the rectangle. The shape of this area is shown in Fig. 6(a). H-alpha analyses were performed for the nine fractures shown in Fig. 2. The results are depicted in Fig. 7. After obtaining these nine results, we can classify them into the following three groups: 1) two fractures at 28.5 and 40.25 m apparently have different properties; 2) fractures at 36.15, 44.8, and 60 m have almost consistent H-alpha distribution patterns, and their properties are believed to be identical to the fracture at 28.5 m; and 3) two fractures at 42 and 47.8 m can be classified into one group with the fracture at 40.25 m, since they have approximately consistent H-alpha distribution. The last two fractures at 24.75 and 55.2 m are also believed to belong to one group.

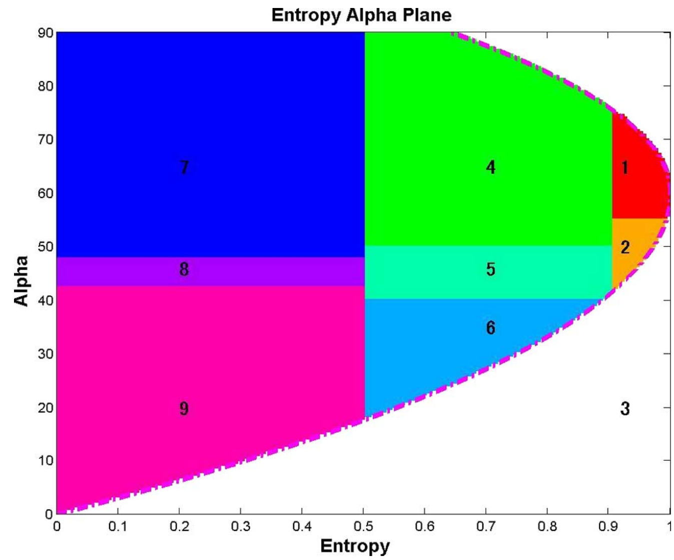


Fig. 5. H-alpha plane for random media scattering problems [13].

The method of classification can be explained by considering two representative fractures at 28.5 and 40.25 m. The H-alpha distribution indicating the scattering mechanism of the fracture at 28.5 m is concentrated in zone 9, which represents low entropy surface scattering. Moreover, low entropy and low alpha angle in zone 9 denote a small number of scattering mechanisms and isotropic surface scattering, respectively. Hence, we assume that the fracture at 28.5 m has an isotropic and smooth scattering surface, which, in turn, indicates that the zone surrounding this fracture has low permeability. The fracture at 40.25 m, on the other hand, shows complex scattering mechanisms: Its entropy value presents a distribution for low entropy to medium entropy, and its alpha value indicates multiple scattering mechanisms for this fracture. We assume that the fracture has greater surface roughness, wider fracture aperture, and higher permeability than the fracture group represented by that

