3D EMI Trajectories for the Visualisation of Metal Object Properties

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Abstract

This paper deals with a method of visualising EMI signals in 3D space, which complements the well known NDT technique of eddy current trajectory patterns, used also for the identification of metallic objects. 2D patterns are created for several (parallel) scans and the results are meshed and rendered into a 3D object. Such a representation yields more information about the nature of an electromagnetic discontinuity than the usual trajectory patterns. Moreover, the 3D plots are easier to read and interpret by an operator and lead to more reliable target identification/discrimination. A similar approach is also proposed and discussed for the analysis of single scans taken with a multifrequency system.

1. Introduction

Despite their many limitations, metal detectors are still widely used in Humanitarian Demining and considered to be the most reliable and effective tools. In order to increase the probability of detection and, in particular, to minimise their high false alarm rate, they are often combined with other sensors such as, for example, GPR or NQR detectors [3]. Many efforts have been undertaken to improve the performance of metal detectors with respect to detection range, ground rejection or object identification. The latter factor becomes more and more important for a deminer since minefields are very often littered with metal clutter and debris. Each of such targets must be carefully checked, which increases the clearance time and causes a loss of the deminer's concentration. It is on the other hand open for discussion whether we should provide a deminer with a tool which assesses a target for him and decides whether it is a mine (or Unexploded Ordnance) or not. It is the deminer who not only risks his life but must also convince the local population that a demined area is indeed mine free [8].

This paper deals with a method that allows to obtain more information about a target from a conventional eddy-current metal detector. The information is presented in the form of a 3D picture which can either be viewed (and analysed) directly by an operator, or further processed by target identification algorithms.

2. Metal Detector Signal Processing

Most of the versatile off-the-shelf metal mine detectors provide an audio indication only. The aim of limiting the indication to the audio one is to reduce cost and to make mine detection systems easier to operate. The audio signal is generated by analysing a signal received by a magnetic or an eddy current probe, in the time or frequency domain. Mine detectors that utilise the latter method are very often called continuous wave (CW) detectors, although they sometimes use square wave excitation too. As the received signal includes, apart from the target signal, interference from external sources, ground noise etc., the audio signal is ambiguous. Hardware and software means are provided that improve the probability of proper detection with a low false alarm rate. These are focused on ground and interference rejection rather than positive target recognition.

In a general case, we can distinguish two approaches to the design of metal detection systems, as presented in Fig. 1.

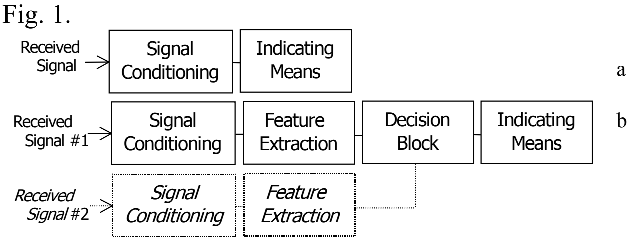


Fig. 1 Block diagrams of metal detection systems: with simple (a) and sophisticated (b) signal processing.

The simpler approach, using the metal detector as an anomaly detector only, assumes no sophisticated signal analysis. The signal-conditioning block consists of some de-noising means such as band-pass amplifiers and phase detectors. The target indication is usually obtained using simple thresholding techniques. More complex systems include circuitry capable of some signal feature extraction, e.g. phase shift in CW detectors or decay components in time domain systems. More than one signal analysis is possible. For example, signals from another coil (multi-coil arrangements), signals at another frequency (multifrequency systems), or even signals of a different nature such as GPR signals may be processed.

If we take a closer look at a conventional eddy-current CW mine detector we can distinguish at least three signal features that can be observed and analysed:

1. **Amplitude**: It is a function of the size of the object, its distance from the sensor and, to a lesser extent, material properties of a target.
2. **Phase shift**: It is less affected by the distance to the target but greatly depends on the composition of the material, signal frequency and orientation for ferromagnetic objects [1][10].
3. **Signal duration**: It yields some information on the size and depth of the object [6][11] but is also strongly affected by the sweeping speed of the sensor.

All factors are affected somehow by soil properties. The use of other signal parameters and factors is detailed in ref. [4], these proceedings.

3. Phase Shift Based Target Identification

One of the very important facts that seem to be overlooked while modelling a mine detection and recognition system is that we know the relative position of the sensor on very rare occasions only. In fact, in most cases we roughly know where the target is, whereas many target detection algorithms were developed for idealised situations such as objects lying just beneath the centre of the sensor. Even a ferromagnetic metal sphere can be wrongly classified, if the relative position of the sensor is not taken into account.

