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Constructing migrated image scans by post-stack remigration

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ABSTRACT

Optimal electromagnetic wave-propagation velocities and subsurface images for ground-penetrating radar (GPR) data can be specified by using a new imaging method. This implies in principle nothing else but time- or depth-migrating the radar time-domain reflection data by continuously changing the constant migration velocity. Rather than time-migrating the unmigrated GPR section we, however, propose to remigrate the already time-migrated section by a new one-step remigration operator. This allows us to create many time-migrated images for different constant migration velocities. In this way, the computation time for the time-migration process is very much reduced. Considering time-migrated sections, one observes that time-migrated reflector images "propagate" when the constant migration velocity is continuously changed. For this "propagation" there exists a wave-equation-type partial-differential equation (PDE). With the proposed scheme time-migrated sections can thus be looked upon as snapshots depicted for a certain migration velocity. The time-migrated reflector images in the snapshots consequently behave like "waves", which are called image-waves (Hubral et al., 1996). The concept of seismic image-waves thus helps very much to understand the remigration and velocity determination process. This is applied to a real GPR-data example acquired in a concrete-body environment within which a steel-cable frame is buried. It will be shown that by the proposed method one is able to perform a quick migrated–image scan in order to find a reliable migration velocity leading to the best time-migrated image.

INTRODUCTION

Seismic data processing methods have been successfully applied to Ground-Penetrating Radar (GPR) data by various authors (Maiyala, 1992; Fisher et al., 1992a,b, 1994). It is possible to treat GPR data for the purpose of subsurface imaging like seismic data when the geological environments are of low attenuation loss or unconductive. This is generally the case for GPR frequencies in the range $(0.1 - 1.0)10^9$ Hz, see Davis et al. (1989). In a high resistive geological environment ($\sigma = 0$) the electromagnetic wave propagation can therefore be assumed to dominate the conduction. For that matter one

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can treat radar wave propagation similar to acoustic wave propagation. One can also use various seismic methods to process the radar data, such as wave-equation migration. It will be shown in the description of the method that one can in fact approximate the electromagnetic (EM) radar-wave propagation, by a scalar wave propagation if certain requirements are fulfilled. Radar waves then propagate in

a medium with the propagation velocity

$$v = \frac{1}{\sqrt{\mu\epsilon}}, \tag{1}$$

where ϵ and μ are the electric permittivity and the magnetic permeability, respectively.

Wave-equation migration is one of the most important processing steps, either for seismic or GPR data, because it can be viewed as solving the imaging problem by "moving the reflected/scattered energy from the surface back to the respective subsurface reflecting/scattering points " thus providing their subsurface depth-migrated image. The work of Fisher et al. (1992b) pioneers the application of migration to single-channel GPR profiles. It successfully applies reverse time migration to GPR data, thus allowing for a high-resolution interpretation of a stratigraphic soil sequence over a complicated fluvial environment. A successful wave-equation migration requires, however, the propagation velocity above the subsurface reflectors of interest. For near zero-offset reflection data this is difficult to obtain. Moreover the accuracy requirements for the velocity are also quite different for depth migration or time migration. A higher accuracy is required for the depth migration and a smaller one for the time migration. This makes the latter process more attractive in seismic and GPR imaging even though depth migration (with a very good migration velocity) is certainly the more desirable task to be solved. It is, therefore, a principal task in reflection imaging to find a time-migration algorithm, which permits improving the (possibly wrong) propagation velocity in an easy and efficient way. Such kind of imaging procedure is offered and discussed.

The imaging process required to construct from a given time-migrated zero-offset section other ones for a continuum of migration velocities is subsequently referred to as "remigration". This term generalizes the terms residual or cascaded migration (Rothman et al., 1985; Larner and Beasley, 1987) or velocity continuation (Fomel, 1994; Goldin, 1990). By a remigration time-migrated images for updated migration velocities are obtained. This is achieved by applying a migration operator to an already time-migrated section rather than to the unmigrated zero-offset data. Only the two-dimensional case is subsequently considered.

