Frequency domain analysis of the polarimetric ground penetrating radar response of landmines and minelike targets

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ABSTRACT

This paper presents a study on using polarimetric ground penetrating radar (GPR) for the identification of plastic antipersonnel mines. In general, the polarimetric radar response of a surface-laid or buried object depends on the orientation of the object with respect to the transmitting and receiving antennas. Hence, in order to make identification possible, it is crucial to measure the full scattering matrix and transform the data into the target frame, in which the response is orientation independent. In this paper, we present an impulse ultrawideband ground penetrating radar with a polarimetric antenna system. Using this radar, the scattering matrices for a set of surface-laid targets with different shape and internal structure have been measured. The measurements were done for different target orientations. Transformation of the measured response into the target frame was achieved by matrix diagonalization in the frequency domain. The eigenvalues obtained by matrix diagonalization constitute a set of orientation invariant features and have been studied as possible target discriminators. In particular, we addressed the problem of classifying targets with respect to shape (rotationally symmetric versus elongated). The results suggest the possibility to distinguish between targets by looking at how the eigenvalues change as a function of frequency. Moreover, matrix diagonalization yielded an angle of orientation and the significance of this angle for small minelike targets and elongated targets is discussed. The analysis was repeated for scattering matrices acquired over buried targets and the results are compared against those obtained for the surface-laid objects.

Keywords: polarimetric ground penetrating radar, landmine identification, scattering matrix, frequency domain, target frame, orientation invariant target features

1. INTRODUCTION

Ground Penetrating Radar (GPR) is a sensing technique, which uses electromagnetic waves to locate objects or interfaces beneath the surface of the earth or man-made structures. Recently, the possible use of GPR for the detection and identification of landmines has received a lot attention for the following reasons. First, since GPR provides a target scattering signature, it is possible not only to detect but also to identify objects. Second, using GPR dielectric and conductivity discontinuities can be detected; thus this technique can detect metal and plastic, surface-laid and buried targets. Furthermore, the antennas of a GPR system do not need to be in contact with the ground thereby allowing rapid and less dangerous surveying.

With a polarimetric GPR system, the scattered field is measured by two receiving antennas: one oriented parallel and the other perpendicular to the transmitting antenna. Typically all antennas are linearly polarized. The two receiving antennas measure the co-polar and the cross-polar components of the field scattered by the target, which determine its

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polarization.[1] The polarization of the scattered field depends not only on the polarization of the incident field but also on target characteristics such as size, shape, composition and the orientation of the target.[2] Therefore, analysis of the polarimetric target response can provide information about these target characteristics. Moreover, in some cases it is possible to determine the orientation of the target.

To make target identification possible, it is necessary to obtain a polarimetric scattering response that is independent from the orientation of the antenna system with respect to the target. This is achieved by matrix diagonalization, which transforms the polarimetric response into the so-called target frame. In the target frame, the scattering matrix is diagonal and its diagonal elements are orientation independent target features.

So far research on polarimetric GPR has focused on data analysis in the time domain.[3,4] This approach produced good results when extracting linearity and orientation features from the late-time response of subsurface unexploded ordnance (UXO)[3] and determining the orientation of geological structures and pipes[4]. In this paper, a frequency domain approach was chosen since experience showed that diagonalization results are easier to interpret when working with scattering matrices that are scaled by the incident field through multiplication rather than convolution.

We describe the measurement and analysis of polarimetric scattering responses for a set of surface-laid and buried minelike targets and pipes. The data were collected in the time domain with two polarimetric ultrawideband GPR systems developed at the International Research Centre for Telecommunications-transmission and Radar (IRCTR). As mentioned in the previous paragraph, all data were transformed and analyzed in the frequency domain. The main objective of the analysis was to obtain orientation independent target features. Since a lot of antipersonnel mines have a rotationally symmetric casing/shape, we investigated the possibility to use the polarimetric scattering response to classify targets into rotationally symmetric or elongated objects. Furthermore, the polarimetric data analysis provided an angle of orientation and the significance of this angle with regard to target orientation is discussed.

The paper is organized as follows. In section 2, a brief review of the theory of polarimetric GPR including the transformation of the scattering matrix into the target frame is given. Section 3 describes laboratory GPR measurements over a set of surface-laid minelike targets. The polarimetric processing of the laboratory GPR data is presented in section 4. In section 5, more data examples and processing results are shown, which have been obtained for buried targets. A concluding discussion on the use of polarimetric GPR measurements and processing for landmine identification follows in section 6.

