



## **METAL DETECTOR TRIALS**

DETECTOR TEST RESULTS AND THEIR INTERPRETATION



Croatia  
2003

Mozambique  
2000

Mozambique  
2005

Afghanistan  
1999 & 2002



Laos  
2004

Cambodia  
1998 & 2004

Nicaragua  
2001

Colombia  
2003

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**AUTHORS:** D M Guelle, A M Lewis, P Ripka

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## Table of Abbreviations

Table: 1 *Abbreviations-*

BT	Technical Board (body of the CEN)
CCMAT	Canadian Centre for Mine Action Technologies
CEN	Comité Européen de Normalisation, European Committee for Standardization
COTS	Commercial off the shelf
CWA	CEN Workshop Agreement
CW	Continuous wave
EC	European Commission
FAR	False alarm rate
FFE	Free from explosive
FRY	Former Republic Yugoslavia
GC	Ground Compensation
HD	Humanitarian Demining
IMAS	International Mine Action Standards
IPPTC	International Pilot Project for Technology Co-operation
JRC	Joint Research Centre
MA	Mine Action
MAC	Mine Action Centre, (national) organ responsible for MA in a country
NGO	Non-governmental organisation
POD	Probability of detection
UN MAC	United Nations' MAC
UN MAPA	UN Mine Action Programme for Afghanistan
ROC	Receiver Operating Characteristic
UXO	Unexploded Ordnance Explosive ordnance that has been primed, fused, armed, or otherwise prepared for use and used in an armed conflict. It may have been fired, dropped, launched, or projected and should have exploded but failed to do so.
WG 126	Working Group 126 of CEN (dealing with HD)

## 1 Executive Summary

This document is devoted to eddy-current metal detectors used for finding mines. Its purpose is to collect the information split amongst the various test reports published during the period from 1997 and analyse it from a technical point of view and to evaluate the main factors influencing detector performance.

The second chapter gives an overview and background, describing the development of humanitarian demining operations into the modern Mine Action industry, with its main sensor technique remaining the metal detector. It lists the test campaigns that have taken place and the changes as they developed. Outstanding are the IPPTC and STEMMD trials, which give an overview about the capabilities of the metal detector at the time. Lab tests were added to the common field tests, and blind reliability tests, similar in content to those of non-destructive testing and evaluation, were introduced. With the introduction of a CEN Workshop Agreement in 2003, a new period began in which there was international agreement on how to conduct thorough tests.

The reliability test is the most complex test because it assesses all components of the detection system, based on statistically valid data, consisting of the intrinsic capabilities of the metal detector, the human factor, and the environment, including the rules for mine clearance operations. We describe how 3 basic components are split into evaluation criteria, which are demonstrated by test results. Various possibilities for design and statistics are included as well as explanations of how to create Receiver Operating Characteristic (ROC) curves showing the main factors which influence the test results.

Chapter 4 is devoted to the ground and its influence on the detection capability of the detectors. The frequency dependence of the magnetic susceptibility is the main factor directly influencing the metal detectors. The measuring instruments available for this are described. Other electromagnetic factors having less influence are mentioned. Using a metal detector for empirical soil measurements is good enough for establishing a rough overview about problem areas for metal detector employment. These data can easily be collected during impact or technical survey. We explain the limits for using detectors without ground compensation and discuss the effectiveness of the ground compensation. Not all detectors have good enough ground compensation to cope in some regions with high frequency-dependence soil. The STEMMD trial in Mozambique focused on the influence of soil. 12 latest-models, representing all recognised metal detector manufacturers were tested against 13 targets and 7 soil types. The results showed, beside the limits of soil compensation of some detectors, also that in-air testing with a detector set up to the soil does not deliver reliable data and should not be used for detection prediction in soil.

The special trial in Laos allowed a direct comparison of 4 UXO detectors to normal detectors. The trial results showed the advantages and limits of both types of detectors, concerning sensitivity, power consumption and pinpointing.

Next is a features assessment of currently available detectors. The general conclusion is that the basic sensitivities of the detectors are not very different but some other features are different, and make influence their effectiveness. Ground compensation and the interface to the user are a lot better in some detectors than others. There are several different approaches and possibilities for setting up and using the detector.

The authors believe that there are still possibilities for improving the metal detector's capabilities by improving the data analyses collected from targets. This may concern target discrimination and three-dimensional data signatures.

## 2 Background

### 2.1 Introduction

Metal detectors are the main tool for detecting landmines in humanitarian demining (HD) and an accurate understanding of their capabilities and limitations is of great importance to people working in the field. When modern HD began, at the end of the 1980's, tools and practices were taken over from army manuals by consultancies, often staffed by ex-military personnel. With experience, the equipment and methods were sometimes found to be inappropriate. The main difference is that the military are usually interested in breaching a minefield for passage but in humanitarian demining all mines must be removed from an area so that it can be returned for civilian use.

Concerning the detectors, humanitarian deminers do not care what colour they are painted, whether they are visible in infrared or whether they can be used lying prone to avoid enemy fire. They do care that their detectors are affordable and long-lasting, that they can use them for six hours without straining their arms or changing batteries and above all, that they will find low-metal mines reliably enough that they can hand over land confident that all mines have really been removed.

Due to the scale, the expertise involved and the specialist equipment required, activities associated with humanitarian demining have become, in effect, a new industry: Mine Action (MA). It is to a large extent an industry financially dependent not on its real end-users, the local populations, but on sponsors: donor governments, NGO's and individuals. From the very beginning, these sponsors required that comparative tests be carried out to obtain information about the different types of equipment that was being procured for the operations they were paying for. The United Nations Mine Action Centre began to organise such trials from 1997. It was soon recognised that resources would be wasted if testing was duplicated by every interested organisation. In June 2000 representatives of six donor governments and the EC<sup>1</sup> signed the Memorandum of Understanding of the International Test and Evaluation Program (ITEP), with the remit of conducting joint test and evaluation projects and exchanging the results.

A substantial amount of information was collected during the different trials and new elements were introduced to address specific requirements of the users and donors. Taken together, the information collected in all the trials demonstrates the changes and development of techniques, capabilities, and design of detectors during this relatively short period.

The purpose of this document is to collect the information split amongst the various reports published during the period from 1997 and analyse it from a technical point of view and to evaluate the main factors influencing detector performance

### 2.2 The mine detector industry

The only technology used on a large scale to find mines is the metal detector based on eddy currents. During the time of the development of MA, some of the metal detector manufacturers became established as regular suppliers to the HD-Community and their equipment was more often accepted. In alphabetic order, these major manufacturers are:

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<sup>1</sup> ITEP currently has eight partners: Belgium, Canada, EC, Germany, The Netherlands, Sweden, UK, USA. Discussions are ongoing for enlargement and for the establishment of cooperation agreements with other governments and organisations but the EC is discontinuing its direct membership from June 2006.

- CEIA (Italy)
- Ebinger (Germany)
- Foerster (Germany)
- Guartel (United Kingdom)
- Minelab (Australia)
- Schiebel (Austria)
- Vallon (Germany)

There are other manufacturers and their products may be competitive with those above mentioned, for example, those in countries formerly excluded from the market as a result of trade restrictions remaining from the Cold War. A much larger ground-search metal detector industry also exists for treasure hunting, and such products have also sometimes been considered.

The tables below list the principal features of the latest models. Table 2 shows information about operational features which need to be known by the operator. Table 3 shows some engineering details.

Table: 2 Technical detector features with immediate affect on use

Detectors	Manufacturer	Principal Features											
		Mode		Coil		Set-up						Software access	Signal <sup>4</sup>
		Static	Dynamic	Single	Double-D	Sensitivity adjustment			Ground compensation				
						Fixed	Stepped	Continuous	Automatic	Manual	None	YES/NO	A/L/V
MIL-D1	CEIA	X	-	-	X	-	-	X	X	-	-	Y	A
EBEX® 421GC	Ebinger	-	X	X	-	-	-	X	-	X	-	-	A
EBEX® 420HS	Ebinger	-	X	X	-	-	-	X	-	-	X	-	A
MD8+	Guartel	-	X	-	X	-	3	-	-	-	X	-	A/L
Minex 2FD 4.500	Foerster	X	-	-	X	-	3	-	X	-	-	-	A
Minex 2FD 4.510	Foerster	X	-	-	X	-	3	-	X	-	-	Y	A
F1A4	Minelab	-	X	X	-	X	-	-	X	-	-	Y	A
F3	Minelab	X	-	X	-	X <sup>2</sup>	-	-	X	-	-	Y	A
ATMID™	Schiebel	-	X	X <sup>1</sup>	-	-	-	X	X	-	-	-	A
M90	SHRIMT	-	X	X	-	-	-	X	-	-	X	-	A
VMH3	Vallon	-	X	X	-	-	-	X <sup>3</sup>	X	-	-	Y	A/L/V
VMH3 (M)	Vallon	-	X	X	-	-	-	X <sup>3</sup>	X	-	-	Y	A/L/V

<sup>1</sup> Double coil (separate sending and receiving coils)  
<sup>2</sup> The sensitivity level is normally fixed but can be changed (see detailed description in Section 8).  
<sup>3</sup> A large number of digitized levels are available, so the adjustment is effectively continuous.  
<sup>4</sup> The signal may be delivered to the operator via audio signal (A), LED/display (L), vibration (V) of the handle.

The “mode” may be either static, if the detector continues to emit a sound when it is held stationary over a metal target or dynamic if it must be moved over the target to signal.

Some detectors have the receive-coil divided into two halves, the “double-D” design, which has a zero line in the middle where the signal stops or changes, to enhance pinpointing.

The manner and capability of detection and pinpointing depend on both these factors. The deminer should be aware of them and they should be emphasised during training. A detector with a double-D coil behaves very differently from one with a simple circular coil and it is dangerous to confuse the two, because the shapes of the sensitive areas are different. Similarly, it is important to understand that a dynamic mode detector can be silent, even over a metal object, when it is not moved.

Sensitivity adjustment in some detectors is made with a switch with a limited number of positions, such as low, medium and high, with others it is made with a continuously variable knob and others have fixed sensitivity.

Setting of the soil compensation, where the detector has it, is usually made by invoking an automatic procedure which allows the detector to “learn” the soil properties. Older detectors required the operator to adjust the soil compensation manually. The Ebinger 421GC is the only modern model of which we are aware which retains a completely manual adjustment. The CEIA Mil D-1 makes its soil compensation adjustment automatically, but the manually-adjusted sensitivity setting affects it. The detailed procedures are different for each detector and it is important to follow precisely the instructions of the manufacturer for the model in question.

Some of the most recent detectors allow the user access to the software via a communications port, for example it may be possible to download updates from the manufacturer, or make special changes to adapt the detector to particular conditions on the operational site.

All detectors have an audio indication when metal is detected and this is generally considered superior to visual indication to avoid distracting the operator from looking at the ground. The VMH3 and MD8+ do provide also visual indication by LEDs on the handle. Vallon have also recently introduced a vibrator in the handle as a tertiary indication.

We include below some technical details concerning the working principles of the devices, which are not normally apparent to the user but which are important for engineers. The principle of electromagnetic induction is common to all metal-detectors but there are many variations in the way it is used. The participating detectors represent a broad spectrum of different practical technical solutions [ref. JRC Metal Detector Handbook].

Briefly, the “wave shape” type refers to whether the magnetic field is in the form of a smoothly varying wave or brief pulses. The “polarity” type refers to whether the magnetic field is always in one direction or reverses direction on each pulse or wave, to avoid initiating magnetic influence fuses. The “domain” type refers to whether the receiving circuit measures the returned signal at specific time points on the wave or extracts and measures sinus wave signals of specific frequencies. Some detectors have separate coils for sending the signal and receiving it, others use just one coil for both.

Table: 3 Technical principles of latest detector designs

Detectors	Manufacturer	Technical Principles & Design							
		Wave shape		Polarity		Domain		Send/receive Coil	
		Pulse	Continuous wave	Bipolare	Unipolar	Time	Frequency	Single	Separate
MIL-D1	CEIA	-	X	X	-	-	X	-	X
EBEX® 421 GC	Ebinger	X	-	X	-	X	-	X	-
EBEX® 420HS	Ebinger	-	X	X	-	-	X	-	X
MD8+	Guartel	X	-	-	X	X	-	-	X
Minex 2FD 4.500	Foerster	-	X	X	-	-	X	-	X
Minex 2FD 4.510	Foerster	-	X	X	-	-	X	-	X
F1A4	Minelab	X	-	-	X	X	-	X	-
F3	Minelab	X	-	X	-	X	-	X	-
ATMID™	Schiebel	-	X	X	-	-	X	-	X
M90	SHRIMT	-	X	X	-	X	X	?	?
VMH3	Vallon	X	-	X	-	X	-	X	-
VMH3 (M)	Vallon	X	-	X	-	X	-	X	-

### 2.3 The metal detector trials

The order of the test campaigns is as follows:

Table: 4 Trials considered

Date	Location	Organisation	Comments
January 1997	Sarajevo, Mostar	UN Mine Action Service (UNMAS)	16 detectors, 11 manufacturers; to provide a <i>list of detectors acceptable for FRY</i> , support decision for purchase
1998-2000	Cambodia, Croatia, Canada, Netherlands	IPPTC, US, UK, Netherlands, Canada, EC – later ITEP members	28 detectors, 13 manufacturers; to provide a <i>COTS overview of different capabilities of metal detectors tested under lab and field conditions, soil properties measured (conductivity, susceptibility)</i>
September 1999 to march 2000	Peshawar, Jalalabad, and Kabul	MAPA	13 detectors, 8 manufacturers; <i>soil properties measured - Bartington D</i> , support decision for purchase
Autumn 1999 & 2000 for 5 months time in summary	Maputo, Gaza, Inhambane provinces	UNADP Mozambique	9 detectors, 6 manufacturers; <i>field trial in minefields and focus on soil influence on metal detectors (GRH)</i> , support decision for purchase
2001	Nicaragua	US-Army	7 detectors, 5 manufacturers; support decision for purchase small-scale trial
February 2002	Jalalabad, Kabul	MAPA, UNOPS, ITEP (inv.)	7 detectors, 7 manufacturers; support decision for purchase
July 2003	Colombia	Defence R&D Canada	5 detectors, 5 manufacturers; <i>First use of a Total Station</i> support for purchase armed forces
May – Nov 2003	Germany, Croatia	BAM Germany ITEP (inv.)	4 detectors, 4 manufacturers; <i>Reliability trials based on non-destructive testing and evaluation</i>
August 2004	Cambodia	CMAC, ITEP (inv.)	5 detectors, 4 manufacturers; support decision for purchase
October 2004	Laos	STEMD JRC, ITEP (inv.)	8 detectors (4 of them UXO), 6 manufacturers; <i>comparison of UXO and normal metal detectors</i> , support decision for purchase
April 2005	Mozambique	STEMD JRC, ITEP (inv.)	12 detectors, 8 manufacturers; <i>overview about current COTS and the influence of soil</i>

As the table demonstrates, eleven trials were carried out on five continents within eight years. The table includes only tests with international importance, no local tests for NGOs or commercial mine clearance operations are included. The demand for tests of metal detectors was and remains clear. Today, results are of interest to a much wider circle, if not the whole HD technical community.

