

Fusion of Multifrequency GPR Data Freed From Antenna Effects

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Abstract—Several data fusion approaches have been developed to optimize both resolution and characterization depth for multifrequency ground-penetrating radar (GPR). In this study, we propose a novel physically based method to merge radar data coming from antennas operating in different frequency ranges. The strategy relies on the removal of the source and antenna effects from GPR data and the subsequent fusion of the resulting signals, which are now normalized, in the frequency domain. The approach used to filter out antenna effects resorts to an intrinsic, closed-form solution of Maxwell's equations to describe the radar-antenna-medium system. We validated the multifrequency GPR data fusion approach through laboratory experiments with measurements performed in far- and near-field conditions above a copper plane and pipes buried at different depths in a sandbox. The results demonstrated the benefit of filtering the frequency-dependent antennas effects before data fusion. Enhanced radargrams were subsequently obtained as a result of the broadening of the spectral bandwidth. This physically based fusion approach appears to be very promising to improve subsurface imaging.

Index Terms—Antenna effect removal, full-wave inversion, Green's functions, ground-penetrating radar (GPR) multifrequency antenna data fusion.

I. INTRODUCTION

GROUND-PENETRATING radar (GPR) is a nondestructive tool that has been efficiently used in a wide range of environmental, archaeological, and civil engineering applications [1]–[3]. The acquisition of two-dimensional (2-D/3-D) GPR datasets allows providing qualitative and quantitative information about the investigated medium and the structures contained in it. This task is achieved through the analysis of the electromagnetic waves backscattered at electromagnetic contrasts. However, the complexity of the medium under investigation sometimes prevents the detection, characterization, and localization of the structures/defaults of interest using a single GPR

dataset. Therefore, several strategies have been developed to maximize the information content in the radar data [4].

A first approach involves the combination of data acquired with GPR and other nondestructive techniques such as ultrasonic [5]–[7] or electromagnetic induction methods [8]–[10]. The association of GPR with a different nondestructive technique permits to get rid of some limitations specific to GPR systems (e.g., acoustic waves pass through metallic objects) and provides complementary information about objects and material properties. Despite these valuable benefits, resorting to such a methodology leads to several drawbacks: It requires the knowledge and manipulation of different instruments, the representative elementary volume sampled by these ones can be variable, and the measurements conducted with the instruments are not always spatially coincident.

Another valuable approach used to increase the information content consists in carrying out measurements using antennas having different operating frequencies or polarities and fusing their respective contributions. The information brought by the radar system is determined by the orientation of the antenna and the bandwidth in which the electromagnetic waves are emitted and received. The choice of the antenna, and thereby, the frequencies at which the GPR should operate, is therefore an essential concern as it controls the penetration depth of the electromagnetic waves and the expected temporal and spatial resolutions [2], [11]. Data fusion, which improves the resolution penetration depth tradeoff, is an active field of research as it is sometimes difficult to detect and discriminate the layers and buried utilities of various sizes. Nevertheless, merging multifrequency GPR data into a single radargram has remained a major challenge due to the inherently varying antenna gains with frequencies and different antenna designs.

Over the last decade, several GPR data fusion techniques have been proposed. A first approach, which is empirical, consists in selecting horizontal slices from radar images acquired with different antennas and gathering them to form a composite image [12]. To go one step further, semi- and fully automated procedures have been developed to identify the optimal transition depth range for which the outputs from two antennas can be merged [13]. The fusion is then performed by the following.

- 1) Determining the lines of pixels close enough to move together;
- 2) joining them; and
- 3) deleting/tapering off the lines of pixels that would abruptly end at the junction.

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Although this kind of approach simplifies the analysis of the subsoil, it does not physically merge the datasets. Kohl *et al.* [14] overcame this issue by directly combining spatially coincident, multipolarized datasets using the maxima of signal amplitudes as data fusion algorithm. Some other studies inspected retaining walls by acquiring high-resolution multisensor and multipolarized GPR datasets [15], [16]. The corresponding datasets are subsequently merged using various data fusion methods, namely the average of amplitudes, the maxima of amplitudes, and the continuous wavelet transform fusion algorithm. In cases related to fusion of multipolarized datasets, there is no need of using automatic algorithms for weighting the datasets prior to the fusion. However, this step appears to be relevant when dealing with multifrequency data fusion.

In that respect, several works demonstrated the ability of composting spatially coincident GPR datasets acquired with different antennas operating at different frequencies to expand the spectral bandwidth of the GPR wavelet [17], [18]. The procedure requires an amplitude scaling step, which is achieved by optimizing, in a least-squares sense, the match between the amplitude spectra of the frequency-limited datasets and an idealized composite amplitude spectrum. Soldovieri and Orlando [19] proposed another strategy based on tomographic inversion and summation/multiplication of the tomographic images to combine data acquired with antenna showing partially overlapping frequency bands. They highlighted the ability of the method to improve the quality of the subsoil images.

More recently, Xiao and Liu [20] developed a fusion method able to merge multifrequency GPR data using the extrapolation with a deterministic deconvolution (EDD) algorithm. This approach, which assumes a negligible antenna-medium coupling and considers the attenuation as a linear function of frequency, proved to be promising for data acquired above a railway subgrade. The same authors also proposed to use the forward and inverse S-transform as an alternative to EDD in order to fuse the multifrequency GPR data and improve the image resolution [21], [22]. The method permits to improve the detection of subgrade defects having different depths and sizes but requires some preprocessing stages including resampling and amplitude balancing.

Although substantial progresses have been achieved, the various data fusion approaches previously cited suffer from drawbacks. In most of the studies, the data fusion procedure is generally applied on GPR signals, which are unprocessed or which necessitate nonphysical amplitude equalization prior to the summation of individual band-limited signals. The broadening of the spectrum bandwidth using this kind of methods is especially inappropriate when the overlap of the spectra is not good enough. In addition, distortions arising from the different frequency-dependent gains of antennas are neglected. Another major limitation deals with the forward electromagnetic models used in some studies. They usually do not account for a series of phenomena, and in particular, those related to the radar antenna effects, including antenna-medium coupling.

In this study, we propose a novel approach valid in far- and near-field conditions for fusing datasets acquired with antennas

operating in different frequency ranges. The underlying method relies on a filtering procedure aiming at removing antenna effects from the GPR data. To achieve this task, we resort to the physically based radar equation of Lambot *et al.* [23]–[25], which includes, in particular, antenna effects and its interactions with the medium through intrinsic global transmission and reflection coefficient functions. Wave propagation in a 3-D layered media is modeled using exact 3-D Green's functions.

Removing antenna effects as well as the source allows computing and merging the response of the medium in the frequency domain without having recourse to empirical amplitude scaling. In far-field conditions, we used the analytical filtering procedure proposed by Lambot *et al.* [23] to remove antenna effects from GPR data and obtain “measured” Green's functions, freed from antenna effects. In near-field conditions, the radar equation is more complex and prevents the analytical computation of the medium response. Therefore, we used the full-wave, numerical filtering procedure recently proposed by De Coster and Lambot [26] as a generalized filtering strategy. In this paper, we tested the far- and near-field data fusion methods in laboratory conditions for radar measurements performed with different antennas over pipes buried in a sandbox.

