An Experimental Study Of Seismoelectric Signals In Logging While Drilling

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Abstract
Acoustic logging while drilling (LWD) may be complicated because of contamination by waves propagating along the drill collar (the tool waves). In this paper we propose a new method for separating tool waves from the true formation acoustic arrivals in borehole acoustic LWD. The method utilizes the seismoelectric signal induced by the acoustic wave at the fluid-formation boundary. The basis for seismoelectric conversion is the electric double layer (EDL) that exists in most rock-water systems. EDL does not exist at the tool (conductor) water interface. Therefore, there should be no seismoelectric signals due to tool modes. In this paper, borehole monopole and dipole LWD acoustic and seismoelectric phenomena are investigated with laboratory measurements. The main thrust of the paper is the utilization of the difference between acoustic and seismoelectric signals, to eliminate the tool waves and enhance the formation acoustic signals in acoustic LWD.

1. Introduction

In the LWD, the detection of formation acoustic arrivals over the tool mode contamination is complicated by the presence of tool waves in acoustic LWD measurements. With some degree of coupling between the sources and receivers in the drill collar, the presence of tool waves is inevitable. The tool waves can contaminate the true formation acoustic waveforms, causing difficulty in the determination of formation velocities. The contamination is more likely for the dipole LWD logging in slow formations.

The basis for seismoelectric conversion is the presence of electric double layer (EDL) that exists in most rock-water system. Acoustic waves propagating in a borehole generate an electric field (seismoelectric) at the fluid rock interface (Zhu et al., 1999; Markov and Verzhbitskiy, 2004). Seismoelectric signals are not generated at the interface between the steel tool and the borehole fluid. This means that the acoustic and electrical fields are recorded with a transducer and a electrode mounted on the drill collar, as done in LWD, one would be able to identify the acoustic signals propagating in the borehole (formation sensitive waves) and through the tool (tool waves). The electrical field measured would be due to only the seismoelectric signal generated at the fluid-formation interface by the acoustic waves in the borehole. The combined analysis of the acoustic and seismoelectric fields measured in LWD should make it possible to separate and filter out the tool waves.

Although borehole seismoelectric phenomena have been studied by several authors (e.g., Zhu et al., 1997; Zhu , 2003; Haartsen et al., 1995; Mikhailov 1998; Mikhailov et al., 2000) in recent years, the seismoelectric signals generated in the LWD process and their potential applications have not been investigated. This paper represents the first attempt in this direction of research. We first design physical LWD experiments in the laboratory to collect both simulated LWD monopole, dipole acoustic and seismoelectric signals using a scaled-down borehole in a sandstone block and a similarly scaled LWD tool. By analyzing the acoustic and electric signals in the time and frequency domains, we can observe differences between these signals, which are mainly tool modes and noise. Then we apply a coherence method to pick out the similarities of the acoustic and seismoelectric signals, which are the related to the pure formation modes.

2. Seismoelectric phenomena in a borehole

The idea of using borehole seismoelectric measurements to characterize rock formation in-situ was suggested by Ivanov in 1940. The advantage of borehole seismoelectric logging over existing formation evaluation methods is its detection of fluid flow in a porous rock formation induced by a known pressure gradient (Mikhailov, 2000). Experimental studies of electrokinetic conversions in fluid-saturated borehole models have been carried out by Zhu et al. (1999). Field measurements of electric fields induced by a borehole Stoneley wave was made by Mikhailov et al. (2000) to detect fractured (permeable) zones along the borehole. In our experiment, the seismoelectric signals recorded are the electric fields generated by different monopole and dipole modes in a borehole drilled in a homogeneous block of Sandstone.

3. Laboratory experiment setup and borehole model

The experimental borehole model we use is an isotropic sandstone formation with dimensions of 30 cm x 29 cm x 23 cm shown in Figure 1. The P- and S- velocities are given in Table 1. The scaled LWD tool ID is 0.4 cm, the OD is 1.0 cm, and borehole diameter is 1.7 cm. The model parameters of our tool and borehole are shown in Table 1.

To simulate the LWD measurement, we built a scaled multipole acoustic tool composed of three parts: the source, receiver array, and a connector to mimic a drill-string between the source and receivers. Working in the ultrasonic frequencies the tool is put into the scaled borehole model to measure the monopole and dipole acoustic waves. Both the source and receiver acoustic transducers are made of PZT crystal disks of 0.635cm in diameter and 0.37cm in thickness. The source is made of four separate crystal disks shown in the B-B profile of Figure 2. The arrows on the disks indicate their piezoelectric polarization. Each disk has two electrodes attached to it. Altogether the eight electrodes are connected to a multipole switch. Using the switch to change the electric polarization applied on each crystal disk, we can achieve a working combination to simulate a monopole or dipole source. The receiver is composed of six pairs of crystal disks. The polarizations of each disk pair are shown in the A-A profile of Figure 2. The connector is made of a steel pipe threaded on each end. The source and receiver sections are tightly connected by the steel pipe to simulate the drill-string connection in LWD.

To measure the seismoelectric signal, we need to change the receiver section from acoustic transducers to electrodes. The electrodes used for this experiment are point electrodes of 1.0 mm in diameter. Each electrode on the electrode array detects the electric field around it. We replaced the array of the six pairs of transducers by an array of six pairs of electrodes spaced at the same interval. The holes in which the electrodes are imbedded are filled with sand glued by epoxy. The surface is coated with conducting glue and connected to the steel tool. The components and dimension of seismoelectric measurement tool are shown in Figure 3.

