PHASE VELOCITY PROCESSING FOR ACOUSTIC LOGGING-WHILE-DRILLING FULL WAVEFORM DATA

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ABSTRACT

This paper presents the principle and demonstrates the advantages of using a Phase Velocity Processing technique (PVP) applied to the full wave acoustic data recorded by a logging-while-drilling tool. Phase Velocity Processing is particularly well suited for handling the characteristics of LWD data that may degrade the results of Semblance method. Among them are: large tool-mode content, high signal attenuation across the receiver array, and strong road noise. Another advantage of applying PVP is its high vertical resolution: due to the common receiver mode of operation vertical resolution of the calculated slowness is equal to the offset between adjacent receivers. By comparison, the Semblance method delivers results averaged across the entire receiver array span.

The PVP algorithm employs series of Fast Fourier Transform procedures to (a) filter the data using Heisenberg's method, (b) define time domain distribution of the phase arrivals using a Hilbert transform, and finally (c) perform the Phase Velocity analysis. Large number of phase arrival points provides efficient mechanism to calculate standard deviation of the results, quality indicators are added to show how well the algorithm was able to calculate both compressional and shear slownesses. Processing package includes filters operating in the frequency, time, slowness or space domains to minimize competing acoustic modes, especially the tool arrivals that are frequently present in LWD waveform data.

Examples demonstrate improvement of the slowness calculation performed with the PVP over the results delivered by the Semblance method. The results obtained in attenuating formations, across the bed boundaries, and in thin beds are presented. The ability of the new filtering technique to identify and suppress the tool mode arrivals is also demonstrated.

INTRODUCTION

The acoustic logging-while-drilling tools that were introduced six years ago (Minear et. al., 1995, Heysse et. al., 1996, Minear et. al., 1996) are by necessity full waveform recording devices. The drilling noise and the requirement for rigidity in an LWD environment prevented the use of a simple threshold technique as employed in the older wireline acoustic tools. The semblance method was the most commonly utilized processing technique at the time. It was implemented in the form of embedded firmware for downhole processing and as the surface system application for memory waveform data analysis.

Semblance processing has a number of drawbacks, such as its requirement for constant amplitude and velocity across the receiver array, the smoothing of the waveforms across the receiver span, the ability to mask defective data collected by an under performing tool, and not in the least its numerical complexity and therefore long execution time. We introduce here the Phase Velocity Processing algorithm implemented to process full waveform data recorded with a logging-while-drilling acoustic tool.

ACOUSTIC LWD WAVEFORM AND LWD TOOL ARCHITECTURE

The very nature of acoustic measurements performed under drilling conditions has necessitated the recording of full waveform data. This has complicated not only the construction of the acoustic LWD tools but also the downhole processing, as real-time sonic slowness calculations are required.

A constant presence in LWD waveforms is tool mode, defined as the signal traveling from the transmitters to the receivers, either directly in the tool body or deflected by the borehole wall. The isolator sections in acoustic LWD tools are not perfect due to the fact that the LWD devices, contrary to wireline units, need to be absolutely rigid: the collar strength cannot be compromised by the introduction of the electronics and isolators. Tool mode signal is characterized by the constant arrival time and a generally constant amplitude reduced by the isolator. Compressional and flexural tool modes can be recognized.

The acoustic LWD tool in **Figure 1** has two transmitters located symmetrically on both sides of an array of four receivers: one transmitter is positioned above and one below the array. All transmitters and receivers are aligned on one side of the tool. Such a configuration shows advantages over the typical omnidirectional monopole acoustic tool:

- Single side architecture is similar to that of a dipole tool, where the transmitters and receivers are aligned to perform directional measurements. The acoustic source located on one side of the tool generates both monopole and dipole excitations. Therefore this source can be considered as a hybrid between a monopole and a dipole source and can be called a unipole transmitter. A unipole tool generates simultaneously formation compressional and borehole flexural waves during a single recording cycle.
- Simplicity of the unipole tool architecture provides higher quality data since there is no need for well balanced sources and carefully matched receivers as required by true dipole setup.
- Much simpler electronics are needed for a unipole tool design improving the failure rate over equivalent monopole/dipole tool configuration.

PHASE VELOCITY PROCESSING METHOD

The Phase Velocity Processing (PVP) method, which is sometimes referred to as a complex signal analysis (Tanner, 1979), is based on the Hilbert transform of the recorded real time domain waveforms. The slowness of the acoustic mode of interest (compressional, shear) is computed by finding constant phase trajectories. The data flow illustrating the PVP algorithm is shown in **Figure 2**. This algorithm represents the Phase Velocity Picking step in the full processing flow diagram in **Figure 3**.