The aims are still focused on specific interests of Mine Action Centres (MAC), but they have the intention to deliver information about and for a regional problem or - as the IPPTC started - to give an overview about the current detector fleet at that time. These two approaches are not necessarily completely different. The IPPTC field trials in Cambodia and Croatia were, in fact, to some extent tuned for specific regional needs and STEMMD placed greater emphasis on this; its

trial in Laos being focused on the UXO problem there<sup>2</sup> and its trial in Mozambique having the specific aim of characterising the influence of soil on detection performance for mines and mine simulants, with currently available international COTS detectors. Both IPPTC and STEMMD were originally planned with third field trials which regrettably were not completed.

## ***2.4 Quality, comparability and availability of data from metal detector trials***

The results from the earlier tests were not comparable due to different approaches and focus on specific requirements. A breakthrough was achieved in 1998 when the International Pilot Project for Technology Co-operation (IPPTC) was launched. IPPTC was the most comprehensive trial ever conducted. 5 research organisations and 2 national mine action centres carried out a broad range of tests on 28 devices under controlled conditions in laboratories, and in blind field trials in two countries, with the intention of assessing their performance under as wide a range of conditions as possible.

The methods developed in all these trials were standardised in CEN Workshop Agreement CWA 14747 in 2003 and incorporated as a normative reference in the International Mine Action Standards (IMAS). The CWA is comprehensive, defining tests for all factors relevant to the user (Annex A). Of key importance are the measurement of detector sensitivity to targets under various conditions and the measurement of the overall detector performance statistics.

One difficulty in analysing data from past trials is the availability of information. In the past, the reports were often restricted in circulation.<sup>3</sup> The participants in the IPPTC trial sought to move away from this attitude, and the results were made broadly available in a consumer report in 2000. Since then, the ITEP website has become a well-used information source for test results.

The precedent of IPPTC and subsequent trials and the standardisation exercise of CWA 14747 mean that today one may have far more confidence in the manner in which trials are carried out. The quality and comparability level have therefore substantially increased.

During the execution of lab tests the intrinsic capabilities of the detector can be established as well as a part of the ergonomics. Some of them can exclude the human factor using mechanical scanners for moving the detectors and electronic means for measuring the results.

Blind trials and their execution allow one, to a certain degree, to define the influence of the human factor on the probability of detection, beside the other factors. It is easy to understand that the probability of detection (POD) is a function of target depth and also that with an increase of POD, in general the false alarm rate (FAR) increases. This can be done for the sensors as well as for the operators. Typically a curve of POD versus FAR is plotted while a sensitivity or threshold parameter is varied. This curve is called Receiver Operating Characteristics (ROC) and it shows a trade-off between selectivity and sensitivity. With this the individual performance of a person or a sensor can be demonstrated. It is important that the data collected have statistical value and allow such an assessment. Other factors which may be inherent to the different technical

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<sup>2</sup> UXO (unexploded ordnance) is formally defined as explosive ordnance that has been primed, fused, armed, or otherwise prepared for use and used in an armed conflict. It may have been fired, dropped, launched, or projected and should have exploded but failed to do so. UXO from the Vietnam war is present in Laos in enormous quantities. Smaller items, such as submunitions from cluster bombs and small-calibre shells, are located by methods similar to those used to find mines. The STEMMD trial focused on identifying suitable metal detectors for these smaller UXO.

<sup>3</sup> The motives for this could have been worries about possible allegations of discrimination or even malfeasance from manufacturers not selected for purchases as a consequence of a poor trial result; or not selected for business reasons, in spite of a good trial result. Another reason may simply have been professional habit on the part of ex-military staff accustomed to working in secret.

solutions of the sensors (sensitivity, ease of use, interface, ground compensation capability etc.) or the operator's abilities (experience, technical knowledge, health, mental situation etc.) together with the environment will have influence on the results. The decision YES/NO is always dependent on a subjective interpretation of the signal by the individual. In most cases only an audio signal is available. In tests, it is important to create a situation which is similar to the normal environment where such tasks as mine clearance are normally executed. But even the best simulation can not replace the real threat as it will be in a mine field. As in most cases a trade off has to be found to reduce the testing efforts to an acceptable level concerning personnel and time.

## **2.5 Lab trials**

### **2.5.1 Overview of lab tests**

Detection capability i.e. the distance at which it is possible to detect a given object, was measured in the field in the earlier tests conducted by the UN. It was recognised that tests of this nature are essentially deterministic in character and it would be preferable to measure them in a fully-controlled laboratory environment. This recommendation is made explicitly in the report of the UN trial in the Former Yugoslavia in 1997.

IPPTC addressed the question thoroughly by conducting three separate laboratory trials: in-air detection capability tests in a non-metallic laboratory at the Canadian Centre for Mine Action Technology (CCMAT) in Suffield, Alberta; in-soil detection capability tests in a controlled outdoor facility at TNO, The Hague and ergonomic tests at CCMAT, by experts from the Defence and Evaluation and Research Agency (DERA) of UK<sup>4</sup>.

A number of key variables were identified which must be controlled to obtain reliable results in lab-tests: lab-temperature, moisture, detector set-up and drift, sweep speed and batteries. In-air testing also included plots of the sensitivity-cone, the three-dimensional region within which a particular object may be detected. . The cone is measured by sweeping the detector with a mechanical scanner at various heights and recording the signal to determine the "footprint", the two-dimensional region within which the object may be detected at that height. The sensitivity cone depends on the target's metal content, shape and orientation.

Using the methods of CWA 14747:2003, the JRC's STEMMD trial is the only trial giving an overview about the current detector fleet as the IPPTC did. The main reason why few really complete series of lab tests have been conducted is the large amount of labour required. It is increasingly recognised that covering all the tests in CWA 14747:2003 is impractical for almost all organisations. Rather than revising an already agreed document, current thinking is that a set of guidelines are required which would advise on which tests to carry out under different circumstances, to obtain the best possible assessment given resources likely to be available.<sup>5</sup> (Ref. BAM Workshop December 2005).

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<sup>4</sup> The ergonomic assessment is described in the IPPTC report as a "human factors" assessment, a term which we prefer to reserve to describe issues concerning the behaviour of the operator. The ergonomic factors are properties of the detector which influence the human factors.

<sup>5</sup> The different circumstances under which CWA tests might be used could even include metal detectors applications in areas other than Humanitarian Demining.

## **2.5.2 Major sources of uncertainty in detection capability measurements**

### **Subjectivity of interpreting the detector signal**

CWA 14747:2003 Section 5.5 attempts to control this by defining what should be considered a confirmed detection. In practice, background noise in the lab, differences in hearing between operators and an element of judgment required for some types of audio alarm mean that uncertainties as bad as  $\pm 2$  cm can occur.

### **Positioning errors**

in manual handling of the search head are another source. In determining detection capability, one is essentially seeking the tip of the sensitivity cone, so any lateral error or pitching of the head will cause the measurement to be too low.

### **Uncertainties of the sensitivity and soil compensation settings**

especially for detectors having continuous adjustments, are to be individually assessed. Automatic compensation circuits generally show no visible indication of the setting at which they have locked.

### **Electromagnetic interference**

This aspect was not touched on during the trials analysed here. The interference may degrade the performance of the detector, but (like ground effect) under some circumstances it may apparently increase the detection distance: when the interference signal is close to the detection threshold, only a very small target may be enough to trigger the detector.

### **Uniformity of the test targets**

Chrome steel balls from different sources give very similar detection depths. The weak dependence on the parameters of the target (conductivity and permeability) [ref.Lewis and Bloodworth EUDEM-SCOT] can be explained by the fact that for used frequencies the penetration depth of the steel is always very small (about 1 mm at 10 kHz) compared to the ball size (3 to 25 mm). The “equivalent ideal current loop” characterizing the effect of the eddy currents has therefore a diameter which is similar to the ball diameter and which is not very sensitive to the material properties.

A quick check of the test balls can be done using a measuring solenoid: the change of the coil impedance after inserting the ball is a measure of the ball permeability and conductivity.

### **Sweep speed**

All detectors will lose sensitivity if swept too quickly, because of the use of low-pass filtering in the electronics. Some, termed dynamic mode detectors, also lose sensitivity if swept too slowly. Others, termed static-mode detectors, will continue to alarm when held stationary over a target. The details vary considerably, for example, some of the latest smart static detectors even show some dynamic behaviour for very small targets. CWA requires that the dependence on sweep speed should be established before other detection capability measurements. The individual habit of the testing personnel may affect the measured detection depth but, in our experience, the dependency on sweep speed is not very strong and it is sufficient for the tester to be aware of the general characteristics of the detector in this respect.

### **Testing the latest models**

The tendency to design more intelligent detection systems with more and more complicated behaviour creates problems with testing. The more the device is self-adaptive, the more difficult is to achieve the reproducibility of the tests performed in the complicated environment.

### 2.5.3 Lab tests advantages and limits

The advantages of measuring in laboratory conditions are:

- Precise jigs and scanners to control positions and speeds in in-air measurements
- Controlled air temperature and shade
- Controlled moisture conditions for soil measurements (soil in boxes)
- No rain or dew causing moisture on detector heads
- Lighting
- Quiet
- No wind

The disadvantages of working in the laboratory are:

- Targets encountered in the territory of interest are often not available in the lab
- Soil and rocks available in the lab may not match those in country
- Technical staff may handle detectors differently from deminers in-country
- Labour costs are usually higher than working in-country
- Interference between detectors may prevent several being switched on in the lab at one time, so they must be tested one by one; in a large field, many can work simultaneously
- Research institutions are often locations with high electromagnetic interference

We would also point out that in practice some effort is required to achieve a really good laboratory environment for metal detector testing because temperature and noise level are more difficult to control in a special metal-free structure than in a conventional building.

The main advantage of working in a laboratory is simply that measurements may be repeated if an anomaly is observed. This is often not possible in the field, where campaigns normally have to be made to tight schedules because of logistic constraints and the costs of keeping staff away from their home bases for long periods.

#### **Inferring expected performance in the field from lab data**

In general all in-air measurements from the lab should be repeatable with an identical detector and target in-air in the field if there are no sources of EMI.

Difficulties for direct comparison of the lab with field results appear under the following conditions and have to be taken into account:

- Detection capabilities for specific mines may vary, because the mines themselves vary in their manufacture and state of ageing. For example, the common PMN AP mine has a metal retaining ring around its rubber cap which forms an electric circuit and renders the mine detectable at 40cm or even more, but as soon as the ring is broken e.g. by rust, the detection distance drastically drops.
- In-soil testing in the lab is normally restricted to a limited number of soils with certain magnetic susceptibility and frequency dependence, conductivity, and humidity and can only give direct predictions of performance in soils with exactly similar electromagnetic properties (see Chapter 4 for more detail).
- The lab for testing metal detectors should exclude EMI sources as stated in the CWA. Strong EMI sources are likely to be encountered all over the mine-affected country, and a facility such as a radar station, radio antenna, power line etc. may often have had mines placed around it and need to be cleared. Some of the metal detectors are able to a certain degree to be balanced to EM-noise and may function as designed, others will not.
- Other factors such as temperature, acoustic noise (wind, traffic, animals etc.) may influence the test results, but not necessarily the detector performance.

## 3 Reliability tests / blind trials

### 3.1 Introduction

A target which can be found in the lab conditions may nevertheless be missed in the field if the operator loses concentration, or does not sweep over the point where it lies, or sweeps too fast or too slowly for the detector electronics, or misinterprets a weak mine signal as a soil signal. An operator may also incorrectly signal the presence of a mine when none is there, if there is a signal from a small area of magnetic soil minerals or a small piece of metal clutter or electronic noise. Such errors are unpredictable but one may measure the probability of their happening in statistically-based blind reliability trials, in which a team of operators attempt to find rendered safe mines or other targets buried at locations unknown to them. The Probability of Detection (POD) for a given target in given conditions and the False Alarm Rate (FAR) are dependent on the detector design as well as the operator behaviour and their measurement therefore is part of test and evaluation. Details of the method are now standardized in CWA 14747 Section 8.5. POD and FAR are related in the sense that they both decrease if the operator adjusts down the sensitivity of the instrument, or implicitly does so by requiring a clearer sound before calling an indication. It is therefore the usual practice to quote POD and FAR together. The graph of POD against FAR is called a Receiver Operating Characteristic (ROC)<sup>6</sup>. Generally, the deeper the target is placed the smaller the POD. Therefore, it is meaningless to quote a POD without also quoting the target depth and it is common practice to show graphs of POD against target depth.

