VELOCITY ANALYSIS USING N–TH ROOT STACK

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ABSTRACT

The estimation of seismic wave velocity in the subsurface is one of the most important process in seismic data processing. The result is very crucial for the conversion of seismic data from time section into depth section.

The N-th Root Stack which has not been widely used in the industry is in fact a powerful method for estimating seismic wave velocity from seismic record. The method attenuates the background/random noise effectively which facilitates the fitting of the velocity spectrum can be done accurately. In addition, the noise is also effectively suppressed during the CDP stacking, yielding the clear maximum stacking amplitude.

Synthetic records have been used to demonstrate the effectiveness of the N-th Root Stack. Comparison with the Delay and Sum method also demonstrate the superiority of the N-th Root Stack.

I. INTRODUCTION

Seismic wave velocity is one of the most important parameter in seismic exploration. It is used to convert seismic section from time into depth. If well is available, this velocity can be measured accurately using a common techniques such as well velocity survey/check shot survey or Vertical Seismic Profiling (VSP). However, well velocity survey or VSP cannot be done extensively since it will be to expensive to drill well in every kilometres or in every shot point. A specific method is required to estimate the seismic wave velocity from seismic data.

A common method in determining seismic wave velocity from seismic data is the velocity analysis from Common Depth Point (CDP) record (Mayerhoff, 1986, Cressman, 1968; Galbraith and Wiggins, 1968; Buchhaltz, 1972; Dunkin and Levin, 1973; White, 1977). This analysis is usually done in conjunction with NMO or dynamic correction. Basically, it involves delay and summing all primary CDP reflections into the apexes of the hyperbolas which represents the time - distance curve of the primary CDP reflection. A trial of velocity is usually done to approximate the actual primary CDP reflection time distance curve. The best approximate velocity will yield maximum stacking amplitude.

In this paper, a more powerful method for velocity estimation will be discussed. This method called the N-Root Stack (NRS) is a class of multichannel, non linier filter. The advantage of this method is that not only does the velocity of the seismic wave can be estimated more precisely, but also, at the same time, the background/random noise will be strongly suppressed.

The N-Root Stack was first introduced by Muirhead (1968) in connection with automatic detection of seismic events. It was further extended and applied by Kanasewich et al (1973). Both Muirhead and Kanasewich used the NRS for crustral studies which dealt with low frequency seismic signal. In this paper, the NRS is used for seismic exploration purposes using a higher frequency seismic signal. Synthetic examples have been used to demonstrate the effectiveness of this method.

II. THEORETICAL BACKGROUND

The most interesting feature of the N-th Root Stack multichannel filter is the strong attenuation of signals which are different in amplitude and/or in phase, and conserves signals,which has the same phase and equal amplitude.

Asumming that the travel time of the expected signals on the detectors is known, the signals will be aligned. The processing takes the average of the N-th root value of the data, then raises the result to the N-th power.

Suppose there are k traces to be processed, the input data at time t_n on the m^{th} trace is $y(t_n, x_m)$, the NRS is defined by Muirhead (1968) as :

$$\overline{Y(t_n)} = \frac{1}{k}\sum_{m=1}^{k} \text{sgn}\left[e_m\, y(t_n + d_m , x_m) \right] \left| e_m\, y(t_n + d_m , x_m) \right|^{1/N} \quad (1)$$

$$Z(t_n) = \text{sgn}\left[\overline{Y(t_n)} \right] \left| \overline{Y(t_n)} \right|^{N}$$

$y(t_n, x_m)$ is the input data or signal amplitude of the m^{th} trace at recording time t_n.

d_m is the desired signal delay time of the m^{th} trace relative to the reference position.

k is the number of traces or channel.

N is the degree of the root, a positif integer.

e_m is a correction factor for the signal at the m^{th} trace.