Most commercially available target identifying metal detectors use phase shift analysis to distinguish between different metal objects. It has been shown that the phase shift allows to discriminate non-ferromagnetics quite well. A phase shift response to ferromagnetic objects is on the other hand complex, which makes the identification of such targets a challenging task. One of the methods of ferromagnetic object identification is to draw a phase shift histogram, showing the phase shift distribution while scanning over a target [1][4][9].

3.1. Standard Eddy-Current Trajectory Patterns (2D)

More information on the target's nature, in the form of Lissajous-like patterns, can be obtained if the received signal is continuously displayed on an impedance plane (see Fig. 2). Such systems have been developed from NDT eddy-current methods, originally used for the inspection of non-ferrous metals. Their use for the identification of ferrous and non-ferrous metallic targets is presented in [1][10]. For an extensive discussion of their properties, advantages and limitations within the context of landmine detection refer to [2] and [4] in these proceedings.

In the following we extend this method and propose the introduction of another dimension to the plots.

3.2. Enhanced Eddy-Current Trajectory Patterns (3D)

When we look at Fig. 2, in which a set of trajectories for an exemplary ferrous target is presented, we can see that they differ considerably even though they are taken for the same target. Each trajectory was created for a single search head sweep, yet for different positions (the number by a trajectory indicates a shift, in inches, from the axis of symmetry of the sensor).

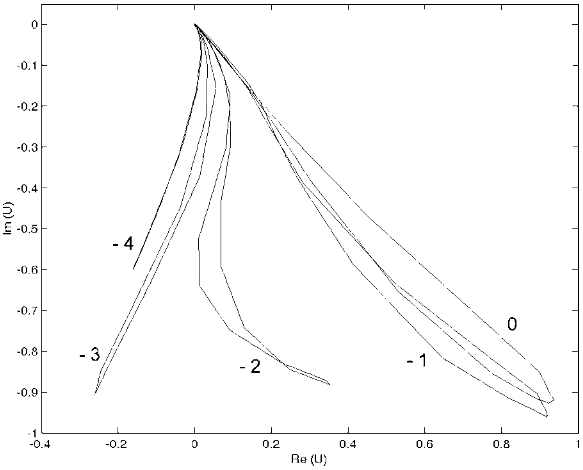
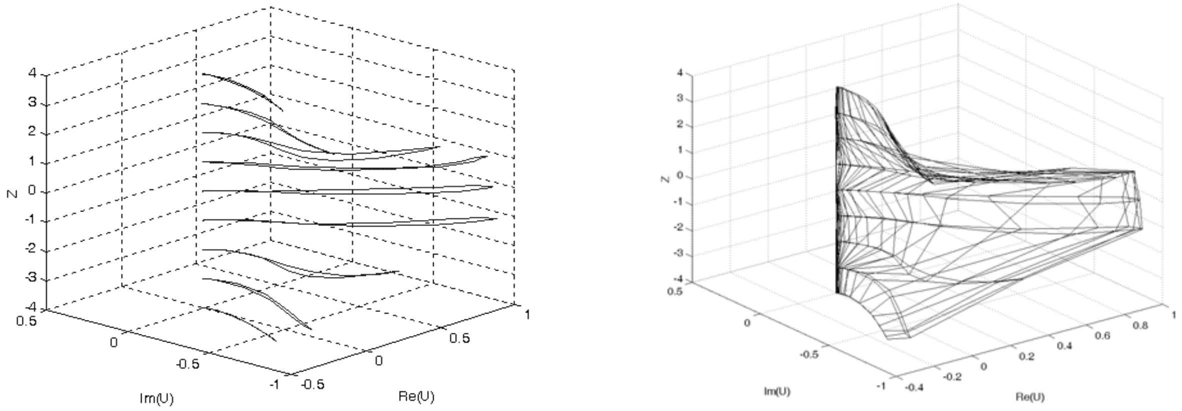