2. THEORY

Using a horizontal coordinate representation (x,y), the relationship between the incident field and the field scattered by a target is expressed by the following frequency domain equation:

$$\begin{pmatrix} E_x^s \\ E_y^s \end{pmatrix} = \mathbf{S}(f) \cdot \begin{pmatrix} E_x^i \\ E_y^i \end{pmatrix}, \qquad (1)$$

where E_x^s, E_y^s are the x and y components of the scattered field and E_x^i, E_y^i are the x and y components of the incident field. $\mathbf{S}(f)$ is the scattering matrix with coefficients $S_{xx}(f), S_{xy}(f), S_{yx}(f)$, $S_{yy}(f)$, i.e.

$$\mathbf{S}(f) = \begin{pmatrix} S_{xx}(f) & S_{xy}(f) \\ S_{yx}(f) & S_{yy}(f) \end{pmatrix}, \qquad (2)$$

where $S_{xy}(f)$ is equal to $S_{yx}(f)$ as a result of reciprocity.[5]

When doing polarimetric radar measurements, the scattering matrix is measured in the antenna coordinate frame. For a linearly polarized antenna system, this coordinate frame is determined by the direction of the electric field radiated by the transmitting antenna (*x*) and the direction orthogonal to it (*y*).

In general, the scattering coefficients depend on the orientation of the antenna system with respect to the target. Applying matrix diagonalization, the measured scattering matrix can be transformed into a coordinate frame, which is independent from the antenna orientation and referred to as the target frame. The target frame is defined by the main scattering axis of the target and the axis orthogonal to it.

The scattering matrix in the target frame is diagonal:

$$\mathbf{S}_T(f) = \begin{pmatrix} \lambda_{\parallel}(f) & 0 \\ 0 & \lambda_{\perp}(f) \end{pmatrix}, \tag{3}$$

where $\lambda_{\parallel}(f)$ is the stronger eigenvalue of the scattering matrix $\mathbf{S}(f)$ and $\lambda_{\perp}(f)$ is the weaker one. $\lambda_{\parallel}(f)$ and $\lambda_{\perp}(f)$ describe the scattering behavior of the target along its main scattering axis and the axis orthogonal to it. As $\lambda_{\parallel}(f)$ and $\lambda_{\perp}(f)$ do not depend on the orientation of the antenna system, they constitute a set of orientation invariant target features. How they change with frequency can be used as a target discriminator. In particular, for a perfectly rotational symmetric object $\lambda_{\parallel}(f) = \lambda_{\perp}(f)$, while for an infinitely long and infinitely thin wire $\lambda_{\perp}(f) = 0$. Accordingly, the field scattered by a perfectly rotational symmetric object has the same polarization as the incident field. In contrast, the infinitely long and infinitely thin wire only scatters the component of the incident field parallel to the wire. The electric field reradiated by the wire is linearly polarized and parallel to the wire. In general, for elongated objects like pipes and cables, it is possible to say that they have a preferential scattering axis that coincides with the long axis of the object.

The scattering matrix in the target frame is related to the scattering matrix in the antenna frame by the expression

$$\mathbf{S}_T(f) = \mathbf{V}^t(f) \cdot \mathbf{S}(f) \cdot \mathbf{V}(f) \ , \tag{4}$$

where $\mathbf{V}(f)$ is simply the rotation matrix

$$\mathbf{V}(f) = \begin{pmatrix} cos\alpha(f) & sin\alpha(f) \\ -sin\alpha(f) & cos\alpha(f) \end{pmatrix}. \tag{5}$$

The angle $\alpha(f)$ describes the rotation of the target frame with respect to the antenna frame. It is the angle formed by the *x* axis of the antenna frame and the axis of the target along which maximum scattering occurs. For targets whose target frame coincides with the target geometry, the angle $\alpha(f)$ can be used to find the orientation of the target.

A parameter that quantifies the linearity of the target geometry is the so-called estimated linearity factor $ELF(f)$ defined as:[3]

$$ELF(f) = \frac{\left| |\lambda_{\parallel}(f)| - |\lambda_{\perp}(f)| \right|}{\left| |\lambda_{\parallel}(f)| + |\lambda_{\perp}(f)| \right|} \ . \qquad 0 \leq ELF(f) \leq 1 \tag{6}$$

Since a rotationally symmetric object does not have a preferential scattering axis, for this target $|\lambda_{\parallel}(f)| = |\lambda_{\perp}(f)|$ and $ELF(f)$ is equal to zero. On the other hand, for a highly linear target $|\lambda_{\parallel}(f)| >> |\lambda_{\perp}(f)|$ and $ELF(f)$ is close to 1.