In the initial step, input time domain waveforms are converted to the complex form using a Hilbert transformation. Figure 4 shows the raw data and Figure 5 shows the Hilbert transformed waveforms. As the result, the data measured by each receiver are converted to its time domain real and imaginary components. The real part of the Hilbert transformed signal is identical to that of the input data. The imaginary part, in conjunction with the real part, represents the magnitude and the phase of each time domain point of the input data.

In the second step, the Hilbert transformed signal of each receiver is used to compute its time domain phase arrivals $F_i(t)$, utilizing equation (1).

$$F_i(t) = arctan\ im[H(x_i(t))] / re[H(x_i(t))] \qquad (1)$$

where: $x_i(t)$ is the input time domain data recorded with *i-th* receiver and the *H( )* function is its Hilbert transform. In the absence of competing acoustic modes, functions of class (1) vary quasi linearly within the range of $(-p, +p)$, and with a periodicity equal to that of the input signal (**Figure 6**).

Next, the time domain slowness distribution of each receiver pair is calculated by means of a constant phase trajectory **(Figure 7),** using equation (2).

$$S_{i,j}(t) = [F^{-1}_j(t) - F^{-1}_i(t)] / z \qquad (2)$$

where the symbol $F^{-1}_i(t)$ denotes an inverse solution to equation (1) and z is the spatial interval between receivers i and j $(j>i)$. In the absence of interfering acoustic modes, functions of class (2) show semi-constant slowness values across the entire processing window width (**Figure 7**). Should frequency dispersion affect the data, as often happens when recording borehole flexural wave, the slowness time domain distribution curve will show some variability (**Figure 8**). In such a case equation (2) can be utilized to estimate and compensate for the dispersion effects.

Finally, a single slowness value is computed by integrating (averaging) equation (2) over the desired travel time interval as follows:

$$DT_{i,j}=(S\ S_{i,j}(t))/(t_{max}-t_{min}) \qquad (3)$$

where summing is performed over the travel time interval limited by the t_{min} and t_{max}.

PHASE VELOCITY PROCESSING

Data flow utilized by the Phase Velocity Processing algorithm that is implemented for LWD full wave acoustic tool is shown in **Figure 3**. The PVP algorithm employs a sequence of digital signal processing techniques to:

- Suppress tool mode arrivals using a depth domain filter. This filter is optional and is invoked by the user if needed.
- Reduce high frequency road noise by utilizing 5-th order moving average depth domain kernel filter This filter is also optional.
- Extract desired acoustic arrivals (compressional or flexural) by simultaneously employing Heisenberg zero phase shift frequency filter (**Figure 9**) and the time domain tracking routine.
- Calculate formation slowness by performing Hilbert transformation and the Phase Velocity analysis as illustrated earlier.

All of the processing steps described above are repeated iteratively for each of the transmitter firings. Final formation slowness is calculated as the correlation weighted average of the results obtained with each of the transmitters individually. When shear wave arrivals are present in the recorded data, the PVP calculations are repeated with different frequency and time domain tracking filters.

VERTICAL RESOLUTION

The Phase Velocity Algorithm has an option to compute the slowness in common receiver mode (CRM) instead of common transmitter mode (CTM), which is the basic method for semblance processing. **Figure 10** shows the difference between these two processing techniques.

In common transmitter mode, CTM, four receiver signals are processed for the same transmitter firing. The vertical resolution of the computed slowness is equal to the span of the receiver array, three feet in the discussed tool.

In common receiver mode, CRM, the slowness is computed from the three pairs of receivers located at the same depth, by utilizing three different transmitter firings. This method of slowness calculation enhances the vertical resolution of the measurement to the offset between two adjacent receivers, one foot in the figured tool. The quality of the CRM results in an LWD environment depends on depth sampling rate, which in turn depends on the drilling rate of penetration and the tool time sampling rate. At depth sampling rates different than one sample per foot, an interpolator is utilized to provide CRM with the waveforms aligned at proper depth intervals.

PHASE VELOCITY VERSUS SEMBLANCE PROCESSING

The Phase Velocity Processing method shows several major advantages over the semblance technique:

- It can be derived from equation (1) that time domain phase arrivals of the receiver waveform do not depend on the amplitude of the signal. Due to the self-normalization of the Hilbert transform, two identical signals (in the sense of shape) will have exactly the same phase distributions, even if their amplitudes differ by orders of magnitude. In practice it means that the PVP algorithm will provide valid slowness calculations even if the rock is either highly attenuating or the receiver array is poorly calibrated for amplitude. Furthermore, the number of calculated phase points is limited only by the numerical capabilities of the computer system used to execute the algorithm (Equation 3), thus yielding high accuracy of slowness computations.
- The PVP method will compute formation slowness based entirely on the waveform transit time measurements. By comparison, the semblance algorithm calculates amplitude weighted group velocities. Therefore semblance results are strongly affected by propagation losses and receiver amplitude characteristics.
- The PVP method, due to its high vertical resolution in Common Receiver Mode, provides a stable response that is not affected by the receiver array crossing a boundary with a high acoustic impedance contrast. Again by comparison, semblance will produce erroneous multiple peaks yielding not only data smoothing but also false or frequently artificial slowness readings. User defined processing setup also might affect semblance response. En example of such a behavior is discussed in the examples.
- The PVP method provides a way to monitor the response of each receiver pair (Equation 2). Therefore as long as there are at least two reliable receiver signals, the raw data can be utilized to produce valid slowness log.
- The PVP method is based on the Hilbert transform, closely related to the Fast Fourier Transform, which makes it an order of magnitude faster then the semblance algorithm. Therefore it is well suited for all the applications that demand real-time or very short turn around time.

EXAMPLES

Tool Mode Removal: Tool mode is the signal traveling in the tool body from the transmitters to the receivers. Because the isolator sections in sonic LWD tools are not perfect, as LWD tools need to be absolutely rigid for the drilling operations to which they are subjected, tool mode is a constant presence in the LWD waveform. **Figure 11** shows a 150 ft section of raw waveforms (left) compared to the signal with the tool mode removed (right). The waves are presented in a variable density log format from 200 to 600 microseconds after the start of the recording. The constant arrivals that can be seen at about 330, 410 and 500 microseconds in the raw waveforms mask the underlying compressional arrival. The tool mode removal filter has successfully suppressed the constant component of the waveform (tool mode) while properly maintaining slowly changing compressional arrivals.

Comparison of formation slowness estimation delivered by PVP with the Semblance Processing results: The semblance processing response is affected by the presence of thin beds in conjunction with processing setup parameters as shown in Figure 12. Track 1 and track 2 present the results obtained from semblance processing and PVP respectively. The processing window width was varied from 100 μsec (black curves) up to 250 μsec (green curves). Track 3 shows the raw waveforms and track 4 the filtered data with tool mode suppressed. The PVP algorithm delivers matching slowness curves that are virtually independent from the processing setup. The semblance response shows high susceptibility to the processing parameters. The semblance processing either over- or under-estimates the formation slowness depending on the selected processing window width, especially where the receiver array is crossing thin beds or high acoustic impedance contrast zones. In the presence of competing modes as shown in the later part of the wave train shown on the **Figure 13**, semblance will generate erroneous results, computing slowness readings affected by large bias (**Figure 12**).

A Gulf of Mexico data set comparing Semblance processing results and those of the Phase Velocity method is shown in **Figure 14**. This is a 200-foot interval of sandstone, siltstone and shale. There is a good agreement between the PVP compressional slowness (DTP) which is the correlation weighted average of the upper and lower calculated delta-t values and the semblance processing results for both upper and lower transmitter data sets, curves labeled DTP1_sem and DTP2_sem respectively. Additionally the PVP processing delivers a better overall bed resolution.

Individual waveform data for the lower transmitter firing and for the depth indicated by the arrow in **Figure 14** are shown in **Figure 15**. The figure shows the waveforms recorded for each of the four receivers and a hand picked correlation. Note how the hand picked delta-t of 112.3 μsec/ft correlates well with both processing methods, of approximately 112 μsec/ft slowness.

Another section of the log, at a shallower depth, is shown in **Figure 16**. There is a large discrepancy between the PVP slowness, curve labeled DTP, and the semblance processed delta-t values, curves DTP1_sem and DTP2_sem, over the whole 125 foot interval shown. At the depth indicated by the arrow near the top of a siltstone, the two processing techniques disagree by approximately 25 μsec/ft (130 μsec/ft versus 106 μsec/ft). The interval is comprised of shale and siltstone. Examination of the individual waveforms indicate excellent waveform data quality as shown in **Figure 17**. Manual correlation of the data indicates a clear 106 μsec/ft slowness, which matches the Phase Velocity Processing result. The faster delta-t is the correct one. It can be clearly correlated with the waveform data and it matches the Gamma Ray response (faster delta-t in the siltstone than in the above shale). The waveform data in track 3 of **Figure 16** indicate a faster formation than the overlying shale by the earlier arrival in transit time of the compressional wave.

The only distinctive feature about this interval is the attenuation of approximately 4.2 db/ft. This is not unreasonably high, but indicates fairly attenuating strata. Such conditions are encountered quite frequently, primarily due to the fact that drilling noise forces the tool to operate in a frequency bandwidth above 10 kHz. On **Figure 17** a manual correlation is also shown that matches the semblance correlation results of approximately 130 μsec/ft slowness. The semblance processing correlated peaks of same relative amplitude. This is one of the major drawbacks of the semblance correlation technique; it yields an amplitude weighted group velocity.