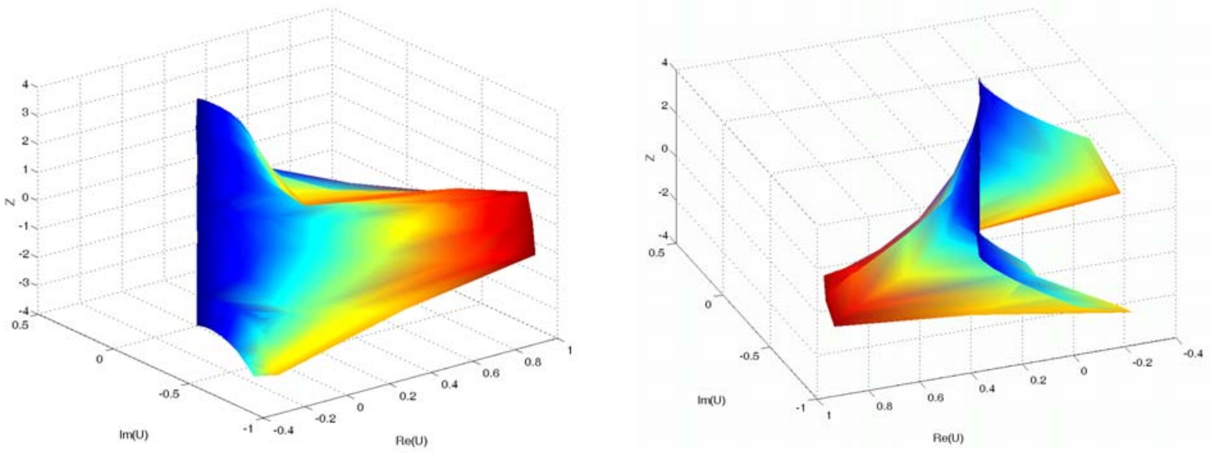
Fig. 2 A set of trajectory patterns obtained for a balanced coaxial search head [10] scanned over a ferromagnetic disk perpendicular to the surface of the head. The number by a pattern denotes distance, in inches, between the axes of the target and the sensor. Trajectories are normalised.

Each trajectory in Fig. 2 shows that the signal phase shift varies with the position of the sensor for a single sweep. If we relied on phase shift (single lobe slope) only, a target might not be properly identified. However, as each signal is usually checked with multiple (parallel) sweeps, a group of trajectories can be produced. This group of trajectories can be used to create a graphic mesh and then rendered into a 3D object (see Fig. 3 for plots created with Matlab®) which is easier to look at and interpret by an operator than a group of several trajectories drawn on the standard impedance plane. Such an object's properties do also yield more information



a) "Classical" eddy-current trajectories placed in space (9 parallel trajectories, same setup as Fig. 2)

b) A mesh generated by linking some points of neighbouring trajectories



c) A rendered 3D object

d) A rendered and rotated 3D object

Fig. 3 Steps to create 3D trajectory patterns.

about the nature of an electromagnetic discontinuity than the usual trajectory patterns. Note that Fig. 2 presents only 5 trajectories, for the sake of clearness, whereas 9 of them are displayed in Fig. 3 for the same object.

The major technical problem here is the proper scanning procedure over the object. For hand-held instruments some hardware and/or scanning procedure must be introduced to provide the sensor's spatial location (the utilisation of solid state accelerometers could be considered, for instance). If we use vehicle-mounted sensor arrays, that are common, the implementation would be easier; the lateral resolution will however be reduced.

Assuming subsequent scans are parallel and that the height of the sensor above the ground is constant, only the distance between each sweep, as the deminer or vehicle advances, has to be known. On the contrary, other scanning based signal or image processing methods require the full XY position of the sensor. For comparison, see Fig. 4a and 4b showing respectively typical 2D and 3D pictures created for the previously investigated target, where the XY co-ordinates must be known. In fact, although these plots show only the signal's amplitude variation, they do carry a lot of additional information; for instance, in Fig. 4a it can be clearly seen that the metallic object is elongated. Their use should therefore not be entirely disregarded.

The 3D trajectories featured in Fig. 3 show both amplitude and phase variations, so that a deminer can suspect that a ferrous object is being detected (for non-ferrous metals the phase shift does not vary significantly with the sensor position [1]). Also, as the 3D object is symmetrical, the target has to be symmetrical too. Of course, the target's axis of symmetry was known *a priori* during the experiments. In the field a deminer should check the target under inspection sweeping from several angles to find if the object is symmetrical.

As mentioned, the sensor used was co-axial but similar trajectories can be obtained for other EMI sensors too.