It is important that as many buried targets as possible are contributing usefully to the statistics. Targets buried so deeply that the POD is zero are essentially wasted; therefore it is important to have some idea of the maximum detection depth before starting. It is possible to specify a set of fixed depths but in principle random depths are also possible providing the depths of all targets are recorded. It is not clear to the authors that there is a great advantage either way. The distance of targets should be as high as possible. The proximity of one target may affect the POD of finding a neighbour. For the sake of simplicity, normally a minimum separation distance is imposed (0.5m in CWA)<sup>7</sup>. Furthermore, the density of targets must not be too high, to avoid a regular pattern spontaneously appearing, which could give a clue to the operator about the location of the next target. As far as we are aware, no statistically-based reliability trial has been conducted where questions of discrimination between adjacent targets and targets and clutter items were systematically investigated. This will be necessary when tests of dual sensors are compared with metal detector tests.

### 3.2 Design of trial for best statistics, number of repetitions

The reliability trial provides an estimate of the POD and FAR, to which is attached a statistical uncertainty. It is necessary to repeat the test until this uncertainty has been reduced to a level deemed acceptable. Confidence bounds for both POD and FAR may be calculated easily using standard statistical methods [ref. Simonson 1998, Wilrich 2003, Gaal et al 2004] .

The Simonson study is the first of which we are aware which addressed the question of the statistical considerations for mine detector trials. The calculation of confidence intervals was fully explained but, regrettably, its impact was not sufficient for the recommendations to be adopted properly in IPPTC and no error bars are attached to the performance values in the final report of this trial.

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<sup>6</sup> The name was adopted from the testing of radar receivers, to which the same trade-off applies.

<sup>7</sup> On the basis of experience in 2003-2004, BAM recommended increasing this to 70cm.

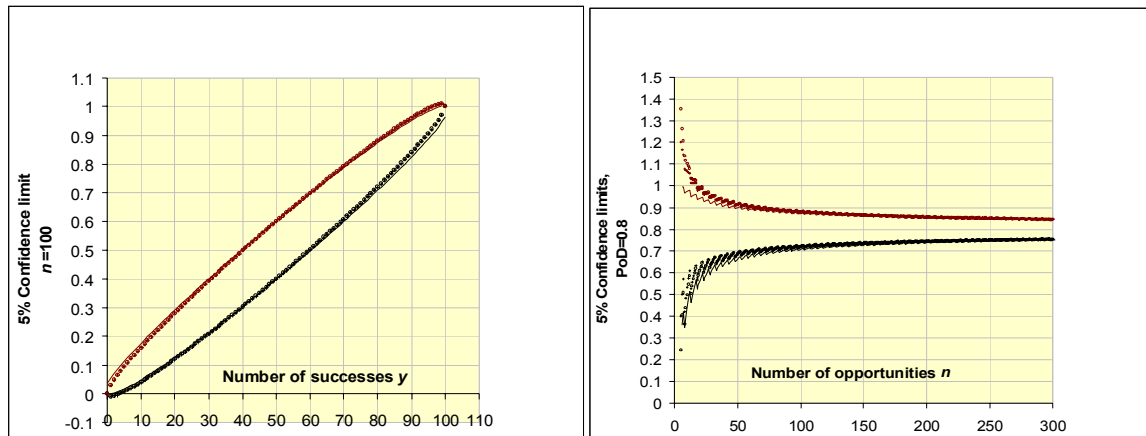


Fig.: 5 Example values of 95% confidence limits

Figure 5 shows graphs with example values for 95% confidence intervals (upper and lower bounds) in the POD, calculated using the 2 standard error approximation (+), normal (o) and binomial (—) estimates. The left hand graph shows the confidence intervals plotted against the number of successes for 100 opportunities to find the target. When 50 targets are found (= successes) out of 100 (= opportunities), the estimate for POD is  $0.5 \pm 0.1$ . In this case the uncertainty is maximum. For 90 targets found, the estimate for POD would be  $0.9 \pm 0.6$ . The right-hand graph shows the upper and lower confidence bounds (confidence interval) plotted against number of opportunities [ref.Gaal et al 2004] for fixed  $POD = 0.8$ . It is clearly seen that the lowest reasonable number of opportunities (= number of targets  $\times$  number of test repetitions) is about 75, giving the estimate  $POD = 0.8 \pm 0.1$ . The repetition of the test allows also the evaluation of statistical parameters on real measured data. This was used in tests performed by BAM.

### 3.3 Trial Matrices

It is of the highest importance in a comparative trial to pay great attention to the removal of any systematic bias by ensuring that each detector is tested with an equivalent combination of the other variables. The IPPTC field trials were not satisfactory in this respect, because the large number of detector models tested made it impractical to have sufficient number of different operators use each one. There was therefore a risk that apparent differences in performance between detectors were in reality due to the differences between the operators.

A “full-factorial” test matrix which included all of the variations of all of the factors (Test Lane, Operator, Detector Type and Detector Specimen) is the most obvious way to construct an unbiased matrix but it will also be a large matrix. As discussed in the previous section, there are diminishing returns as the number of repetitions is increased, so very large trials entail much labour to little benefit. It is possible, instead, to use a matrix in which each detector is tested with each variation of each factor, but not with all the possible combinations. An example of such a matrix is shown in Table 6. Providing that the factors are uncorrelated, (a significant assumption), this will give an unbiased test with considerably fewer runs than the full factorial design [ref. Mueller et al, Gaal et al.]

Table: 6 Double Graeco-Latin square test matrix ABCD are operators,  $\alpha\beta\gamma\delta$ ,  $\alpha'\beta'\gamma'\delta'$  are detectors (ref. BAM 2004)

		start							
		1	2	3	4	5	6	7	8
test field	1	A $\alpha$	C $\gamma'$	B $\beta$	D $\delta'$	C $\gamma$	A $\alpha'$	D $\delta$	B $\beta'$
	2	B $\gamma$	D $\alpha'$	A $\delta$	C $\beta'$	D $\alpha$	B $\gamma'$	C $\beta$	A $\delta'$
	3	C $\delta$	A $\beta'$	D $\gamma$	B $\alpha'$	A $\beta$	C $\delta'$	B $\alpha$	D $\gamma'$
	4	D $\beta$	B $\delta'$	C $\alpha$	A $\gamma'$	B $\delta$	D $\beta'$	A $\gamma$	C $\alpha'$

The implementation of systematic statistical methods for trials is one of the most important advances in detector testing that has been made in the period under review.

### 3.4 Different results and reasons for differences (IPPTC, BAM, STEM D)

Data comparing detectors and data comparing different approaches

The trials in the nineties including IPPTC focused more on a broad spectrum of targets and less on the statistical figures how many opportunities were given to detect with one detector type the same target. The IPPTC report acknowledged that some of the trial results were not statistically rigorous, due to the small number of opportunities to detect the targets, but it did not give a detailed analysis. All data documented during the other trials at that time did not include statistics or even refer to them.

Some trials included assessments of factors directly influencing the POD (laboratory sensitivity measurements, ergonomics assessments, questionnaires for operators) but in no case was there any attempt to combine the information with the results of the blind reliability trials.

During the discussions of the CEN workshop, a conceptual framework adopted from knowledge of non-destructive evaluation (NDE) and testing (NDT) was introduced.

Overall performance =

- + Intrinsic capability of the detector
- Environmental factors (+ clearance procedures)
- Human factors

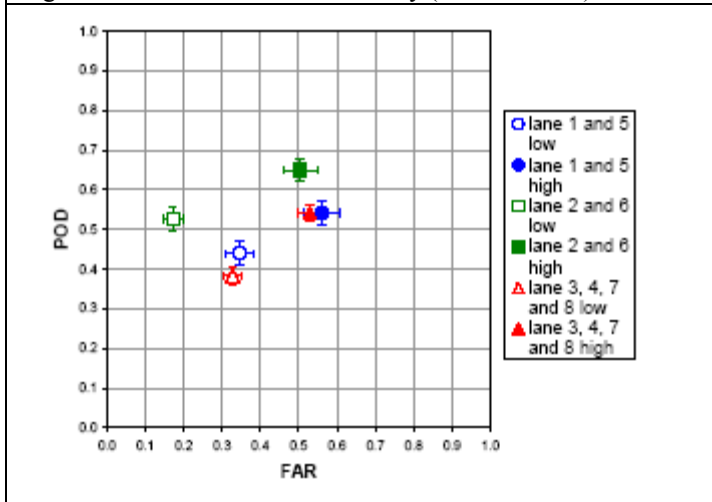
The intrinsic capability would normally be the in-air detection capability of the detector for a target; the Environmental factors would be the soil-type and burial depth and the working rules; and the human factor the operator. The CEN Workshop recognised the value of this contribution and included it in the CWA in the description of the reliability trials. It should however be appreciated that the three factors are not really simply added together, but influence each other. For example, the affect of the soil is dependent on the quality of the ground compensation, an intrinsic factor, and the thoroughness with which the operator covers the ground, a human factor, is affected by the extent he is distracted by signals from the soil, an environmental factor etc.

In the 2003 BAM trial, the first blind tests to establish the reliability of detection which properly took account of all the statistical considerations were carried out. In the trial report detection reliability is defined as *“the degree to which the metal detector is capable of achieving its purpose, which is to have maximum capability for giving true alarm indications without producing false alarm indications.”*

### 3.4.1 Intrinsic physical capabilities

#### a. Sensitivity

Fig.: 7 Tests with different sensitivity (ref. Gaal at al)



The result returned during a trial will depend on the sensitivity setting employed. On the ROC diagram, reducing the sensitivity corresponds to a reduction of false alarms and of POD, that is to say, moving to the left and down. In the BAM 2003 trials, runs were made over the same lanes and targets first with the highest sensitivity and then a second time with a reduced sensitivity, to plot two points on the ROC. It has to be borne in mind that this ROC included all the different targets used in the lanes, with different shapes and amounts of metal and different depths.

Deliberate reduction of sensitivity to reduce false alarm rate is sometimes used in practice. The deminer uses a so-called “needed” sensitivity which will safely allow the detection of the given mine(s) to the required depth, but not much greater. An absolute precondition for applying this method is that the information about the laid mines is reliable

#### c. Search head shape and size

For the search head shape the same statement as above can be made. All the above mentioned reports never stated the different shapes as an advantage or disadvantage for mine detectors. These are the effects of increasing the head size:

- large targets can be detected at greater depths because the field spreads vertically to a depth similar to the diameter of the head
- sensitivity to small targets decreases, because the field is spread over a larger area and therefore reduced in strength. The smallest targets may no longer be detected
- in consequence, the false alarm rate decreases
- in consequence, the rate of ground-coverage increases
- the energy required to drive the current around the large coil is greater, so there is an increase in power consumption, shortening the battery life
- it is harder to pinpoint the object as precisely with a larger head

This becomes important if the metal detectors are used to find UXO. Such detectors were evaluated during the Lao STEMMD trial. The requirements of UXO Lao were to use two types of UXO: the cluster submunition BLU-26 (locally named “bomby”), and the 20mm cannon shell. Both were heavily employed during the Vietnam War and today present the main threat to the population.

The influence of the above mentioned factors was also a part of the trial assessment after the field trial in Laos. During the detection reliability trial operators had to pass 30m lanes with targets placed in different depth. By recording the time for one pass from the very beginning over the trial time conclusions about detector use, “clearance speed”, and of course the reliability of detection could be made.



Fig.: 8 CEIA Mil D1/DS double-head UXO detector under test in the STEMMD Laos trial

When assessing the time the UXO detectors needed to “clear” the lanes the advantage is with the UXO versions for mainly two reasons. One is the reduction of false alarms due to the lower sensitivity to small metal fragments and the second is the large area covered by sweeping the detector.