DESCRIPTION OF THE METHOD

In this work we demonstrate the usefulness of seismic image waves (Hubral et al., 1996) to perform an optimal time-migration imaging procedure on the GPR data. The procedure involves nothing else but to "propagate" (or velocity-continue) reflector/scatterer images in the time-migrated section by constantly changing the migration velocity. This change is, however, implicitly done by the remigration equation given below. Thus we can very quickly establish the (most) correctly time-migrated image, and its migration velocity. Throughout the work we only consider the time-migration process and recall that a time-migration image differs from a depth-migration image only by a simple velocity-dependent vertical depth-to-time scaling operation.

Useful solutions for radar signals can be found by considering the equation (Ward and Hohmann, 1989; Born and Wolf, 1980)

$$\nabla^2 \mathbf{p} \;=\; \mu\sigma\frac{\partial \mathbf{p}}{\partial t} \;+\; \mu\epsilon\frac{\partial^2 \mathbf{p}}{\partial t^2}, \tag{2}$$

which can be derived from Maxwell's equations for the case of a 2-D homogeneous isotropic medium. The constants ϵ, μ and σ are the electric permittivity, magnetic permeability, and conductivity of the medium, respectively. The above equation (2) is obtained after decomposing the electromagnetic field into uncoupled electric and magnetic vector components. This is possible as we work with media that are homogeneous with respect to the propagation velocity. In the above case $\mathbf{p}(x, z, t)$ describes either the electric or magnetic vector, i.e., $\mathbf{p} = [p_x, p_y, p_z]^T$. As we are interested only in one arbitrary component, we denote this with $p(x, z, t)$. The first term on the right side of (2) represents conduction of charge. It causes attenuation of the electric-magnetic field. The second term describes the displacement of the charge caused by the propagating electromagnetic field. Equation (2) leads for small values of σ to the same eikonal equation and rays as the scalar wave equation

$$\frac{\partial^2 p}{\partial x^2} \;+\; \frac{\partial^2 p}{\partial z^2} \;=\; \frac{1}{v^2}\frac{\partial^2 p}{\partial t^2}\,, \tag{3}$$

for which $\sigma = 0$ and where v is the radar-propagation velocity given by $v = \dfrac{1}{\sqrt{\mu\epsilon}}$ [see Eq. (1)].

REMIGRATION EQUATION

With the remigration equation one solves the following initial-value problem (Mann and Jaya, 1997), generalized to 3-D case,

$$p(x, y, t, v_0) \;\rightarrow\; p(x, y, t, v)\;;\; v_0 < v, \tag{4}$$

involving the PDE (Fomel, 1994; Hubral et al., 1996; Schleicher et al., 1997; Mann and Jaya, 1997).

$$\frac{\partial^2}{\partial v \partial t} p(x, y, t, v) + vt\tilde{\nabla}^2 p(x, y, t, v) = 0. \tag{5}$$

where p denotes a scalar variable as e.g., pressure or any component of the electromagnetic wavefield (see equation 3). $\tilde{\nabla}^2$ corresponds to $\frac{\partial^2}{\partial x^2}$ for 2-D case and $\tilde{\nabla}^2$ to $\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$ for 3-D case.

The initial value condition also allows for

$$p(x, y, t, v_0 = 0) = p_0(x_0, y_0, t_0), \tag{6}$$

where $p_0(x_0, y_0, t_0)$ is the ZO or CMP-stacked section. The initial-value problem (5) and (6) can be solved by using some finite-difference schemes as recently showed by Mann and Jaya (1997) or by spectral theory (Jaya et al., 1996).