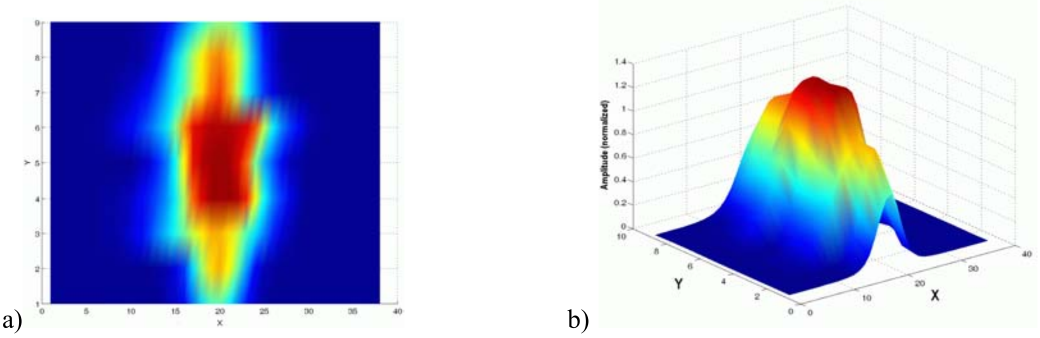
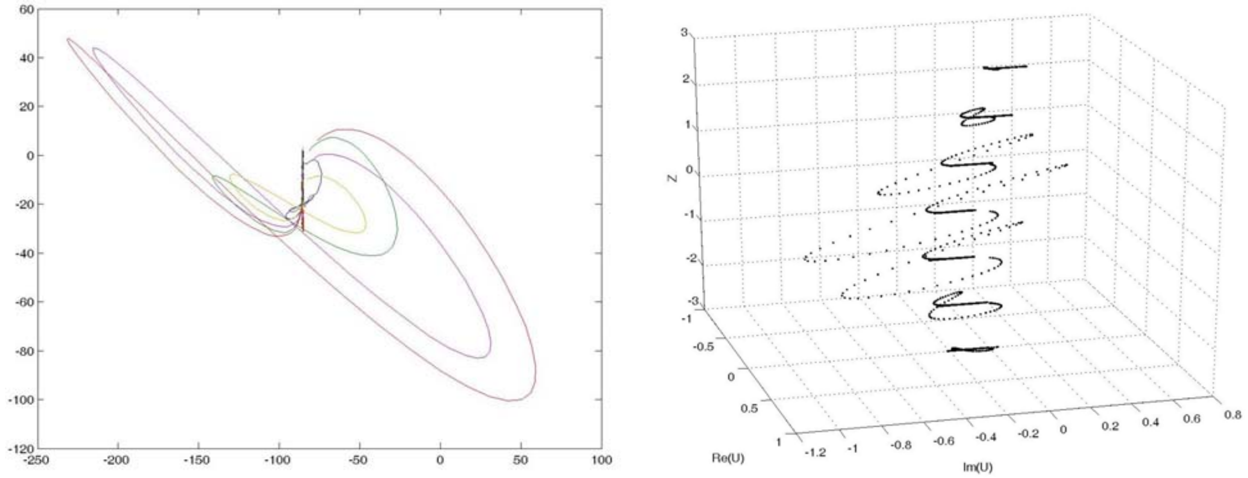


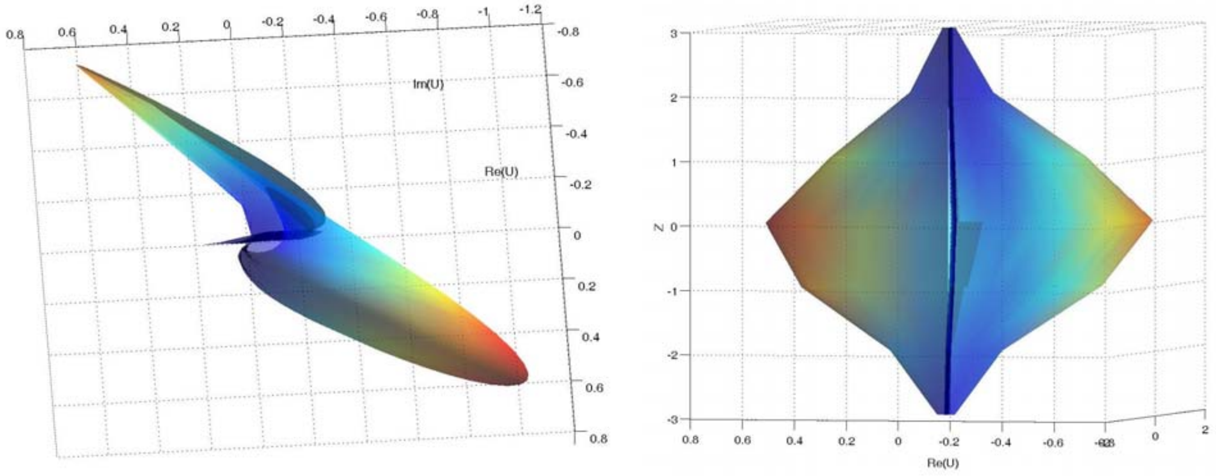
Fig. 4 Typical images showing target amplitude response (XY position must be known).

