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Virtual multi-offset reflection profiling with interferometric imaging for borehole radar

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A B S T R A C T

Interferometry is one of the most advanced signal-processing and imaging techniques. It is widely used in geophysical detection and remote sensing. Application of interferometric processing significantly improves the resolution in geophysical imaging. This paper reports the application of an interferometric imaging approach to cross-hole multi-offset transmission (CHMOT) borehole radar data to generate a virtual single-hole, multi-offset reflection (SHMOR) profile with the validation of a real SHMOR data set. In subsurface material property imaging, SHMOR is an effective technique for interface and fracture detection. However, borehole radar survey in SHMOR fashion is not practical for most cases. Transforming cross-hole transmission mode radar data to virtual single-hole, multi-offset reflection data using a wave interferometric virtual source (WIVS) approach was proposed previously but not fully validated with real SHMOR data. In this study, we compare WIVS-derived virtual SHMOR to real SHMOR profiles using data sets acquired in two boreholes (SIMA1 and SIMA2) drilled into crystalline igneous bedrocks. As the calibration and validation, the reflection from borehole SIMA2 (as the known object) is clearly imaged by both the real and WIVS-derived virtual SHMOR profiles in SIMA1. The diffractions and amplitude decay from sharp stratigraphic change also registered at both the real and WIVS-derived virtual SHMOR profiles. The results of this study demonstrate the potential of the WIVS approach to improve structural imaging in bedrocks for hydrogeological, geothermal, and petroleum reservoir development applications.

1. Introduction

Interferometry technique is one of the most advanced signal processing and imaging techniques developed in the last century that have gained wide applications in all disciplines in science and technology such as astronomy, geoscience, and remote sensing [1–3]. Interferometry dramatically improved the resolution of the geospaced data and images [4]. Application of the interferometry techniques (e.g., interferometric synthetic aperture radar (inSAR), and polarimetric radar) has generated a large amount of new information and knowledge about the land and ocean surface of the earth and made great breakthroughs and advancements in earth sciences.

Interferometry has also been introduced for ground penetrating radar (GPR) in solid earth geophysics for imaging the subsurface of the earth. Mason et al. [5] discussed synthetic aperture borehole radar interferometry, similar to air-borne or space-borne inSAR by using single-hole, constant-offset reflection (SHCOR) radar surveys in a pair of boreholes. Up to date, SHCOR, or monostatic, i.e., a borehole radar survey fashion with fixed transmitter-receiver spacing is still the most commonly used survey fashion in borehole radar measurements.

SHCOR borehole radar is a powerful tool that allows for the identification of subsurface targets and planar features such as fractures [6,7]. Lane et al. [8] and Dorn et al. [9] demonstrated that the SHCOR imaging technique can be used to monitor saline tracer movement within millimeter-scale aperture fractures. However, as Ref. [8] pointed out, fractures do not always orient sub-parallel to and intersect with the borehole so that SHCOR has its limitations in fracture imaging. Compared with the constant-offset reflection, use of multi-offset reflection data [8] can

1) increase the resolution of the reflectors near the borehole;
2) decrease the effects of direct coupling, antenna ringing, and system noise; and

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3) improve the resolution of post- to pre-injection difference images that used to identify the effects of the saline tracers on reflections from transmissive fractures.

Moreover, multi-offset data enable the application of pre-stack migration algorithms, which can improve fracture imaging at greater distances from the borehole.

Regrettably, because commercial multi-channel borehole radar systems are not available in the market, practical difficulties hinder routine collection of multi-offset reflection data in a single borehole. A wave interferometric virtual source (WIVS) approach has been proposed to transform the cross-hole multi-offset transmission (CHMOT) mode radar data to single-hole, multi-offset reflection (SHMOR) data [10]. However, because the observed SHMOR data were not available at the time of study carried out in [10], only the SHCOR results are compared between the direct survey and the WIVS-derived virtual profile; and the results are generally in good agreement for representing the major features in a borehole drilled into crystalline bedrock. Direct comparison of SHMOR for the direction observation and the WIVS-derived synthesis is not practical at the present time due to the rare availability of the field observed SHMOR data.

Continuing the study conducted in Ref. [10] we report the study of a more extensive verification and validation of the WIVS-derived SHMOR approach by comparing it with newly collected SHMOR data set in the same well field where the CHMOT radar data were collected for previous WIVS studies [10]. The rest of this paper is organized as follows. In Section 2 we briefly review the theoretical outline of the WIVS approach and its application to borehole radar. Section 3 describes the geological and hydrogeological setting of the well field from where the borehole data were collected. Section 4 summarizes the major procedure and parameters of CHMOT and SHMOR borehole data acquisition. Section 5 presents the major features of the profiles and discussions of the comparison of field observed and WIVS-derived SHMOR profiles. Finally, Section 6 draws the conclusions and prospects for future development.

2. Theory of interferometry

Application of the wave interferometric virtual source (WIVS) approach provides a powerful tool for imaging the interior of rock formations. For an observation array distributed in a medium stimulated by any definitively or stochastically distributed energy sources (in both time and space), cross-correlation among different receiving nodes in this array can turn each node into a virtual "source" to radiate energy that can be sensed by other receiving nodes [11–14]. WIVS has been used for nondestructive testing of construction materials [15], biomedical imaging [16], and imaging the structures beneath complex overburden and salt domes [17].

Geophysical waves (e.g., radar waves) propagating through the earth traverse a highly reverberant environment result from wave-medium interaction due to the existence of numerous scatterers. For numerical modeling purposes, the medium can be bordered by i) a perfectly reflecting medium (the Dirichlet boundary condition) to form a closed medium; or ii) a perfectly transparent medium (the absorption boundary condition) to form an open medium; or iii) some combination of i) and ii) on different sides of the model. We consider a two-dimensional, open medium case. It is straightforward to extend the approach described below to three-dimensions.

