GROUND PENETRATING RADAR AND INDUCTION COIL SENSOR IMAGING FOR ANTIPERSONNEL MINES DETECTION

Claudio Bruschini, Bertrand Gros, Frédéric Guerne, Pierre-Yves Pièce, Olivier Carmona

LAMI-DeTeC, Swiss Federal Institute of Technology, IN-F Ecublens, CH-1015 Lausanne, Switzerland
detec@epfl.ch

ABSTRACT

DeTeC (Demining Technology Center) is developing a sensor system for humanitarian demining able to reduce the number of false alarms and usable by a man or an autonomous robot (see http://diwww.epfl.ch/lami/detec/).

We have chosen to concentrate our first experiments on a commercial impulse ground penetrating radar with a 1 GHz antenna and an induction coil sensor (metal detector) used for imaging purposes. The metal detector should help to distinguish two objects with similar radar echoes but different metal content, e.g. a mine and a stone of the same size. The GPR should in turn differentiate a mine from metallic debris, which often gives a similar metal detector answer.

An experimental setup, constisting of a double sandbox with a computerized system that allows the automated positioning of the sensors, has been constructed. Preliminary results of data acquisition and treatment on both sensor technologies are presented with a comparison between the induction coil sensor and the GPR data.

Key words: landmines, impulse GPR, metal detector, induction coil sensor imaging

INTRODUCTION: THE LANDMINE PROBLEM

More than 100 million antipersonnel (AP) mines have been laid in the world, killing or maiming innocent civilians every day. A large fraction of them is similar to the minimum metal mine pictured in Figure 1, which is made almost entirely of plastic. Their metallic content is indeed often of the order of one gram (but can be as low as 0.1 g), and they contain from 20 g of explosive upwards. AP mines are usually placed close to the surface (especially the smaller ones), but can be found as deep as 20-30 cm and be displaced from their original position as a consequence of natural events such as floods or drifting sands.

It must be noticed that solutions developed for the military are normally not suitable for humanitarian demining. In the first case the goal is to make quickly a breach in a minefield, and mine finding or destruction rates of typically 80% are accepted. For humanitarian mine clearing it is obvious that the system must have a detection rate approaching the perfection (UN specifications require better than 99.6%) (Nicoud, 1996).

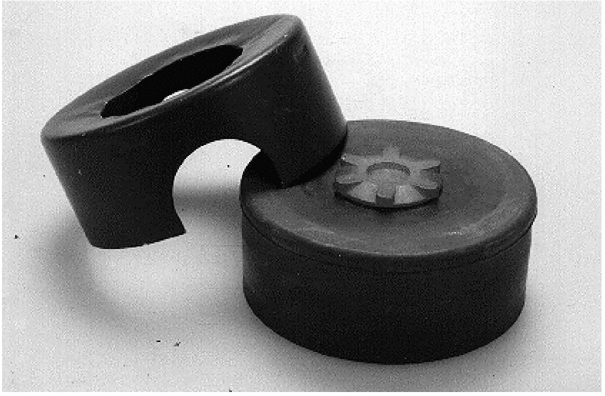

Figure 1: An example of a minimum metal antipersonnel mine (diameter: 8 cm, height: 3.5 cm).

Manual Demining: the Current Situation

The metal detectors currently used by demining team cannot differentiate a mine from metallic debris, which leads to 100-1000 false alarms for each real mine in minefields where the soil is contaminated by large quantities of shrapnel, metal scraps and cartridge cases. Although the detectors can be tuned to be sensitive enough to detect the small amount of metal in modern mines, this is not practically feasible, as it will also lead to the detection of smaller debris and augment the false alarms rate. The only current alternative is to prod the soil at a shallow angle using rigid sticks of metal to determine the shape of an object; this is an intrinsically dangerous operation.

The need for new, efficient and affordable demining technologies and sensor systems is therefore obvious. An overview of the current research status is given in (Mächler, 1995) and (Gros and Bruschini, 1996). Conferences dealing with this problem are listed in (Nicoud, 1996).

DeTeC DESCRIPTION AND AIMS

DeTeC has three main objectives (as detailed at http://diwww.epfl.ch/lami/detec/):

- To develop and test on the field by the end of 1997, a man transportable anti-personnel mine sensor that significantly reduces the false alarm rate in a selected environment. A combination of “proven” sensors will be used, including at least a metal detector (MD) and a ground penetrating radar (GPR). The Pemex-B robot will be improved to carry the sensors, but its use may not be generalized at the current cost level, since deminers are paid less than $ 1000 per year in countries such as Angola and Cambodia.

