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Adaptive Filtering Processing for Target Signature Enhancement in Monostatic Borehole Radar Data

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Abstract

In B-scan data measured by a pulse-type monostatic borehole radar, target signatures are seriously obscured by two clutters that differ in orientation and intensity. The primary clutter appears as a nearly constant time delay, which is caused by internal ringing between antenna and transceiver in the radar system. The secondary clutter occurs as an oblique time delay due to the guided borehole wave along the logging cable of the radar antenna. This issue led us to perform adaptive filtering processing for orientation-based clutter removal. This letter describes adaptive filtering processing consisting of a combination of edge detection, data rotation, and eigenimage filtering. We show that the hyperbolic signatures of a dormant air-filled tunnel target can be more distinctly enhanced by applying the proposed approach to the B-scan data, which are measured in a well-suited test site for underground tunnel detection.

Key Words: Adaptive Filtering, Clutter Removal, Monostatic Borehole Radar, Target Signature.

Ⅰ. INTRODUCTION

Borehole radar systems have been widely used for anomaly detection and geophysical exploration in deep subsurface [1, 2]. In a single borehole, a bistatic borehole radar may detect underground targets in any direction but it requires a sufficiently long separation to reduce direct coupling between the transmitting and receiving antennas. One alternative configuration could be a monostatic borehole radar with a single antenna and an embedded transceiver module. For a pulse-type monostatic borehole radar, target signatures within B-scan data may be obscured by two clutters with different orientation and intensity. As dominant components, primary clutters are caused by internal ringing between the antenna and the transceiver module in the radar and are distributed as a nearly constant time delay in the data. Secondary clutters result from cable-guided borehole waves and give rise to obliquely time-delayed patterns in the data. Generally, conventional clutter reduction techniques are based on the row and column data organization, and the primary clutters can be easily removed from the raw data [2–5]. However, the secondary clutters with different orientations still remain in the data. This letter provides a solution to this problem by proposing a clutter-orientation-based adaptive filtering technique. This filtering technique consists of a combination of edge detection, data rotation, and eigenimage filtering. We show that use of this technique with real B-scan data can remove both primary and secondary clutters, and provides sufficient enhancement of the target signatures.

Ⅱ. ADAPTIVE FILTERING PROCESSING TECHNIQUE IN MONOSTATIC BOREHOLE RADAR DATA

In monostatic borehole radar data, the received electro-

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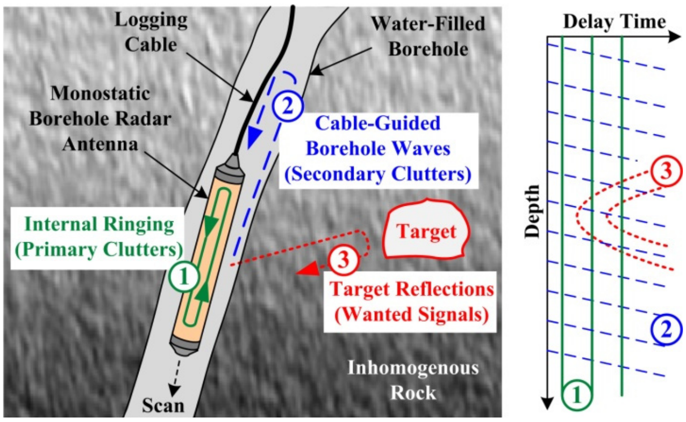


(a) (b)

Fig. 1. Conceptual view of monostatic borehole radar data. (a) Received components of electromagnetic waves at an arbitrary depth and (b) corresponding patterns in B-scan data.

magnetic waves consist of primary clutters caused by internal ringing reflections from both the antenna and the transceiver module, and secondary clutters due to cable-guided borehole wave reflections and target reflections, as shown in Fig. 1. In the case of a pulse-type monostatic borehole radar, primary and secondary clutters have constant and obliquely time-delayed patterns, respectively, as shown in Fig. 1(b). Clutter echoes are greater than localized target echoes, so the hyperbolic signatures of the targets are seriously obscured by these clutters. Thus, many publications describe how clutter reduction and target signature enhancement both present challenges for the development of additional signal processing techniques [2–5]. As shown in Fig. 1, we use the different properties of the two clutters and target signatures as a basis for clutter-orientation-based adaptive filtering.

First, an orientation angle of clutters may be determined by employing edge detection techniques in digital image processing. Second, the B-scan data are rotated by means of the orientation angle. We use standard left-handed 2-D Cartesian coordinates, and employ a delay time t directed to the right and a depth z directed downward. Thus, the rotation from the coordinates (t,z) to a new coordinate (t',z') is given by

$$\begin{bmatrix} t' \\ z' \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} t \\ z \end{bmatrix}, \tag{1}$$

where θ is the rotation angle. For a positive θ, the direction of the rotation is clockwise. In contrast, if θ is negative, the rotation becomes counterclockwise. Thus, the raw data matrix $B(t,z)$ with M by N is transformed to the rotated data matrix $B_{rot}(t',z')$ by means of the orientation angle θ. Third, as an eigenimage filtering scheme, the singular value decomposition approach [3] is employed for separating clutters from the rotated data. The rotated data $B_{rot}(t',z')$ can be decomposed as

$$B_{rot}(t',z') = \sum_{i=1}^{N} E_i(t',z') = \sum_{i=1}^{N} \sigma_i u_i v_i^T, \tag{2}$$