However, the detector with the largest effective search head in this trial was the the CEIA MIL-D1/DS, which was the slowest, because of the human factor. This detector has small sending and receiving coils mounted perpendicularly an adjustable distance apart (see Fig. 8). Here the unusual design created a barrier in the mind of the operators which was difficult to overcome. The group of four persons using the detector was split in understanding and using it. One person (Operator A of Fig. 9.) achieved outstanding results compared to other detectors while the other three operators had problems using it and returned higher FARs

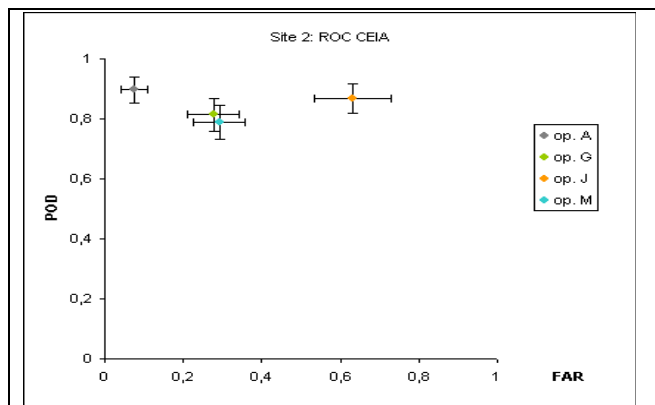
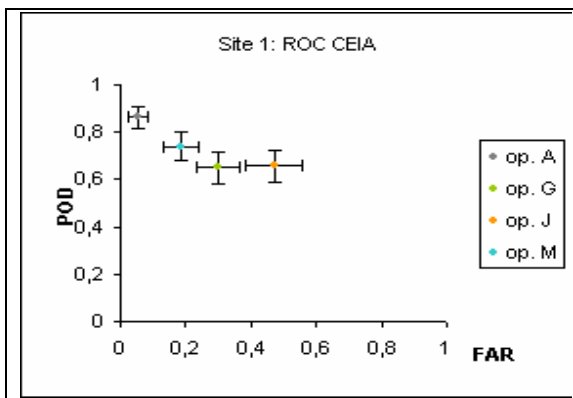
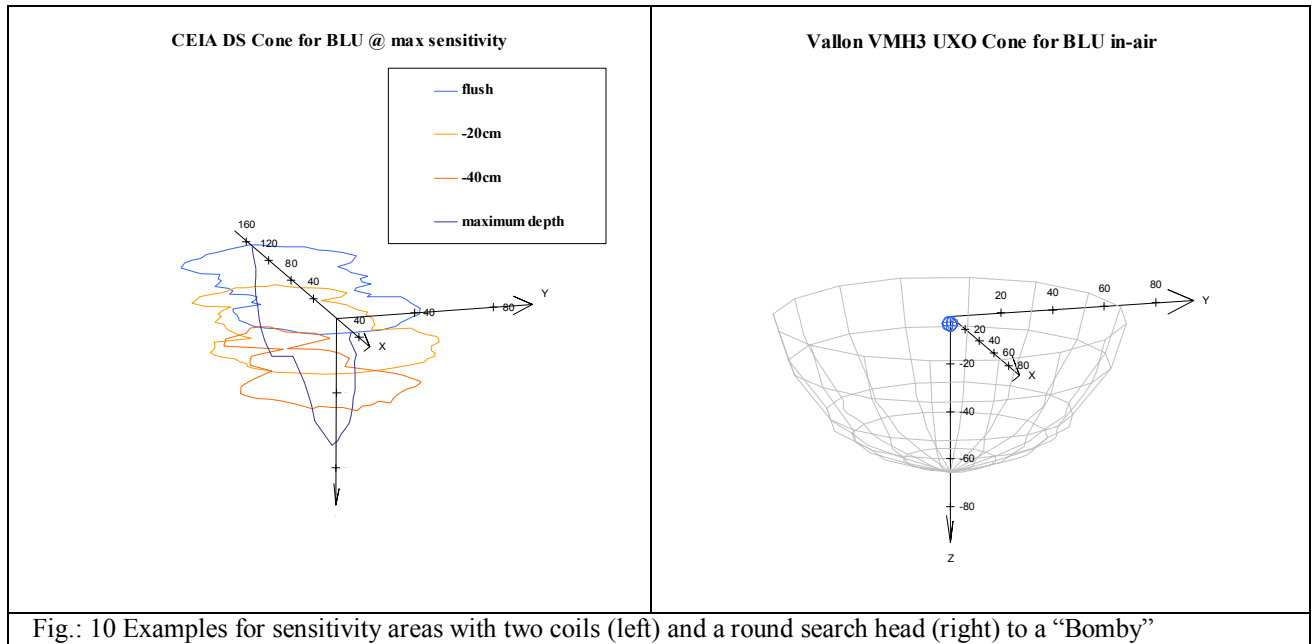


Fig.: 9 Receiver operating characteristic charts for CEIA Mil D1-DS during first week.

68 BLU 26B submunitions and 68 cannon shells 20mm calib. distributed approx. evenly over depths 0.1, 0.15, 0.2 and 0.3m.

Second week,

The above mentioned reduction of false alarms for large head detectors can easily be enhanced by knowing the effect that small metal pieces create a signal only directly under the antenna (outer border of the search head). If a weak signal is created by the detector or two signals – each only at the edges of the search head – than it may be from a small target. After the pinpointing the source of the signal move the detector vertically down and keeping the pinpointed area in the centre of the search head. If now the detector does not create a signal then it is a small target that may be ignored. This can only be done when no other targets than UXO are confirmed in the search area. A weak signal may also be created by a deep buried target but that will in every case create a signal in the middle of the search head too. Below are the CEIA and Vallon detectors sensitivity areas. The point of maximum sensitivity is about the first third of the x-axis for the Ceia whilst the Vallon has the maximum sensitivity to UXO sized targets in its centre.



#### d. Ground compensation effectiveness

For the reliability of detection it became obvious that a substantial proportion of minefields have ground conditions where the detector cannot be used without adapting it. Due to its magnetic properties the detector creates a signal without the presence of metal. For reducing the influence of the ground most of the detectors have a feature to assist. This feature is named ground compensation. There are different approaches to eliminate/reduce the soil influence on the detector. They are:

##### for time domain processing:

- taking multiple samples from the time response and subtracting the measured soil response
- multiple types of the excitation pulse are sometimes used

##### for frequency domain processing:

- adjusting the phase of the reference signal so that the soil signal is nulled
- multiple frequencies are used

Unfortunately the process of ground compensation does influence the sensitivity of the detector. In some cases the detectors retain a good level of sensitivity and can detect minimum metal mine to the required clearance depth, e.g. the IMAS default depth of 130 mm. In some cases it was even observed that the presence of the soil increases the detection depth. But often the detectors are losing so much sensitivity that they cannot achieve the required clearance depth to low metal content mines. The effects of ground on the detection ability and indications of the effectiveness of ground compensation are discussed in more detail in Chapter 4.

#### b. Pulse and sine-wave induction

Finally, we should mention that none of the trials found evidence of advantage of one type of excitation (pulse or continuous wave) over the other. It seems to be confirmed that whether a detector uses the pulse induction or continuous wave system has no direct influence on the results. Neither approach has a clear advantage.

### 3.4.2 Procedures and environment

#### Effect of selected procedure

Results achieved by reliability trials demonstrate how different approaches in carrying out reliability trials may influence the results in POD and FAR. The first trials with the clear intention to establish ROCs by the help of statistically valid data were during the reliability trials executed in Germany and Croatia. A significant improvement was also achieved as the procedures of the SOP<sup>8</sup> were applied to the trial, i.e. the supervisor was evaluating the job made by the operator; the performance of the supervisor under control of a quality assurance person. Another approach is the trial execution as designed for a blind trial and to make the lane metal free afterwards. This is the most realistic way if one has enough time and space to plant the necessary amount of targets for statistically valid data. A repetition is in this case not possible. The results of this kind of tests as the last run of the trial were compared with average results achieved in the reliability trials on the same lane with the same detector model. Four results of the excavation test were higher, two were lower, and one was the same as the corresponding results of reliability trials [ref.Mueller at al ]. However, the error bars attributed to these results are so large, that only very uncertain conclusions can be made about a higher performance on average.

In all cooperative lanes (with negligible soil magnetism) all alarms came from the buried targets or from metal pieces found and excavated during this last pass, there were no signals coming from the soil. The only exception was Lane 2 [ref.Mueller at al] in, where three “hot stones” were found – stones that cause a detector to alarm. These findings indicate that the vast majority of false alarms of the reliability trials in the cooperative lanes actually came from very small metal pieces overlooked during the preparation of the trials and that they are not a consequence of the electromagnetic properties of the soils. In Lane 5 with ground reference height different from zero there were some false alarms coming actually from soil.

#### Effect of weather, locality (vegetation, EMI etc.)

The environmental conditions are to be registered during trials as established in the CWA. The information includes:

- The location, local conditions (vegetation, ground)
- Meteorological conditions; temperature soil/air, barometric pressure, wind speed and direction during trial time
- Not foreseen events during the trial
- EMI,

All these conditions and factors have different influence on detector performance and the main influencing factors are in detail explained elsewhere in this document.

Well-engineered detectors should not be affected by changes in temperature, so that they may be operated in both hot and cold weather. Of the detectors tested in STEMMD, some showed sensitivity changes but all were usable from 0 to 60 degrees C with the exception only of the SHRIMT M90 detectors,, which alarmed continuously at high temperature but returned back to its initial performance after cooling to room temperature.

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<sup>8</sup> SOP – Standing Operating Procedures, rules how to carry out the work

### 3.4.3 Human factor

Includes: operators' mental and physical state, knowledge and experience, ergonomics<sup>9</sup>

#### Mental and physical state of the operator

It is generally understood that there is a relationship between the mental and physical state of the operator and detection performance. Until recently, little work had been done to investigate this part of the human factor.<sup>10</sup> Some aspects may be readily addressed in tests, others not.

Clearly, a minefield is an extremely stressful environment in which to work, so it is reasonable to expect the effect of stress to be significant. In trials, this element of stress is absent. On the other hand, danger creates good motivation.

Two factors, which can be examined in trials, are the degree of training and the amount of experience of the operators.

We would also point out that stress and training are connected. A deminer not confident in the use of his metal detector would be subject to even greater stress than normal. Private problems can influence this strong that trained rules are violated and create accidents as investigations showed.

#### Knowledge and experiences

Below, the ROC diagrams demonstrate significantly different results with the same detectors and similar targets, the only changes being in the human factor. 6% more targets were detected in the November test in comparison to the May test. The data are taken from the specific reliability test. Full details are given in the report which is available from the ITEP website (Mueller at al). The targets are a mixture of low and high metal types, mostly AP mines with some AT mines and ITOP surrogate fuzes. Burial depths were also mixed, from just below the surface to 20cm, but mainly in the range 5-10cm.

Fig.: 11 ROC diagrams for different soil, human factor conditions Oberjettenberg May&Nov2003

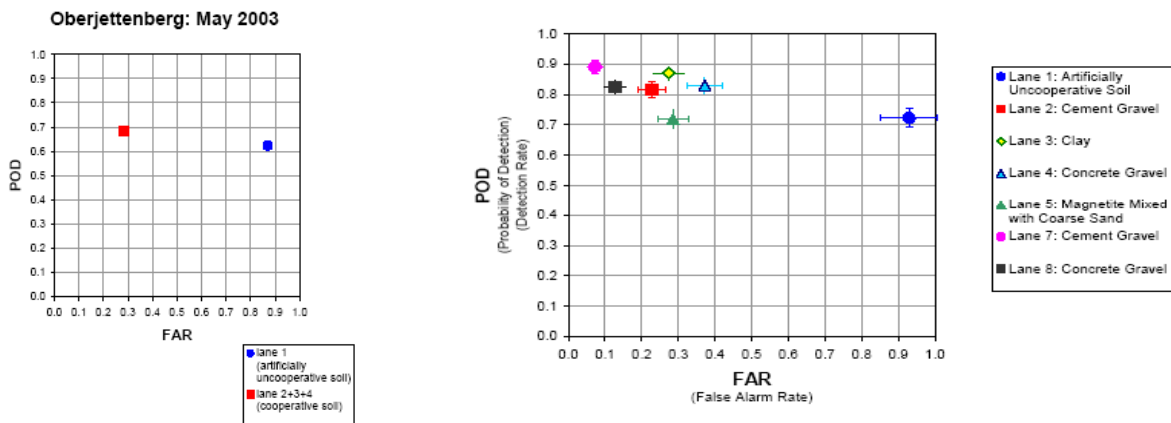


Figure 11 demonstrates the effect of degree of training on ROC curves [ref.Mueller at al].

What has changed the POD level from lower than 0.7 to more than 0.8, on average? Just two changes concerning the human factor had been made, the other conditions stayed similar:

<sup>9</sup> The ergonomics should normally be included into the assessment of the detector above. But they are placed here because their influence on the performance will be over the human being/the operator.

<sup>10</sup> Evaluations for dog handlers and dogs have taken place, but this is different detection system and the results cannot be translated to manual demining with metal detectors.

The training time was doubled by reducing the number of detectors to be used by the operators from 4 to 3 in one group and only 2 detectors in another group

The other change was to reduce the amount of runs during a day to reduce the stress of the operator. In May they had an average of eight runs while in November they had six.

The graph below is another example from the same report concerning experience of the deminer and its influence on the results. Two groups of four “experienced” operators carried out the blind trials; the first group included three actual deminers. All other operators were much more experienced in demining management and actually in higher position but did not use a detector on a daily basis.

### Experience and its influence

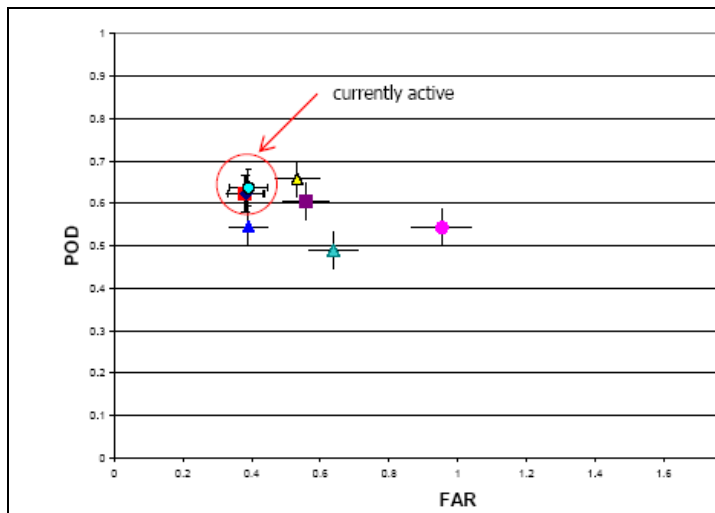


Fig.: 12 Influence of current experience

In Figure 12 it is very obvious that the three currently working deminers/operators were, during the trial, following better practice in using metal detectors than the others. The one “manager” belonging to the group was the operator with the lowest results in POD and highest FAR.