3. LABORATORY MEASUREMENTS OVER SURFACE-LAID MINELIKE TARGETS

Measurements were made over a set of 11 surface-laid targets.[6] This paper only discusses the results obtained for four of these targets, which in the remainder of the text will be referred to as the 'mine 1', the 'mine 2', the 'metal pin' and the 'plastic pipe'. Photographs of these targets are shown in figures 1 and 2. The 'mine 1' and the 'mine 2' consist of a cylindrical plastic casing (8 cm diameter, 4 cm height) filled with paraffin wax. They have been modeled after the PMA-3 antipersonnel mine.[7] The 'mine 1' and the 'mine 2' have equal size, shape and composition except for a metal pin, which has been inserted into the 'mine 2'. This difference allows studying the influence of internal structure and small metal parts on the target response. Paraffin wax was chosen as an explosive substitute because it has a dielectric constant similar to that of TNT used in real mines ($\varepsilon_r \approx 2.2$ for paraffin wax, $\varepsilon_r \approx 2.8$ for TNT).[8] The 'metal pin' is a small metal cylinder (1.2 cm diameter, 5 cm length), which is very similar to the one inside the 'mine 2'. In addition, the results for a 'plastic pipe' are shown in order to analyze and compare the scattering response of an elongated object against that of small minelike targets. The 'plastic pipe' is a PVC air-filled pipe (5 cm diameter, 1 m length).

The measurements were made with the VIRLAD video impulse radar system.[9] Its antenna system consists of a transmitting dielectric wedge antenna and two receiving loops, that are fixed 28.5 cm below the aperture of the wedge antenna (figure 3).[10] The loop antennas are oriented such that they measure the co-polar and the cross-polar components of the field scattered by the target.

The dielectric wedge antenna has tapered metal flairs. It radiates signals over an ultrawide frequency band (260 MHz to 2880 MHz on –20 dB level) with small ringing and has linear phase characteristics over the whole operating frequency band. The signal radiated by the transmitting antenna is shown in figure 4, while figure 5 presents the amplitude spectrum of the radiated signal normalized to its maximum amplitude value. The receiving loops are made of semi-rigid cable (3.8 cm inner diameter, 4.6 cm external diameter). They are linearly polarized and maximal sensitivity is obtained in the frequency band from 1.1 GHz up to 3.3 GHz, which corresponds to its bandwidth on –10 dB level.

The measurements were made with the antenna system positioned right above the target. The scattering response with and without the target was measured in order to determine unwanted reflections such as the reflection from the ground surface and correct for them. The measurements were repeated for different target orientations (0, 45, 90, 135 degrees). The A-scans taken for a target orientation of 0 and 90 degrees were combined to obtain the scattering matrix for the initial target orientation of 0 degrees. Analogously, combining the A-scans measured for a target orientation of 45 and 135 degrees yielded the scattering matrix for the initial target orientation of 45 degrees.

4. DATA ANALYSIS FOR SURFACE-LAID TARGETS

The data analysis consisted of the following processing steps. First, the background was subtracted and time-windowing was applied in order to isolate the target responses. Second, the scattering matrices were transformed into the frequency domain and filtered in order to eliminate high frequency noise. Third, the scattering coefficients $S_{xy}(f)$ and $S_{yx}(f)$ were averaged to remove small deviations from symmetrical form. Matrix diagonalization was then applied to the real matrices obtained by taking the modulus of the scattering coefficients. Finally, the eigenvalues and eigenvectors obtained by matrix diagonalization were used to compute the estimated linearity factor $ELF(f)$ and the angle of orientation $\alpha(f)$.

Figure 6 shows the processing results obtained for the 'mine 1'. Since this target has a rotationally symmetric structure, the scattering coefficient $S_{xx}(f)$ is almost equal to $S_{yy}(f)$ and the cross-polar component $S_{xy}(f)$ is close to zero. The eigenvalues $\lambda_{\parallel}(f)$ and $\lambda_{\perp}(f)$ are approximately equal, which indicates that the target does not have a preferential scattering axis. The plotted graphs refer to the moduli of the scattering coefficients. Note also that their amplitudes are scaled by the incident field. Consequently, in order to interpret the results correctly, it is necessary to consider only the frequency band determined by the spectrum of the radiated wave (260 MHz - 2880 MHz). The computed $ELF(f)$ is close to zero as expected for a rotationally symmetric target.

Figure 7 shows the results obtained for the 'metal pin' given the target orientations of 0 and 45 degrees with respect to the antenna system. The scattering coefficients change with target orientation and a strong cross-polar component is observed when the 'metal pin' is oriented at 45 degrees. In contrast, the eigenvalues $\lambda_{\parallel}(f)$ and $\lambda_{\perp}(f)$ remain approximately the same when the target is rotated. This confirms that the eigenvalues do not depend on the orientation of the antenna system with respect to the target and can be considered orientation invariant target features. In the frequency band of interest, $\lambda_{\perp}(f)$ is much weaker than $\lambda_{\parallel}(f)$ and $ELF(f)$ is close to 1. Accordingly, the 'metal pin' is seen as an elongated object. Furthermore, this indicates the presence of a strong preferential scattering axis. The orientation of this axis is clearly defined by the angle $\alpha(f)$. $\alpha(f)$ is close to 0 degrees when the pin is oriented parallel to the transmitting antenna (0 degrees) and close to 45 degrees when the target orientation of 45 degrees is considered. This proves that the preferential scattering axis of the 'metal pin' coincides with its long axis.