- To participate in long term research projects at the international level to develop better demining technologies (bio-sensors, low cost GPR, image processing, sensor fusion, robots, navigation sensors, etc.).
- To encourage information exchange on demining technologies, through the Web and related scientific conferences (E-mail: detec@epfl.ch).

THE DeTeC TEST SYSTEM

Extensive tests in a “sand box” are required to get varied data under well known conditions, allowing for software development. Many situations have to be simulated and a large amount of data has to be acquired.

A sand box must be large enough so that the measurement data are not influenced by the surrounding structures. We built a system consisting of two adjacent concrete block containers with an internal volume of 3.2 x 3.2 x 1.2 m^3 each. Metal has been avoided as far as possible. One container is filled with clean sand, the other with loamy soil for more realistic test. Concerning the humidity rate which affects the attenuation of the electromagnetic signal, it varies for the sandy soil from 0.1% on surface up to 2.3% at 30 cm.

In order to position the radar with a good precision and repeatability, we have built a cartesian positioning system which moves the sensor under test over the ground (see Figure 2). For the time being, we are not controlling the vertical motion, but we can put the sensor at a fixed height above ground; a spring adjusts the pressure of the sensor when it touches the ground. The stepping motors control box receives displacement orders from a serial line, and the acquired data is stored on a PC’s disk and transferred later to some server. Most of these files are available on our Web site.

More realistic tests will be carried out later in the open. The cartesian positioning system is in fact easy to dismantle and carry. It just needs 4 support points for installation and can operate with the PC from a small power generator.

Concerning mines we are encountering a lot of trouble to obtain original (albeit inert) ones and also, surprisingly, replicas. We are therefore relying, for the time being, on an inert AP mine obtained from the swiss military authority (see Figure 1), the explosive having been replaced with wooden pieces of the same form. In the future we will use simple explosive simulants such as beeswax, paraffin or nylon, or Dow Corning RTV 3110 and 3112 silicone rubber. The latter match quite closely, over the 100 MHz - 1 GHz range, the dielectric properties of explosives commonly used in AP mines, i.e., respectively, TNT and “Composition B” (60% RDX/40% TNT) (see Table 1).

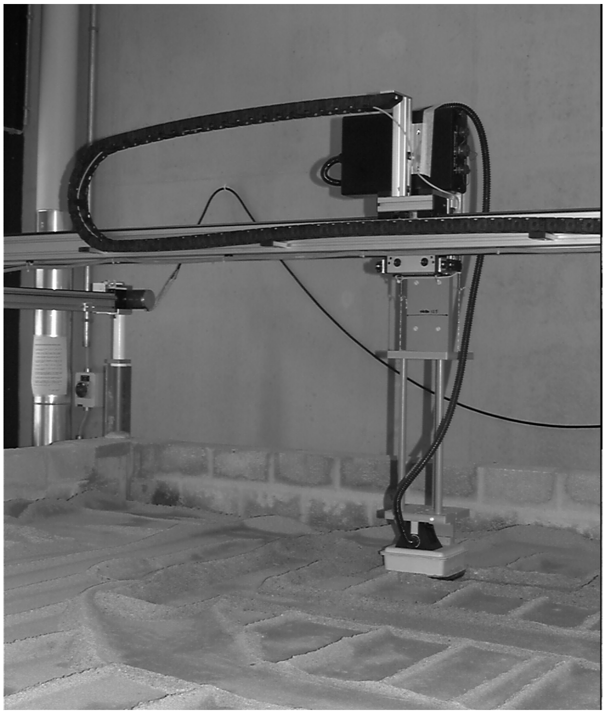

Figure 2: DeTeC test system: sand box, cartesian robot, 1 GHz antenna and radar head (top).

Table 1: Dielectric properties of some explosives and simulants at different frequencies of interest, (von Hippel, 1995), (Broach, 1996) and (Paca, 1996).

