Coherent interferometry migration for hard rock diamond drill-bit seismic

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SUMMARY

We use the direct wave interferometry migration with coherency measurement to image the diamond drill-bit. The sucess of such imaging can prove if the direct waves from the drill-bit can be detected. The drilling signals usually contain strong narrow band inteference noises. We suggest to use interferometry by deconvolution for migration, which widens the cross spectrum, hence the weak coherent features can be better observed. Additionally, we suggest to integrate coherent measurement of semblance or Multiple Signal Classification (MUSIC) into the algorithm in order to detect weak drill-bit signal. We test both methods with a synthetic and a diamond drill-bit seismic-while-drilling (SWD) field data. MUSIC coherency shows relatively better spatial resolution in contrast to semblance method. It also demonstrates better detectability of weak signal than summation and semblance. Our field SWD data also indicates that the interferometry migration can image the diamond drill-bit with appropriate survey parameters, and the MUSIC method achieves a high spatial resolution.

INTRODUCTION

One of important applicaton of interferometry imaging, which is also known as cross correlation migration, is for passive seismic imaging. One of the advantages is that there is no need to know the source position and the form of its wavelet (Schuster et al., 2004; Yu and Schuster, 2006). Herein, we focus on using interferometry imaging for searching the drill-bit direct wave, and imaging the diamond drill-bit. One of the drill-bit imaging potential applications is to obtain time depth information while drilling. The velocity can be used to calibrate the surface seismic image. It can further help to steer drill-bit to the desired target by locating the drill-bit on the surface seismic image.

In our SWD experiment, we acquired drilling data with a diamond drill-bit in hard rock formation. In order to detect its weak bit signal under noisy drilling environments, we need to use a signal detection method. In this paper, we propose to use coherency measurement, semblance and Multiple Signal Classification (MUSIC), to increase signal detectability. Semblance is widely used in seismic processing. MUSIC coherency is not conventionally used, but we show it is also a robust technique for seismic coherency analysis.

In this paper, we test the migration method with synthetic and field SWD data. The synthetic data shows improved spatial resolution and detectability with coherent interferometry migration. In particular, the MUSIC method demonstrates better result than summation and semblance methods. Our field experiment shows that the drill-bit signal can be detected, and its imaged position is where expected.

THEORY

The interferometry migration inverts the correlated seismic data for the reflectivity or source distribution (Schuster et al., 2004). Figure 1 illustrates interferometry imaging with an unknown

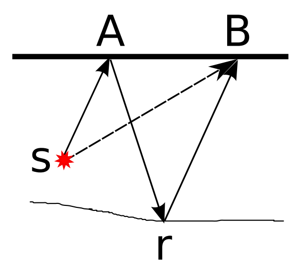


Figure 1: Interferometry migration for source location and reflectivity imaging

source position and its wavelet. It only shows the ray path of direct wave (SA, SB), and the first order multiples ($SArB$).

In frequency domain, the receivers at position A and B in a homogeneous lossless media can be modeled as,

$$\begin{aligned} d_A(\omega) &= s(\omega)e^{-i\omega t_{sA}} \\ d_B(\omega) &= s(\omega)e^{-i\omega t_{sB}} + s(\omega)Re^{-i\omega(t_{sA}+t_{Ar}+t_{rB})} \end{aligned} \tag{1}$$

where $s(\omega;x)$ denotes the source functions at position s, and ω is angular frequency, t_{sA} and t_{sB} denote travel time from s to A and B, and t_{Ar} and t_{rB} are travel times of first order multiple from A to r and r to B. Then the cross correlation between trace A and B, taking $d_A(\omega)$ as the reference is

$$\Phi(\omega) = d_A^* d_B = \underbrace{|s(\omega)|^2 e^{-i\omega(t_{sB}-t_{sA})}}_{\text{direct wave time delay}} + \underbrace{|s(\omega)|^2 Re^{-i\omega(t_{Ar}+t_{rB})}}_{\text{reflectivity}}, \tag{2}$$

where asterisk denotes the complex conjugate. Here I ignore some other terms, such as correlation noises. The image of the underground source position with direct wave time delay term in the correlation domain is achieved by summation of time delayed response of a receiver array against the pilot channel, namely (Schuster et al., 2004; Yu and Schuster, 2006),

$$m(x) = \sum_{A,B}\sum_{\omega} \Phi(A,B;\omega)e^{i\omega(t_{xB}-t_{xA})}, \tag{3}$$

where (A,B) denotes the sum over pair traces for correlation, A denotes the reference channel, and B belongs to a receiver array indexed from 1 to N. Φ denotes the correlation between traces A and B. The kernel of interferometry migration for unknown source position is the first term of $e^{i\omega(t_{xB}-t_{xA})}$.

