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Summary

Crossed dipole (cross-pole) antennas are not commonly used for ground penetrating radar (GPR) measurements, but can contain valuable information about the subsurface. Recently, a multi-component imaging algorithm has been derived which combines parallel dipole (co-pole) and cross-pole antenna measurements to obtain an image of the subsurface. The performance of this multi-component imaging algorithm is investigated by imaging modelled data of a point scatterer with a conductivity (real-valued) contrast in a homogeneous halfspace. The imaging is carried out for one single frequency at the depth of the point scatterer, which results in a resolution function. The contributions of the cross-pole and co-pole antenna measurements are imaged separately. The combination of the cross-pole and co-pole antenna imaging results show a circular-symmetric real-valued resolution function, which adequately represents the point-scatterer. Experimental results show that cross-pole antenna measurements contain valuable information of objects present in the subsurface, which is shown for an oblique pipe.

Introduction

Three-dimensional (3D) data collection and imaging of GPR data is becoming more and more feasible for commercial use. This is caused by the increased computing power and the development of user-friendly GPR systems. The three important parameters, which must be incorporated in the imaging algorithm to obtain a good image of the subsurface are, in order of importance, the wave speed, the polarisation and the radiation characteristics of the source and the receiver antennas. Radzewicius and Daniels (2000) showed that a maximum reflection from a buried pipe is obtained when the polarisation of the electric field is parallel oriented with respect to the orientation of a pipe. Guy et al. (1999) showed that cross-pole antenna measurements contain valuable data that was successfully used for site characterisation.

Several 3D imaging algorithms exist for GPR data, but most of them are based on scalar (seismic) imaging algorithms. Recently more and more attention is paid to incorporate the radiation patterns of source and receiver antennas and the vectorial character of the electromagnetic waves in the imaging algorithms for GPR data (Wang and Oriastaglio, 2000). Van der Kruk et al. (2000; 2001) derived a multi-component imaging algorithm, which uses cross-pole antenna measurements together with co-pole antenna measurements. In this paper, the contribution of the cross- and co-pole measurements to the final image is investigated.

Forward model

Van der Kruk et al., (2000; 2001) showed that a bounded imaging operator was obtained by combining more components of the measured electric field and used a tensorial description of the scattering formalism. This tensorial scattering formalism describes the influence of the wave speed, polarisation and radiation characteristics of the source and receiver on the measured reflections and is given for the zero-offset scattering mechanism by

$$\hat{E}(\mathbf{x}^M, \omega) = \hat{S}(\omega) \int_{\mathbf{x}^c \in \mathbf{D}^c} \hat{D}(\mathbf{x}^M - \mathbf{x}^c, \omega) \chi(\mathbf{x}^c) dV, \quad (1)$$

where \(\mathbf{D}^c\) is the scattering domain, \(\mathbf{x}^M\) is the position of the source and receiver antenna and \(\hat{E}(\mathbf{x}^M, \omega)\) is given by

$$\hat{E}(\mathbf{x}^M, \omega) = \begin{pmatrix} \hat{E}_{11} \\ \hat{E}_{12} \\ \hat{E}_{21} \\ \hat{E}_{22} \end{pmatrix}(\mathbf{x}^M, \omega). \quad (2)$$

The quantity \(\hat{D}(\mathbf{x}, \omega)\) is the tensorial 3-D two-way wave field extrapolator for zero-offset, which consists of the inner-product of two Green’s functions. The first Green’s function describes the propagation of the vectorial electric field due to an electric current source \(J\) to the location of the contrast \(\chi\) at position \(\mathbf{x}^c\). The second Green’s function describes the propagation from the scatterer at \(\mathbf{x}^c\) towards the receiver (van der Kruk et al., 2001). The quantity \(\hat{E}_{\alpha\beta}\) describes the propagation from the scatterer to the location of \(\chi\) at position \(\mathbf{x}^c\). The contrast \(\chi\) is defined as \(\chi = \hat{\eta}^s - \hat{\eta}\), where \(\hat{\eta}\) and \(\hat{\eta}^s\) describe the properties of the background and the scatterer, respectively.