Material	Frequency					
	0.3 GHz		1 GHz		3 GHz	
	ϵ_r	$\tan\delta$	ϵ_r	$\tan\delta$	ϵ_r	$\tan\delta$
TNT	2.89	.0039	—	—	2.89	.0018
Composition B	3.20	.0035	—	—	3.20	.0020
RTV-3112	3.13	.0036	3.32	.0155	—	—
RTV-3110	2.88	.0016	2.97	.0084	—	—
Nylon	3.08	.0138	—	—	—	—
ABS Plastic	2.67	.0285	2.91	.0784	—	—
Paraffin wax	2.20	.0203	—	—	—	—

GPR ACTIVITIES AT DeTeC

Radar Type and Hardware Characteristics

We are fully aware that current GPR systems are still way too expensive to be used in large number for humanitarian demining, such as done now with metal detectors. But we hope that prices will fall when the efficiency for mine detection will be proven and when the manufacturers will realize the potential market available.

A GPR for landmine detection must have a wide frequency band to achieve a good resolution, but since higher frequencies do not propagate well, the chosen range is always a tradeoff between resolution and penetration depth. For antipersonnel mines, a center frequency of 1 to 2 GHz, and a bandwith of the same magnitude, seem to be a good choice for most types of soil and for “typical” APs with a diameter of 8-10 cm. Smaller mines might require correspondingly shorter wavelengths, which will shorten the usable depth range too.

The radar choosen for our experiments is a SPRScan commercial system made by ERA Technology (UK). Its sampling head is able to acquire a maximum of 195 A-scans, of 512 points each, per second (or 390 A-scans of 256 points in coarse mode) with 16 bit resolution and a maximum equivalent sampling rate of 40 GHz (25 ps time resolution). Before the A/D conversion the signal is analogically averaged (10 or 20 samples) to improve the S/N ratio and a time varying gain correction of 0.4 dB/ns is applied to partially compensate for the soil attenuation. The acquired data is buffered in two FIFOs able to store one A-scan each and is displayed in real time as a scrolling B-scan on the LCD screen of a rugged 486, 66 MHz PC.

A prototype resistively loaded parallel dipoles antenna has been used for our acquisitions (size: 195 x 195 x 95 mm). The pulse generator (pulse width: 200 ps, repetition rate: 1 MHz) is integrated in the antenna case to minimize losses and transmission reflections. This antenna has a nominal bandwidth of 800 MHz to 2.5 GHz, which leads to an expected resolution of less than 5 cm.

Data Collection, Format and Availability

In the first part of the project, all our acquisitions are done in our sand box. All data are directly stored on the internal hard disk of the GPR and after that, files are transferred to a separate PC for data analysis. Most of them are freely available on Internet at http://diwww.epfl.ch/lami/detec/gprimages.html for image processing studies. A brief description of the experimental conditions is given for every file as well as a complete description of the SEG-2 file format used by the radar. Objects measured are antipersonnel mines and “false positives” (stones, bricks, wood and pieces of metal buried up to 30 cm). All these data are stored in one database and serve as input for algorithm evaluation.

Amongst the current available files we have chosen to use the data corresponding to the three objects shown in Figure 3 for an initial comparative study of the GPR versus the metal detector. A stone has been chosen because it could be hard to distinguish it from a mine with a GPR; the debris for the same reason in the metal detector case.

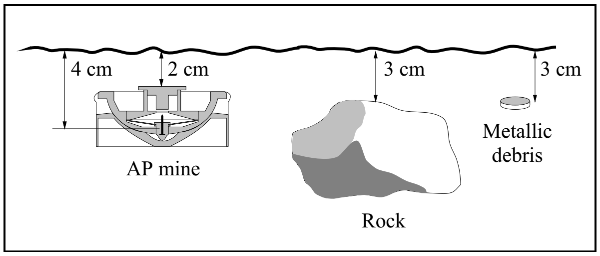

Figure 3: The 3 objects used for initial comparative tests (scale of objects is respected).

Software Environment

Software embedded in the radar is limited to some basic functions, mainly designed to improve the image quality and is not sufficient for antipersonnel mines image analysis. Affordable GPR software for real-time applications seems not to be available on the market. Systems developed for military use are often mentioned, but are usually either classified or prototypes.

A program specific to our application will have therefore to be written. In the first part of the project, we have chosen to focus on the Reflex off-line processing package written by Sandmeier (1996), which is of seismic data processing origin. Several modules are available for data analysis (display of B-scans, 1D and 2D filters, special purpose functions like migration) and data interpretation (comparative viewing of several profiles, computation of time slices, 3D visualization). We are using it mainly to evaluate the effects of standard filtering techniques and algorithms. To test algorithms not included in Reflex we rely on the technical computing environment MATLAB. This interactive system allows us to evaluate all steps of the data processing chain.

