Picking and fitting of first-break times measured on Gabor transforms of uncorrelated Vibroseis VSP signals

Wong, J.

ABSTRACT

Estimates of the bulk dispersive velocities of an earth volume can be obtained from the Gabor transforms of uncorrelated Vibroseis signals recorded in VSP surveys. The transforms provide time-frequency displays on which first-break times can be picked automatically using a modified energy attribute. Analysis of these times gives directly measured estimates of the frequency-dependent velocity of the bulk rock volume through which the seismic waves have propagated. Due to low signal-to-noise ratios that occur in real field data, the picked times will usually have outliers and random variation across the frequency axis. After eliminating the outliers, least-squares nonlinear regression based on a relatively simple fitting function smoothly fits and interpolates the picked times.

INTRODUCTION

Directly measured estimates of the bulk anelastic properties of an earth volume can be obtained from first-break times on Gabor transforms of uncorrelated Vibroseis signals recorded in VSP surveys (Innanen, 2014; 2015; 2016)). In a typical field walk-away VSP survey, there will be many surface shots (on the order of hundreds) shooting into a downhole array of many receivers (again on the order of hundreds). Using the technique devised by Innanen (2014; 2015), Gabor transforms are calculated for many of the received uncorrelated signals and the first-break times must be picked on the transforms. When the number of such transforms run into tens of thousands, only automated time-picking is feasible.

Automatic first-break time picking based on modified energy ratios (MER; see Appendix A) works well when signal-to-noise ratios (SNRs) are high. But when SNRs are low, the picked times often exhibit random variations and large outliers. These cause the picked time to deviate from what should be a smooth curve along the frequency axis. The outliers can be removed using a criterion based on the estimated SNRs at the picked times. If the SNR expressed in decibels at a particular picked time is below a defined cutoff value, that picked time is discarded. A nonlinear continuous non-negative function characterized by a small number of parameters can be used to smoothly fit the kept noisy picked times and interpolate within the gaps caused by removal of the outliers. Applying the MATLAB utility function **nlinfit** (see Appendix B) with the fitting function yields optimized (in the least-squares sense) fitting parameters.

METHOD AND RESULTS

The results in this report are based on vertical-component accelerometer data from the Snowflake walkaway VSP survey conducted in 2018 (Hall et al., 2018). Figure 1 shows the Gabor transform of the programmed Vibroseis sweep signal recorded on the SEGY files from the survey. The first-break times for the transformed sweep have a linear frequency dependence:

$$t_s(f) = T/(f_{max} - f_{min}) \cdot f \ . \qquad (1)$$

For the field survey, f_{min} (the start frequency of the sweep) is 2Hz, f_{max} (the end frequency of the sweep) is 150Hz, and T (the duration of the sweep) is 20 seconds. The times $t_s(f)$ are plotted as the black line on Figure 1. The yellow circles are the automatically picked first-break times.

