Subsurface imaging with low frequency SAR – Field validation in Egypt using a Ground-Penetrating Radar

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ABSTRACT: We study the capabilities of low frequency radar systems to sound the subsurface in arid countries. This approach is based on the coupling between two complementary radar techniques: the airborne Synthetic Aperture Radar (SAR) used in L-band (1.2 GHz) for imaging large scale subsurface structures, and the Ground-Penetrating Radar (GPR) used between 500 and 900 MHz for sounding soils at a local scale, from the surface down to several meters. In this paper, we first recall the results obtained on the well-known site of Bir Safsaf (southern Egypt). The comparison between L-band SAR and GPR sections shows that penetration effects occur in many places, revealing rich subsurface structures. A numerical model is then proposed for quantitatively interpreting the SAR/GPR data. This model is based on electric field extrapolation in the frequency domain, taking into account the looking specificities of both the SAR and GPR systems. Simulated signals from given realistic geological cross sections can then be analyzed in order to understand the contribution of volume backscattering on both of radar systems. These results suggest that airborne radar systems in a lower frequency range (P-L band) should be able to detect soil structures down to several meters, leading to innovative Earth observation systems for geological and hydrogeological mapping in arid regions.

1 INTRODUCTION

In most of arid countries, the durable development of deserts has a growing interest. This development is mainly conditioned by the enlargement and the growth of cultivable domains, depending on the water resource and landscape planning. This statement takes place in a context where new space technologies could offer solutions because of their capacity to measure in time geophysical parameters at large scale. Radar remote sensing technologies has come to maturity and demonstrated its potentialities in several application fields. In addition to surface parameters, as the slope, the roughness and the soil moisture, radar techniques can have access to subsurface information, down to several meters for large wavelengths (Ulaby et al., 1981-86). Our objective is to validate this capability by identifying the radar signature related to subsurface heterogeneity due to geological structures or moisture (Fig.1). We address this problem by using two complementary radar techniques: the polarimetric Synthetic Aperture Radar (SAR) used in L-band (1.2 GHz) for imaging large scale subsurface properties, and the Ground-Penetrating Radar (GPR) used between 500 and 900 MHz for sounding the soils at a local scale from the surface, down to several meters. This geophysical technique provides pseudo cross-sections which can be processed in order to retrieve soil dielectric parameters. We will show that this information can be used to constrain backscattering models in order to quantify the penetration capabilities of SARs.

We applied the SAR/GPR method to a site located in Eastern Sahara, the Bir Safsaf region in south-central Egypt. This site was already intensively studied by McCauley et al. (1982, 1986) and Schaber et al. (1986, 1997), since the SIR-A L-band SAR revealed some buried paleodrainage channels. Bir Safsaf is located in the southern-central Egyptian Desert (Fig.2), close to the Arbain area. This one is

Figure 1. Comparison between a LANDSAT 7 (top) and a SIR-C (bottom) scene of the same 6 x 4 km area. White line represents the 2.5km long GPR profile.
mainly floored by Cretaceous Nubia formation made up of cross-bedded sandstones and shales whose clastic units are informally known as Nubian sandstones, and by low sporadic outcrops of granite and granitic gneiss of the Precambrian African shield. Vegetation is almost entirely absent except at the minor oases or wells, known as birs. The desert floor is mostly covered by yellowish to slightly reddish windblown sand in extensive, thin, and flat sheet deposits.

In order to compare the backscattered power $\sigma_0$, derived from SIR-C data, to GPR signals, we derived from them the $P_w$ parameter, representing the time integrated total power received by the GPR antenna for each acquisition position (Grandjean et al., 2002):

$$P_w(x) = \int_0^{t_{\text{max}}} \sqrt{S^2(x,t) + Q^2(x,t)} \, dt$$  \hspace{1cm} (1)$$

$S(x,t)$ being the GPR amplitude signal recorded at the position $x$ along the profile versus time, and $Q(x,t)$ being the quadrature signal of $S(x,t)$. Figure 2 shows a 900 MHz profile with the $\sigma_0$ and $P_w$ curves (Paillou et al., in press). It can be noticed that the average trend of $P_w$ and $\sigma_0$ curves looks comparable, since it mainly represents the diffuse backscattered volume component in both case. This parameter provides a new valuable tool to help in interpreting SAR images from local GPR acquisitions, revealing subsurface structures over large areas.

