

## Seismic characterization of reservoirs with variable fracture spacing by double focusing Gaussian beams

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### Summary

Fractured reservoirs account for a majority of the oil production worldwide and often have low recovery rate. Fracture characterization is important in building reservoir flow models for enhanced oil recovery. Information about fracture orientation, fracture spacing, and fracture compliances is essential. When a fracture network consisting of multiple sets of fractures with variable fracture spacing/orientation is present, we have to determine the spatial information about them as this may represent important connectivity information for fluid flow. We present a seismic method that can achieve the above goals in the context of seismic scattering, when the fracture spacing is on the order of half of the wavelength. The method is based measuring the beam interference pattern for two Gaussian beams focused on a fractured reservoir location, one beam from the sources and the other from the receivers. Numerical examples show that our method can provide spatially dependent information on fracture parameters.

### Introduction

Naturally fractured carbonate reservoirs occur worldwide and they account for the bulk of oil production. Fractures may provide essential porosity and permeability for fluid flow (Nelson, 2001). In the Mideast and Mexico, the bulk of the oil production is from fractured reservoirs. The fractured reservoirs are usually associated with low recovery factor. Characterizing the fracture network, fracture orientation and spacing is important. Fracture compliances, which measure how easy fracture surfaces can slip against each other (tangential compliance) or how easy the fracture can be opened (normal compliance), are important too. Another incentive to characterize fractures is that fracture orientations can place constraints on the stress state of the field and yielding better geo-mechanical models. Therefore to enhance oil production in fractured reservoirs, we need better characterize the fractures. Kang et al. (2011; 2013) showed that if fracture plane orientation, spacing and permeability are known, one could better capture flow transport behavior in fractured media.

There are several existing methods for fracture characterization. Direct coring of the borehole or formation micro-imager (FMI) logger provides local information on the scale of inches. Extrapolating information from these

measurements away from the wellbore is difficult. In cases where a fracture intersects a borehole with downhole seismic instrumentation, seismic waves generated by the source impinging upon the fracture can squeeze fluid from the fracture into the borehole and generate borehole tube waves, which can be used to study compliance of the single fracture (Huang and Hunter, 1982; Beydoun *et al.*, 1984; Beydoun *et al.*, 1985; Li *et al.*, 1994; Kostek *et al.*, 1998a; Kostek *et al.*, 1998b; Bakku *et al.*, 2013). A fractured reservoir having aligned fractures whose spacing is much smaller than a wavelength (i.e. less than tenth of the wavelength) can be treated as an equivalent anisotropic medium with HTI anisotropy if fracture planes are vertical (Assad *et al.*, 1992; Tatham *et al.*, 1992). Common methods based on seismic anisotropy includes the Amplitude-Versus-Azimuth (AVAz) analysis of reflected P waves (Ruger and Tsvankin, 1997; Johns *et al.*, 2008; Sabinin and Chichinina, 2008) or shear wave splitting analysis (Tatham *et al.*, 1992; Sayers, 2002; Vetri *et al.*, 2003; Rial *et al.*, 2005; Yang *et al.*, 2005; Verdon *et al.*, 2009). These methods usually assume a single set of parallel fractures. However, multiple sets of fractures cutting each other are readily observed in the field and it is not clear how effective those methods could be in this regard. Fractures are mechanical discontinuities that scatter seismic waves. When the fracture spacing is large, the equivalent medium cannot work. Based on the azimuthal variation of the common-mid-point (CMP) stacks, Willis et al (2006) proposed a seismic scattering index method, which studies the azimuthal variation of the CMP stack for fracture-scattered signals. However, this method is not effective in distinguishing multiple sets of fractures. Zheng et al. (2013) proposed a new method which is based on interfering two focused Gaussian beams onto the fractured reservoir location with one beam from the surface sources and the other from the surface receivers. This method has been shown to be very effective in characterizing fractures in an orthogonal fracture network with constant fracture spacing but spatially variable fracture compliances. However, in reality, the fracture spacing may be variable too. In this abstract, we investigate this case.