The results for the 'mine 2' (figure 8) show that, similar to the 'metal pin', the field scattered by this target has strong cross-polar components. Since this target has a rotationally symmetric shape but asymmetric internal structure due to the presence of the pin, this demonstrates that internal structure influences the target response. Like for the other targets the eigenvalues are orientation invariant features. Unfortunately, the computed $ELF(f)$ changes with frequency and therefore does not provide any useful information. Also the angle $\alpha(f)$ changes with frequency. This means that the target frame rotates with frequency, suggesting that it does not coincide with any target geometry, e.g. the long axis of the pin inside the 'mine 2'.

The analysis of the 'plastic pipe' demonstrates again that the eigenvalues $\lambda_{\parallel}(f)$ and $\lambda_{\perp}(f)$ are invariant with respect to the target orientation (figure 9). The angle $\alpha(f)$ clearly indicates the orientation of the target frame, which is equal to the actual orientation of the pipe. This agrees with the fact that pipes have a preferential scattering axis, which coincides with their long axis. Nevertheless, it is observed that $ELF(f)$ does not classify the 'plastic pipe' as an elongated object. Most likely this can be attributed to its finite diameter (5 cm), which results in a relatively strong $S_{yy}(f)$ even for a target orientation of 0 degrees.

5. ANALYSIS FOR BURIED TARGETS

The analysis was repeated for buried targets. Polarimetric data was acquired over the sandlane of the test facility for landmine detection systems at TNO.[11] For the acquisition IRCTR's newly developed polarimetric video impulse radar was used.[12] The new radar uses the same transmitting wedge antenna and receiving loops as the VIRLAD radar, however the antenna system of the new radar consists of two transmitter-receiver pairs. This configuration allows for quasi-simultaneous measurement of all four elements of the scattering matrix. Furthermore, the new radar comprises two signal generators (0.5 ns or 0.8 ns monocycle) allowing the user to choose the appropriate operational bandwidth with regard to the size and depth of the target of interest. The data analyzed in this paper has been acquired with the 0.5 ns generator, which yields an operational bandwidth covering the range of 790 MHz to 3040 MHz on –10 dB level. The peak amplitude frequency lies at approximately 2.15 GHz, which is a higher than that of the VIRLAD system (figure 5). Before showing the results, it should be noted that the analysis was limited by the fact that each target type could only be analyzed for one orientation because of the way the targets are buried in the sandlane.

Figure 10 shows the polarimetric response of a 'PMN mine' buried 1 cm deep. Note the strong cross-polar components in spite of the mine's cylindrical casing. These cross-polar components can most likely be attributed to the presence of the detonator and other internal structure. As a result of these cross-polar components, the 'PMN mine' does not give rise to an estimated linearity factor $ELF(f)$ close to zero as shown in figure 11. Furthermore, the target frame rotates as a function of frequency as can be seen from the computed angle $\alpha(f)$. In this sense, the 'PMN mine' behaves similar to the 'mine 2'. This agrees with the fact that both the detonator in the 'PMN mine' and the metal pin inside the 'mine 2' are lying in the horizontal plane (along the *x* axis).

For comparison, figures 12 and 13 show the polarimetric response and processing results for a circular 'metal plate' having a diameter of 10 cm and buried 6 cm deep. As expected for a perfectly rotational symmetric target, the cross-polar components of this target response are negligible and $ELF(f)$ is close to zero over the operational bandwidth. The angle $\alpha(f)$ is not shown, since the ‘metal plate’ does not have a preferential scattering axis. These results agree with the results obtained for the ‘mine 1’, which is also perfectly rotational symmetric.

Figures 14 and 15 show the polarimetric response and processing results for a rectangular construction ‘brick’ having a length of 15 cm, a width of 7 cm, a height of 4 cm and buried 6 cm deep. The measured cross-polar components are smaller than for the ‘PMN mine’ and $ELF(f)$ is close to zero with the exception of a steep rise at 1.8 GHz. Accordingly, for the most part of the frequency spectrum, the estimated linearity factor sees the ‘brick’ as being rotationally symmetric in spite of its rectangular shape.