To increase the narrow band weak signal detectability in the correlation domain, we utilize deconvolution interferometry migration, which widen the cross spectrum by deconvolving with a reference trace. Then the correlation can be conveniently expressed as (Vasconcelos and Snieder, 2008),

$$D(\omega) = \frac{d_A^*(\omega) d_B(\omega)}{|d_A(\omega)|^2} = \frac{d_B(\omega)}{d_A(\omega)}, \tag{4}$$

where asterisk denotes complex conjugate. By deconvolving with reference trace d_A, this operation removes the receiver function d_A, and widens the cross spectrum. Hence, the resolution of time delays is increased. Additional benefits of this procedure is that it removes ghosts or contaminations from other distinct sources in an open scattering medium (Derode et al., 2003; Weaver and Lobkis, 2006).

Here, we employ the coherency measurement into the migration process. Using the degree of coherency for imaging is useful to minimize the destructive interference in summation, and it is more applicable for weak coherent signals. Then the correlation migration can be expressed as,

$$m(x) = coherency\left(\sum_{\omega} D(A,B;\omega;\tau) e^{i\omega(t_{xB}-t_{xA})}\right), \tag{5}$$

where τ denotes the coherent time window, which belongs to $(-w,+w)$, where w denotes the sample points. We investigate two coherency measurements, semblance and multiple signal classification (MUSIC). Former one is commonly used in seismic coherency analysis, and the latter one has potential advantages of higher imaging resolution over semblance.

Semblance is most commonly used for coherency analysis. The semblance is normalised output to input energy ratio of a windowed hyperbola (Taner and Koehler, 1969; Yilmaz, 2001; Landa and Keydar, 1998), given as

$$S(x_0,t_0) = \frac{1}{M}\frac{\sum_{\tau=-w}^{w}\left(\sum_x u(x,t(x)+\tau)\right)^2}{\sum_{\tau=-w}^{w}\sum_x u(x,t(x)+\tau)^2}, \tag{6}$$

where M is the number of traces indexed by x, and τ ranges over a time window $(-w,+w)$. The semblance has value in range $0 < S < 1$. The advantage of using semblance over the simple summation is that it takes into account of the similarity of the signals in the given time window. The length of the time window controls the trade-off between a reduced resolution in time domain and low S/N detection (Bona et al. 2013).

MUSIC (Multiple SIgnal Classification), is an algorithm classically used for direction of arrival (DOA) estimation, and was first proposed by Schmidt (1986) for multiple emitter locations and signal parameter estimation. For applications of seismic imaging, it can also be used to coherency analysis. We invite readers to refer to Asgedom et al. (2011) for more detailed description. The MUSIC coherency can be expressed as

$$P_{MU}(t_0,x_0) = \frac{a^T \cdot a}{a^T[E_n \cdot E_n^T]a} \tag{7}$$

where $a = [1,1,1,\cdots,1]^T$ is a fixed steering vector. $E_n = [e_{W+1},\cdots,e_M]$, where W split the signal and noise subspaces of left unitary matrix of singular value decomposed data matrix D_w. The D_w is time shifted windowed data D. While one only needs to steer the data in a time window to measure the degree of coherency, MUSIC can be integrated into seismic coherency analysis nicely.

SYNTHETIC EXAMPLE

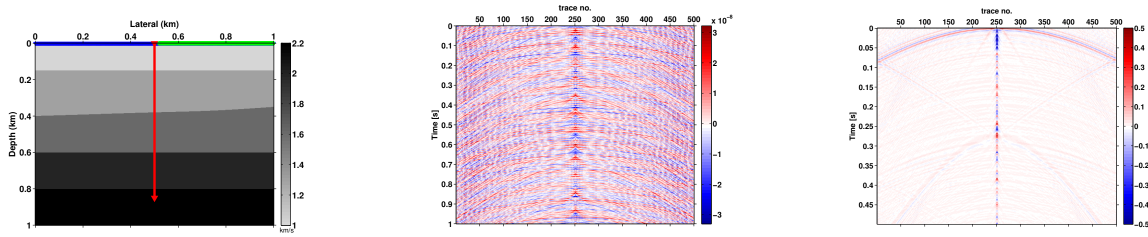
The interferometry migration by deconvolution is tested with a synthetic data. In a 2D model as shown in Figure 2(a), there are multiple layers (one dipping layer) with gradually increasing velocity. Both ends of the red line triangle denote the source positions (rig and bit), and the receiver spacing is $2m$. The surface source is modeled with a real diamond drilling data from Hillside, South Australia, which is recorded at about $15m$ from the rig. The buried source at depth of $850m$ is modeled with $80Hz$ Ricker wavelet convolved with white noise and $14Hz$ periodict signal. Figure 2(b) shows 1*second* modeled data gather.