### Theory and Method

To illustrate the basic idea, let us first consider the simplest fracture system where the fractures are vertically situated in a homogenous medium and are parallel to each other. The spacing between neighboring fractures is  $a$  and all fracture planes are within the same vertical interval. Let us consider

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plane wave incidence upon this periodic medium. If the incident plane wavenumber is  $\mathbf{k}^s$ , the scattered plane wave  $\mathbf{k}^g$  must be discrete,  $\mathbf{k}^g = \mathbf{k}^s(n)$  (e.g., Rayleigh, 1907; Aki and Larner, 1970; Ishimaru, 1991). Although  $n$  can be any integer, we only consider the first backscattering. In this case, the horizontal wavenumbers must satisfy the following relation:

$$\mathbf{k}_r^g = \mathbf{k}_r^s - \frac{2\pi}{a} \hat{\phi} \quad (1)$$

where  $\mathbf{k}^s = (\mathbf{k}_r^s, k_z^s)$ ,  $\mathbf{k}^g = (\mathbf{k}_r^g, k_z^g)$ , and  $\hat{\phi}$  is the fracture orientation defined as a unit vector perpendicular to the fracture plane. We emphasize that equation (1) is valid not only for singly scattered waves but also for multiply scattered waves in the vicinity of the fracture reservoir. The important information in equation (1) is that the scattered wave number  $\mathbf{k}^g$  is directional and is related to the fracture spacing  $a$  and orientation  $\hat{\phi}$ . From equation (1), we can see that the minimum fracture spacing we can resolve is  $\lambda/2$  for  $P$ -to- $P$  scattering where  $\lambda$  is the  $P$  wavelength near the fractured reservoir. Similar analyses can be done for other modes of scattering. Shear waves can also be used to probe fractures with smaller spacing. We will now construct the double focusing Gaussian beam stacking algorithm.

We have observed that fracture scattered signals are directional and related to fracture orientation and spacing. This requires that our propagator for stacking the seismic data must have propagation direction information. Since the fracture parameters may vary with location, the propagator must also be localized in space. A propagator simultaneously localized in both the space and the wavenumber domains is a beam propagator. Gaussian beams (e.g., Cerveny, 1982; Popov, 1982; Hill, 1990, 2001; Cerveny, 2005; Gray and Bleistein, 2009) hence are natural choices. It is well known that Gaussian beam is a globally regular propagator and can handle caustics in complex smooth media for high-frequency waves; the amplitude preserving property of the Gaussian beams is essential for retrieving fracture compliance values. Details concerning Gaussian beam solutions can be found in the above-cited references. Assume that, at the target location  $\mathbf{r}$ , a Gaussian beam with unit amplitude, zero beam-front curvature (i.e., a local plane wave), and beam width  $w_s$  is shot upward (Figure 1) along the slowness vector  $\mathbf{p}^s$  and recorded at source location  $\mathbf{x}_s$

$$b_s(\mathbf{x}_s | \mathbf{r}, \mathbf{p}^s, w_s, \omega) = A_s(\mathbf{x}_s) e^{i\omega\tau(\mathbf{x}_s)}$$

where  $A_s$  is the complex amplitude,  $\tau(\mathbf{x}_s)$  is the complex traveltime. If we time-reverse the source beam  $b_s$  and propagate it into the medium and we should recover it. The same is true for the receiver beam  $b_g$

$$b_g(\mathbf{x}_g | \mathbf{r}, \mathbf{p}^g, w_g, \omega) = A_g(\mathbf{x}_g) e^{i\omega\tau(\mathbf{x}_g)}$$

is the receiver beam with complex amplitude  $A_g$  and complex traveltime and beam width  $w_g$  at the fracture target. However, the direction of the source beam and the receiver beam are related by (1). The double focusing Gaussian beam interference pattern at a fractured target is

