CSCanada
Energy Science and Technology
Vol. 6, No. 1, 2013, pp. 79-89
DOI:10.3968/j.est.1923847920130601.3658

ISSN 1923-8460[PRINT]
ISSN 1923-8479[ONLINE]
www.cscanada.net
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First Arrival Time Auto-Picking Method Based on Multi-Time Windows Energy Ratio

SONG Jianguo[a],*; CAO Xia[a]; XU Weixiu[b]; YANG Jing[b]

[a]School of Geo-Science and Technology, China University of Petroleum (East China), Qingdao, China.
[b]Sinopec Oil Engineering Geophysical Limited Company Shengli Branch, Dongying, China.
*Corresponding auhtor.

Received 1 August 2012; accepted 14 September 2013

Abstract

First arrival time auto-picking technique plays an important role in seismic exploration. It is widely used in shallow layer tomography and static correction. Conventional method that based on sliding time windows energy ratio is not stable. Here a new method based on multi-time windows energy ratio is proposed. Combining with automatic quality control and phase-domain first arrival estimation technique, our method performs perfectly on seismic records of normal S/N ratio. In the computational process of conventional sliding time windows energy ratio method, first arrivals are often determined by the maximum energy ratio of two adjacent sliding time windows. It is well known that for low S/N ratio data the conventional picking is not effective, and for high S/N ratio data weak reflections are hardly detected. The reason is that first arrival time does not correspond to the maximum energy ratio. Meanwhile conventional method sometime picks local secondary extreme of energy ratio. The new method of multi-time windows energy ratio method takes both maximum and local secondary extreme in consideration. Hence new method promotes the stability and accuracy of first arrival picking. Combined with automatic quality control and phase-domain first arrival estimation, the new method performs well in its application in the middle part of Dzungarian Basin(Northwest China).

Key words: First arrival time picking; Multi-time windows; Energy ratio; Quality control

SONG Jianguo, CAO Xia, XU Weixiu, YANG Jing (2013). First Arrival Time Auto-Picking Method Based on Multi-Time Windows Energy Ratio. *Energy Science and Technology*, *6*(1), 79-89. Available from: URL: http://www.cscanada.net/index.php/est/article/view/10.3968/j.est.1923847920130601.3658
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INTRODUCTION

First arrival picking has found wide application in seismic data processing, especially in near-surface static correction and computerized tomography. Preciously, many algorithms do not perform well in first arrival picking of low S/N ratio data, needing great amount of human interaction. Therefore, researches of first arrival auto-picking algorithms have its practical significance. The algorithms with high stability and accuracy are of great value socially and economically.

So far people have proposed various first arrival picking algorithms, for example correlation method (Gelchlnsky et al., 1983) and inflexion correction method (Peraldi et al., 1972). Both of them are based on the incorrect hypothesis of invariable pulse form (Gu, Zhou, & Zhang (1992). Eatherrly (1980) proposed a first arrival picking method that combined linear prediction with inflexion correction. Coppens (1985) put forward the energy ratio method. In the recent years, more methods have been proposed, such as the method based on image processing, fractal dimension method, neural network method, etc.

The current first arrival picking methods can be mainly divided into three classes (Coppen, 1985):

(1) Methods based on instantaneous properties: extremum method, energy ratio method, instantaneous intensity ratio method, etc. The weakness of these methods is its sensibility to noise. In the case of low S/N ratio, first arrivals can not be picked accurately.

(2) Methods based on the properties of the entire seismic data volume: correlation method, linear least square method, bound first arrival picking method, etc. These methods can resist the affection of noise to some extent, but are restricted by the correlativity of seismic traces, thus they always fail in complex surface condition.

(3) Artificial intelligence methods integrating comprehensive information of first arrivals: neutral network picking method, fractal travel-time picking method, etc. These methods are the most complex ones, thus their shortcoming is inefficiency.

Currently, the effect of many first arrival picking methods lies greatly on S/N ratio. The method that can be applied effectively to shallow seismic refraction prospecting has not been found yet. The key problem under disputed is the stability of algorithm, namely improving its noise immunity. Sliding time windows energy ratio method (Zuo, Wang, & Shui, 2004) is a fast picking method, but it is not stable enough and its effect is affected significantly by S/N ratio, for it detects first arrivals using only one property of a single trace. If the energy of subsequent waves varies greatly, the ratio of anterior and posterior time-window energy becomes very large which may lead to the occurrence of picking errors. It is also inaccurate when picking refraction waves from far offsets, because it may pick direct waves instead of refraction waves for the energy of the former is much larger. When it is applied to low S/N ratio data with waveform aberration, what it picks are not accurate first arrivals. Additionally, the width of time windows also affects its accuracy.

Therefore the first arrival picking method based on multi-time windows energy ratio is proposed. It takes in consideration both maximum and secondary extreme of energy ratio, thus being capable of picking weak refractions and reducing picking errors. For improving the stability of this method, automatic quality control method is proposed, including singular point detection and phase-domain first arrival estimation. Singular point detection technology can detect the incorrect points automatically and get referential first arrivals by interpolation, then search first arrivals again in the small zone which is determined by the referential first arrival point, according to energy ratio properties. To solve the mismatch between first arrivals picked by energy ratio method and accurate first arrivals, phase-domain first arrival estimation is applied (Liu, 2007).

1. THOERY

1.1 Energy Ratio Method

First arrival is a kind of wave which has the earliest arriving time and strong energy. Energy ratio method was proposed by Coppens in 1985. Energy ratio is defined by the ratio of the signal energy within one period to the entire time-window energy:

$$R(\tau) = \int_{\tau-L}^{\tau} x^2(t)dt \Big/ \int_{0}^{\tau} x^2(t)dt \tag{1}$$

where $R(\tau)$ is energy ratio function, x(t) is the amplitude of seismic data and L is the length of apparent period.

Energy ratio function $R(\tau)$ is sensitive to first arrivals. Its maximum point can be regarded as an approximation of first arrival location. Hence an appropriate time shift is applied to get the first arrival point (Jiang & Zhong, 1995).

1.2 Algorithm

The method performs very well where the waveform of first arrivals varies slightly. However, when it comes to those areas where the waveform of first arrivals varies significantly, this method may fail for its weakness in noise immunity (Jiang & Zhong (1995).

