Automatic Time Picking and Velocity Determination on Full-Waveform Sonic Logs

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Summary

Manual picking of first arrivals on full waveform sonic logs is not practical on a regular basis, as a typical full waveform sonic log consists of thousands to tens of thousands of seismograms. We develop an automatic picking method based on a modified energy ratio attribute. Noise reduction schemes are used to provide significant improvement on picking accuracy. Velocity values for rock formations can be determined using refraction analysis on first-arrival times. However, a more accurate alternative is based on finding the time shifts to align the waveforms of three receivers. The automatic time-picking and velocity determination algorithms are used to analyze full waveform sonic logs from the U of C Rothney test well.

Introduction

First-arrival picking on seismic survey data has been well-studied (Willis and Toksoz., 1983; Coppens, 1985; and Boschetti et al., 1996). This fundamental task is ubiquitous in seismic processing. For example, it is a required first step in analyzing refraction data to determine near-surface velocity values needed to make static corrections. Similarly, first-arrival times must be picked from full-waveform sonic well logs in order to determine interval velocities of rock formations encountered by the logging tool as it moves up or down a well. Picking first arrivals on full-waveform sonic well logs reliably and efficiently is a crucial part of well log processing.

P-wave seismograms were acquired by a full-waveform sonic logging tool with a monopole source in the University of Calgary test well. The logging geometry inside the well is shown on Figure 1. The tool, which consists of a piezoelectric transmitter (Tx) and three piezoelectric receivers (Rx1, Rx2, and Rx3), is centralized in the water-filled well. The distance between adjacent receiver channels is 0.3048m (1 foot). The distance between the transmitter and the first channel Rx1 is 0.915m (3 feet). Seismograms from the three channels are recorded in a computer file with a 4μs sampling rate and trace lengths of 2000μs. The starting acquisition depth is 3.9m; the ending depth is about 125m. Traces are recorded every 0.1m, so that the total of 1212 recording depths covers about 121m of formation. The first 500μs of the seismograms are plotted on Figure 2 with AGC and bandpass filtering.

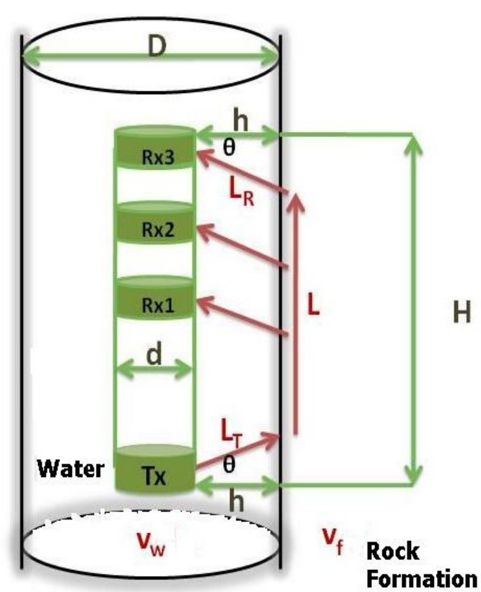


Fig. 1: The full waveform sonic logging geometry inside the well. The arrowed red lines represent the refracted wave raypaths.

Noise Reduction by Channel Averaging and Depth Averaging

P-wave arrivals can be seen clearly except at those depths where there is poor coupling between the casing and the rock formations. Coupling is especially poor above the water table at 30m. Both random noise and tube waves are present in the seismograms. These can interfere with automatic first-arrival time picking.

We eliminate slow, high-amplitude tubes waves that follow the first P-wave arrival by windowing the traces. The depth increments between receiver channels and recording stations are small, and the piezoelectric source is highly repeatable. Consequently, the windowed waveforms of adjacent seismograms are quite similar, so that averaging them to reduce noise is a valid procedure. Noise reduction by averaging provides significant improvement on the picking accuracy. We use a minimum variance principle to do trace averaging on the windowed seismograms.