During measurements, we only need to rotate the switch to change the mode from monopole to dipole. This allows us to conduct the multipole logging without changing or moving the tool position. Therefore, the experiment results can be compared under the identical conditions.

4. Experimental mechanism and procedure

In the sandstone borehole model, an EDL is developed at the borehole wall. When the acoustic waves move along the borehole wall, a localized electric field is generated and the electrode will detect this electric field. Since the conductivity of the borehole fluid (distilled water) is very low, the recorded voltage between the electrode and ground can represent the electric field generated at the borehole wall very well. There is no measurable electric field generated at steel – water interface. Thus, in the seismoelectric signals, what we record is purely the electric field excited by the formation acoustic waves propagating along the borehole wall with the apparent velocities of multipole formation acoustic modes. No electric component propagating at the apparent speed of the tool wave can be observed in the electric signals.

The sandstone borehole model with a vertically drilled hole is placed into a water tank. The source and receiver sections are put into the borehole from two sides. The acoustic source is a high voltage generator and the receiver signal go to a preamplifier and a filter before being displayed on an oscilloscope. The working system is shown in Figure 4. The High Power Pulse Generator generates a square pulse with a duration of 10us. This means that the source wavelet has a center frequency of 100 kHz. While the excitation voltage for the acoustic measurement is only around 4-5 volts the excitation voltage for the seismoelectric measurement is about 750 volts.

The sampling rate is 500 ns. For each trace we record 512 points. The filter range, set from 300 Hz to 500 kHz, is broad enough to include all the dominant acoustic and electric modes.

We first study the acoustic properties of our scaled multipole tool by placing the tool wave in the water tank. Then we take measurements in the borehole to record monopole and dipole acoustic waves. After finishing recording of the acoustic signals, the acoustic receiver section is replaced by the electrode section to make the seismoelectric measurements.

5. Analysis of laboratory results

In this section, we analyze the acoustic and seismoelectric signals obtained in our laboratory experiments to understand the seismoelectric phenomena in the LWD process and investigate the potential application of the LWD seismoelectric signals. We use the semblance method in both the time and frequency domains to analyze the experimental array data.

5.1 Acoustic and seismoelectric signals with the tool in the water

In order to understand the properties of monopole and dipole tool modes of our specific scaled multipole tool, we first conduct measurements by putting the tool into the water tank in the absence of a borehole and formation. Using time domain semblance we obtain a monopole tool wave velocity of 3500 m/s and a dipole tool wave speed of 800 m/s (Figure 5A). The seismoelectric signal generated at the steel–fluid interface is too weak to be detected. It's obvious that the magnitude of the monopole seismoelectric signal is much smaller than the monopole acoustic signals recorded for the same time length (Figure 5B). For the seismoelectric measurements steps need to be taken to enhance the signal to noise ratio, such as shielding all cables, placing the transducer and electrode completely into the water and grounding the water tank with silver coated paper, and averaging 512 sweeps. We also subtract the mean of the six traces in the array from each trace to eliminate the propagating random noise and then use a high pass filter to eliminate a DC component of source noise.

5.2 LWD acoustic and seismoelectric signals in the sandstone borehole

As pointed out previously, since the EDL at the steel tool-fluid interface is very weak and the tool is effectively grounded in the experiment as well as in field measurement, the seismoelectric signal excited in the acoustic LWD process should contain no signals with the apparent velocity of the tool modes. We now examine the two kinds of signals under monopole and dipole excitation using time and frequency domain semblance (Figures 6 and 7). The theoretical dispersion curves, which are calculated by using the model parameters in Table 1, are superposed on the frequency domain semblance results to identify various modes. From the acoustic waveform data we can see clearly a monopole tool wave arriving between the P and S waves, and a low frequency dipole tool wave coming in the late part of the wave train. In the time domain semblance we can observe the peaks at the monopole and dipole tool wave velocities in the acoustic signals (left panels of Figures 6 and 7). These peaks are absent in the seismoeletric signals (right panels of Figures 6 and 7). It's also clear in the frequency domain semblance that the dispersive monopole and dipole tool modes are absent. These results show that measuring the seismoelectric signal during LWD can potentially eliminate the effect of tool waves .

5.3 LWD acoustic and seismoelectric signal coherences and filtering

By measuring the seismoelectric signal in the LWD process, we not only obtain a new physical measurement related to formation properties, but more importantly the seismoelectric measurements do not contain tool mode-induced signals. Since the acoustic and seismoelectric signals are different in content, we can use the seismoelectric signal to filter the acoustic signal to remove tool modes. We calculate the coherence (cross correlation of the frequency spectra) for the LWD acoustic and seismoelectric signals. The high coherence at high frequencies corresponds to the formation modes. Conversely, the low coherence at low frequencies corresponds to the tool modes and noise. Thus, we can remove the tool waves from the formation arrivals in the acoustic signals by simply applying a filter obtained from the coherence function between the seismoelectric and acoustic signals.

Figures 8 and 9 show the results of this process for the monopole and dipole data. The LWD acoustic and seismoelectric waveforms for the monopole source are shown in Figure 8 (a). The Fourier spectra of the two sets of waveforms and the coherence between the two as a function of frequency are shown Figure 8 (b). The original acoustic waveforms, and those filtered using the coherence function are shown in Figure 8 (c). The semblance results in Figure 8 (d) show that the tool waves have been effectively removed and only the formation P and S and the Stoneley waves are observed (right panel of Figure 8 (d)).