H_1 = 300 m	v_1 = 2500 m/sec
H_2 = 200 m	v_2 = 3000 m/sec
H_3 = 500 m	v_3 = 3500 m/sec
H_4 = 500 m	v_4 = 4000 m/sec

Figure 1. Subsurface model with 4 horizontal layers used in this experiment

The correction factor e_m includes the differences in wave attenuation through the propagation distance and/or the variations in gains on various traces.

$$\text{sgn}(p) = -1 \text{ if } p < 0$$
$$= 0 \text{ if } p = 0$$
$$= 1 \text{ if } p > 0$$

It can be seen that the NRS filter consist of two steps. The first step is to take the average value of the data which has undergone N-th root equation. The second step is to raise the power of the average value to N.

Let us observe the situation where the delay time correction and the amplitude correction have been applied, in other words $d_m = 1$ and $e_m = 1$.

Equation (1) reduces to

$$\overline{Y(t_n)} = \frac{1}{k}\sum_{m=1}^{k} \text{sgn}\left[y(t_n, x_m) \right] \left| y(t_n, x_m) \right|^{1/N} \quad (2)$$

$$Z(t_n) = \text{sgn}\left[\overline{Y(t_n)} \right] \left| \overline{Y(t_n)} \right|^{N}$$

Suppose the amplitude of each seismic trace is + a. The output of the NRS (equation 2) is

$$\overline{Y(t_n)} = + a^{1/N}$$

$$Z(t_n) = + a$$

This proves that signals with equal amplitude and the same phase will be conserved.

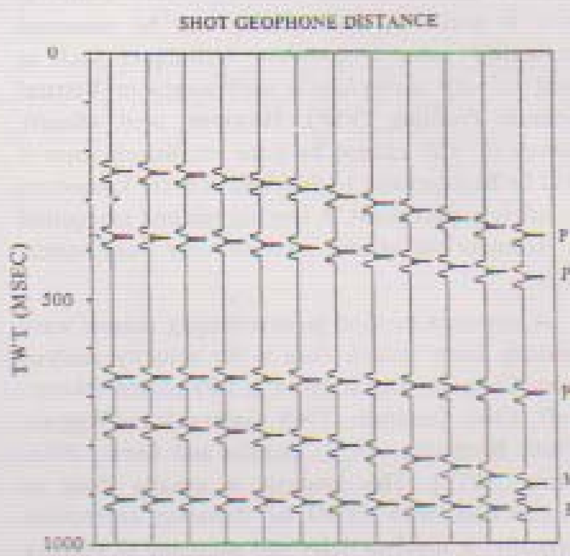

Figure 2. Noise-free synthetic record uncluding free surface multipe.

III. VARIATION OF OUTPUT AMPLITUDE WITH INPUT DATA

The effect of the input data y_m on the output amplitude of the NRS can be investigated by taking the partial derivative of $y_m^{1/N}$ with respect to Y_m.

$$\frac{\partial Y_m}{\partial y_m} = \frac{1}{N} Y_m^{1/N - 1}$$

$$= \frac{1}{N} \frac{1}{Y_m^{1-1/N}} \qquad (3)$$

It is clear that the increase in y_m causes the increase in $Y_m^{1/N}$, but its rate of change with y_m is decreasing. This means that the incremental difference between successive $Y_m^{1/N}$ is smaller among the larger than among smaller y_m. Consequently, the deviation between $|\ Y(t_n)\ |$ and the individual $Y_m^{1/N}$ will be smaller for the larger y_m group if $y(t_n, x_m)$ are all of the same phase, where as they will be larger if they are not all of the same phase.

The output amplitude $|\ Z(t_n)\ |$ will be less attenuated for the larger y_m group if they are all the same phase and not the same amplitude, and will be more suppressed if they are not the same phase.

