Title: GPR data migration velocity estimation using a local diffraction multi-focusing criterion

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Summary

We use constant velocity migration of Ground Penetrating radar (GPR) sections over a predefined range of migration velocities for the validation of diffraction focusing, using local slopes distribution, with the scope to estimate a migration velocity model. We avoid the user dependent diffraction analysis to circumvent subjectivity and use overlapping x-t windows to retrieve diffraction focusing validation for the entire dataset. The estimated migration velocity is utilized as an attribute whose sensitivity in water variation saturation is tested as a complementary method to the Electrical Resistivity Tomography (ERT) method for the assessment of soil moisture.

Introduction

Velocity analysis is crucial for effective migration of Ground Penetrating Radar (GPR) data and thus imaging of the subsurface. This involves the challenging task of building an appropriate migration velocity model. Velocity estimation requires multi offset GPR data rich in reflection events as well as a dense network of CMP locations. Since this setup is not the standard, an alternative is to apply hyperbola analysis techniques (Dou et al. 2017), which except from time consuming includes subjectivity and dependence of diffractions density within the section. To reduce user interference and create a migration velocity model with relatively high accuracy, several researchers have utilized sequential constant velocity migrations in order to study the behaviour of the diffractions and conclude to the most diffraction focused results (Novais et al., 2008; Clair and Holbrook, 2017; Li and Zhang, 2021). Other researchers have avoided building velocity models, by adapting a constant-velocity time migration-based strategy for diffractions focusing and applying multipath weighted summation (Economou et al. 2020; Hamdan et al. 2020).

Migration velocity, except from effectively migrating a GPR section, can be treated as an attribute since velocity of electromagnetic waves is directly associated with dielectric permittivity which in its turn, can be used as an indicator of water saturation, especially at time lapse approaches. Interval velocity values could be directly transformed to dielectric permittivity values, if a low loss approximation is used.

Here, we propose a local multi-focusing criterion technique in order to estimate migration velocity and provide an attribute with the scope to integrate it with electrical resistivity values and test its sensitivity to water saturation variation. The implementation utilizes constant-velocity time migration and a window-based diffraction focusing estimator from local slopes of the entire dataset in an effort to establish an attribute which provides insight of the local distribution of migration velocities.

Method

Even though the hyperbola branches of GPR data diffractions are sensitive to the migration velocity model, their apices remain stationary. To evaluate the behaviour of hyperbola branches we apply sequential constant-velocity migrations and estimate the local slopes using a 4-point filter and triangular weighted time and space filtering, as firstly proposed by Claerbout (2004), using the local plane-wave equation:

$$\frac{\partial P}{\partial x} + \sigma \frac{\partial P}{\partial t} = 0 \qquad (1)$$

where P is the wavefield, σ is the local slope and x and t are the space and time variables. Local slopes can also be used for the application of Plane Wave destruction (PWD) method (Claerbout, 2004; Fomel, 2002).

The estimation of the global standard deviation (SD) values of the local slopes distribution for each constant velocity migrated section can be used as a focusing attribute (Economou et al. 2020). Sections with unfocused diffractions are expected to have higher SD values of the local slopes distribution in comparison with efficiently migrated sections. Here, we use the local SD values to estimate local migration velocity. This implement involves the following processing steps:

1. Constant-velocity time migration of the GPR data using a range of velocity values between 0.04m/ns and 0.24 m/ns with 0.005 m/ns step.
2. Estimation of local slopes sections for each constant velocity time migrated section.
3. Estimation of the SD values of local slopes within the x-v-t cube in x-t windows for each migration velocity value.
4. Assignment of the highest inverse SD value for each x-t window to the corresponding migration velocity.

5. Migration velocity image generation whose axes denote the window coordinates (e.g. x-t coordinates of its center).

Synthetic example

A synthetic example was created with the use of the frequency - wavenumber modeling approach of Bitri and Grandjean (1998). We simulated propagation in a three-layered subsurface structure with lateral and depth extent of 5 m and 1 m respectively. The structure's dielectric layers were set to be characterized by 0.07 m/ns, 0.11m/ns and 0.07 m/ns EM velocity. Time and space intervals were set to 0.0312 ns and 0.02 m. For constant velocity migration, we chose a velocity range between 0.04 m/ns and 0.24 m/ns, with 0.005 m/ns step (Figure 1a). To enhance the diffractions amplitudes, we suppressed the reflectors using PWD (Li and Zhang, 2021; Fomel, 2002), with a window operator size of 0.624 ns x 0.4m (Figure 1b).