To solve the problem mentioned above, many improved methods have been proposed, among which the most common one is sliding time windows energy ratio method. It is defined by the energy ratio of two adjacent time windows: the former time window and the back time window (as illustrated in FIG.1). Select two time windows in seismic trace x(t) along time axis. T_1 is the starting point of the first time window. T_0 is the end point of the first time window and the starting point of the second time window. T_2 is the end point of the second time window. Then the energy ratio of the former time window to the back time window can be expressed as:

$$A_i = \left[\frac{\sum_{t=T_0}^{T_2} x^2(t)}{\sum_{t=T_1}^{T_0} x^2(t)} \right] \tag{2}$$

In practical computational process, the amplitude of some points anterior to the first arrival point may be tiny, approaching zero. As a result, the denominator of Equation 2 approaches zero and A_i produces singular value or extremely large value. To avoid this problem and improve the stability of first arrival picking, a stability factor is introduced into the equation as the coefficient of the anterior and the posterior time-window energy (Zhang & Zhao, et al., 2002). So Equation 2 can be revised as:

$$A_i = \frac{\left[\sum_{t=T_0}^{T_2} x^2(t) \right]^{\frac{1}{2}} + \alpha w}{\left[\sum_{t=T_1}^{T_0} x^2(t) \right]^{\frac{1}{2}} + \alpha w} \tag{3}$$

where $w = \frac{1}{N}\left[\sum_{t=0}^{T} x^2(t) \right]$ is the relative energy of seismic trace, N is the number of points of seismic trace, and α is stability factor.

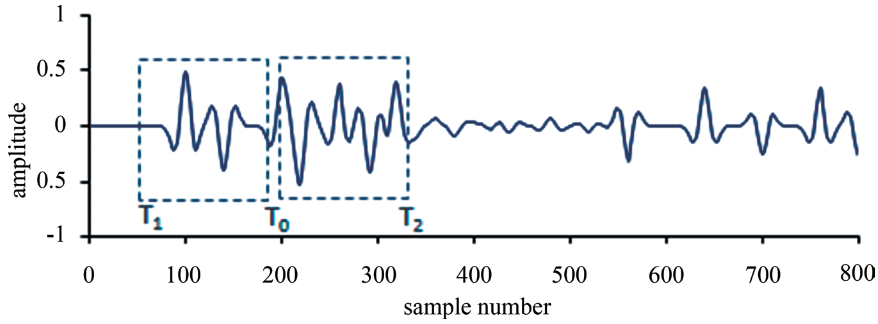


Figure 1
Energy Ratio of Sliding Time Windows

Slide the time window from the beginning to the end of the trace(as illustrated in FIG. 2). Δx is the sampling interval, namely the step length of each movement. It is generally taken equal to 1, or other values according to actual conditions. Calculate the energy ratios of the back time window to the former time window after each movement. Seek the maximum among them, and then look for the maximal amplitude point in the corresponding former time window. Its corresponding time is first arrival time (Zhang, Wang, et al., 2009; Zuo, Wang, & Shui, 2004).

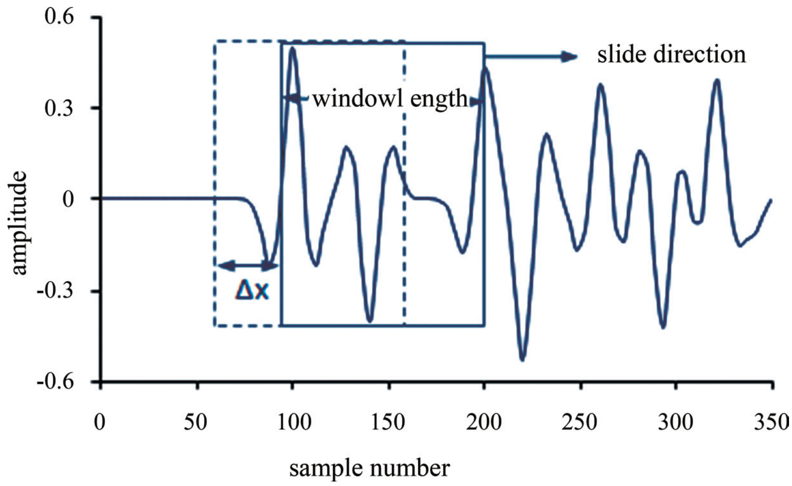
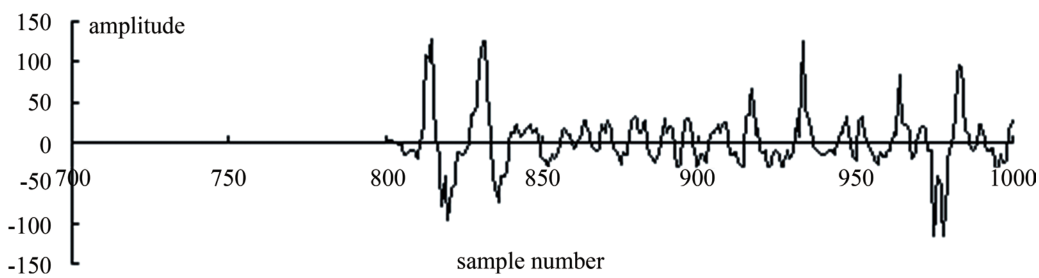
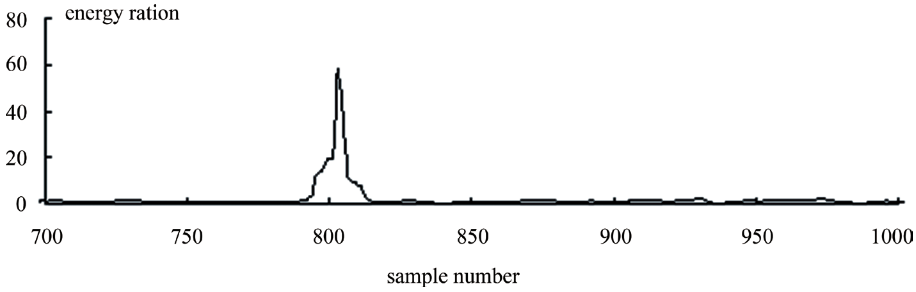