But this approach remained qualitative because of the difficulty to identify the different components of the resulting signals and understand their origin. Actually, improving accuracy of coupled SAR/GPR interpretations needs to refer to a physical model able to simulate both SAR and GPR backscattered powers from a realistic subsurface model. In the following, such a model is presented with emphasis on stated physical hypotheses. Modeling is applied to the Bir Safsaf site for demonstrating the perspectives that could be derived in future applications.

2 THE BIR SAFSAF SITE

The simplified subsurface structure proposed in Paillou et al. (in press) was considered (Tab.1). In this five-layer model, the main radar reflector, i.e. the place where most of the incident signal is backscattered, is located at the interface between the compacted sand layer (CSL) and the calcified pebble-gravel (CPG). As it was described by Schaber et al. (1986, 1997), the incident radar wave penetrates the first modern sand sheet (MSS) and compacted sand layers, and is reflected and diffused by the rougher CPG layer that generally covers the “Nubia sandstone” bedrock (NSB). Observed paleodrainage channels are generally filled with small pebble alluvium (SPA), sometimes containing CPG and sandstone gravels (Fig.3).

This simple model for the near surface is also consistent with recent studies by Maxwell et al. (2001), which conclude that the actual landscape is a combination of an initial fluvial landscape inherited from Tertiary erosion, and climatic cycling during the Quaternary that formed the low relief aeolian surface. As the first sand layers are rather transparent for the radar, sand deposits that could produce surface changes have a low effect on the backscattered signal that remains constant over time. The main part of the observed SAR signal is constituted of the backscattered component due to a buried interface that is then very stable with time (Fig.4).
Figure 4. Observed GPR profile and related power curves (From Paillou et al., in press).

Table 1. Dielectric model compiled from Paillou et al. (2003). Variance and correlation length of soil texture were estimated from field observations (Fig. 5). Averaged values of the dielectric permittivity were measured on soil samples.

<table>
<thead>
<tr>
<th>Height (m)</th>
<th>Name</th>
<th>Variance</th>
<th>Correlation Length</th>
<th>Dielectric Permittivity</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>MSS</td>
<td>0.05</td>
<td>0.20</td>
<td>2.85+i0.05</td>
<td>60</td>
</tr>
<tr>
<td>0.05-1</td>
<td>CSL</td>
<td>0.07</td>
<td>0.05</td>
<td>2.95+i0.08</td>
<td>40</td>
</tr>
<tr>
<td>0.5-2</td>
<td>SPA</td>
<td>0.10</td>
<td>0.02</td>
<td>3.15+i0.15</td>
<td>20</td>
</tr>
<tr>
<td>0.05-0.5</td>
<td>CPG</td>
<td>0.15</td>
<td>0.07</td>
<td>3.80+i0.17</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>NSB</td>
<td>0.05</td>
<td>0.20</td>
<td>3.55+i0.16</td>
<td>20</td>
</tr>
</tbody>
</table>

3 THE NUMERICAL MODEL

Most of the power received by radar system comes from dielectric contrasts existing in the medium due to volume scatterers and layer roughness. Computing the received power cannot be realistically performed without taking into account such heterogeneities. Because of the difficulty to consider them in a deterministic manner, we opted for random descriptions of the dielectric medium. By computing random realizations with a spectral method, their implementation in the propagation model becomes easy because the formulation is fully developed in the Fourier domain.