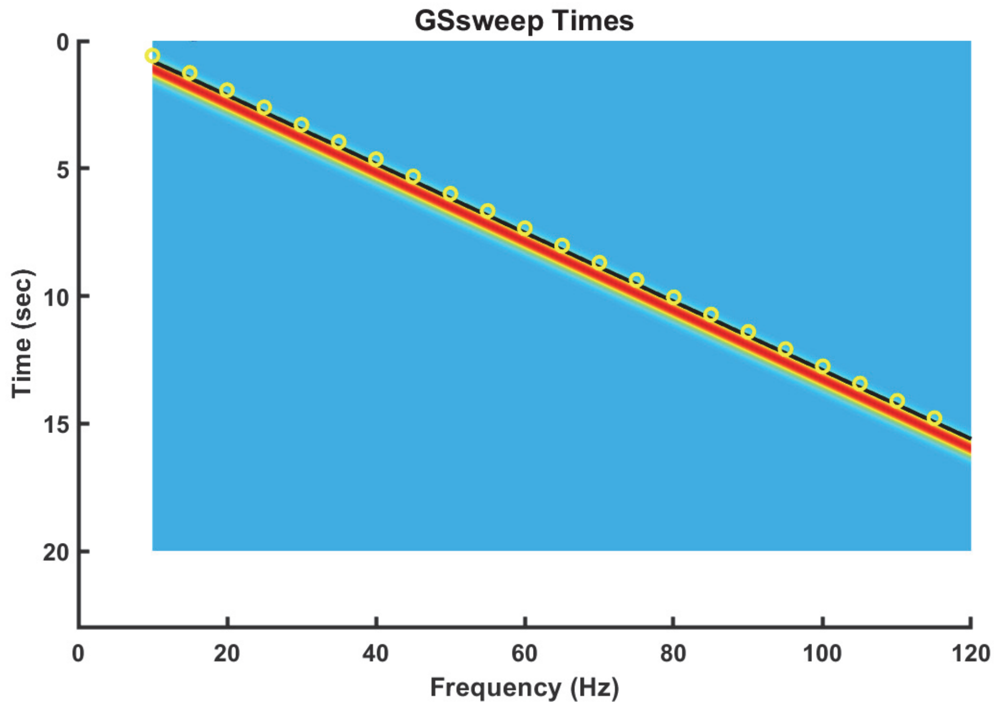


Fig. 1: Gabor transform of the programmed Vibroseis sweep. The yellow circles are automatically picked first-break times using the MER technique. The black line plots the times calculated according to Equation 1.

Figure 2 shows an example of the Gabor transforms of an uncorrelated vertical component signal obtained at a near-surface vertical-component accelerometer. Although noise exists at certain frequencies, we can see that, in general, the main event on this display seems to have a smooth trajectory composed of a linear component and a smaller nonlinear component. We assume the time-frequency dependence has the form

$$t_m(f) = (\ a_1 \cdot f + a_2) \ + \ b_1 \cdot \exp(-b_2 \cdot ((f + b_3)\hat{\ }2)) + b_4 \ . \qquad (2)$$

The linear term involving the coefficients $[a_1 \ \ a_2]$ is well approximated with the slope $a_1 = T/(f_{max} - f_{min})$ from Equation 1 and the intercept $a_2 = 0$. The nonlinear term involving the coefficients $[b_1 \ \ b_2 \ \ b_3 \ \ b_4]$ is a modified Gaussian function. Subtracting the linear term leaves the nonlinear component which we must fit using the modified Gaussian function. Using the MATLAB function **nlinfit**, we find parameters for the nonlinear component that (when added to the linear component) will smoothly fit the noisy observed picked times while interpolating to fill any gaps. The results in this report were obtained by setting the value of b_3 to 40 and not allowing it to change.

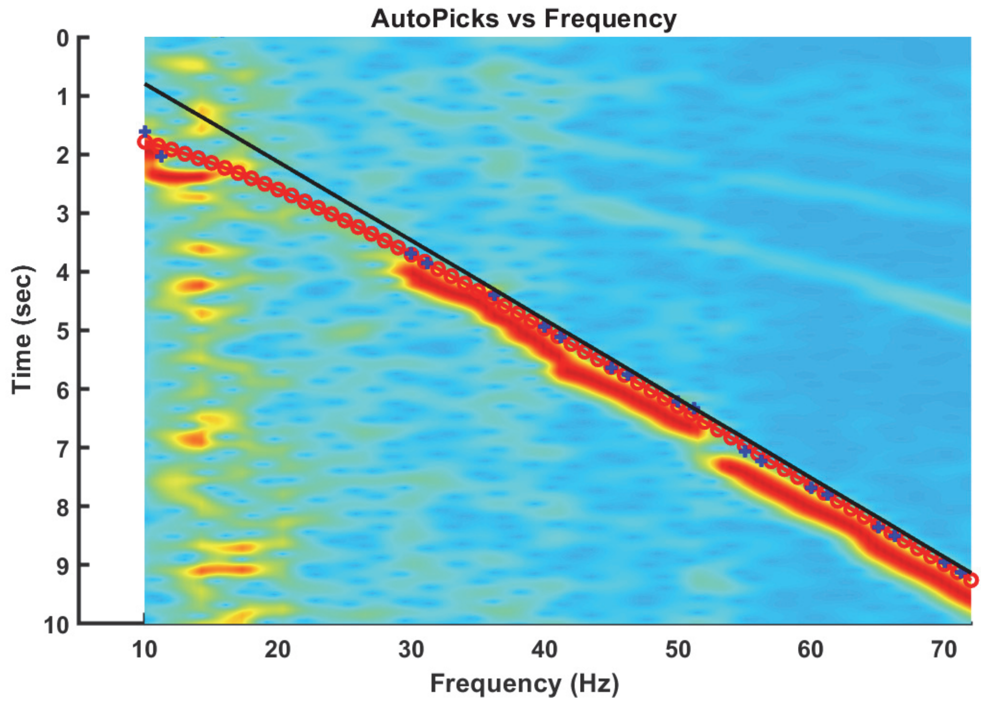


Fig. 2: Gabor transform of the uncorrelated signal from a receiver at depth = 1m. Blue crosses are automatically picked first-break times with outliers eliminated. The black line plots the times calculated according to Equation 1. Red circles are the interpolated times calculated according to Equation 2 after using **nlinfit** to find optimized values for the parameters b_i.