Figure 2
Sliding the Time Window

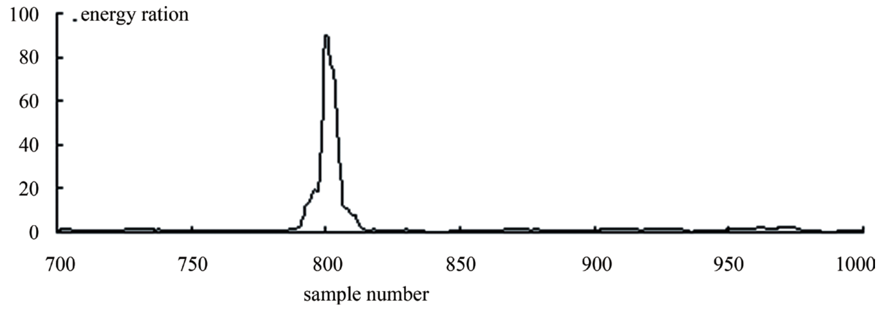
Time-window width is one of the important factors that significantly affect the picking accuracy of the method based on energy ratios of sliding time windows. It is usually selected according to experience and estimation. Try time windows of different widths and select the best one. Figure 3 shows the energy ratios using different time-window width applied to a certain seismic trace. The sampling interval is 4ms. When time-window width is 48ms, the maximal energy ratio corresponds 3208ms. When time-window width is 60ms, the maximal energy ratio corresponds 3196ms. They have a difference of 12ms, namely 3 sampling points. Thus time-window width affects the picking accuracy to some extent.



(a) A real seismic trace



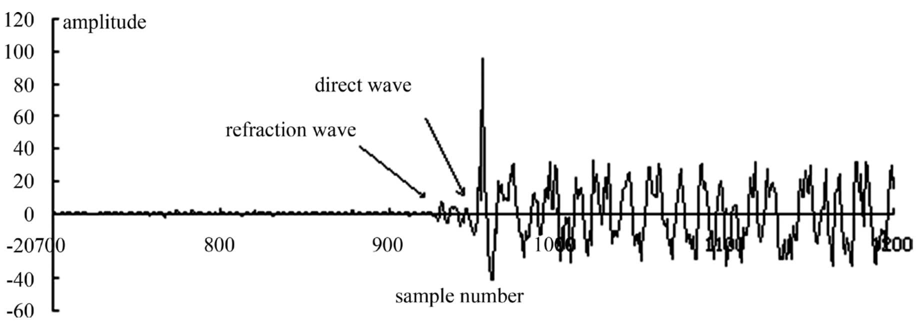
(b) Time-window width L=48ms, corresponding time of maximal energy ratio(T=802×4ms)



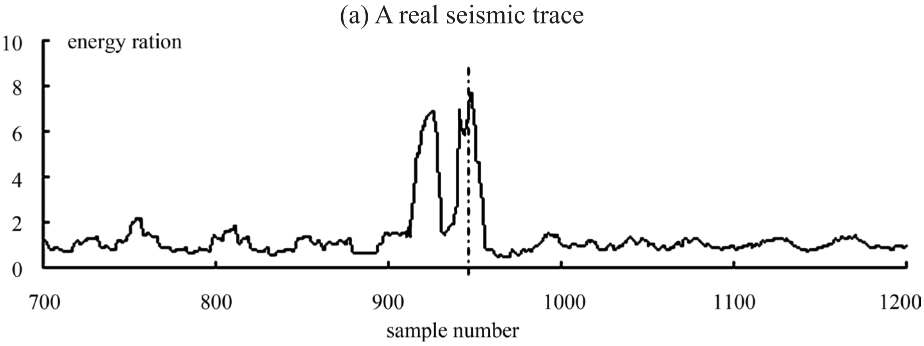
(c) Time window length L=60ms, corresponding time of maximal energy ratio(T=799×4ms)

Figure 3
Energy Ratio Extrema in Different Time-Window-Width Conditions

The method based on energy ratios of sliding time windows get first arrival time simply by seeking the maximum of energy ratio. It has an inherent defect which leads to the occurrence of picking errors because first arrival time does not always correspond the maximum of energy ratio. This method does not perform well in far-offset data, especially in weak reflection conditions. Figure 4(a) is a certain far-offset seismic trace, and Figure 4(b) shows its energy ratio curve. The energy of direct wave is stronger than that of refraction wave, and energy ratio curve reaches maximum there. But refraction wave arrives earlier and picking error occurs. Additionally, if the energy of subsequent waves varies greatly, some certain local energy ratios may exceed that of first arrival wave. The reasons above demonstrate the instability of this method.



(a) A real seismic trace



(b) The energy ratio curve

Figure 4
Far-Offset Seismic Trace and Its Energy Ratio Curve

1.3 Multi-Time Windows Energy Ratio Method

To solve the problem which exists in the method based on sliding time windows energy ratio, the method based on multi-time windows energy ratio is proposed. Not only the maximum of energy ratio, but also the secondary extrema are taken into consideration. Four time windows(L_1, L_2, L_3 and L_4) are needed(as illustrated in FIG. 5).

The energy ratio of L_1 and L_2:

$$R_1(t)=\left[\frac{\sum_{i=0}^{L_1}x^2(t+i)+aw}{\sum_{i=0}^{L_2}x^2(t-i)+aw}\right]^{\frac{1}{2}} \tag{4}$$

The energy ratio of L_1 and L_3:

$$R_2(t)=\left[\frac{\sum_{i=0}^{L_1}x^2(t+i)+aw}{\sum_{i=0}^{L_3}x^2(t-i-\mathrm{d})+aw}\right]^{\frac{1}{2}} \tag{5}$$

The energy ratio of L_4 and L_2:

$$R_3(t)=\left[\frac{\sum_{i=0}^{L_4}x^2(t+i+d)+aw}{\sum_{i=0}^{L_2}x^2(t-i)+aw}\right]^{\frac{1}{2}} \tag{6}$$

where $w=\frac{1}{N}\left[\sum_{t=0}^{T}x^2(t)\right]$ is the relative energy of seismic trace, t is the current sampling point, d is the interval between the back time window and the third time window, N is the number of seismic trace points and αis stability factor which is commonly chosen from 0.5 to 2.0.