Figures 9 (a) – 9 (d) show the equivalent results for the dipole data. Note the disappearance of low frequency tool flexural waves after the filtering (Figure 9 (d)). The semblance results confirm that 800 m/s tool flexural waves are indeed removed and the formation dipole (shear) arrival clearly stands out.

6. Discussion and Conclusions

The study of the borehole seismoelectric phenomena in LWD operations demonstrates the importance of the simultaneous measurements of acoustic and seismoelectric fields. Acoustic waves in the borehole produce a seismoelectric effect at the fluid formation boundary. Tool waves propagating in the drill collar do not produce a seismoelectric effect. Thus, the seismoelectric field can be used to remove the tool waves from the LWD acoustic signals. By correlating the LWD seismoelectric and acoustic signals, we can effectively separate the formation modes from the tool modes. A simple filter based on the coherence function between the LWD seismoelectric signal and the acoustic signal was effective in removing the tool modes while preserving the formation acoustic wave modes.

7. Acknowledgements

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	P-velocity	S-velocity	Density	Outer radius
Inner fluid	$1500\,m/s$	-------	$1000\,kg/m^3$	0.4cm
Tool (Composite)	$4185\,m/s$	$2100\,m/s$	$7700\,kg/m^3$	1.0cm
Outer fluid	$1500\,m/s$	-------	$1000\,kg/m^3$	1.7cm
Formation	$4660\,m/s$	$2640\,m/s$	$2100\,kg/m^3$	∞

Table 1 LWD lab borehole model parameter

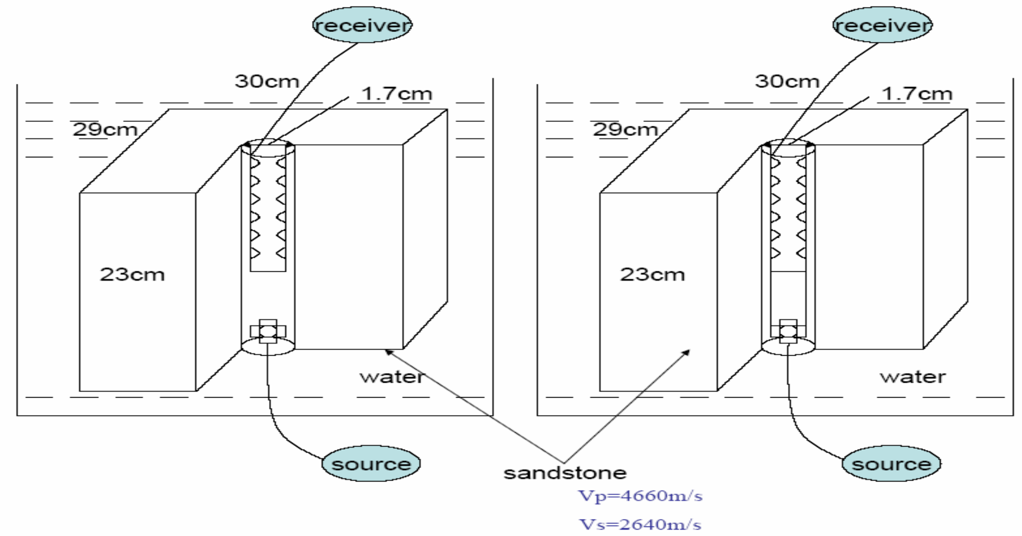


Figure 1 – Laboratory borehole models. Left is without a grid connector between source and receiver array. Right is with connector.