Data Visualization and Interpretation

Different visualization techniques are being evaluated to find the most suitable one, from a practical and computational point of view. One has also to bear in mind that in the demining case GPR data will have ultimately to be interpreted by non expert personnel.

Line or B-scan: the most common GPR data visualization consists in displaying the data as a vertical slice, whilst moving the antenna along a line on the surface. Thinking of hand-held equipment this is indeed the most natural one, being similar to what is currently done with metal detectors, sweeping in arcs of circle. As we are looking for the real shape of the buried targets, a reliable position information must be provided to the system to compensate for the non uniformity of the displacement. After a suspicious region has been detected, it may be necessary to pass over it again to get more information for a more sophisticated (but slower) recognition algorithm. The minimum distance between two scans necessary to catch an echo of a buried mine with our antenna is of about 10 cm, as we have observed in our sandbox. But in other types of soil with higher attenuation we expect that this distance must be lowered.

If the real size of the buried target is needed by the recognition process, pulse deconvolution and migration algorithms will be necessary to transform the target response into a more compact one. We are still looking for a robust and fast algorithm which must be able to work on cluttered images. As soil characteristics plays an important role in the migration aperture, it will also be useful to develop an adaptive algorithm.

Figures 4 and 5 are examples of B-scans showing the images of the mine and the stone after background removal (resolution of the acquisitions: 1 trace/cm and 25 ps/sample). The mine does not exhibit a clear hyperbola shape as in the case of the stone, which could be due to the fact that the layers of materials inside the mine produce interfering echoes. The metallic debris does not have a visible echo and its B-scan is not shown here.

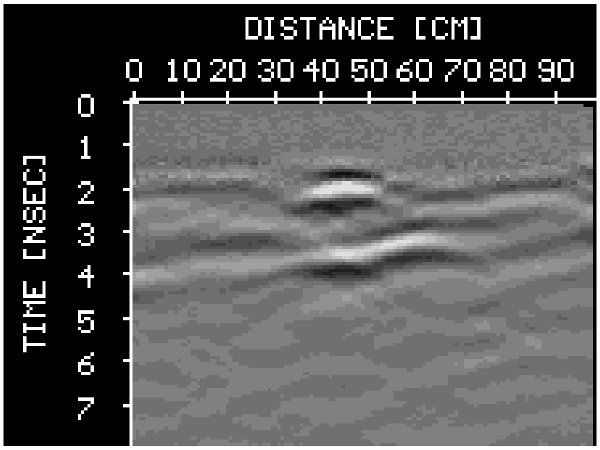

Figure 4: B-scan of an AP mine in sand.

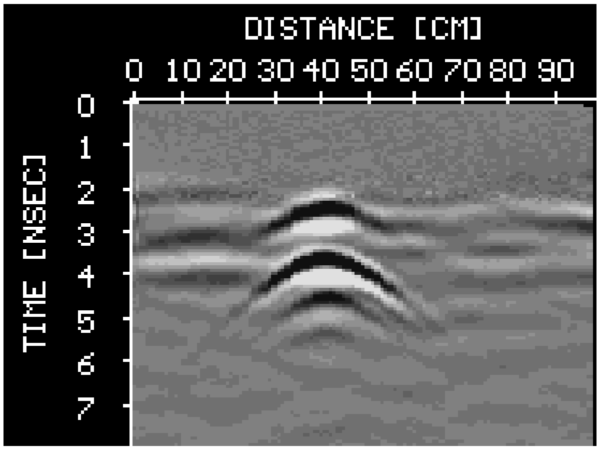

Figure 5: B-scan of a stone in sand.

Area or C-scan: in order to distinguish an object's shape it might be necessary to display horizontal views of the ground at different depths (time slices), from 0 to 30 cm. In this case it is necessary to combine data from several parallel scans. The distance between two parallel scans is an important parameter, in order to reconstruct the real shape of the buried object.

We have choosen to perform parallel scans each 20 mm, with an acquisition each 10 mm. In order to improve the resolution we take a second set of measurements orthogonally to the first one. The area of a minimum metal AP mine of diameter 8 cm is therefore covered by about 40 A-scans. Figures 6 and 7 show images of the previously used objects. Their circular nature can be clearly seen and, as no migration has been applied to the data, they obviously appear larger than in reality.

