

Earthtones: nonstationary colour correction in ProMAX

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ABSTRACT

When applying statistical deconvolution techniques to seismic data, it is almost universal to assume that the spectrum of the earth's reflectivity is white over some particular bandwidth. In situations where seismic data are acquired in reasonable proximity to an existing well with one or more reflectivity logs, however, the nonstationary deconvolution of the seismic traces can be improved by replacing the conventional white reflectivity spectral assumption with a simple 2D colour function (of frequency and time), whose shape has been derived from spectral analysis of the actual well log. Least-squares fitting of log reflectivity spectra to low-order polynomial curves has been shown to provide a convenient representation of the 'colour' of well log spectra. To facilitate the testing and application of 'colour-correction' in the nonstationary Gabor deconvolution algorithm to large data sets, the colour-correction scheme has been added to our existing ProMAX Gabor deconvolution and analysis modules. We describe here the specifics of those modules, including parameter selection and format requirements for the ASCII file which conveys into Gabor deconvolution the polynomial coefficient tables from MATLAB well log analysis; and we demonstrate the updated algorithms on field data.

INTRODUCTION

One of the key assumptions used to make statistical deconvolution possible is that the shape of the desired earth reflectivity spectrum is known, and that it is, in fact, flat, or 'white'. This assumption, coupled with the assumption that the spectrum of the propagating source signal is smooth and minimum phase allows us to deconvolve seismic traces by factoring and smoothing their spectra. Peng and Margrave (2008, 2009) have shown, however, that when the actual earth spectra differ from 'white', deconvolved reflectivity data have not only unrealistic amplitude spectra, but incorrect phase, as well, when compared with synthetic seismograms based on well logs. Tang et al (2010) showed how to compensate the effect of the "white" assumption on stationary deconvolution, while for the nonstationary case, Peng and Margrave (2008, 2009) have showed that representing the shape of well log reflectivity spectra by low-order polynomial curves is an effective way in which to capture the 'colour' of the local earth function. They have developed a technique which derives the polynomial coefficients which best fit the spectra in each of a series of overlapping time windows applied to a well reflectivity log, and have successfully shown that these coefficients can then be used to create a 2D colour amplitude function to combine with the normal time-frequency deconvolution operator in Gabor deconvolution. The result of applying this 'colour-corrected' Gabor deconvolution is deconvolved seismic traces that are more likely to tie properly with local well logs, both in event character and phase.

While it is convenient and appropriate to derive the polynomial colour function from a well log using software in MATLAB, it is less convenient to actually apply the function to a seismic survey in this package. For this reason, and to make a more appealing

software release to sponsors, we have upgraded two of our ProMAX modules, Gabor2, and Gabor_sc to enable them to incorporate and use polynomial colour spectra from the MATLAB analyses, both to generate diagnostics (Gabor_sc), and to colour-correct the nonstationary deconvolution performed by both modules. In the following material, we describe the upgrades to both Gabor2 and Gabor_sc, and we show in detail how to use both modules. The revised documentation for both modules is included as Appendices.

PRELIMINARIES

In preparation for transferring the colour function information derived from a well log in MATLAB to a ProMAX module, Peng has modified the MATLAB script to write out an ASCII file containing a header of five lines of character information (text) identifying the well and specifying various analysis parameters, followed by one line of numerical values for each Fourier analysis window used to analyze the input reflectivity log. Hence, if spectral analysis was performed on 100 overlapping windows on a given log, the ASCII file for that log will contain 105 lines (five lines of headers, 100 of numerical data). Each data line consists of the start time of the particular analysis window followed by N+1 numerical values, where N is the order of the polynomial curve least-squares fitted to the Fourier amplitude spectrum of the log reflectivity within the window (Peng and Margrave 2009). Appendix III shows an example of an appropriate ASCII file for a well log.

The described ASCII file is the source of the colour-correction information used in our ProMAX modules. Although somewhat clumsy, we currently allow only a certain fixed number of ‘words’ in each line of the file header, where a word is any combination of symbols up to twelve characters in length, and the ‘words’ are separated by blanks. The current standards allow seven words in line one, eight words in line two, ten words in each of lines three and four, and twelve words in line five. This standard was essentially determined by examining the header information of Peng’s original ASCII file and setting up the Fortran formatted character data input in the ProMAX modules accordingly. We may modify this standard to a more natural one at some point, but the requirements outlined above don’t seem too onerous; and an ASCII file is easily edited to conform.

GABOR2 UPDATE

The most visible update to Gabor2 is the addition to the Menu of the ‘Colour correction’ switch, whose default is ‘No colour correction’. If the ‘Apply colour correction’ option is chosen, however, five new parameters appear in the menu, all required for the colour-correction procedure. The first parameter is the number of windows used in the well log analysis, the second is the time in ms from the beginning of each window to its centre (window half-width), the third is the order of the polynomial curve used, and the fourth is an exponent used to control the temporal normalization of the spectra within the windows (more detail later). Parameter five is a character string, to be edited by the user to provide the pathname for the ASCII file containing the well analysis data.

Behind the scenes, when the colour correction switch is selected, during the preparation and parameter reading stage of ProMAX, Gabor2 opens the file whose

pathname appears in the menu window. The program reads the first five lines of the file as character data (as detailed above), then reads the designated number of data lines in the file, before closing the file. The character data from the file are then listed in the standard program listing, as are all the coefficient values, as a check against the original file values. During program execution, if colour correction has been selected, at the point where the deconvolution operator is constructed, a new subroutine is called to create the 2D colour function from the stored input parameters and coefficients. The colour function, on the same time/frequency grid as the deconvolution operator, is divided point by point into the operator, so that application of the modified deconvolution operator applies the colour correction to the current trace.

Within the colour function subroutine, the polynomial coefficients of each order are interpolated from the well log window centre times at which they are posted to the times of the window centres for the Gabor deconvolution. For window centres outside the range of well log times, the first and last coefficient values are extrapolated. The colour function is then created by evaluating the polynomial at each window centre, using the frequency grid increment of the Gabor deconvolution. This results in a colour function which matches the sampled deconvolution operator point by point in both the time and frequency dimensions.

It has been observed that applying the temporal amplitude variation in the colour function prestack is problematic (Cheng et al, 2010), so an optional normalization can be applied in the time dimension to dampen or eliminate the temporal amplitude variation altogether. For each polynomial spectrum in the colour function, the maximum amplitude in the frequency range from zero to one quarter Nyquist is determined, and the polynomial spectrum is divided by this amplitude raised to a power between zero and one. When the exponent is zero, no normalization occurs, but when it is unity, the spectrum is completely normalized with respect to its neighbours...all temporal amplitude variation is removed.

GABOR_SC UPDATE

The preparation stage of Gabor_sc is the same as Gabor2 in that if the colour correction switch is set to the affirmative, the same five parameters are expected, including the path for the ASCII file created in the MATLAB well analysis routine. What differs in Gabor_sc is the optional ability to construct the colour correction function for the sole purpose of displaying it in diagnostic mode, like the Q-function or other factors of the Gabor spectrum of an input seismic trace. In this case, the colour function is output as seismic traces, each of which is the polynomial spectrum at a corresponding Gabor window centre. These traces can be plotted in colour or greyscale as a diagnostic display to study the true 'earth function' colour (at least as portrayed by well log information). Since the colour function is evaluated on the same grid as the other factors of the Gabor spectrum, its plot can be conveniently compared with the plots of any other Gabor factor.

If applied in deconvolution mode, Gabor_sc uses the constructed colour function as a divisor for each deconvolution operator, so that the colour correction is applied to each output trace. Note that since the colour function is constructed from data independent of the seismic traces, it is estimated only once, unlike the other components of the

deconvolution operators in Gabor_sc, which are re-estimated during every iteration. Furthermore, the colour function is incorporated into each operator only once, just prior to computation of the operator minimum phase.

EXAMPLES

To illustrate the operation of both updated ProMAX modules, we use Gabor_sc in the diagnostic mode to display colour contour plots of 2D colour functions, both synthetic and real, and Gabor2 to apply these functions to ensembles of real field data. While Gabor_sc has the capability to apply colour correction, as well, it is only suited to applying the correction to the individual traces of a complete seismic line, since Gabor_sc is a surface-consistent, iterative algorithm. Gabor2, on the other hand, can apply colour correction not only to single traces and trace ensembles, but also to post-stack traces.

Figure 1 shows a synthetic 2D colour function whose magnitude varies only in the frequency dimension (stationary in time). This particular function is constructed using a second order polynomial in frequency: and its first order coefficient (linear slope) is negative, making the spectrum “red”, since its largest magnitudes are at low frequencies. Figure 2 shows, in contrast, a “blue” synthetic 2D colour function, also stationary in time, constructed using a second order polynomial with a positive first order coefficient. Both these plots were created using Gabor_sc in diagnostic mode, where the values of the colour function are output as traces whose samples are spectral magnitudes, one trace per Gabor analysis window.

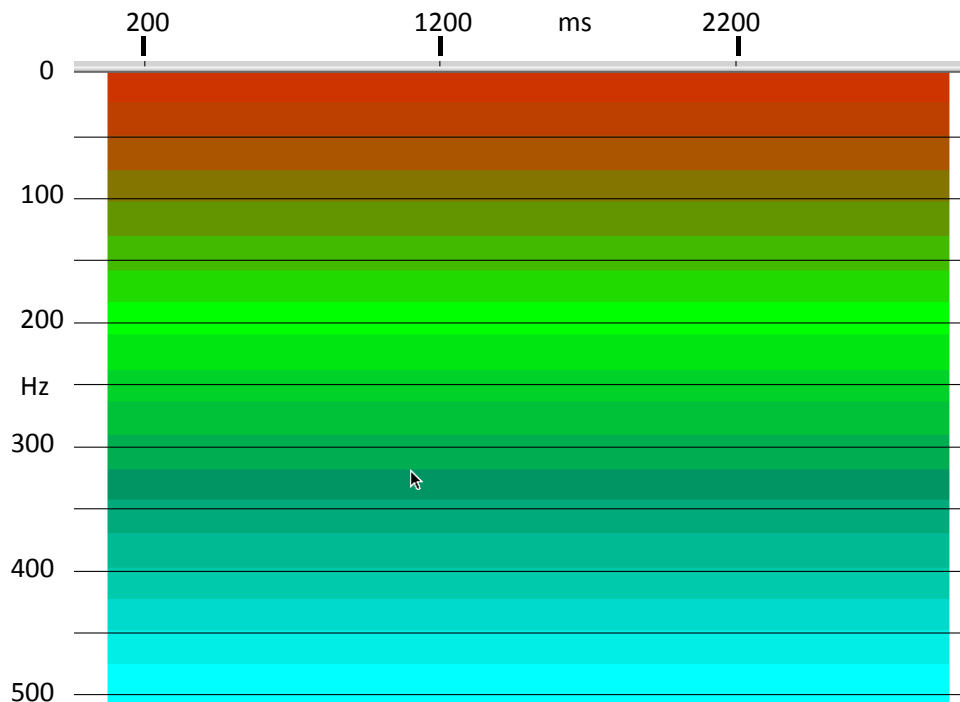


FIG. 1. Synthetic 2D colour function constructed from second order polynomial in frequency. The function is constant in time, hence no temporal colour variation. Blue indicates low magnitudes, and red high magnitudes, so this is a “red” spectrum (high magnitudes at low frequencies). This plot was prepared using Gabor_sc