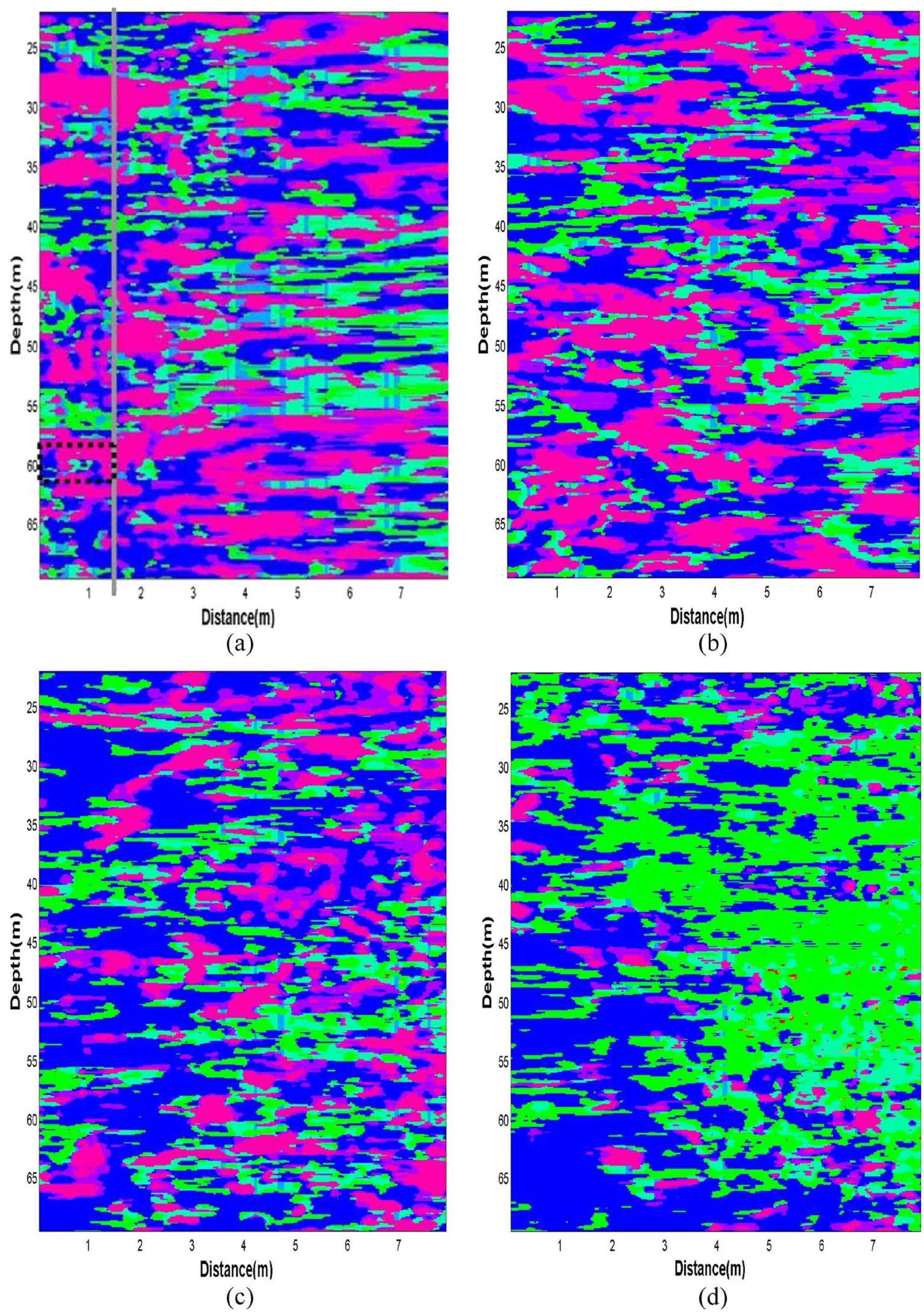


Fig. 6. H-alpha distribution in the frequency domain. (a) 30 MHz. (b) 50 MHz. (c) 80 MHz. (d) 100 MHz.

at a depth of 28.5 m. Borehole-geophysical logging, hydraulic tests, and tracer testing have all identified two transmissive fracture zones, which provide hydraulic connection among the four boreholes FSE-1, -2, -3, and -4. This has been published in an earlier USGS study [7]: one transmissive zone is at a depth of about 40 m and the other transmissive zone at about 47 m. This provides evidence to verify the entropy decomposition result. The third group with two fractures at 24.75 and 55.2 m is believed to be of medium entropy and medium alpha. We conjecture that this fracture group has different physical characterization from the group represented at 40.25 m, although it is very difficult to say that the two groups have a distinct entropy–alpha distribution pattern. One plausible interpretation is that the surface roughness of the third group is between those of the two other groups. The physical characterization information for the three groups was added in Table I. Thus, a general regularity exists in subsurface fracture characterization based on eigenvector-based decomposition: H-alpha distribution with low entropy and low alpha implies an isotropic surface scattering mechanism from fractures with smooth surfaces; on the contrary, the distribution trend of relatively high entropy and high alpha reveals an anisotropic multiple scattering (or volumetric scattering) mechanism, which corresponds to fractures with rough surfaces. In conclusion, the increase in both entropy