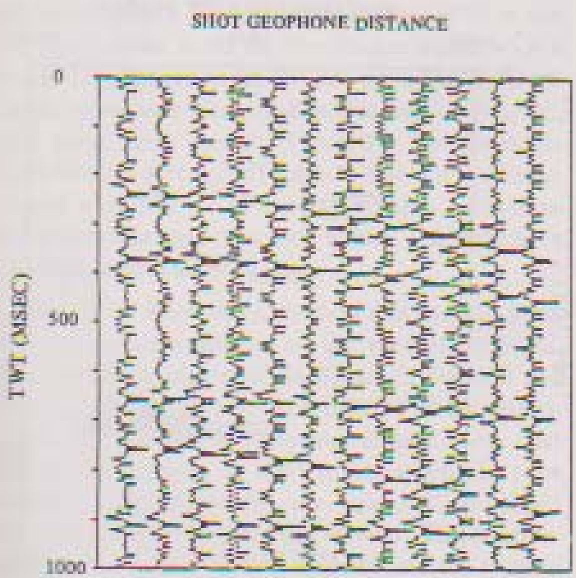

Figure 3. Synthetic record Figure 2 with random noise added. The S/N =2

IV. AMPLITUDE VARIATION WITH N

To observe the variation of output amplitude $Z(t_n)$ with N, the degree of the root, let us first observe the variation of $Y_m^{1/N}$ to N. In this case y_m is considered to be constant. It can be derived (see for example Pambudi, 1989) that

$$\frac{\partial Y_m}{\partial N} = -\frac{1}{N} Y_m^{1/N} \ \text{ln}\ Y_m^{1/N} \qquad (4)$$

Equation (4) tells us that the increase in N causes the decrease in $Y_m^{1/N}$. Its rate of change of $Y_m^{1/N}$ with N also decreases, which means $Y_m^{1/N}$ decreases if N increases. Now, let

$$S(t_n) = \overline{Y(t_n)}$$

$$Z(t_n) = Z(t_n) \qquad (5)$$

By substituting equation (5) into (2) we obtain

$$S(t_n) = \overline{Y(t_n)} = \frac{1}{k}\sum_{m=1}^{k} \text{sgn}\ [\ y(t_n, x_m)\ ]\ y(t_n, x_m)^{1/N} \qquad (6)$$

$$Z(t_n) = |\ Z(t_n)\ | = S^N (t_n)$$

The practical aspect of equation (5) can be seen clearly by observing two separate cases. Case one is the seismic events $y(t_n, x_m)$ which have the same phase at recording time t_n. The expected signal is supposed to be in this first case. Case two is the seismic events $y(t_n, x_m)$ which are not all of the same phase at recording time t_n. The random noise will belong to this second case.

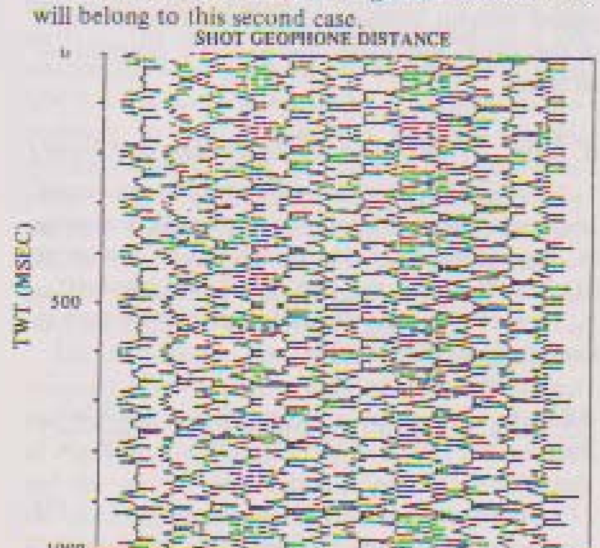

Figure 4. Synthetic record Figure 2 with random noise added. The S/N =1

A. Case – 1 (Signal)

In the first case, we will show that the output amplitude decreases with increasing N unless the input amplitude y_m are all perfectly equal on every trace.

For the derivation of the rate of change of $Z(t_n)$ with N see for example Greenhalgh (1987)

$$\frac{\partial Z(t_n)}{\partial N} = S^{N-1}(t_n)\,[S(t_n)\ln S(t_n) - \frac{1}{k}\sum_{m=1}^{k} Y_m^{1/N}\ln Y_m^{1/N}] \quad (7)$$

It is clear that

1. $\frac{\partial Z(t_n)}{\partial N} < 0$ if $Y_m^{1/N}$ are not all equal

2. $\frac{\partial Z(t_n)}{\partial N} = 0$ if $Y_m^{1/N}$ are all equal

The first conclusion implies that the absolute value of the output decreases with increasing N. In other words, the output amplitude of the expected signal decreases with increasing N if the signal amplitude are not all equal on every trace.