The random dielectric medium

We describe the medium as a random continuum where the dielectric constant $\varepsilon(x)$ is a continuous function of position. Taking the Gaussian model as more appropriated to describe dielectric fluctuations in soils (Chilès and Delfine, 1999), the correlation function is then defined by:

$$B_n(r) = \langle n^2 \rangle \exp(-r^2/l^2)$$

where $r$ is the radial distance between two points of the medium, $\langle n^2 \rangle$ is the variance and $l$ is the correlation length for which the correlation function falls off to $e^{-1}$ for $r=0$. We then define the spectral density $\Phi_n(k)$ of the medium as the Fourier transform of $B_n(r)$. In two dimensions, the spectral density function can be computed by the spectral stochastic simulation method (Pardo-Iguzquiza and Chica-Olmo, 1993). In this technique, the amplitude and phase components are respectively related to the spectral density $\Phi_n(k_x,k_y)$ and a random series comprised between 0 and $2\pi$. Imposing that coefficients are hermitian, the inverse Fourier transformation of these quantities then produces a simulated random field respecting the given covariance properties. As example, figure 5 shows simulations for two geological layers featuring the Bir Safsaf site (Tab. 1). If the inverse Fourier is not applied, we keep the random field expressed in the Fourier domain, and we have a quick and accurate protocol for computing directly the dielectric impedance field $R(k_x,k_z)$. It is finally inserted in the propagation model without difficulties as described in the following.

Figure 5. Simulated random fields of the real relative dielectric permittivity related to a) MSS and b) SPA layers.

The propagation model

In the last few years, several physical models based on ray tracing (Powers, 1995; Cai and McMechan, 1995), finite differences (Moghaddams et al., 1991) or pseudo-spectral methods (Carcionne, 1996), have been developed to propagate radar waves. The modeling method used here was initially conceived to simulate GPR experiments in heterogeneous and dispersive media. Because the GPR is running in monostatic mode, the algorithm uses the exploding reflector principle (Claerbout, 1985), where the up-going field $E^+$ diffracted from the local dielectric contrasts and recorded to the receiver is only considered, providing that velocities are divided by two. The two dimensional calculated GPR signal is then expressed in the Fourier domain by:

$$E(k_x,k_z)=E^+(k_x,z,\omega)e^{-ik_zz}$$

(3)

where $k_x$ and $k_z$ are the wavenumbers in the $x$ and $z$ direction, and $\omega$ is the angular frequency. The implementation of this model was performed by using a phase shift technique (Gazdag, 1978; Stoffa et al., 1990) in the $\omega-k$ domain (Bitri and Grandjean, 1998) which provides low computation times without neglecting main physical processes of radar waves propagation (Grandjean et al., 2001). In this algorithm, the medium can be parameterized accord-
ing to a numerical grid, so that dielectric discontinuities—such as geological layers—can be introduced. Frequency, bandwidth, polarization mode of the signal, can also be stipulated. The slit-step technique then allows propagating the $E$-field from the model maximum depth to the surface. This is the basis of the proposed model.

To meet the above-mentioned needs, two main specificities have furthermore to be considered: (i) the model has to work with heterogeneous media, including multi-layers, complex geometry, and volume and interface roughness, since the subsurface is highly heterogeneous at the considered wavelengths; (ii) both SAR and GPR systems specificities have to be taken into account, especially for the incidence and beam width angles.

The heterogeneity of the medium can be specified by the random dielectric impedance $R(k_x, k_z)$ above-defined. For extrapolating the $E$-field along the the $z$-axis, we must insert the $z$-Fourier transformed quantity $R(k_x, z)$ into (3). This lead to extrapolate the $E$-field from the $z$-$\Delta z$ to $z$ depth:

$$E(k_x, z = z - \Delta z, \omega) = \int R(k_x, k_z) e^{-ik_zz} \, dk_z.$$

$$E^*(k_x, z, \omega) e^{-ik_z\Delta z}$$

The integration of the looking characteristics is also hardly simplified since the antenna radiation patterns can be simply imposed with a Blackman angular filter $A(k_x, k_z)$ depending on the spatial wavenumbers. This filter is centered on the incidence angle, $a \tan(k_x / k_z)$ and is defined for a bandwidth adapted to the radar mode:

$$E(k_x, z = z - \Delta z, \omega) = \int A(k_x, k_z) R(k_x, k_z) e^{-ik_zz} \, dk_z.$$

$$E^*(k_x, z, \omega) e^{-ik_z\Delta z}$$

In that scheme, GPR and SAR system modes will be respectively features by a zero and 45° incidence angles, with large (45°) and narrow (2°) half-aperture angles. From (5), we are now able to compute the calculated $\sigma_0$ and $P_W$ as described in (Grandjean et al., 2002), except that we need to take into account the reference level at which the $E$-field is calculated for each system. The GPR antennas emit and record the radar waves in the first few centimeters of the ground, while the SAR systems are operating in the above air layer. We thus need to consider that the SAR power is furthermore affected by the first specular reflection along the air/ground interface. The following factor $R_0$ is multiplied to the calculated powers defined in (5) in order to compensate this effect:

$$\begin{cases} 
\text{for GPR : } R_0 = 1 \\
\text{for SAR : } R_0 = 10.\log(1/e) 
\end{cases}$$

4 DISCUSSION

We aim now to integrate this geological interpretation into a physical model in order to understand the relationship between soil structures and recorded radar signals. The first step consists in building a dielectric model so that (i) it reproduces structures observed on the GPR section, (ii) volume heterogeneities respects those observed on the subsurface excavation and (iii) dielectric parameters refers to measured ones (Tab.1). Because we use a grid to parametrize the model, its dimensions must be reasonable not to overflow the computer’s memory.

We opted for a 400 m long by 2.5 m deep profile (Fig.6) which restricted the grid size to around 4.6 $10^6$ cells for a nominal frequency of 900 MHz. The power curves were then computed both in the GPR and SAR modes, with incidences of 0° and 45°, and with half-aperture angles of 45° and 2° respectively. To decrease effects of local variations the curves were smoothed with a sliding average window of 12 m, corresponding to the SAR pixel size.

Figure 7 compares observed with computed $P_W$ and $\sigma_0$ curves. Among the similarities that can be observed, one is related to the relative power difference between GPR and SAR (around 20 dB), both in observed and calculated cases. We also note that curves decrease in the same manner when the dielectric structure is deepening: from 0 to -15 dB for GPR and from 15 to almost -30 dB for SAR. Concerning GPR curves, a relatively good correlation between observed and calculated ones is shown, especially for medium and large wavelengths. Even if discrepancies occur in some place, they don’t exceed few decibels and concern local dielectric variations of soil that are difficult to measure and to integrate in the model. These differences thus remain acceptable both in amplitude and wavelength so that the model can be considered as reliable for GPR simulations. On the other hand, the comparison between observed and calculated $\sigma_0$ appears less easy. As it was
already observed in Paillou et al. (in press), these curves have the same global tendency but anomalies of 5 to 10 dB make them locally uncorrelated for medium and short wavelengths. This effect probably comes from the 2D approximation introduced in the modeled structures. Actually, the calculated $\sigma_0$ is averaged on a distance of 12 m along the profile, but depends only to the structures of the 2D dielectric model. In the contrary, the observed $\sigma_0$ is averaged on a pixel of 12 by 12 m; the structures located aside the profile affect even more the measured $\sigma_0$ since the structures are laterally changing. This last point should prompt us to consider 3D dielectric models in order to take into account variations along the strike direction, at least on a distance comparable to the pixel size. Except limitations related to computing resources, 3D models can easily be implemented in the algorithm scheme by considering 3D Fourier transforms instead of 2D ones. This will be the main perspective planned for the next mission: operating GPR so that several parallel profiles give information on lateral variations, and simulating subsurface GPR so that several parallel profiles give information on lateral variations, and simulating subsurface imaging in moderate dispersive media, Geophysical Prospecting, vol 60, pp. 87-96.


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