Fig. 5 presents the steps used to create a 3D trajectory, in the case of a typical anti-personnel (AP) mine (Russian PMN), when employing a Förster Minex 2FD differential sensor (see [2] for details). In this case each full scan produces a two-lobe trajectory, in contrast with one-lobe trajectories as in Fig. 2.



a) Set of 2D trajectories for several parallel scans over a PMN mine (values in mV)

b) The trajectories placed in 3D space (XY normalised, Z arbitrary unit)



c) A rendered 3D object (side view)

d) A rendered and rotated 3D object (bottom view)

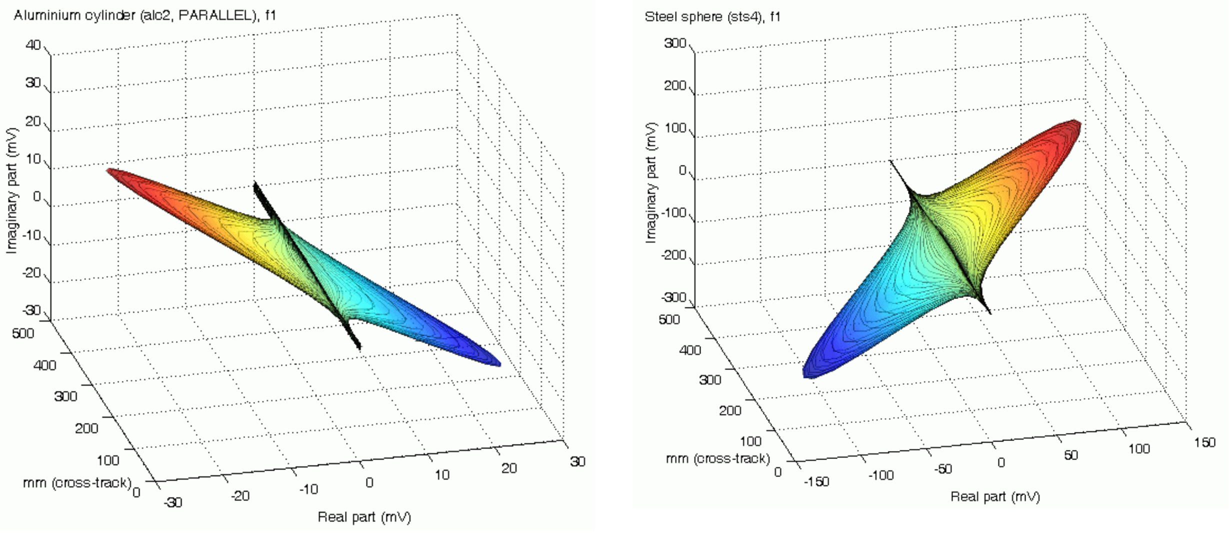
Fig. 5. Steps to create 3D trajectory patterns for a PMN AP mine (Förster Minex differential detector, 5 cm above surface).

The information seems to be different, but actually it is not. The phase response yields the same information. The only significant difference here is that the signal nulls over (or close to) the centre of the target.

The 3D objects were created basically with the Matlab® standard *surf* (M) function and shaded for better viewing (the colour represents the signal magnitude). It does the job well, provided the samples, visible as dots in Fig. 5b, are uniformly spaced and gathered line by line (parallel scanning). For hand-held instruments other dedicated algorithms must be developed.

