Development of a Single-Borehole Radar for Well Logging

Tingjun Li*, Haining Yang2, Qing Zhao3, Zheng-ou Zhou4

1,2,4 School of Electronic Engineering, University of Electronic Science and Technology of China, Chengdu, Sichuan, 611731, China, +86-028-61830770
3 School of Physical Electronics, University of Electronic Science and Technology of China, Chengdu, Sichuan, 610054, China, +86-028-83201385
*corresponding author, e-mail: tjli@uestc.edu.cn

Abstract

An impulse-based single-borehole radar prototype has been developed for well logging. The borehole radar is comprised of subsurface sonde and surface equipment. An armored 7-conductor well logging cable is used to connect subsurface sonde and surface equipment which is well compatible with the other well logging instruments. The performance experiments of the prototype have been conducted in a test field. The results show that the prototype system is capable of detecting the target which is 8 meters away from the borehole. This radar prototype has been employed in a real oil field well. Compared with conventional resistivity well logging tools, the prototype system provides comprehensive well-bore formation analysis information.

Keywords: single-borehole radar, well logging, armored multi-conductor well logging cable.

Copyright © 2012 Universitas Ahmad Dahlan. All rights reserved.

1. Introduction

Borehole radar technique has been widely used for decades in geosciences and remote sensing applications, such as mining, hydrology, engineering detection and archeology. It has the advantages of higher resolution and larger detection range over conventional borehole geophysical tools [1].

Borehole radar technique has been a worldwide popular issue in the field of remote sensing since the 1990s. Sixin Liu proved borehole radar capable of measuring the surrounding conductivity and dielectric constant at 60~90 MHz, even in a conductive formation [2]. Satoshi Ebihara from the Osaka Electro-Communication University proposed a method-of-moments (MoM) analysis including the borehole effects on cross borehole radar and investigated the influence of radar sonde eccentricity on a direct wave in a single-borehole radar [3-7]. Hannuree Jang from Pukyong National University studied the infiltration process in the vadose zone with cross-borehole radar and proposed inversion algorithm based on singular value decomposition (SVD) and maximum first-cycle amplitude to accurately determine the travel time of direct arrival [8, 9].

However, the study of borehole radar system, especially the single-borehole radar system in exploration field, is only at the initial stage worldwide [2, 10]. It sets higher demands for the radar performances for exploration at greater depths and more difficult environments.

An optical fiber is adopted in most conventional borehole radar systems [11-15]. However, it is difficult to meet the demands for well logging instruments, due to its poor tensile properties and small operating temperature range.

In this paper, we proposed a single-borehole impulse radar prototype for well logging. In our borehole radar prototype, an armored 7-conductor well logging cable is used to connect subsurface sonde and surface equipment which is well compatible with the other well logging instruments.

The performance experiments of borehole radar prototype were carried out in Dujiangyan, China. The experiment results showed that the prototype system was capable of detecting the target which was 8 meters away from the borehole.

The radar prototype also has been employed in a real oil exploration well located in Qingyang, China. The 2-D image of the subsurface structures of the well was displayed and the
radar echo energy along the depth was in good agreement with the results of conventional resistivity well logging tools.

The rest of this paper is organized as follows. The statement of the single-borehole radar prototype architecture is given in Section 2. The clutter reduction method adopted in the radar performance experiments is proposed in Section 3. The experimental measurements are described in Section 4. Lastly, conclusions are given in Section 5.

2. System

The block diagram of the single-borehole radar prototype is shown in Figure 1. The radar system consists of two main parts: surface equipment and subsurface sonde. Figure 2 shows the data transmitting and receiving unit of the surface equipment.

In the subsurface sonde, the pulse source produces a 800V-impulse signal. The pulse width is about 7 ns and its repeat frequency is 10 KHz. The pulse signal is applied to an dipole transmitting antenna (TA) and radiated into the medium around the borehole. The receiving antenna (RA) is also dipole antenna.