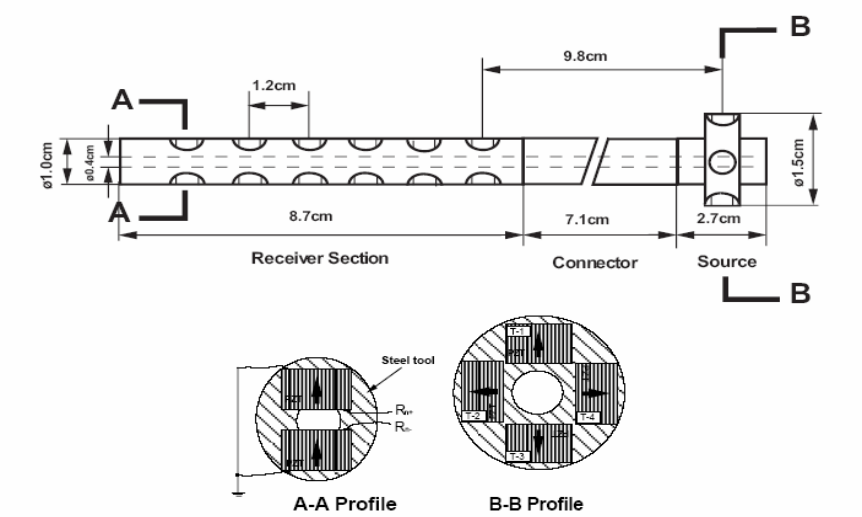
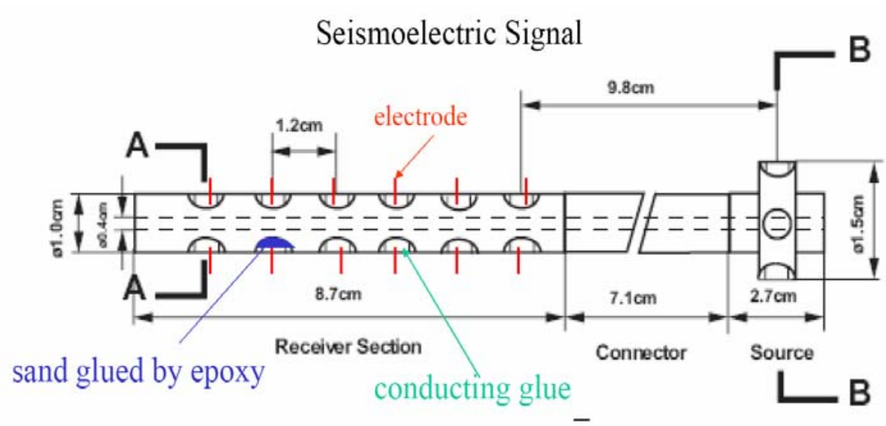
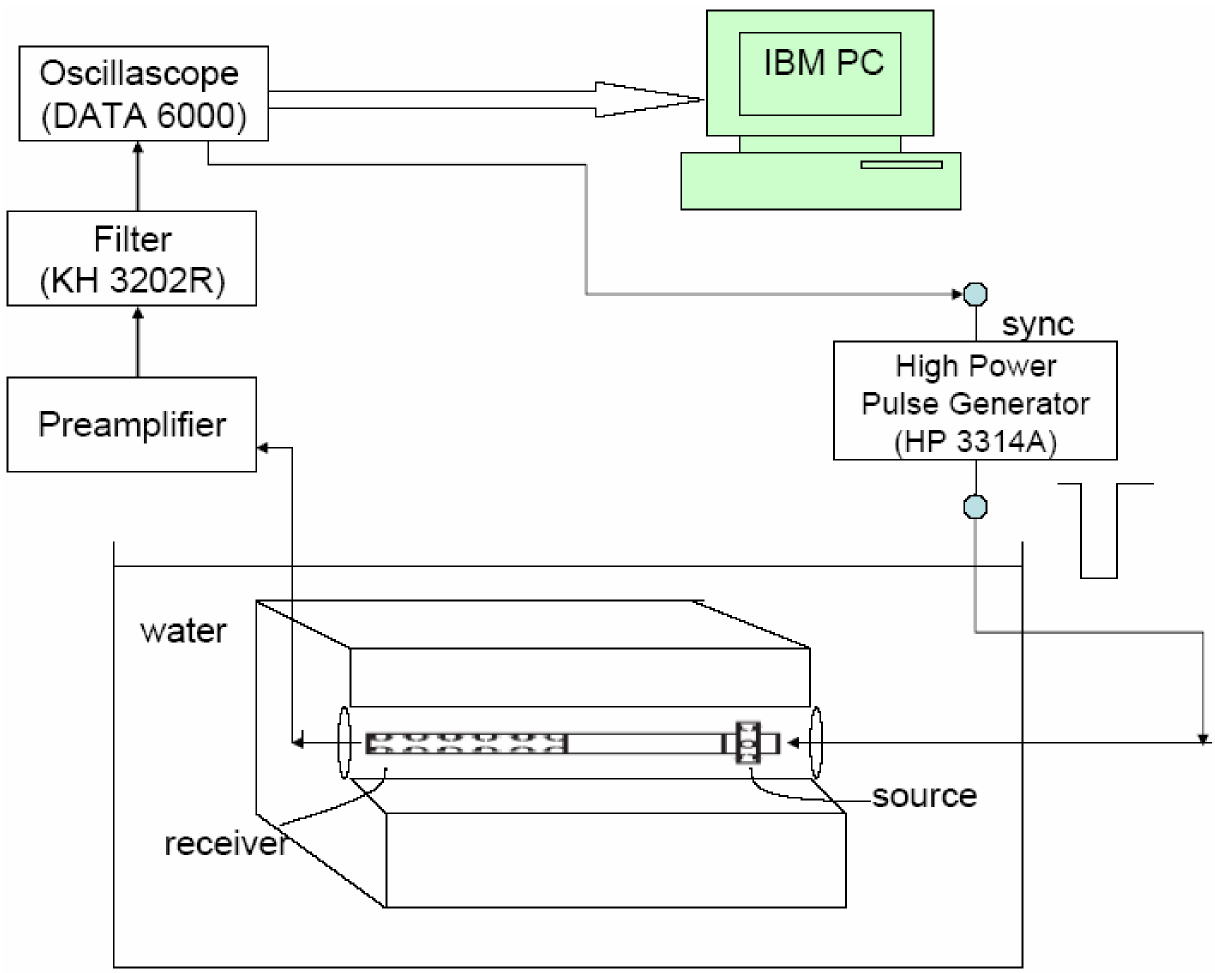


Figure 2 – Schematic diagram of the scaled multipole logging tool. The arrows indicate the polarization of the PZT disks.



Figureure 3 – Schematic diagram of the scaled lab multipole tool in the seismoelectric measurement.



Figureure 4 – Schematic diagram of the experiment working system.