### Ergonomics of detector

The manufacturers of metal detectors undertook to the end of nineties/beginning of the new century immense efforts in this direction. This resulted in the one piece detector with different ways to communicate with the operator. The trend is that the user will be able to adjust the detector to specific environmental conditions in the area of employment. The ergonomics belong to applied science of equipment design intended to maximize productivity by reducing operator fatigue and discomfort. It should remove barriers to quality, productivity, and safe human performance by fitting products, tasks and environments to people. In other words, the operator should not experience discomfort but feel support from the used tool. In the case of the metal detector it means the design, the weight, ease of use including the interface to the operator, fault signals, and transport cases are to be assessed. Those assessments have never been an object of a trial but in a form of questionnaire information about those facts were everywhere included. The factors which contribute first hand to the POD are the signal cleanness and weight.

The results of the Laos trial had some clear example that the operators were influenced by the design, ergonomics and the ease of use of the detectors.

**The design** concerning ergonomics was done for the basic versions of the detector and the large search head for UXO was added later. This is clearly visible for the Minelab and the operator feels it when he has to use the detector for a longer time. The force for using the Minelab is significantly higher as for the normal version. The design of the Ceia is so different that the Laos trial design with 1.2m wide lanes created problems in the use of the detector within the lane width. It is recommended to use the detector with a harness, due to its weight.

### **Training of operators for trials and its effect on results**

If the object of a trial is to assess the performance of detectors with which the operators are unfamiliar, such as new models or models not used by organisations for which they have worked, then it is necessary to train the operators beforehand to ensure that they handle the detectors as competently during the trial as they would in a real operation. The need for training was acknowledged early and systematic efforts seem to have been made in all trials.

The results of the different trials express the influence of the time for training and the training level reached, the amount of information given to the operator, his length of experience in using the detector tested and how current are his skills in handling detectors in general.

Evidence for the operators' performance measurably increasing as the training is made more thorough has been obtained in a study by University of Western Australia, to be published [ref.Trevelyan].

### **Objectivity and avoidance of interference**

Since the marker location measurement does not require subjective judgment, there is no need to perform double-blind trials i.e. with target-burial performed by a separate team. It is sufficient that supervisors and trainers do not interfere with the operators as they work and that any manufacturers' representatives present are kept away from the lanes.

The degree to which such interference was rigorously avoided is difficult to judge from a report. Amongst the trials where the authors were personally present, at IPPTC Croatia 2000 the supervisors sat a few metres back from the start of the lane and avoided approaching the operators to within closer than about 20 m when measuring. In the BAM and UXO Lao trials similar practices were applied. No manufacturers' representatives were present in IPPTC trials. We do not know of any detection reliability test which has been performed in double-blind fashion. The single-blind method was accepted by CEN Workshop 7.

### **Operating point: why are the POD's measured in trials so low?**

During the first three blind trials the achieved probability of detection did not reflect the reality in mine clearance. The POD with this low level would mean that much more accidents should have happened during clearance operations. On the other hand those trials did not intend at the first stage to reflect the reality of mine clearance but tried to explain the reliability of the system as it is. The purpose of such a test is a comparison of metal detectors and this question is in every case the main question for an organization to be answered. Their true performance in a minefield will be very close connected to those results, not from the POD level or the FAR but in their ranking. From the statistical point of view, the test has to be designed so that the average estimated POD is about 0.5. If one is looking at the clearance records and the results of quality assurance and accident statistics the probability of detection in real minefield clearance operations is actually much higher.

The operating point on the ROC curve is controlled by the detector sensitivity setting and the rigour with which the operators cover the ground and indicate every sound made by the detector. A good demining operation should be conducted at a high FAR in order to obtain high POD. Trials cannot be conducted at very high FAR because if all detectors return near 100% POD an unfeasible number of repetitions is needed to bring the confidence intervals down low enough to compare them (see statistical plots below). Therefore, in a trial one is obliged to operate at a POD of no higher than about 95%.

In practice, it is not normal to instruct the operators in trials to be less rigorous than they would in a real mine field<sup>11</sup>, it tends to happen anyway and the problem is more the opposite: to ensure that they are careful enough. PODs as low as 60% are often seen. There has been some concern in the demining community that these low values could be representative of real operations – this point is explicitly made in the IPPTC report. It should be borne in mind that there are other reasons why it may happen: the self-preservation instinct is absent; the schedule may be tighter in a trial than in practice and operators using a detector daily will inevitably be better than newly trained ones. For each detector, operators achieving higher PODs did not generally have higher FARs which implies that they had a superior technique. The results of Site 2 (Laos trial 2004) are better than on Site 1 (Fig. 13), although Site 2 (Fig. 14) had more difficult ground conditions. We believe that this is because the operators were more familiar with the detectors in the second week and had additional training, which we gave in response to their request. In particular, it appeared from their behaviour that the operators had not, at first, fully understood the unusual location of the most sensitive point of the CEIA Mil D1-DS.

Where essentially no changes to the normal detector and its manner of use were made by transforming it into a UXO detector, apart from to make the head bigger, better results in time have been observed. At the same time the UXO detectors' results could be kept on a better level in comparison to the false alarm rate of the normal detectors.

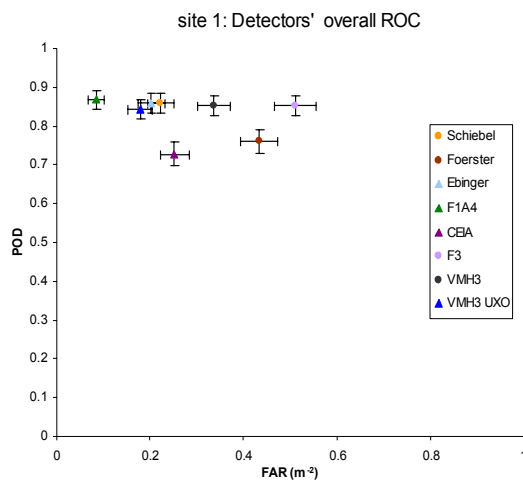


Fig.: 13 ROC of the detectors

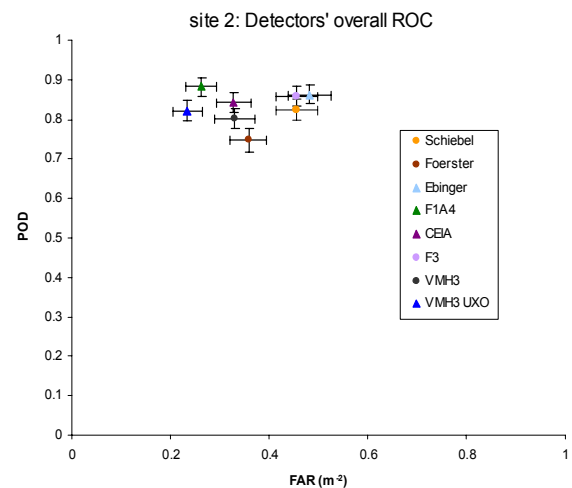


Fig.: 14 General increase of POD after two week's use

Although the ROC is in quite common use in mine detection trials, one should be aware of its fundamental limitation: many of the most important factors affecting POD do not affect FAR, and vice versa. Changing these factors does not just cause the results to go up or down the same ROC but may give a different ROC altogether. In the example shown above from the STEMD Lao trial, an increase of confidence in the detector use (normal and UXO) has caused a reduction in FAR in some detectors, so the results bunch closer to each other, but the PODs are either unaffected or increase.

<sup>11</sup> The authors know of one exception to this, in IPPTC Croatia 2000.

## 4 Soil and its influence on detector performance

### 4.1 Soil characterisation and the main factors influencing the detector

Traditional electromagnetic induction metal detectors operate in the band below 100kHz. At these frequencies, the electromagnetic field is influenced by two material properties: the magnetic susceptibility and the conductivity. In this respect, metal detectors differ from radar sensors which operate at much higher frequency so that they are mainly influenced by the permittivity (dielectric constant<sup>12</sup>) of the material, a negligible factor for metal detectors. If the susceptibility and/or conductivity of the soil are too large, it may be impossible to raise the detector sensitivity sufficiently to detect minimum metal mines without the detector alarming constantly when near the soil. It might be imagined that the very high conductivity of metals would always lead to a signal much bigger than that from non-metallic soil materials, but it should be borne in mind that the volume of soil interacting with the electromagnetic field is essentially the entire roughly hemispheric region under the head, and is much larger than the objects which it is required to detect.

Metal detector manufacturers are well aware of the soil problem and have devoted a great deal of research and development effort to overcoming it. High-quality modern detectors are equipped with ground-compensation systems which reduce their sensitivity to the soil without reducing the sensitivity to metal very much, if at all [ref. JRC Metal Detector Handbook, , and STEMMD Interim Report, Field Trial Mozambique].

#### Susceptibility

Values of susceptibility for soils range from less than  $10^{-5}$  to up to  $10^{-2}$  SI (some authors and manufacturers use  $10^{-5}$  SI as a basic unit, to give similar values to older units). Anything above about  $10^{-4}$ , which is by no means unusual, is sufficient to give a signal in a highly sensitive detector circuit. All good detectors today can eliminate the basic effect of soil susceptibility by using phase-sensitive detection for continuous wave detectors or time-domain windowing for pulse induction detectors. Unfortunately, real soils may have frequency-dependent susceptibility (e.g. dropping by 10% or more with each decade of frequency) and give responses which are out of phase with the inducing signal.<sup>13</sup> In the time domain this means that the soil generates magnetic field long after the excitation pulse is off. Practically observed decay rates for the voltage induced by the soil signal are around  $V = 1/t$ . This is slower than the decay of the target signal, which is about  $V = 1/t^2$ . It was shown that this property is caused by nano size particles present in some soils. The best detectors employ advanced techniques to overcome this. The continuous-wave detectors use multiple frequency excitation and phase-sensitive detection at all excitation frequencies. Pulse detectors use multiple pulse lengths and/or multiple time windows. A good review of relevant patents was conducted within the EUDEM 2 European network on demining research and development [ref. Gaudin, Sigrist and Bruschini].

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<sup>12</sup> That property of a dielectric which determines the electrostatic energy stored per unit volume for unit potential gradient. In other words the term used to describe a material's ability to store charge when used as a capacitor dielectric. It is the ratio of the charge that would be stored with free space as the dielectric to that stored with the material in question as the dielectric.

<sup>13</sup> It may be shown mathematically that these two properties are connected by the Kramers-Krönig relation.

## **Conductivity**

Even in the absence of significant magnetic susceptibility, soil conductivity can also affect the detectors. Typical values of conductivity in metals and soils in siemens per metre ( $\Omega^{-1} \text{ m}^{-1}$ ) are:

Aluminium	40 million S/m
Stainless steel	1 to 1.75 million S/m
Wet soil	0.01 to 0.001 S/m
Dry soil	0.0001 to 0.00001 S/m

In spite of the very small values compared with metal, the soil conductivity can still have an influence on the detector because of the difference in volumes mentioned above. This practically happens only for salt wet soils.

## **Homogeneity**

Many detectors (in fact most of the continuous-wave detectors) use gradient sensing (double-D) coils. If the detector coil is perfectly parallel with the flat soil surface and the soil is homogenous, the error soil signal would be cancelled even without soil compensation. On the other hand, non-homogenous regions cause erroneous signal even when the soil compensation is perfect. The source of non-homogeneity can be shallow rocks and voids.

The effectiveness of the soil compensation is therefore a key performance factor to assess in test and evaluation. It is also very important to know the soil conditions in which any test campaign is carried out, since these will have a significant effect on the results.

## **4.2 Soil measurements necessary for this characterisation (lab, field)**

A number of commercial instruments are available to measure the relevant soil properties. These may be divided into field instruments designed to be placed on the ground and to give a reading characteristic of the soil property underneath and lab instruments designed to be used with samples of soil.

Some examples of the former are the Geonics EM38 which measures in-phase and quadrature parts of the response at 14.6kHz and the Bartington MS2D, which measures magnitude of response at 958 Hz. MS2D response is labelled as “susceptibility” since, as a rule, the magnetic effect when it is there is the stronger but, strictly speaking both conductivity and susceptibility affect it. The phase discrimination employed in the EM38 does allow the two parameters to be separated: to first approximation the in-phase part is a measure of the susceptibility and the quadrature part a measure of the conductivity.

Another type of portable instrument is suitable for measurement of rocks, as it has small detection coil and the reading does not much depend on the size of the rock. Pocket instruments for measurement of rocks include SatisGeo KT-6 (10 kHz) and very similar SM-20 by ASC scientific.

Examples of lab instruments are the Bartington MS2B which measures magnitude of response at 465 and 4650 Hz, the Sapphire SI-2B (825Hz and 19 kHz), Kappabridge KLY-2 (920 Hz), Agico KLY 4 (875 Hz), Agico KLF 4 (2 kHz) and Agico MFK1 (976 Hz, 3904 Hz, 15616 Hz) Magnon MS 200 kappameter measures from 54 Hz to 10 kHz.

Contact details for some of the above manufacturers are given at the end of this report.

It is also possible to measure the response with general purpose laboratory instruments such as A/D plug-in cards, lock-in amplifiers or precise impedance analyzers. West and Bailey described an instrument for the measurement of complex susceptibility from 100 Hz to 70 kHz [ref.West and Bailey 2005] and measurements have also been conducted more recently from 480 Hz to 480 kHz using an impedance analyzer by Ripka [ref.Ripka et al.].

The available result show that the real (in-phase) part of susceptibility of most soils is uniformly decreasing with logarithm of frequency and the imaginary part is much smaller and frequency independent. Clear deviations from this rule were observed by Dabas [ref.Dabas 1992] and other authors, but mainly on soils containing metal particles. This indicates that it is not always sufficient to measure the soil samples only at two different frequencies.