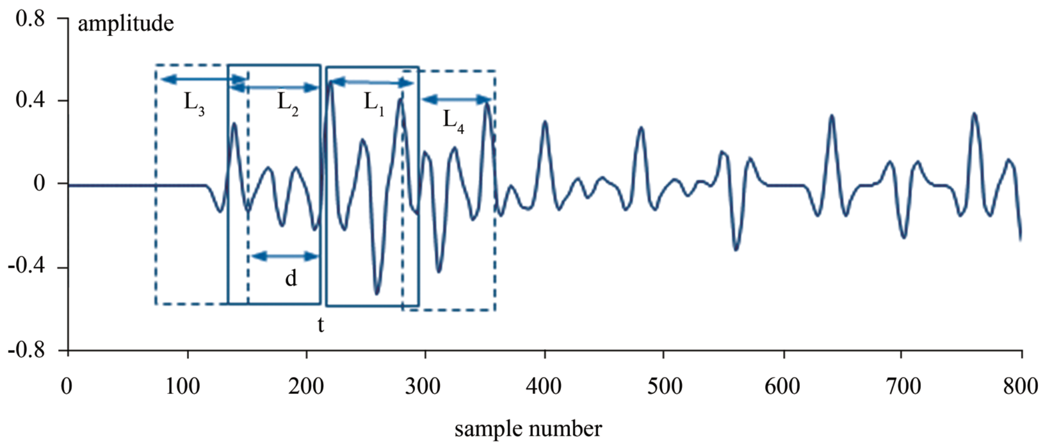


Figure 5
The Method Based on Energy Ratios of Multi-Time Windows

Figure 6(a) is a simulated seismic trace where there is a short but strong continuous noise anterior to first arrival wave and a strong effective wave posterior to first arrival wave. Choose a 80ms-width time window to calculate energy ratios (while d=70ms). The results are shown in Figure 6(b)(c). Multiple local extrema can be observed in $R_1(t)$ whose maximum corresponds the effective wave posterior to first arrival wave. It must lead to a wrong picking result using conventional energy ratio method. $R_2(t)$ and $R_1(t)$ can reach extremum simultaneously at the first arrival point and at the location of the short continuous noise, while a d-length delay exists between the extremum of $R_2(t)$ and $R_1(t)$ at the location of the subsequent wave. $R_3(t)$ and $R_1(t)$ can reach extremum simultaneously at the first arrival point and at the location of the subsequent wave, while a d-length advance exists at the random noise anterior to first arrival. Thus the local extremum at the first arrival point and at the location of the subsequent wave can be determined by $R_1(t)$ and $R_2(t)$ while the extremum at the first arrival point and at the location of the short continuous noise can be determined by $R_1(t)$ and $R_3(t)$. This method improves the stability of energy-ratio first arrival picking algorithm to some extent. It performs well in weak far-offset refractions.

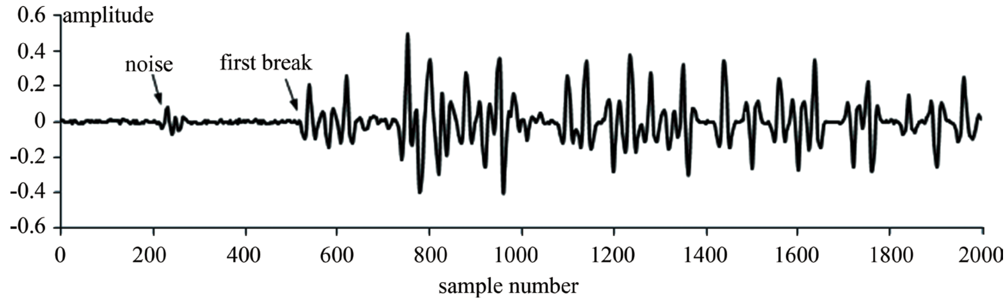
Similarly, slide time window from the beginning to the end of seismic trace. Calculate energy ratios after each movement. It is better to make the width of four time windows equal for reducing computation. Because of the invariable form of the loop, the only thing to do is a one-time-window-width shift. The computational process is shown below:

Calculate $R_1(t)$ using Equation 4; Seek the maximum R_{max} of $R_1(t)$ in the ergodic process of the entire seismic trace and record its corresponding time T_1.

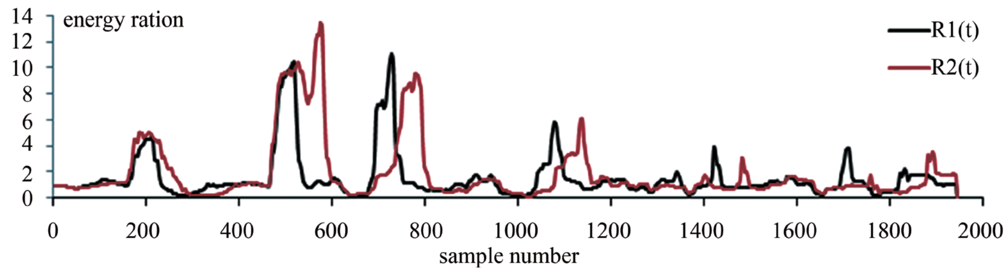
Seek the secondary extremum R_{max} from the beginning to the end of seismic trace. If $R'_{max}/R_{max}\geq\alpha$, go to step 3. If otherwise, the first arrival time equals to T_1.

Calculate $R_2(t)$ and $R_3(t)$ at the secondary extremum point (corresponding time t) according to Equation 5 and Equation 6. If $R_2(t)/R'_{max}\geq\beta_1$ and $R_3(t)/R'_{max}\geq\beta_2$, the corresponding time of the sampling point t is the correct first arrival time. If otherwise, the first arrival time still equals to T_1. Go back to step 2, repeat the loop to the next secondary extremum point until the the traversal of the entire trace is accomplished.

