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New developments in real-time processing of full waveform acoustic televiewer data

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Abstract

The new full wave Acoustic Borehole Imager tool (ABI) is a multi-echo (amplitude and traveltime) system that gives optimum performance under a wide range of borehole conditions and is an improvement over existing single echo acoustic televiewer tools. The principle of the multi-echo system is the digital recording of each reflected acoustic wave train. Then, real-time processing of the acoustic data is made by a downhole Digital Signal Processor (DSP) to extract all valuable information, which is further compressed before transmission to the surface such that no special requirements are imposed on data transmission rates or on logging speed. Also, recording of the full acoustic waveform enables major improvements to the dynamic range of the system. Information about echoes from the tool's acoustic window provides the possibility to predict tool generated coherent noise and allows detection of echoes from the borehole wall, which are much smaller than coherent noise signals. When used in a PVC cased borehole, the system can be automatically adapted to record both the reflection at the casing and at the borehole wall. When used inside steel casing, the tool can detect echoes from the inner wall and the outer wall of the steel casing and the resulting data can used to calculate amount inner corrosion, outer corrosion, and remaining casing thickness. If the borehole casing was grouted with cement, information can be gathered about the presence and absence of cement and the quality of cement bonding.

Keywords: Borehole geophysics; Acoustic image; DSP real-time processing; Casing inspection; Image through plastic casing; Environmental geoscience

1. Introduction

AcousticTeleviewer logging has been successfully applied to geotechnical investigations and mineral exploration (Schepers et al., 2001) due to advances in beam focusing, increased dynamic range, digital recording techniques, and digital data processing (Schepers, 1991). Acoustic Televiewer tools scan the borehole wall with a rotating acoustic beam. In the FAC40 and the new ABI40 Televiewer (Fig. 1) manufactured by Advanced Logic Technology (ALT), the acoustic beam is created by a rotating mirror. The mirror is used to focus the beam such that maximum resolution is achieved at the borehole wall. The non-moving acoustic transducer first sends out a burst of acoustic energy and later records reflected signals. An acoustic image of the surrounding formation is produced by recording echoes of the acoustic

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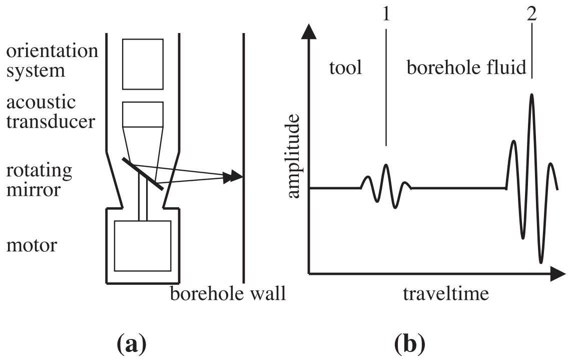

Fig. 1. Principle of Televiewer measurements. (a) Outline of the mechanics of the tool. The conical part of the tool housing represents the acoustic window, which is made of a special synthetic material for optimum transmission of the acoustic energy through the acoustic window. (b) Acoustic waveform received by the acoustic transducer. From left to right, the first signal (1) is the reflection from the acoustic window and the second signal (2) is the reflection from the borehole wall.

signal generated at the interface between borehole fluid and rock. At each scan point, the maximum amplitude and the corresponding traveltime of the reflected signal are measured.

In principle, in an open hole environment, two major reflections are observed (Fig. 1a): The first reflection is from the tool's acoustic window, where the acoustic energy penetrates from the inside of the tool into the borehole fluid. For a specific tool and a specific beam direction, this reflection occurs approximately at the same time. The second reflection is from the borehole wall and can occur at any time beyond the first reflection time. Recording of amplitude and traveltime of the reflection from the borehole wall is be made by appropriate tool electronics. This simple case is depicted in Fig. 1b.

In the case of low impedance rock, irregularities in the borehole wall, certain mud conditions, and decentralization of the tool, reflected signal amplitudes from the borehole wall can become very small. Under such conditions, electronic noise, acoustic noise, and coherent acoustic noise (multiple reflected and scattered signals inside the transducer and the tool body) may make it difficult to identify reflections from the borehole wall.

In Fig. 2, a full acoustic wave train is displayed, as it is received by the acoustic transducer while measuring in an open borehole. The first echo (1) is the reflection from the acoustic window. The second echo (2) is the multiple reflection of the acoustic window. The third echo (3) is the desired reflection from the borehole. As the arrival time of the multiple reflection from the acoustic window is known approximately, the detection of the echo from the borehole wall is no problem in the case of Fig. 2.

However, the real measure of Televiewer performance under a wide range of borehole conditions is the identification of the correct echo within the received acoustic wave train.