II. GENERALIZED ANTENNA MODEL

A. Model Formulation

The model relies on a full-wave solution of the 3-D Maxwell's equations accounting simultaneously for the antenna and wave propagation in planar layered media. In near-field conditions, the backscattered field distribution over the antenna aperture is influenced by the medium properties as well as the distance between the medium and the antenna. The assumption of a homogeneous field over the antenna aperture, as adopted in [23], can therefore not be applied. In that respect, Lambot and André [24], [25] generalized the intrinsic antenna model of Lambot *et al.* [23] to near-field conditions. The antenna radiation properties are taken into account by considering a source made up of a set of infinitesimal electric dipoles, whereas the receiver consists of an equivalent set of points for which the scattered field is calculated. The distribution of the backscattered field over the antenna aperture is thereby decomposed into a series of homogeneous fields by resorting to the superposition principle. The chosen number of points is finite and depends on the complexity of the backscattered field distribution. The wave propagation between the radar reference plane and these source/field points is described through complex and frequency-dependent global reflection and transmission coefficients, that account for the variations of impedance along the propagation paths within the antenna. Taking these complex phenomena physically into account constitutes the benefit of this model compared to other existing approaches. The model, in particular, permits to inherently describe antenna-medium coupling. The generalized radar equation is formulated in the frequency domain as follows [24]:

$$S(\omega) = \frac{b(\omega)}{a(\omega)} = T_0(\omega) + \mathbf{T}_s (\mathbf{I}_N - \mathbf{G}^0 \mathbf{R}_s)^{-1} \mathbf{G} \mathbf{T}_i \quad (1)$$

with

$$\mathbf{T}_i = [cT_{i,1}(\omega) T_{i,2}(\omega) \cdots T_{i,N}(\omega)]^T \quad (2)$$

$$\mathbf{T}_s = [cT_{s,1}(\omega) T_{s,2}(\omega) \cdots T_{s,N}(\omega)] \quad (3)$$

$$\mathbf{R}_s = \text{diag}([R_{s,1}(\omega) R_{s,2}(\omega) \cdots R_{s,N}(\omega)]) \quad (4)$$

$$\mathbf{G} = \begin{bmatrix} G_{11}(\omega) & G_{12}(\omega) & \cdots & G_{1N}(\omega) \\ G_{21}(\omega) & G_{22}(\omega) & \cdots & G_{2N}(\omega) \\ \vdots & \vdots & & \vdots \\ G_{N1}(\omega) & G_{N2}(\omega) & \cdots & G_{NN}(\omega) \end{bmatrix} \quad (5)$$

and

$$\mathbf{G}^0 = \begin{bmatrix} G_{11}^0(\omega) & G_{12}^0(\omega) & \cdots & G_{1N}^0(\omega) \\ G_{21}^0(\omega) & G_{22}^0(\omega) & \cdots & G_{2N}^0(\omega) \\ \vdots & \vdots & & \vdots \\ G_{N1}^0(\omega) & G_{N2}^0(\omega) & \cdots & G_{NN}^0(\omega) \end{bmatrix} \quad (6)$$

where $S(\omega)$ denotes the radar signal, i.e., the ratio between the backscattered field $b(\omega)$ and the incident field $a(\omega)$ (radar source) at the radar reference plane, ω refers to the angular frequency, I_N is the N -order identity matrix where N is the number of point sources or field points, $T_0(\omega)$ is the global transmission/global reflection coefficient of the antenna(s) in free space, $T_{i,\cdot}(\omega)$ denotes the global transmission coefficient for the fields incident from the radar reference plane onto the source points, $T_{s,\cdot}(\omega)$ is the global transmission coefficient for the fields incident from source points onto the radar reference plane, and $R_{s,\cdot}(\omega)$ is the global reflection coefficient for fields incident from the layered medium onto the field points and permits to account for infinite wave reflections between the antenna and the medium (antenna-medium coupling). Finally, $G_{\cdot,\cdot}(\omega)$ and $G_{\cdot,\cdot}^0(\omega)$ are the layered medium Green's functions, i.e., the exact solutions of the 3-D Maxwell's equations for describing wave propagation in planar multilayered media. $G_{\cdot,\cdot}(\omega)$ and $G_{\cdot,\cdot}^0(\omega)$ refer, respectively, to the transmitter-receiver and receiver-receiver Green's functions.

When far-field conditions are fulfilled [27], we can assume that the backscattered field over the antenna aperture is homogeneous, and hence, the number of source/field points N is equal to 1. In monostatic mode, (1) that expresses the relation between the measured field and the 3-D layered medium Green's function reduces to [23]

$$S(\omega) = \frac{b(\omega)}{a(\omega)} = R_i(\omega) + \frac{G_{11}(\omega)T_1(\omega)}{1 - G_{11}(\omega)R_{s,1}(\omega)} \quad (7)$$

with $R_i(\omega)$ corresponding to $T_0(\omega)$ for zero-offset source-receiver and T_1 corresponding to the product $T_{s,1} \times T_{i,1}$.

B. Determination of the Antenna Characteristic Functions

The antenna characteristic functions are determined through the specific calibration procedure detailed in Lambot and André [24]. It consists in performing a number of measurements at different distances in both far- and near-field conditions from either

a perfect electrical conductor (PEC) or any well-known layered medium such as, for instance, water. The layered medium Green's functions $G_{\cdot,\cdot}(\omega)$ and $G_{\cdot,\cdot}^0(\omega)$ can thereby be calculated, the radar signal $S(\omega)$ can be measured, and (1) can be solved numerically in order to determine the antenna characteristic coefficients. As the number of complex unknowns is quite large in near-field conditions, an inverse procedure requiring the optimization of a multidimensional objective function is performed to retrieve the global reflection and transmission coefficients.

III. DATA FUSION STRATEGY

A. Far Field

In this paper, the data fusion methodology can be easily applied for data acquired in far-field conditions as the antenna effect removal is straightforward in such conditions. In this specific case, (7) can be analytically inverted and Green's functions can be computed from the radar measurements as follows (e.g., [28]):

$$G_{11}(\omega) = \frac{S(\omega) - R_i(\omega)}{T_1(\omega) + S(\omega)R_{s,1}(\omega) - R_i(\omega)R_{s,1}(\omega)}. \quad (8)$$

The Green's functions resulting from the calibration procedure correspond to the medium response and are expected to be identical for a given medium, no matter which radar source (e.g., frequency vs. time domain radar) and which antenna we use to perform the measurements. The fusion step is subsequently achieved by appending Green's functions computed for each antenna in the frequency domain and by averaging their values for the frequency observations that overlap. It is worth noting that the data fusion procedure assumes the source/field point of each antenna to be located at an identical height.

B. Near Field

We see from (1) the impossibility of analytically filtering out antenna effects from GPR data when near-field conditions apply ($N \neq 1$). The absence of antenna effect removal can lead to an inappropriate data fusion procedure as the distortions caused by the different frequency-dependent gains of antennas and interactions with the medium are not taken into account. In order to address this issue, we resort to the novel antenna effect removal approach proposed by De Coster and Lambot [26]. The proposed methodology allows filtering out the antenna multiple internal reflections, antenna-medium ringing, and antenna height variation effects from GPR data acquired in near-field conditions above a locally multilayered medium.