The second conclusion means that the absolute value of the output remains the same irrespective of the changes in N. In other words, the signal is passed without attenuation and without distortion if the signal amplitudes are perfectly constant on all traces.

B. Case – 2 (Random Noise/Background Noise)

In the second case, we will show that the output amplitude does not always decrease with increasing N. Agains, the derivation of the rate of change of $Z(t_n)$ with N for the case where the input $y(t_n, x_m)$ are of the same algebraic sign can be seen in Greenhalgh (1987), where

$$\frac{\partial Z(t_n)}{\partial N} = S^{N-1}(t_n)\,[S(t_n)\ln S(t_n) + N\frac{\partial S(t_n)}{\partial N}] \quad (8)$$

Since not all amplitudes are of the same sign, we will have cases where

$$\frac{\partial Z(t_n)}{\partial N} < 0 \quad \text{and} \quad \frac{\partial Z(t_n)}{\partial N} > 0$$

which means that the output amplitude does not always decrease with increasing N.

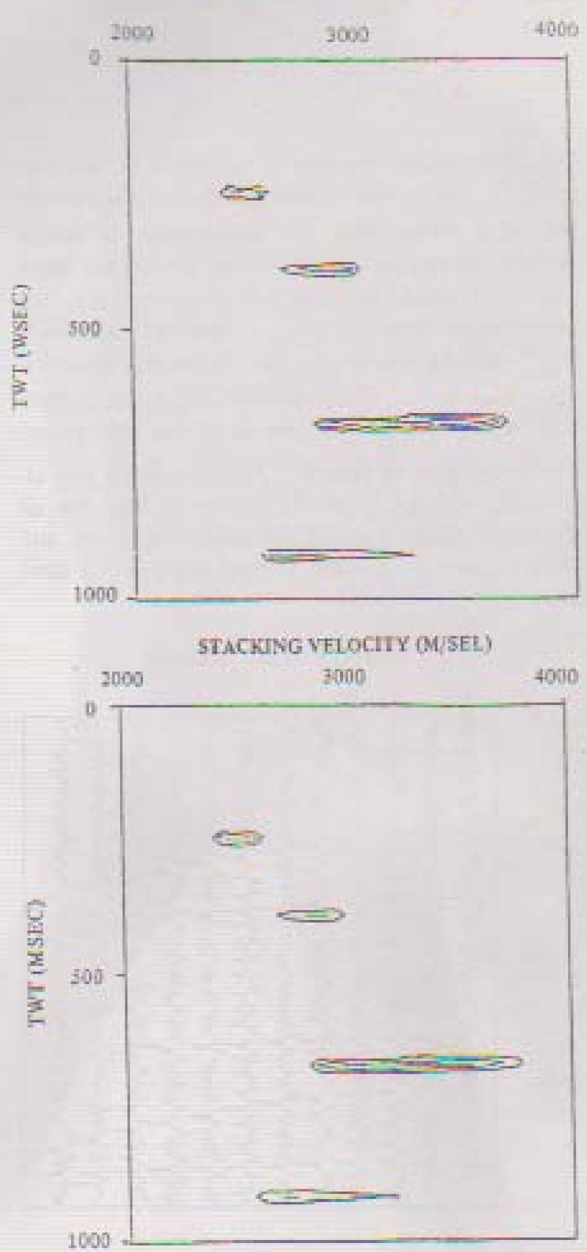

Figure 5. Velocity spectrum of the data shown in Figure 2

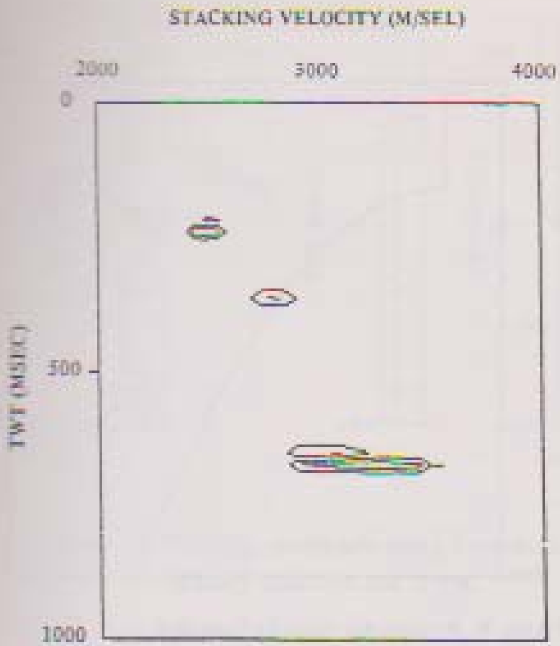

Figure 7. Velocity spectrum of the data shown in Figure 3

V. EXPERIMENTAL RESULT AND DISCUSSION

Artificial records were generated from the model given in Figure-1. The geophone interval is 30 m and the first offset is 50 m. The Ricker signal with a dominant frequency of 25 Hz was chosen. Three kinds of records were used in this experiment, i.e., the noise free record (Figure-2), the synthetic record with S/N = 2 (Figure-3) and the synthetic record with S/N = 1 (Figure-4). Primary reflections from interfaces and the free surface multiple have been taken into account.

The N-th Root Stack method was used to generate the velocity spectra of the synthetic records. The result are illustrated in Figure-5, Figure-6 and Figure-7. It can be seen that velocity at the corresponding TWT can be estimated closely. Note that the velocity picked in the velocity spectrum is the stacking velocity, while the velocity mentioned in the model is the interval velocity. The relationship between the stacking velocity and the interval velocity is well known. The stacking velocity is the root mean square velocity which is always less than the interval velocity. The free surface multiple is not clearly represented in the velocity spectrum because its velocity contour merges with the velocity contour of the primary reflection from the third interface. We can see that the velocity contour is wider then the other.