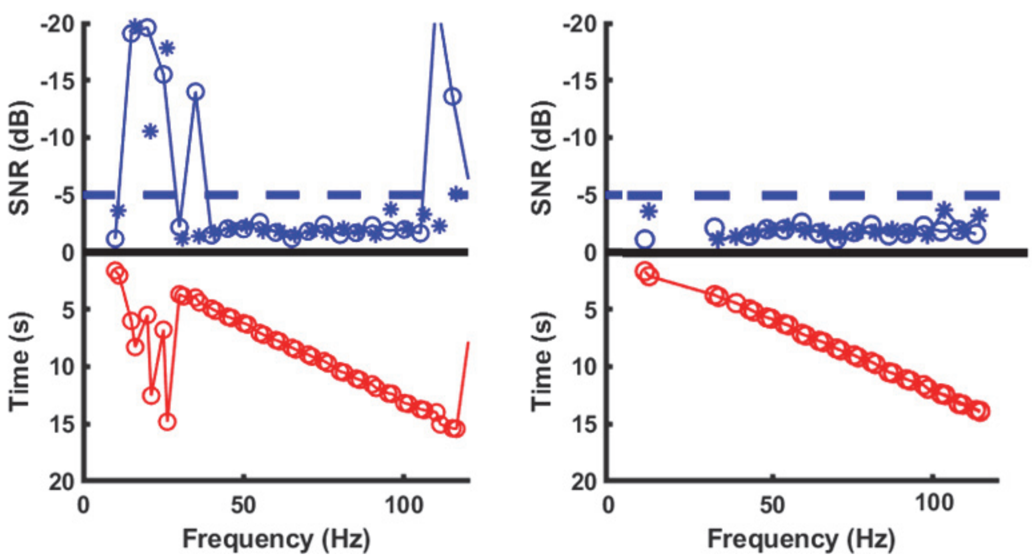


Fig. 3: Left: SNRs (blue) and automatic time picks (red) for the Gabor transform shown on Figure 2. Low SNR values and outlier times are associated with the noisy transform values at frequencies between 12Hz and 32Hz. Right: SNRs and automatically picked times with outliers eliminated.

The output of the automatic picking technique includes estimates of the SNRs at the picked times. Details on the MER method are given in the Appendix. Automatically picked first-break times for a few selected frequencies are plotted in red on Figure 3. Note the outliers and random fluctuations in the SNRs and time picks shown on the left side of the figure. The outliers are eliminated by discarding the picks with SNRs less than -.5dB. The remaining picked times are shown on the right side of Figure 3.

The left side of Figure 4 is a replot of the SNRs and picked times without outliers. The difference between these picked times and the sweep times calculated from Equation 1 at the same frequencies are the noisy residual times shown by the black crosses on the right side of Figure 4. These residuals are fitted in the least-squares sense using the modified Gaussian function with the MATLAB utility **nlinfit**. The fitted and interpolated values for the residuals are plotted in red. The sum of interpolated linear sweep times and nonlinear residual times is plotted on Figure 2 as red circles.