In the early days of Televiewer logging, successful measurements were made transmitting the analog acoustic signal to a surface unit, recording the signal

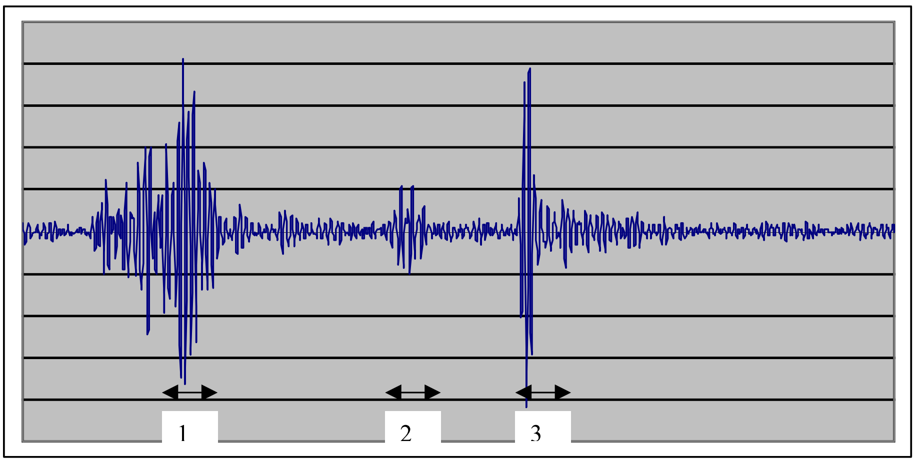

Fig. 2. Acoustic data recorded by ABI40 tool in an open hole.

on analog video tape and using this huge amount of data to look at reflected features at and beyond the borehole wall (Broding, 1981). The disadvantage of such an approach is that the dynamic range of the analog signal is low due to the limited analog transmission capabilities of logging cables.

2. Tool architecture

Different tool hardware architectures will be discussed as they evolved over the last three decades. To explain and to illustrate the performance of different detection approaches, synthetic seismograms (reflected acoustic wave trains) were calculated for a generic Televiewer tool applied under different hole conditions; i.e., the synthetic seismogram displayed in Fig. 3a is calculated for a tool in an open hole. The apparent reflection coefficient at the borehole wall is assumed to be 0.1. Besides the impedance contrast, the apparent reflection coefficient includes mud attenuation and tilt of the borehole wall relative to the incident beam, because to the recording system, it is of no importance which factor has influenced the amplitude of the received echo. The apparent reflection coefficient is a relative measure. The value of 1 is attained for a non-fractured granite rock in a water-filled 6-in. diameter borehole. The synthetic seismogram of Fig. 3b can be considered to be a noise-free version of the acoustic trace in Fig. 2. The first three echoes are the same as in Fig. 2. Due to the assumption of a small borehole diameter, a fourth echo (4) occurs which is the multiple generated by the borehole wall reflection between acoustic window and acoustic transducer. The first two events are at approximately fixed position depending on specific tool constructions. The two other events will vary depending on the distance between the tool and borehole wall.

2.1. Analog detection

The frequency range of the transmitted acoustic signal of Televiewer tools typically is between 0.4 and 1.4 MHz. In the early tools, fast analog electronics

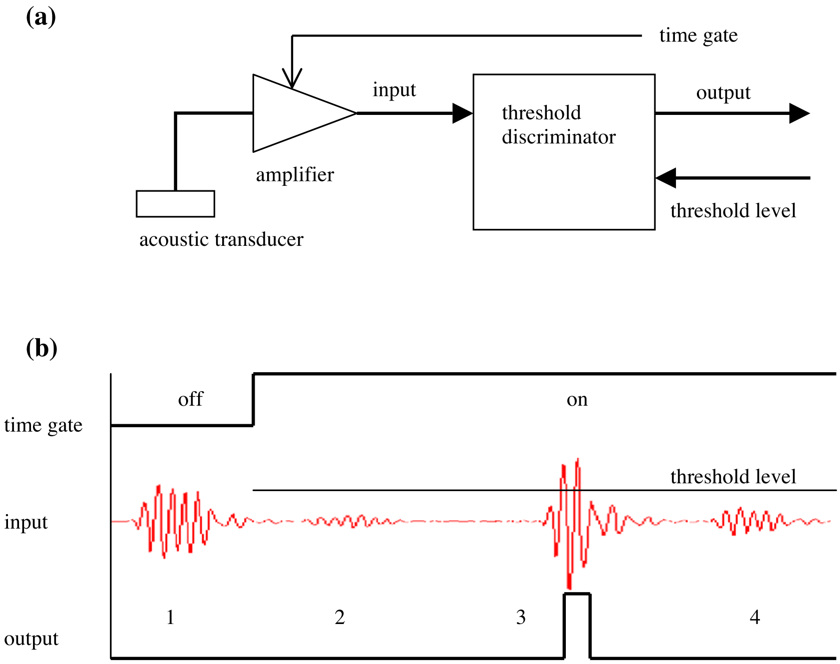

Fig. 3. Hardware and measurement principle of analog tools. (a) Basic components of an analog recording system. (b) Acoustic waveform received by the acoustic transducer and display of time gate and threshold that are used to detect amplitude and traveltime of the reflection from the borehole wall (3). Signal (1) is the window reflection and signals (2) and (4) are multiples.

(but no fast A/D-converters) were available. The tool electronics was designed to detect the first echo with a signal level higher than a threshold value.

To record the amplitude and traveltime of the borehole wall reflection, a measurement time gate opens the signal input at a time when the amplitudes of the acoustic window reflection have died off. Normally, the start time of this measurement time gate is fixed. The output signal is produced in such a way that energy recording is enabled as soon as the signal energy is above the threshold level, and is disabled as soon as the energy drops below the threshold level. The amplitude of the output pulse is equivalent to the maximum energy within the gate. The threshold level has to be set higher than the amplitude of the first multiple echoes. Because the amplitude of this multiple event depends on borehole conditions (pressure, temperature) and on amplifier gain, an optimum setting of the threshold level is difficult. The amplifier gain is changed manually by the logging operator.