The velocity spectra obtained above were used to construct the velocity distribution which is required to obtain the stacking amplitude as a function of the TWT. In this experiments, two kinds of velocity distribution were used, the constant velocity stack (Figure-8) and the velocity function stack (Figure-9).

The result of N-th Root Stack using constant velocity distribution can be seen in Figure-10, while the result using the velocity function can be seen in Figure-11. Both using N=4. Similar experiment was also done using N=8, the results are illustrated in Figure-12 and Figure-13.

It can be observed that the N-th Root Stack attenuates the random noise effectively which enables the method to estimate the velocity precisely.

To demonstrate the superiority of the NRS compared to the common technique used in the industry, i.e., stacking which is based on delay and sum (DS method), similar experiments have also been done.

Figure-14 is the velocity spectrum of the noise – free record (see Figure-2) obtained by using DS method. The velocity spectrum obtained using DS method from the synthetic record with S/N = 2 and S/N = 1 are given in Figure-15 and Figure-16 respectively. It can be observed that the velocity spectra obtained using DS method is worse compared to the velocity spectra obtained by using the NRS method. The determination of the velocity distribution from the velocity spectrum obtained by DS method is less accurate compared to the NRS method.

Let us assume that the velocity distribution obtained from the above velocity spectra is correct and we will use the velocity distribution depicted in Figure-8 and Figure-9. By using the DS method and the velocity distribution (Figure-8) we obtained the stacking amplitude as illustrated in Figure-17. If instead of using constant velocity distribution, we use velocity function (Figure-18. This experiment demonstrate that DS method does not suppress the background/random noise as effective as the NRS method. Keeping is mind, that if the noise is still present in velocity spectrum, it will reduce the accuracy in determining the velocity itself.