Volume or 3D imaging: a sequence of images could be created rather easily from single frames and be played back and forth at variable speed (short movie), helping the operator to visually correlate neighbouring images. A true 3D representation seems to need too much computer power for an embedded application and is not necessarily helpful for automatic recognition.

Data Processing

Several unwanted components of the received signal, such as random noise or clutter, must be removed to improve the quality of the image of a target object.

Random noise, i.e. a signal which is not directly related to the radar source, is strongly reduced by the averaging hardware integrated in the radar head; in addition the stacking of several successive A-scans could be done to improve the result. Different types of lowpass filters can be used to reduce the clutter response caused by irregularities in the ground surface.

The background component of the image must be removed too, given that we have to detect objects which might be placed just underneath the surface. If we assume that the soil properties exhibit only random variations around a location-independent mean, and that target echoes are present only in a small amount of data, then we can take the mean of a large number of traces as a measure of the fixed background and subtract it from the raw data. The two B-scans presented before (Figures 4 and 5) show the efficiency of that method with data acquired in the sand box; its suitability for use in inhomogeneous soils must still be tested.

Finally we note that it could be necessary to discard waveforms of little interest by selecting early in the recognition process areas containing potential targets, in order to increase the speed of a recognition algorithm. The size of the image to be analyzed could be reduced, for example, by integrating the total energy in each waveform and considering only those above a given threshold. Note that this technique will need to be adapted to the case of heavily cluttered soil.

INDUCTION COIL SENSOR IMAGING

Instead of converting the information given by induction coil sensors, as done in conventional metal detectors, to an audio signal, it is possible to use it for imaging purposes

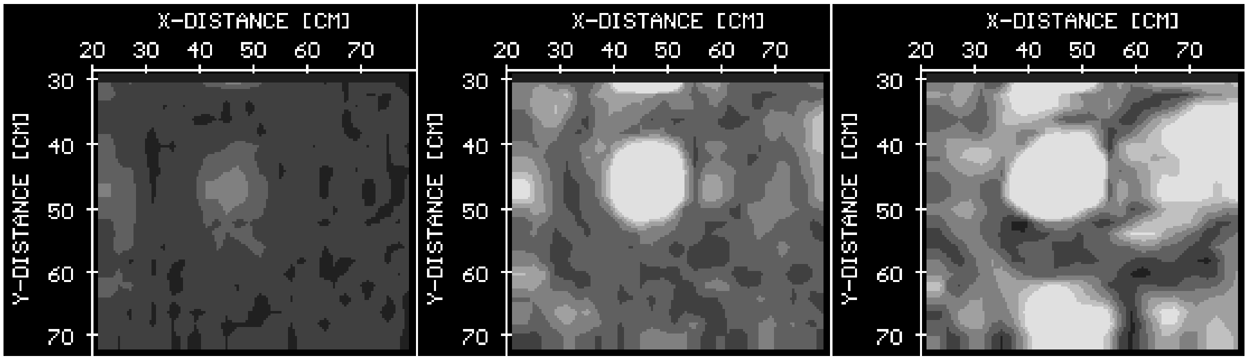

Figure 6: Horizontal slices at 1 / 1.5 / 2 ns of an AP mine in sand.

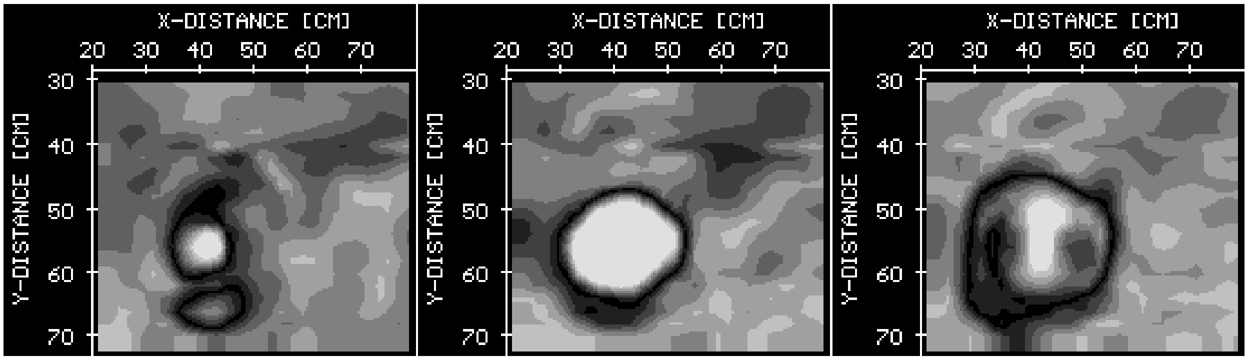

Figure 7: Horizontal slices at 3 / 3.5 / 4 ns of a stone in sand.