The results obtained for the buried targets confirm that the estimated linearity factor $ELF(f)$ is unsuited for robust characterization of the target shape. It only works well for simple targets such as the ‘metal plate’. In contrast, the eigenvalues $\lambda_{\parallel}(f)$ and $\lambda_{\perp}(f)$ show distinct behavior for each of the three targets, which suggests using them as features for target identification.

6. DISCUSSION

The data examples demonstrate that the GPR response of a surface-laid or buried target generally depends on the orientation of the target with respect to the antenna system. The antenna configuration of the video impulse radars developed at the International Research Center of Telecommunications-transmission and Radar (IRCTR) was found to be well suited for measuring target scattering matrices, which satisfy reciprocity ($S_{xy}(f) \approx S_{yx}(f)$). Because of this property, the scattering matrices can be transformed into the target frame using simple matrix diagonalization. The eigenvalues $\lambda_{\parallel}(f)$ and $\lambda_{\perp}(f)$ obtained by diagonalization are orientation invariant target features. The way these eigenvalues change as a function of frequency was found to be target dependent and suggests their use for target identification.

The measured polarimetric responses of the ‘mine 2’ and the ‘PMN mine’ show that the response of a landmine with cylindrical casing can contain significant cross-polar components due to internal structure (figures 8, 10-11). On the other hand, the response of a rectangular target such as the ‘brick’ can have cross-polar components close to zero (figures 14-15). Consequently, identifying landmines by looking for targets with negligible cross-polar response is not to be recommended. The influence of internal structure is also reflected in the values obtained for the estimated linearity factor, which tries to characterize the target shape as being either rotational symmetric ($ELF(f) \approx 0$) or elongated ($ELF(f) \approx 1$). It was found that this only works for simple targets such as the ‘mine 1’, the ‘metal pin’ or the ‘metal plate’ (figures 6-7, 13). For all other targets $ELF(f)$ did not indicate the correct target shape.

Similar observations were made for the angle $\alpha(f)$, which specifies the orientation of the target frame. Only for the ‘metal pin’ and the ‘plastic pipe’ could $\alpha(f)$ be used to determine the orientation of the target (figures 7 and 9). For these two targets the axis of the target frame associated with $\lambda_{\parallel}(f)$ coincides with the long axis of the target. For targets with internal structure such as the ‘mine 2’ and the ‘PMN mine’, $\alpha(f)$ exhibited a complicated behavior suggesting that the target frame rotates as a function of frequency (figures 8 and 11).

In conclusion, measuring the full polarimetric GPR response of a target is crucial for obtaining orientation independent features, which can be used for target identification. The eigenvalues $\lambda_{\parallel}(f)$ and $\lambda_{\perp}(f)$ obtained by diagonalization of the scattering matrix are one example of such orientation independent target features. Whether these can be used for robust target identification requires further research and measurements with more types of surface-laid and buried objects.

ACKNOWLEGEMENTS

This research was funded by the Dutch Technology Foundation STW, applied science division of NW0. The authors wish to thank J. van Heijenoort and A.G. Yarovoy from IRCTR for their help during the laboratory measurements.

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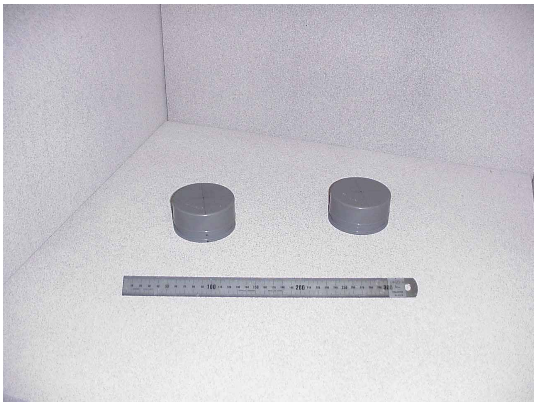


Figure 1: The ‘mine 1’ and the ‘mine 2’ (with metal pin).

Figure 2: The ‘metal pin’.

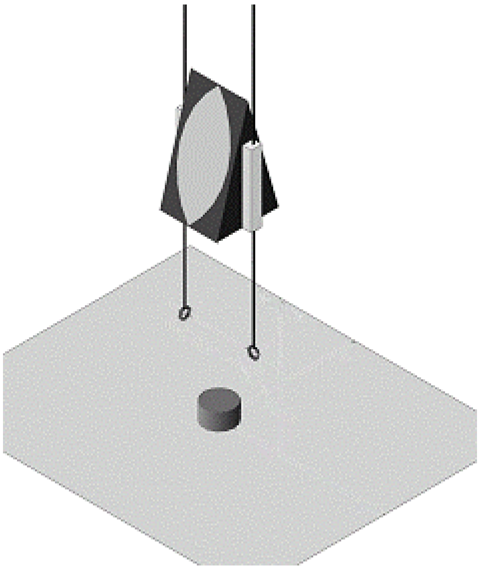


Figure 3: Drawing of the VIRLAD antenna system above a surface-laid target.