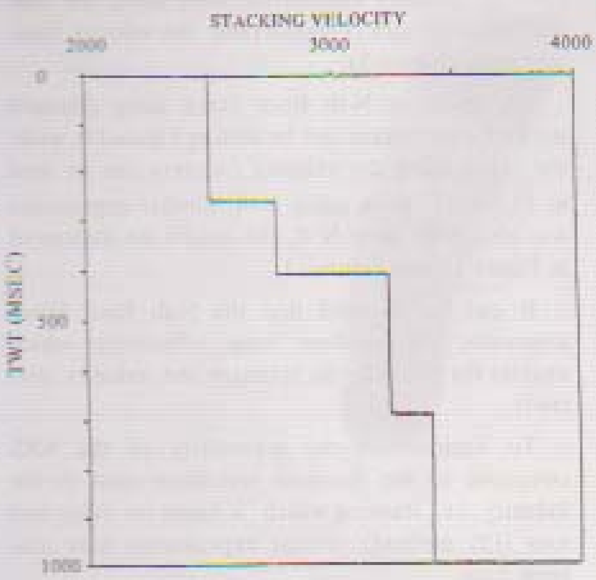

Figure 8. Constant velocity model

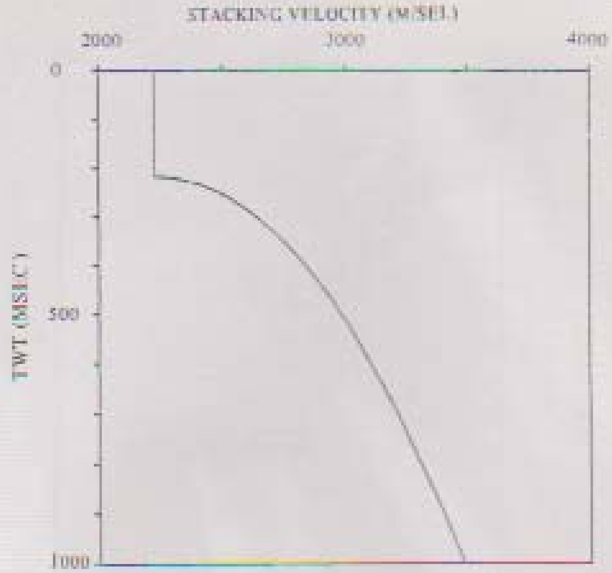

Figure 9. Hyperbolic velocity function

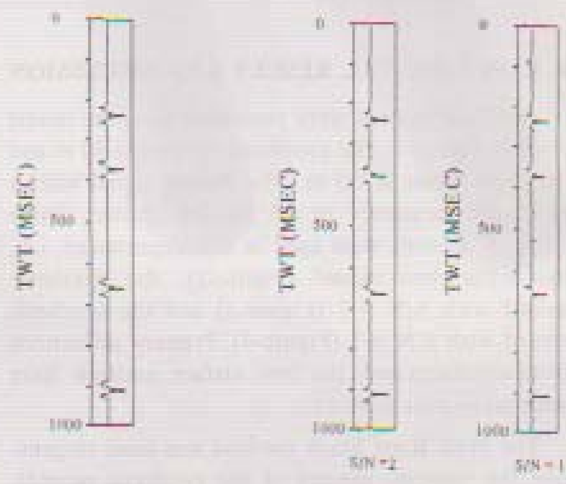

Figure 10. Stacking amplitude using constant velocity model and N = 4

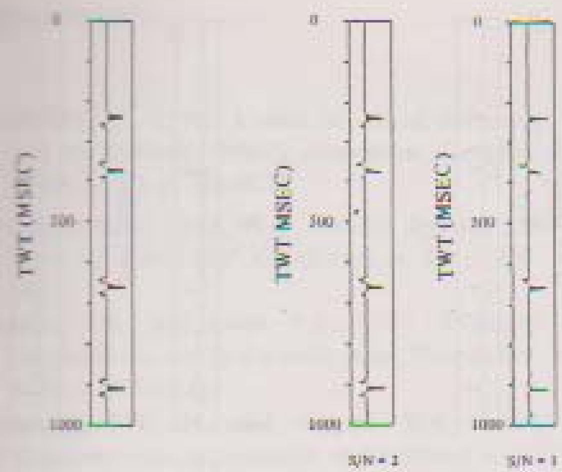

Figure 11. Stacking amplitude using hyperbolic velocity function and N = 4

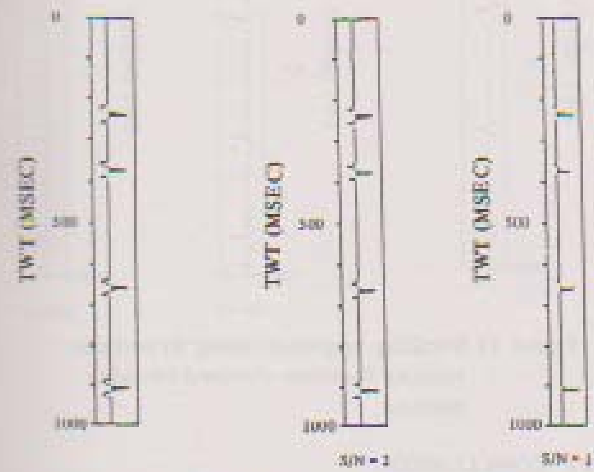