(displaying a map of the metal content in the soil), and to calculate a metallic object's parameters. With respect to this approach, the ODIS project at DASA-Dornier (Borgwardt, 1995) has demonstrated encouraging results in the detection of unexploded ordnance. In its current version it is able to detect metal parts of less than 1 cm^3 to a depth of 50 cm, computing their magnetic center (± 2 cm), depth ($\pm 10\%$), shape and metallic volume, and determining if they are ferromagnetic or not.

For our studies we also decided to rely, as ODIS is doing, on a Foerster Minex 2000SL metal detector, which generates two continuous wave frequencies, f1 and f2, at 2.4 kHz (for ferromagnetic objects) and 19.2 kHz (for stainless steel and alloys) respectively. It is a differential left-right system, its output audio signal vanishing (no tone) when the detector's mid axis crosses the object's center, thus allowing a very precise spacial localization along one dimension. To fully exploit the detector's capabilities we intercept, at the output of the receiver-transmitter module, four signals corresponding (in the complex plane) to the real and imaginary parts of the analog signals f1 and f2 induced in the receiving coils.

These signals are shown in the following plots for the objects represented in Figure 3, in order to allow a first comparison with the GPR data presented in an earlier section. Data collection has been carried out as done with the GPR (straight line across the object's center, sensor just above ground level), recording the signals with a LeCroy digital oscilloscope (8 bit resolution, smallest range 0.020 V, 10^4 samples/sec with a time base of 0.5 sec). In the future we will employ a dedicated 16 bit conversion card. The data was then resampled at 1/10 times the original rate, low-pass filtered with a median filter, and centered (subtraction of mean value).

Concerning the detector's response to a stone (left part of Figure 8), note that the imaginary parts of f1 and f2 show large fluctuations, probably due to soil inhomogeneities. On the other hand they are practically overlapping, i.e. strongly correlated, which is the main reason why the metal detector does not react, allowing to reject this "GPR false alarm". The response to the minimum metal mine (containing only a striker pin of 0.1 g!), on the right of the same image, is characterized by very clean and unambiguous real components. The imaginary parts show an irregular behaviour and are again overlapping, with the notable exception of the target area (real and imaginary parts have been separated for graphical reasons only). A clear indication of the presence of a metallic object is therefore given, which, combined with the corresponding GPR image, would lead to an overall alarm.

Figure 9 shows the response to the metallic debris (3.5 g), this time over a shorter length: signals are clear and allow again to localize precisely its center. A phase plot of f1 and f2 is shown on the right: its analysis might permit in the future to determine unambiguously the material type. The GPR response to this object is on the other hand negligible, as already said, which should allow to reject this type of false alarm.

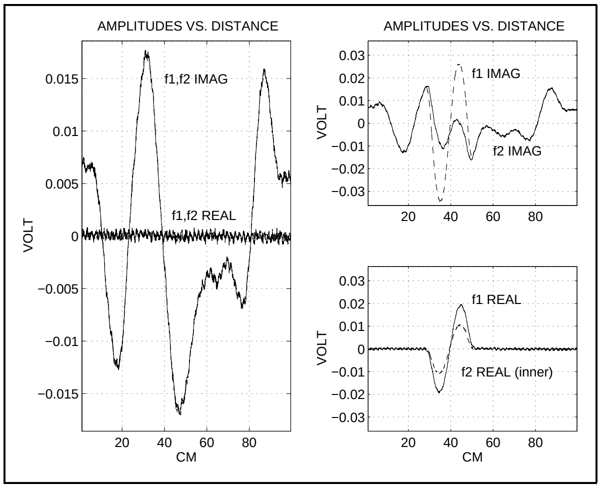

Figure 8: Metal detector response to a stone (left) and an AP mine (right) in sand (center: 40 cm).

