Report 14

Improved Autocorrelogram Imaging Condition for Obtaining IVSP’s While Drilling

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ABSTRACT

I present the equations for migrating IVSPWD (inverse VSP while drilling) autocorrelograms. These equations extend the Katz IVSPWD method to 2-D and 3-D media, and also provide a formal mathematical justification for inverting the reflectivity distribution from IVSPWD autocorrelograms. In addition, I describe a new imaging condition which images the primary-reflection energy compared to the Katz IVSPWD method which images the layer reflections that emanate from a free-surface ghost reflection. Raypaths associated with ghost reflections are typically 2-3 times longer than primary reflections, and so attenuate much more from geometrical spreading and anelastic losses. Consequently, the primary-reflection imaging condition promises to provide an order-of-magnitude improvement in reflection strength over that of the ghost-imaging condition. It is recommended that this new imaging condition be used for the standard autocorrelation IVSPWD method.

INTRODUCTION

TOMEX is a method for obtaining inverse vertical seismic profiles (IVSP) from seismic signals generated by a rotating drill bit and recorded by surface-located geophones. A geophone is placed at the drilling rig to record the source wavelet associated with the rotating bit, and this wavelet is used to deconvolve the reflected signals recorded by a seismic array on the surface. Although the TOMEX method has provided useful results to the oil industry, DOE recently funded an effort to look at an alternative IVSP method based on the patent of Lew Katz.
Lew Katz proposed the idea of constructing inverse vertical seismic profiles while drilling (IVSPWD) by computing the autocorrelation of seismograms recorded on the surface. The source energy emanates from the drill bit that randomly bounces around the bottom of the drill hole, where the autocorrelation of the drill-bit signal is assumed to be an impulsive zero-phase wavelet. The theoretical advantage of Katz’s IVSPWD method over that of the TOMEX method is that the source wavelet does not need to be known, hence the problems with TOMEX’s source deconvolution can be avoided to give a higher frequency signal. Two potential shortcomings of the IVSPWD method are that 1). its formulation is for a 1-D model only, and 2). the layer reflections emanate from a free-surface ghost arrival which are much weaker than the primary reflections generated by the direct wave in the Tomex method.

In this paper I overcome the two potential shortcomings of Katz’s IVSPWD method by extending its applicability to 2-D and 3-D media and by developing a new imaging condition that uses the direct-wave signal, not the free-surface ghost reflection, as the source of layer reflections. Moreover, I present theoretical formulae which provide a rigorous foundation to the autocorrelation IVSPWD method.

**MIGRATION OF IVSPWD AUTOCORRELOGRAMS**

The extension of Katz’s IVSPWD method to 2-D and 3-D media is simple: autocorrelate the seismograms recorded at the surface and migrate the autocorrelograms using the autocorrelogram imaging condition reported in Schuster et al. (1996). It is shown in that report that the migrated image is proportional to the gradient of the autocorrelogram misfit function. Details are given in Schuster et al. (1996) but the imaging formulae will be presented in this article. These imaging formulae are valid for 2-D and 3-D media and can easily be adjusted to take into account particle velocity information recorded by multi-component phones.

Assume seismic energy emanating from a drill-bit source at depth \( r_s \) and recorded by geophones at \( r_g \) on the surface, where the observed data are given by \( s(r_g, r_s, \tau) \). The autocorrelated data are given by \( \phi_{ss}(r_g, r_s, t) = s \otimes s \), and the migrated image \( m(\mathbf{x}) \) is given by the following formula:

\[
m(\mathbf{x}) = \sum_{g,s} \ddot{\phi}_{ss}(r_g, r_s, \tau = \tau_{sx} + \tau_{gx} - \tau_{sg}), \quad (14.1)
\]

where the summation is over all source depths and geophone positions on the surface; \( \tau_{sx}, \tau_{gx}, \) and \( \tau_{sg} \) are the traveltimes for energy to directly propagate, respectively, from the source to the image point at \( \mathbf{x} \), from the geophone to the image point, and from the source to the geophone location; and \( \ddot{\phi}_{ss} \) is the second-time derivative of the wavelet’s autocorrelation function. Multiplicative factors related to geometrical spreading and inversion (Schuster et al., 1996) have been harmlessly dropped,
and we assume that the autocorrelograms have been deconvolved using the wavelet autocorrelation function.

Equation 14.1 says that the image at point $\mathbf{r}$ is obtained by summing trace energy along the curve defined by $\tau = \tau_{sx} + \tau_{gx} - \tau_{sg}$, where the direct wave traveltime $\tau_{sg}$ is subtracted from the two-way scattered traveltime $\tau_{sx} + \tau_{gx}$. Compare equation 14.1 to that for migrating reflection seismograms:

$$m(\mathbf{x}) = \sum_{g,s} \hat{s}(\mathbf{r}_g, \mathbf{r}_s, \tau = \tau_{sx} + \tau_{gx}),$$

(14.2)

which says that the image at point $\mathbf{r}$ is obtained by summing trace energy along the pseudo-hyperbola curve defined by $\tau_{sx} + \tau_{gx}$.

### IVSPWD Ghost Reflection Imaging Condition

The Katz IVSPWD method uses layer reflections that arise from the free-surface ghost reflection. The associated ghost-reflection imaging condition in equation 14.1 is given by the following formula:

$$\tau \rightarrow \tau_{sx_0} + \tau_{x_0,x} + \tau_{xg} - \tau_{sg},$$

(14.3)

where the raypaths are depicted in Figure 14.1 and $\mathbf{x}_0$ defines the ghost-reflection point on the free-surface. These traveltme fields can be computed by a ray-tracing method, or by a finite-difference solution to the eikonal equation using the symmetry condition shown in Figure 14.2.