Consider two receiver points a at $\mathbf{x}_a$, and b at $\mathbf{x}_b$, and a source point c at $\mathbf{x}_c$, and the source is excited with a time function $e(t)$. The two receivers and one source are randomly located in this domain with many multiple scatterers. If $T(\mathbf{x}_a, \mathbf{x}_c, t)$ is the wave field recorded at $\mathbf{x}_a$, and $T(\mathbf{x}_b, \mathbf{x}_c, t)$ is the wave field recorded at $\mathbf{x}_b$ due to the source at $\mathbf{x}_c$, respectively. Our goal is to recover the response at Location $\mathbf{x}_a$ caused by a virtual source at Location b, denoted as $R(\mathbf{x}_a, \mathbf{x}_b, t)$, through the responses of $T(\mathbf{x}_a, \mathbf{x}_c, t)$ and $T(\mathbf{x}_b, \mathbf{x}_c, t)$. As a sequence of processing steps, first, we can express the recorded wavefield at the two locations as

$$\begin{aligned} T(\mathbf{x}_a,\ \mathbf{x}_c,\ t) &= e(t)*g_{ac}(t) \\ T(\mathbf{x}_b,\ \mathbf{x}_c,\ t) &= e(t)*g_{bc}(t) \end{aligned} \tag{1}$$

where $g_{ac}(t)$ and $g_{bc}(t)$ are the impulse responses between a and c, and b and c, respectively; and * denotes the process of convolution. Eq. (1) stands for that the responses at $\mathbf{x}_a$ and $\mathbf{x}_b$ are the convolutions of the impulse response at the respective point with the source excitation function $e(t)$, i.e., $g_{ac}(t)$ and $g_{bc}(t)$ are the Green's functions for locations $\mathbf{x}_a$ and $\mathbf{x}_b$ when it has an exciting source at c in this particular inhomogeneous domain. The cross-correlation of the wavefield recorded at a and b is then

$$\begin{aligned} R(\mathbf{x}_a,\ \mathbf{x}_b,\ t) &= \int_{-\infty}^{\infty} T(\mathbf{x}_a,\ \mathbf{x}_c,\ t)\cdot T(\mathbf{x}_b,\ \mathbf{x}_c,\ t+\tau)\mathrm{d}\tau \\ &= T(\mathbf{x}_a,\ \mathbf{x}_c,\ t)*T(\mathbf{x}_b,\ \mathbf{x}_c,\ -t) \\ &= e(t)*g_{ac}(t)*e(-t)*g_{bc}(-t) \\ &= g_{ac}(t)*g_{bc}(-t)*f(t) \\ &= g_{ab}(t)*f(t) \end{aligned} \tag{2}$$

where the factor $f(t) = e(t)*e(-t)$ depends only on the excitation function $e(t)$ imposed at the source. Eq. (2) indicates that (1) the impulse response between locations $\mathbf{x}_a$ and $\mathbf{x}_b$ is contained in $g_{ab}(t)$, so that is the Green's function for the response at $\mathbf{x}_a$ for a source at $\mathbf{x}_b$; and (2) the real response $R(\mathbf{x}_a, \mathbf{x}_b, t)$ and the Green's function $g_{ab}(t)$ are proportional to each other and only differed by a factor of $f(t)$. Moreover, it should be noted that $R(\mathbf{x}_a, \mathbf{x}_b, t)$ has a length of $2^*N\text{-}1$ in time with N the original time length of the records. The above discussion is assumed that only one source exists at Location $\mathbf{x}_c$. In practical geophysical surveys it is necessary to use as many sources at different locations as possible. Availability of multiple resources provided better constraints for improving the accuracy of the WIVS extracted Green's functions.

Numerous previous studies [14,19,20] have demonstrated that for an ideal case with many true sources or scatterers/reflectors available in the domain, the following relationship exists:

$$\begin{aligned} &\int_S T(\mathbf{x}_a,\ \mathbf{x}_s,\ t)*T(\mathbf{x}_b,\ \mathbf{x}_s,\ -t)ds \\ &= T_S(\mathbf{x}_a,\ t)*T_S(\mathbf{x}_b,\ -t) \\ &= \delta(\mathbf{x}_a - \mathbf{x}_b)\delta(t) - R(\mathbf{x}_a,\ \mathbf{x}_b,\ -t) - R(\mathbf{x}_a,\ \mathbf{x}_b,\ t) \end{aligned} \tag{3}$$

To make the relationship more explicit, it is straightforward to justify that we can drop the first two terms on the right hand side of (3). The first term with the delta functions is mostly irrelevant to the problem, and the second term is non-causal with $t < 0$, so that only the third term has physical meanings. Finally we get:

$$R(\mathbf{x}_a,\ \mathbf{x}_b,\ t) = -T_S(\mathbf{x}_a,\ t)*T_S(\mathbf{x}_b,\ -t) \tag{4}$$

Eq. (4) states that the response between $\mathbf{x}_a$ and $\mathbf{x}_b$ is simply the cross-correlation of the two records at $\mathbf{x}_a$ and $\mathbf{x}_b$, which contains all information on the inhomogeneities and scatterers of the media.

For the case considered here, i.e., to get the reflection response as if the source (virtually, either point a or b) and receiver (point b or a) located in the same borehole, from the transmission response while the source (point c) and receivers (point a and b) in separate boreholes, (4) can be understood as more specifically with the letter R standing for reflection, and letter T for transmission as