Monopole Acoustic Signal

with tool in the water tank

Dipole Acoustic Signal

with tool in the water tank

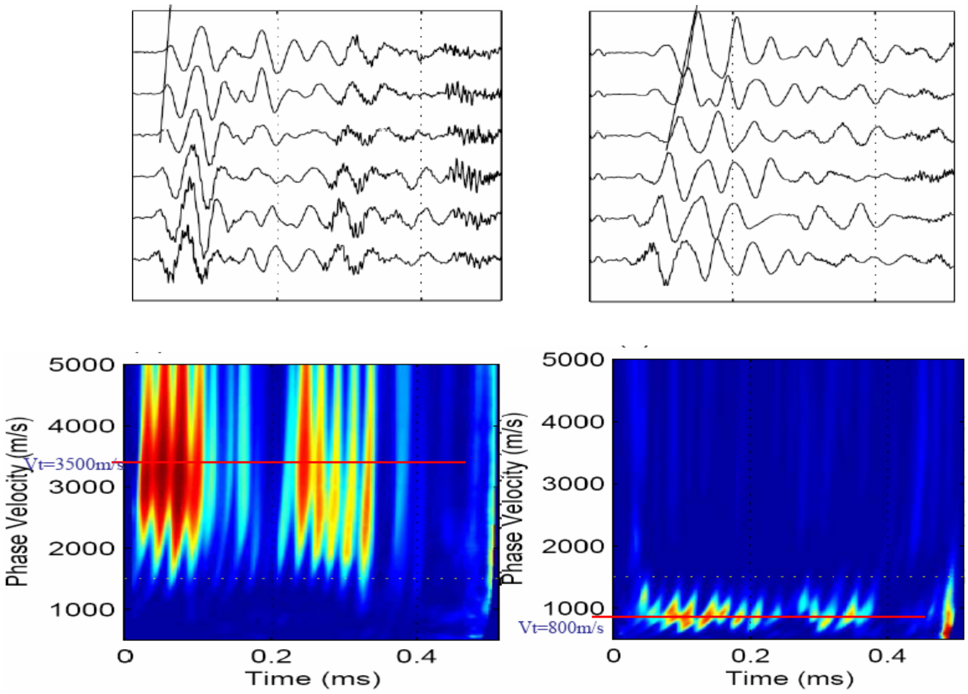


Fig 5 A

Monopole Seismoelectric Signal

with tool in the water tank

Monopole Acoustic Signal

with tool in the water tank

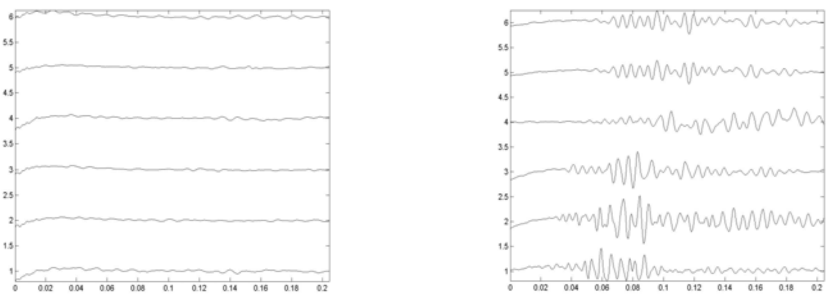
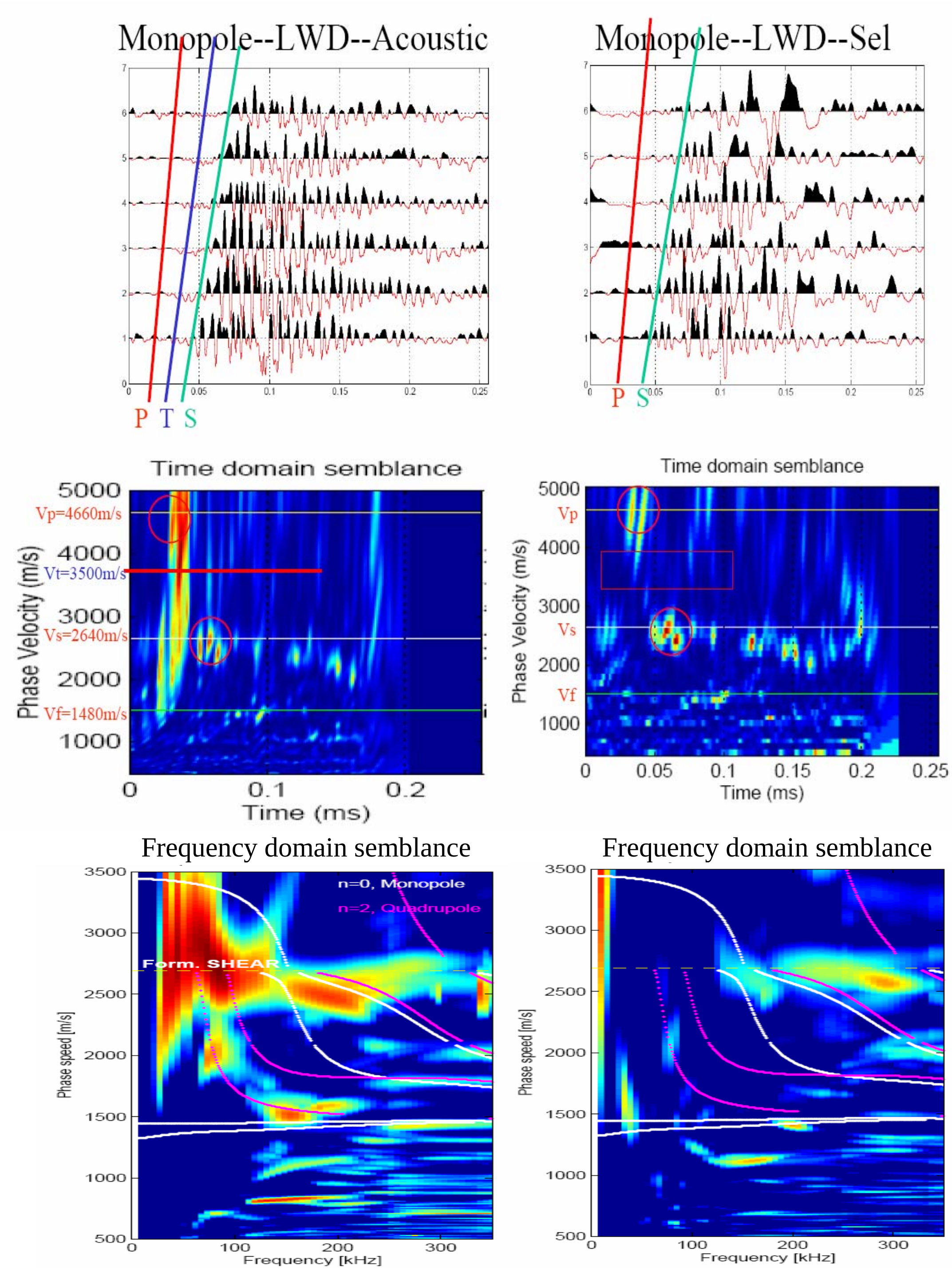