On account of the subsurface space limitations, the technique of interleaved sampling is adopted to adequately sample the echo in this borehole radar system. The effective sampling rate is up to 1GHz. The radar receiver consists of three-cascaded radio frequency (RF) amplifiers. This design has the advantages of gain-control and large dynamic range. The echo is amplified by the low noise amplifier (LNA) and held for about 100us by the sample-and-hold circuit in the receiver. Then the held signal is sampled by a 16-bit analog-to-digital converter (ADC) on the data acquisition board. The signal to noise ratio (SNR) of the system is enhanced through data stacking. The radar parameters are shown in Table 1.

The data transceiver, timing control, interleaved sampling and data stacking are all realized in a Field Programmable Gate Array (FPGA). The FPGA implementation saves the space resources in the subsurface system and makes the design flexible. Figure 3 shows the control unit and receiver of the subsurface sonde.
The subsurface diagram of the borehole radar prototype is illustrated in Figure 4. The subsurface sonde is set into a fiber glass reinforced plastics (FGRP) vessel. The FGRP vessel is water-resistant and high-pressure-resistant. A 1.2-meter-long spacer vessel is placed between the receiving unit and transmitting unit for insulation.

An armored 7-conductor well logging cable is used to connect subsurface sonde and surface equipment. The No.1 and No.4 cores of the 7-conductor cable are used for the prototype communication, and the No.3 and No.5 cores are adopted to supply the power. The No.2 and No.6 cores are used by the other well logging instruments, such as resistivity logging and nature gamma ray logging instruments.

Figure 5 depicts the borehole radar prototype mounted at the surface.

<table>
<thead>
<tr>
<th>Table 1. Radar parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pulse width</strong></td>
</tr>
<tr>
<td>7 nS</td>
</tr>
</tbody>
</table>

3. Clutter Reduction

To a considerable extent, the borehole radar performance depends on the conditions of the well. The well is drilled with mixtures as drilling mud, which is a very sticky and very conductive liquid. So the well is similar with a steel pipe, and the strong direct waves between transmitting and receiving antennas along the well wall impacted on the target signals recorded at the receiver. The direct waves are the main clutters, which will disturb the target echoes. In order to improve the signal-to-clutter (SCR) of the received signal, a clutter reduction method is adopted in our experiments. In this case, the borehole radar received signal at different depth $h$ can be represented as

$$r(t, h) = c(t, h) + s(t - \tau, h) + n(t, h)$$

(1)

Where $c(t, h)$ are the clutters, $s(t - \tau, h)$ are the target echoes we interested, $\tau$ is the delay time of the echoes, and $n(t, h)$ is the Gaussian noise at the receiver.
It should be noted that the major clutters were constant along depth due to the fact that the relative positions of the subsurface sonde and the well wall were not changed. So (1) may be rewritten as

\[ r(t, h) = c(t) + s(t - \tau, h) + n(t, h) \]  

(2)

In order to reduce the impact of the strong direct waves along the depth, a filter \( f \) is designed as

\[ f \left( r(t, h) \right) = r(t, h) - \overline{r}_h(t, h) \]  

(3)

Where \( \overline{r}_h(t, h) \) is the average value of the the received signal \( r(t, h) \) along the depth. With this filter \( f \), we are able to suppress the major clutters as follows

\[ R(t, h) = f \left( r(t, h) \right) = r(t, h) - \frac{1}{H} \sum_{h=1}^{H} r(t, h) = S(t - \tau, h) + n(t, h) \]  

(4)

Where \( S(t - \tau, h) \) is the target echo with clutter reduction. \( H \) is the maximal sampling depth.

4. Experimental Measurements

In this section, the performance experiments and the real oil field well experiments of the single-borehole radar prototype are described respectively.