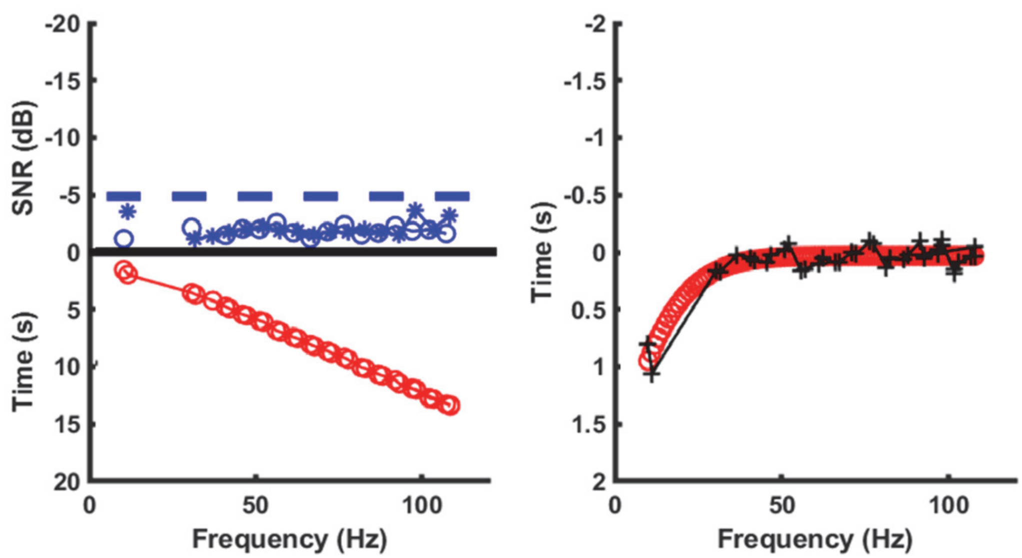
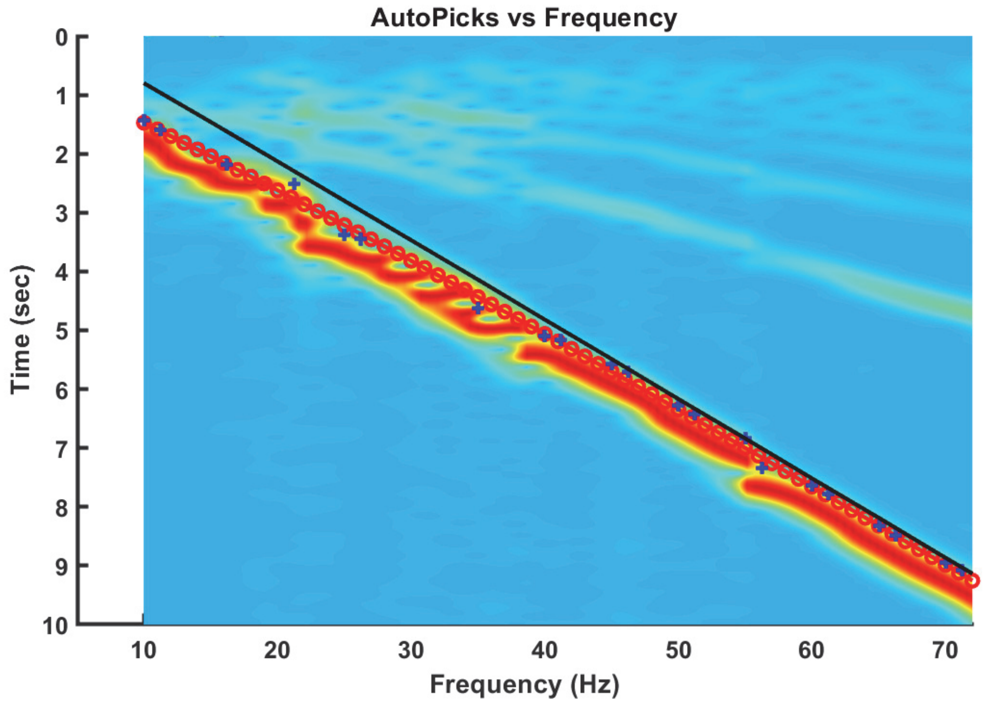


Fig. 4: Left: SNRs (blue) and automatic time picks (red) without outliers for the Gabor transform shown on Figure 2. Right: Black crosses are noisy residual times with outliers eliminated; red are smoothed and interpolated values after fitting the noisy residual times using the modified Gaussian function with **nlinfit**.

Figure 5 shows the Gabor transform of the uncorrelated vertical component signals for a receiver located at a depth of 20m. This transform is much less noisy compared to the one for the near-surface receiver. Again, the main events on these displays seem to follow smooth trajectories composed of a linear component and a smaller nonlinear component. The left side of Figure 6 shows the SNRs and automatically picked times for the Gabor transform of Figure 5. The SNRs are all larger than the cutoff value of -.5dB, so there are no outliers to be eliminated. On the right side of Figure 6, the noisy residual picked times are shown as black crosses. These residuals are fitted in the least-squares sense using the modified Gaussian function with **nlinfit**. The fitted and interpolated values for the



residuals are plotted in red. The sum of interpolated linear sweep times and fitted residual times is plotted on Figure 5 as red circles.