The proposed methodology estimated the migration velocity in x-t moving windows of 1.2m-10ns, with 80% overlap (Figure 1c). Figure 1d depicts the superimposition of the migration velocity image over the revealed diffractions of the section.

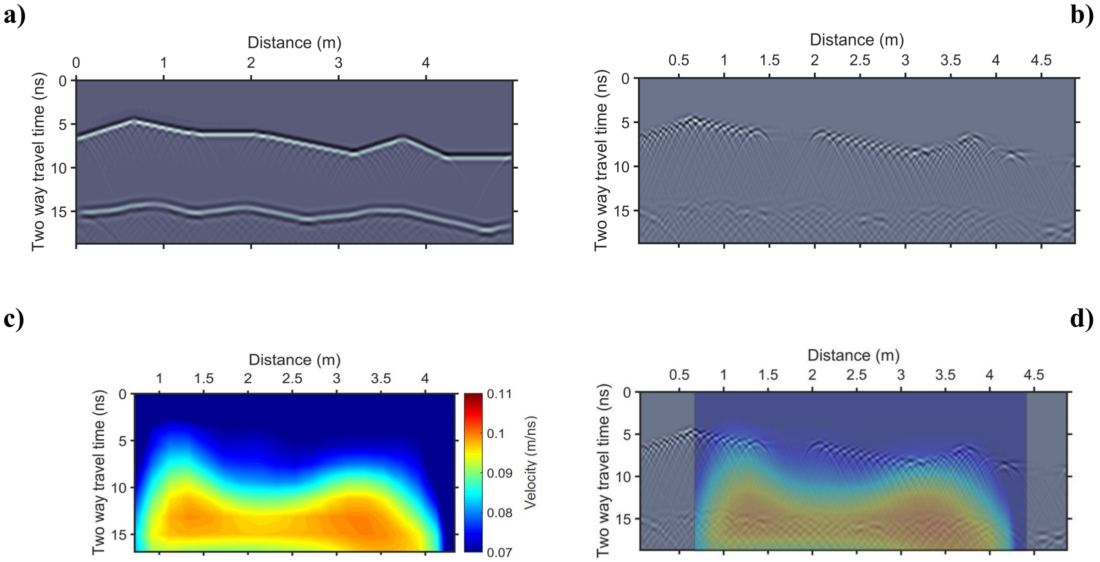

Figure 1 *Migration velocity estimation. a) Synthetic dataset, b) is (a) after PWD, c) is the estimated migration velocity image and d) is (c) superimposed on (b).*

Despite the general efficiency in the estimation of the migration velocity, several drawbacks can be observed in Figure 1d. The first is the limited lateral resolution derived due the relatively large x-t windows used. At the edges of the derived velocity image (from 0.6m to 1m and from 4m to 4.4 m) the migration velocity values seem to also be affected by the time window procedure. At distances from 1.5 m to 2.5m, the migration velocities are also affected by the lack of diffractions from 1.3m to 2.2m, indicating a diffractions density dependence of the method.

Real data example

The real data example comes from a water saturation estimation survey in Greece Chania, using both the methods of Electrical Resistivity Tomography (ERT) and GPR. We involved a GSSI 900 MHz antenna, where time and space intervals were set to 0.0488 ns and 0.02 m respectively. The initial processing included De-wow, adaptive band-pass filter (Economou, 2016) and time varying gain

(Figure 2a). We did not apply PWD as the section depicts enough diffractions for the application of the proposed methodology.

The migration velocity was estimated in x-t windows of 2m-10 ns with 80% overlap (Figure 2b). We extracted a portion of the GPR section (Figure 2a), based on the migration velocity information derived. The superimposition of the migration velocity image is depicted in Figure 2c.