Each time amplifier gain settings are changed, the threshold level has to be adjusted. In practice, the required setting of a threshold severely limits the dynamic range of the system.

2.2. Digital detection

Higher dynamic range can be achieved with digital tool electronics. Due to the limited data transmission rate on standard logging cables, it was not possible to send the full digital waveform to the surface unit. Fast 8-bit A/D-converter and fast conventional logic devices were on the market, but microprocessors were still slow. Therefore, the aim of the early digital Televiewer systems was to detect the highest value (peak) of the reflected signal in an operator defined time gate and the traveltime of that peak value.

The schematic layout of the digital electronic is given in the upper part of Fig. 4. To increase the dynamic range of the 8-bit A/D-conversion, an automatic gain process is implemented.

The amplifier gain settings are dynamically changed via commands from the microprocessor. A special algorithm is used to calculate on the basis of previous values of the optimum gain setting of the next measurement.

The digitized signal is fed into a numerical hardware coded maximum detector device. No critical threshold settings are required to get the maximum amplitude and

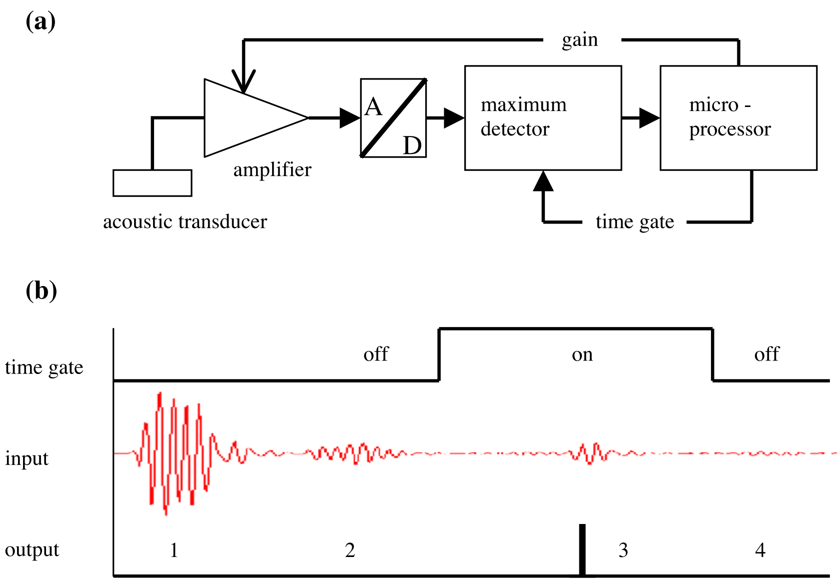

Fig. 4. Hardware and principle of measurement of digital tools. (a) Basic components of a digital recording system. (b) Acoustic waveform received by the acoustic transducer and display of time gate that is used to detect amplitude and traveltime of the reflection from the borehole wall (3). Signal (1) is the window reflection and signals (2) and (4) are multiples.

the corresponding traveltime within the defined measurement time gate. The system allows the operator to select the start time and the end time of the measurement time gate. This offers the advantage to further increase the dynamic range. However, careful consideration is required when setting the measurement time gate, taking into account the borehole diameter, expected variation of borehole diameter, expected decentralization, and expected variation of acoustic velocity in oil (inside tool) and in borehole fluid.

For the calculation of the synthetic seismogram (Fig. 4b), an apparent reflection coefficient of 0.01 was assumed. The amplitude of the borehole wall reflection is nearly equal to the first acoustic window multiple. With the actual measurement time gate setting, the borehole wall echo will be properly detected even if it becomes much smaller than the coherent noise event outside the measurement time gate. This is an ideal case, which may often not occur in the field.

2.3. Intelligent software-driven detection

Until recently, Televiewer tools recorded only one amplitude and one traveltime of the complete reflected signal. Real-time analysis of the full waveform allows extraction of more reliable information from the reflected acoustic signal. This will open new applications for the Televiewer tool.

The principle is to digitally record the complete full waveform and to rely on intelligent and sophisticated software to detect and to identify useful echoes. This is possible now, because fast 14-bit A/D-converters and ultra-fast Digital Signal Processors (DSP) are available.

The hardware in the new Televiewer system (Acoustic Borehole Imager, ABI) is simple (Fig. 5a). No amplifier is necessary because the fast 14-bit A/D-converter easily covers the dynamic range of available acoustic transducers. The full digital acoustic wave train is directly transferred to a fast DSP. The microprocessor in the previous Televiewer had a command execution cycle of 2 μs, whereas the comparable value of the new DSP is 15 ns. In addition, the DSP has a number of standard signal processing routines implemented as functions. Therefore, the DSP is a powerful tool to apply real-time digital filtering and processing and to implement complex signal-detection algorithms.