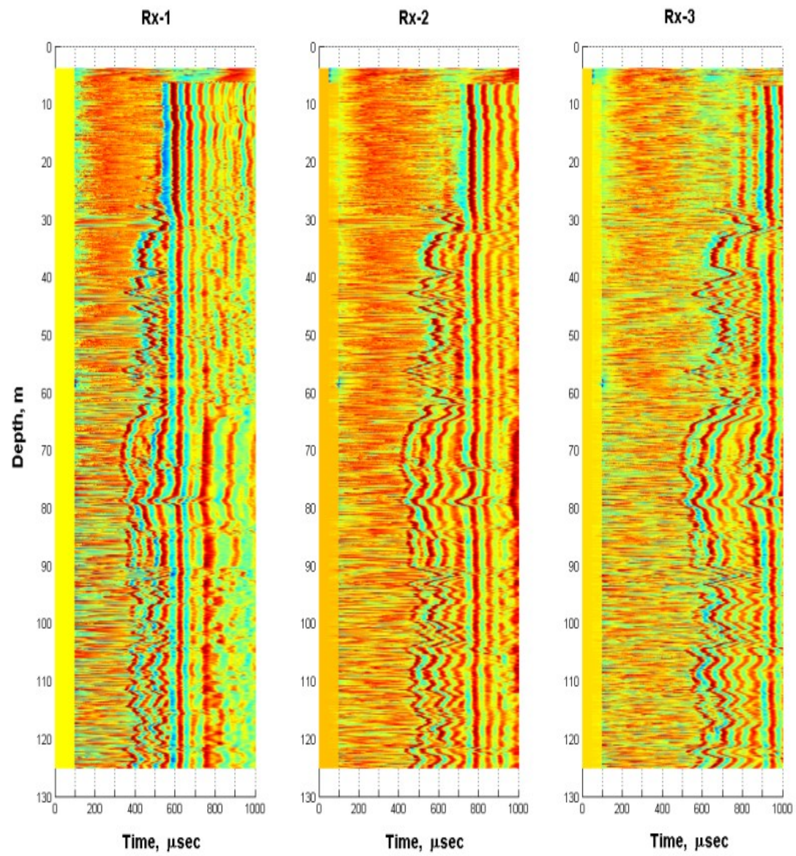


Fig. 2: Full waveform seismograms from the U of C test well. No P-wave arrivals through rock exist above the water table at about 30m.

First arrivals on the three channels at each recording depth are delayed in a systematic way as the channel distance from the transmitter increases, and the delays are related to the formation velocity. Keeping Rx3 unshifted, we systematically shift Rx2 and Rx1 traces forward by times of Δt and $2\Delta t$, and average the three. We then find the difference or error between the average trace and each shifted input trace at each time index. The sum of the squared errors over all the time indices is referred to as the variance v(t). The variance is calculated for many values of Δt, and will be a minimum when the windowed waveforms from the three channels are in phase (see Figure 3). The variance $v(\Delta t)$ as a function of time shift Δt between the windowed input traces Rx1(t), Rx2(t), and Rx3(t) and the averaged sum trace m(t) is calculated by the following formulae:

$$v(\Delta t) = \sum_{t=0}^{tmax} \{[m(t) - Rx1(t + 2\Delta t)]^2 + [m(t) - Rx2(t + \Delta t)]^2 + [m(t) - Rx3(t)]^2\}, \qquad (1a)$$

$$m(t) = \frac{[\,Rx1(t + 2\Delta t) + \; Rx2(t + \Delta t) \;\; Rx3(t)\,]}{3} \; . \qquad (1b)$$

Similarly, random noise on seismograms can be reduced by averaging over depth. For a given receiver channel, windowed traces immediately above and below and centered about a reference depth are time shifted and added to get an average trace (the trace at the reference depth is not shifted, and time shifts for the traces above and below can differ in both sign and magnitude). The average trace giving the minimum variance with respect to the input traces is used to replace the reference trace for first-arrival picking. The average trace is usually calculated with input traces from 3, 5, 7, 9, or 11 depths.