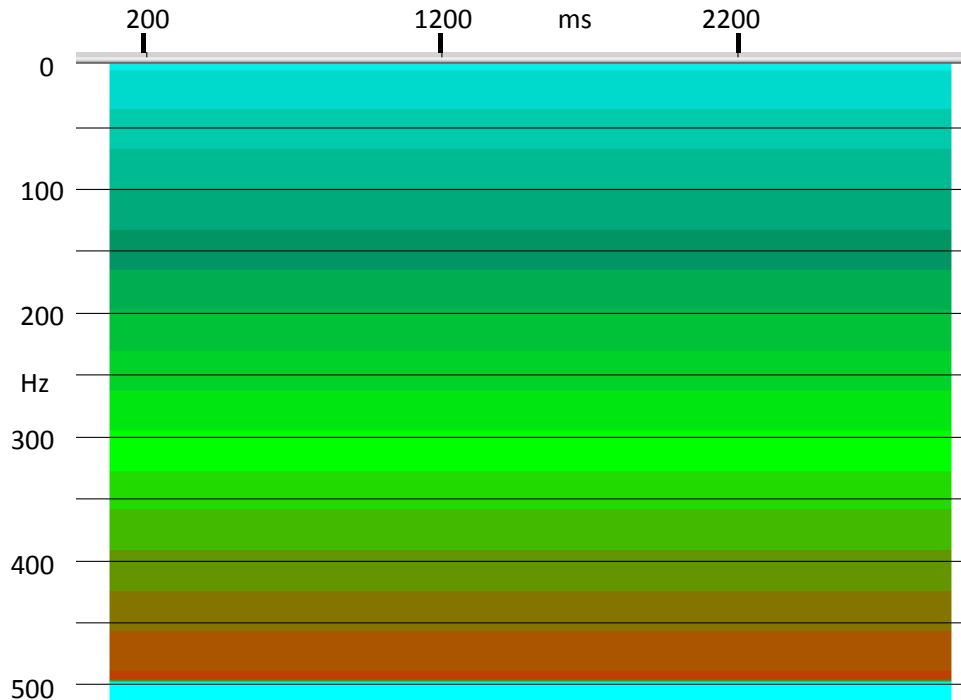


FIG. 2. Synthetic 2D colour function constructed from second order polynomial in frequency. The function is constant in time, hence no temporal colour variation. This is a “blue” spectrum (high magnitudes at large frequencies). This plot was prepared using Gabor_sc

To show the influence of the colour function on Gabor deconvolution, we used a group of seismic traces from the Spring Coulee vertical component data set. Figure 3 displays the traces after Gabor deconvolution using the “white” spectrum assumption (no colour correction). Figure 4 shows the same traces after deconvolving the traces using the “red” colour function instead of the “white” assumption. Comparing this figure with Figure 3, only minor differences in appearance of the traces can be seen. In Figure 4, the higher frequencies are somewhat diminished relative to the low frequencies, as we expect. In Figure 5, however, where the traces have been deconvolved using the “blue” colour function, significant differences can be seen, not only in the frequency content of the deconvolution, but in the apparent phase of the events, as well. In particular, the higher frequency content of each event shifts the energy forward in the event, in keeping with the minimum phase constraint intrinsic to the deconvolution.

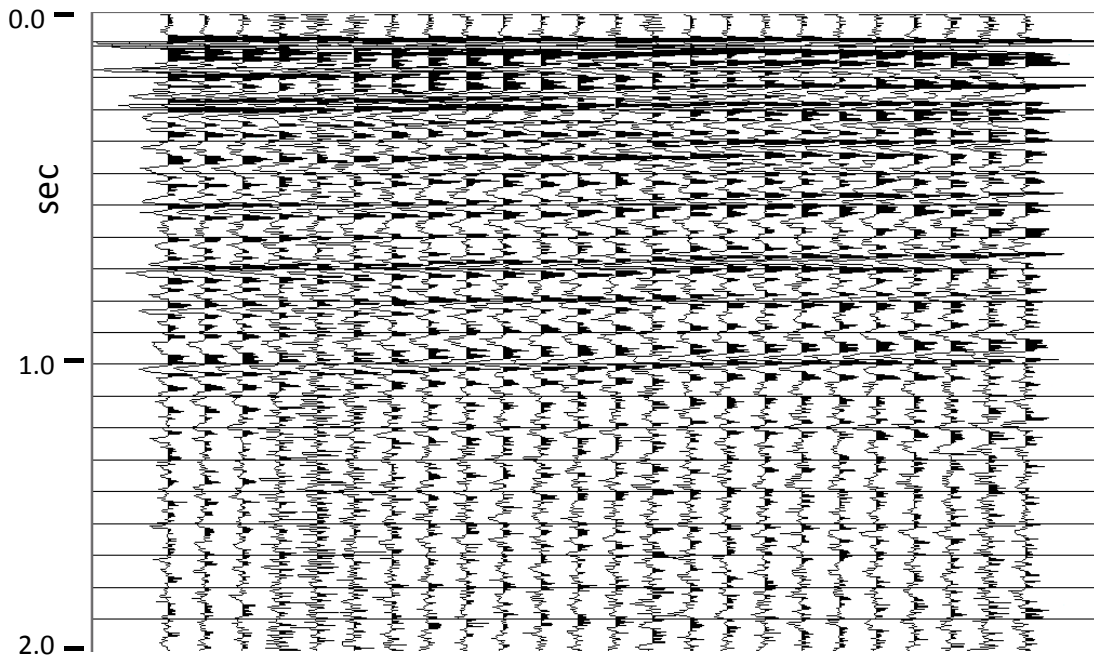


FIG. 3. A group of Spring Coulee seismic traces deconvolved using Gabor2 with no colour correction.

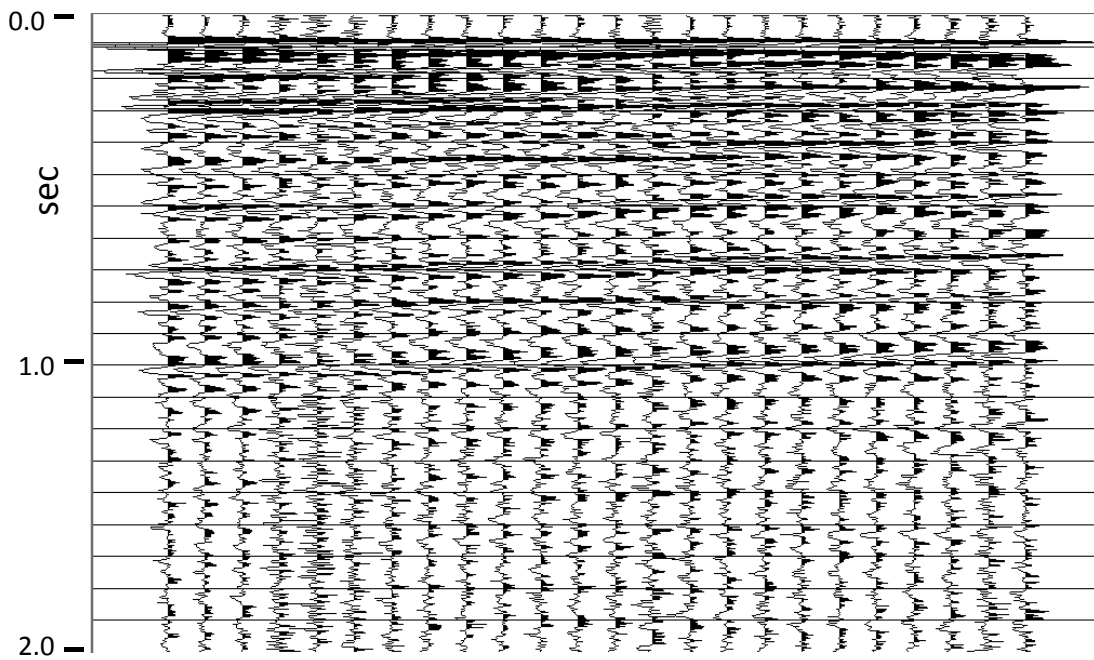


FIG. 4. Spring Coulee traces deconvolved in Gabor2 with colour correction, using the “red” colour function of Figure 1. Differences between these traces and those in Figure 3 are relatively small.

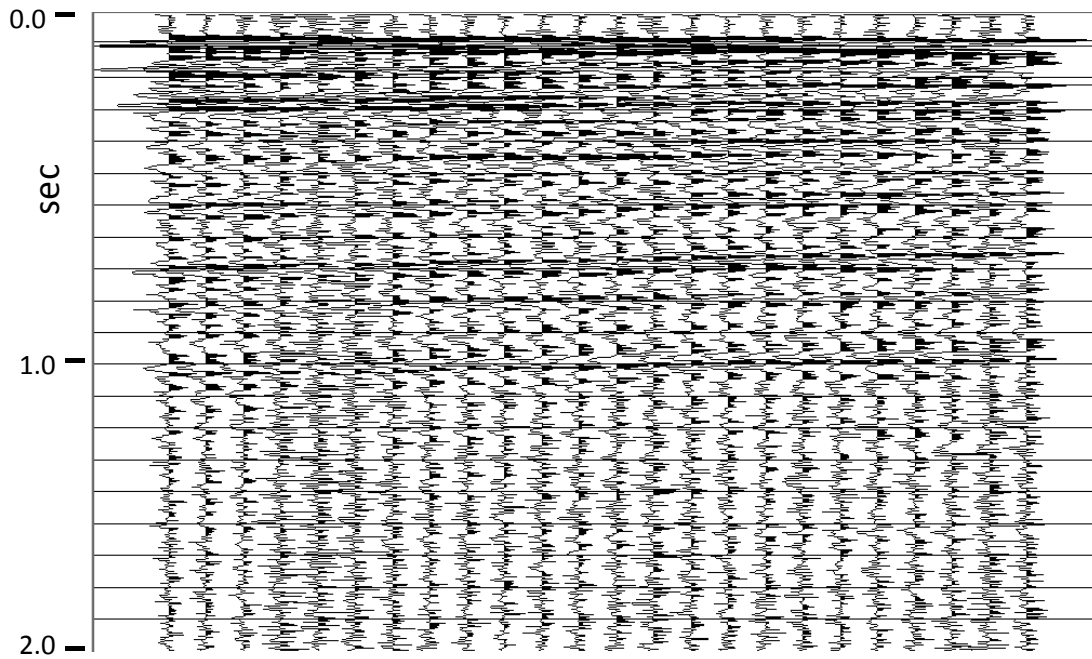


FIG. 5. Spring Coulee traces deconvolved in Gabor2 with colour correction, using the “blue” colour function of Figure 2. The increased bandwidth of these traces compared with those in Figure 3 are obvious. Small phase differences for some of the more prominent events above 1 sec. can also be seen.