As shown in previous works [23], [29], [30], the response of a multilayered medium (also called Green's functions) is a function of global reflection coefficients. These global reflection coefficients account for all reflections and multiples occurring in the multilayered medium. They can be determined using a recursive procedure calling upon the computation of local reflection coefficients at different interfaces. The local reflection coefficients depend themselves on the following electromagnetic properties: the magnetic permeability, the dielectric permittivity, and the electrical conductivity of the layers. The knowledge of the electromagnetic properties of each layer

therefore permits to compute the global reflection coefficients, which is in a sense a representation of the impedance discontinuities in the medium. The retrieval of these electromagnetic properties is achieved using an inverse modeling approach based on the minimization of an objective function. However, determining the values of the parameters is a nonlinear optimization problem, which rapidly becomes difficult when the number of parameters to estimate increases.

The idea behind the antenna effect removal strategy is based on the fact that any multilayered medium can be mathematically reduced to an equivalent half-space medium assuming the upper half-space as free space. This equivalent half-space medium is characterized by a frequency-dependent global reflection coefficient, and hence, corresponding effective permittivity ($\epsilon_{\text{eff}}(\omega)$) and conductivity ($\sigma_{\text{eff}}(\omega)$). This substitution represents an exact mathematical equivalence as these properties account for all reflections in the original layered medium [23], [29], [30]. The strategy adopted to retrieve these effective medium parameters involves inversion. We used a sequential combination of the global multilevel coordinate search (GMCS) [31] algorithm with the Nelder–Mead simplex (NMS) algorithm [32]. It represents a robust and efficient optimization approach for minimizing the objective function $\phi(\mathbf{b})$ [see (9)]. The antenna height is considered as known as it can be calculated or measured independently. The inversion problem is formulated in the least-squares sense and the objective function to be minimized is formulated as follows:

$$\phi(\mathbf{b}) = |\mathbf{S}^* - \mathbf{S}|^T |\mathbf{S}^* - \mathbf{S}| \quad (9)$$

where $\mathbf{S}^* = S(\omega)$ and $\mathbf{S} = S(\omega, \mathbf{b})$ are the vectors containing, respectively, the observed and the simulated radar data, T denotes transpose and $\mathbf{b}$ is the parameter vector $[\epsilon_{\text{eff}}, \sigma_{\text{eff}}]$ to be estimated. Inverting GPR data and retrieving $\epsilon_{\text{eff}}(\omega)$ and $\sigma_{\text{eff}}(\omega)$, independently for each frequency, permits to compute the complex effective conductivity ($\eta_{\text{eff}}(\omega)$) found in the frequency-domain Maxwell's equations [see (10)]. It is worth noting that the denomination comes from the term located ahead of the electric field in the total current density formulas:

$$\eta_{\text{eff}}(\omega) = \sigma_{\text{eff}}(\omega) + j\omega\epsilon_{\text{eff}}(\omega). \quad (10)$$

This frequency-dependent effective conductivity characterizing the equivalent half-space medium therefore represents the physical multilayered medium in terms of the inner multiple reflections and transmissions that occur. The conversion of (10) into the time domain using the inverse Fourier transform therefore provides the radar image from which antenna effects have been removed:

$$\eta_{\text{eff}}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \eta_{\text{eff}}(\omega) e^{j\omega t} d\omega. \quad (11)$$

It is worth noting that $\eta_{\text{eff}}(t)$ is not freed from the multiple reflections occurring between the medium layers. For specific spatially coincident measurements, the complex effective conductivities computed for two antennas operating at different frequency ranges can be merged by simply combining their spectra in the frequency domain and averaging the overlapping parts. Stacking the time-domain complex effective conductivities

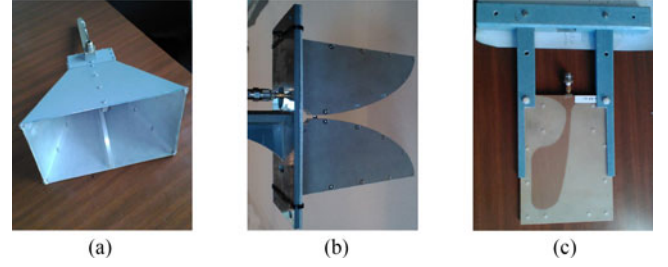


Fig. 1. (a) Horn (BBHA 9120 A, Schwarzbeck), (b) home-made Vivaldi [33], and (c) tapered slot Vivaldi [34], [35] antennas used to acquire data above the sandbox. The two horn antennas have identical dimensions and the same shape.

TABLE I
DIMENSIONS, FREQUENCY RANGES, AND FREQUENCY STEPS OF THE ANTENNAS USED IN THE LABORATORY EXPERIMENTS

	BBHA 9120A	BBHA 9120D	Home-made Vivaldi	Tapered slot Vivaldi
Height [m]	0.195	0.195	0.200	0.150
Aperture [m]	0.140	0.140	0.147	0.240
Range [MHz]				
Far field	800–3700	3300–6200	–	–
Near field	2200–4000	–	800–2600	600–2600
Step [MHz]				
Far field	2	2	–	–
Near field	10	–	10	30

calculated for each position provides a fused radar image from which antenna effects have been removed. In the obtained image, time zero exactly corresponds to the medium surface.

IV. DESCRIPTION OF THE LABORATORY EXPERIMENTS

A. Radar Setup

Laboratory experiments were conducted in the Georadar Research Center of the Université catholique de Louvain (<http://sites.uclouvain.be/gprlouvain>) in order to assess the proposed data fusion procedure. To achieve this goal, we used a stepped-frequency continuous-wave radar system composed of a vector network analyzer (VNA, ZNB8, Rhode & Schwarz, Munich, Germany) and four different antennas operating in different frequency ranges and acting as transmitter–receiver units (see Fig. 1). The dimensions and acquisition parameters related to the two double-ridged horn antennas (BBHA 9120 A and BBHA 9120 D, Schwarzbeck, Schönau, Germany), the home-made Vivaldi antenna [33], and the tapered slot Vivaldi antenna [34], [35] used in the laboratory experiments are described in Table I. The antennas were, each one in turn, connected by a 50 Ω impedance coaxial cable to the reflection port of the VNA. The VNA was calibrated at the connection between the antenna feed point and the coaxial cable using a standard open-short-match calibration kit. The radar system was fixed on an automated positioning table. We used a computer to remotely control the acquisition process, i.e., to automatically move the radar to spatially coincident positions and to carry out the measurements.

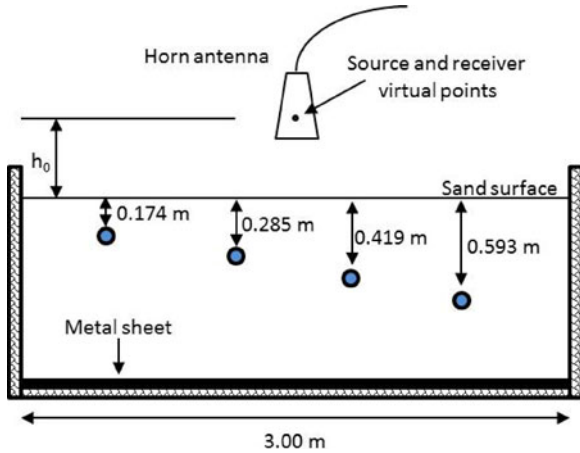


Fig. 2. Far-field configurations used in laboratory experiments: Antennas located at 0.3 m above a $3 \text{ m} \times 3 \text{ m} \times 1 \text{ m}$ sandbox in which pipes filled with water were buried.