CONCLUSION

A new technique for correlating acoustic waveform data, Phase Velocity Processing (PVP), has been introduced and described. The technique works very well with the LWD full waveform data. PVP results do not depend on the amplitude of the processed waveform, nor are they sensitive to the formation attenuation. Additionally, the slowness calculation is based entirely on the measurement of the waveform transit time and thus has a high vertical resolution, essentially equal the receiver spacing. The PVP method is also much faster in execution than the semblance correlation technique traditionally used.

ACKNOWLEDGEMENTS

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ABOUT THE AUTHORS

Marek Kozak holds a Ph.D. in EE/ Measurement Systems from the Warsaw University of Technology in Poland. He has been instrumental in the development of MPI's pulsed power wireline induction and acoustic logging tools, and processing software. Prior to joining MPI in 1990 he was for 10 years with the Warsaw University of Technology, conducting research in theoretical and applied magnetics sponsored by Polish Academy of Sciences, teaching classes in measurement of non-electrical quantities, and working as the industry consultant in DSP systems. He is a member of SEG and Planetary Society.

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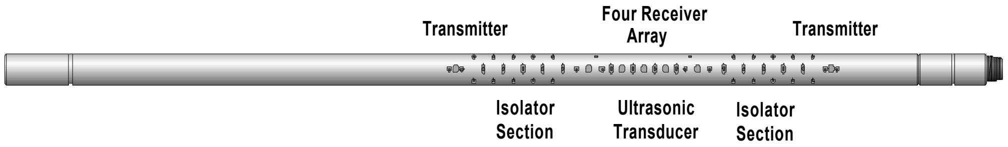

Figure 1. Acoustic Logging-While-Drilling Tool

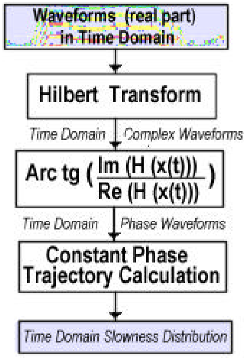

Figure 2. Phase Velocity Algorithm Data Flow

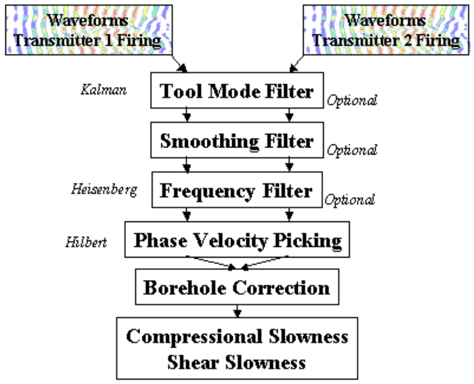

Figure 3. Phase Velocity Processing Data Flow

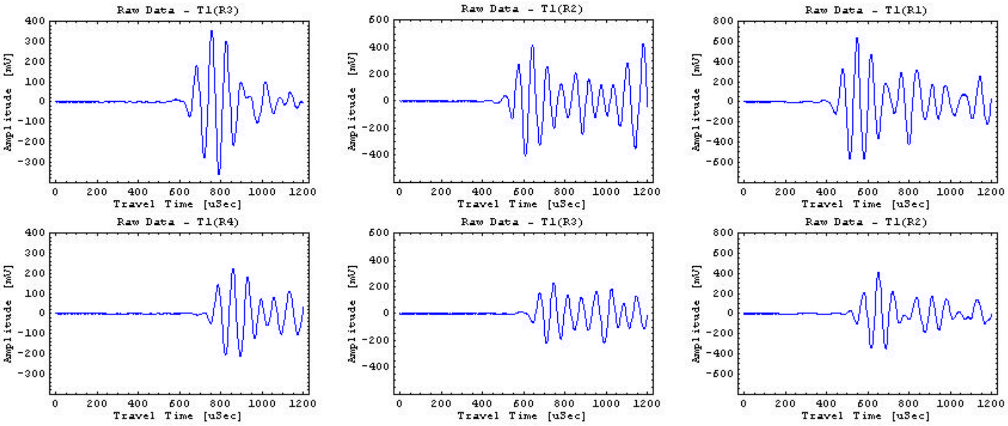

Figure 4. An example of raw LWD sonic waveforms (shown in common receiver depth mode). Right column presents receiver pair #12, the middle column – pair #23, and the left column – pair #34 shown in common receiver mode.