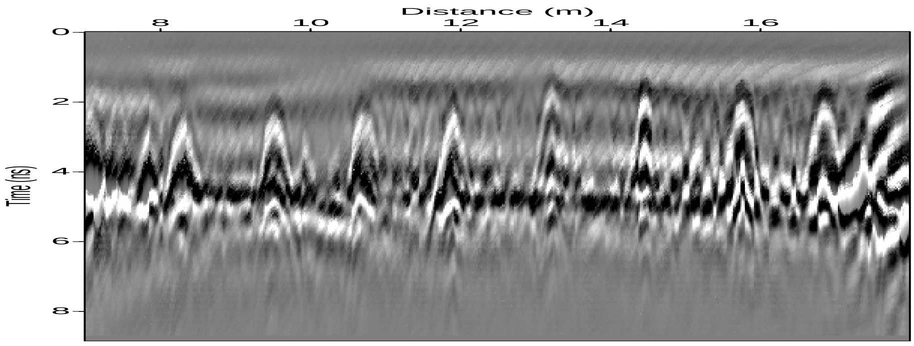

Figure 1: Zero-offset radar time section. The distance between two adjacent zero-offset traces is 0.02 meter. The sample rate is 0.039 ns.

CONSTANT-VELOCITY SCAN

Only by solving for one operator equation (5) one has as the result a sequence of time-migrated panels for many migration velocities. The only task of the interpreter is then to pick the best focused (i.e., the best migrated) image from the time-remigrated panels. The migration velocity used in that best migrated image may therefore define a reliable velocity model. This is the key of using remigration for the velocity scan.

Thus, the constant-velocity scan procedure may be performed in three cascaded ways:

- searching for a target zone with a gently curved/dipping reflector where a predefined or a-priori “constant-velocity” region may be assumed,
- doing the remigration or in this case perturbing the (unmigrated/migrated) section by continuously changing the migration velocity,
- scanning the animated images produced by the above step and searching for a focusing events caused by a collapses of presumably hyperbolic-like events.

REAL DATA EXAMPLE: RESULT AND DISCUSSION

For the renovation of the surface layer of a bridge, a set of holes have to be drilled into the concrete body in order to anchor the new layer. Because of the safety of the drilling

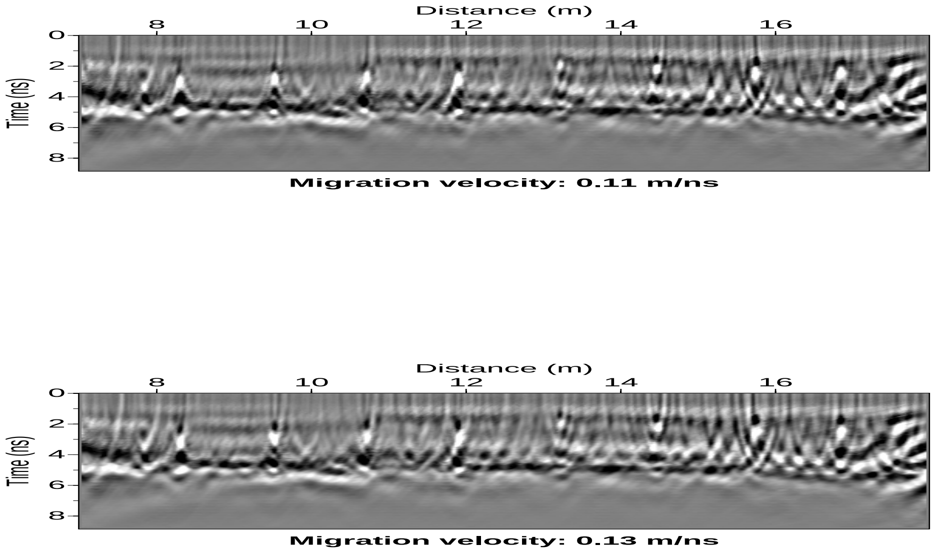

Figure 2: Panel of time-migrated images. The migration velocity of 0.11 m/ns is used for the upper image. In the lower image we depict the time-migrated image for migration velocity of 0.13 m/ns.