$$\sigma = \sigma(a, \hat{\phi} | \mathbf{r}, w_s, w_g, \omega) \quad (2)$$

which measures diffraction created by a set of fractures localized at  $\mathbf{r}$ . We can compute  $\sigma$  by summing over all surface sources and receivers within the support of the beams:

$$\sigma \cdot \iint A_g^2(\mathbf{x}_g) d^2\mathbf{x}_g = 2i\omega p_z^s \iint d^2\mathbf{x}_g \iint d^2\mathbf{x}_s F^*(\mathbf{x}_g, \mathbf{x}_s | \mathbf{r}, \mathbf{p}^s, \mathbf{p}^g, \omega) D(\mathbf{x}_g, \mathbf{x}_s, \omega) \quad (3)$$

where the *double focusing Gaussian beam stacking operator*  $F^*$  reads:

$$F^* = A_s^*(\mathbf{x}_s) A_g^*(\mathbf{x}_g) e^{-i\omega\tau(\mathbf{x}_s) - i\omega\tau(\mathbf{x}_g)} \quad (4)$$

and  $D(\mathbf{x}_g, \mathbf{x}_s, \omega)$  is the frequency-domain seismic data.

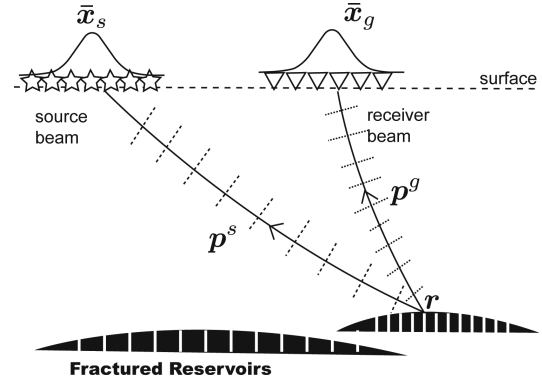


Figure 1. Schematic for double focusing Gaussian beams.

### Examples

We perform a numerical example to show the methodology. A fractured reservoir is embedded in a 3D layered model (Figure 2). There are 4 layers with constant layer thickness of 200m. The fracture network is in the

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third layer. We call FracX the set of fractures parallel to the X-axis, and FracY the set parallel to the Y-axis. For both FracX and FracY, all fractures are parallel to each other but with variable fracture spacing between fractures. We simulate seismic shot gathers using a 3D staggered grid finite-difference method (Coates and Schoenberg, 1995; Fang *et al.*, 2013). Fractures in the model are treated as linear-slip boundaries (Schoenberg, 1980). An absorbing boundary condition using perfectly matched layers (PML) is imposed on all sides of the model. The source time function is a Ricker with the central frequency 40 Hz. Fracture spacing varies from 40 m to 100 m. In our test, we simulated full elastic wave propagation in the model with 4C acquisition (i.e., pressure and 3-component particle velocities). However, in the double beam stacking we only used the pressure component recorded by the receivers. So in this case, only the normal compliance field is determined.