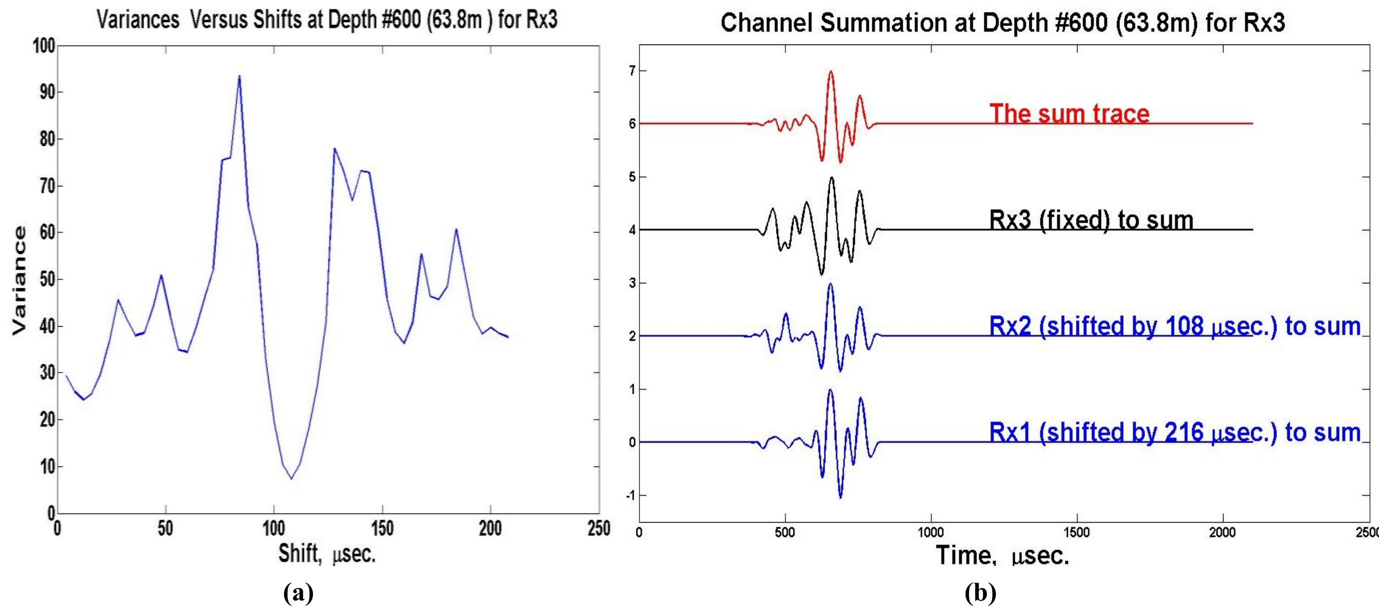


Fig. 3: Minimum variance noise-reduction method over three receiver channels. (a) Variance as a function of time shift; (b) the averaged sum trace (in red) of optimally-shifted windowed seismograms; the optimal time shift $\Delta t = 108$ µs corresponds to the minimum variance in (a) .

Modified Energy Ratio Method for Time Picking

For every windowed seismogram, we define a modified energy ratio er3(i) according to:

$$er(i) = \sum_{j=i+1}^{i+L} grm(j)^2 \Big/ \sum_{j=i-L}^{i-1} grm(j)^2 \; ; \quad er3(i) = er(i)^3 * abs\big(grm(i)\big) \;, \tag{2}$$

where $grm(j)$ is the seismogram value at time index j, er3(i) is the modified energy ratio at time index i, and L is the length of the energy evaluation windows preceding and following the test point i. The first-arrival time pick occurs where er3(i) is a maximum, and this can be determined automatically by computer when interference from random noise and tube waves are minimized. Figure 4 compares manual and automatic time picks and shows the effect of noise reduction on the automatic picks. Noise reduction by averaging over channels appears to be more effective in matching automatic time picks with the manual time picks.