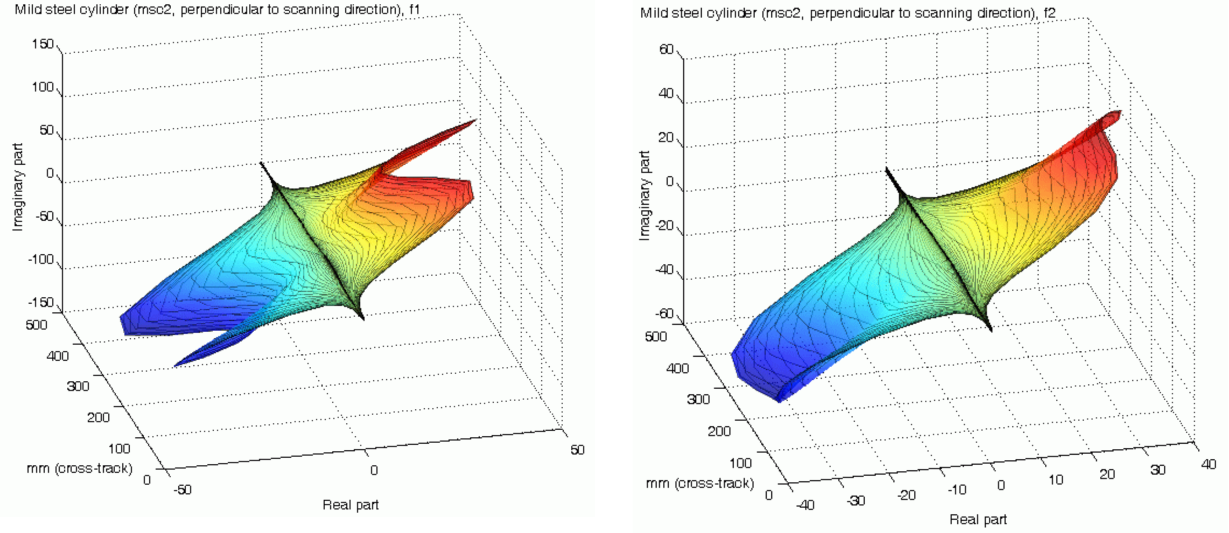
Additional examples of 3D trajectory patterns obtained with the Förster Minex two frequency differential detector are detailed in Fig. 6 and Fig. 7, for a few reference objects and landmines, respectively. In this case we employed the user interface described in [7]. The real and imaginary parts do not share the same scales; the objects' slopes are therefore qualitatively, but not quantitatively, correct.

Concerning the reference targets, the aluminium cylinder is characterised by a constant, negative phase response (slope), which translates into a flat 3D object. The same is true for a steel sphere, although in this case the phase response is clearly positive (Fig. 7). Both phase response trends are indeed well known [2]. Where the 3D representation shows a clear advantage over the standard 2D complex plane representation is for example in the case of a mild steel cylinder placed perpendicularly to the



Aluminium cylinder (length: 7 cm, diameter: 0.7 cm) @ f1

Steel sphere, ferromagnetic (diameter: 2 cm) @ f1



Mild steel cylinder (length: 7 cm, diameter: 0.7 cm) @ f1(left) and f2 (right)

Fig. 6. Examples of 3D trajectory patterns: *reference objects*, 26 parallel scans at an interval of 2 cm (Förster Minex differential detector; f1=2.4kHz, f2=19.2kHz). Objects flush, detector 2-3 cm above surface.

scanning direction: the target does not exhibit strong phase changes along the scan when looking at individual scans [2], but from the overall 3D picture it is quite clear that the phase changes from one scan to the next. The corresponding 3D object is therefore flat and twisted.