Figure 12. Stacking amplitude using constant velocity model with N = 8

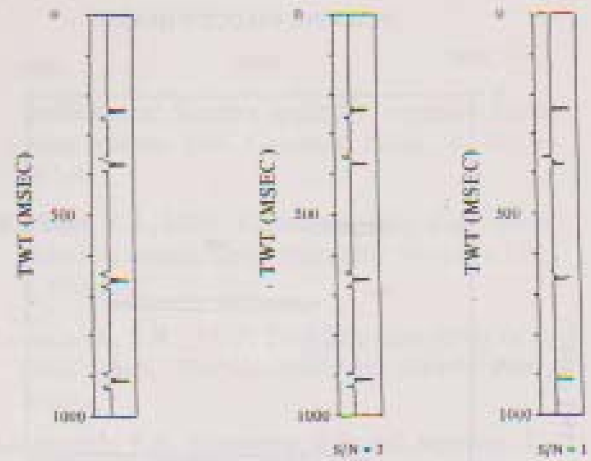

Figure 13. Stacking amplitude using hyperbolic velocity function with N = 8

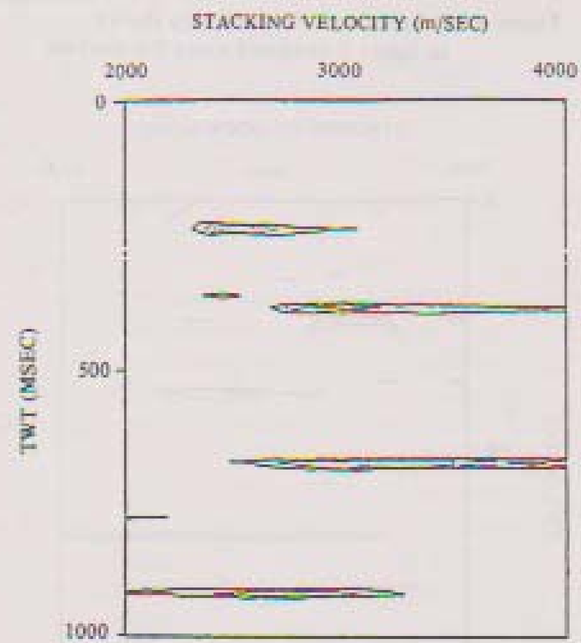

Figure 14. Velocity spectrum of data, Figure 2, using DS method

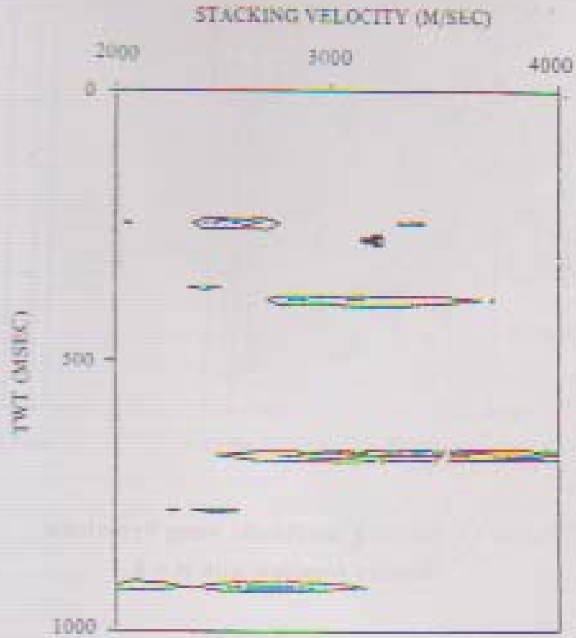

Figure 15, Velocity spectrum of data shown in figure 3 obtained using DS method.