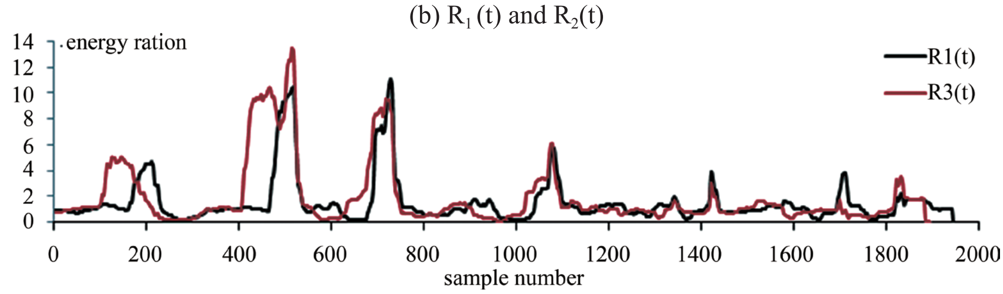
In the computational process, α,β1 and β2 are selected according to the quality of seismic data, and are commonly chosen between 0.5 to 1.0.



(a) A seismic trace



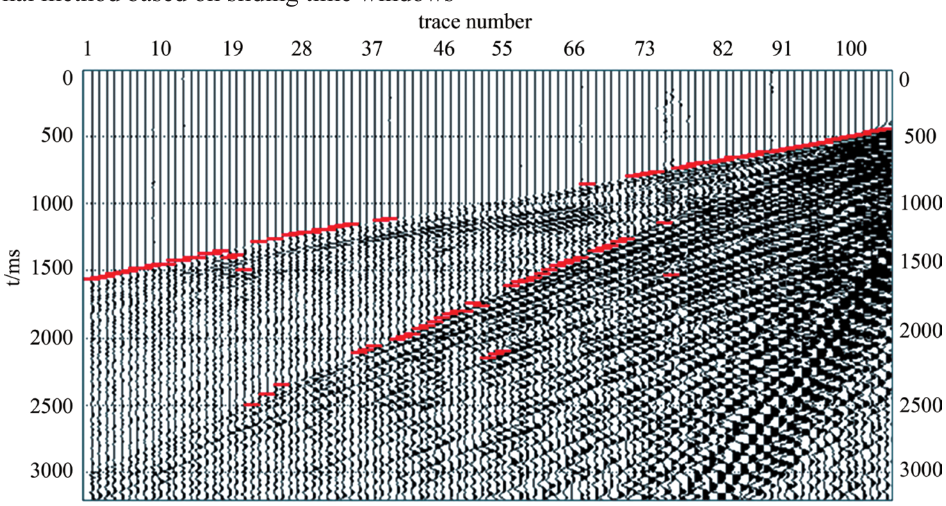
(b) R_1 (t) and R_2(t)



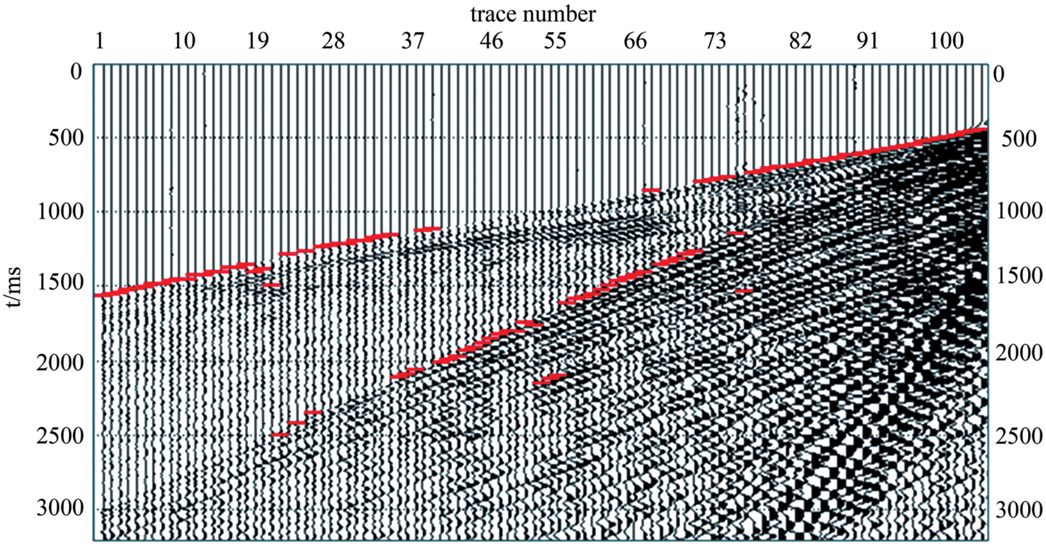
(c) R_1 (t) and R_3(t)

Figure 6
Contrastive Analysis

Figure 7 is a seismic record of one shot where the refractions at far offsets are weak and the direct waves are strong. Figure 7(b) shows the first arriving picking result of the conventional method based on sliding time windows energy ratio. Figure 7(c) is the result of the method based on multi-time windows energy ratio. Obviously, the latter method is more stable than the former. It can detect weak first arrivals effectively.



(a) The conventional energy ratio method



(b) The multi-time windows energy ratio method

Figure 7
The First Arrival Picking Effect of Far-Offset Seismic Data

2. AUTOMATIC QUALITY CONTROL METHOD

Like conventional ways, the multi-time windows energy ratio method only considers one energy property. Thus its picking effect is also affected by noise. When S/N ratio is low, picking errors occur. Figure 8 shows the picking result of seismic data with low S/N ratio. Because of the interference of noise, picking errors can be observed at trace 210, trace 220, etc.

