Postprint: Detection Depth of Time-Domain Impulse Radar Based on Correlation Coefficient Method

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Abstract

Time-domain impulse radar is widely employed in Earth exploration, lunar and deep space exploration, among other fields. Investigating radar detection depth facilitates analyzing whether targets fall within the radar' s detection range. Conventional calculation methods predominantly rely on the classical radar transmission equation, necessitating a priori assumptions regarding subsurface medium structure and properties during practical computation to derive theoretical penetration depth. To surmount the limitations of traditional detection depth calculation approaches, this study proposes a novel computational method that eliminates the need for prior assumptions about the detection medium. This method derives radar detection depth directly from measured radar data by computing correlations within the radar data. Two specific computational approaches are presented: one incorporating wavelet formulation and another utilizing trace correlation formulation. Both methods are elaborated upon, and their efficacy in calculating radar penetration depth is validated through simulations. Additionally, the limitations inherent to these two computational methods are analyzed. This research provides a solution for subsequent processing of time-domain impulse radar penetration depth issues.

Full Text

Research on Detection Depth of Time-Domain Pulse Radar Based on Correlation Coefficient Method

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Abstract

Time-domain pulse radar is widely used in Earth exploration, lunar exploration, and deep space missions. Understanding radar detection depth is essential for determining whether targets fall within the instrument' s effective range. Traditional calculation methods rely primarily on the classical radar transmission equation, which requires prior assumptions about subsurface structure and medium properties to estimate theoretical penetration depth. To overcome these limitations, this paper proposes a novel approach that requires no prior assumptions about the 探测 medium. Instead, it calculates radar detection depth directly from measured radar data by analyzing correlations between data traces. Two specific implementations are presented: a wavelet-based method and a trace-correlation method. Both approaches are described in detail, and their effectiveness for calculating radar penetration depth is validated through simulations. The limitations of each method are also analyzed. This research provides practical solutions for processing time-domain pulse radar penetration depth in subsequent studies.

Keywords: Radio astronomy; Ground Penetrating Radar; Penetration depth; Correlation coefficient method

Introduction

Time-domain pulse radar offers rapid, high-resolution imaging and serves as a widely applied shallow electromagnetic 探测 technique. It finds extensive use in engineering and environmental geophysics, quality inspection, hydrogeological surveys, and planetary exploration. The lunar penetrating radar onboard the Chang' e-3 rover operates on time-domain pulse principles with scientific objectives to measure lunar regolith thickness and characterize subsurface structure. Preliminary results from Chang' e-3 radar data processing have been reported in the literature. The radar transmits high-frequency electromagnetic pulses that propagate through subsurface media. Electrical parameter variations affect the amplitude, waveform, and frequency characteristics of these waves, allowing inference of subsurface structure and dielectric properties from received echoes. A critical practical question concerns the maximum detection depth: whether targets reside within the radar' s effective range and whether identified features represent valid signals rather than noise. Traditional depth estimation methods require predicting subsurface layering and physical properties, then applying classical radar transmission equations. These approaches yield only theoretical estimates due to their reliance on prior assumptions without incorporating actual radar measurements.

This paper proposes a correlation coefficient method to determine the limit of radar detection depth directly from measured data without subsurface assumptions. The method identifies the boundary between the last useful echo signal and noise. Below this boundary, signal components are dominated by noise. While some weak signals may exist, their correlation is corrupted by noise, making them undetectable by this method (though other signal processing techniques might extract them under specific constraints). Two computational approaches are introduced: a wavelet method and a trace-correlation method.

Correlation Coefficient Methods

This section presents two correlation-based methods for calculating radar detection depth limits.

Wavelet Method

The wavelet method requires prior measurement or estimation of the radar source wavelet. Its theoretical basis is that reflected signals exhibit high correlation with the wavelet, while noise shows low correlation. The last high-correlation signal position in the correlation matrix indicates the detection depth limit. Wavelet acquisition can be performed through simulation or direct measurement. In simulation, transmitter and receiver antennas are placed in free space with fixed separation and absorbing boundaries; the received waveform serves as the wavelet. For measurement, this can be done in an anechoic chamber or open field without reflective objects. Alternatively, wavelets can be extracted from measured data using established techniques.