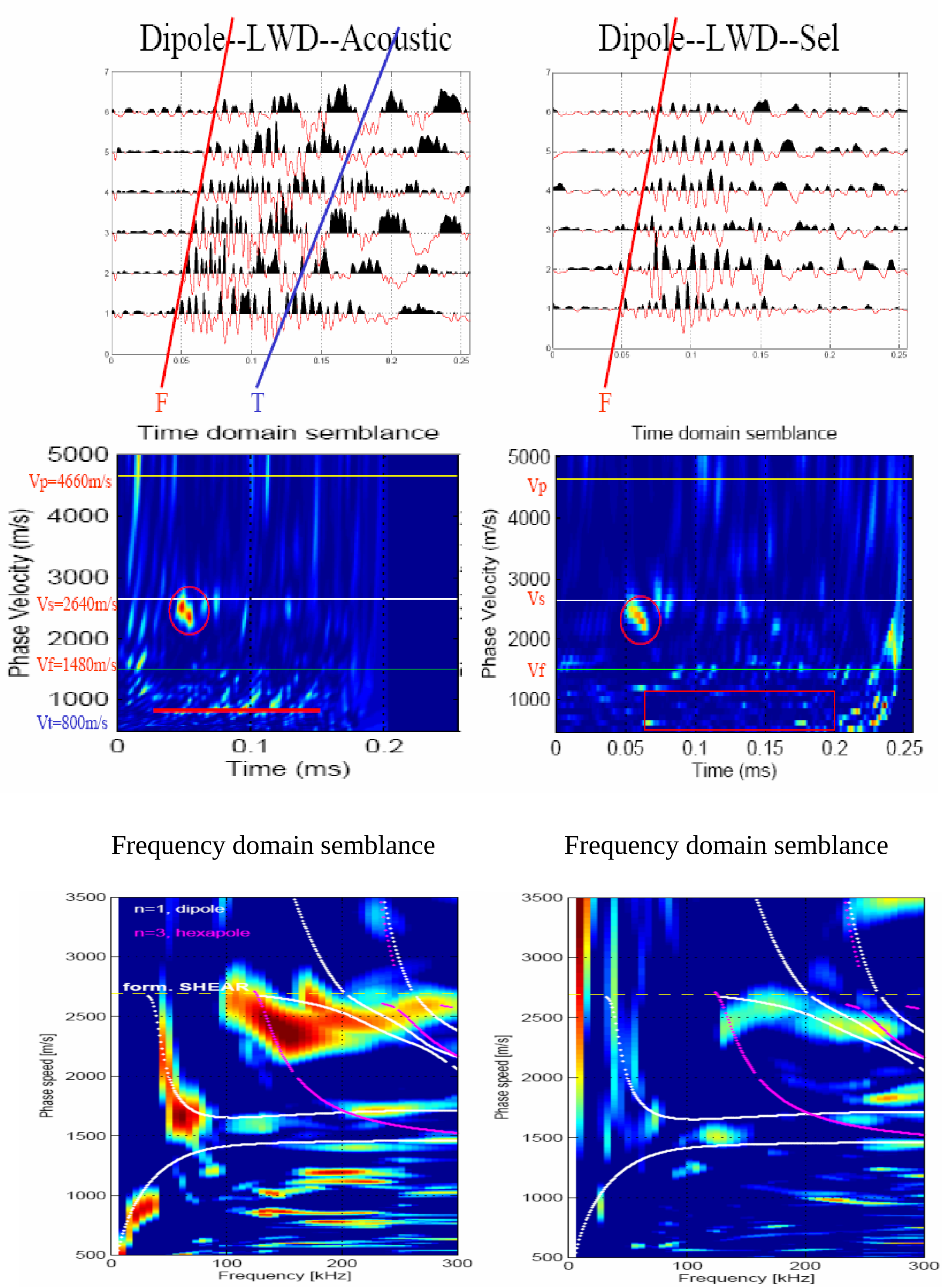
Fig 5 B

Figureure 5 A – Acoustic Waveforms and time domain semblance of 0.512 (s) for monopole (left) tool and dipole tool (right) submerged in a water tank. Red lines (Vt) indicated the tool waves.