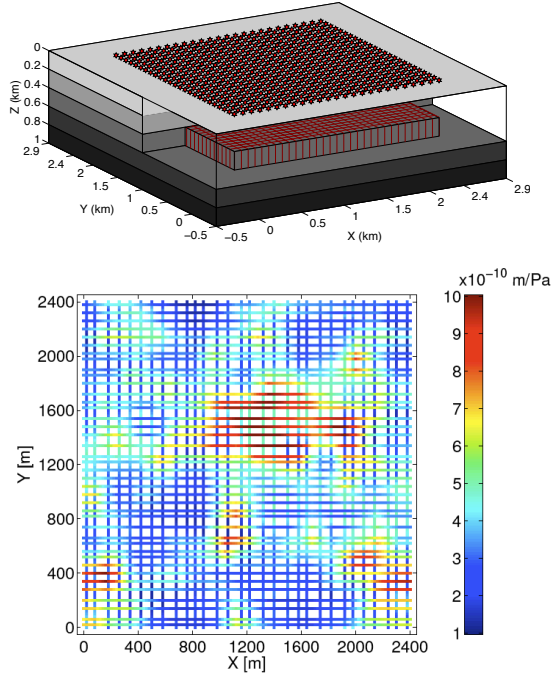


Figure 2: Fracture network for the fractured reservoir. Color indicates fracture compliance field. All fractures are vertical. The fracture network has two sets of fractures orthogonal to each other, with variable fracture compliance and spacing. The background model has five layers. The layer thickness is uniform 0.2km. P-wave velocities are 3.0, 3.2, 3.5 and 3.8km/s from the top to the bottom layer. We use a constant velocity ratio for P-wave ( $V_p$ ) to S-wave ( $V_s$ ):  $V_p/V_s=1.7$ . Densities for the layers are 2.2, 2.22, 2.25 and 2.28g/cm<sup>3</sup> from top to bottom. Both the sources and receiver are within a square  $[0,2400m] \times [0,2400m]$ . The source spacing is about 50m and the receiver spacing 10m. There are 1200

shots total. The variation in the fracture spacing is  $\sim 30\%$  of the mean spacing.

To implement the double focusing Gaussian beam algorithm, we choose a frequency of 50Hz. However, using multiple frequencies can increase the detection robustness and accuracy. In this paper, we only show results for this frequency. At 50Hz, the P wavelength is about 70m and therefore the minimum fracture spacing that can be theoretically resolved is  $\sim 35m$ . We set the beam widths to be 100m, e.g.,  $w_s = w_g = 100m$ . Since our method is target oriented, we choose 21x21 fractured targets at depth 420m, within a square  $[0,2400] \times [0,2400]m$ . The targets are uniformly distributed with a distance of 120m between targets in both X and Y directions. For each fracture target, we scan all possible fracture spacings and orientations.

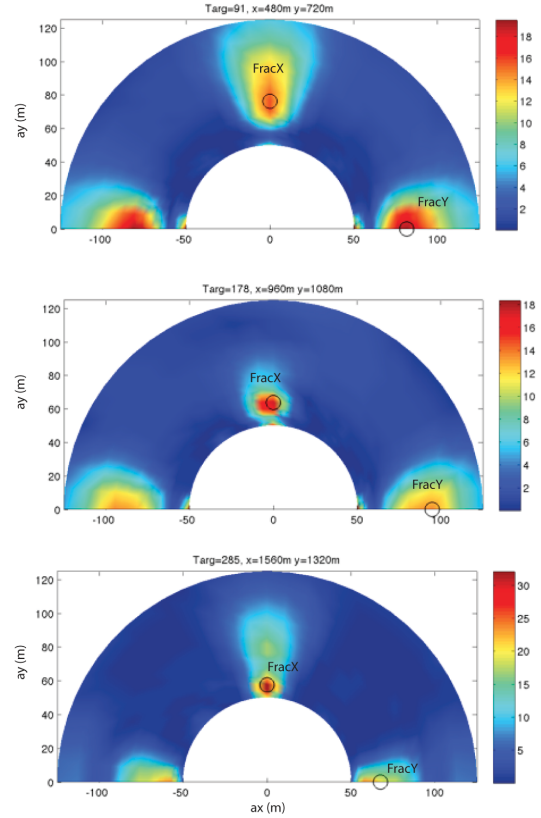


Figure 3. Double focusing Gaussian beam results  $|\sigma|$  for three fracture locations, showing that two orthogonal fracture sets (FracX and FracY) are present. The radius  $a = \sqrt{a_x^2 + a_y^2}$  indicates the fracture spacing from 50m to 120m. The angle,

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$\tan^{-1}(a_y/a_x)$ , counter-clock-wise from the positive horizontal axis, measures the pole orientation of the fracture. There is a 180-degree ambiguity. So the FracY pattern is symmetric about the vertical axis. The color indicates focusing amplitude at the target for the double Gaussian beams. Circles are picked fracture parameters.