The synthetic seismogram of Fig. 5b is calculated under the condition of plastic casing inside the borehole. Thickness of the casing is 6 mm and the distance between casing and borehole wall is 5 mm. The apparent reflection coefficient of the borehole wall is assumed to be 0.1. Four major events with more or less the same amplitude are visible. The first event (from left) is the acoustic window reflection (1), second is the reflection from the inner casing surface

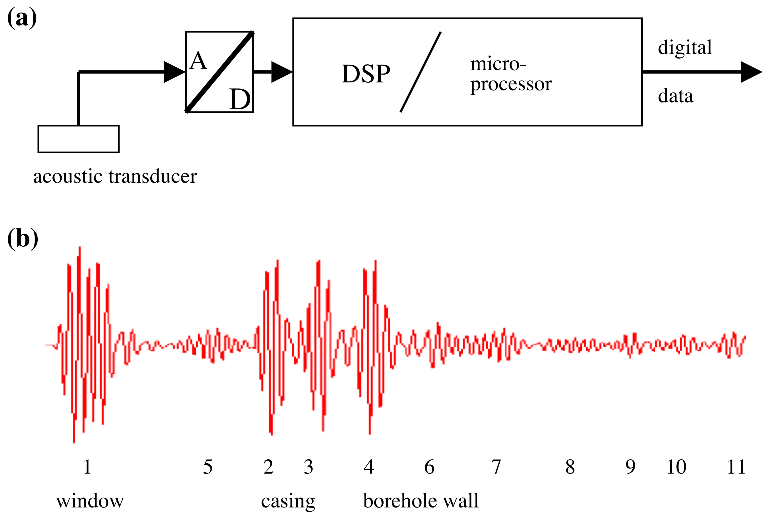

Fig. 5. Hardware principle of ABI40 and typical acoustic trace as handled by the system.

(2), third is the reflection from the outer casing surface (3), and fourth is the borehole wall reflection (4). The system will not only detect these four events but also 7 minor events (5 to 11), which are multiple reflections.

None of the previous Televiewer tools can handle an environment as shown in Fig. 5b. The new system will be able to identify the borehole wall reflection independent of decentralization of the tool inside the casing or of the casing inside the borehole.

To properly process an acoustic signal as shown in Fig. 5b, the operator has to supply only borehole environmental information to the tool. Three different environmental conditions can be chosen:

1. Open hole, classic environment
2. Cased hole, logging behind casing
3. Casing thickness, casing inspection

An acoustic wave train measured with the ABI40 tool in a borehole containing PVC-casing is shown Fig. 6. After each rotation of the acoustic head, the tool sends one full acoustic wave train to the surface unit. The ALTLogger software of the surface unit continuously displays this acoustic trace on screen. On the acoustic trace shown Fig. 6, the acoustic window can be seen at 76.3 μs. At 103.4 μs, two reflections from the inner and outer wall of the casing are shown, and at 142.1 μs, the reflection from the borehole wall is shown. The last event on the right is a multiple echo between casing and borehole wall. If the cased hole environment setting is selected, the system will be able to correctly identify the casing reflections and the borehole wall reflection in the acoustic trace of Fig. 6 and it will send only this information to the surface.

The ALTLogger allows the operator to activate two traveltime/amplitude image browsers, which are displayed in Fig. 6 above the acoustic trace. The two image tracks of the left browser represent traveltime to (narrow track) and reflection amplitude of the borehole wall. The browser on the right side gives the corresponding images of the casing. A fourth browser, which displays the traveltimes of one complete revolution of the acoustic head, is visible in front of the other browsers. In this borehole cross-section presentation, two traveltimes are shown. The hatched area in

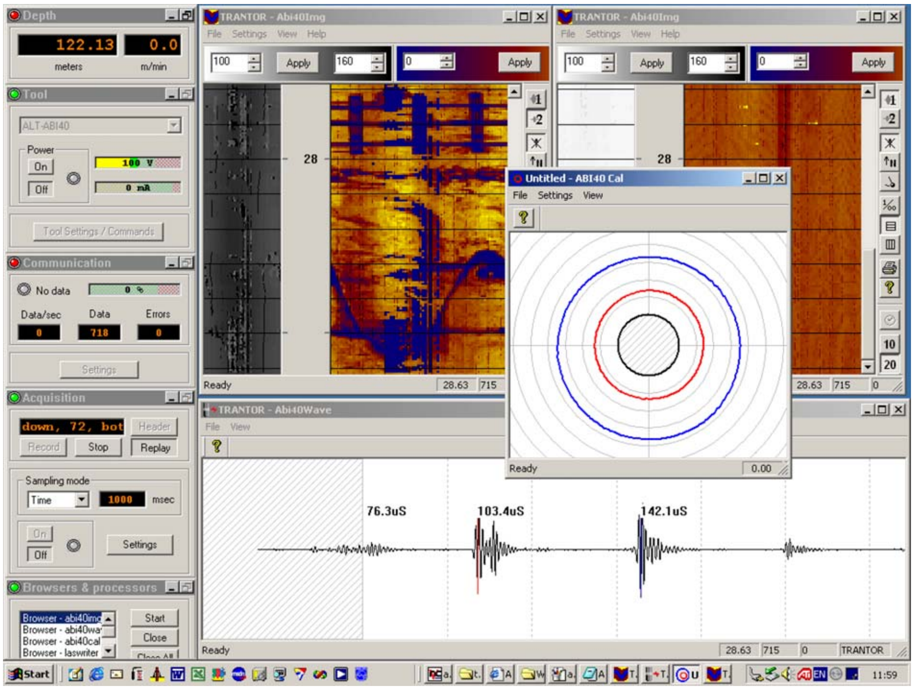

Fig. 6. Screen display of the ALTLogger surface unit during logging operation.

the center represents the tool. The red curve gives the distances between tool and casing, whereas the blue curve indicates the distances between tool and borehole wall respective between casing and borehole wall.

With all these data display browsers, the operator has excellent on-line control of tool performance. According to the tool philosophy as explained above, no further operator input is necessary to gain optimum results under varying borehole conditions.

3. Signal processing

Below, some of the signal processing algorithm will be described that could be implemented by a DSP-based tool.