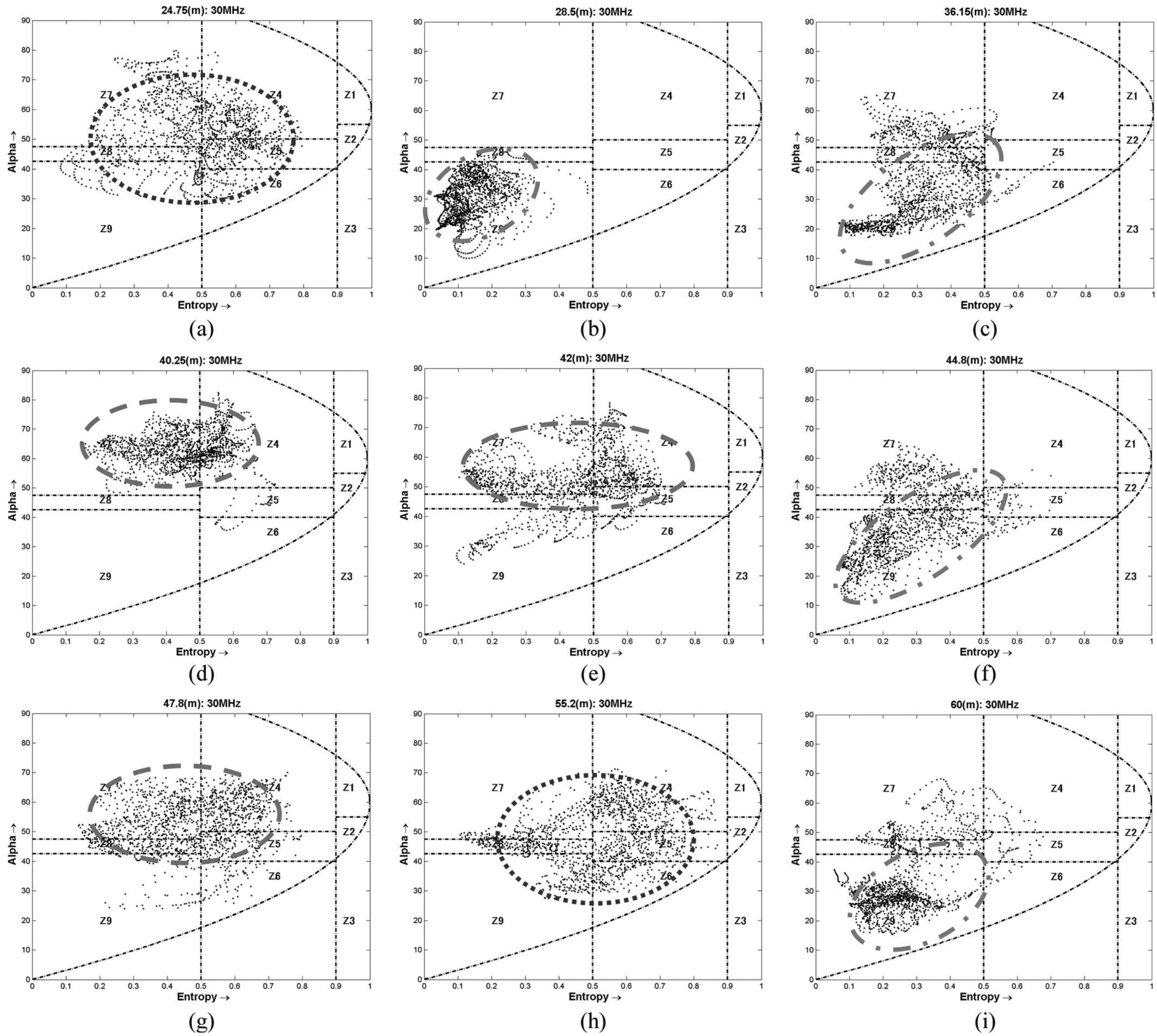


Fig. 7. H-alpha distribution results corresponding to nine fractures at 30 MHz [localized area for H-alpha distribution analysis was chosen as a square surrounding one fracture as described in Fig. 6(a)]. Fracture at the depth of (a) 24.75 m, (b) 28.5 m, (c) 36.15 m, (d) 40.25 m, (e) 42 m, (f) 44.8 m, (g) 47.8 m, (h) 55.2 m, and (i) 60 m.

and alpha reflects changes in surface roughness of fractures due to multiple-scattering effects.

In a previous paper, Sato *et al*. [8] calculated power-scattering matrices for the nine fractures shown in Table I. According to their results, fractures at 42, 42.25, and 47.8 m had much stronger cross-polarized components than all other fractures, whereas the fractures at 24.75, 28.5, and 60 m had weaker cross-polarized components. Different fracture surface roughness was believed to cause the difference of cross-polarized scattering energy: relatively smooth surfaces produced strong copolarized energy, whereas rough surfaces produced strong cross-polarized energy [6], [8]. The fracture characterization result obtained by the power-scattering matrix shows consistency with that obtained by the entropy decomposition method; however, we would argue that the entropy decomposition shows better accuracy.

V. Conclusion

In this paper, the world's first application of radar polarimetry analysis methodology to subsurface fracture characterization and classification was presented. Polarimetry analysis based results showed that the fully polarimetric borehole radar system in conjunction with a radar polarimetry processing scheme provides innovative insights into the physical properties of subsurface fractures, which is impossible to be inferred by means of conventional borehole radar systems due to low resolution. The developed radar polarimetry processing scheme consists of data preprocessing and further radar polarimetry decomposition procedures. It was demonstrated that three critical processing algorithms, i.e., antenna-characteristic compensation for polarimetric calibration, F-K migration for image reconstruction, and time–frequency analysis for single-frequency data set construction, were effectively implemented at the data preprocessing stage. Noticeably, if the inhomogeneity of the subsurface medium is substantial, one has to turn to other migration approaches, as the assumption of constant velocity cannot be met.

Use of radar polarimetry decomposition can provide important polarization information of subsurface fractures. Through the Pauli decomposition and entropy decomposition approaches, the different scattering performances corresponding to different fractures can be observed. In particular, the implementation of the H-alpha decomposition was very useful and showed promising results for recognizing the surface roughness of subsurface fractures by analyzing their polarimetric scattering mechanisms. Furthermore, the analysis of the H-alpha distribution pattern enables the qualitative classification of fractures. The fracture characterization method based on a power-scattering matrix and hydraulic testing provides powerful evidence to justify the result of H-alpha distribution analysis for characterizing subsurface fractures.

We think that this fully polarimetric borehole radar system with the proposed polarimetric analysis procedures has the potential to provide polarimetry information beyond current radar resolution capabilities, with the objective of characterizing subsurface fractures qualitatively. However, we need to emphasize that this H-alpha decomposition was derived strictly for the open propagation, surface scattering scenario for airborne/spaceborne remote sensing and not for the closed polarimetric borehole radar fracture scattering description. We conjecture that a properly amended H-alpha decomposition method for the polarimetric borehole radar application will become a much more powerful tool to accomplish fracture characterization and classification. In addition, further research on the potential of quantitative analysis for fracture characterization is needed.

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