Fig. 5. Gabor transform of the uncorrelated signal from a receiver at depth = 20m. Blue crosses are automatically picked first-break times. Red circles are the interpolated times calculated according to Equation 2 after using **nlinfit** to find optimized values for the parameters b_i.

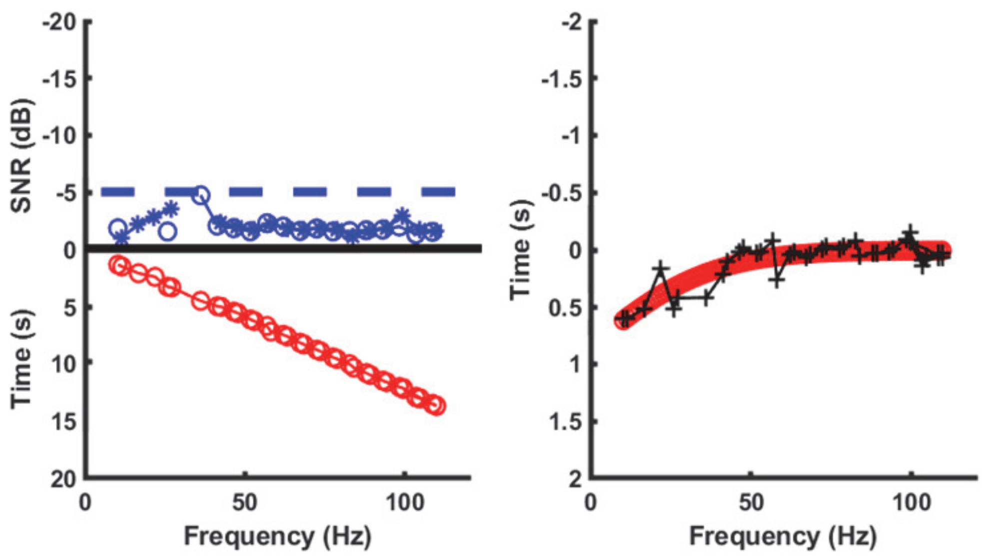


Fig. 6. Left: SNRs and automatic time picks for the Gabor transform shown on Figure 5. Right: Black crosses are noisy residual times; red are smoothed and interpolated values after fitting the noisy residual times using the modified Gaussian function with **nlinfit**.