As described by Peng and Margrave (2009), the 2D colour function of a well log may display variation in time as well as frequency, the so-called ‘temporal colour’. One difficulty in analyzing and using the temporal colour has been the magnitude of the overall amplitude variation with time displayed by some real logs. Figure 6 displays the 2D colour function computed using polynomials of order 3 for a well log in the Blackfoot area. Since the log covers only the upper second of seismic data, its spectra are extrapolated to later times. The magnitudes of the polynomial spectra vary greatly with time, and this colour function applied to the deconvolution produces results which, even if they are realistic portrayals of reflectivities, would be difficult to use in interpretation. In Figure 7 is an ensemble of vertical component seismic traces from the Blackfoot 2D 3C survey, with a bandpass and AGC applied for display purposes. Figure 8 shows the same traces after Gabor deconvolution with no colour correction, while Figure 9 displays the result after colour correction with the function in Figure 6. The faint amplitudes around the 1000-1200 ms zone (emphasized by the AGC) are due to the greatly diminished extrapolated amplitudes of the colour function in that zone, which is unrealistic. Note that in order to properly register the reflection times with the temporal colour variations of the colour function, NMO has been applied to the trace ensembles. This, however, distorts the spectral colour of the traces at shallow times, thus interfering with the proper spectral colour correction during deconvolution. For this reason, before stack, only spectral colour correction should be applied, hence deferring temporal colour correction to poststack.

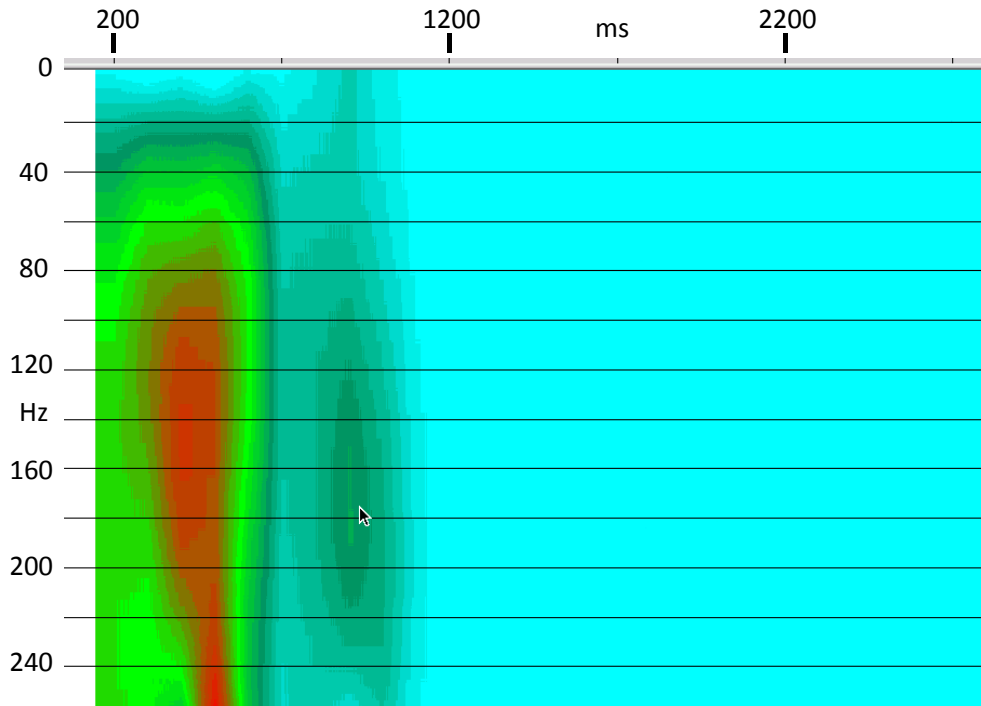


FIG. 6. 2D colour function derived from spectral analysis of a Blackfoot reflectivity log (courtesy of P. Cheng). This function is third order in frequency. The temporal variations in amplitude are quite large, and lead to unrealistic amplitudes in the deconvolution. Since the well log extends down to only a little over one second, the function is extrapolated below those times.

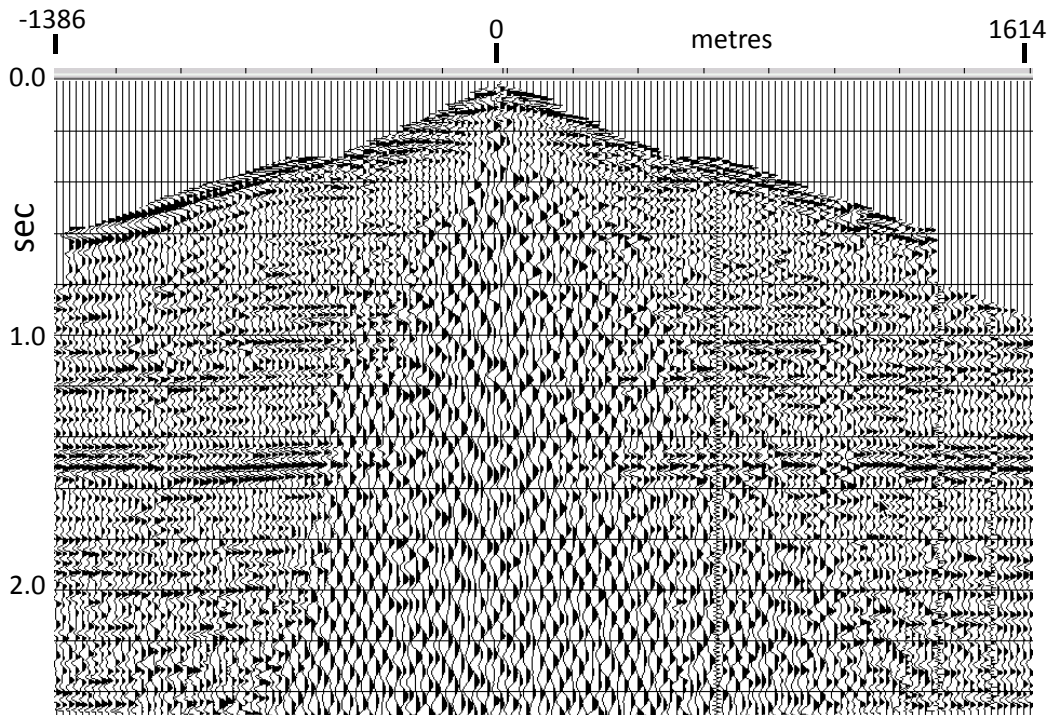


FIG. 7. A Blackfoot shot gather prior to deconvolution. Bandpass filter and AGC applied for display.

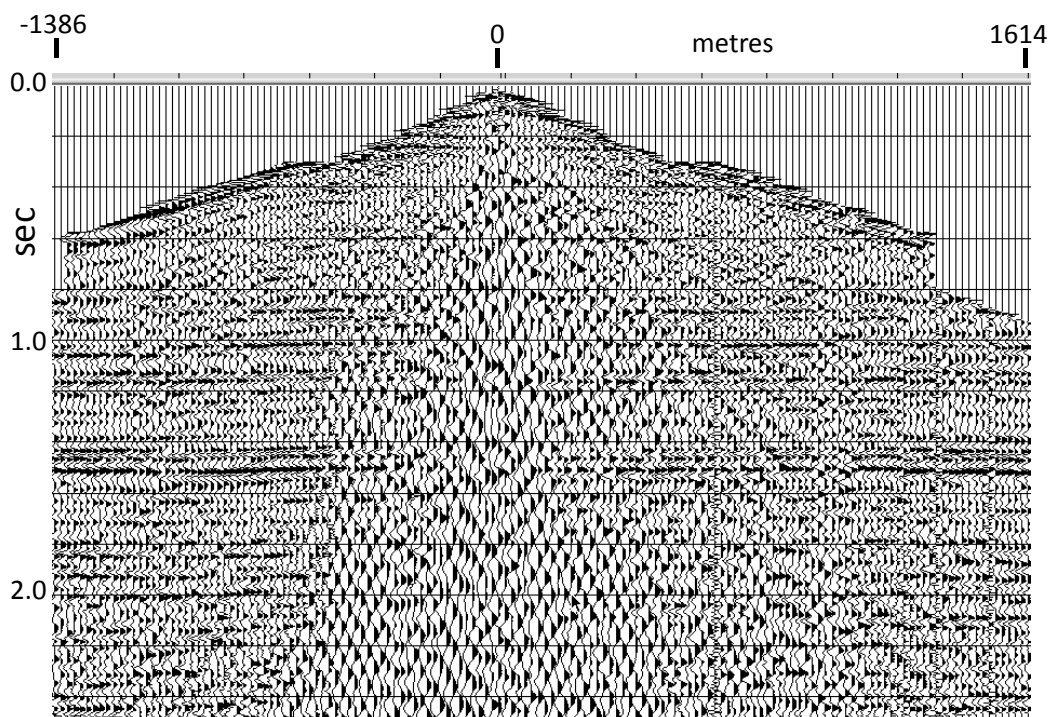


FIG. 8. Blackfoot shot gather from Figure 7 after Gabor deconvolution with no colour correction.

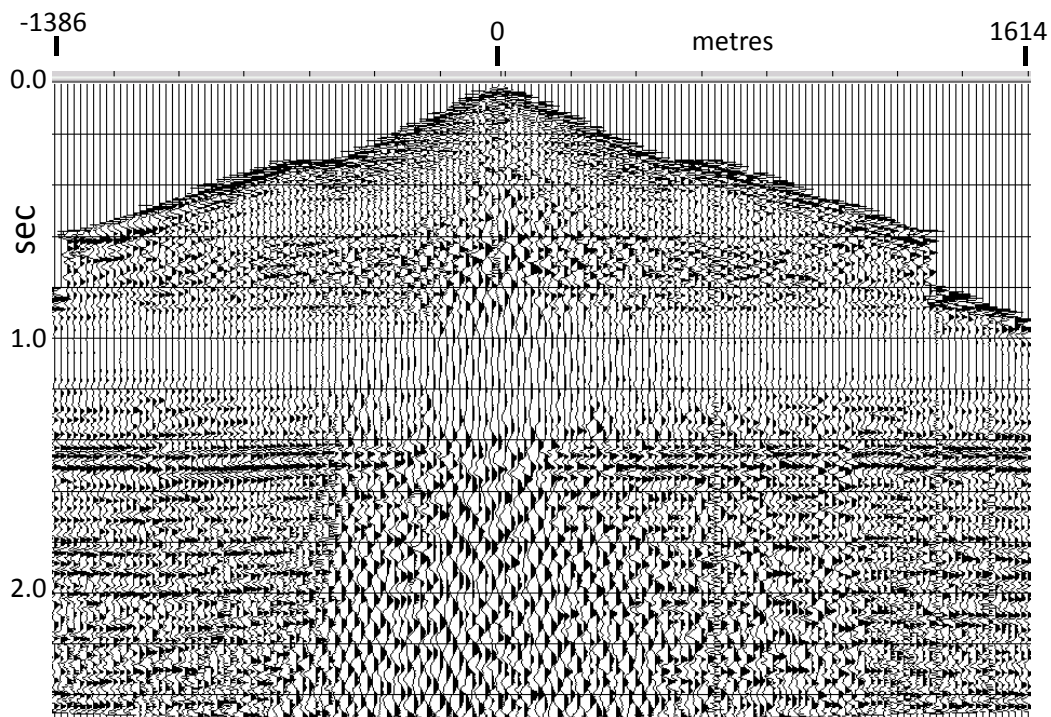


FIG. 9. Blackfoot shot gather after Gabor deconvolution with colour correction, using the colour function from Figure 6. The large temporal amplitude variations in the colour function cause the weak amplitudes in the deconvolution (which are expanded by AGC later in the record).