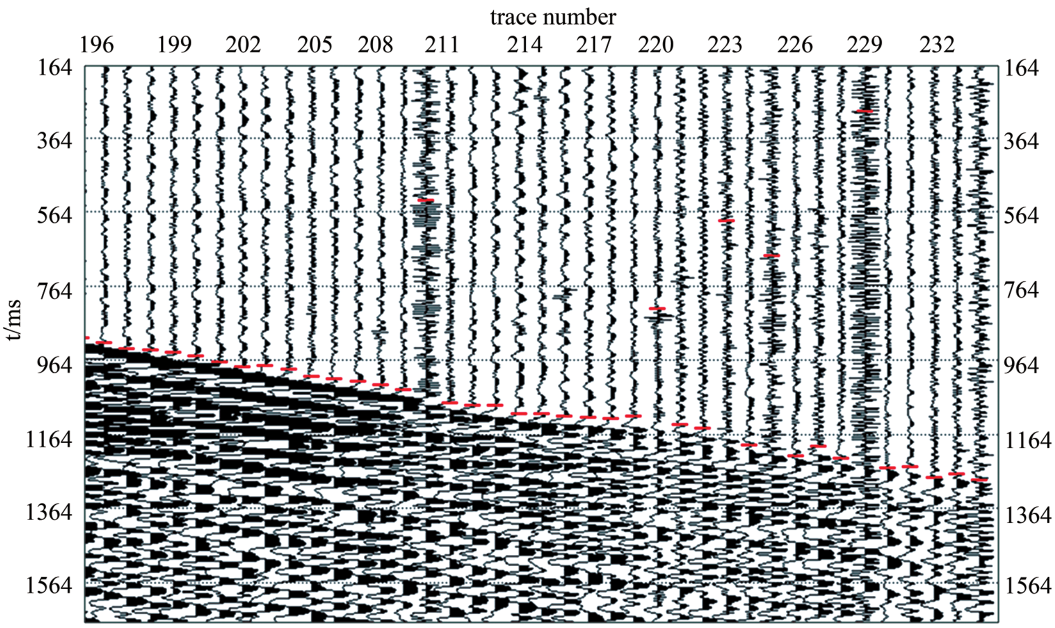


Figure 8
The Picking Effect of Low-S/N-Ratio Data

Automatic quality control method is applied for reducing manual correction while reducing picking errors and improving picking accuracy of low-S/N-ratio data.

2.1 Singular Value Detection

Based on surface consistent condition, the singular value detection method should take the following two factors into consideration (Yang, 2007): (1) first arrival time is a finite monotonous function of offset; (2) within a finite trace interval, the saltation of first arrival points indicates picking error. Seek abnormal values and delete them. Get the referential first arrival point by interpolation. Make it the center of the controlling time window whose function is limiting the searching zone. Then pick first arrival time again according to energy ratios.

In CSP gathers, assume that t_i is the first arrival time of each receiver of one shot. Thus the first arrival time difference between two adjacent receivers is:

$$\Delta T_i = |t_{i+1} - t_i| \qquad (i = 1, 2, \cdots, n) \tag{7}$$

Its average is:

$$\overline{\Delta} = \frac{1}{n}\sum_{i=1}^{n} \Delta T_i \tag{8}$$

Its standard deviation is:

$$\sigma = \left[\frac{1}{2}\sum_{i=1}^{n}(\Delta T_i - \overline{\Delta})^2\right]^{\frac{1}{2}} \tag{9}$$

Assume that:

$$d_i = \left|\Delta T_i - \overline{\Delta}\right| \qquad (i = 1, 2, \cdots, n) \tag{10}$$

Thus the determinate equation of first arrival time picking is:

$$d_i > \xi\sigma \qquad (i = 1, 2, \cdots, n) \tag{11}$$

where ξ is the controlling parameter of error which is chosen according to the quality of first arrival curve and is commonly chosen from 1 to 2. The points satisfied Equation 11 are regarded as abnormal points. If first arrival curve is approximately linear, the referential first arrival time is determined by Equation 12:

$$t_i = (t_{i-1} + t_{i+1}) / 2 \qquad i \in [2, n-1] \tag{12}$$

If first arrival curve is nonlinear, apply spline interpolation to get the first arrival time of the current receiver, according to the first arrival times of adjacent receivers.

The process of automatic quality control is shown below:

Calculate average time difference and standard deviation of adjacent first arrival points in the current CSP gather (according to Equation 7).

Scan all the first arrival points in the CSP gather from near to far offset, while calculating the difference between the first arrival time of the current trace and that of the former trace. If the time difference satisfies Equation 11, the first arrival point of the current trace is an abnormal point which should be deleted. The remaining are correct first arrival points.

Apply interpolation to those traces to which the deletion has been done, according the correct first arrival points. Calculate referential first arrival point using Equation 12. Make it the center of the controlling time window. Pick first arrival again according to energy ratios.

Recalculate the average time difference $\overline{\Delta}$ of adjacent first arrival points in the CSP gather. Stop the process if $\overline{\Delta}$ does not reduce any more. If otherwise, repeat step 2.

With this quality control method, the stability and noise immunity are significantly strengthened, thus the accuracy of first arrival picking is improved. Figure 9 and Figure 8 are two different first arrival time picking effects of a same data volume. Automatic quality control method is applied in the computational process of Figure 9 while it is omitted in that of Figure 8. In Figure 9, first arrival times are correctly picked even in far-offset traces such as trace 210, trace 220, etc.