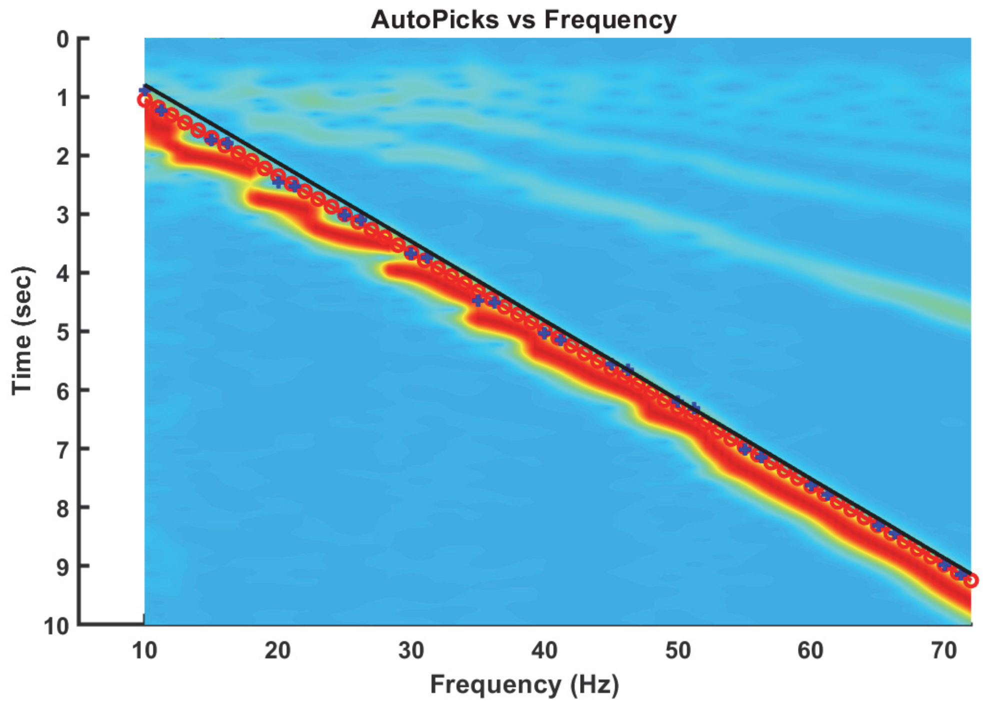


Fig. 7. Gabor transform of the uncorrelated signal from a receiver at depth = 97m. Blue crosses are automatically picked first-break times. Red circles are the times calculated according to Equation 2 after using **nlinfit** to find optimized values for the parameters b_i.

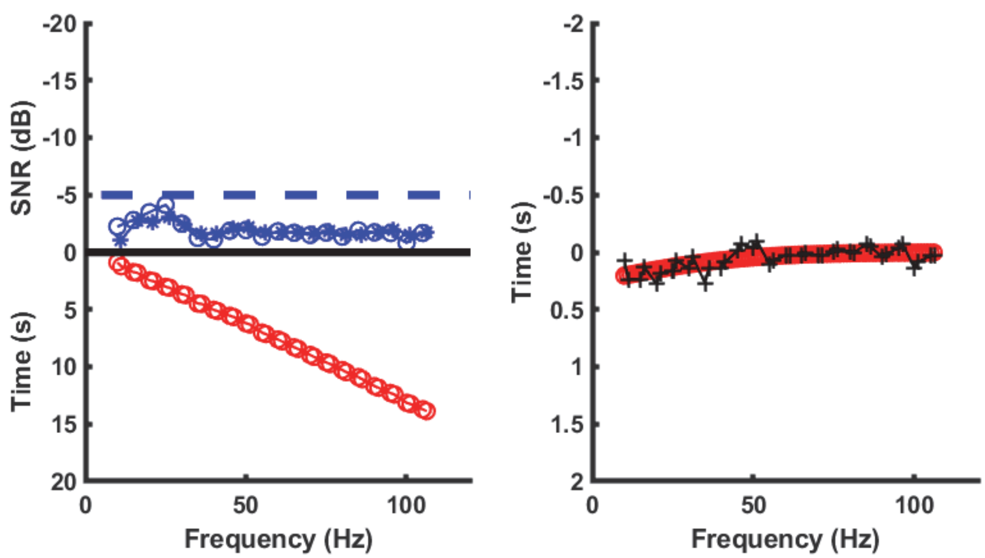


Fig. 8. Left: SNRs and automatic time picks for the Gabor transform shown on Figure 7. Right: Black crosses are noisy residual times; red are smoothed and interpolated values after fitting the noisy residual times using the modified Gaussian function with **nlinfit**.

Figure 7 shows the Gabor transform of the uncorrelated vertical component signals for a receiver located at a depth of 97m. The transform is also much less noisy compared to the one on Figure 2 for the near-surface receiver. Again, the main events on these displays seem to follow smooth trajectories composed of a linear component and a smaller nonlinear component.

The left side of Figure 8 shows the SNRs and automatically picked times for the Gabor transform of Figure 7. The SNRs are all larger than the cutoff value of -.5dB, so there are no outliers to be eliminated. On the right side, the noisy residual picked times are shown as black crosses. These residuals are fitted in the least-squares sense using the modified Gaussian function with **nlinfit**. The fitted and interpolated values for the residuals are plotted in red. The sum of interpolated linear sweep times and fitted residual times is plotted on Figure 7 as red circles.

DISCUSSION AND CONCLUSION

Directly-measured estimates of body-wave velocity dispersion of in a geological setting can be obtained using the Gabor uncorrelated signals from field surveys conducted with a Vibroseis source. The technique involves picking the first-break times on the transforms of signals from many sources and receivers, the totality of which may run into the tens or hundreds of thousands. In such a scenario, only automatic picking is feasible. In this report, we have described a nonlinear regression method for matching a relatively simple function with four parameters to automatically-picked times for which outlier times caused by noise in the transform have been removed. Three examples from a Vibroseis walk-away VSP survey indicate that our method of automatic picking and nonlinear regression succeeds in providing accurate, noise-free first-break times required for determining velocity dispersion in a bulk geological volume.