To enable pre-stack colour correction using spectral colour variations only, we added a normalization scheme to the colour function generation subroutine. This scheme first finds the maximum of each polynomial spectrum in the 2D colour function, in the frequency range below one fourth Nyquist, then finds the largest maximum. Each polynomial spectrum is then divided by a fractional power of the largest maximum to effectively damp the large magnitude temporal fluctuations in the colour function. Figure 10 displays the 2D colour function of Figure 6 after normalizing it by the largest magnitude to the first power (full normalization). As can be seen, all the overall magnitude variation with time has been removed, leaving only the variation in spectral shape. Figure 11 shows the same colour function normalized by the $\frac{3}{4}$ power of the largest magnitude; so some of the overall magnitude variation with time remains.

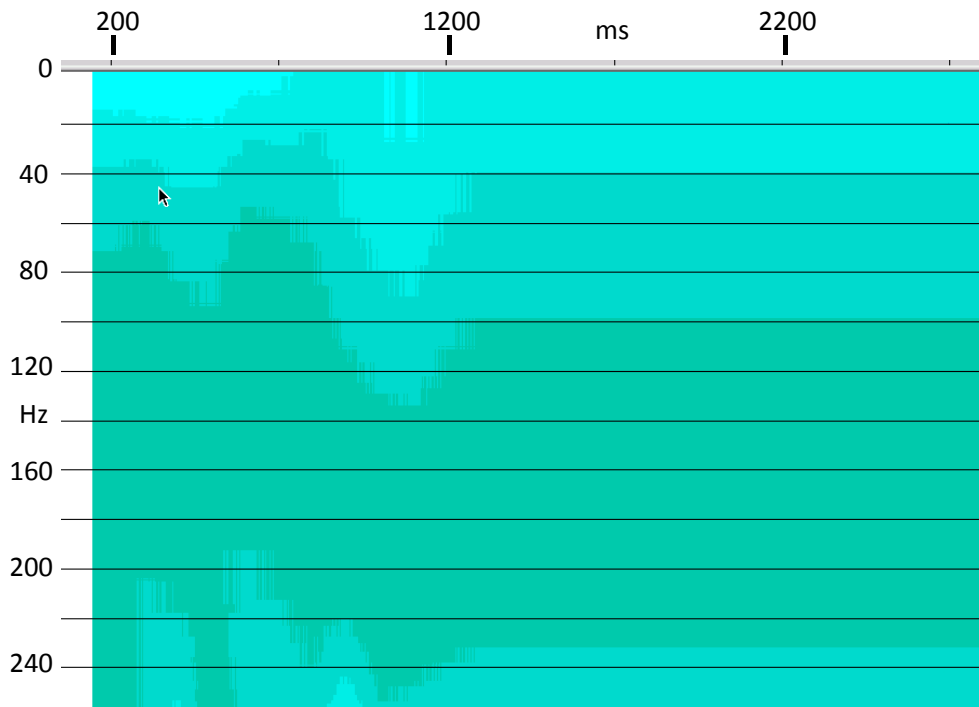


FIG. 10 2D colour function from Figure 6 after normalizing the spectra by the largest magnitude of the individual spectra that comprise the colour function. Only the shapes of the individual spectra vary with time, not their overall magnitude.

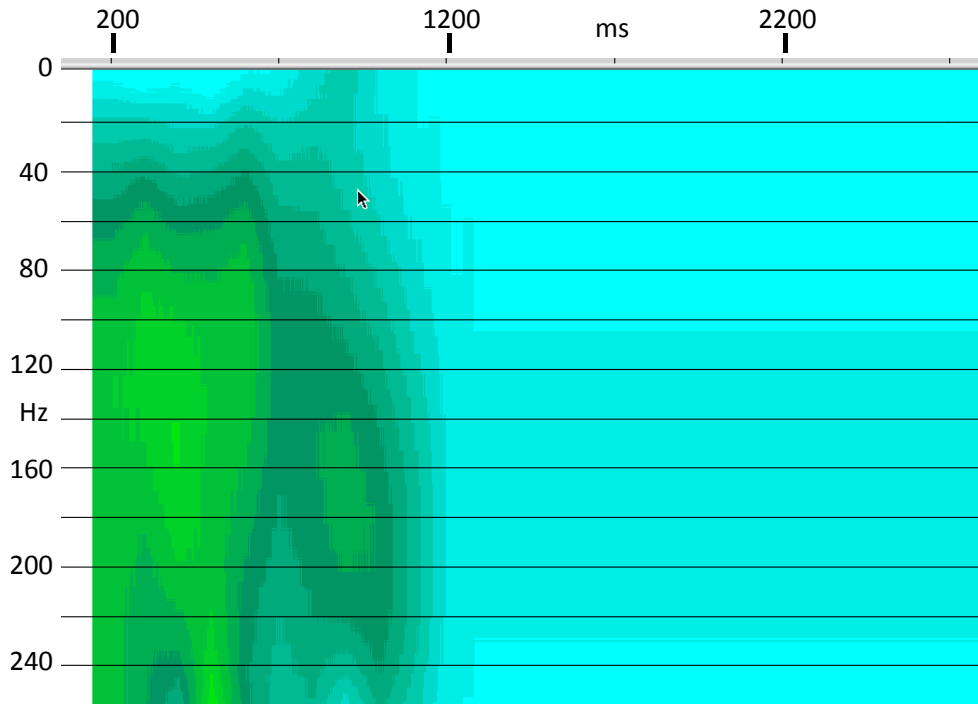


FIG. 11. 2D colour function from Figure 6 after being normalized by the $\frac{3}{4}$ power of the largest spectral magnitude. There is temporal variation in spectral magnitude as well as shape, in this function.

Figure 12 shows the Blackfoot trace ensemble deconvolved with the fully normalized colour function (Figure 10), while Figure 13 shows the same traces deconvolved with the colour function in Figure 11. Close comparison of these figures with Figure 9 shows the rather large influence of the magnitude variation in the temporal colour, especially in the zone from about 800 ms to 1300 ms. For a more detailed look, Figures 14-18 show, respectively, a close-up of some of the traces before deconvolution (AGC only), the traces after deconvolution with no colour correction, the traces after colour correction with no normalization of the colour function, colour correction with fully normalized colour function, and colour correction with $\frac{3}{4}$ power normalization. The differences, in both amplitude and phase, of the deconvolved traces can be readily seen.

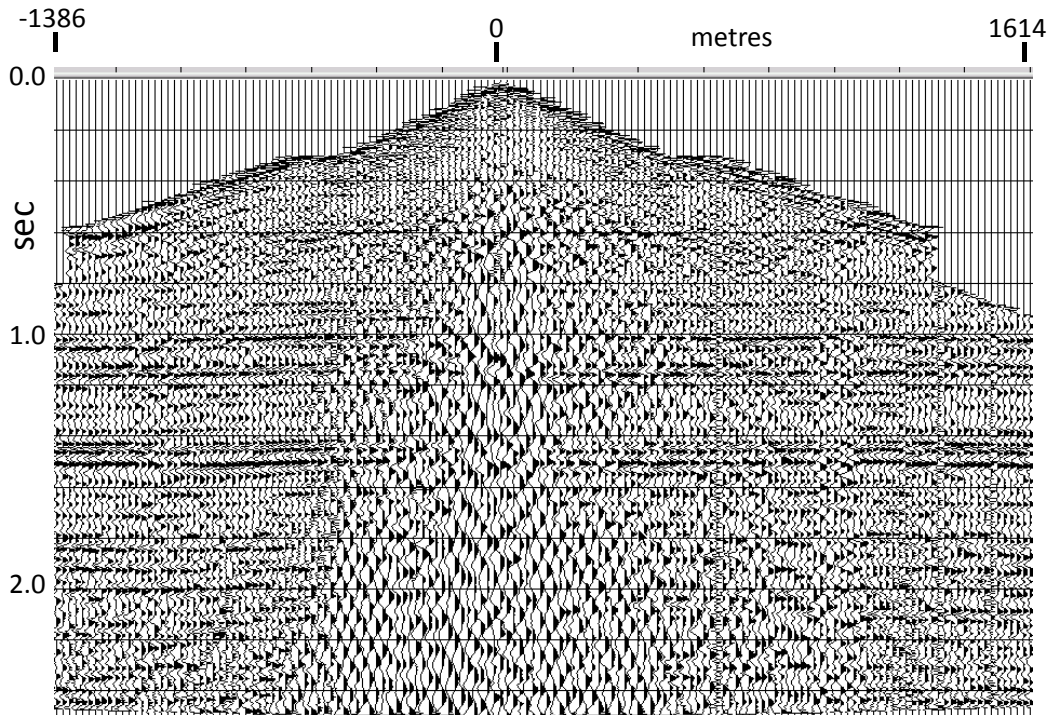


FIG. 12. Blackfoot shot gather deconvolved with Gabor with colour correction, using the colour function in Figure 10, with full normalization.

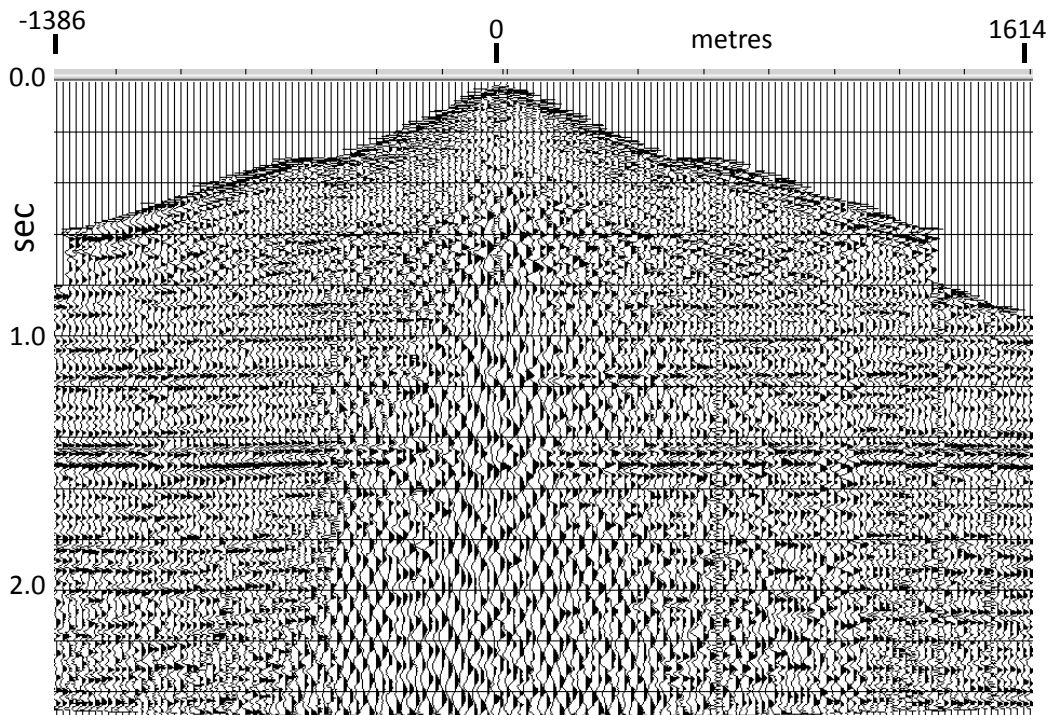


FIG. 13. Blackfoot shot gather deconvolved with Gabor2 with colour correction, using the colour function in Figure 11, with normalization by the $\frac{3}{4}$ power of the maximum spectral magnitude.