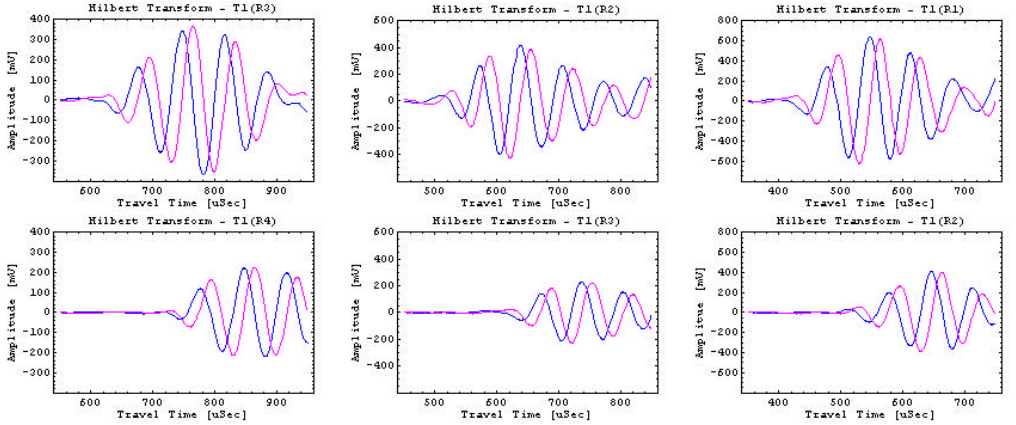

Figure 5. Time domain complex waveforms obtained after Hilbert transform (shown in common receiver depth mode). Dark lines denote real part of Hilbert transformed data, grey – the imaginary component.

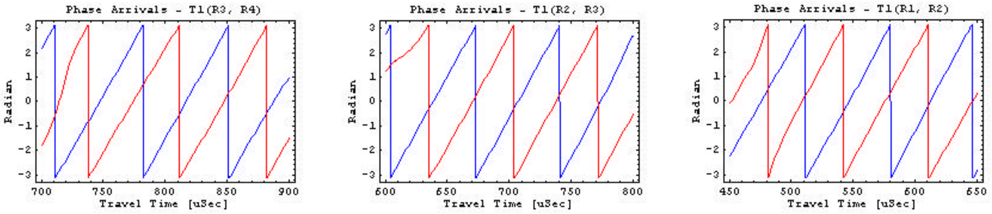

Figure 6. Time domain phase arrivals of the raw LWD sonic waveforms. Dark lines denote the phase distribution of the near receivers (closest to the transmitter), grey lines – far receivers (CRM mode).

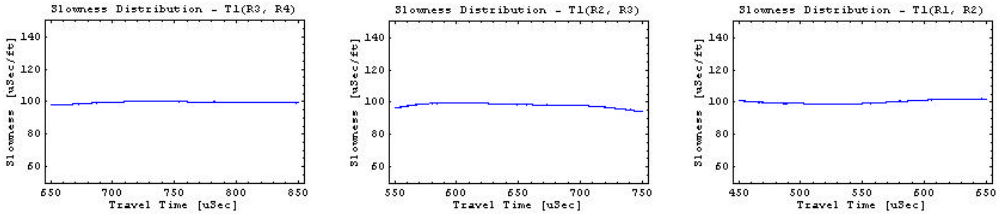

Figure 7. Time domain slowness distribution of the raw LWD sonic data obtained with each receiver pair. Right column shows the receiver pair #12, the middle column – pair #23, and the left column – pair #34 (CRM mode).

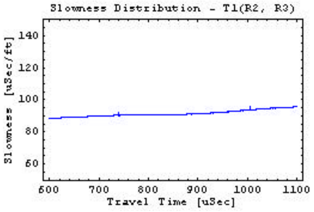

Figure 8. Time domain slowness distribution of the raw LWD flexural wave obtained with receiver pair #23. Note small dispersion effect expressed as a gradual bias toward higher slowness values.

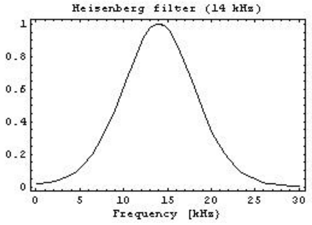

Figure 9. Frequency characteristic of typical Heisenberg filter.

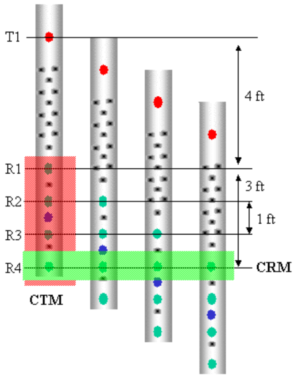

Figure 10. Comparison of CRM, Common Receiver Mode, and CTM, Common Transmitter Mode mode of operation.