ACKNOWLEDGEMENT

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APPENDIX A: AUTOMATIC TIME PICKING USING A MODIFIED ENERGY RATIO (MER) ATTRIBUTE

Figure A1(a) summarizes the definition and use of the energy ratio and the MER attribute for a digitized seismic trace sampled with time Δt.

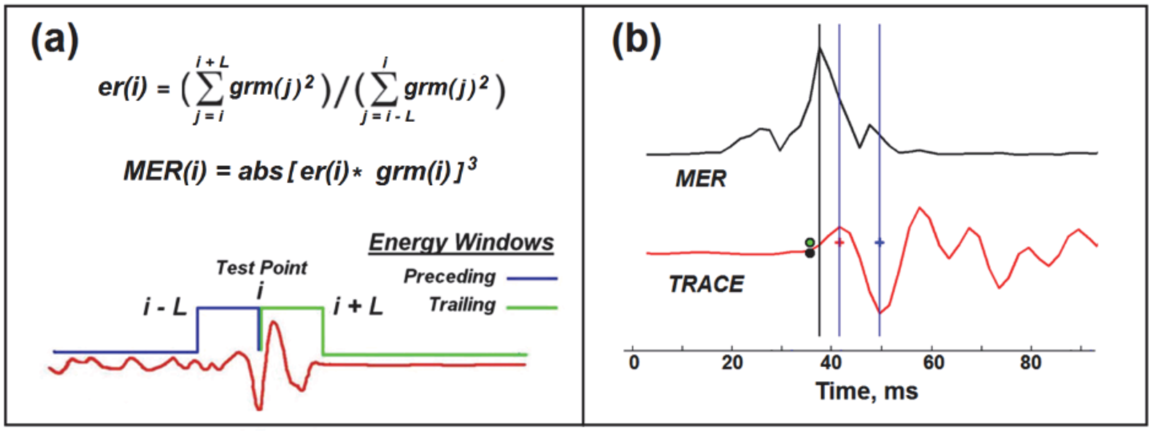

Fig. A1: (a) Definition of the MER attribute of a seismic trace. The preceding and trailing energy collection windows have equal lengths *L* located at a test point *i*. For noisy data, *L* should be two to three times the dominant period of the seismic arrival. For noise-free data, *L* can be a fraction of the dominant period. (b) The vertical black line is the time of the peak MER value; the black and green dots indicate manually-picked first-break times.

For moderately noisy seismic traces, the peak MER time is a very close estimate of the manually-picked first break time. Red and blue crosses indicate the first peak and trough times of the seismic trace. The energy ratio

$$er(i) = \sum_{i}^{i+L} grm(j)^2 \,/ \sum_{i-L}^{i} grm(j)^2$$

expressed in decibels is an estimate of the SNR at the test point. We deem that if the SNR is greater than about 6dB, then the peak MER time is a reliable representation of the first-break time.