3.1. Despiking and envelope

Pre-processing of the data prior to any signal detection process is most important for low amplitude reflected signals from the borehole wall. One problem is electronic noise, because practical field logging can impose some requirement on borehole tools, which make low noise performance difficult to obtain.

The trace in Fig. 7a was measured with the new ABI tool. In the right part of the trace, there is a weak, but still clearly visible borehole wall reflection. Due to digital devices as main sources of electronic noise, a despiking filter is appropriate to suppress this type of noise. The trace in Fig. 7b was produced applying first a simple and fast despiking filter, and subsequently a low pass filter.

The detection of reflection events can be simplified if the instantaneous amplitude or envelop of the trace is derived. The envelop is calculated from the Hilbert transform of the trace (Taner et al., 1979). The trace in Fig. 7c is the envelop of the trace in Fig. 7b. It is obvious that signal detection can be made more easily on this envelop trace.

3.2. Acoustic window reflection processing

Detection of the window reflections is no problem, because the approximate traveltime and amplitude are known and the window reflection is always the major echo from inside the tool. The identification of the acoustic window reflection is important within the concept of the new tool, because amplitude and traveltime of the acoustic window reflection are essential for tool diagnostic, calibration and prediction of coherent noise.

For diagnostics, one complete acoustic trace per revolution of the acoustic head is sent to the surface (Fig. 6). For example, the acoustic tool works properly as long as the acoustic window reflection stays the same under similar environmental condition. Small changes can occur in the borehole due to temperature and pressure changes, and due to mud conditions. If logs measured with different tools have

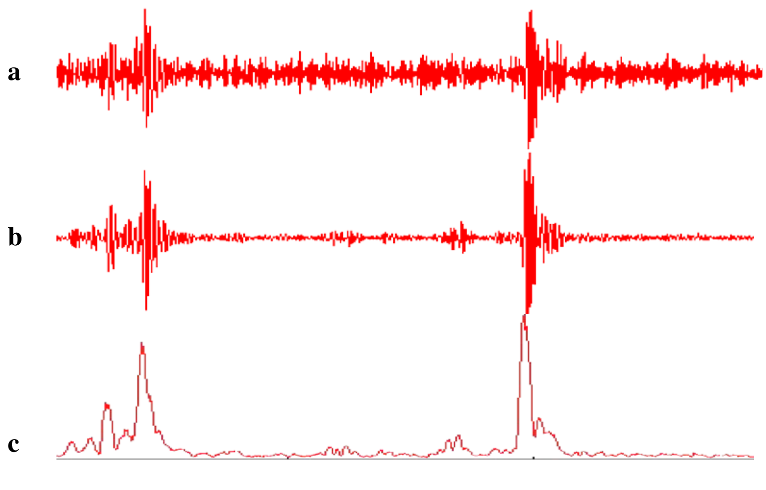

Fig. 7. Random noise filtering and envelope calculation. (a) Noisy trace, (b) trace 1 after filtering, (c) envelope of trace 2.

to be compared, the amplitude of the acoustic window reflection can be used for calibration.

The caliper measurement is no longer influenced by the traveltime of the acoustic signal inside the tool. The traveltime of the new tool is always related to the outside of the acoustic window.

Knowledge about the acoustic window reflection is most critical to remove coherent noise from the recorded acoustic trace such that echo from the borehole wall smaller than coherent noise signals can be detected.

3.3. Echo detection and identification

Predictive decomposition of the trace can be made based on amplitude and traveltime of the acoustic window reflection (Robinson, 1967; Peacock and Treitel, 1969; Hubral et al., 1980). This approach allows the new tool automated detection under a wide range of borehole condition. No settings have to be changed by the operator.

The way useful information is extracted from the acoustic trace will be explained with regard to the synthetic seismogram of Fig. 5. This trace is once again displayed in Fig. 8a. First, the trace is filtered and the envelop trace is calculated. In the second step, an echo detection process is applied. The result of this process is the trace, which is labelled "detected echo" (Fig. 8b). In a third step, the window reflection is identified and a predictive filter is constructed to calculate coherent noise echo (Fig. 8c). This trace together with a neural network approach (Murat and Rudman, 1992) is used to identify, in a fourth step, coherent noise signals (predicted echo) and useful echo. Output of this final step is a trace labelled "useful echo", which contains just the three reflections from the casing and the borehole wall. Only traveltimes and amplitudes of the three useful echoes are transmitted to the surface.

The detected and the predicted coherent noise signals must not correlate exactly as in this synthetic example. The neural network approach allows for some differences in amplitude and traveltime between detected and predicted events.

3.4. Detection of weak signals

Previous acoustic Televiewer tools had the problem that the dynamic range was limited by unavoidable electronic and acoustic noise. This is no longer the case with the real-time signal processing capabilities of the new ABI tool. To demonstrate this, first a synthetic seismogram without a borehole wall reflector was calculated. A short time interval around the acoustic window multiple reflection time is shown Fig. 9a.