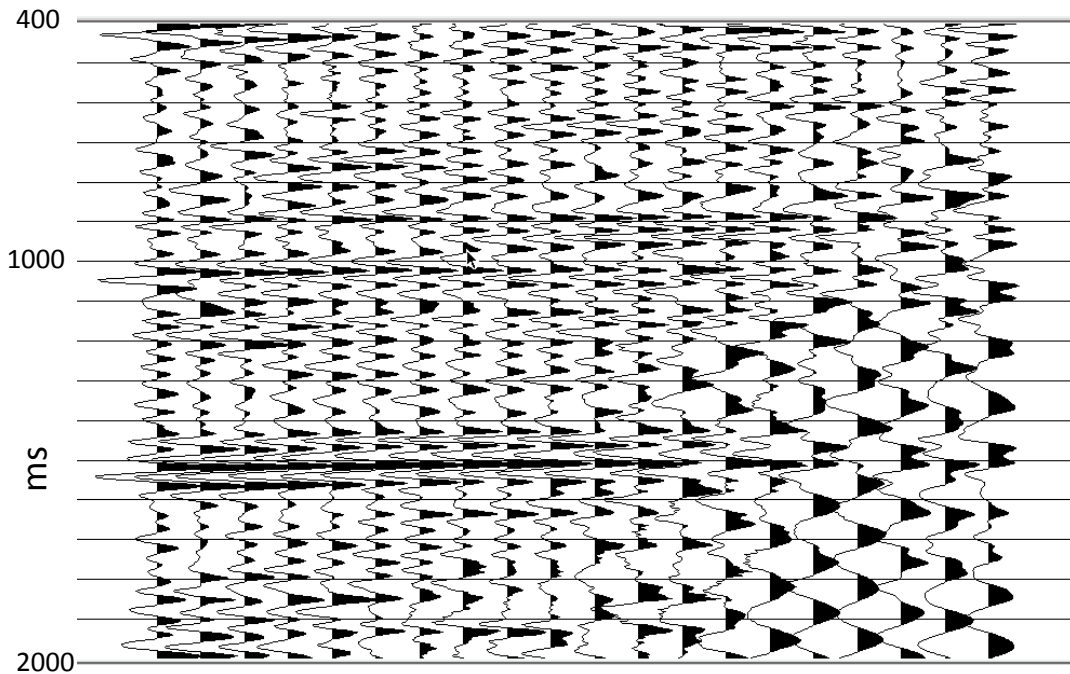


FIG. 14. Close-up of Blackfoot traces before deconvolution.

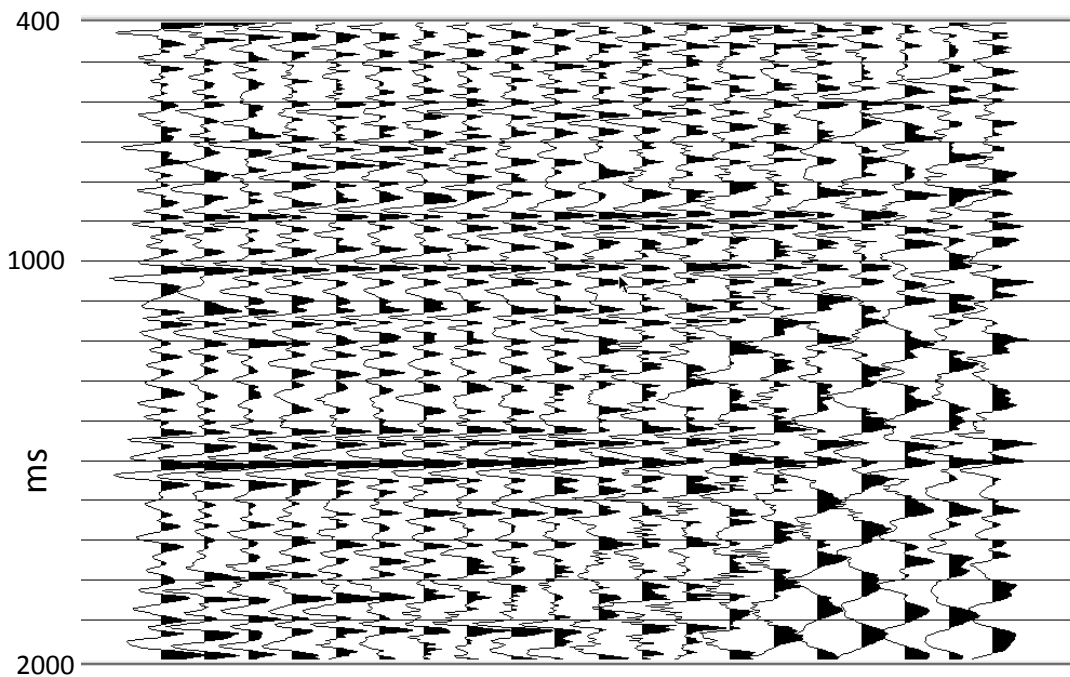


FIG. 15. Blackfoot traces from Figure 14 after Gabor deconvolution with no colour correction.

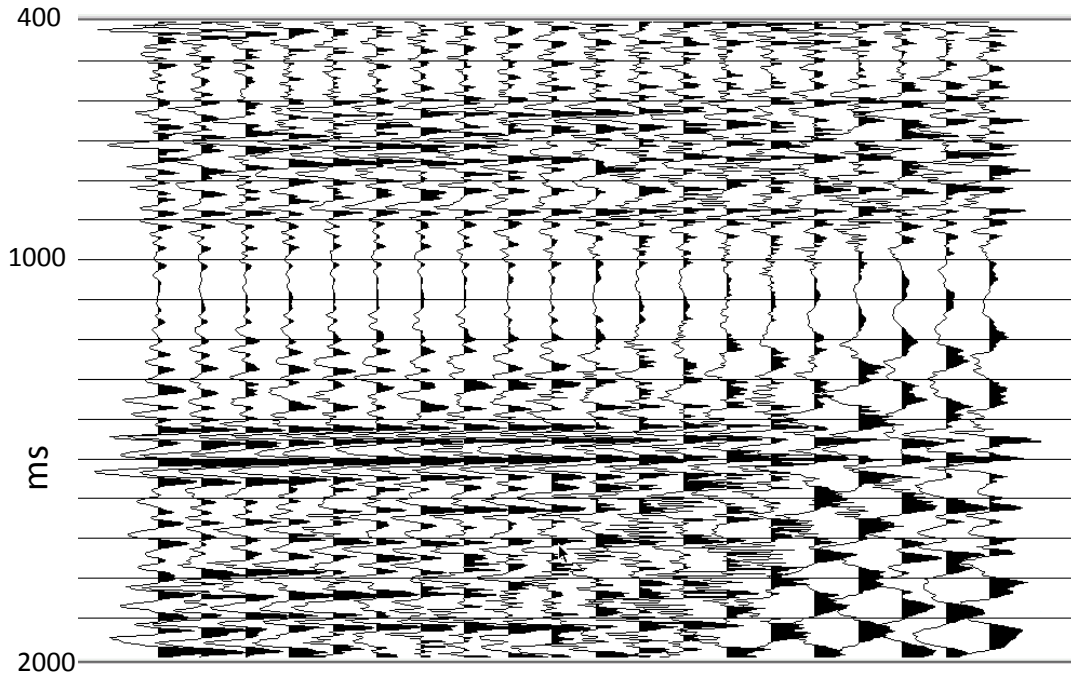


FIG. 16. Blackfoot traces from Figure 14 after Gabor deconvolution with colour correction, using the colour function in Figure 6. Temporal variations in the colour function cause unrealistic amplitudes in these traces. AGC has inflated trace amplitudes below 1300 ms.

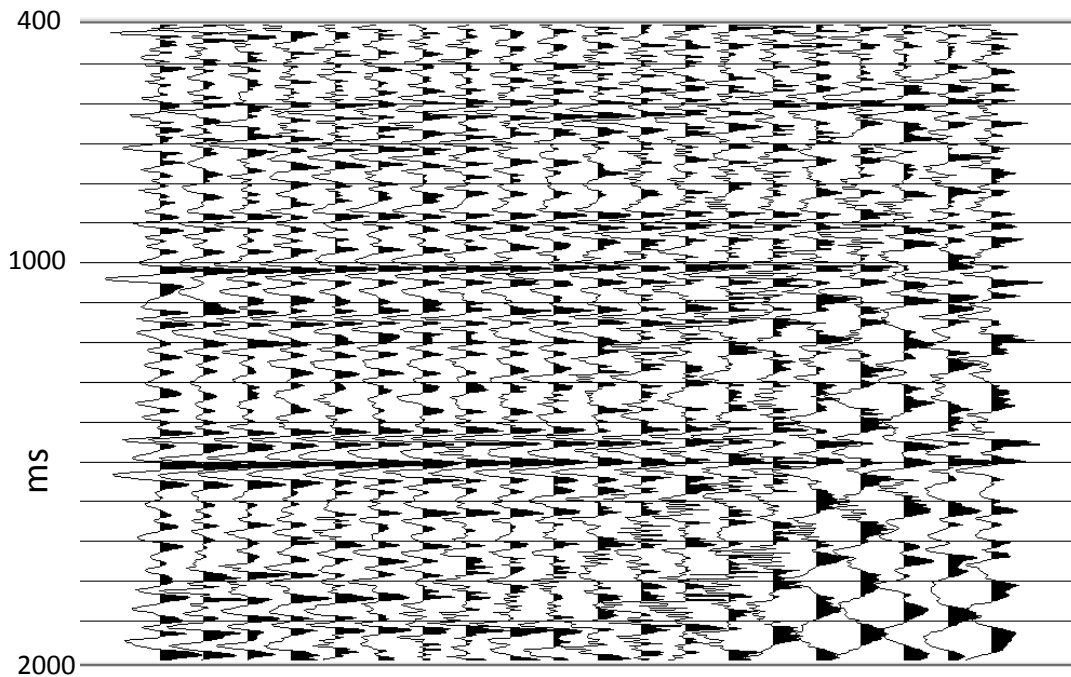


FIG. 17. Blackfoot traces after Gabor deconvolution with colour correction, using the colour function in Figure 10. Temporal amplitude variations are not present.