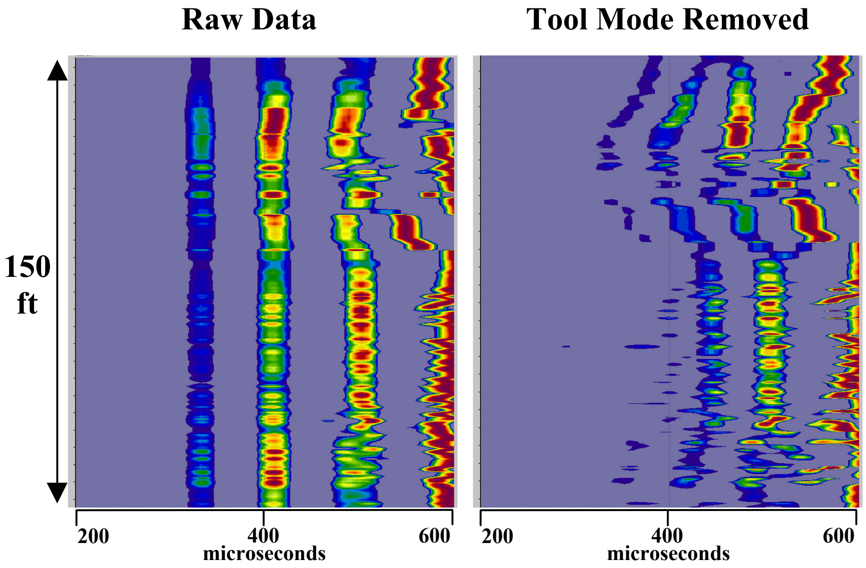

Figure 11. Example of the effectiveness of tool mode removal algorithm over a 150-foot interval.

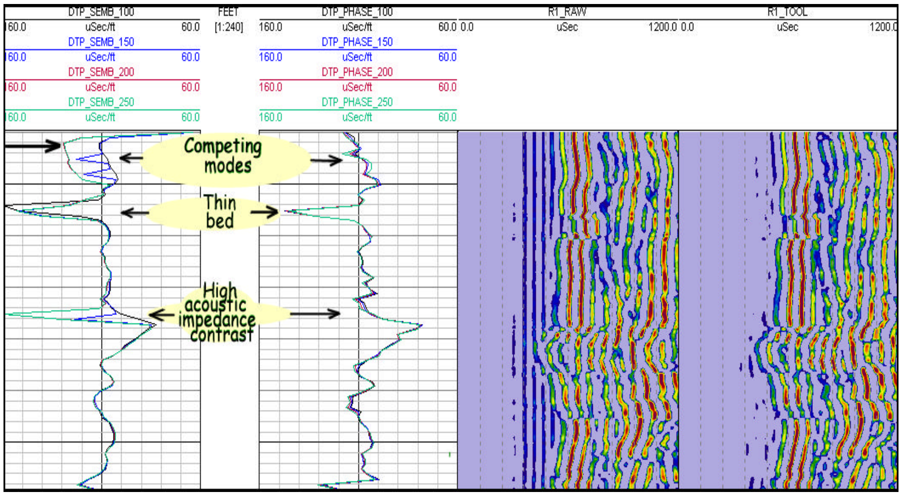

Figure 12. Comparison of Phase Velocity and Semblance Processing response to formation features, with different user defined processing setups. Note how response of the Semblance method depends on the formation type and processing window width (100 µsec, 150 µsec, 200 µsec, 250 µsec). Raw waveform data recorded at the depth indicated with the black arrow in the upper left corner is shown in the time domain in the Figure 13.