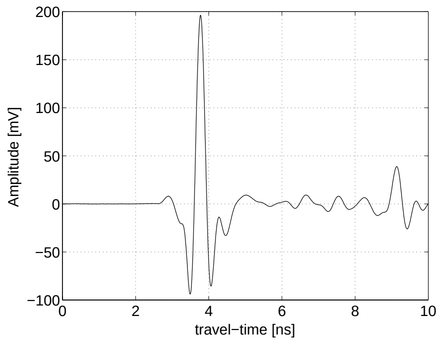


Figure 4: The signal radiated by the VIRLAD radar. The peak arriving at 9.1 ns is the reflection from the ground (antenna height above the ground = 87.5 cm).

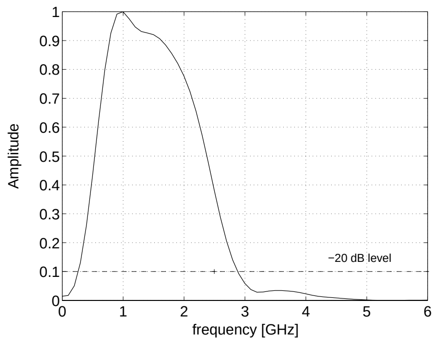


Figure 5: The amplitude spectrum of the signal radiated by the VIRLAD radar (normalized to its maximum amplitude value).

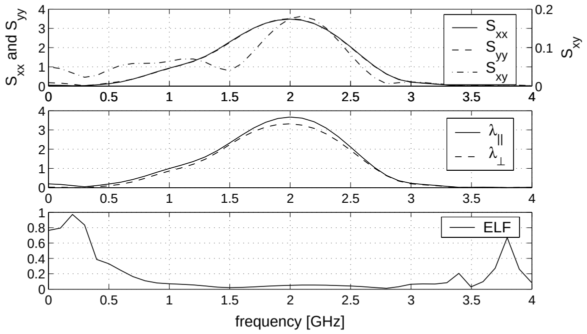
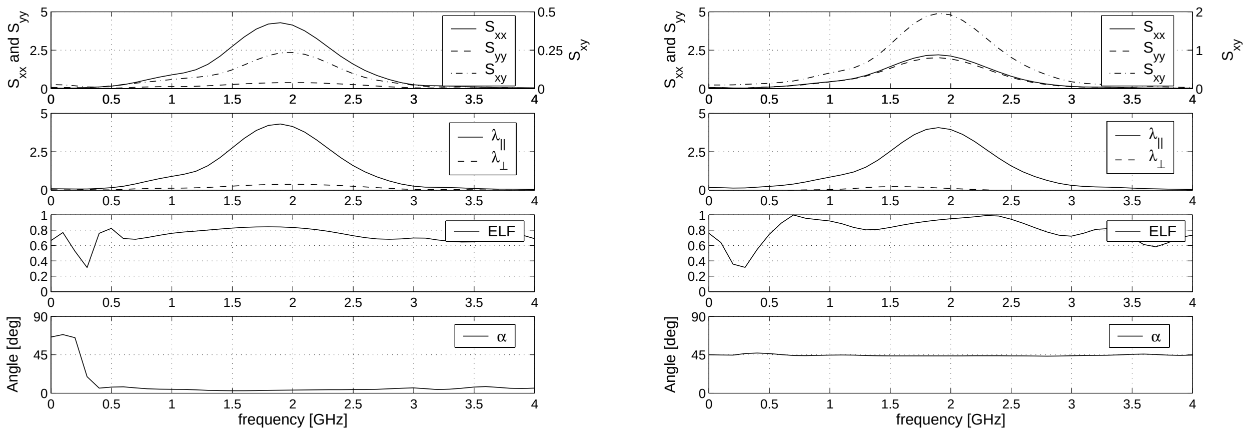
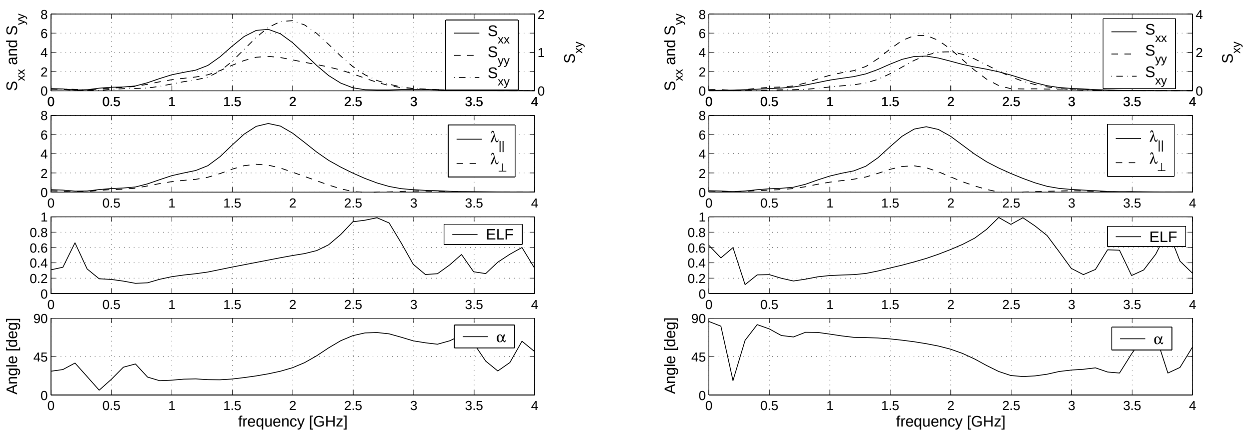