worker and because of stability reasons of the bridge, the reinforcement steels should not be damaged by this work. Therefore it was necessary to determine very precisely the position of the steel cables. For their detection we used electromagnetic waves in the GPR-frequency range of 900 MHz. The transmitter and receiver dipole were oriented parallel to the cables, while the antenna crossed them perpendicular. The resulting time section consists of 900 scans, which are in fact common offset traces. We then have applied a static shift in order to get the ZO time section. The spatial-trace and the time-sample interval are $\Delta x = 0.02$ m and $\Delta t = 0.039$ ns, respectively. Since we can assume that the electrical conductivity σ in this case is small, the proposed remigration technique can be applied to estimate the velocity which is necessary for the determination of the cable depth.

Strong diffraction pattern at two-way traveltimes of about 1 to 3 ns indicate the steel cables (see figure 1). This plays a very important role in the determination of the migration velocities. The reason is very simple; the remigration process lets the hyperbola-like diffraction pattern collapse into its so-called focusing point. This is the case when the migration velocity corresponds to the medium velocity. This fact immediately justifies to perform a migration-image scan in order to search for the correct migration-velocity and the best possible image. However, horizontal reflector elements are not changed at all by changing the constant migration velocity.

Figure 2 and 3 show a set of remigration results for a velocity range $0.11 - 0.17$ m/ns with the migration velocity step 0.02 m/ns. By the above remigration algorithm this scanning procedure is in fact very easily performed as many time-migrated images result from applying equation (5) to the time-migrated image wavefield $p(x, t, v)$. One

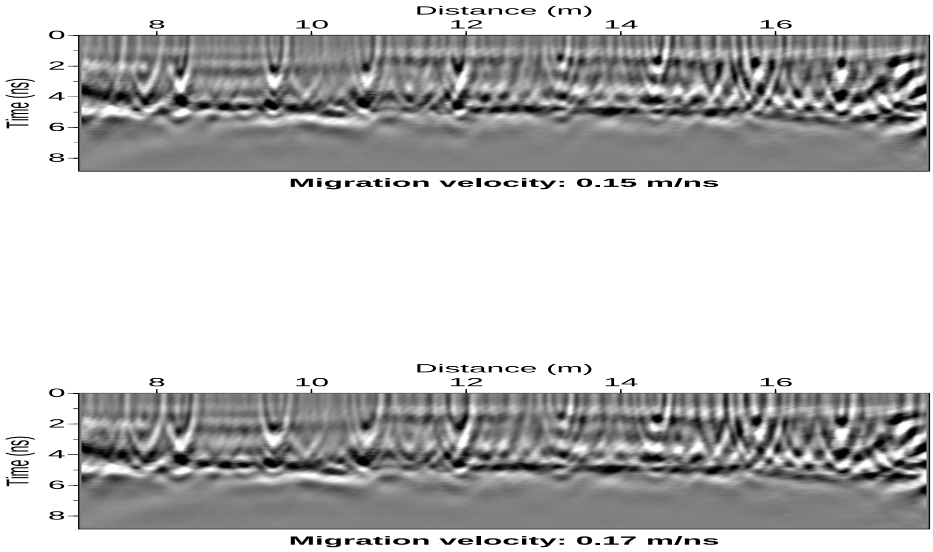

Figure 3: Panel of time-migrated images. The migration velocity of 0.15 m/ns is used for the upper image. In the lower image the time-migrated image is depicted for migration velocities of 0.17 m/ns.

observes that the remigration process acts very clearly on the diffraction pattern as we have mentioned above. The only task of the interpreter is to pick the best focused (i.e., the best migrated) image. The best result is obtained for the range of migration velocities of $v = 0.11 - 0.13$ m/ns. Figure 4 shows a cross section of the concrete bridge body for a length of 11 m which corresponds to the coordinate range of $7 - 18$ m of the GPR-profile. The estimated positions of the steel cables are indicated by small dots. Note that the reflection from the interface concrete-air in the depth 0.7 m is out of the recording range.