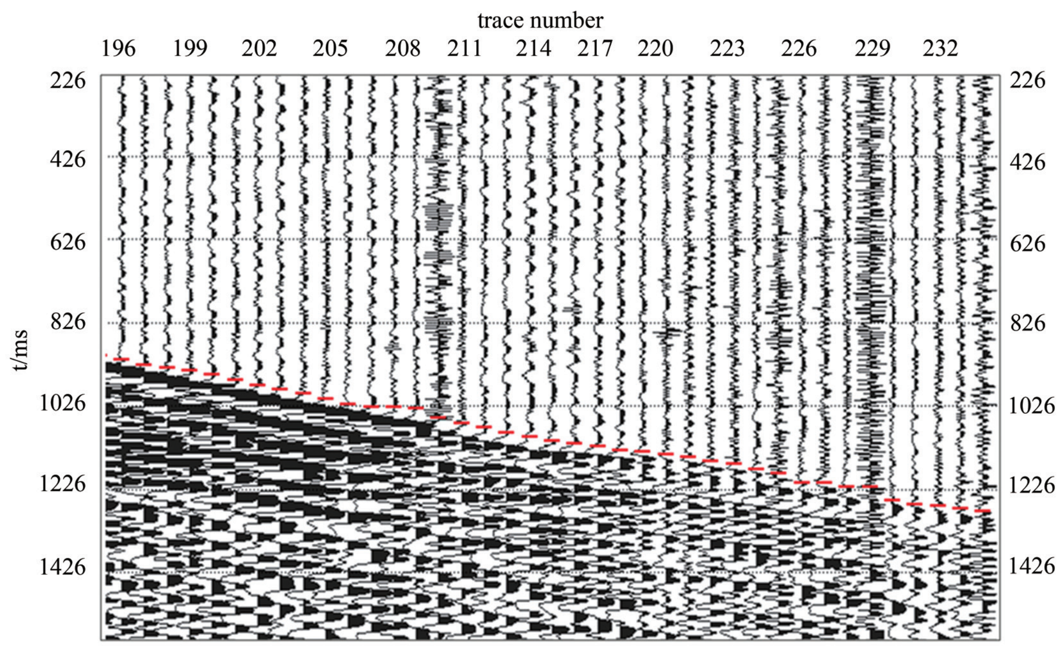


Figure 9
The Picking Effect with the Application of Automatic Quality Control

2.2 Phase-Domain First Arrival Time Estimation

The accuracy of the conventional energy ratio method is affected by time-widow width, thus its picking result is an approximation of first arrival time, not the accurate value. To get accurate first arrival time, get the first arrival crest time according to the detected first arrival time, then apply an adequate time shift.

The Hilbert Transform of seismic trace x(t) can be defined by Equation 12:

$$h(t) = \frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{x(\tau)}{t-\tau} d\tau = x(t) * \frac{1}{\pi t} \tag{12}$$

where h(t) is the Hilbert transform of x(t), t is time, and * represents convolution.

Thus plural seismic trace can be expressed as:

$$C(t) = x(t) + jh(t) \tag{13}$$

Instantaneous envelope is:

$$a(t) = \sqrt{x^2(t) + h^2(t)} \tag{14}$$

Instantaneous phase is:

$$\theta(t) = \arccos\frac{x(t)}{a(t)} = \arcsin\frac{h(t)}{a(t)} \tag{15}$$

If cosine equals to 1 at a point, define it a crest point. Similarly, define it a trough point where cosine equals to -1. Define it a positive zero point where sine equals to 1. And define it a negative zero point where sine equals to -1. The four special phase points are shown in Figure 10. Obviously, the crest point, trough point, positive zero point and negative zero point of a signal can be expressed and determined accurately by phase function.

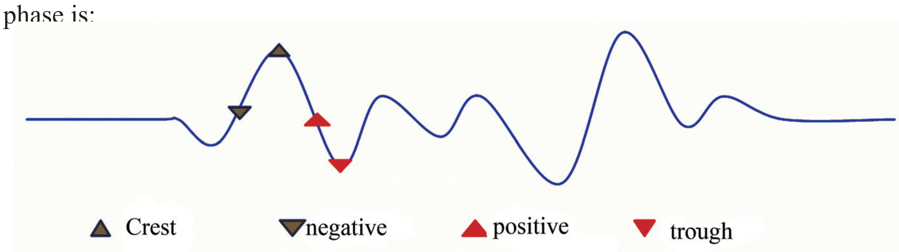


Figure 10
The Four Special Points of Phase Function

Noise is the direct obstacle of detecting crest and trough of seismic trace x(t) for it produces false crest or trough sometimes. The problem can be avoided by using phase function. Though noise can also be observed in phase function $\cos\theta(t)$, it does not reach crest or trough if S/N ratio is larger than 1. Thus the crest and trough of a seismic trace x(t) can be found effectively by detecting crest and trough of .

The conventional way to estimate first arrivals of explosive source is applying a fixed time shift to move it from the crest to the correct point. Wave frequency changes in propagation because of the absorbency of stratum. Therefore, it is also inaccurate to correct first arrival points by a fixed time shift. The time-shift quantity should be varied by offset. In Literature (Liu, 2007), the period which is got from each trace is used to estimate the time-shift quantity for correcting first arrival points. The fact that the frequency of first arrival waves varies with offset, receiver point and shot point is considered in that method. However, a random error exists in the estimation of period using the difference of phase points in practical computation. Unlike Literature (Liu, 2007), the method of this paper is calculating the time difference $\Delta\tau_i$ (1/4 period) between crest ($\cos\theta(t) = 1$) and positive zero point ($\sin\theta(t) = 1$) of each first arrival wave in adjacent m traces of current trace. Thus time-shift quantity can be determined by Equation 16:

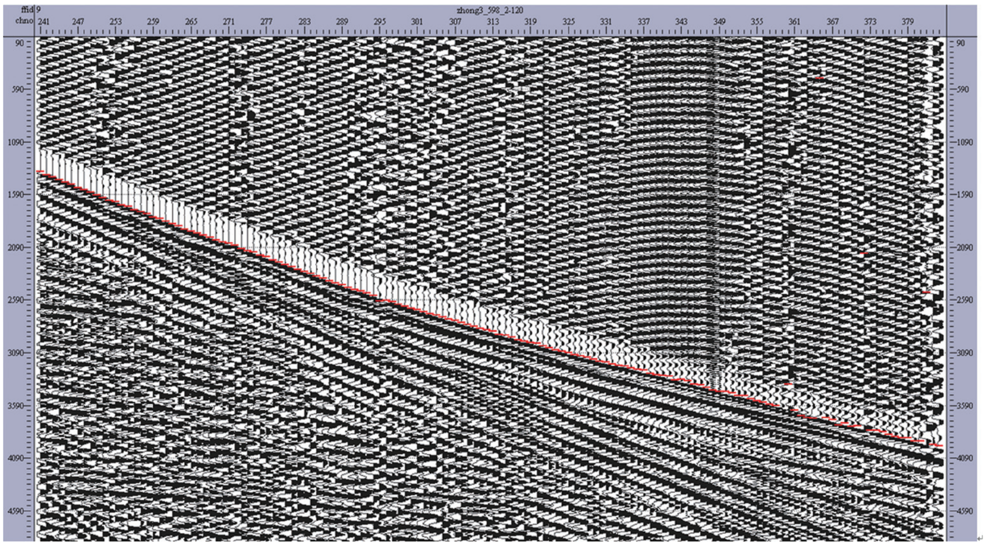
$$\Delta\tau = \frac{3}{4}T = \frac{3}{4m}\sum_{i}^{m}\Delta\tau_i \tag{16}$$

Where T is first arrival period. Equation 16 can reduce the occurrence of errors in period estimation to some extent. The accuracy of period estimation increases with the increase of m. But m should not be too large because of the restriction of first arrival frequency variation with offset, receiver point and shot point.