For a 1-D layered model, this migration image reduces to the image produced by the IVSPWD method of Katz. In addition, for a 1-D model no migration velocity is needed because a semblance analysis can be easily performed to determine the most focused time-migrated image. Two additional merits of this migration equation are that it is valid for 2-D or 3-D media and it is also underlain by a rigorous theoretical foundation.

### IVSPWD Primary Reflection Imaging Condition

The problem with the ghost-reflection imaging condition is that it relies upon the ghost reflection as a source of seismic waves. For a deep drill bit located at depth $d$ just above a reflecting layer interface, the associated ghost-reflection raypath is about three times the length of the primary-reflection raypath. Consequently, ghost-reflection energy from a slightly deeper reflector degrades by geometrical spreading as $0.1/d^2$ compared to a degradation of $1/d^2$ for primary reflections generated by the direct wave (see Figure 14.3). Moreover, the viscoelastic attenuation of energy will be much greater for the ghost reflections because their raypaths will be approximately three times longer than the primary-reflection raypaths. Figure 14.4 clearly shows that the amplitude of the primary reflections is more than an order-of-magnitude stronger than the corresponding ghost reflections for Q’s equal to 40 or less.
Figure 14.1: Ghost reflection from the free surface and associated rays denoted by the dashed lines. The traveltime for energy to directly propagate from $a$ to $b$ along a raypath segment is denoted as $\tau_{ab}$. Also depicted is the direct wave denoted by the dotted line.

And finally, reverberations within the near surface will tend to distort the ghost source wavelet and thereby smear the ghost reflections. For these reasons, the primary reflections should also be exploited and perhaps take precedence over the ghost reflections in obtaining IVSPWD.

The primary-reflection imaging condition is given by setting $\tau$ in equation 14.1 to

$$\tau \rightarrow \tau_{sx} + \tau_{gx} - \tau_{sg},$$

where the associated raypaths are shown in Figure 14.3, and $x$ is always located below the drill bit. Note, this migration imaging condition is valid for 2-D or 3-D media and utilizes the primary-reflection events like the TOMEX method, except the source wavelet does need to be known. Its advantage over the ghost-imaging condition is that it extracts reflection signals that are more than an order-of-magnitude stronger.

**Other IVSPWD Imaging Conditions**

Other imaging conditions can be created in an obvious manner. For example, a primary SP-reflection imaging condition can be implemented with equation 14.4 by computing traveltimes associated with downgoing S waves and upgoing reflection P waves. This type of imaging could be important because the drill bit may have a radiation pattern that is strong in direct shear waves but weak in direct P waves. Obviously, there are many other imaging conditions that can be created to exploit the strongest signals contained in the IVSPWD data, where equation 14.1 is the keystone equation.
Figure 14.2: Image model created by reflecting Figure 1 model across the free surface. Placing a source at the drill bit (denoted by a star) and solving the eikonal equation will yield the traveltime field $\tau_{sx_0} + \tau_{xp_x}$. 
Figure 14.3: Primary reflections where the direct-wave energy reflects off a reflector deeper than the drill bit. The free-surface ghost that reflects off this reflector (see Figure 1) has a raypath that is about three times longer the primary-reflection raypath shown above. Consequently, the primary-reflection energy will be about 10 times stronger than the corresponding ghost reflection because of geometrical spreading effects.

**SUMMARY**

I presented a rigorous theoretical foundation for an improved autocorrelation IVSPWD method that is applicable to 2-D and 3-D media. Moreover, a variety of imaging conditions can be used to utilize the dominant signals in the recorded traces. For example, a primary-reflection imaging condition is presented that, in principle, will produce a reflection signal that is more than an order-of-magnitude stronger than the ghost-reflection signal utilized by the Katz IVSPWD method. The strength of this reflection signal is similar to that used in the TOMEX method, except the source wavelet does not need to be recorded. Another example is the imaging condition for PS primary reflections which can exploit the dominant shear energy that is characteristic of some drill-bit radiation patterns in certain geologic strata.

A disadvantage of the primary-reflection imaging condition is that it only focuses energy beneath the drill-bit, compared to the ghost imaging condition which reveals reflections throughout the model. The migration velocity needs to be known for 2-D and 3-D media, but not for 1-D media.

It might also be useful to explore the possibility of simultaneously using these different imaging conditions together to increase the signal-to-noise ratio of the reconstructed reflectivity section. It appears that the primary-reflection imaging condition should be significantly superior in imaging the reflectivity distribution than provided by the ghost-imaging condition. Hence, I recommended that this new imaging condition be used for the standard autocorrelation IVSPWD method.
Figure 14.4: Direct waves, primary reflections (R1 and R2) and ghost reflections (R1g and R2g) for a source at a depth of 6000 feet and layer interfaces at depths of 7000 feet and 8000 feet. These synthetic data are generated for different Q values by a 3-D ray tracer, where the offset between the well and the surface geophones range from 0 to 12,000 feet. The free-surface ghost reflection has a raypath that is about three times longer than the primary-reflection ray. Consequently, the primary-reflection energy can be more than 100 times stronger than the corresponding ghost reflection because of attenuation and geometrical spreading effects. Each plot is normalized to the maximum R1 amplitude in that plot.
REFERENCES