where E_i is the ith weighted eigenimage. u_i is the ith left eigenvector of B^TB and v_i is the ith right eigenvector of BB^T. The subscript T indicates the transpose operation. σ_i is the ith singular value, which is the positive squared root of the eigenvalues of B^TB or BB^T. Dominant clutters are approximated to a set of low-rank eigenimages as

$$C(t',z') \approx \sum_{i=1}^{r} E_i(t',z'),\ 1 \le r \le N, \tag{3}$$

where r is the filtering rank, which is easily determined by singular value analysis. As the low-rank eigenimage filtering of dominant clutters, a clutter removal process is written by

$$B_{rot}^{LR}(t',z') \approx B_{rot}(t',z') - C(t',z'). \tag{4}$$

Finally, through re-rotation of Eqs. (3) and (4), clutters and target signatures can be extracted from the B-scan data. In the case of θ=0 or 90°, since the rotation-based eigenimage filtering is consistent with conventional eigenimage filtering [3], the data rotation process is not required. If an arbitrary orientation of other clutters exists, data rotation and eigenimage filtering should be performed as a function of clutter orientation angle.

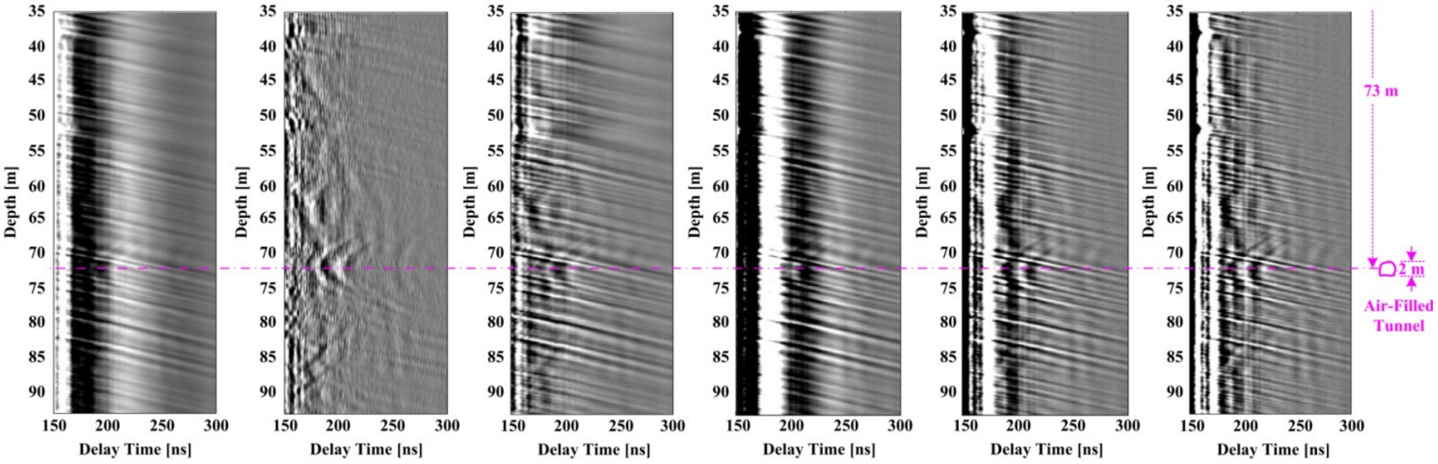
III. COMPARISON RESULTS

Fig. 2(a) shows the B-scan data measured in a well-suited test site for air-filled tunnel detection using a self-designed monostatic borehole radar system. Up to about 250 ns, constant time-delayed patterns result from primary clutters. Throughout the depth range, obliquely time-delayed patterns are widely distributed as secondary clutters. The hyperbolic signatures of the tunnel target are seriously obscured by both clutters.

For validation, we applied the proposed filtering technique to the raw data in Fig. 2(a). As shown in Fig. 2(b), the hyperbolas of the tunnel target at a depth of 73 m are clearly seen. This means that the proposed filtering provides target signature enhancement as well as sufficient reduction of both primary and secondary clutters. For comparison with existing approaches, we also apply background removal filtering [2, 5] and high-pass filtering [2] to the raw data. As shown in Fig. 2(c)–(f), although the target signatures are slightly visible at the depth of 73 m, these signatures are seriously blurred by primary and secondary clutters. Thus, when compared with existing approaches, the proposed technique provides sufficient clutter reduction and target signature enhancement.

IV. CONCLUSION

The B-scan data of our pulse-type monostatic borehole radar were subjected to adaptive filtering processing for clutter



(a) (b) (c) (d) (e) (f)

Fig. 2. Comparison results. (a) Raw data, (b) proposed adaptive filtering, and conventional approaches, such as (c) background removal filtering [2, 5], and high-pass filtering [2] with cutoff frequencies of (d) 20 MHz, (e) 30 MHz and (f) 40 MHz.

reduction and target signature enhancement. The B-scan raw data measured in a well-suited test site for air-filled tunnel detection showed that the hyperbolic signatures of a tunnel target are severely obscured by two clutters with different orientations. The clutters are caused by internal ringing and cable-guided borehole waves. The differences in orientation and intensity properties between two clutters become the basis for clutter-orientation-based adaptive filtering. We show that both clutter reduction and target signature enhancement can be achieved through the proposed adaptive filtering.

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