Synthetic data

To show the response for co-pole (\(E_{11}\) and \(E_{22}\)) and cross-pole (\(E_{12}\) and \(E_{21}\)) antenna setups, synthetic data were calculated using far-field expressions for a dipole source and receiver present on a dielectric halfspace for a real-valued contrast \(\chi = \sigma^s - \sigma = 1\). A point scatterer is present below the origin at a depth of 0.6 m. The response in the frequency-domain for \(f = 500\) MHz is depicted in Figures 1 and 2 for the co-pole (\(E_{11}\)) and the cross-pole (\(E_{21}\)) configurations, respectively. The modelled data were calculated for \(\mathbf{x}^M \in \mathbf{D}^{RR}\), where \(-1.6 < x^M_1 < 1.6\), \(-1.6 < x^M_2 < 1.6\) and \(x^M_3 = 0\). Note that the response of \(E_{21}\) in Figure 2 changes polarity across the symmetry.

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Multi-component imaging

For the multi-component imaging algorithm, two horizontal components of the electric field are measured and combined to obtain an image of the subsurface. The inverse wavefield extrapolators for the co-pole ($\vec{H}_{11}$) and the cross-pole ($\vec{H}_{12}$) configuration are denoted by $\vec{H}_{11}$ and $\vec{H}_{12}$, respectively. The inverse wavefield extrapolators $\vec{H}_{11}$ and $\vec{H}_{12}$ are obtained by a matrix inversion in the spatial Fourier domain and take into account the radiation characteristics of the source and receiver antennas on a dielectric halfspace and the offset between the source and receiver antennas (van der Kruk et al., 2000; 2001).

To investigate the contributions of each separate component we investigate the imaging of both components separately by introducing

$$\chi_{i}^{co}(x) = \frac{1}{\omega} \frac{d\omega}{S(\omega)} \int \vec{H}_{11}(x^i|x^Z^O,\omega)\vec{E}_{11}(x^Z^O,\omega)dA,$$

$$\chi_{i}^{cross}(x) = \frac{1}{\omega} \frac{d\omega}{S(\omega)} \int \vec{H}_{12}(x^i|x^Z^O,\omega)\vec{E}_{21}(x^Z^O,\omega)dA,$$

and

$$\chi(x^i) = \chi_{i}^{co}(x^i) + \chi_{i}^{cross}(x^i).$$
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Spatial resolution functions

The contributions of $\chi^{co}_1$ and $\chi^{cross}_1$ to the multi-component imaging result $<\chi(x')I>_{11}$ is investigated by imaging a point scatterer in a homogeneous halfspace for one single frequency $f = 500$ MHz at the depth of the point scatterer, which results in a resolution function. In Figures 5 and 6 the imaging results are depicted using the cross-pole measurement $\chi^{cross}_1$ and the co-pole measurement $\chi^{co}_1$, respectively. Note that the imaginary part of $\chi^{cross}_1$ is in antiphase with the result of $\chi^{co}_1$. Adding both results will return an imaginary part which equals zero and thus a real-valued resolution function which is circular symmetric (see Figure 7). This is an adequate representation of the point scatterer, which shows no longer the angle-dependency of the source and receiver antennas as is the case for scalar imaging algorithms (van der Kruk et al., 2001).

Experimental results

Measurements were made with the 900 MHz pulseEKKO system using different polarisations of the source and receiver antennas in a controlled testing environment. For the multi-component imaging result, surfaces of constant absolute value are plotted in Figure 8 where both $\chi^{co}_1 + \chi^{cross}_1$ are used. In Figure 9 a depth slice shows the separate contributions of the cross- and co-pole measurements to the final multi-component imaging result. The presence of the oblique metal pipe (object G) is clearly indicated. Note that the image result using the cross-pole antennas has a smaller amplitude compared with the image result using the co-pole antennas, but contains valuable information. Due to the manual acquisition of the data, positioning errors occurred, which probably resulted in a distorted image. This is especially the case for the cross-pole imag-
Fig. 8: Multi-component imaging result using 900 MHz pulseEKKO antennas.

Fig. 9: Depth slice at $x_3 = 0.45$ m. to investigate the contributions of the cross- and co-pole measurements on the imaging of objects D, E and G.

Conclusions

The multi-component imaging algorithm uses both co-pole and cross-pole antenna configurations to obtain an image of the subsurface. Synthetic results show that important information can be obtained using the cross-pole measurements and a combination with the co-pole measurements returns a circular symmetric real-valued resolution function. Experimental results show that cross-pole antenna measurements contain valuable information of objects present in the subsurface, which is shown for an oblique pipe.

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