APPENDIX B: USING THE MATLAB UTILITY FUNCTION NLINFIT TO FIT NOISY DATA

The following MATLAB script demonstrates the use of the MATLAB function **nlinfit**.

```
% ***********************************************************
% Script noisySin(x, amp, ampNoise);
 % This example demonstrates the use of the MATLAB function nlinfit.
 % For more information, type help nlinfit in the MATLAB Command window.
clc
close all

% Define a noisy data vector in the interval 0 to 10:
x = (0:.2:10);
```

```
amp = 1;
ampNoise = 0.5;
for i = 1 : length(x)
    y(i) = amp*sin((x(i)-.5)/2) + (rand-.5)*ampNoise + amp;
end

% Assume the nonlinear fitting function is a modified exponential
%           function [yout] = modExp(x,b);
% The code for the local function modExp is found at the end.

% Set up requirements for using nlinfit with modExp
myfun =  @(b,x)(modExp(x,b));

% Initial guess for fitting function parameters.
bGuess = [-6.0; 0.5; -0.4; .9 ] ;
[yGuess] = myfun(bGuess, x) ;

% Set up to use nlinfit to find better fitting parameters beta.
% For more information, type help statset in the MATLAB Command window.
statset.MaxIter = 50 ;      % the default is 100
statset.TolFun = 1e-5 ;   % the default is 1e-8
statset.Display = 'final' ;

% Apply nlinfit to find better fitting parameters beta
[beta, r] = nlinfit(x, y, myfun, bGuess) ;

% The root-mean square values between the input vector and the fitted
% values are given by r.

% Display the initial guess and final parameters:
parms(:,1) = bGuess; parms(:,2) = beta;
disp( 'bGuess   beta')
disp(num2str(parms));
disp(strcat('RMS error =',num2str(rms(r))))

% Get noise-free, interpolated values using the updated parameters
xout2 = [0: .1: 10];
yout2 = myfun(beta, xout2);

% Plot the various vectors
figure; hold on
plot(x,y, 'r-+')               % the input noisy data
plot(x,yGuess, 'k-+')      % the guess data
plot(xout2,yout2, 'b-o')   % the noise-free interpolated fitted data
  axis([0 10 -.5 2.5])
  grid
  xlabel('X', 'fontsize', 22,'FontWeight', 'bold')
  ylabel('Y', 'fontsize', 22,'FontWeight', 'bold')
  set (gcf,'color', 'white') ;
  set (gca,'FontWeight', 'bold') ;
  set (gca,'FontSize',20,'LineWidth',2)

return

% This is the inline function.
function [yout] = modExp(x ,b);
for i = 1:length(x)
```

```
   x1 = (x(i) + b(1))*b(2);
  yout(i) = b(3) + b(4)*exp(-x1^2);
end
end % function
% ************************************************************
```

Figure B1 is the output produced by the above script.

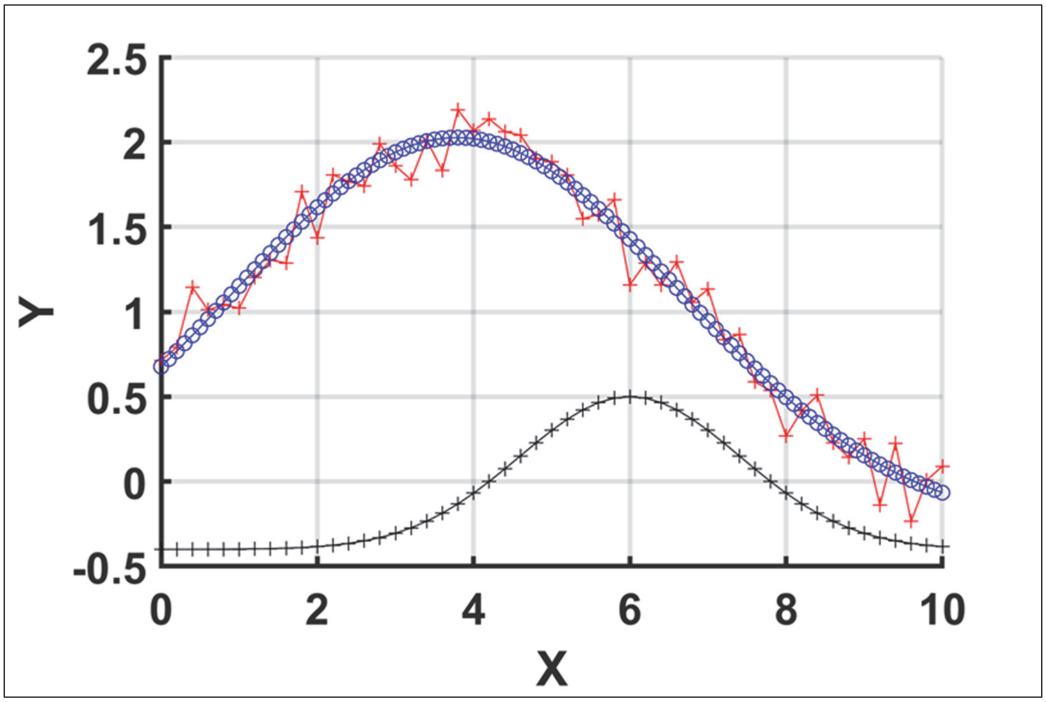

Fig. B1. Red: Noisy input data, assumed to originate from an experiment. Black: calculated data using initial guess parameters for the modExp function. Blue: calculated data for final fit after 50 iterations of **nlinfit**.

The initial guess and final parameter values for the function modExp as well as the final rms value of residuals are given below.

Initial Values (bGuess)	Final Values (beta)
-6	-3.7876
0.5	0.2473
-0.4	-0.2841
0.9	2.3105

RMS error (noise) = 0.12865