B. Far-Field Acquisition Procedure

With respect to the far-field methodology validation, measurements were performed with the two horn antennas at 0.30 m above a $3 \text{ m} \times 3 \text{ m} \times 1 \text{ m}$ sandbox in which four plastic pipes filled with water were buried (see Fig. 2). Far-field conditions were respected because the antenna height above the sand was higher than 1.2 times the aperture of the antenna [27]. The pipes had an outer diameter of 0.08 m and were located at 0.174 m, 0.285 m, 0.419 m, and 0.593 m depth, respectively. A copper sheet acting as a PEC was placed at the bottom of the sand layer to analyze the fusion effect on a planar reflector and further avoid unidentified reflections of the underlying materials. In total, 51 profiles of 2-m length and spaced by 0.02 m were performed with each antenna. As shown in Table I, we constrained the bandwidths of the horn antennas to 0.8–3.7 GHz and 3.3–6.2 GHz for the BBHA 9120 A and BBHA 9120 D, respectively. In order to facilitate the interpretation of the results, we attributed the nomenclature low frequency (for LF) and high frequency (for HF) to the horn antennas operating in the 0.8–3.7 GHz and 3.3–6.2 GHz frequency ranges, respectively.

The antennas were calibrated using the analytical procedure proposed in [23], which is equivalent to consider one source–receiver point in the generalized model (1). The transfer functions of each antenna allowed us to analytically filter out the antenna effects from each radar signal. The resulting Green’s functions were then merged using the procedure describe in Section III-A. The results of Green’s functions fusion were then compared to the results computed with the procedure removing numerically the antenna effects (see Section III-B). Finally, the most adapted method was chosen to provide the 2-D and 3-D fused images of the objects buried in the sandbox. We refer to Lopera *et al.* [28] to provide more details about the layered medium assumption in presence of local targets when filtering antenna effects.

C. Near-Field Acquisition Procedures

Two laboratory experiments were conducted in order to validate the numerical antenna filtering and fusion methods in

near-field conditions. Three antennas were used to acquire the near-field datasets, namely the horn antenna BBHA 9120 A, the home-made Vivaldi antenna, and the tapered slot Vivaldi antenna. The antennas were calibrated using the procedure described in Section II-B. For that purpose, the antennas were modeled using an equivalent set of six source/field points evenly distributed along a line. As shown in a previous work [36], the number of points is expected to be a good tradeoff between the modeling accuracy and the computation time for these antennas. The match between the measured and modeled radar data above the copper plane is extremely good for the tapered slot and home-made Vivaldi antennas whereas it was slightly less satisfactory for the horn antenna. Their maximum relative errors in terms of signal amplitude are equal to 0.75%, 1.81%, and 3.78%, respectively.

The numerical filtering approach required to merge the near-field data assumes that the antenna height is known and can be determined independently for each antenna position. We used the model described in Section II-A and conducted full-wave inversions by restricting the inverse problem to the surface reflection. The used procedure is described in Lambot *et al.* [37]. This methodology avoids inversion errors, which could arise from the presence of layers/objects buried close to the sand surface. The strategy employed to invert data involves a sequential combination of GMCS and NMS algorithms.

1) *Study Case n° 1:* Measurements were performed at 0.05 m above the sandbox in which three plastic pipes filled with air were buried [see Fig. 3(a)]. The 1.2 m long pipes had an outer diameter of 0.05 m and were located at 0.069 m, 0.287 m, and 0.506 m depth, respectively. It is worth noting that, compared to the far-field laboratory experiment, this near-field setup presents an increasing difficulty due to the smaller diameter of the pipes and the much lower relative permittivity contrast at the sand-pipe air interface (permittivities are quite similar and destructive interferences occur). A profile of 2.41 m long was acquired with a sampling density equal to 100 scans per meter using the double-ridged horn antenna BBHA 9120 A used in the far-field experiments and the tapered slot Vivaldi antenna [34], [35]. For the fusion step, we constrained the bandwidth of the tapered slot Vivaldi and horn antennas by limiting their frequency ranges to 0.6–2.6 GHz and 2.2–4.0 GHz, respectively.

2) *Study Case n° 2:* Measurements were performed at 0.05 m above the same sandbox in which a metallic pipe was buried [see Fig. 3(b)]. The 1.05 m long pipe had an outer diameter of 0.04 m and was located at 0.175 m depth (top of the pipe), respectively. A profile of 2.00 m long was acquired with a sampling density equal to 100 scans per meter using the double-ridged horn antenna BBHA 9120 A and the home-made Vivaldi antenna [33]. For the fusion step, we constrained the bandwidth of the home-made Vivaldi and horn antennas by limiting their frequency ranges to 0.8–2.6 GHz and 2.2–4 GHz, respectively.

V. LABORATORY RESULTS

A. Far Field

Fig. 4(a) shows an example in the frequency domain of spatially coincident radar data acquired with the two antennas

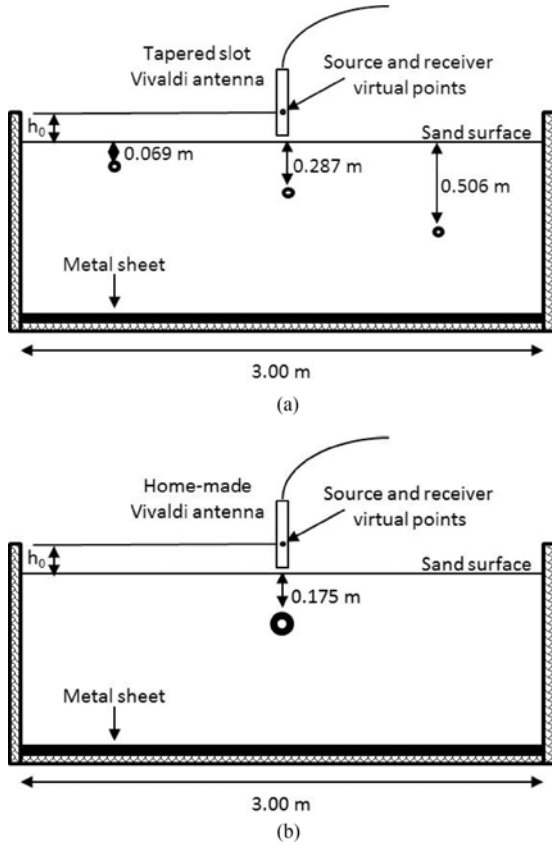


Fig. 3. Near-field configurations used in laboratory experiments: Antennas above a $3 \text{ m} \times 3 \text{ m} \times 1 \text{ m}$ sandbox in which (a) three small empty pipes and (b) one metallic pipe were buried. (a) Study-case $n^\circ 1$, (b) Study-case $n^\circ 2$.

operating in two different frequency ranges. The analysis of the amplitude and the phase of the radar measurements evidences perceptible jumps at the end points of the window where frequencies overlap. Fig. 4(a) highlights the inappropriate nature of data fusion when the different frequency-dependent gains of antennas are not considered. To address this issue and merge the contributions of the two antennas, it is necessary to filter out antenna effects. The analytical and numerical filtering procedures were both tested to remove antenna effects from far-field GPR data. The signals resulting from the two filtering methods represent quantities that are physically different (Green's functions for the analytical method and complex effective conductivity for the numerical method).