Figureure 5 B – Monopole seismoelectric signals (left) at the steel – fluid interface of 0.256 (s) and acoustic signals (right) of 0.256 (s) with the tool submerged in a water tank. (All the traces in Fig 5 B are normalized by the same scale factor.)



Figureure 6 – Monopole acoustic (left) and seismoelectric signal (right) comparison. (Vp is P wave velocity, Vs is S wave velocity, Vf is fluid velocity and Vt is the tool wave velocity.) In the frequency domain semblance, the white lines are the calculated theoretical dispersion curves for the monopole tool wave, Pseudo-Rayleigh wave and Stoneley wave, the red lines are the quadrupole modes.



Figureure 7 – Dipole acoustic (left) and seismoelectric signal (right) comparison. (Vp is P wave velocity, Vs is S wave velocity, Vf is fluid velocity and Vt is the tool wave velocity.) In the frequency domain semblance, the white lines are the calculated theoretical dispersion curves for the dipole tool wave, flexure wave, the red lines are the hexapole modes.

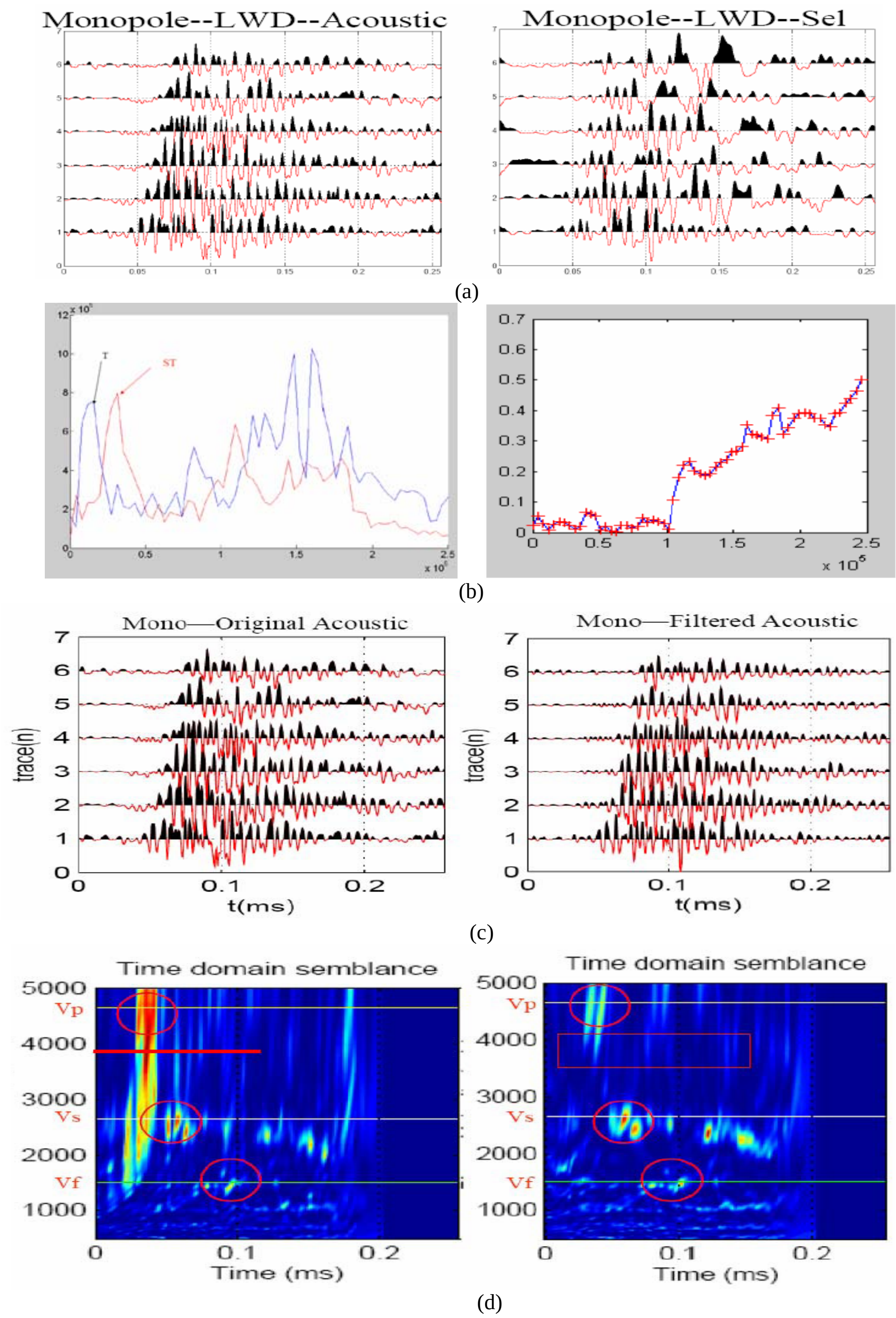
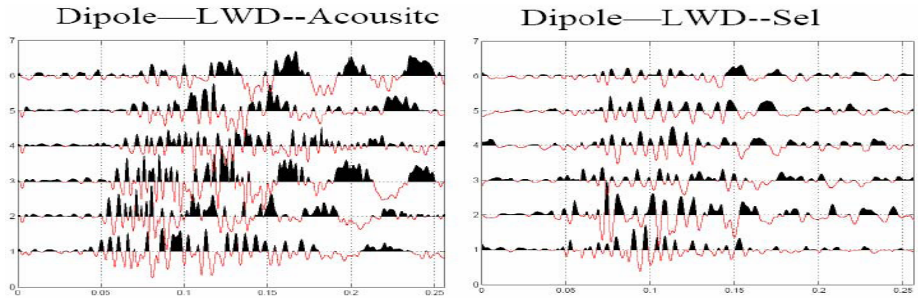
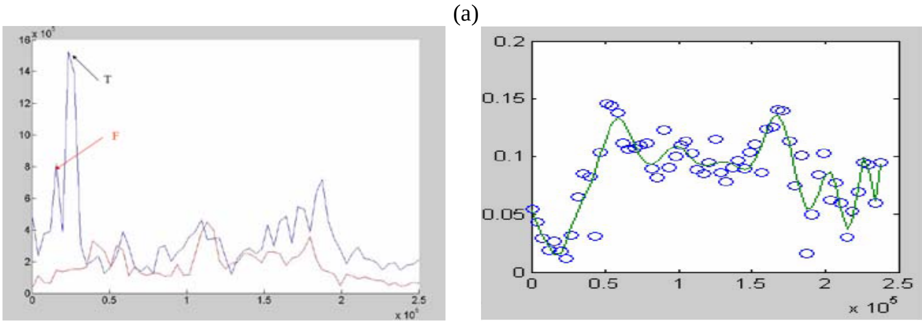