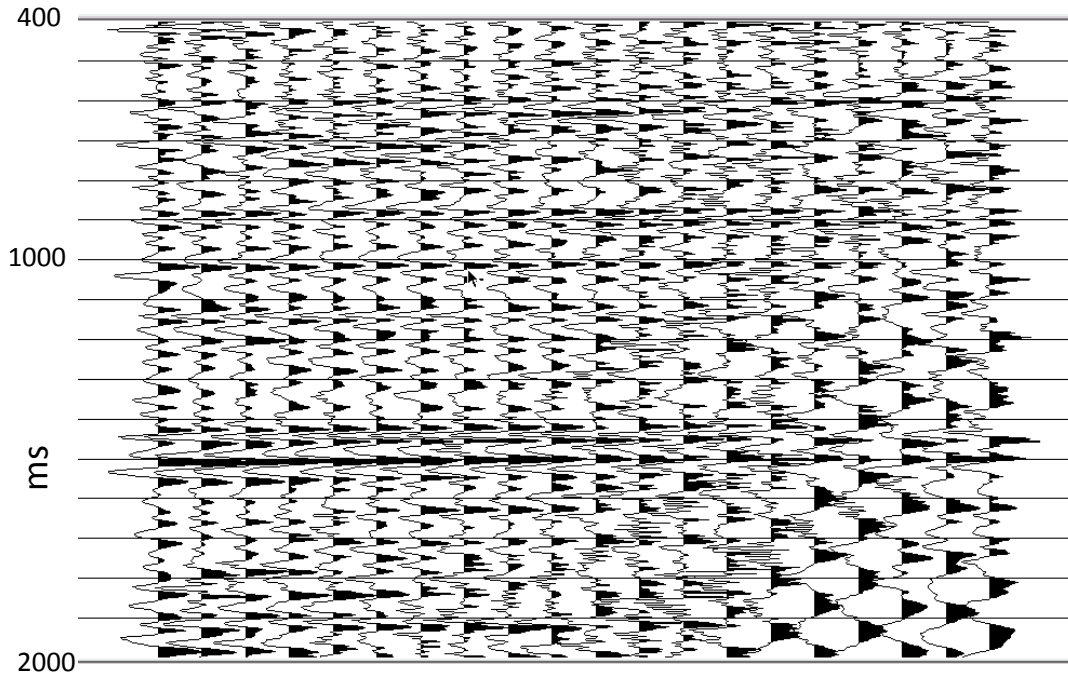


FIG. 18. Blackfoot traces after Gabor deconvolution with colour correction, using the colour function in Figure 11. Comparing with Figure 17, temporal amplitude variations are present, and phase differences can be seen in the vicinity of more prominent events.

DISCUSSION

We now have fully functional versions of both Gabor2 and Gabor_sc, updated to read files of polynomial coefficients derived from non-stationary well log analysis in order to reconstruct 2D colour correction functions for modifying the “white” spectral assumption used in earlier versions of Gabor deconvolution algorithms. While both programs read and reconstruct the colour functions and can apply them to modify the deconvolution, only Gabor_sc has a diagnostic mode which can be used to output the colour functions themselves in a form suitable for colour contour plotting. In the course of our implementation, we discovered that the temporal colour variations obtained from the well log analysis can lead to unrealistic temporal variations in prestack traces. Furthermore, the application of NMO to the input traces to ensure proper temporal registration of the traces with the temporal variations of the colour function causes unwanted distortions in the spectra of the traces; so the temporal colour variations of the colour function must be normalized in some fashion, either during analysis, or during application within Gabor deconvolution, at least for prestack deconvolution. Full colour correction, including temporal colour may be applied during poststack deconvolution. This is a suitable topic for future investigation.

ACKNOWLEDGEMENTS

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APPENDIX I

Following is the updated documentation for Gabor2, also available by executing ProMAX and accessing the help file from the Gabor2 menu window.

Gabor Deconvolution II

This module applies a technique known as Gabor Deconvolution to a panel of seismic traces, either as an ensemble, or trace-by-trace. Gabor deconvolution is a time-varying deconvolution whose operator adapts to the characteristics of the particular data captured by a time-overlapped set of windows. Gabor deconvolution II differs from its predecessor in that the windows are "Lamoureux" window functions instead of time-shifted Gaussian windows as in the original. A deconvolution operator is constructed by smoothing the magnitudes of the Gabor Transform of a seismic trace, and computing the corresponding phase. A Gabor operator array can be constructed for each trace and applied to that trace or constructed from the summed Gabor magnitudes of a trace ensemble and applied to each trace in that ensemble. Gabor deconvolution II is an experimental procedure, with several parameters which may be varied to attempt to optimise performance. This version of Gabor deconvolution has a much faster run time than the original...perhaps as much as an order of magnitude, depending upon the parameter choice.

Updates

Version (1.4.1) of Gabor Deconvolution has two major bug fixes. The first bug consisted of two problems with the stability factor...first, and most fundamental, the factor was scaled by a spectral magnitude value, but then the unscaled value was used in the computation. Second, since the scaling value was based on the smallest maximum spectral value in the Gabor transform for a given trace, if the trace was padded with low-level noise, a Gabor window filled totally or mostly with this noise would yield an unacceptably low scalar. The bug fix tests that the smallest spectral maximum in any Gabor window is no more than 20 dB below the largest spectral maximum in any gabor window for the same trace. Variation of the stability factor now affects decon output results in exactly the way one would expect...the smaller the factor (0.001 or less), the whiter the resulting decon.

The second bug detected was the inoperability of the ensemble derive mode for the deconv operator due to improper indexing of the Gabor windows during the second Gabor transform of each trace (the transform must be performed twice, since the first results are averaged over the ensemble, in order to derive a deconv operator). This feature now works correctly.

Gabor2 version 1.6.1 has the added ability to apply 'colour correction' derived from well log analysis to the deconvolution operation. Prior to applying colour correction, a well log from a well associated with the seismic data being deconvolved must be analyzed in a separate MATLAB program. This program derives the time-dependent coefficients of a polynomial of order N (0 to 5) which best fits the spectrum of the well log in a series of time windows. The coefficient values for each time window are supplied by the MATLAB program in an ASCII file, to be read by Gabor2. Gabor2 reads the file and builds a time-varying colour spectral function, which is used to modify the default "white" spectrum normally used in the derivation of the Gabor deconvolution operator. The spectral modification occurs before minimum phase computation, so the deconvolution operator phase should be as correct as possible, given the knowledge of the earth spectrum conveyed by the colour function.

Theory

Gabor deconvolution is based on the Gabor Transform, which is a way to analyse a seismic trace for time-varying spectral characteristics. Because this transform explicitly captures the non-stationary behaviour of a seismic trace, it constitutes a natural basis for its deconvolution. The deconvolution is applied in the frequency domain by performing a complex division of the Gabor Transform by the derived deconvolution operator. The time-dependency of the resulting array is removed by summing over the time-gate dimension of the array.

Usage

Gabor deconvolution is intended for use either on individual traces or ensembles of traces. The traces can be pre-stack or post-stack traces. Data most suited to this application are those on which time-varying phenomena are superimposed (various types of noise), or which show visible non-stationarity (isolated "bright" events, loss of bandwidth with time, etc.). Because there are many parameters to select, the default values have been chosen to allow reasonable results to be obtained from Gabor deconvolution with no intervention by the user. However, the performance can usually be considerably enhanced by experimenting with the parameters.

Choose single trace or ensemble mode--This switch determines whether Gabor deconvolution is derived and applied one trace at a time, or whether the summed Gabor

Transform of a whole ensemble of traces is used to derive an operator, which is then applied to each of the traces in the ensemble. The ensemble mode may not be appropriate for entire shot or receiver gathers with large offset ranges, but such gathers can be decomposed into smaller ensembles having limited offset ranges; and such ensembles may be appropriate for doing deconvolution on data which is non-stationary in both time and offset.

Restore trace amplitude levels on output--Each input data trace is automatically scaled by its average absolute amplitude to condition the data against arithmetic difficulties due to extremely large or small values. This switch parameter allows the user to choose whether or not to de-scale by the same value upon output from the algorithm. (This feature is currently disabled, 2Aug02, and is not displayed)

Half-width of the analysis/synthesis window—This is the half-width in seconds of the Lamoureux window functions used for analysis and synthesis of the data traces. Since the Lamoureux functions have a finite width between their zero amplitude points, the half-width is half the distance between the zero amplitude points, not the $1/e$ amplitude points as in Gaussian functions.

Window increment factor--Lamoureux windows are properly overlapped and normalised if the start point (zero amplitude) of one window coincides with the centre of the preceding window, and the end point (also zero amplitude) coincides with the centre of the succeeding window. In order to keep this proper window normalisation, the increment between windows may be decreased only by applying additional properly overlapped sets of windows, offset from the original windows by increments evenly divisible into the original window width. Hence an increment factor of 2 generates an additional overlapped set of windows, offset from the original set by one fourth of the window width; an increment factor of 3 generates two additional overlapped sets of windows, the second and third offset from the first by $1/6$ and $1/3$ of the window width, respectively, and so forth. Proper normalisation is maintained by dividing the windowed data by the window increment factor, which is equal to the total number of unity-normalised sets of overlapped windows used to sample the data. Using a value greater than one appears to stabilise the result, particularly on noisy data.

Factor to extend window before FFT--This factor is applied to the window length to determine the actual length of the FFT used to analyze the windowed trace segment. The trace segment is extended by this factor, then further extended to the next largest power of two prior to the FFT.

Pad input traces before windowing--This is a switch parameter which determines whether or not the input traces are padded before windowing, to diminish end effects. If this switch is set to true, the following parameter is used to determine the length of pad to be added to both beginning and end of the traces. The pad values are random noise whose level is set to -300 dB of the rms amplitude level of the current trace, in order that windows never encounter an all-zero trace segment.

Fraction of window width for trace padding--If the switch above is set to true, this parameter is used to determine the number of pad values to append to either end of the

trace. The recommended value is more than half a window width, to move end effects off the visible seismic trace.

Slope exponent for Lamoureux window function--This integer is used as an exponent in the computation of the values of the Lamoureux window. Its default value of 2 is a safe choice. Larger values can lead to window artifacts under conditions of high noise, low signal level, and small window overlap.

Application exponent for analysis window--Prior to being applied to the input trace, the values of the analysis window function are raised to this power (actually a root, since the value must be ≤ 1.0). The values of the synthesis window function are then raised to the complementary power (1.0 minus application exponent). A value of 0.5 applies a square root window to both analysis and synthesis; one applies a full strength analysis window and no synthesis window; zero applies no analysis window function and a full strength synthesis window.

Choose type of spectrum for wavelet estimate--This parameter chooses whether the Fourier Transform or the Burg algorithm is used to compute the spectral magnitudes used to construct the deconvolution operator. The Burg algorithm is somewhat slower than the FFT, if used with many coefficients.

Number of coefficients for Burg spectrum--This parameter only appears if Burg spectra are used in the decon operator. In general, the more coefficients, the more detail the Burg spectrum contains. Since the spectra are smoothed to obtain the decon operator, a small number of coefficients (3-5) will often be more effective than a larger number (10) and will run somewhat faster as well. Using a small coefficient number is similar to applying more smoothing, so the spectral smoothing parameters below can be smaller in this case.

Choose minimum or zero phase deconvolution--While a minimum phase decon would be the norm here, zero phase can be chosen, and it takes less time to construct the operator.

Choose hyperbolic time-frequency or 2-D boxcar smoothing--This parameter is used to determine the wavelet estimation method. If hyperbolic smoothing is chosen, the input Gabor spectrum is smoothed along hyperbolae of constant time-frequency to yield a Q-factor spectrum, which is then removed from the Gabor spectrum before estimating the wavelet spectrum by 2-D boxcar smoothing. If boxcar smoothing is chosen the hyperbolic smoothing step is omitted, but a constant-Q pre-whitening may be applied prior to wavelet estimation, instead.