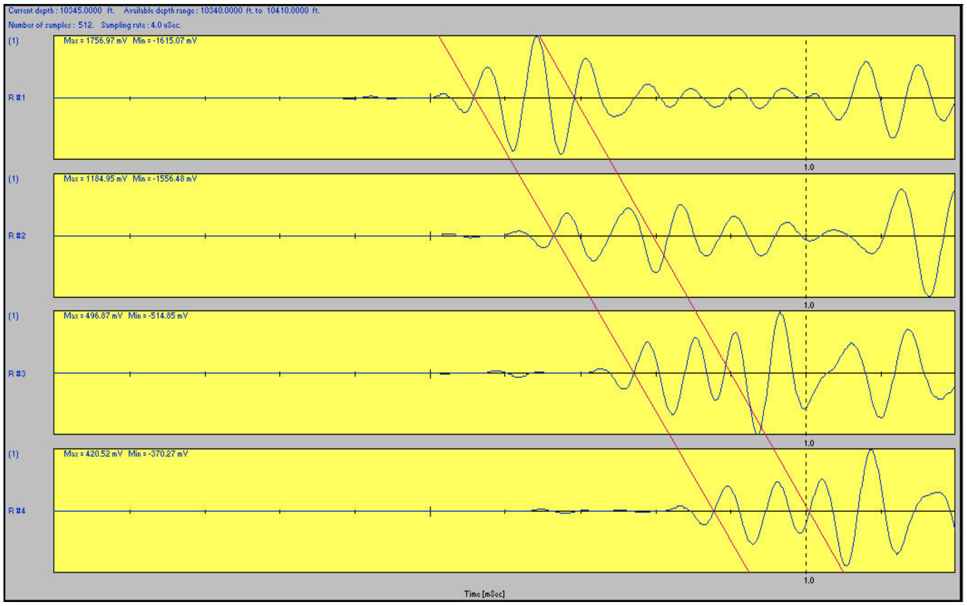

Figure 13. Raw waveform data recorded at the depth indicated (Competing Modes) on the Figure 12, shown in the time domain. Note poor signal coherence present in the later part of wave train, causing the Semblance to overestimate formation slowness.

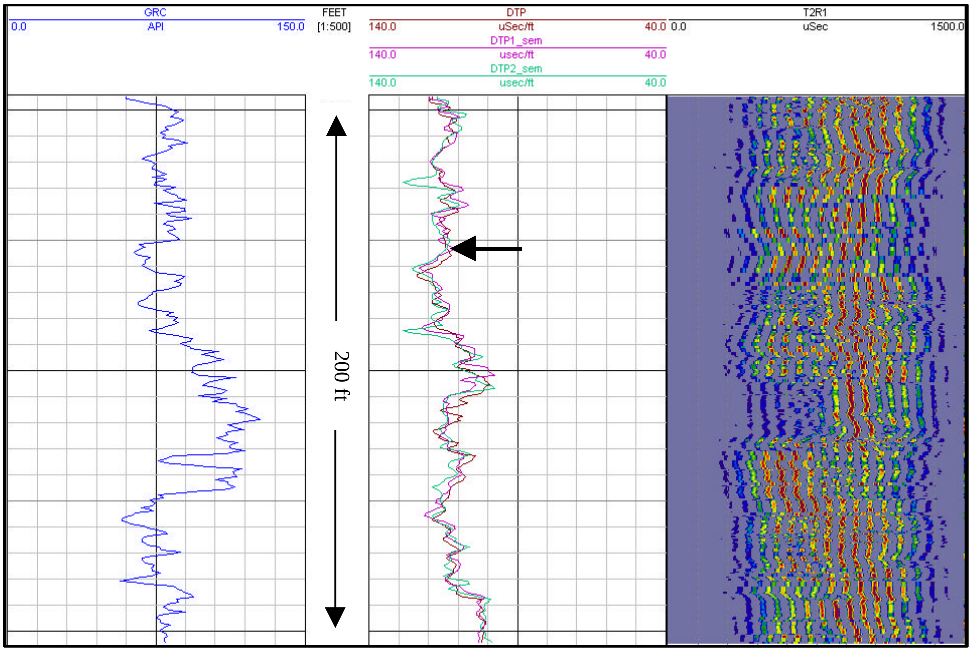

Figure 14. An 200-foot interval from the Gulf of Mexico showing agreement between Semblance and Phase Velocity processing results.

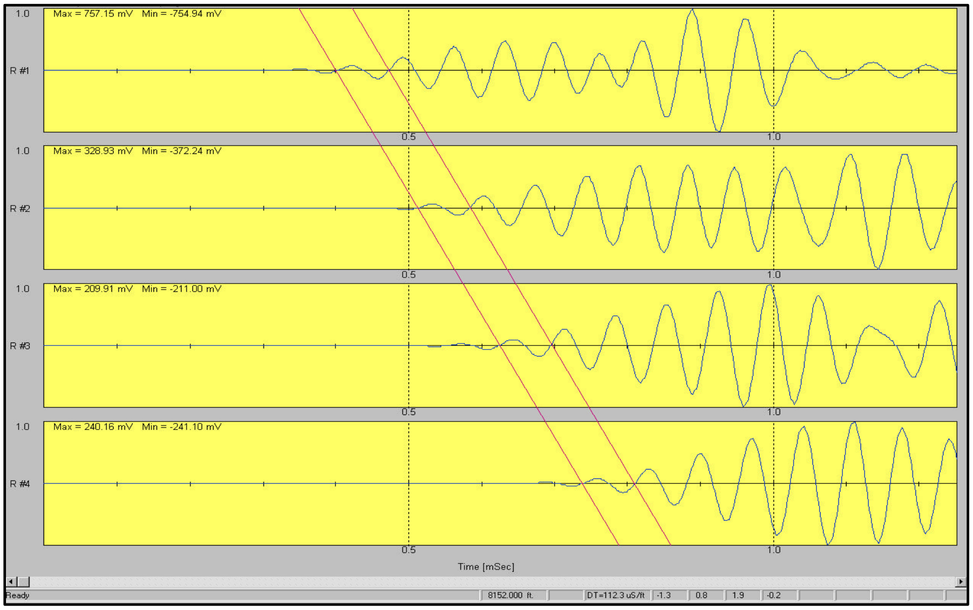

Figure 15. Waveforms at the depth indicated in Figure 14 and manual correlation of data indicating 112.3 μsec/ft slowness.