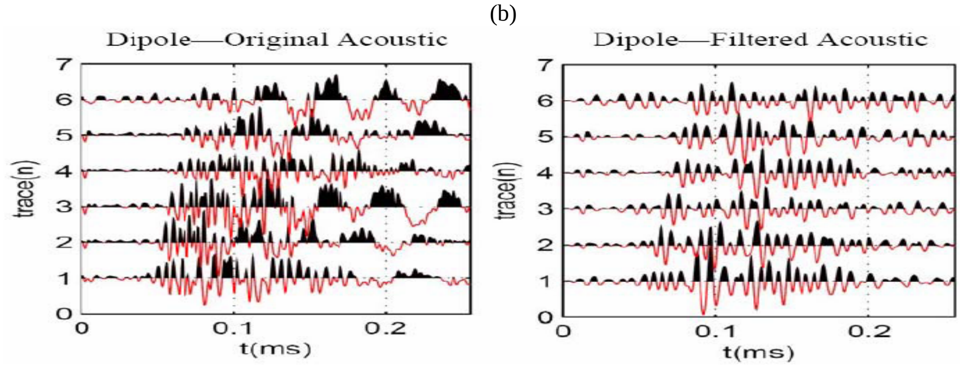
Figure 8 – (a) Monopole acoustic (left) and seismoelectric (right) waveforms; (b) monopole acoustic (black line) and seismoelectric (red line) Fourier amplitude spectra (left) and coherence as a function of frequencies (right); (c) monopole unfiltered acoustic (left) and filtered (right) waveforms; and (d) their domain semblances. (T means frequency peak due to tool wave, ST stands for Stoneley wave).



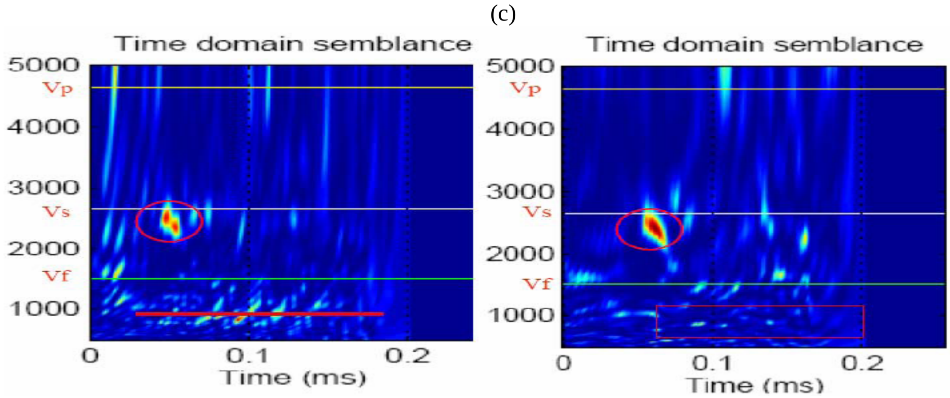
(a)



(b)



(c)



(d)

Figure 9 – (a) Dipole acoustic (left) and seismoelectric (right) waveforms; (b) dipole acoustic (black line) and seismoelectric (red line) Fourier amplitude spectra (left) and coherence as a function of frequencies (right); (c) dipole unfiltered acoustic (left) and filtered (right) waveforms; and (d) their domain semblances. (T means frequency peak due to tool wave, F stands for Flexural wave).