Choose corridor width of hyperbolic smoothing in Hz-sec--This parameter determines how much smoothing occurs in the constant time-frequency method. A wide corridor applies more smoothing, forcing more of the time-dependency into the subsequent wavelet estimation. This parameter appears only if the above parameter selects for hyperbolic smoothing.

Enter estimated Q for pre-conditioning--Often, trace amplitudes are poorly conditioned...they have too large a dynamic range to be handled properly by spectral techniques without numerical instability. One way to alleviate the problem is to "pre-whiten" the data by applying a time and/or frequency dependent scale factor to reduce the dynamic range of a data array prior to spectral computations, then to remove the same scale factor after processing. In the Gabor algorithm, such a factor is applied, simulating the removal of inelastic absorption; the so-called Q-filter. The parameter here is simply the estimated Q value for the data. In this case, the estimate can be a "guesstimate", since it's just a processing parameter. Values between 20 and 200 seem to be effective. The default is set to 1.0e06 so that the effect is NO application of pre-whitening. Care has been taken to apply the pre-whitening function only to the data values, NOT to the zones of the Gabor transform which contain random noise padding. This parameter is only shown if hyperbolic smoothing (and Q-estimation) is NOT chosen above

Choose number of passes of smoothing--Smoothing is applied to the magnitude array in both the frequency and time directions. Since the smoothing operator is a uniform weight "boxcar", other types of weighting can be used by applying the boxcar more than once in succession (twice gives triangular weighting, for example). This parameter determines how many times the smoothing is applied in BOTH directions.

Choose the type of boxcar smoothing to use--The standard smoothing is simply the running mean, but the choice of the running median is also offered, for data expected to have isolated spectral peaks and notches to be smoothed. Use of median smoothing can lead to wrap-around artefacts in the output.

Wavelet smoothing window length in seconds--Determines the number of spectral magnitude points to be smoothed in time.

Choose whether to apply colour correction to deconvolution operator--When this switch is set, the program expects to read an ASCII file of polynomial coefficient values derived from curve-fitting a well log spectrum, then to construct a colour function to replace the usual "white" spectrum used in the deconvolution operator derivation.

Enter the number of windows used to analyze the well log--This parameter only appears when the previous parameter choice is colour correction. It is the number of time windows used to analyze the well log...and hence the number of values for each order of coefficient. Four coefficients are required for a cubic polynomial, so four values will be expected for each of the windows.

Enter the time in ms to shift each colour correction window--This parameter only appears when colour correction is chosen. Its value is used to shift the entire set of colour correction windows up or down in time to match the appropriate analysis windows in the deconvolution operator. If the time values specified for the well log analysis windows are window centres, the shift value should be zero.

Enter the order of the polynomial used to fit the well log--This parameter only appears when colour correction is chosen. Colour analysis is based on fitting a polynomial series to the spectrum of the portion of well log in each analysis window. The polynomial can

have order 0 through 5 (DC through fifth order). The order selected here must match that used in the actual log analysis.

Enter the normalization exponent for colour spectra--Since the magnitude of polynomial spectra can vary considerably from time window to time window, The maximum of each polynomial spectrum in the frequency range from 0 Hz to 1/4 Nyquist is found, and the spectrum normalized by this spectral maximum raised to some exponent between -1.0 and +1.0. The default is 0.0, which means no normalization.

Enter the file pathname for colour correction coefficient tables--This parameter only appears when colour correction is chosen. This is a character data parameter intended to convey the file pathname for the ASCII file to be read by the program in order to obtain the polynomial coefficients for constructing the colour correction function. The reading procedure expects the ASCII file to conform to the following format: Five lines of character data (7 items in line 1, 8 in line 2, 10 each in lines 3 and 4, and 12 in line 5. Following the character data, are several lines of numerical data items, one line per analysis window. Each line will contain the window centre time, in ms, followed by the value of each of the polynomial coefficients of order zero through 5, all separated by blanks. If the polynomial order chosen is 0, two values per line must appear; if the order is 1, three values per line; order 2 means four values, order 3 means 5 values per line, etc.

Choose whether to apply post-decon T-varying filter--A time-varying bandpass may be applied to the deconvolved Gabor spectra prior to collapsing them to a seismic trace. This parameter allows this filter to be applied or not. Since the post-decon filter is time-varying, its bandlimit parameters are designated at one point in time, then varied to fit the constant-Q model of seismic absorption, constrained by Nyquist limits and minimum bandwidth specifications. (The high frequency parameters are not allowed to exceed 75% Nyquist for the -3 dB point or 100% Nyquist for the -80 dB point. In addition, the -3 dB high frequency point is not allowed to be less than 3.0 times the low frequency -3 dB point, and the -80 dB high frequency point cannot be less than the -3 dB high frequency point plus a third of the -3 dB bandwidth.)

Choose zero or minimum phase for filter--The post-decon time-varying filter may be chosen to be either zero or minimum phase, using this parameter.

Specify reference time, T_{REF} in seconds, for bandlimits--This is the reference time at which the following bandlimits apply. Default is 1.0 second.

Select low frequency -80 dB point at T_{REF} seconds in Hz--This parameter is the low frequency point on a Gaussian curve that is -80 dB down from the maximum spectral amplitude.

Select low frequency -3 dB point at T_{REF} seconds in Hz--This parameter is the low frequency point on a Gaussian curve that is -3 dB down from the maximum spectral amplitude.

Select high frequency -3 dB point at T_{REF} seconds in Hz--This is the -3 dB frequency for the high frequency end of the post-decon time-varying bandpass (Gaussian curve).

Select high frequency -80 dB point at T_{REF} seconds in Hz--This is the -80 dB frequency for the high frequency end of the post-decon time-varying bandpass (Gaussian curve).

Begin time in seconds for Q estimation or time-varying bandpass--This parameter determines the time before which estimated Q factor is constant, also the time before which time-varying bandpass parameters are held constant.

End time in seconds for Q estimation or time-varying bandpass--This parameter determines the time after which estimated Q factor is constant, also the time after which time-varying bandpass parameters are held constant.

Stability factor for spectral division operations--This parameter determines the fraction of the maximum spectral magnitude to be added to all spectral magnitudes to prevent any division by zero. The same factor is used as an additive to the Q -factor pre-whitening, and it is used in the minimum phase computation for the post-decon time-varying bandpass filter. The default value is a safe option.

References

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APPENDIX II

Gabor surf consistent

This module applies Gabor Deconvolution in a surface-consistent manner to a panel of seismic traces, trace-by-trace. Gabor deconvolution is a time-varying deconvolution whose operator adapts to the characteristics of the particular data captured by a time-overlapped set of windows. Gabor surface consistent differs from its predecessors in that the decon operator derived from the first pass of a trace is split into an offset wavelet component, source wavelet component, receiver wavelet component, and Q -factor component. These components are stored according to their offset, source, receiver, and midpoint header values, respectively. Subsequent trace decon operators are summed into these offset, source, receiver, and midpoint arrays, also according to their associated trace header values. After all the traces in a line are read, the program begins a second pass through the trace file. During the second pass, averaged decon operator components are retrieved from the respective arrays according to matching trace headers, combined into a single decon operator for each trace, the phase computed (either zero or minimum phase) and the composite decon operator applied to the trace. Currently, the composite wavelet is the product of offset, source and receiver wavelets, divided by the Q -factor.

An experimental extension of the routine uses the second, and subsequent passes through the data set to iterate the estimated offset, source and receiver wavelet arrays by dividing

products of pairs of the previous estimates for offset, source and receiver into the composite wavelet estimate from the current pass to obtain new estimates for offset, source and receiver wavelets. These estimates are summed into new offset, source and receiver wavelet arrays and accumulated for the whole line. Third and subsequent passes through the data retrieve the iterated offset, source and receiver wavelets for each trace, as well as the non-iterated Q-array and builds a composite deconvolution operator for each trace. In the current release, traces are output after the second pass and all subsequent passes, thus providing increasingly iterated versions of the surface-consistent deconvolved traces.

This experimental version of surface-consistent Gabor decon is experimenting with offset-dependence, placing it on a par with source and receiver dependence. As our ideas evolve, we may decide to fold it into the Q-factor instead. Currently, the "wavelet" magnitudes extracted from the input Gabor transform after hyperbolic smoothing are summed into arrays indexed by source surface position, receiver surface position, and source-receiver position difference (equivalent to absolute offset). This means that as ideas for incorporating offset-dependence are available, the offset-summed wavelet estimate will be immediately available for incorporation into the spectral arithmetic within the decon operator computation.

Updates

This version of Gabor surface consistent is the first and has not been thoroughly tested.

A diagnostic mode has been added to the surface-consistent Gabor deconvolution module. In this mode, only diagnostic traces are output, no actual deconvolution is performed. Five kinds of diagnostics, all Gabor magnitude spectra, can be requested: 1)Raw Gabor spectra of input traces; 2)The residual raw Gabor spectra (after dividing out the Q-function); 3)The Q-function derived during hyperbolic smoothing; 4)The smoothed residual Gabor spectra used to estimate the wavelet, 5) The externally generated colour function. (see below).

A new release of `gabor_sc` incorporates the ability to read an external ASCII file of polynomial coefficients, derived from fitting well log spectra, to construct a time-varying spectral colour function, and to apply the function to the deconvolution operator to compensate the deconvolution for the inherent shape of the well log spectrum. The colour function is applied prior to phase computation, in order to ensure that the phase of the deconvolution properly reflects that of the underlying earth spectrum. This release of `gabor_sc` also allows the colour function to be computed and plotted, in diagnostic mode.

Theory

Gabor deconvolution is based on the Gabor Transform, which is a way to analyse a seismic trace for time-varying spectral characteristics. Because this transform explicitly captures the non-stationary behaviour of a seismic trace, it constitutes a natural basis for its deconvolution. The deconvolution is applied in the frequency domain by performing a complex division of the Gabor Transform by the derived deconvolution operator. The

time-dependency of the resulting array is removed by summing over the time-gate dimension of the array.

Surface-consistency is invoked for deconvolution anytime it is considered that the "wavelet" derived for each trace has particular features attributable to either the source location or receiver location, or both. Surface consistent arithmetic thus leads to more robust estimates for the parts of the deconvolution wavelet peculiar to its endpoints

Usage

This version of Gabor deconvolution is intended for application to pre-stack data, since it specifically requires certain trace headers for its proper functioning. The input data may be source gathers, receiver gathers, or CDP gathers. The program must estimate memory requirements in the initialization phase and thus requires the existence of a database for any line submitted, from which it finds the total number of offsets, shots, receivers, and CDPs. Any line for which there is no pre-existing database must have one created using the 'Extract database files' function following the 'Disk data input'.

In order for the program to function properly, the 'Disk data input' which precedes it must have the "Read data multiple times" option set to "yes", and the number of iterations immediately below it set to 2 or more. If the data set is read twice, the output from the program will be the input traces deconvolved with the first-pass-estimated source and receiver wavelets. If the data set is read three or more times, the output will consist of the input traces first deconvolved with the source and receiver wavelets from the first pass, then the same input traces deconvolved with the source and receiver wavelets estimated by iteration. The complete data sets are distinguished from one another by the trace header 'DISKITER', which is set to '2' for the traces deconvolved by the first wavelet estimates and '3', (or more) for the traces deconvolved by the iterated wavelet estimates. This trace header thus allows several output data sets to be written as separate files, using, for example, an 'IF'--'ENDIF' loop to test the value of 'DISKITER'.