Figure 2(c) shows cross correlation by deconvoluton of the synthetic data. Trace 240 is used as the pilot channel; It is located $20m$ from the modeled rig position. Figure 3 shows the interferometry migration of the bit. We compare the migration results between summation of standard cross correlation and coherent correlation migration. Both semblance and MUSIC are used. The imaging is limited in a $200m \times 200m$ area. Figure 3 (a) shows the standard migration result, where the displayed data is the envelope of the summed traces. For an impulse source, the standard migration should be robust and have higher resolution than semblance, because semblance is measured in a defined time window. However, with the drilling signal it shows lower resolution than coherent migration. This is primarily due to correlated signal bandwidth, which shows strong side lobes. The other reason causing the low vertical resolution in all three imaging results is due to limited aperture. Figures 3(b) and (c) show coherent correlation migration results using semblance and MUSIC respectively. Both semblance and MUSIC use 20 time sample window. Although the synthetic model consists of multiple layers, we use an effective constant velocity for imaging. Velocity of $1560m/s$ shows best imaging result as the effective velocity for the overburden above the underground source. However, due to the presence of a dipping layer, the imaged source position doesn't exactly match the true position (marked as triangle). The coherent correlation migration results demonstrate MUSIC's higher resolution over semblance. The semblance result is comparable to the standard migration in this model.

Coherent window width and timing errors

In Figure 4, we introduce zero mean timing errors in the model to evaluate the sensitivity of imaging to such errors. These errors may be caused by an imperfect velocity model, statics errors or complicated overburden on land seismic. As shown, the timing errors are represented by black solid line and red dashed line, where the black line indicates the $2ms$ standard deviation timing errors, and the red line indicates the $4ms$ standard deviation timing errors.

When using semblance as coherent interferometry migration,



(a) Velocity Model

(b) Seismogram

(c)

Figure 2: (a) 2D Synthetic Velocity Model. (b) 1*second* modeled raw data. (c)Array deconvolved with trace 240

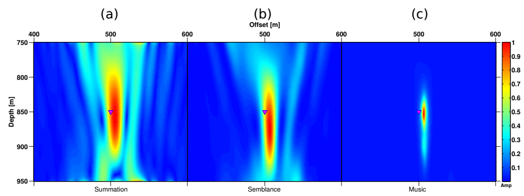


Figure 3: Coherent interferometry migration with large aperture based on summation displayed using envelope of the sum (a); semblance (b); MUSIC (c)

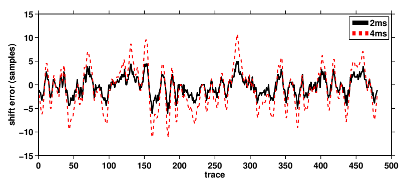
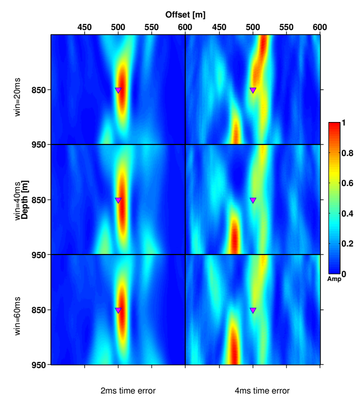


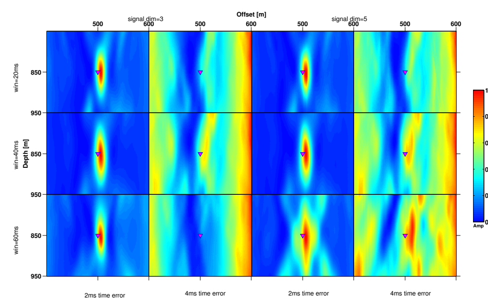
Figure 4: Introduced timing erros to the surface receiver array. The black solid line indicates the timing error with standard deviation of 2*ms*. The red dashed line indicates 4*ms* standard deviation timing error.

it has an extra parameter of coherent window to control the migration over the summation. Figure 5 (a) show the migration results with increasing coherent window length from top to bottom. However, the results show that the window length doesn't improve the resolution. The semblance method works as well as summation in the low timing error case, but is not able to resolve the true source under higher timing errors.

Besides the coherent window length, MUSIC coherent interferometry migration needs another parameter input, namely the signal space dimension, to control the measured coherency. Figure 5 (b) shows the migration results for different timing errors. The same coherent window length is used as for the semblance method, increasing along the rows. The signal dimension of 3 is used for first two columns, and the last two columns use 5. With 2*ms* std timing error, in general, MUSIC migration performs better than semblance in terms of resolution. Comparing different signal space dimensions, using low dimension shows better resolution. When there is higher std timing errors, it is also difficult for MUSIC to achieve proper imaging. However, for this 4*ms* std timing error data, with 40*ms* coherent window and signal space dimension 3 and 5, the imaged source starts to emerge. When we use 60*ms* coherent window and signal space dimension 5, as shown at the bottom right corner of Figure 5 (b), in spite of noisy image, the source position can be approximately identified.