The amplitude of the excitation magnetic field of metal detectors is usually below 10 A/m. The susceptibility of known soils in this field range is independent of the field magnitude. However, the excitation field in some measuring instruments may be higher and this may cause errors in some soils. De Wall and Worm observed false “frequency dependence” of some samples caused by the fact that Bartington instruments do not have the same measuring field at all frequencies [ref.de\_Wall and Worm 2000]. The field amplitude used by Bartington instruments is 80 A/m and the observed field difference was 7%.

Measurement of the time-response to pulse excitation is possible, but the results are poorly reproducible as the response heavily depends on the shape of the excitation field pulse and on unavoidable parasitic capacitances.

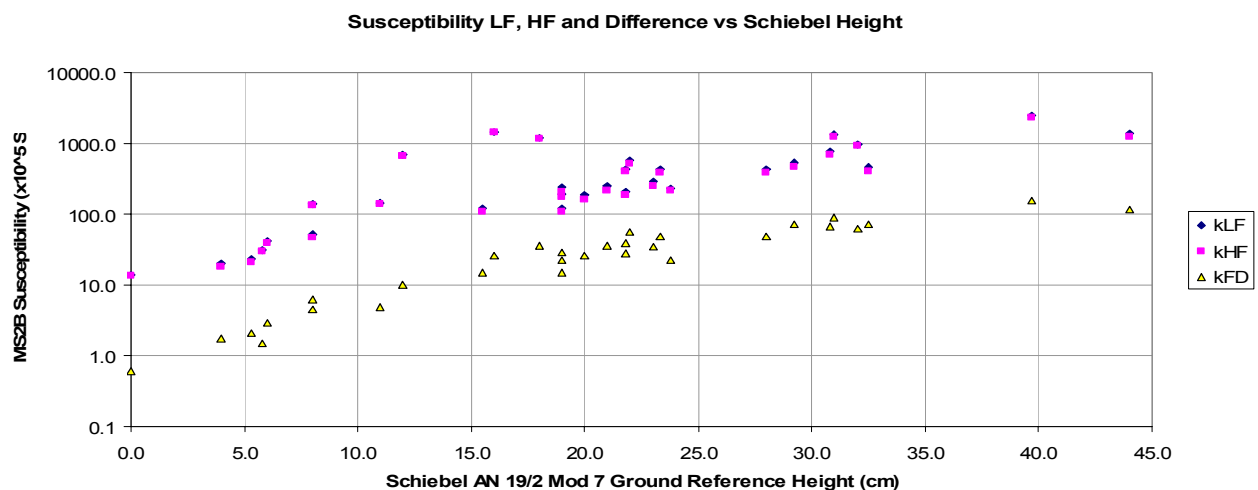
Still another class of instruments which may be useful are prodding-type conductivity probes such as the Delta-T WET sensor. These measure the true conductivity and give an indication whether the quadrature part is due to frequency-dependent susceptibility or ionic conductivity.

### 4.3 Empirical approach by means of the Ground Reference Height

To assess the degree of severity of the soil effect it is not necessary to possess a special instrument. An empirical measure is the height above the soil to which it is possible to bring a detector before it sounds. This can be made more reproducible by selecting a specific model and calibrating it in a defined way. One of us (DMG) has proposed the use of the Schiebel AN19 Mod 7 detector, adjusted to just be able to detect a 10 mm steel ball at 140 mm as a suitable standard. The same sensitivity may be achieved by using the detector’s test piece at a distance of 100 mm from the search head centre. We term this the Ground Reference Height.

This term was firstly used in a field trial (UNADP Mozambique 2000) where no measuring instruments for magnetic soil properties were available.

Fig.: 15 Correlation between GRH and frequency dependence



GRH is well correlated with frequency difference of susceptibility as measured using a Bartington MS2B (Insert Fig. 15). It may also indicate a presence of magnetic rocks in the soil. Explanation of this dependence is straightforward: AN19 is a pulse detector which samples the response 35  $\mu$ s after the decay of the excitation pulse. If the soil is magnetic but its susceptibility is frequency independent, its response decays almost instantly, so that after 35  $\mu$ s the signal disappears. But if the susceptibility is frequency dependent, the soil response decay slow so that the detector gets signal.

#### **4.4 *Recording of Magnetic Properties in Survey***

Since the measurements needed to know how severe the soil problem is likely to be at any one location are very simple and quick to make, it is perfectly possible to include them at the Technical Survey or even earlier at the country wide impact survey stage. There is not even really a need for a mine-clearance organisation to buy a special instrument: the Ground Reference height method is enough.

Ideally, one would seek to know something about the distribution of soil properties at the Country Survey stage. In 2002, Y Das of CCMAT identified a remarkable opportunity to obtain, relatively easily, a systematic survey of the frequency-dependence of soil magnetic susceptibility in an entire mine-affected country. Bosnia-Herzegovina has an archive of soil samples collected for the purpose of agricultural planning by the Agropedology Institute of Sarajevo (AIS). The archive survived the Yugoslav war, with some damage, and CCMAT were able to organise its repackaging and measurement with MS2B's. JRC contracted Cranfield University to assist in training AIS staff and mapping the final results.

Ecopedological (soil property) maps are available for many parts of the world and in some places, detailed chemical analyses are published. Usually, the underlying thinking in mapping the soil was to facilitate agricultural planning. Certain categories of soils indicated on ecopedological maps contain high concentrations of the iron and titanium minerals known to affect detectors. Can this information be used to predict where soils problematic for metal detectors are likely to be found, before even making measurements on samples?

In March 2004, J Hannam, T J Bloodworth and A Logreco succeeding in locating some very highly noisy soil in the Montagnola area of Toscana, Italy, by using published soil maps to identify so called "Terra Rossa" [ref. Bloodworth and Logreco]. This is an obsolete classification that covers a wide range of soil types defined in current classification systems but, using old soil maps of Italy, the areas marked as Terra Rossa were identified. Then, using a recent ecopedological map, those areas were correlated with zones having the appropriate soil classification and underlying limestone geology. Terra Rossa typically forms on calcareous limestone by weathering *in situ* over a very long time-scale. Such soil that is removed by alluvial action does not typically preserve its magnetic properties, so the most likely deposits of the soil with the properties required will be on limestone outcrops. About 2 tons of the soil was subsequently brought to Ispra for use in metal-detector tests in the JRC's "C F Gauss" lab.

#### **4.5 *Performance of detectors with and without ground compensation***

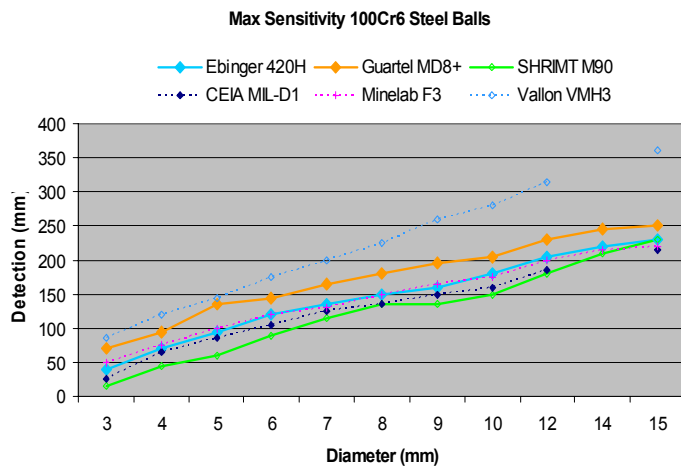
##### **4.5.1 Limited use of detectors without compensation**

In the middle of the nineties detectors with the capability for ground compensation (GC) were rare but by 2006 none of the internationally recognised manufacturers in humanitarian demining

were issuing new designs without it.<sup>14</sup> Many demining organisations still possess and use the older designs of detectors without soil compensation and it is still possible to procure them. World-wide the mined areas cover very different places if one is looking at the environmental conditions as vegetation, climate and geological issues. As before explained the ground is still the main factor limiting the performance of metal detectors.

In the in-soil measurements conducted at TNO (Netherlands Organisation for Applied Scientific Research) for the IPPTC trial, the change in the ranking of the detectors in magnetic soil could be seen. For example, the Guartel MD8 was ranked 1st out of 28 in the sand and peat lanes, but only 12th in the ferruginous soil, whose mean susceptibility was much greater than that of the others. However, this difference was not as apparent in the field trials.

Fig.: 16 Sensitivity of detectors with and without GC

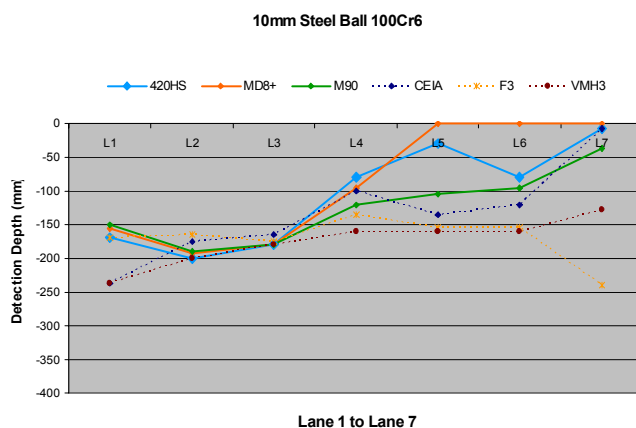


The lab results of Ispra and the results of the Mozambican trial demonstrate that the detectors without GC are in between the sensitivity of the other detectors if set up to maximum sensitivity in-air, concerning their sensitivity to 100Cr6 steel balls, see Figure 16. The dotted lines are the detectors with GC. A complete different picture appears in Figure 9 where starting with lane 4 the detectors without GC significantly lose sensitivity to the 10 mm steel

ball (lanes were filled with different soils, the higher the line number, the higher the susceptibility frequency change).

It has to be added that the achieved results in the lanes in Mozambique were only possible because the operator knew that they work in test lanes and there is no danger by trying different settings to achieve a reading.

Fig.: 17 L1 to L7 & sensitivity to a 10mm steel ball (Mozambique trial)



The detectors with GC can keep a certain level of their sensitivity in every soil (excluding the Ceia in L7). The MD8+ can not be used and in practise the other detectors without GC too. The operators manipulated the sensitivity (they were allowed to do so) and used fixed height for reaching a maximum sensitivity, which is possible in the test lanes, but never in minefields.

The detectors without GC can keep up with the other detectors up to the ground conditions of L3 (about 6 SI  $10^{-5}$  units frequency difference of the magnetic susceptibility measured by the Bartington meter). All conditions

<sup>14</sup> There are some newer specialized models which are exceptions such as the EBEX® 420-HS, which is an alternative for situations where no soil compensation is needed. This detector has very low power consumption and uses a solar panel to recharge the battery. The Vallon MW 1630B designed for underwater use is another exception.

behind this level of susceptibility are dangerous for the user of detectors and the use of detectors without GC should not be allowed in practice.

#### Soil measurements in trials

Earlier trials mentioned above were conducted without any quantitative assessment of the soil properties. The UN MAPA (Mine Action Programme for Afghanistan) trial did intentionally include measurements in soil under a former brick kiln where the fired earth caused significant effects on the detectors.

The need to measure and control the soil properties was recognised and began to be implemented in IPPTC . One ferruginous soil was introduced in the in-soil laboratory tests at TNO. The field trial in Cambodia was conducted with one lane made up with local laterite soil and the field trial in Croatia was conducted in an area known to CROMAC to be difficult for metal detectors.

CCMAT (Canadian Centre for Mine Action Technologies) at this time established collaboration with specialists from the Canadian Geological Survey (GSC) able to make detailed measurements on soil magnetism<sup>15</sup> and began to advocate the measurement of frequency-dependence of susceptibility in trials. The final text of CWA 14747:2003 used absolute susceptibility only in its classification of soil types but did mention frequency-dependence as an important parameter. Systematic measurement of susceptibility using both MS2B and MS2D instruments was introduced for the BAM/JRC tests in 2003 and used in all subsequent BAM and JRC trials.

Measurements by GSC indicated the IPPTC Test Lane near Obrovac in Croatia to have a frequency difference of susceptibility between 4650 and 465Hz of  $25.5 \times 10^{-5}$  SI m<sup>3</sup>/kg, lying between those of Lane 4 and Lane 5 at the Moamba site in Mozambique. The lanes at Benkovac in Croatia are similar. Test Lanes 6 and 7 at Moamba have 45 and 57 respectively and the soil brought from Toscana for the JRC's test box has 62. The most extreme soil the authors have ever measured is that of Site 3 of the STEMMD Laos trial, where readings of several hundred were found. A chemical analysis of this soil by the Institut für Geowissenschaftliche Gemeinschaftsaufgaben Hannover showed about 30 % of F<sub>2</sub>O<sub>3</sub> , and 5% TiO<sub>2</sub> .

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<sup>15</sup> To get some inter-comparison of data, JRC contracted GSC to make a study of all the soils on then ISPRA test site and the IPPTC Croatia site.