CONCLUSIONS

Traditional time-migration schemes are based on the scalar wave-equation. They can only provide one post-stack time-migrated section for one migration velocity at a time. With the image-wave equation (5) a complete set of time-migrated sections for a continuum of migration velocities (i.e., a set of snapshots of the propagating image waves) results as part of one and the same algorithm. We have shown that if the medium that we work with is homogeneous with respect to the propagation velo city we can employ the proposed method in a very efficient way. It works very well only for a more or less homogeneous velocity medium. It is, however, applicable to image many different structures such as voids in concrete or limestones, or buried objects like pipes or tanks.

We have shown that the proposed time remigration technique can be used on GPR data in resistive media, where reflection and diffraction events are recorded. The pro-

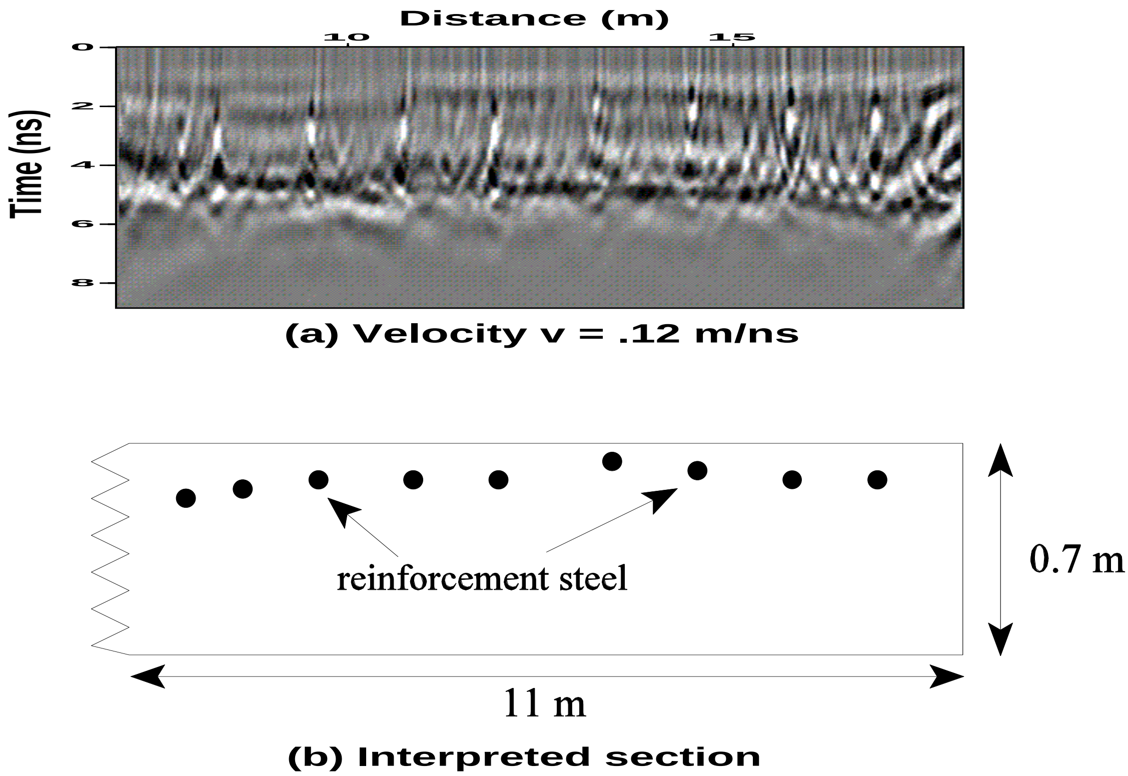

Figure 4: Cross section of the concrete-bridge body. The detected steel cables are indicated by black dots. The horizontal extension corresponds to the coordinate range of $7 - 18$ m of the GPR-profile.

posed theory can of course be generalized to 3-D radar data, see e.g., Grasmueck (1996)

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PUBLICATIONS

Detailed results were published by (Jaya, 1997).