Let the wavelet $wlet$ have length n. The calculation procedure is as follows:

1. The measured radar data $data$ contains m traces, each with n_{data} samples.
2. Define processing intervals x_i for each sample point, sized to match the wavelet width:

$$x_i = \begin{cases} data[j][i:i+n] & \text{if } i \leq n_{data} - n + 1 \\ data[j][i:n_{data}] & \text{otherwise} \end{cases}$$

   where i is the sample index and j is the trace index.
3. Compute the wavelet mean $wlet'$ and interval means x_i':

$$wlet' = \frac{1}{n}\sum_{k=1}^{n} wlet_k$$

$$x_i' = \frac{1}{n}\sum_{k=1}^{n} x_{i,k}$$

4. Calculate correlation coefficients:

$$C_{j,i} = \frac{\sum_{k=1}^{n}(wlet_k - wlet')(x_{i,k} - x_i')}{\sqrt{\sum_{k=1}^{n}(wlet_k - wlet')^2 \sum_{k=1}^{n}(x_{i,k} - x_i')^2}}$$

5. Iterate through all sample points and traces to obtain correlation matrix C.
6. In each column of C, locate the position of the last high-correlation pulse to determine the detection depth limit.

Trace Correlation Method

Unlike the wavelet method, trace correlation requires no wavelet extraction. It exploits the fact that adjacent radar traces sample similar subsurface structures, so useful reflections exhibit high inter-trace correlation while random noise does not. The method identifies the signal-noise boundary using this correlation difference.

The calculation steps mirror the wavelet method but correlate adjacent traces rather than a wavelet. The processing interval should exceed one wavelet width to ensure complete reflection signals are captured. The specific procedure is:

1. Define correlation intervals for each sample point, typically larger than one wavelet width.
2. Compute interval means for each sample position.
3. Calculate correlation coefficients between adjacent traces:

$$C_{j,i} = \frac{\sum_{k=1}^{n}(x_{j,i,k} - x'_{j,i})(x_{j+1,i,k} - x'_{j+1,i})}{\sqrt{\sum_{k=1}^{n}(x_{j,i,k} - x'_{j,i})^2 \sum_{k=1}^{n}(x_{j+1,i,k} - x'_{j+1,i})^2}}$$

4. Generate the correlation matrix and identify the last high-correlation pulse position.

Simulation Validation

A simulation model validates both methods. The process involves: (1) constructing an electromagnetic propagation model, (2) setting a minimum detectable amplitude threshold (signals below this are considered noise), (3) calculating the theoretical detection depth, and (4) comparing it with depths estimated by both methods.

The model configuration [Figure 1: see original paper] simulates a 2 m × 5 m multilayer medium with air at the surface. Relative permittivity increases with depth: 2.9, 5, 10, 13, 17, 21, 25, 30. The antenna system includes one transmitter and two receivers separated by 10 cm, positioned 40 cm above the surface. A Ricker wavelet with 400 MHz center frequency excites the system. The ideal single-trace waveform [Figure 2: see original paper] shows clear reflections from each layer.

In practice, receivers have minimum detectable power. For Antenna A, the threshold is set such that signals below this amplitude are dominated by Gaussian noise. The entire time window contains zero-mean Gaussian white noise. With this threshold, Antenna A detects only the first four reflections, while Antenna B (with a lower threshold) detects the first six. The modified waveforms [Figure 3: see original paper] show these realistic conditions.

Results

Using the wavelet method, the source wavelet is obtained from a free-space simulation [Figure 4: see original paper] with matching antenna separation and absorbing boundaries. The resulting correlation coefficient profiles [Figure 6: see original paper] show enhanced layer identification. The last correlation trough indicates detection depths of 3.511 m for Antenna A and 4.685 m for Antenna B.

The trace-correlation method [Figure 7: see original paper] yields depths of 3.511 m for Antenna A and 4.685 m for Antenna B, with processing intervals exceeding one wavelet width. Both methods amplify useful signals while suppressing noise, making the last useful signal easier to identify than in raw data. For complex, overlapping signals, auxiliary techniques like first-derivative extrema detection or statistical thresholding may be needed.

[Figure 5: see original paper] compares actual versus calculated depths. Trace correlation shows less than 0.27% error for Antenna B and 0.45% for Antenna A. Wavelet method errors are 0.25% for Antenna A and 0.51% for Antenna B. Both methods accurately determine detection depth, though trace correlation performs slightly better. Discrepancies likely arise from simulation artifacts and strong Gaussian noise.

Discussion

The correlation coefficient methods effectively infer radar detection limits. The wavelet method requires accurate wavelet estimation; inaccuracies can affect results. It works best for simple, layered geology where reflections preserve waveform shape. Complex structures with multiple reflections degrade its performance.

The trace-correlation method relies solely on measured data, exploiting high inter-trace correlation of useful signals versus random noise correlation. It performs well even for complex structures since it doesn' t require waveform preservation. However, both methods identify only the last *detectable* useful signal; signals buried in noise with correlation destroyed are beyond this scope.

Conclusion

This paper addresses limitations of traditional radar depth calculation by proposing two correlation-based methods. When the source wavelet is known and geology is simple, the wavelet method is suitable. For complex structures or unknown wavelets, trace correlation is preferable. Simulations validate both approaches. Future work should incorporate additional factors like signal waveform characteristics and equipment status when processing real radar data.

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