Fig. 4(b) shows the frequency domain Green's functions computed for the two horn antennas. The results evidence that, in contrast to what was shown in the raw data case, no amplitude jumps are detected at the extremities of the antenna bandwidths. A small phase mismatch is nonetheless observed between the overlapping part of Green's functions. This issue could be explained by small antenna calibration errors. Fig. 4(c) shows the frequency-domain complex effective values computed for the same antennas. The results demonstrate the appropriateness of the numerical filtering approach as no substantial jumps are observed at the end points of the window where frequencies overlap. However, the phase difference remains below $\pi/2$, which

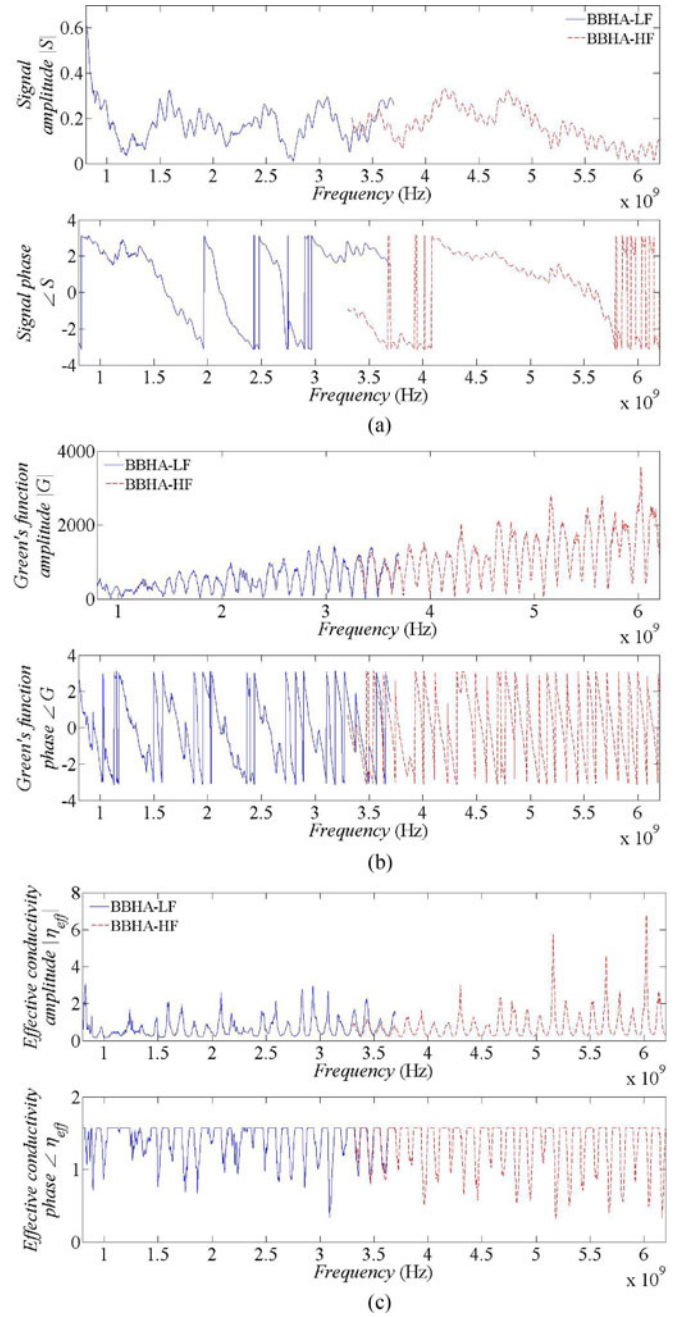


Fig. 4. (a) Raw radar data, (b) Green's functions, and (c) complex effective conductivities in the frequency domain regarding the horn antennas.

leads to some discontinuities. This issue will be tackled in future research.

These two physically based filtering strategies avoid resorting to an empirical amplitude scaling of the datasets. Even if some small discrepancies are observed, both filtering procedures evidence a good adequacy between the filtered signals of the two antennas, either it is in terms of amplitude or phase. The overlapping parts of the bandwidths confirm that the response of the medium recorded by each antenna is identical for a given position. Therefore, we can merge the data as explained in Section III if the analytical or the numerical antenna effect

removal approaches are beforehand applied. In a practical point of view, the analytical approach is preferred in far-field conditions because it takes only a few seconds to filter out antenna effects from all traces. In contrast, the time allocated to perform the antenna effect removal process with the numerical approach reaches 35 min per trace (Intel Core CPU 3.60 GHz, MATLAB environment). The optimizations required to find ε_{eff} and σ_{eff} for each frequency and each position explain why the numerical approach is time consuming.

Now that we have demonstrated the physical concept of the data fusion methodology on particular traces, we can validate the concept on the entire GPR profiles. We selected the 25th profile of the datasets acquired with the two antennas to achieve this goal. Prior to the fusion, the antenna effects were removed from the GPR images by solving (8). The time-domain Green's functions computed for the LF antenna and HF antenna are shown in Fig. 5(a) and (b), respectively, after applying a triangular gain function. The improvements brought by the antenna effect removal procedure to both GPR profiles are transformed into the time domain by the following phenomena:

- 1) The antenna multiple internal reflections and antenna-medium ringing have been removed from the data;
- 2) the surface reflection has been time shifted and can now be clearly identified; and
- 3) the hyperbolas representing the sand-pipe reflections are more contrasted.

The detection of the pipes is facilitated by the low attenuation of the electromagnetic waves in the dry sand and the strong electromagnetic contrast between this material and the water contained in the pipes. Yet, some differences are observed between the filtered profiles shown in Fig. 5(a) and (b). The higher frequency content contained in data acquired with HF antenna leads to better resolved pipes and surface reflections. The amplitude of these reflections is however less pronounced than those shown in the LF-antenna profile.

The time-domain image resulting from the fusion of the data acquired with the two horn antennas is shown in Fig. 5(c). The broader bandwidth associated with the composite radar-gram enhances the resolution of the reflections accounting for the utilities and layers while preserving an investigation depth equivalent to what was observed for the LF antenna. As antenna effects are filtered out, the two-way travel times between the antenna, the sand surface, and the pipes can therefore be more accurately retrieved using, for example, the straight-ray propagation assumption. The same conclusions can be drawn for all the other profiles acquired during the far-field laboratory experiment. Therefore, we extended the methodology to provide the 3-D visualization of the GPR data.