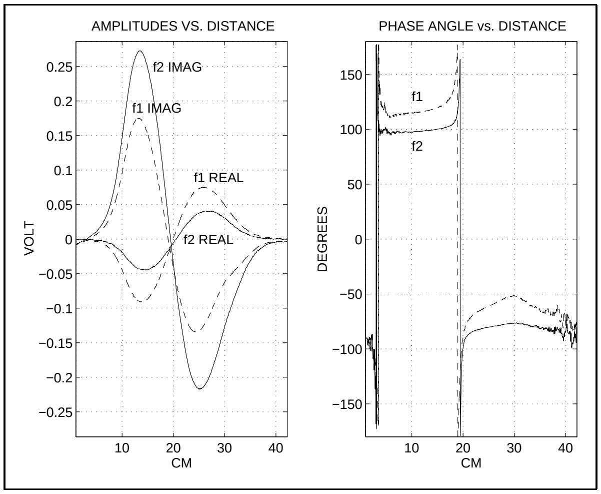

Figure 9: Metal detector response to metallic debris in sand.

Finally, we would like to conclude this section by showing in Figure 10 preliminary imaging data acquired in 10 parallel horizontal scans, at a step of 2.5 cm, over a shallowly buried AP mine (same as above). The interpolated absolute value of the received signal f1 is plotted. Its shape is indeed determined by the detector's sensitive area, which is roughly equivalent to its size (diameter of 25 cm), with the white vertical line in the middle corresponding to the object's central axis. A complementary orthogonal series of scans is necessary to get a "true" bidimensional picture of the object, perhaps deconvolving at the same time the detector's response, before being able to fully correlate it with the corresponding GPR output.

Future Activity

The test system's construction has been finished only recently and a lot of work is left in order to acquire, analyze and correlate data from the two sensors under various conditions. The following task will consist in setting up a database upon which the identification of the objects in the field, our ultimate goal, will be based.

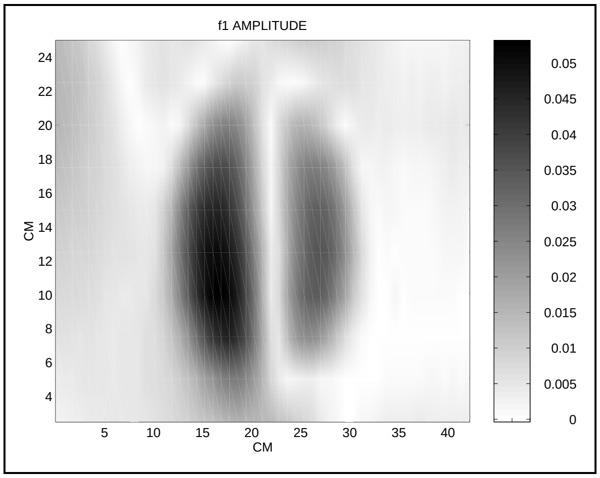

Figure 10: Preliminary metal detector "image" of an AP mine.

Acknowledgments

This work is being supported by the Foundation "Pro Victimis" in Geneva, by the Swiss Department of Foreign Affairs and by the EPFL, who are cordially thanked.

REFERENCES

Borgwardt, C., 1995. ODIS - Ordnance Detection and Identification System. In Proceedings of WAPM'95, Lausanne, Switzerland, June 30-July 1st, 1995, pp. 37–43.

Broach, T., 1996. Private communication. NVESD, Fort Belvoir, VA, USA.

Gros, B. and Bruschini, C., 1996. Sensor technologies for the detection of antipersonnel mines. In Proceedings of ISMCR'96, Brussels, May 9-11, pp. 564–569.

Mächler, P., 1995. Detection technologies for antipersonnel mines. In Proceedings of the Autonomous Vehicles in Mine Countermeasures Symposium, Monterey, CA, USA, April 4-7, 1995, pp. 6.150–6.154.

Nicoud, J., 1996. Mine clearance: not only a problem for the military any more. In Proceedings of ISMCR'96, Brussels, May 9-11, 1996, pp. 6–10.

Paca, F., 1996. Private communication. VSE corp., Alexandria, VA, USA.

Sandmeier, K., 1996. Reflex version 3, users manual. Pfaffstr. 6, 76227 Karlsruhe, Germany.

von Hippel, A., 1995. Dielectric Materials and Applications. Artech House, Boston, 438 pp.