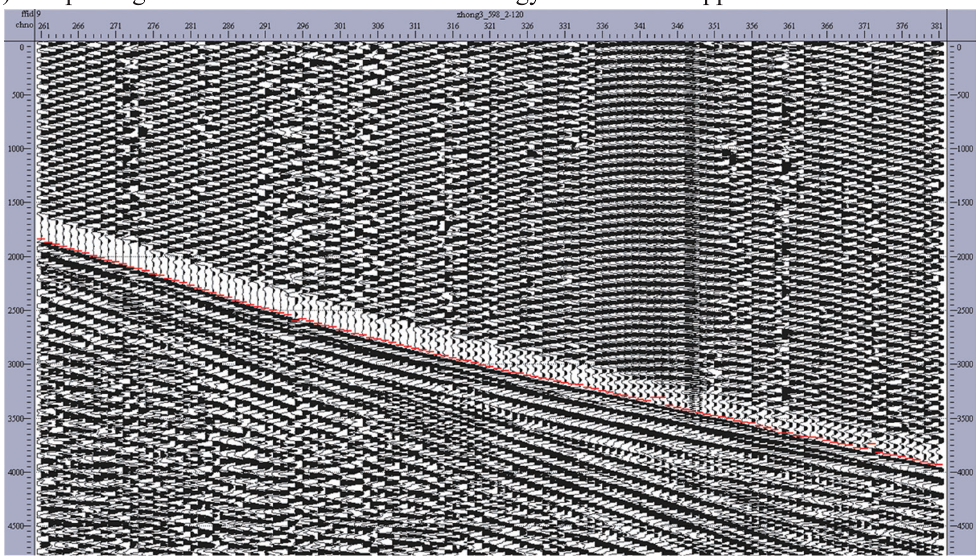
3. APPLICATION

Northwest China is still a hot spot of petroleum prospecting. Mountain, dessert, Gobi, gravel and swamp can be commonly seen in its region which has a complex terrain. For examining the effect of the algorithm discussed in this paper, it is applied to a certain seismic data volume of the middle part of Dzungarian Basin (Northwest China).

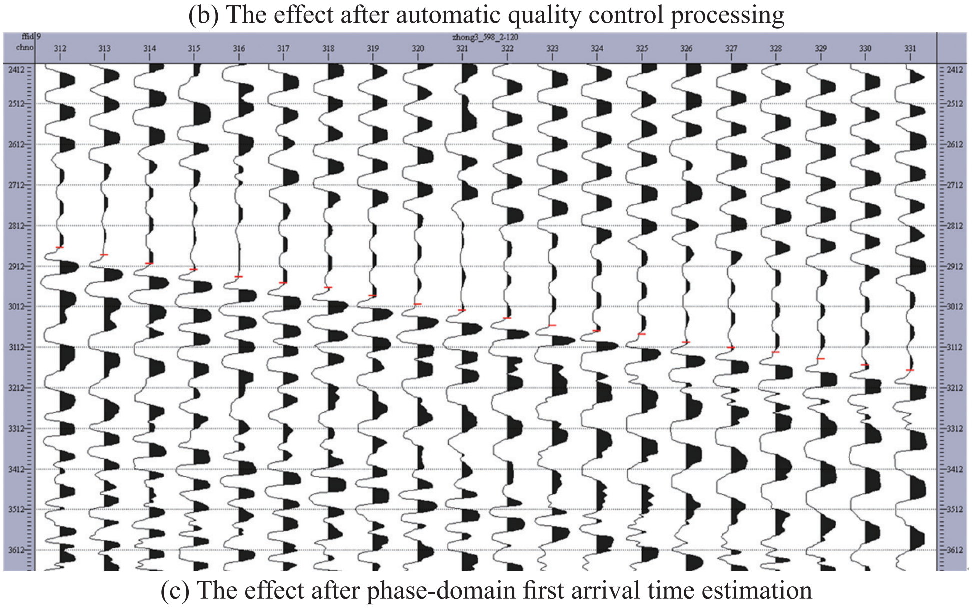
We pick first arrival times by multi-time windows energy ratio method, then detect abnormal values by automatic quality control method and pick first arrivals again. Figure 11(a) shows the picking effect of multi-time windows energy ratio method without automatic quality control and phase-domain first arrival estimation. Several picking errors occur in far-offset traces because of strong noise. The errors can be detected by automatic quality control. Apply interpolation to the traces where picking errors exist to get referential first arrival points. Make a referential point the center of a controlling time window, and pick first arrival point again. As illustrated in Figure 11(b), the picking errors are corrected. To reduce the difference between the first arrivals picked by energy ratio method and the accurate ones, phase-domain first arrival estimation is applied. The result is shown in Figure 11(c). Obviously, the first arrivals are corrected to the accurate locations.



(a) The picking effect of multi-time windows energy ratio method applied to low S/N ratio data



(b) The effect after automatic quality control processing



(c) The effect after phase-domain first arrival time estimation

Figure 11
First Arrival Time Picking Effects

CONCLUSION

Compared to the conventional energy ratio method, the first arrival time auto-picking method which is proposed in this paper is more stable for its higher accuracy of first arrival detection and its better noise-immunity. In this method, not only the maximum of energy ratio is considered, but also secondary extrema. It distinguishes first arrivals by energy properties of multiple time windows. Thus the affection of the short but strong continuous noise anterior to first arrival wave and the energy variation of subsequent waves is avoided to some extent. In seismic data with normal S/N ratio, picking errors are significantly reduced and the accuracy is improved with the application of automatic quality control and phase-domain first arrival estimation. The application of the method in the middle part of Dzungarian Basin (Northwest China) demonstrates its efficiency. Additionally, the method is not suitable to seismic data with extremely low S/N ratio, strong noise interference and visually undistinguishable first arrival waves.

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