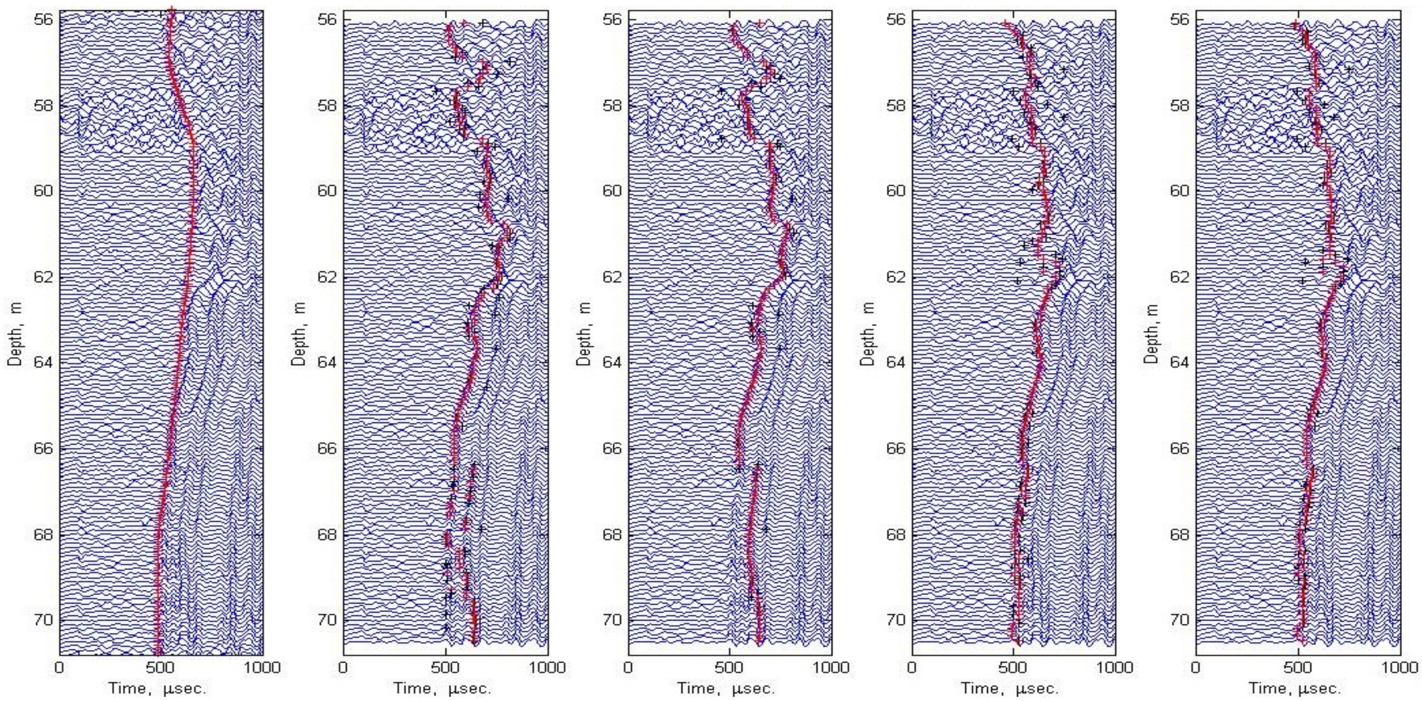
Velocity Determination

The formation velocity v_f can be estimated by assuming the refraction geometry shown on Figure 1 and using the refraction equation for the first arrival time:

$$t_{cal} = \frac{2*h*v_f}{v_w*\sqrt{v_f^2 - v_w^2}} + \frac{H}{v_f} - \frac{2*h*v_w}{v_f*\sqrt{v_f^2 - v_w^2}} \;. \tag{3}$$

For a given receiver, the values h, H, and v_w (= water velocity) are assumed. We calculate values for the first arrival time using Equation 3, systematically varying the value for the formation velocity v_f, until we find a value of v_f that gives a very small difference between the t_{cal} and the observed arrival time t_{obs}.

A second, simpler, method is to take the time shift value Δt from the minimum variance method and divide it into the source-receiver spacing (i.e., $v_f = 0.3048\text{m}/\Delta t$). This second method is more accurate because we need not assume any knowledge about the raypath segments going through the fluid in the well, the casing, and the mud or cement between the casing and the formation. Figure 5 compares the velocities determined from manual and automatic first-arrival picks, and from the time shifts obtained by minimum variance analysis. The overall shapes of the velocity profiles are very similar, but velocity values calculated



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

Fig. 4: Time picks on Rx3 seismograms with and without noise reduction. (a) Manual time picks on seismograms with no noise reduction. Automatic time picks on seismograms: (b) with no noise reduction; (c) with noise reduction over depths; (d) with noise reduction over channels; (e) with noise reduction over both depths and channels.

using the time-shift method are about 10% higher than the refraction formula values, probably due to errors in assumed values for h and v_w (v_w includes the effects of water, casing, and mud).

Conclusions

Our automatic time-picking method is based on noise reduction by averaging over receiver channels, and on the modified energy ratio attribute. Automatic time picks are comparable to the manual ones, but the automatic method is much more efficient. Velocity values based on time shifts that align input traces are favored over those derived from first arrival times and Equation 3.

Acknowledgements

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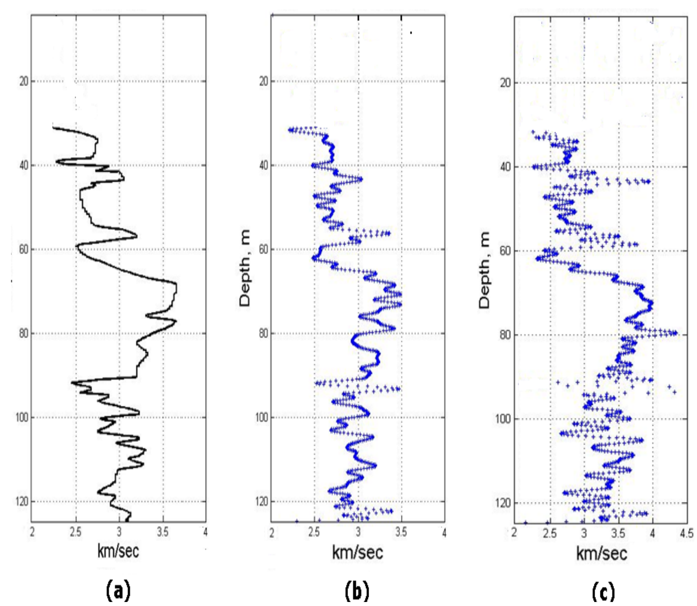

Fig. 5: Velocity profiles derived from Channel 3 seismograms using first-arrival time picks obtained (a) manually, and (b) automatically; (c) velocity profile using the time-shift method.

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