The corresponding envelop trace is displayed in Fig. 9d. The main coherent noise echo is a multiple of the acoustic window (left arrow in Fig. 9d). Due to interfering reverberation inside the acoustic window, three additional events are detected and indicated by

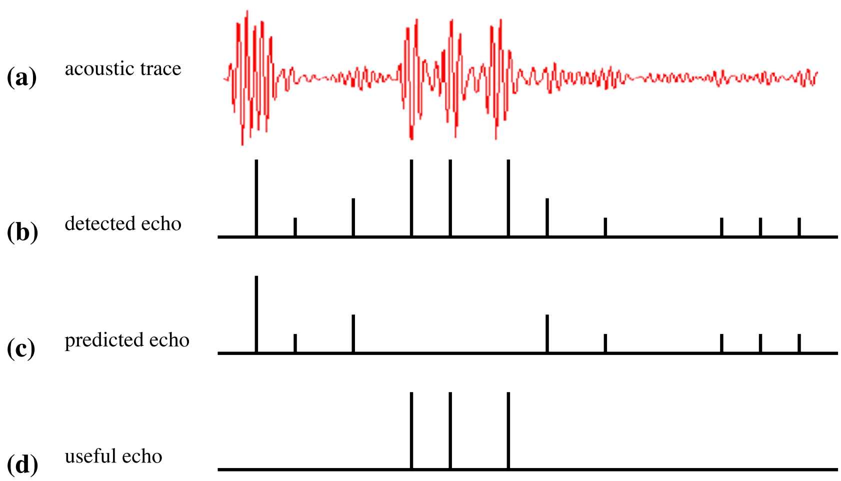

Fig. 8. Processing steps of echo detection (a, b) and identification (c, d).

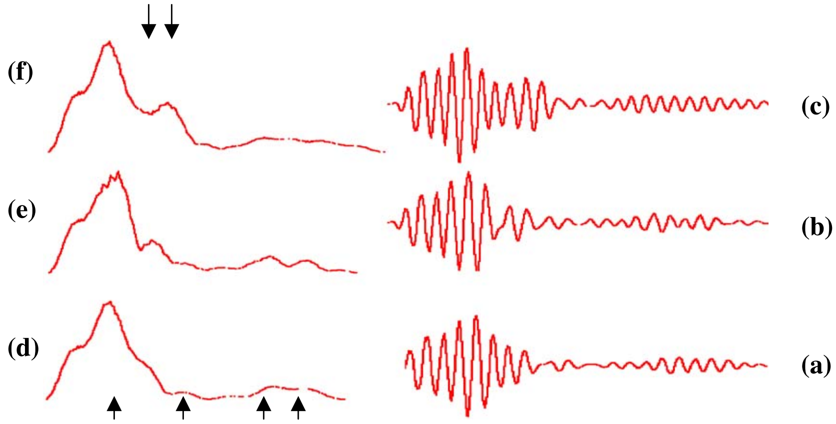

Fig. 9. Detection of very weak echo. (a, b, and c) Synthetic seismograms. (d, e, and f) Corresponding envelop traces. (d) Trace without borehole wall echo. The four arrows mark coherent noise echo. (e and f) The two traces show borehole wall echoes indicated by the two arrows on top.

arrows in Fig. 9d. The envelop in Fig. 9f was gained with a reflector close to the arrival time of the acoustic window multiple and an apparent reflection coefficient of 0.002. The reflection is recognized to be very weak, if the reflection energy is smaller than any neighbouring coherent noise energy. At another time along the acoustic trace, a very weak echo could be stronger or weaker. The very weak echo from the borehole wall is marked by the right arrow on top. The envelop in Fig. 9e was produced by moving the same reflector 2 ms closer to the main coherent noise event. This shifted reflection is marked by the left arrow on top. Application of the processing steps described above results in both cases in a unique identification of the weak borehole wall reflections. Theoretically, it would be possible to detect a very weak echo even if it interferes completely with the main coherent noise event. However, this would require too much processing effort.

4. Field examples

How PVC-casing becomes transparent to reveal most details of an open hole image, will be demonstrated by the results of test measurement with the new ABI40 tool. First, a measurement was made in an open borehole. Before the second log run in the same hole, a PVC-casing was inserted. To centralize the casing in the hole, fixed stand-offs were attached to the outside of the casing. As these stand-offs were not

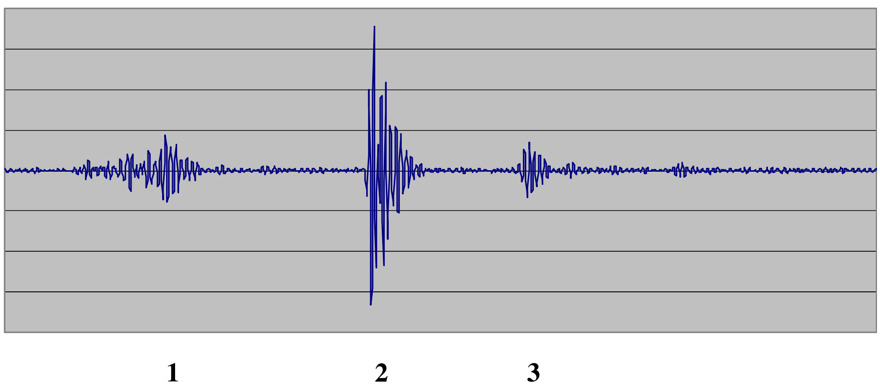

Fig. 10. Acoustic trace recorded in a cased hole.