Figure 6: Data analysis of the 'mine 1'. Shown are the moduli of the scattering coefficients, the computed eigenvalues and the estimated linearity factor.



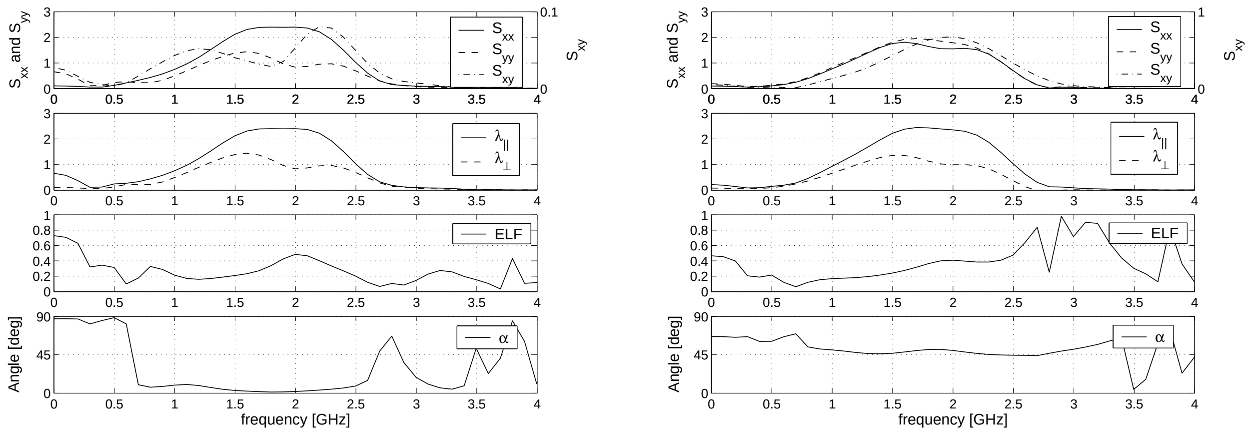
(a) (b)

Figure 7: Data analysis of the 'metal pin' for a target orientation of (a) 0 degrees and (b) 45 degrees. Shown are the moduli of the scattering coefficients, the computed eigenvalues, the estimated linearity factor and the target frame orientation.



(a) (b)

Figure 8: Data analysis of the 'mine 2' for a target orientation of (a) 0 degrees and (b) 45 degrees. Shown are the moduli of the scattering coefficients, the computed eigenvalues, the estimated linearity factor and the target frame orientation.



(a) (b)

Figure 9: Data analysis of the ‘plastic pipe’ for a target orientation of (a) 0 degrees and (b) 45 degrees. Shown are the moduli of the scattering coefficients, the computed eigenvalues, the estimated linearity factor and the target frame orientation.

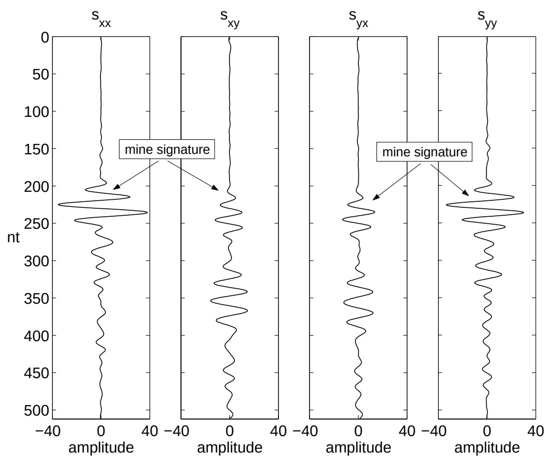


Figure 10: Polarimetric response of the ‘PMN mine’ buried 1 cm deep (after background subtraction).