The comparison of Figure 2b and Figure 3 indicates that within the latter, the resistivity values decrease with depth due to increased soil moisture since the soil in the area is considered to be of relatively stable composition (Figure 3). Migration velocity indicates similar trend, qualitatively validating the estimated migration velocity using the proposed methodology (Figure 2b).

Further research will focus on improving this EM velocity attribute in order to build a migration velocity model for efficient migration and an EM velocity model for time to depth conversion. In combination with attenuation analysis and ERT one could be able to produce dielectric permittivity depth sections.

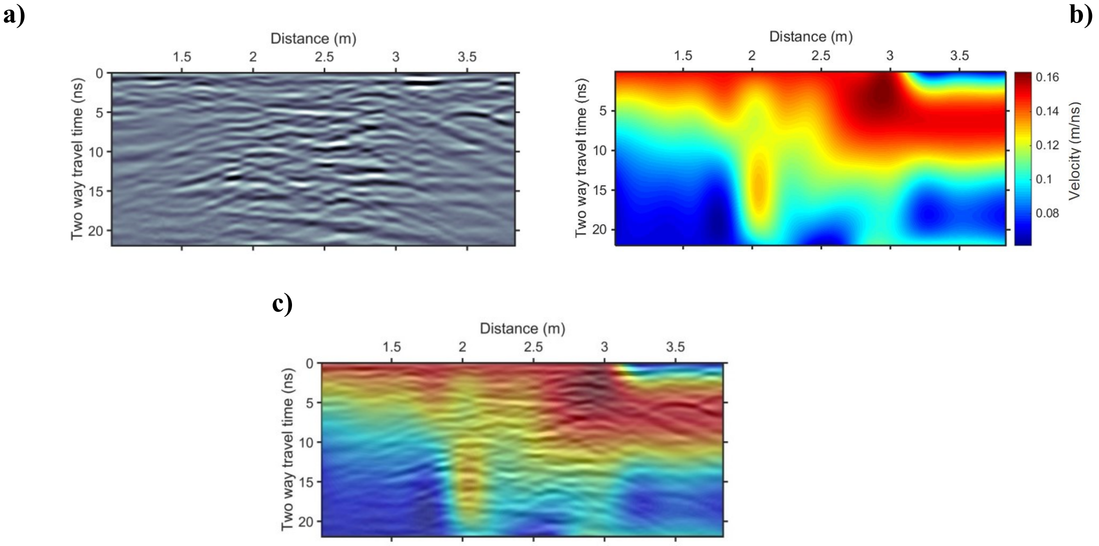

***Figure 2** Migration velocity estimation over a real GPR dataset. a) The GPR section after conventional processing, b) the derived migration velocity* image *for (a) and c) is the superimposition of (b) over (a).*

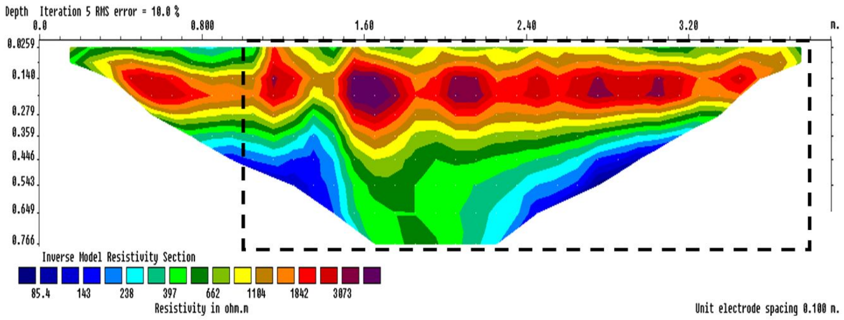

***Figure 3** Electrical resistivity section using the Gradient array and 0.1m electrodes spacing. Vertical axis is depth in m and horizontal axis is electrode location in m.*

Conclusions

We propose a method for the estimation of a migration velocity from GPR data, which uses the local slopes distribution as a x-t window attribute sensitive to diffraction focusing. It requires constant velocity migrations over a predefined velocity range with 0.005 m/ns step. This methodology can be used as a complementary method to ERT for the assessment of soil moisture.

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It is my pleasure to inform you that the paper entitled

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