Fig. 6 shows the 3-D image of the sandbox after the removal of the antenna effects and the fusion of the data acquired with the two horn antennas. We used a WebGL-based viewer for large point clouds named *Potree* (<http://potree.org>) to visualize the processed GPR data. Before visualization, we selected a transparency threshold and applied it to all GPR images. We chose to display amplitudes superior or equal to 4% of the maximum absolute amplitude. The horizontal and vertical sizes of the meshes exhibited in Fig. 6 are equal to 0.2 m. The results show the con-

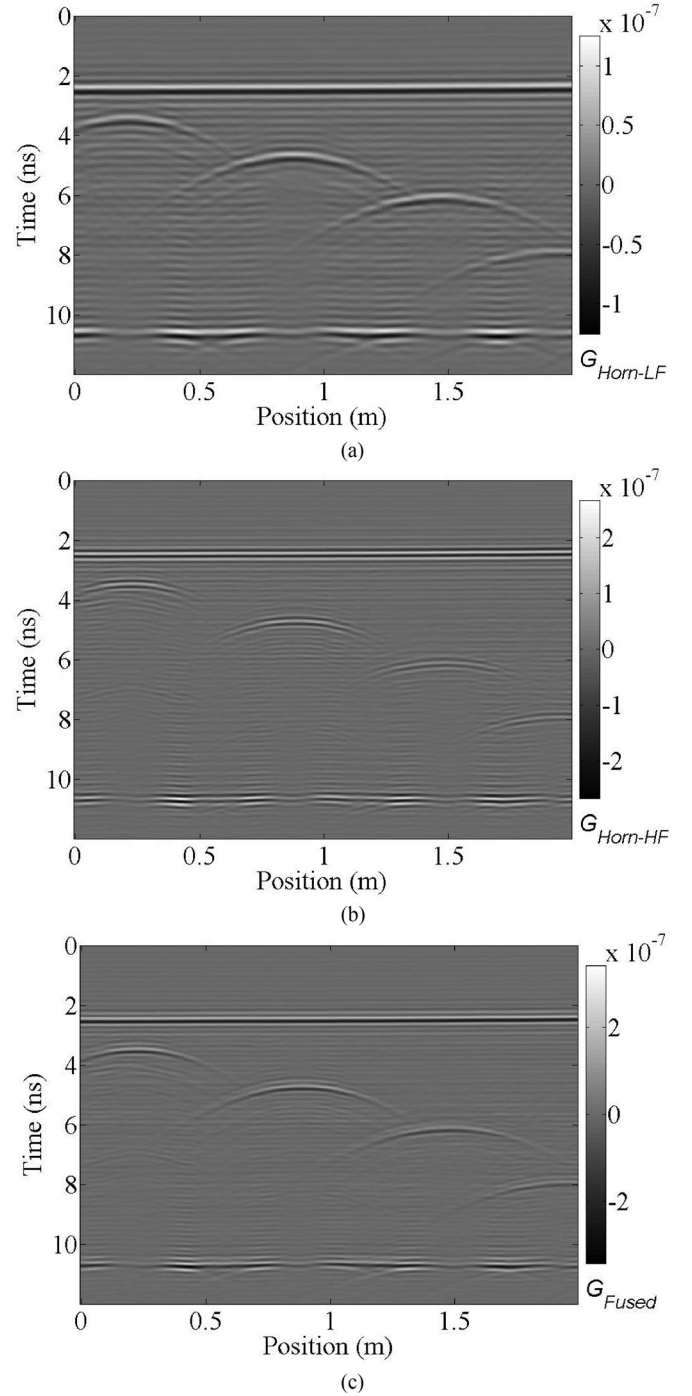


Fig. 5. Time-domain Green's functions with respect to (a) the data acquired with the horn LF antenna (0.8–3.7 GHz), (b) the data acquired with the horn HF antenna (3.3–6.2 GHz), and (c) the fused data (0.8–6.2 GHz).

tinuity of the hyperbolas describing the pipes as well as the PEC and the surface reflections. More generally speaking, the data fusion procedure improves the resolution of the GPR images and allows locating the pipes with a higher accuracy. Compared to raw images, it results in an enhanced discrimination of the pipes with respect to the surface and PEC responses. Through this laboratory experiment, we demonstrated that combining the physically based antenna effect removal with the proposed

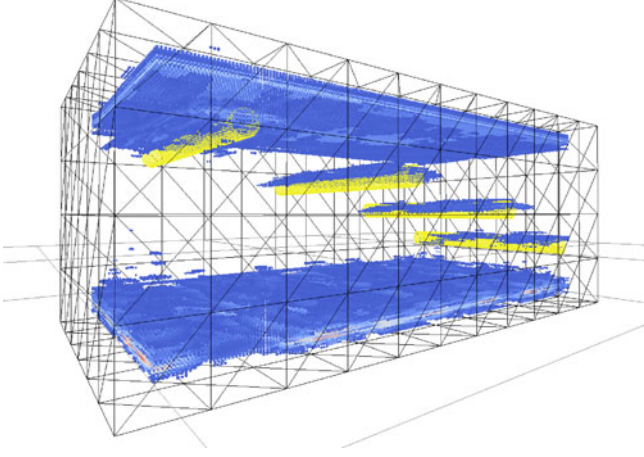


Fig. 6. 3-D time-domain (nonisometric) view of the fused data (frame scale: 20 cm).

data fusion is an efficient strategy to improve the subsurface visualization.

B. Near Field

1) *Study Case n° 1:* We performed a similar experiment to what was done in far-field conditions for near-field conditions. We acquired spatially coincident profiles with the horn and tapered slot Vivaldi antennas and selected the trace corresponding to the middle of the profiles. Fig. 7(a) shows the frequency domain representation of the frequency-limited raw radar signal of each antenna. The analysis of the amplitude and the phase of the radar measurements evidences again that the fusion of raw data cannot be conducted properly due to the different antenna gains with frequency. The conclusions drawn for this specific case are also valid for the fusion of the other traces.

Fig. 7(b) shows the filtered signals in the frequency domain. The results evidence that the amplitude jumps at the extremities of the antenna bandwidths are largely less pronounced than in the raw data. The phase of the filtered signal presents the same behavior as in far-field conditions. The small discrepancies observed for overlapping frequencies arise from the following causes: The numerical errors that occurred during the optimization of the parameters and the calibration of the antennas, especially the one conducted for the horn antenna. The source/field points used to model the antenna are arranged in a line, which could explain why the modeling aspects are really good for the tapered slot Vivaldi antenna (planar shape) and only satisfy the horn antenna (hexahedral shape). However, these observable discrepancies do not prevent us to highlight the benefits brought by the filtering approach with respect to data fusion.

The near-field data fusion principle was therefore extended to the entire GPR profiles acquired with each antenna. The time-domain raw data of the tapered slot Vivaldi antenna shown in Fig. 8 allow identifying the PEC reflection even if its amplitude is quite weak. The shallowest pipe is barely distinguished. The two other pipes located at the center and the right of the profile are, for their parts, not detected. The relatively low permittivity