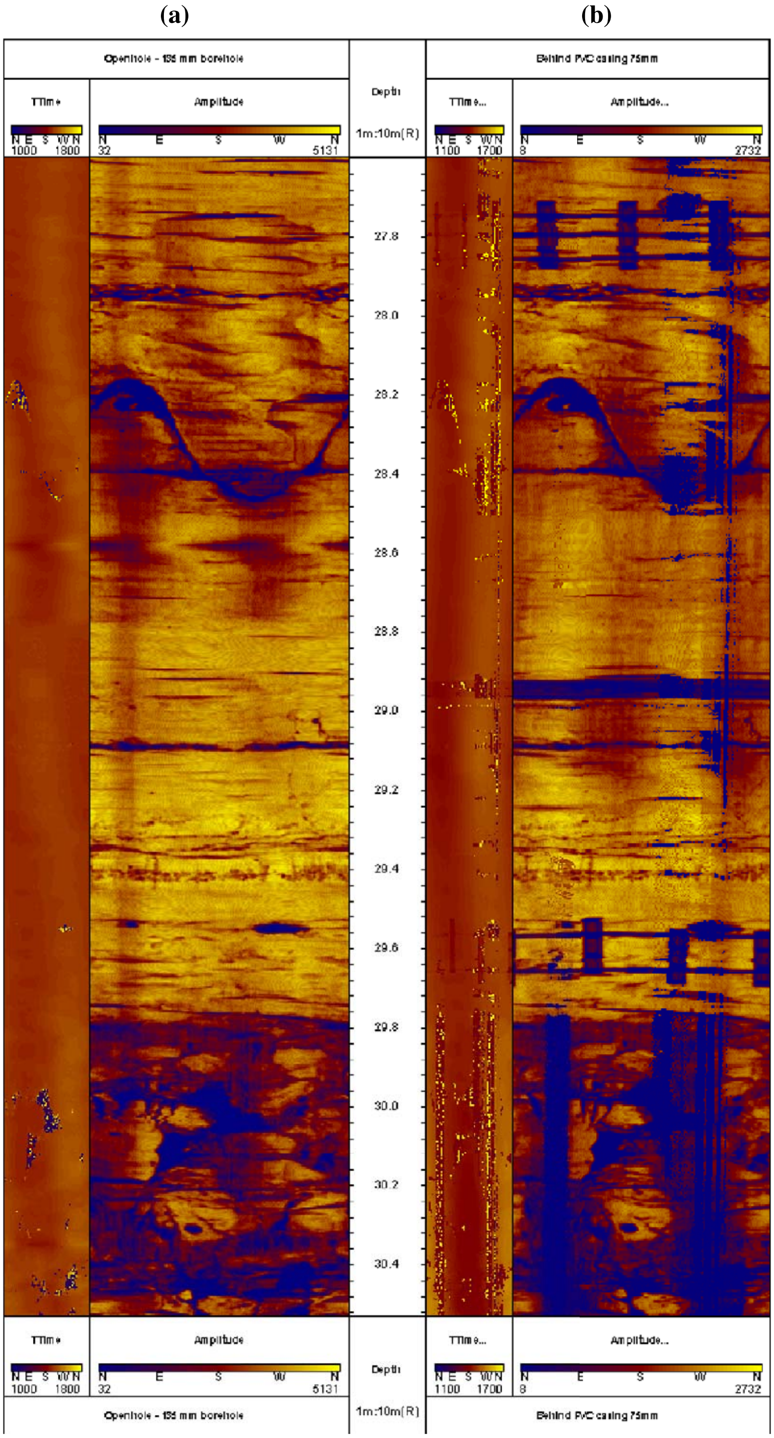

Fig. 11. Comparison of logging in (a) open hole and (b) trough casing.

elastic, centralization was poor in those intervals where the borehole diameter was enlarged. The second logging of the hole was made through casing. An acoustic trace recorded in the cased hole is shown in Fig. 10.

Shown in Fig. 10 from left to right is (1) first the echo from the acoustic window, (2) then a prominent double reflection from the inner and outer wall of the casing, and (3) finally a relatively weak echo from the borehole wall. The distance (time difference) between casing and borehole wall was about 30 mm. Therefore, the echo from casing and borehole wall are well separated. However, as explained above, detection of the borehole wall echo is possible even if the distance is much smaller. For weak reflections, the limit is around 5 mm.

An identical interval of 3 m for two log runs in the same hole is presented in Fig. 11. Fig. 11a shows traveltime (narrow track) and amplitude image of the log run in the open hole. The resulting measurement through casing (Fig. 11b) reproduces very well, in most areas, the image of the open hole log. The main differences are in the interval below 29.8 m, where vertical “stripping” due to decentralization is more severe in the cased hole log. Other differences are unavoidable effects of the pipe installation. The dark horizontal bar in the cased hole log at about 29 m (center) represents a joint between two PVC pipes. The three dark vertical bars at 27.8 m (top) and 29.6 m indicate the position of the attached stand-offs.

With respect to bedding planes, thin fractures and changes of acoustic impedances, nearly no information is missing in the cased hole log as compared to the open hole log.