Inversion results show that there are two sets of fractures, orthogonal to each other (Figure 3). It is interesting to see that for target 285 (Figure 3), there are two strong amplitudes corresponding to FracX. Our computer-based automatic picker picked the stronger one. Careful inspection of target 285 shows that around this target, there is a large gap in fracture spacing (Figure 4) at  $y = 1320m$ . This indicates that method is able to distinguish two-scale fracture spacing within the mutual support of the double beams. We can then pick out the two fracture sets separately and plot the seismic focusing amplitude and compare them to the model compliance fields (Figure 4 and Figure 5).

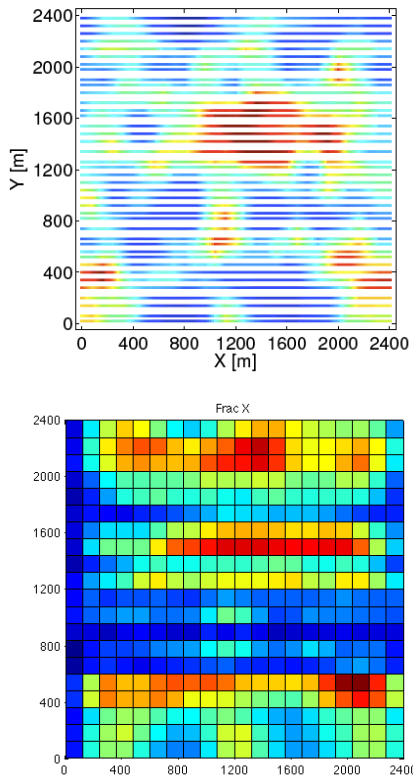


Figure 4. Comparison between the model compliance field (top) and the double focusing Gaussian beam amplitudes (bottom) for FracX. Red indicates large compliance and blue small compliance.

Patterns of the compliance field have been recovered (Figure 4 and Figure 5). The double focusing Gaussian beam method outputs an interference pattern due to scattered waves from different fractures. Scattering strength, which is measured by the double-beam method, is proportional to the ratio of fracture compliance to fracture spacing. Thus, regions with low compliance and small fracture spacing may show up as regions of strong scattering and high apparent compliance in the plots.

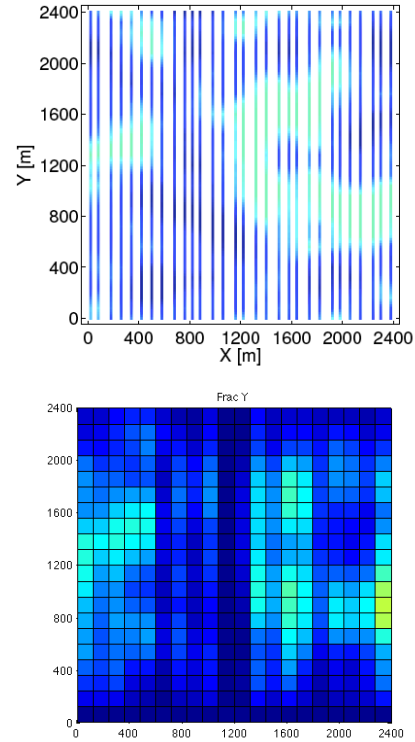


Figure 5. Comparison between the compliance field (top) and the double focusing Gaussian beam amplitudes (bottom) for FracY.

### Conclusions

We have shown that the double focusing Gaussian beams can characterize a fractured reservoir with a fracture network of variable fracture spacing and compliances. The beam focusing amplitude depends on both the true compliance and the fracture spacing. Our model shows with 30% variation in the fracture spacing, our method works well. The method can now be applied to more realistic geology.

### Acknowledgments

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