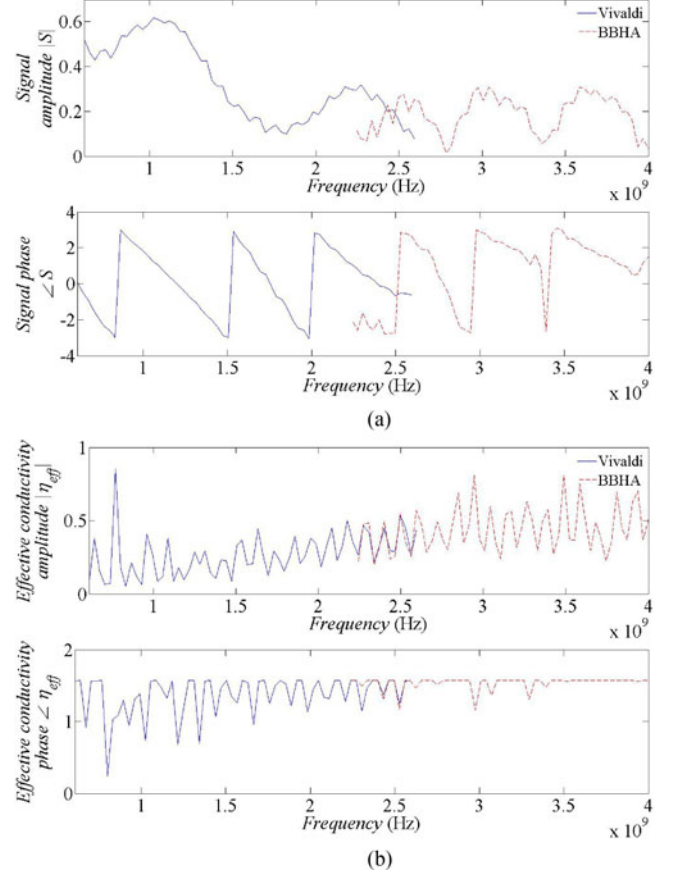


Fig. 7. (a) Raw radar data and (b) complex effective conductivities in the frequency domain regarding the tapered slot Vivaldi and horn antennas.

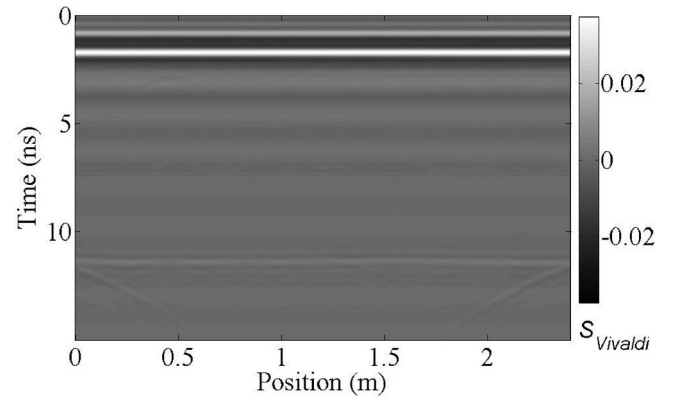


Fig. 8. Time-domain raw data acquired with the tapered slot Vivaldi antenna in the frequency range 0.6–2.6 GHz.

contrast existing between the sand ($\epsilon_r \approx 2.8$) and the pipes filled with air ($\epsilon_r \approx 1.0$) makes the detection of the pipes more complicated. The horizontal reflections appearing in the early part of the radar waveforms represent the multiple reflections occurring within the antennas. The antenna effects prevent the detection of the surface reflection. Regarding the horn antenna data, the interpretation of the raw data processed for the selected frequency range is pretty much the same.

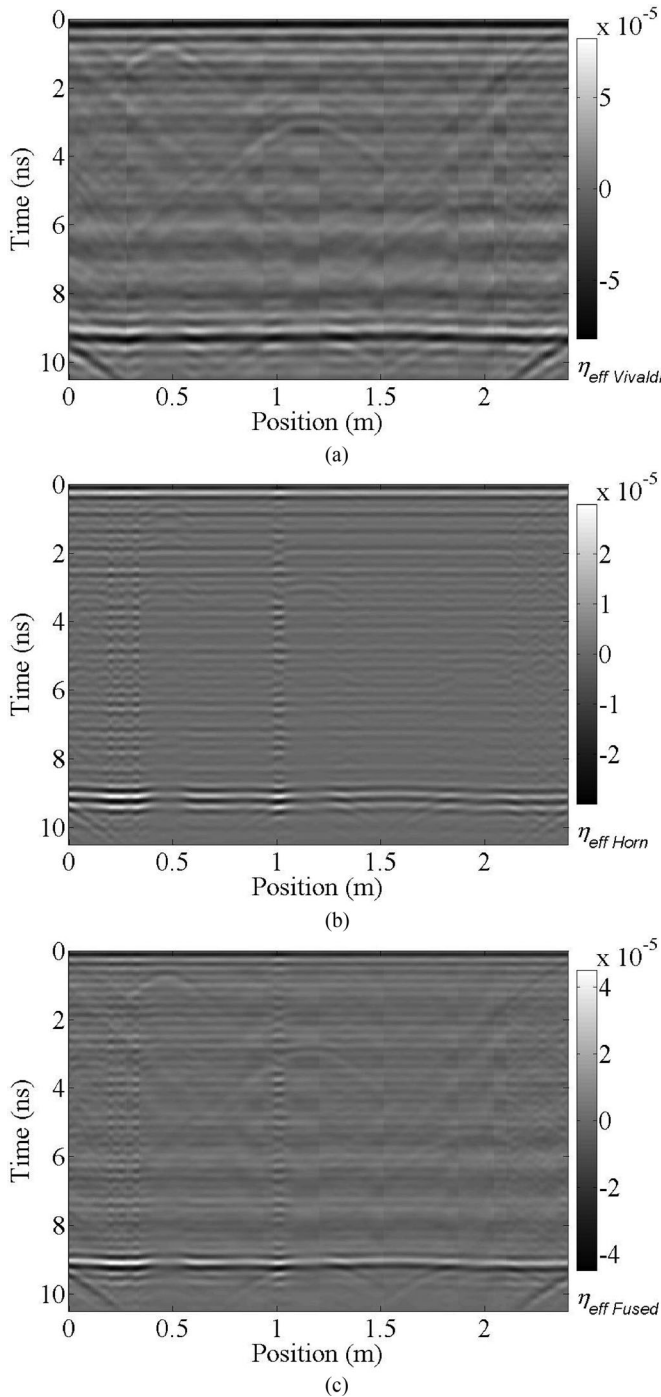


Fig. 9. Time-domain complex effective conductivity with respect to (a) the data acquired with the tapered slot Vivaldi antenna (0.6–2.6 GHz), (b) the data acquired with the horn antenna (2.2–4.0 GHz), and (c) the fused data (0.6–4.0 GHz).

The antenna effects were removed from the GPR images according to the methodology described in Section III-B. The time-domain complex effective conductivity computed for the tapered slot Vivaldi and horn antennas are shown in Fig. 9(a) and (b), respectively. The filtering procedure regarding the tapered slot Vivaldi antenna shows substantial enhancements. The surface reflection is clearly identifiable and always appears at

the same propagation time (0 ns) despite the varying antenna height. In addition, the antenna internal reflections as well as the antenna-medium multiple reflections are removed. As a consequence, the PEC and the reflections of the three pipes are more easily distinguished compared to what was observed in raw radar data. The deepest hyperbola shows a weak amplitude contrast, which makes its detection more difficult compared to the two shallowest ones. The edge effects are clearly visible at the corner of the GPR image. The aliasing effects and the vertical artifacts (few in numbers) are, in this case, the only drawbacks generated by the numerical filtering method. It is worth noting that the propagation time observed here between the surface and PEC reflections differs from the one recorded in the far-field laboratory experiment (see Fig. 5). This difference is due to the preparation of the experimental setups. We buried and extracted pipes before conducting each set of measurements but the sand was not necessarily kept at a constant level.