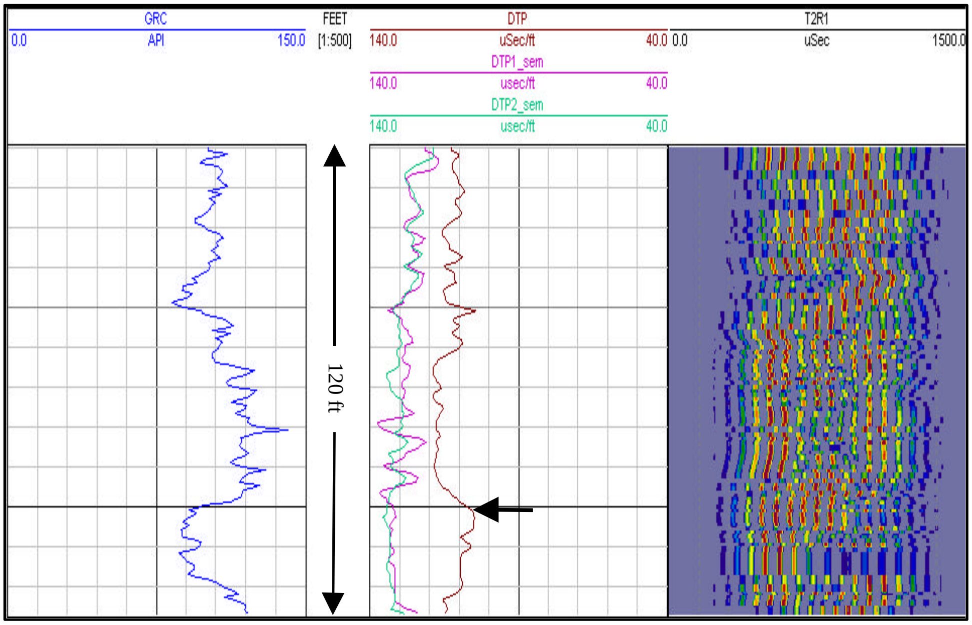

Figure 16. A 120-foot interval from the Gulf of Mexico showing a disagreement between Semblance and Phase Velocity Processing results.

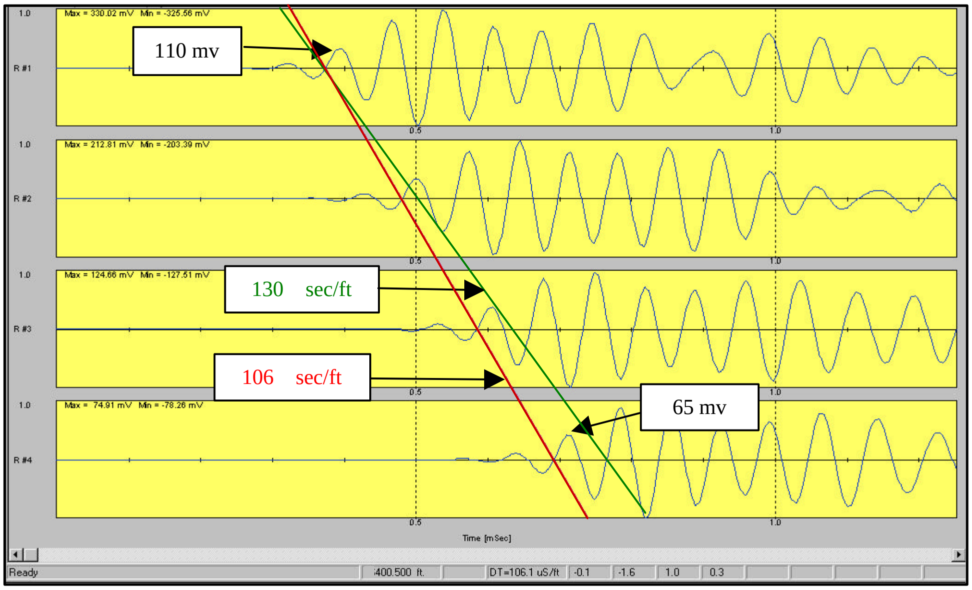

Figure 17. Waveforms from indicated depth of Figure 16 and manual correlation (red) of data indicating 106.1 µsec/ft slowness. 16 and a manual correlation (green) that matches the semblance processing results of 130.6 µsec/ft slowness. Semblance processing found correlation of peaks of near same relative amplitude.