The responses in the cases of landmines (Fig. 7) can

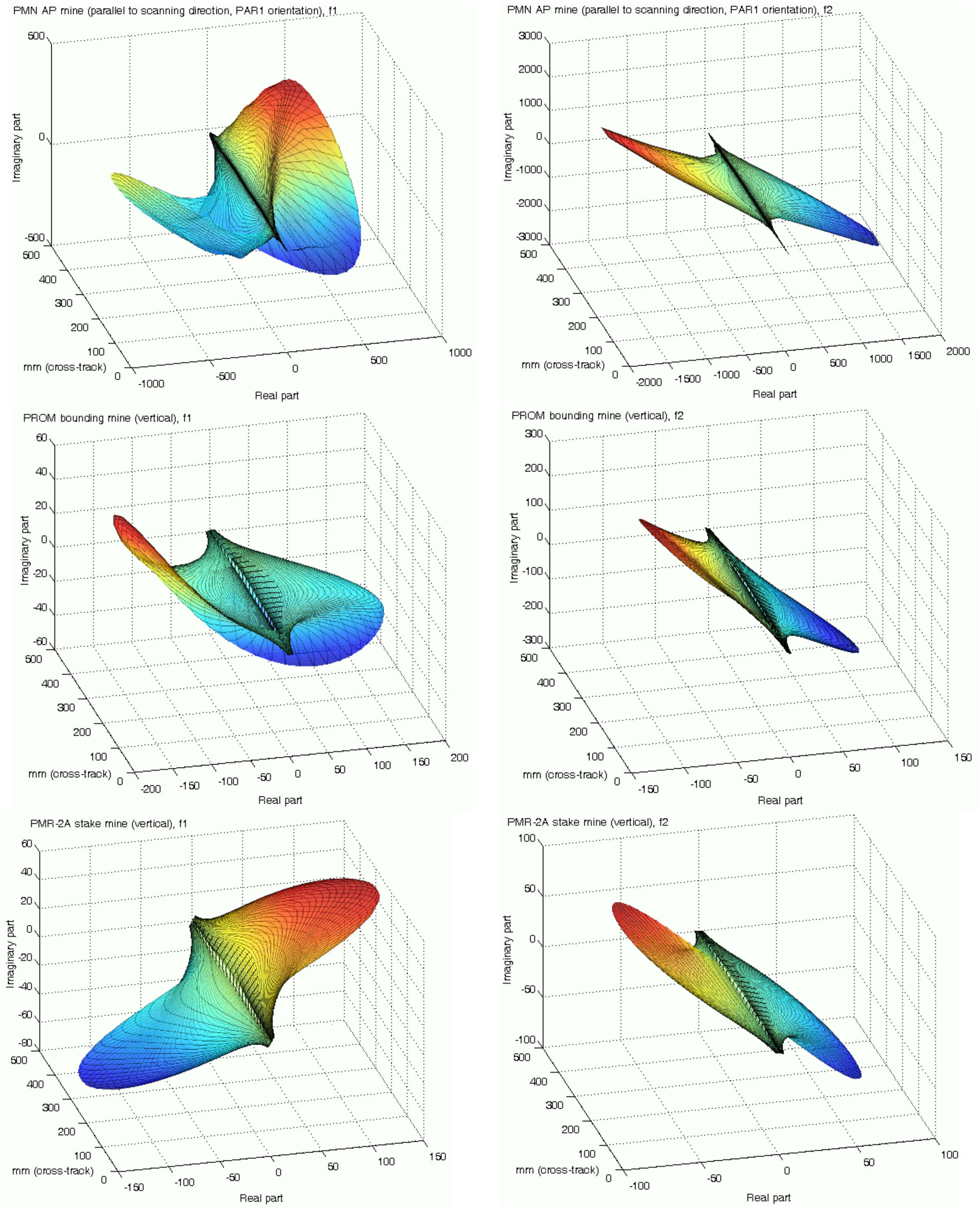


Fig. 7. Examples of 3D trajectory patterns: *mine targets* (Förster Minex differential detector; f1 = 2.4kHz, f2=19.2kHz), 26 parallel scans at an interval of 2 cm (13 scans @ 4 cm for the PMN). Details of experimental setup: see [2].

have a complex structure such as for a PMN mine; the corresponding 3D objects are usually far from flat, in particular at f1 (the lower frequency being more influenced by induced magnetization effects), indicating very important phase and amplitude changes when scanning over the target. The responses of PROM and PMR-2A metallic mines are somewhat more regular, although they are still characteristic of large ferromagnetic objects, especially the PMR-2A with its positive slope at f1 and negative at f2.

3.3. Multifrequency Trajectory Patterns

In modern metal detection systems multifrequency excitation is more and more often used. Example of such multifrequency systems available off-the-shelf are detectors like the Förster Minex 2FD [2], the Geophex GEM-3 [12], and some Minelab metal detectors [5]. It is possible to create with such systems a 3D signal trajectory using a single sweep, and therefore no hardware is needed to record position of the sensor.

Each 2D trajectory represents in this case a target response at an individual frequency (2 trajectories for two frequencies, for instance).

In Fig. 8 EMI trajectories for a PMN AP mine are shown using datasets collected with a Förster Minex 2FD. As this instrument uses only two frequencies (2.4 kHz and 19.2 kHz), the advantage of such a 3D presentation is not immediately apparent (two trajectories on the impedance plane are relatively easy to interpret). The results presented here do however show that such a presentation is possible and provide a feeling for its advantages.

For most targets we can expect phase rotation and signal strength variations with changing frequency. These properties can be used for metal object identification but do not add much to the shape of the resulting trajectories. Therefore, it seems (to be validated) that multifrequency 3D plots can only be advantageous for composite targets or when many targets are under the sensor head being swept.