A second field example demonstrates the capability of the ABI40 tool to measure casing thickness. In

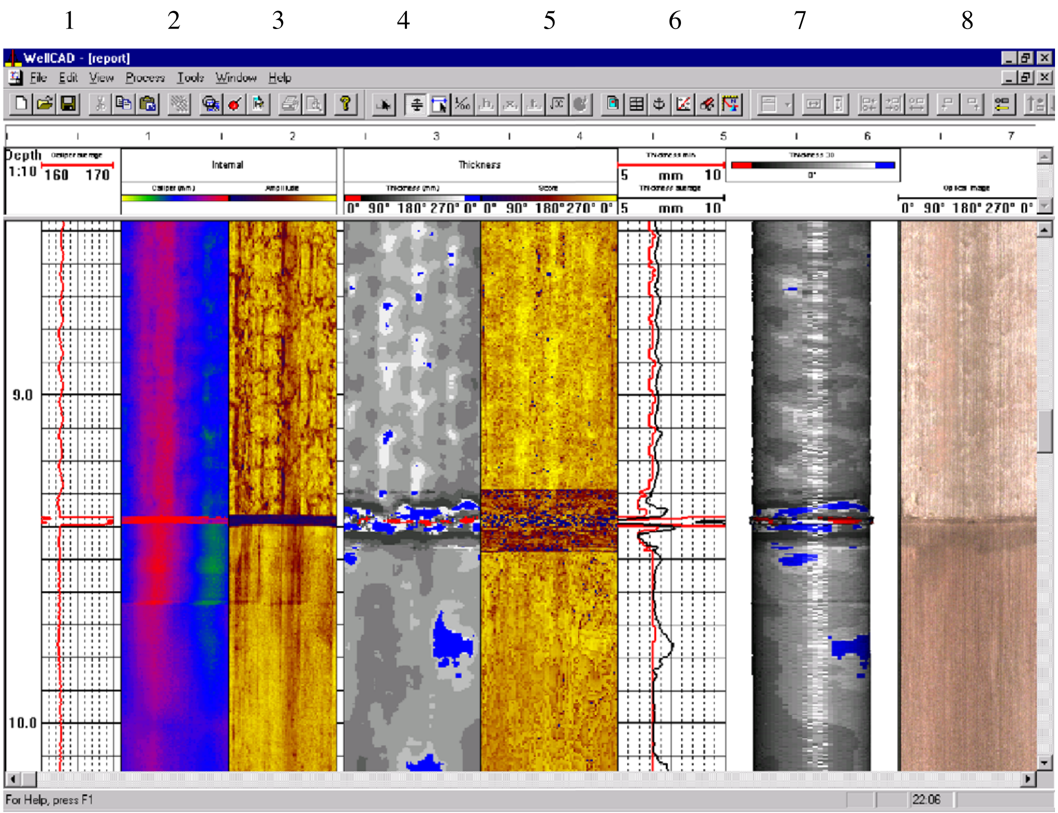

Fig. 12. Casing thickness determination. (1) Inner casing wall caliper, (2) inner casing wall traveltime image, (3) inner casing wall reflection amplitude, (4) casing thickness, (5) quality of casing thickness determination, (6) minimum casing thickness (red) and average casing thickness (black), (7) 3D-display of casing thickness, (8) optical image of inner casing wall.

this case, signals have to be detected which are separated only by a few microseconds. Fig. 12 shows the results of a casing thickness measurement in a short borehole interval where two casing pipes are screwed together. The inner caliper of the casing is 7 in. and nominal casing thickness is 6.7 mm. Track (1) displays the average caliper of the inner casing wall. Track (2) gives the traveltime of the inner casing wall and track (3) the amplitude image of the reflection from the inner casing wall. The increased caliper and traveltime, and the low amplitude in the central part of Fig. 12 indicate that the two pipes are not fully screwed together. It is clearly visible in the caliper track (1) and in the amplitude image (3) that wall of the upper pipe is rougher than the wall of the lower pipe. This is also visible in the optical image (8) of the inner casing wall.

The casing thickness image (4) shows mainly two grey levels, which correspond to thickness of 6.5 and 6.7 mm. The same information is shown as 3D-display (7). The blue patches in the casing thickness image are areas where the system has detected a multiple signal instead of the first reflection from the outer casing wall. The casing thickness determination process calculates also a quality score (5) of the reliability of the casing thickness value. This quality score image reveals very clearly the interval where the two pipes are screwed together. The most important information for casing inspection is given by the red curve (6) of minimum casing thickness which will indicate critical casing thickness due to inner or outer corrosion. The black curve of average casing thickness (6) is affected by the wrong determination at the blue area.

5. Conclusions

The new intelligent, software-driven technology of the ABI40 makes the tool easy to use, increases the dynamic range of the system, and gives optimum performance under a wide range of borehole conditions without any necessary intervention of an operator.

Moreover, problems like imaging through casing and casing thickness determination can be solved under the new tool concept.

As the tool is essentially software driven, future challenges and customer requirements can be met by pure software upgrades.

References

Broding, R.A., 1981. Volumetric scanning well logging. SPWLA 22nd Annual Logging Symposium, Mexico.

Hubral, P., Treitel, S., Gutowski, P.R., 1980. A sum auto-regressive formula for the reflection response. Geophysics 45, 1697–1705.

Murat, M.E., Rudman, A.J., 1992. Automated first arrival picking: a neural network approach. Geophysical Prospecting 40, 587–604.

Peacock, K.L., Treitel, S., 1969. Predictive deconvolution: theory and practice. Geophysics 26, 754–760.

Robinson, E.A., 1967. Statistical Communication and Detection. Griffin, London.

Schepers, R., 1991. Development of a new acoustic borehole imaging tool. Scientific Drilling 2, 203–214.

Schepers, R., Rafat, G., Gelbke, C., Lehmann, B., 2001. Application of borehole logging, core imaging and tomography to geotechnical exploration. International Journal of Rock Mechanics and Mining Sciences 38, 867–876.

Taner, M.T., Koehler, F., Sheriff, R.E., 1979. Complex seismic trace analysis. Geophysics 44, 1041–1063.