In diagnostic mode, the program reads input data gathers only once, so the "Read data multiple times" option in 'Disk data input' must be set to "no". In diagnostic mode, for every trace ensemble read, one diagnostic ensemble is output, with the following characteristics: Each input trace generates a complete Gabor spectrum, which consists of one magnitude spectrum for each of the analysis windows specified by the parameters. This means that for N overlapping analysis windows, N output traces will be generated for each input trace. Hence, the output ensemble has N times as many traces as the input gather. Although the output traces have as many samples as the input traces, only samples up to the Nyquist frequency are non-zero, so the output traces should be truncated externally, before writing to disk, to limit file size.

Since each input trace generates N diagnostic traces, a new trace header, TIMWIN, is introduced to help distinguish those traces--the time in ms associated with the centre of the analysis window associated with that trace. This header can be used to help sort the Gabor spectra externally for other types of display--for example, a display of local spectral changes in a single Gabor analysis window as a function of source position, and so forth. Any kind of trace ensemble can be input to Gabor_sc, so diagnostics can be

generated as a function of source, receiver, midpoint, and offset, just by sorting the input data set externally before input. Of the five diagnostics available, displays of the Q-function can help determine the proper corridor width for hyperbolic smoothing; while displays of the raw input trace residuals compared to the displays of smoothed residuals can help determine the proper smoothing parameters, in both frequency and time, for wavelet estimates. Finally, displays of the colour correction function (if one is constructed) can help diagnose any problems with the function (like negative values) which can cause computational issues in the deconvolution algorithm.

One useful way in which to utilize the diagnostic mode of this program is to place it immediately behind a previous run of Gabor deconvolution, (either Gabor2 or Gabor_sc) in order to evaluate the effectiveness of the deconvolution. In this application, looking at the Gabor magnitude spectra of the raw input traces (actually the output from the previous decon) can help analyze the effectiveness of the decon parameters. In diagnostic mode, any or all of the smoothing parameters in gabor_sc can be set to zero to assist in data analysis (Corridor width for hyperbolic smoothing, Wavelet smoothing window width (Hz), and Wavelet smoothing window length (sec)).

Half-width of the analysis/synthesis window--This is the half-width in seconds of the Lamoureux window functions used for analysis and synthesis of the data traces. Since the Lamoureux functions have a finite width between their zero amplitude points, the half-width is half the distance between the zero amplitude points, not the 1/e amplitude points as in Gaussian functions. A reasonable value is between 0.1 and 0.3 seconds.

Window increment factor--Lamoureux windows are properly overlapped and normalised if the start point (zero amplitude) of one window coincides with the centre of the preceding window, and the end point (also zero amplitude) coincides with the centre of the succeeding window. In order to keep this proper window normalisation, the increment between windows may be decreased only by applying additional properly overlapped sets of windows, offset from the original windows by increments evenly divisible into the original window width. Hence an increment factor of 2 generates an additional overlapped set of windows, offset from the original set by one fourth of the window width; an increment factor of 3 generates two additional overlapped sets of windows, the second and third offset from the first by 1/6 and 1/3 of the window width, respectively, and so forth. Proper normalisation is maintained by dividing the windowed data by the window increment factor, which is equal to the total number of unity-normalised sets of overlapped windows used to sample the data. Using a value greater than one appears to stabilise the result, particularly on noisy data.

Factor to extend window before FFT--This factor is applied to the window length to determine the actual length of the FFT used to analyze the windowed trace segment. The trace segment is extended by this factor, then further extended to the next largest power of two prior to the FFT. Default this unless you know what you're doing.

Pad input traces before windowing--This is a switch parameter which determines whether or not the input traces are padded before windowing, to diminish end effects. If this switch is set to true, the following parameter is used to determine the length of pad to be added to both beginning and end of the traces. The pad values are random noise whose

level is set to -300 dB of the rms amplitude level of the current trace, in order that windows never encounter an all-zero trace segment. Default this value unless you know what you're doing.

Fraction of window width for trace padding--If the switch above is set to true, this parameter is used to determine the number of pad values to append to either end of the trace. The recommended value is more than half a window width, to move end effects off the visible seismic trace. Default this value unless you know what you're doing.

Slope exponent for Lamoureux window function--This integer is used as an exponent in the computation of the values of the Lamoureux window. Its default value of 2 is a safe choice. Larger values can lead to window artifacts under conditions of high noise, low signal level, and small window overlap.

Application exponent for analysis window--Prior to being applied to the input trace, the values of the analysis window function are raised to this power (actually a root, since the value must be ≤ 1.0). The values of the synthesis window function are then raised to the complementary power (1.0 minus application exponent). A value of 0.5 applies a square root window to both analysis and synthesis; one applies a full strength analysis window and no synthesis window; zero applies no analysis window function and a full strength synthesis window. The default value here is safest.

Choose type of spectrum for wavelet estimate--This parameter chooses whether the Fourier Transform or the Burg algorithm is used to compute the spectral magnitudes used to construct the deconvolution operator. The Burg algorithm is somewhat slower than the FFT, if used with many coefficients. This type of spectral analysis is best suited to source wavelets with known prominent frequency peaks.

Number of coefficients for Burg spectrum--This parameter only appears if Burg spectra are used in the decon operator. In general, the more coefficients, the more detail the Burg spectrum contains. Since the spectra are smoothed to obtain the decon operator, a small number of coefficients (3-5) will often be more effective than a larger number (10) and will run somewhat faster as well. Using a small coefficient number is similar to applying more smoothing, so the spectral smoothing parameters below can be smaller in this case.

Choose minimum or zero phase deconvolution--While a minimum phase decon would be the norm here, zero phase can be chosen, and it takes less time to construct the operator.

Choose corridor width of hyperbolic smoothing in Hz-sec--This parameter determines how much smoothing occurs in the constant time-frequency method. A wide corridor applies more smoothing, forcing more of the time-dependency into the subsequent wavelet estimation. A value of 10 to 30 Hz-sec is reasonable for many data.

Wavelet smoothing window width in Hz--Determines the number of spectral magnitude points to be smoothed in frequency. A value of 10 Hz is a reasonable starting point. A smaller value will help deconvolve monofrequency noise components (like 60 Hz)

Wavelet smoothing window length in seconds--Determines the number of spectral magnitude points to be smoothed in time. A reasonable value is one to two times the window half-width (first parameter).

Choose whether to apply colour correction--This is a switch parameter, which selects whether or not gabor_sc applies the colour correction procedure or not. If "apply colour correction" is chosen, four more parameters are displayed.

Enter the number of windows used to analyze well log--This parameter is just the number of time windows used to fit polynomials to the well log spectra. This parameter is only shown if colour correction is chosen by the previous parameter.

Enter the time in ms to shift each time window--If the well log analysis windows are designated by begin time, then this parameter can be used to shift the analysis results to the window centre times, which is what gabor_sc expects. This parameter is only shown if colour correction is chosen by the previous parameter.

Enter the order of the polynomial used to fit the well log--Colour analysis is based on fitting a polynomial series to the spectrum of the portion of well log in each analysis window. The polynomial can have order 0 through 5 (DC through fifth order). The order selected here must match that used in the actual log analysis. This parameter is only shown if colour correction is chosen by the previous parameter.

Enter the normalization exponent for colour spectra--Since the magnitude of polynomial spectra can vary considerably from time window to time window, The maximum of each polynomial spectrum in the frequency range from 0 Hz to 1/4 Nyquist is found, and the spectrum normalized by this spectral maximum raised to some exponent between -1.0 and +1.0. The default is 0.0, which means no normalization.

Enter the file pathname for colour correction coefficient tables--This is a character data parameter intended to convey the file pathname for the ASCII file to be read by the program in order to obtain the polynomial coefficients for constructing the colour correction function. The reading procedure expects the ASCII file to conform to the following format: Five lines of character data (7 items in line 1, 8 in line 2, 10 each in lines 3 and 4, and 12 in line five). Following the character data, are several lines of numerical data items, one line per analysis window. Each line will contain the window centre time, in ms, followed by the value of each of the polynomial coefficients of order zero through 3, all separated by blanks. If the polynomial order chosen is 0, two values per line must appear; if the order is 1, three values per line; order 2 means four values, order 3 means 5 values per line, etc. This parameter is only shown if colour correction is chosen by the previous parameter.

Begin time in seconds for Q estimation--This parameter determines the time before which estimated Q factor is not computed.

End time in seconds for Q estimation--This parameter determines the time after which estimated Q factor is not computed.

Stability factor for spectral division operations--This parameter determines the fraction of the maximum spectral magnitude to be added to all decon operator spectral magnitudes to prevent any division by zero. The default value is a safe option.

Diagnostic switch--This parameter, normally zero, is the switch that enables diagnostic output from the input data, rather than deconvolution. Setting the parameter to one invokes the diagnostic mode and enables the following parameter.

Diagnostic descriptor--This parameter is displayed only if "Diagnostic switch", above, is set to one. There are four possible values: 1 means output the raw Gabor magnitude spectra for the current trace; 2 means output the residual Gabor magnitude spectra after dividing out the Q-function and smoothing; 3 means output the Q-function for the current trace; 4 means output the residual raw Gabor magnitude spectra after dividing out the Q-function; and 5 means output the colour correction function constructed from the polynomial coefficient table read in from an ASCII file. The latter selection only works if the colour correction switch above has been selected to perform colour correction.

References

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APPENDIX III

Below is an example of an ASCII file acceptable for reading by Gabor2 or Gabor_sc. Note that since the header information is read as character data, the number of lines of header data must always be 5, and the number of "words" (groups of characters) separated by blanks, in each line must always be the same for each line: 7 for line 1; 8 for line 2; 10 each for lines 3 and 4; and 12 for line 5. A "word" can be any combination of from 1 to 24 characters. The data lines immediately follow the header lines and must have $N + 2$ real values per line, where N is the order of the polynomial used to fit each spectrum. The first value in each line is the time in ms of the beginning of the analysis window for a particular spectrum, and the subsequent values are the 0th, 1st, 2nd, 3rd, etc. order polynomial coefficients for that spectrum. The number of lines of data (polynomial spectra) must be greater than or equal to the parameter in Gabor2 or Gabor_sc describing the number of analysis windows used for the well log. While the file below has blank lines for clarity, these should not be present in the real file. The example below shows only the first five of over 100 data lines:

Reflectivity Color parameters for well log: 1409.las

Parameters of Gabor window: width(s): 0.1 increment(s): 0.01

Frequency band for polynomial fit: 0 Hz to 250 Hz

Log start time (sec): 0 order of polynomial fit: 3

Normalization of polynomial coefficients: No. #####

0.000000e+000 -2.0743970e-003 1.1441207e-003 -6.7666027e-006 1.1363209e-008

1.0029412e+001 -2.7931841e-003 1.2492323e-003 -7.4904934e-006 1.2831158e-008
2.0058824e+001 -3.4439051e-003 1.3404105e-003 -8.1445551e-006 1.4201834e-008
3.0088235e+001 -4.0458873e-003 1.4171983e-003 -8.7324917e-006 1.5490499e-008
4.0117647e+001 -4.6401993e-003 1.4818495e-003 -9.2786558e-006 1.6756010e-008