Submission code: X0B4G5WQ0Q

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Diffraction-Based Velocity Estimation for GPR Data Migration

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Abstract

This study presents a methodological approach for Ground Penetrating Radar (GPR) data processing, integrating Plane Wave Destruction (PWD) and Residual Diffraction Moveout (RDM) for diffraction detection, velocity modeling, and data migration. Analyzing diffractions makes it possible to estimate the medium's velocity distribution, which is key to enhancing image resolution and correcting distortions. The method was validated with synthetic data and applied to real GPR data from a glacial region. Results show that this diffraction-based approach yields more accurate velocity models than traditional reflection-based techniques, underscoring its potential for detailed subsurface characterization.

Introduction

Ground Penetrating Radar (GPR) interpretation relies on accurate velocity models due to the dependence of electromagnetic wave propagation on dielectric permittivity. Since data are acquired in the time domain, converting to depth is complex. Diffractions, produced by small-scale features, offer valuable velocity information distinct from reflections. Traditional velocity estimation via CMP focuses on horizontal reflectors but is limited in heterogeneous or irregular media. Migration techniques, such as Kirchhoff and frequency-domain methods, reposition reflectors and enhance resolution. In varying-velocity models, remigration is often applied. Diffractions, usually considered noise, can instead aid in velocity modeling due to their independence from layer continuity.

Despite their potential, diffraction-based methods remain underexplored (Figueiredo et al., 2011). This study proposes a methodology combining Plane Wave Destruction (PWD) for diffraction separation and Residual Diffraction Moveout (RDM) for velocity estimation. The resulting model is used for Kirchhoff migration and compared to the 1D CMP-derived model from Travassos et al. (2018). Adapted from seismic applications (Coimbra et al., 2013; Collazos et al., 2014), the method is validated with synthetic data and applied to real GPR data from the Antarctic Peninsula, enabling the evaluation of its performance in mapping subglacial structures and firn-related environmental processes.

Methodology

Diffraction Separation Using Plane Wave Destruction (PWD)

Plane Wave Destruction (PWD) is a directional differentiation technique that attenuates coherent reflections and enhances diffracted events based on the local slope of the events (Claerbout, 1992; Fomel, 2002; Schleicher et al., 2009).

The application of PWD facilitates the identification of diffractors in heterogeneous media, where conventional methods fail. By enhancing diffraction hyperbolae, PWD makes velocity analysis via RDM more effective, contributing to more accurate migration and structural interpretation (Trorey, 1977; Zakarewicz et al., 2024).

Velocity Estimation with Residual Diffraction Moveout (RDM)

Residual Diffraction Moveout (RDM) is used to estimate velocity models by iteratively remigrating diffracted events initially isolated via Plane Wave Destruction (PWD) and minimizing their residual curvature (Coimbra et al., 2013; Collazos et al., 2014). Over or undermigrated shapes indicate velocity errors, which are corrected until event collapse indicates proper migration.

This refinement is guided by equations such as Huygens remigration formula (Hubral et al., 1996) and modeled via image wavefield equations linking spatial variation to migration velocity (Schleicher et al., 2004). The resulting RMS model is converted to interval velocities through depth integration, yielding higher accuracy than traditional methods like the Dix Equation. RDM thus enables the construction of detailed velocity models and improved migrated images without requiring a predefined velocity model (Coimbra et al., 2011).

Results

A synthetic model was developed with multiple layers, inclined interfaces, and distributed diffractors, simulating a complex geological medium with dielectric variations. Diffractions generated by air-filled spheres represented heterogeneities such as fractures and buried objects. The proposed methodology involved applying the Plane Wave Destruction (PWD) filter to attenuate horizontal reflections and enhance diffractions, followed by manually picking hyperbolae. The Residual Diffraction Moveout (RDM) method was then applied to estimate local velocities and construct a 2D velocity model. Using this model, the data were migrated, allowing for accurate interface reconstruction and efficient diffraction collapse. This workflow was applied to both the synthetic model and a real dataset, as shown in Figure 1a–d, with the objective of validating the approach before applying it to more complex scenarios.

Application to Real Data from the Antarctic Peninsula

The methodology was applied to real data acquired by Travassos et al. (2018) during the 2007/2008 expedition to the Antarctic Peninsula, using 100 MHz antennas and GPS positioning. A radargram with a reduced time window of 1500 ns was selected to mitigate noise at greater depths. The firn–ice interface was identified at approximately 135 m depth. A subset of the data was extracted to facilitate better visualization and application of the methodology, with processing performed within the 100–250 ns window along a 300-meter profile, isolating relevant diffractions. This application is illustrated in Figures 1e–h.

Estimated velocities ranged from 0.22 m/ns in shallower zones to 0.17 m/ns at greater depths, consistent with typical values for compacted firn and ice. Migration using the estimated model (Figure 1g) enabled effective collapse of hyperbolae and improved internal structural definition, clearly delineating the firn–ice transition. Additionally, zones associated with recrystallization and local environmental effects, such as melting and seasonal redistribution, were identified, as illustrated in Figure 1i. These results confirm the effectiveness of the proposed methodology for characterizing complex glacial environments.