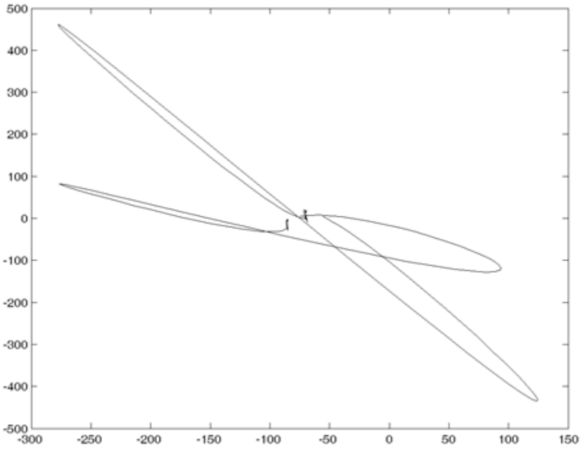
Obviously, the shape of multifrequency 3D trajectories should not be confused with multi-sweep 3D trajectories (compare Fig. 5 and Fig. 8).

4. Summary and Conclusions

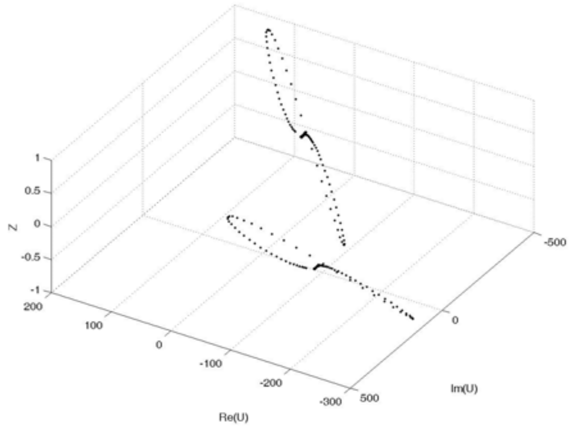
In this paper we presented a new method for the visualisation of EMI signals. With this method an operator is provided with a "user friendly" picture. From the image a user can learn, at least:

- if the target is ferrous (large or small);
- if it is symmetrical.

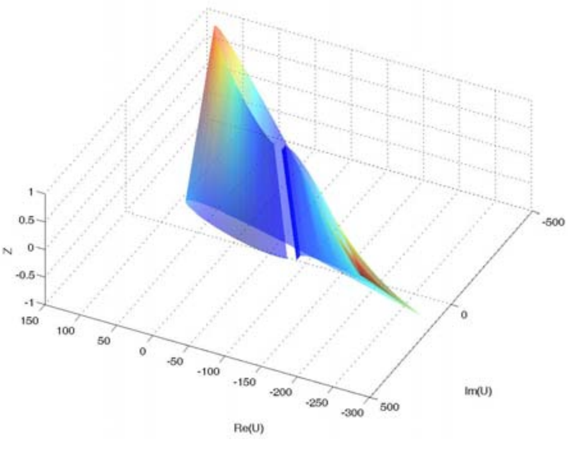
Although in this method a picture is produced, it



a) Two trajectories obtained for a single sweep at two frequencies (2.4 kHz and 19.2 kHz).



b) The trajectories placed in space.



c) 3D image for single-sweep two-frequency visualisation.

Fig. 8. Trajectories obtained from a two-frequency Förster Minex 2FD mine detector for a PMN AP mine (signal strength in mV, Z axis – frequency – in arbitrary units); same setup as for Fig. 5.

obviously should not be confused with target imaging methods, as the shape of the 3D object does not correspond directly to the shape of the metal target.

It is possible to gather and compare responses from targets encountered in a given field and then to create a knowledge database for computer pattern or image recognition algorithms. Of course, an experienced user will be able to recognise similar responses without the aid of such algorithms.

To fully exploit the potential advantages of this method some technical hurdles must however be overcome (e.g. sensor positioning) as well as special visualisation algorithms developed.

It is also worth to note that this method, being a supplement for the standard 2D trajectories method, inherits most of its strengths and weaknesses (see [2] and [4] for a detailed discussion).

The objects presented in this paper were created in laboratory environment and for high S/N ratio. It was also noted that some targets produce 3D trajectories that can be hard to interpret due to their complexity (actually, the trajectory complexity is a kind of information too, but it could be confusing for a deminer).

As an alternative to the multiple-scan method we proposed the use of single-scan multifrequency 3D trajectories, producing an image that shows metal object response variation over a certain frequency range. This method can complement the electromagnetic induction spectroscopy technique [12][13] developed by Geophex in which the frequency response is presented in a plane.

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