## 4.6 Assessment of the detectors concerning the technical solutions and the influence of soil

Fig.: 18 Ground compensation abilities Laos trial

	Detector Copy	Frequency difference of susceptibility $\kappa_{LF}-\kappa_{HF}=\Delta\kappa$ ( $10^{-5}$ SI)				
		78-200	>200-500	>500-870		
Schiebel ATMID	1	Y	Y	Y	N	N
	1'	Y	Y	Y	Y	N
Foerster 2FD 4.500	2	N	N	N	N	N
	2'	N	N	N	N	N
Ebinger 421	3	Y	Y	Y	Y	Y
	3'	Y	Y	Y	Y	Y
GC/LS	4	N	N	N	N	N
Minelab F1A4UXO	4'	N	N	N	N	N
Ceia MIL-D1/DS	5	Y	Y	Y	Y	Y
	5'	Y	Y	Y	Y	Y
Minelab F3	6	Y	Y	N	N	N
	6'	Y	Y	N	N	N
Vallon VMH3	7	Y	Y	Y	N	N
	7'	Y	Y	Y	N	N
UXO	8	Y	Y	Y	Y	N
	8'	Y	Y	Y	Y	N
Ground Reference Height (mm)		480	650	770	820	930

The last paragraph explained the limits of detectors without GC and gave an orientation about their use. This paragraph gives an analysis of the empirical data collected during the STEMMD field trials. When a detector has GC it does not mean that all problems are solved. As clearly visible, the three detectors in Figure 17 with GC (dotted lines) behave quite differently in the lanes. They have different starting sensitivities, different reactions to L4, there is a convergence in L5, and the sensitivities split again from L6 to L7. As earlier stated there is no obvious advantage in GC for one or the other type of detectors concerning the excitation principle used. Traditionally

detectors could be divided into those which processed the signal in time domain and frequency domain. In the era of analogue signal processing there were some indications that making the efficient ground compensation in the time domain is easier. The modern detectors use A/D converters in an early stage and process the signal digitally. It is therefore no longer possible to distinguish as clearly between time-domain and frequency-domain hardware, the main difference is in the firmware or software, which is not accessible to the user.

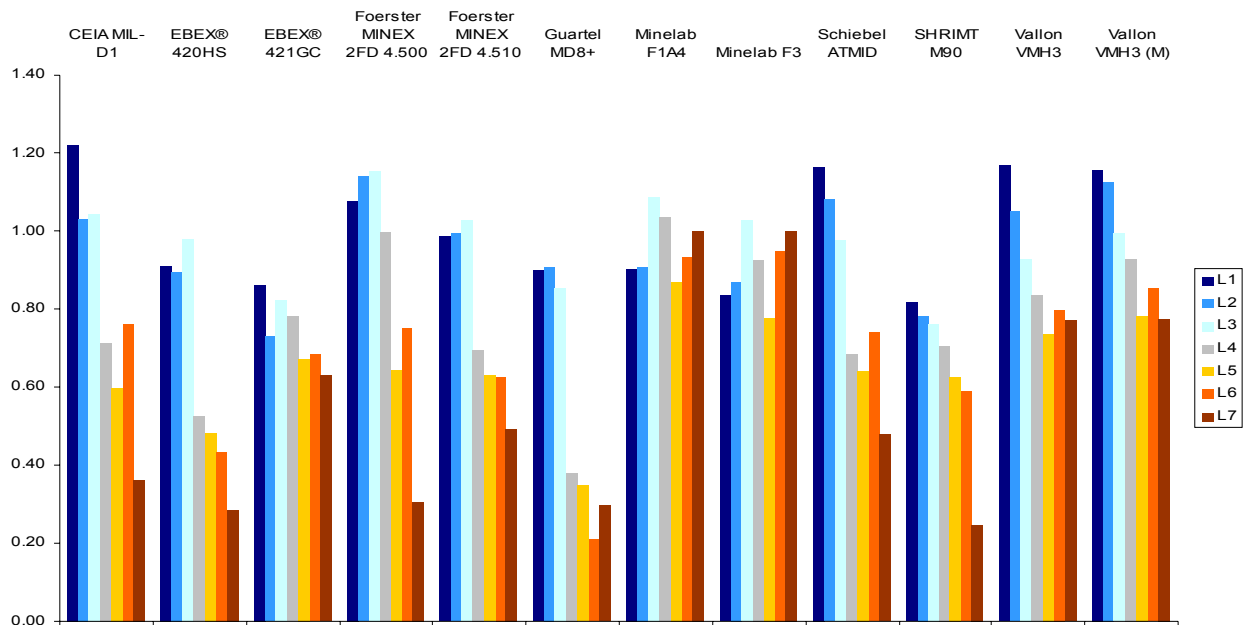
The STEMMD results from Laos and from Mozambique give a good overview where the limits of the detectors in ground compensation are. The most extreme ground conditions we found were in Laos with magnetic susceptibility about  $11,000 \times 10^{-5}$  SI and a difference between low and high frequency measurement of more than  $850 \times 10^{-5}$  SI units. By values of about  $1500 \times 10^{-5}$  SI and frequency differences of 75, some of the first detectors were unable to compensate. At the end only two detector types were able to compensate the ground and still react on a metal fragment.

The influence of the soil on the detection ability is below generalised to the participating detectors in the Mozambican field trial. The performance of twelve metal detectors, three of them without GC, versus an increasing susceptibility from L1 to L7, for thirteen targets is plotted in Fig. 19.

All detectors participating in the trial are listed in alphabetical order on the top. The y-axis indicates the detection distance in millimetre, averaged for all targets. The coloured columns indicate the test lanes 1 to 7 with the related result belonging to the detector.

For L1, for both the in-soil and in-air measurement, the detector was set up to maximum sensitivity in air, because the detector could always be used in this way without reaction to the ground in L1, since it is almost inert. For the other in-air and in-soil results the detector was set up individually to the soil in each lane. Three of the detectors do not have a ground compensation facility – the EBEX® 420HS, Guartel MD8+, and SHRIMT M90.

Fig.: 19 Normalised data Mozambican field trial demonstrating the ground influence on detection ability



The graph shows the pattern of reaction to the magnetic soil properties. A detailed discussion is available in the above mentioned report. It does not include cases where some detectors could not be used to detect smaller targets.

The main trends visible and affecting the POD are:

- A general pattern of significant loss of sensitivity with lane number, i.e. with increasing frequency dependence of soil magnetic susceptibility and ground reference height.
- There are some peaks and valleys in the graph. This indicates that the frequency dependence of the susceptibility is not the only factor influencing the soil influence.

Some other effects are visible when the in-soil data is compared with the data measured in-air, after the detectors have been set up to each lane. **In-air measurements do not always correspond well to the results measured with the same setting in soil. This finding should be further verified, because it has serious consequences: the air sensitivity measurements cannot be used to predict detector performance in soil. If this statement is verified, it would mean that the in-air measurements with detectors set-up for soil have no sense and should be excluded from the CWA.**

## 4.7 Analysis of detector characteristics' affect on performance

### 4.7.1 Introduction

A thorough test regime for metal detectors should be guided by knowledge of the physical principles by which they operate but a full investigation of the internal signal processing chains is not appropriate because it would be irrelevant to the needs of the user, threatening to the proprietary interests of the manufacturers and excessively time-consuming. It would not serve the aims of test and evaluation, which are to provide useful information to the demining organisations, to encourage commercial research and development and to give value for money to public funding bodies.

In all the trials listed above, the detector was regarded as a black-box and was assessed according to its normal audio output, as heard by the user. CWA retains this philosophy.

Projects of which we are aware which investigated internal signals of detectors, did so for research purposes rather than test and evaluation. [refs.Riggs, Bruschini and Sahli, Minesign and

HuminD]. Within STEM D, we did verify the waveforms emitted by the detectors but this is a simple measurement which can be performed in a few seconds without making a direct electrical connection to the circuit. Its relevance to the user is to distinguish between bipolar and unipolar waveforms: the former being less likely to initiate magnetically activated fuses.

## Theoretical modelling

### Basis

There is, however, no objection to trying to understand the behaviour of detectors theoretically and to analysing the electromagnetic response expected from different targets. It is also useful to be familiar with the disclosed information contained in patents, which is especially important in understanding methods of soil compensation. .

The physics of metal detection function is well-understood and we included a description in the Metal Detector Handbook. In principle it is possible to calculate the change in the voltage across a coil carrying a given current, in the presence of different targets. The mathematical details are beyond the scope of this report but, in simple terms, the method is to calculate the magnetic field produced by the coil, determine the currents and magnetic fields induced in the metal and then project these back to the coil to work out the response. To perform the calculation for real mines it would be necessary to include all the geometric details in the model, which implies the use of special electromagnetic analysis software and computers of at least engineering work-station class. This is within the scope of the state of the art for electromagnetic calculation but relatively little work has been published openly. To apply this scheme to real metal detectors, one would also need to know the details of the design, including the criterion used for sounding the alarm, which are not usually revealed by manufacturers.

### Spherical targets

An exact theory for the interaction of a uniform electromagnetic field with a metal sphere has been known for nearly 100 years [ref.Debye, Wait]. At the JRC we have applied this theory to perform a sensitivity analysis to the different parameters [ref.Dietrich] and to generate theoretical detection capability curves for spheres of different diameters [ref.Bloodworth and Lewis].

The main practical conclusion is that the use of metal spheres for in-air testing defined in CWA is theoretically well-grounded. The shape of the curves seen in practice and the weak dependence on material properties, especially on permeability, is expected from theory. Therefore, one would not expect detection capability curves to be unreproducible simply because it was difficult to obtain equivalent spheres from different suppliers. Although one would expect the material properties to vary a little, it will not have a strong effect on the shape and size of the detection capability curve.

Fig.: 20 Calculated in-air sensitivity CW detector

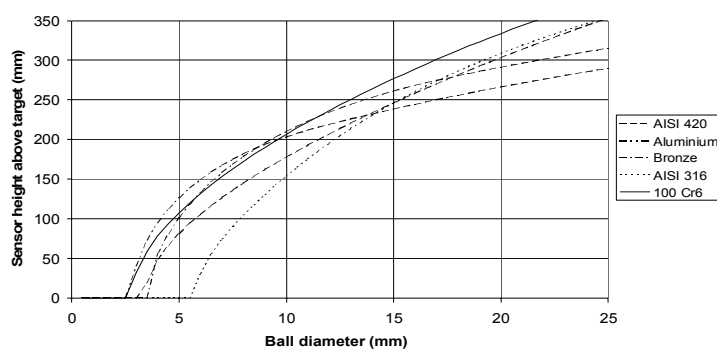


Figure 20 shows calculated, in-air detection curves for a continuous-wave detector having parameters similar to that of the Foerster Minex. Another important conclusion from the sphere model is that while most common metals give similar curves, some, such as the AISI 316 stainless steel shown in Fig. 20, give exceptionally small detection heights because they are neither magnetic nor very good conductors. The fact

that this behaviour is predicted theoretically and observed experimentally gives confidence that the basis of the physics has been well-understood.

### Electromagnetic skin-effect.

The most basic theoretical formula relevant to metal detector use is the formula for the electromagnetic penetration depth, the extent to which the electric and magnetic field penetrate into the surface of the metal.

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu_r\mu_0}}$$

where  $\omega$  is the excitation frequency,  $\sigma$  the electrical conductivity,  $\mu_r$  the relative permeability and  $\mu_0$  the permeability of the open space. In most situations relevant to mine detection, this number is of the order of a millimetre or less, that is to say, the detectors are essentially responding to the surface of the metal. The AISI 316 steel mentioned above is an exception in that the fields may penetrate all the way to the centre of a sphere even several mm across.

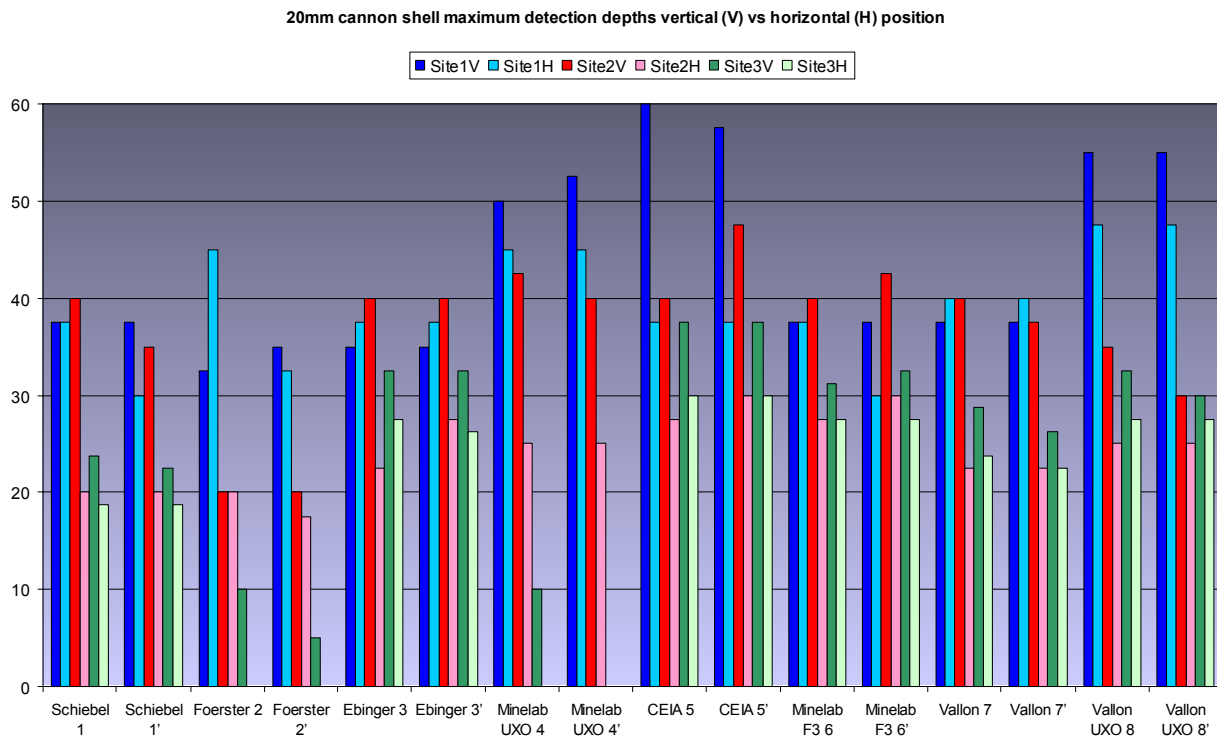
### Numerical Modelling

Some research projects have gone beyond this to numerical models [ref.Dietrich, HuminD]. In the opinion of the present authors, such studies are excessive for test and evaluation purposes but valuable to explore the limits of what is, in principle, achievable with metal detectors in the way of discrimination between targets, extracting of target depth and orientation and data fusion with other sensors. (The JRC's test site has been used extensively for measurements to support such research.)