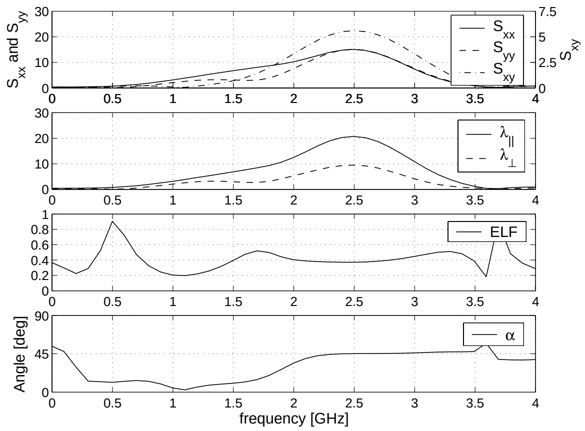


Figure 11: Data analysis of the ‘PMN mine’. Shown are the moduli of the scattering coefficients, the computed eigenvalues, the estimated linearity factor and the target frame orientation.

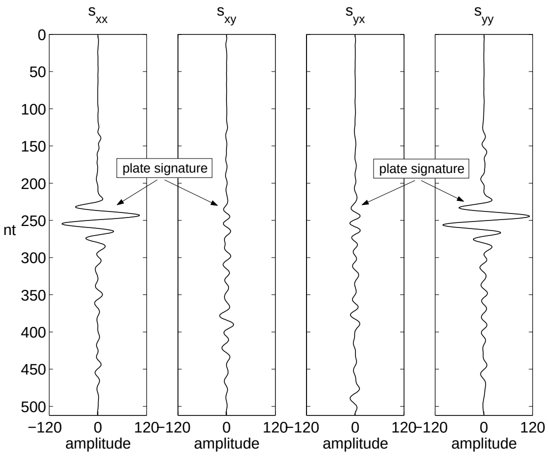


Figure 12: Polarimetric response of the ‘metal plate’ buried 6 cm deep (after background subtraction).

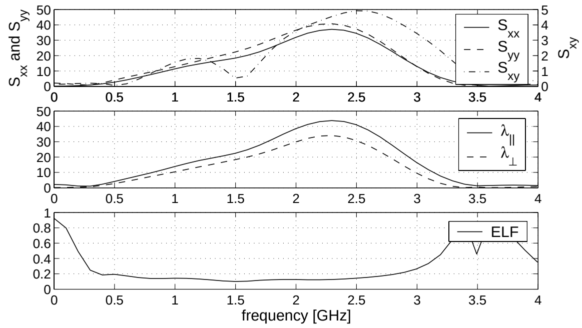


Figure 13: Data analysis of the ‘metal plate’. Shown are the moduli of the scattering coefficients, the computed eigenvalues and the estimated linearity factor.

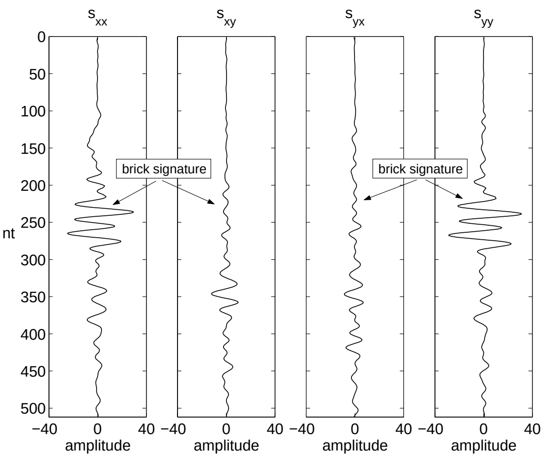


Figure 14: Polarimetric response of the ‘brick’ buried 6 cm deep (after background subtraction).

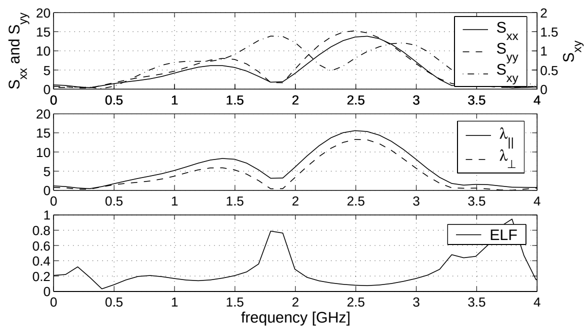


Figure 15: Data analysis of the ‘brick’. Shown are the moduli of the scattering coefficients, the computed eigenvalues and the estimated linearity factor.