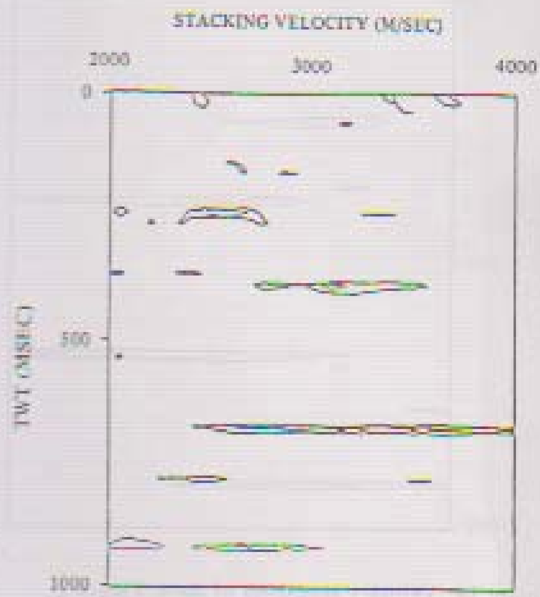

Figure 16. Velocity spectrum of data shown in figure 4 obtained using DS method.

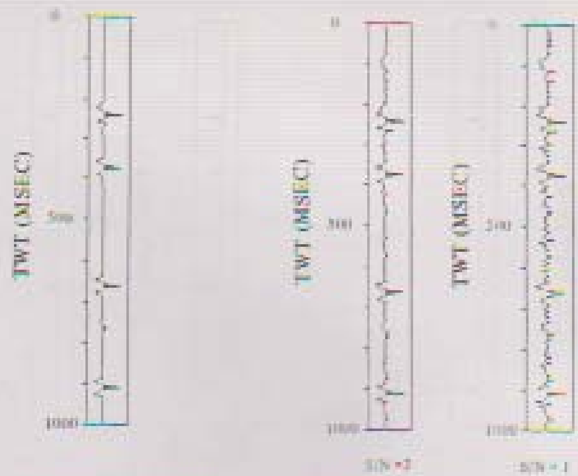

Figure 17. Stacking amplitude using constant velocity obtained by using DS method.

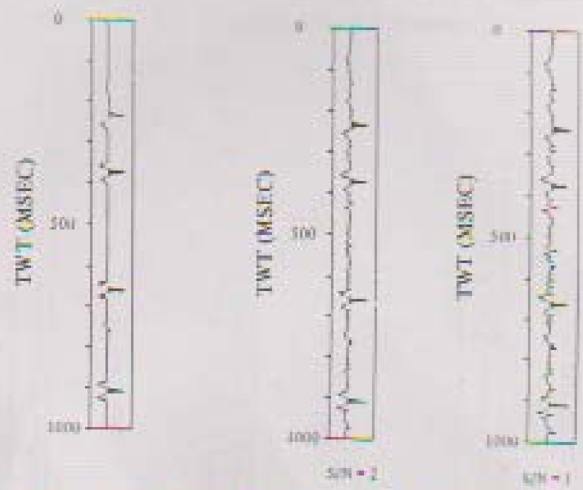

Figure 18 Stacking amplitude using hyperbolic velocity function obtained by using method.

VI. CONCLUSION

The N-th Root Stack is the powerful tool for estimating seismic wave velocity in the subsurface from seismic data.

The N-th Root Stack attenuates the background/random noise effectively which enable the determination of the velocity function can be done accurately.

The N-th Root Stack is much more superior compared to Delay and Sum method which has a wide spread applications in the industry.

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