The image related to the horn antenna shows a little bit more contrasted results. The surface and PEC reflections can be easily detected. They are observed at the same propagation times than those computed for the tapered slot Vivaldi antenna. The hyperbolic shapes describing the pipe-medium contrasts are only visible for the two shallowest pipes. Moreover, these contrasts are slightly pronounced, which makes the detection of the pipes more difficult to achieve. The small permittivity contrast existing between the sand and the pipes prevents the detection of the deepest pipe. The restricted bandwidth and the distribution of the field/source points over the antenna aperture in the modeling approach explain the numerical errors associated to the filtering approach and create the pseudolinear artifacts observed in the image. An optimized distribution of the source and field points would have improved the pipe visualization. Despite these difficult detection conditions, the data fusion principle was successfully applied.

The results of the data fusion procedure are shown in Fig. 9(c). Compared to the filtered image of each antenna, the resolution of the composite image is significantly better due to the broadening of the bandwidth. The benefits of the data fusion are especially highlighted at the level of the surface and PEC reflections. We observed a unique but coarse PEC reflection after filtering the data acquired with the tapered slot Vivaldi antenna [see Fig. 9(a)] whereas the PEC is characterized by a two-peak reflection for the data collected with the horn antenna [see Fig. 9(b)]. The higher frequency content of the horn antenna generates more oscillations for a given time window in the time domain, thereby explaining why the PEC reflections are characterized by two peaks (limited resolution due to narrow bandwidth). On the contrary, one well defined horizontal reflection is present in the fused image [see Fig. 9(c)], which enables us to accurately identify the position of this reflector. The two shallowest hyperbolas are easily detected and also present a refined resolution. However, the fused image is impacted by the numerical errors associated to the antenna effect removal applied on the horn antenna raw data. The artificial clutter brought by this processing step avoids detecting the deepest pipe. Thus, this laboratory experiment highlighted the need to improve the accuracy of the proposed approach especially to deal with low

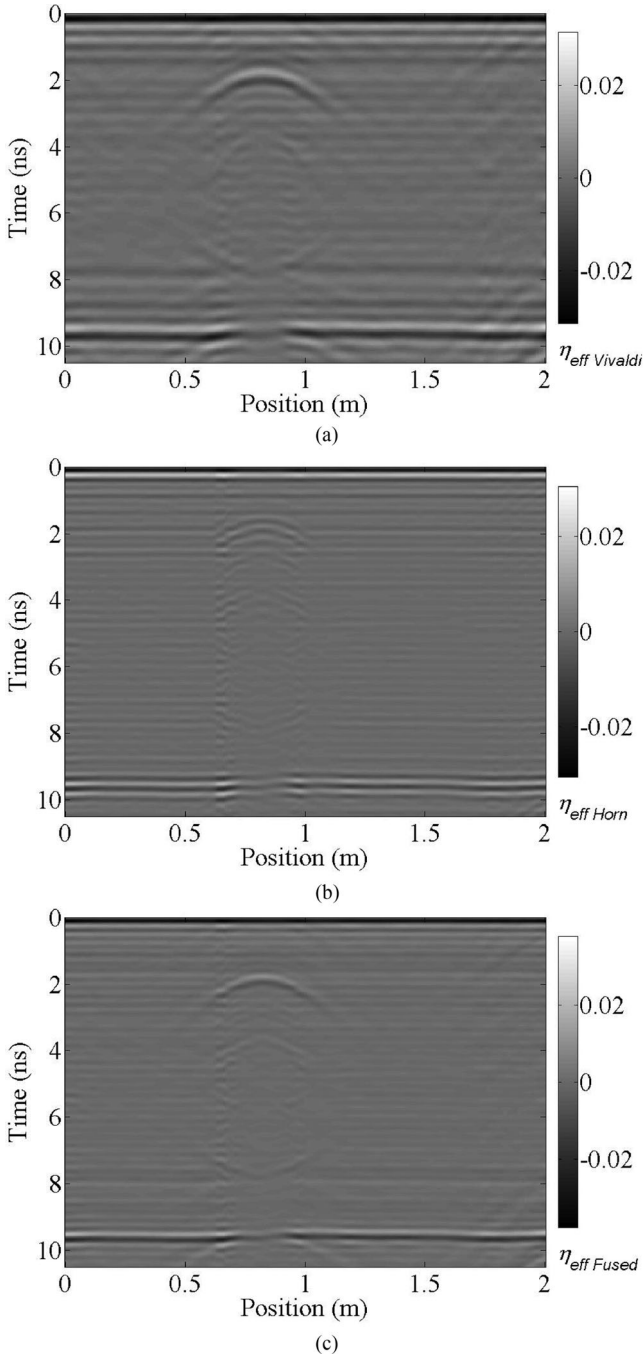


Fig. 10. Time-domain complex effective conductivity with respect to (a) the data acquired with the home-made Vivaldi antenna (0.8–2.6 GHz), (b) the data acquired with the horn antenna (2.2–4.0 GHz), and (c) the fused data (0.8–4.0 GHz).

contrasts. It is worth noting that, like the PEC, objects having electromagnetic properties that deviate from those of the sand would be easier to detect in the fused radar image. However, in spite of these limitations, the near-field mechanistic data fusion strategy showed its ability in bringing additional information for improving the radar image interpretation.

2) *Study Case n° 2*: The same methodology was applied for data acquired over the metallic pipe buried in the sandbox. The raw data (not shown here) are quite similar to what was observed for the previous study case except that the hyperbola

accounting for the pipe is more discernible. The time-domain complex effective conductivity computed for the home-made Vivaldi and horn antennas are shown in Fig. 10(a) and (b). We observe in both figures that antenna effects were removed from raw data and also that we get rid of the antenna height effect. As a consequence, the metallic pipe and the PEC reflections are easily detected due to the high electromagnetic contrast between these objects and the sand. Some numerical artifacts are nonetheless noticed, especially for the home-made Vivaldi antenna. However, Fig. 10(c) evidences that it does not prevent us to properly merge the data and to provide a composite image having a better resolution. The enhancement of the resolution resulting from the data fusion is mainly observed at the level of the PEC and the pipe reflections. This second study case highlights the ability of the physical data fusion approach in merging data coming from antennas operating in different frequency ranges.

VI. CONCLUSION AND PERSPECTIVES

In this paper, we proposed a physically based method to properly merge the data acquired with two antennas operating in different frequency ranges. Two strategies were developed to achieve this task, respectively, in far- and near-field conditions. Both of them required a preliminary removal of the antenna effects prior to data fusion. This step allowed deriving the response of the medium through Green's functions and complex, frequency-dependent effective conductivities for far- and near-field conditions, respectively. The filtered signals were subsequently merged by combining the spectra of the two antennas in the frequency domain and by averaging the overlapping parts. This approach allows removing the distortions arising from the different frequency-dependent gains of antennas and radar sources (e.g., for pulse radars). The resulting 2-D and 3-D images showed substantial improvements in terms of resolution due to the broadening of the bandwidth, either it is in far- or near-field conditions. Even if some numerical limitations have been evidenced in near-field conditions, the data fusion approach showed its efficiency in enhancing the image interpretation. Future research will focus on the optimization aspects related to the antenna effect removal approach as well as on the determination of a better source/field point distribution for nonplanar antennas.

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