(a)



(b)

Figure 5: (a) Coherent interferometry migration using semblance with different coherent window length. top: 20*ms*, middle: 40*ms*, bottom: 60*ms* with timing errors of 2*ms* (left) and 4*ms* (right). (b) coherent interferometry migration using MUSIC wth varying time window length and signal space dimension

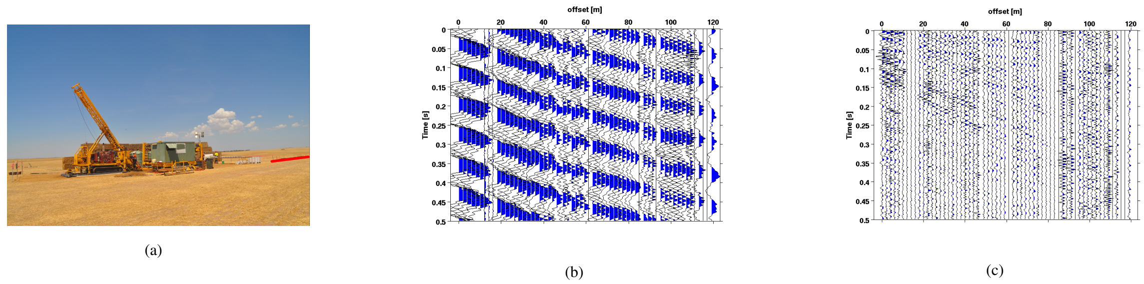


Figure 6: Hillside SWD diamond impregnated drilling (a); Half second raw data from receivers located 89m to 208m from the rig (b); After deconvolution with trace 21, air wave is suppressed with SVD filter

FIELD DATA EXAMPLE

The diamond drill-bit is known as a weak seismic source. By employing the coherent measurement of semblance or MUSIC, we investigate the possibility to detect the direct waves from the drill-bit, and image it. The experiment was done at the Hillside mine site, South Australia. Two days SWD experiment was conducted after a 3D active seismic survey at the mine site. The drill-rig is located about 600m away from the survey area. The drilling direction was towards the west, and dipping at 53^o, as shown in Figure 6(a), where the red line indicates the receiver array. It is approximately above the drill-bit direction. The data collected at 110m measured depth (equivalent to vertical depth of 85m) is used for the following analysis.

Figure 6(b) shows a 0.5s raw data recorded at receiver line. The seismogram is dominated by low frequency energy at 14Hz, which is related to the drilling rotation rate at about 800RPM. Figure 6 (c) shows the cross correlation by deconvolution with channel 21. The correlation result is done after suppressing the air wave using singular value decomposion method (SVD) (Jones and Levy, 1987; Al-Yahya, 1991; Montagne and Vasconcelos, 2006). The high apparent velocity coherent move-out are shown, which is about 3000m/s by measuring the linear move-out of the first arrival. This is unlikely the drill-rig direct move-out, because the velocity is too high for a surface wave. Also this move-out is not observed by correlating with other geophones near the rig. Given only two vibration sources, the rig and the bit, this should be the direct wave from the drill-bit.

The coherent interferometry migration is applied to the data from Figure 6 (c). The pilot channel is about 70m away from the rig. The imaging of the targeted area is only partially illuminated by the limited aperture, which leads to low resolution at depth. The results are shown in Figure 7 with an assumed constant effective velocity. Since we have approximate knowledge of the drill-bit position based on driller's information, We test the imaging focusing result with varying velocity. The triangle denotes the expected the drill-bit position. The velocity of 1400m/s results in the best focus. Also three methods are used, summation, semblance and MUSIC, accordingly from left to right in Figure 7. The summation migration shows weak focus at the expected source position. The semblance shows prominent amplitudes, and MUSIC shows better resolution. This demonstrates usefulness of interferometry migration by deconvolution using coherency, and while imaging the drill-bit position, the velocity information can be obtained in the vicinity of the bore hole.

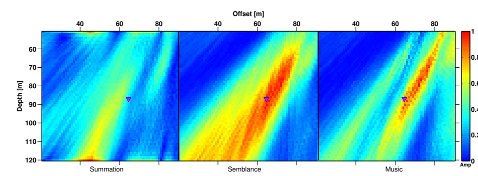


Figure 7: Diamond drill-bit data cross correlation migration using summation (left); semblance (middle); MUSIC (right)

CONCLUSION

We show that the drill-bit signal can be detected when the drilling depth is shallow in the Hillside diamond drill-bit SWD experiment. The coherent interferometry migration is able to image the drill-bit position. The MUSIC coherent migration shows good imaging resolution in comparison with semblance in application to passive seimsic. While locating the drill-bit, we can also obtain updated velocity around bore hole. All these information could benefit drilling engineers and geophysicist.

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