4.1. Performance Experiments

The performance test field locates in Dujiangyan city of Sichuan province, China. And some target detection experiments have been conducted. Figure 6 shows the test configuration. The borehole is 25 meters deep and the diameter is about 0.1 meter. There is a cliff 8 meters away from the borehole which is about 30 meters high. The medium around the borehole is limestone with a relative dielectric constant \( \varepsilon = 8.9 \). So we can get the propagation velocity

\[ v = \frac{c}{\sqrt{\varepsilon}} = \frac{3 \times 10^8}{\sqrt{8.9}} = 1 \times 10^8 \text{ m/s} \]
During the experiment, a 2×4 m\(^2\) metal plate was placed close to the cliff as a target and it could move up and down along the cliff. The test field environment is complicated and there are many fractures around it. The target echo will be interfered by the clutters. In order to reduce the impact of the fracture clutters, we tested the borehole radar as follows. We adjusted the depth of the subsurface sonde to make the midpoint between TA and RA fixed at a depth of 5.5 meters. Then we moved the metal plate outside the cliff and sampled the echo signal in this process. The clutters were constant throughout the sampling process for the reason that the relative positions of the subsurface sonde and the fractures were not changed. With the data processing method mentioned in section 3, the images of one set of sampled data are shown in Figure 7. It is worth pointing out that the horizontal axis \(X\) in Figure 7 represents the distance to borehole and it is described as \(X = \frac{v}{2} \tau\).

As is shown in Figure 7 (a), many signals do not change along the depth of target. These components constitute the coupling signal between the TA and RA, and the clutters of the fractures around the borehole. Figure 7 (b) illustrates the image of sampled data with clutter reduction. The Stolt migration [16, 17] result is presented in Figure 7 (c). As is shown in Figure 7 (c), there is a relatively strong reflection signal at about 5.5 meters depth and 8 meters away from the borehole.

4.2. Oil Field Well Experiments

The real oil field well experiments were conducted in Qingyang city of Gansu province, China. The Jinghe No.44 oil field well was selected. During the experiment, the subsurface equipments were composed of resistivity logging tool, inclinometer and the borehole radar prototype. The armored 7-conductor well logging cable was shared by the three instruments. Figure 8 shows the test rig floor.

![Figure 8. The test rig floor](image)

As many other well, the Jinghe No.44 well is drilled with drilling mud. The parameters are shown in Table 2.

<table>
<thead>
<tr>
<th>Well Diameter</th>
<th>Well temperature</th>
<th>Conductivity of mud</th>
<th>Density of mud</th>
<th>Logging velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 m</td>
<td>45 °C</td>
<td>0.89 Ω m</td>
<td>1.08 g/cm(^3)</td>
<td>900 m/h</td>
</tr>
</tbody>
</table>
The images of one set of sampled data are shown in Figure 9. As is shown in Figure 9 (a), many signals do not change along the depth. These components are mainly the strong direct waves between transmitting and receiving antennas along the well wall.

Figure 9 (b) illustrates the data with clutter reduction. The clutters are suppressed effectively and the target echoes are shown. The right part of Figure 9 (b) illustrates the 2-D image of the subsurface structures of the well. The left part of Figure 9 (b) depicts the echo energy of the radar prototype and the result of resistivity well logging tool. The radar echo energy and the resistivity are normalized respectively. As is shown in Figure 9 (b), the resistivity at the depths of about 860 and 1440 meters is relatively high, which means that the dielectric loss of the medium is smaller and the radar echo energy is larger. The radar echo energy along the depth is in good agreement with the result of conventional resistivity well logging tool. The 2-D data of the prototype provides more well-bore formation analysis information.

5. Conclusion

An impulse-based single-borehole radar prototype for well logging was developed and the performance experiment of the prototype was conducted in a test field located in Dujiangyan, China. During the experimental measurements, we fixed the radar system and moved the target to collect the signal for reducing the impact of the fracture clutters. The results show that the prototype system is capable of detecting the target which is 8 meters away from the borehole.

This radar prototype also has been employed in a real oil exploration. An armored 7-conductor well logging cable is used to connect subsurface sonde and surface equipment in the prototype which is well compatible with the other well logging instruments. The radar echo energy along the depth agrees well with the result of conventional resistivity well logging tools. The 2-D image of the subsurface structures is displayed, which provides comprehensive well-bore formation analysis information. The test results show the application feasibility of single-borehole radar in petroleum exploration field.

Acknowledgements

This work was sponsored by the Technological innovation Foundation of North China Bureau of China Petrochemical Corporation.

References