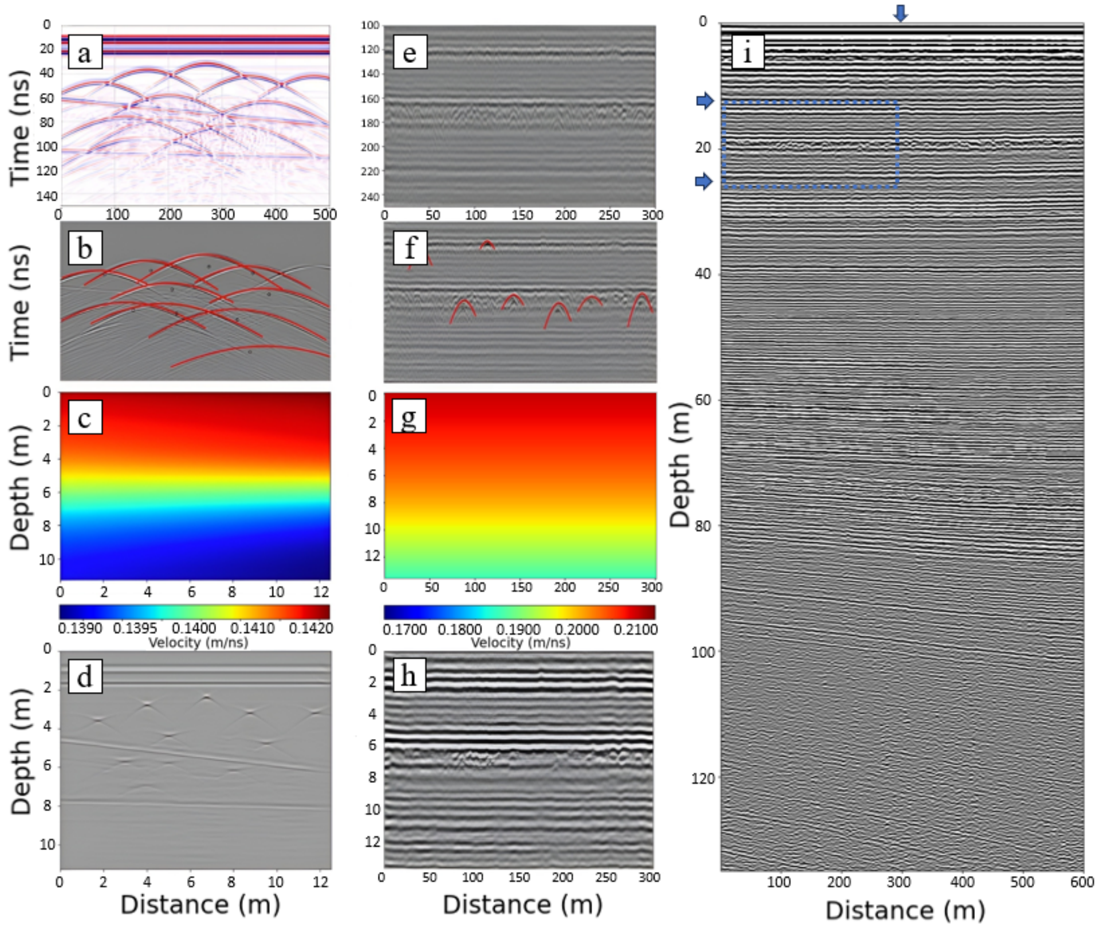

Figure 1: Workflow of the proposed methodology applied to two datasets: a synthetic model (left) and real data from the Antarctic Peninsula extracted from Travassos et al. (2018) (right). (a) Synthetic dataset used for validation; (b) Application of the PWD filter and RDM hyperbola picking; (c) Estimated velocity model; (d) Migrated synthetic section; (e) Cropped real dataset; (f) PWD application and RDM hyperbola selection; (g) Velocity model estimated for the real data; (h) Migrated real section; (i) Complete real dataset after 2D migration using the estimated velocity model. The blue arrows and the rectangular marking indicate where the original data was cropped.

Conclusion

This study presents a methodology for velocity estimation in GPR data based on diffraction separation using the Plane Wave Destruction (PWD) filter and model refinement through the Residual Diffraction Moveout (RDM) method. The approach enabled the identification of diffracted events and constructing detailed velocity models, significantly improving Kirchhoff migration results. It also demonstrated greater sensitivity to local geological variations, enhancing resolution in complex environments such as Antarctic firn. Although effective, the methodology has some limitations, including dependence on the quality of PWD, the noise sensitivity of RDM, and the need for manual hyperbola picking factors that suggest directions for future improvements through automation and integration with other geophysical techniques. Its adaptability makes the approach suitable for various applications, from glacial to urban and archaeological settings, supporting more accurate geological interpretations.

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