### **Target Orientation**

During the Laos field trial the maximum detection distance for 20 mm cannon shell was measured for shell both vertically and horizontally positioned.

Fig.: 21 Maximum detection depth in two positions

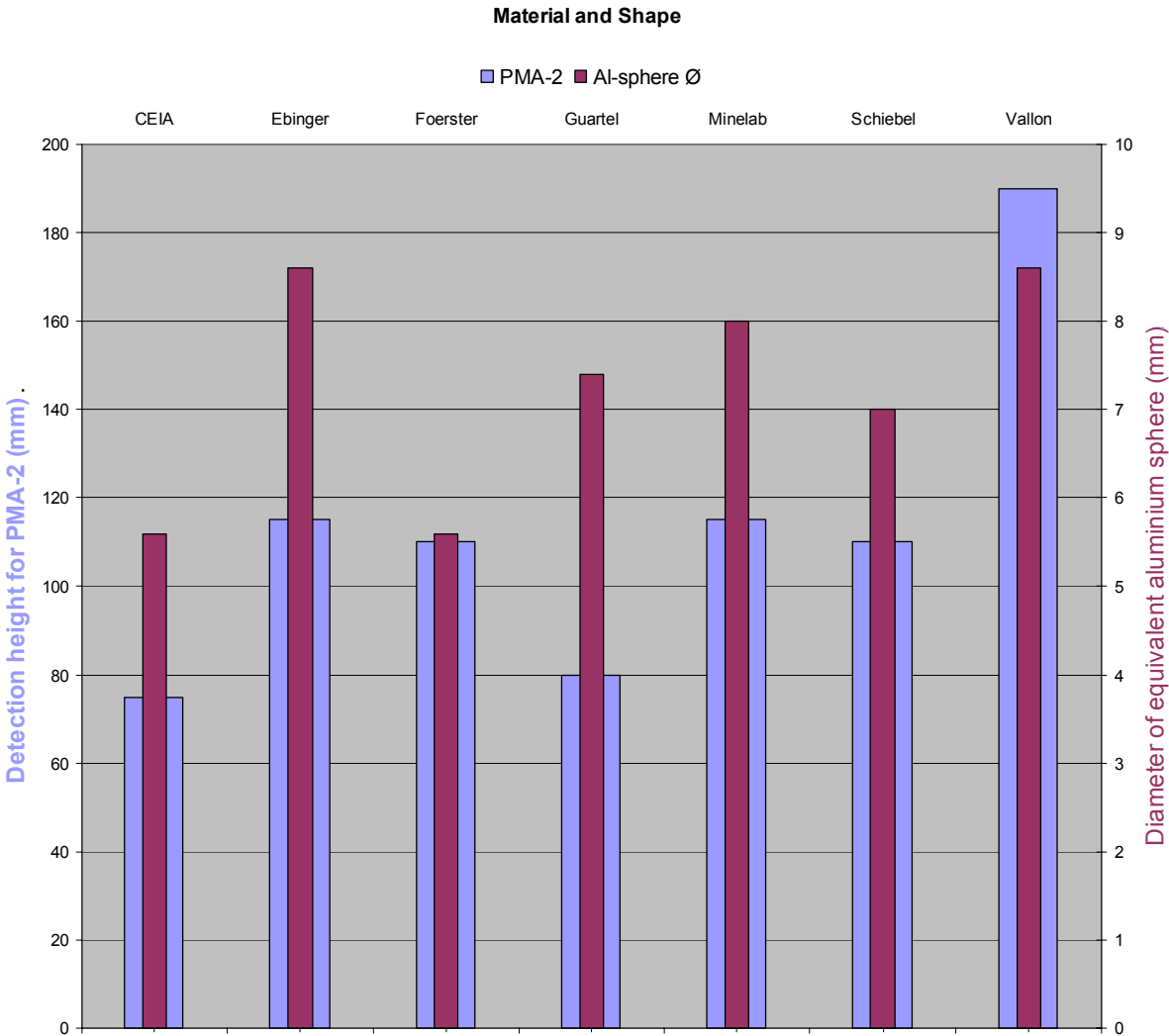


The general tendency is obvious but there are also exceptions which we are not able to explain. In the pits Site 1 with the lowest magnetic ground response, some detectors achieved in the horizontal position equal or better results (Schiebel, Foerster, Minelab, Vallon) , which is not repeated on other sites. Some detectors were not able to execute the GC on Site 3, so the 5th, 6th or both columns are missing.

An example of a minimum metal mine is the former Yugoslavian antipersonnel mine PMA-2. It has the only metal part, a percussion cap, weighing 0.08 g aluminium. This amount of aluminium would form a sphere with about 2mm diameter.

Figure 22 shows with the light lilac-coloured columns the different sensitivities of the detectors to the PMA-2, according to the scale on the left-hand y axis. The dark plum-coloured columns give the diameter of a sphere that would be just detectable at the same height, with each detector, according to the scale on the right-hand y- axis. (The data are interpolated from the Ispra lab trials where the following Al-spheres were available – 5, 5.6, 6.35, 7.4, 8.6, 15.9 mm Ø). The results demonstrate that the metal detectors have diverse sensitivity to the PMA-2, the maximum detection heights varying from 75 to 190 mm in air. Secondly, in all cases the equivalent diameter sphere for detection is much larger than a sphere with the same mass - up to 4 times more than the 2 mm sphere that could be produced from the 0.08 g aluminium present in the PMA-2. This is expected because the metal detector is mainly sensitive to the surface of the object, the electromagnetic become weaker inside the metal because of the skin-effect mentioned

Fig.: 22 Influence of shape and material on detectability



above, and a sphere has the smallest surface-area to volume ratio of any shape. Thirdly, the equivalent diameter aluminium sphere to achieve the same detection height also varies between detectors, from 5.6 to 8.6 mm. This is also expected, because the bandwidth, corresponding to the frequency factor in the formula above, is different for each detector. In the examples shown here, the two smallest equivalent spheres are for frequency-domain detectors having relatively low bandwidth (CEIA and Foerster). (This does not mean to say that their sensitivity is small – it

means that the difference in detection capabilities for a thin-walled metal shape and a compact mass is not as marked for these detectors as for the others.)

## **4.8 Comparison of UXO versions with normal MD**

### **Coil geometry**

The coil geometry is the simplest property of a detector having a direct impact on the user. The effect of increasing coil diameter is to increase the size of the minimum detectable object but also to increase the penetration into the soil. Therefore, large coils are used to detect large objects at greater depths. The JRC/ UXO Lao trial focused on this question.

The magnetic field due to a coil of arbitrary size and shape can be calculated directly<sup>16</sup> and is an easier factor to investigate theoretically than target shape.

### **Influence of the target material, orientation, and shape**

The response of the target may be very different even being from the same material. The response depends on different factors the material, surface of the metal part, shape and position of the target.

A solid sphere has the smallest surface area in proportion to its weight of any shape, so will always be a difficult target to detect, a cylinder from the same amount of metal will be easier to detect. A linear target such as the tripwire for fragmentation mines is very difficult to detect. On the other hand the same tripwire forming a closed circuit (ring) is easy to detect.

Three of the UXO metal detectors were large search-head metal detectors, i.e. similar to the “normal” metal detectors known in humanitarian demining, but with larger diameter search heads. These were in alphabetical order the Ebinger 421 GC/LS, the Minelab F1A4 UXO, and the VMH3 CS UXO. Ceia proposed the UXO version MIL-D1/DS which is of the two-head style, another class of detector used for very deep searching. Two search heads are perpendicularly mounted with respect to each other on a telescope-pole, one emitting a signal the other receiving the response. In this way an area from about 1m up to 1.6 m can be covered.

The further assessment will include the following:

- sensitivity compared to the basic detectors
- effect of a large sensing head on pinpointing
- effect of a large sensing head on battery life

The ideal change from a detector to an UXO detector would be that it would ignore small metal pieces, excluding mines, and only signal from a certain amount metal or signal strength cause the response. The reality is a trade-off; some effects in the wanted direction are clearly visible concerning reduced sensitivity to small metal objects. UXO have in general a much bigger metal amount as mines if those are not metal cased or fragmentation mines.

Below the graphs demonstrate the sensitivity differences between the original metal detectors used for mine clearance and those for UXO search.

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<sup>16</sup> using the Biot Savart law

Fig.: 23 CEIA MIL-D1/DS & MIL-D1

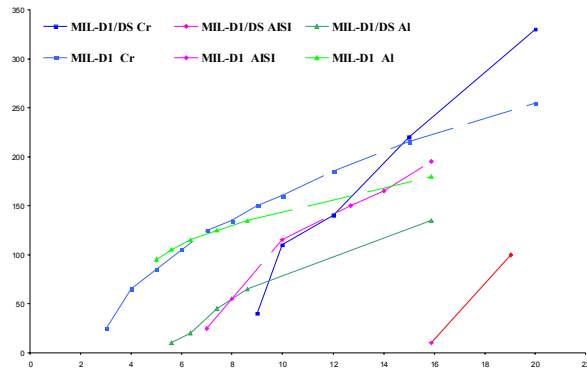


Fig.: 25 Ebinger 421GC/LS & 421GC

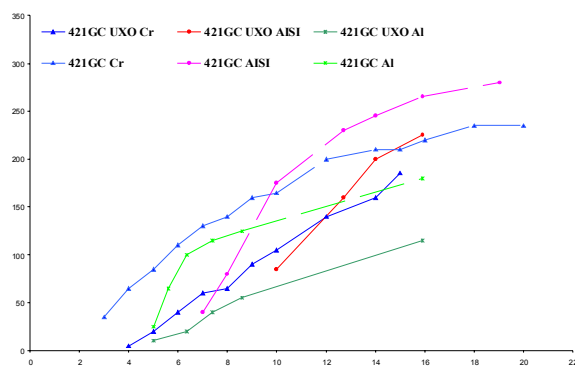


Fig.: 24 Minelab F1A4 UXO & F1A4

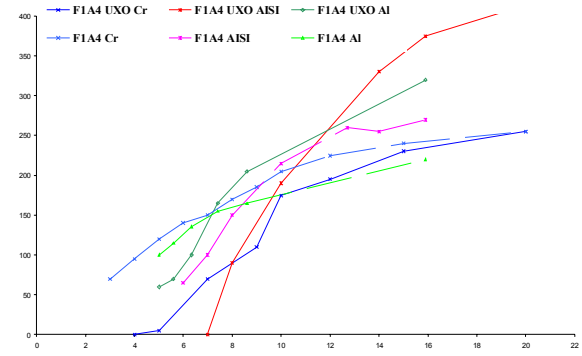
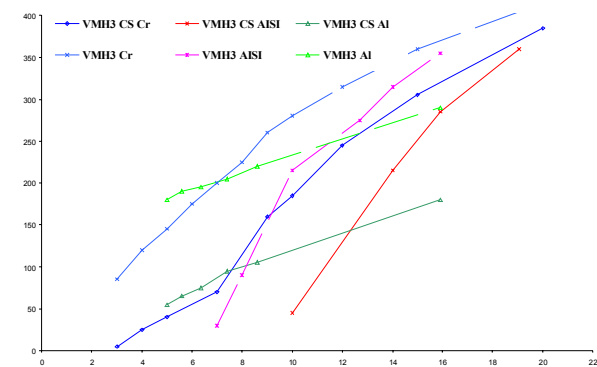


Fig.: 26 Vallon VMH3 CS UXO & VMH3



The graphs show the in-air detection height versus the ball diameter for metal balls made of chrome steel, stainless steel, and aluminium. The ball diameter in millimetres is on the x-axis. Blue colour was used for chrome steel, red for stainless steel, and green for aluminium. The dotted lines are for normal metal detectors and the full lines for the UXO versions.

Figures 24 & 26 have a slightly different y-axis scale (400 mm) due to higher sensitivity of the detectors. It has to be mentioned that most of the UXO detector detected the balls just under the antenna. There was no full sensitivity area under the search heads, so that in the centre of the search head no detection was possible.

The general tendency for all metal types for the normal detectors is characterised by a different sensitivity for different metals. With the increase of the diameter the detection depth changes in a distinct way for each detector, but in every case the curve gradient decreases with the size of the balls. Both these effects are also seen for the UXO detectors. The difference is that the UXO detectors are less sensitive to small metal balls but their curve gradients do not decrease as rapidly with increasing ball diameter. In practice this means that the normal detectors have limited ability to detect larger amounts of metal at greater depth while UXO detectors have limited ability to detect low metal content mines, even at small depths.

Some typical examples for the described tendencies are in Figure 23: for chrome steel balls with 15 mm diameter the UXO and mine detector curves already cross. For nearly all types of metal, the curves in Figure 25 cross.

Special cases are visible for the other detectors and aluminium (Figures 23, 24, 26) where it seems as if the crossing will appear much later and the curves are almost parallel.

Knowing this behaviour and knowing the dominant type of metal one is looking for, may help to influence on the setting of the detector or to discriminate small pieces of metal.

In other words:

- Reduction of false alarms
- Reduction of time for area checking

may be influenced in this way.

Practical use of metal detectors with a large search head should only be allowed when technical survey had confirmed the absence of landmines, especially low metal content mines.

#### 4.8.1 Sensitivity comparison UXO versus mine detectors to ITOP mine simulants

Fig.: 27 Different sensitivity of UXO and normal metal detectors

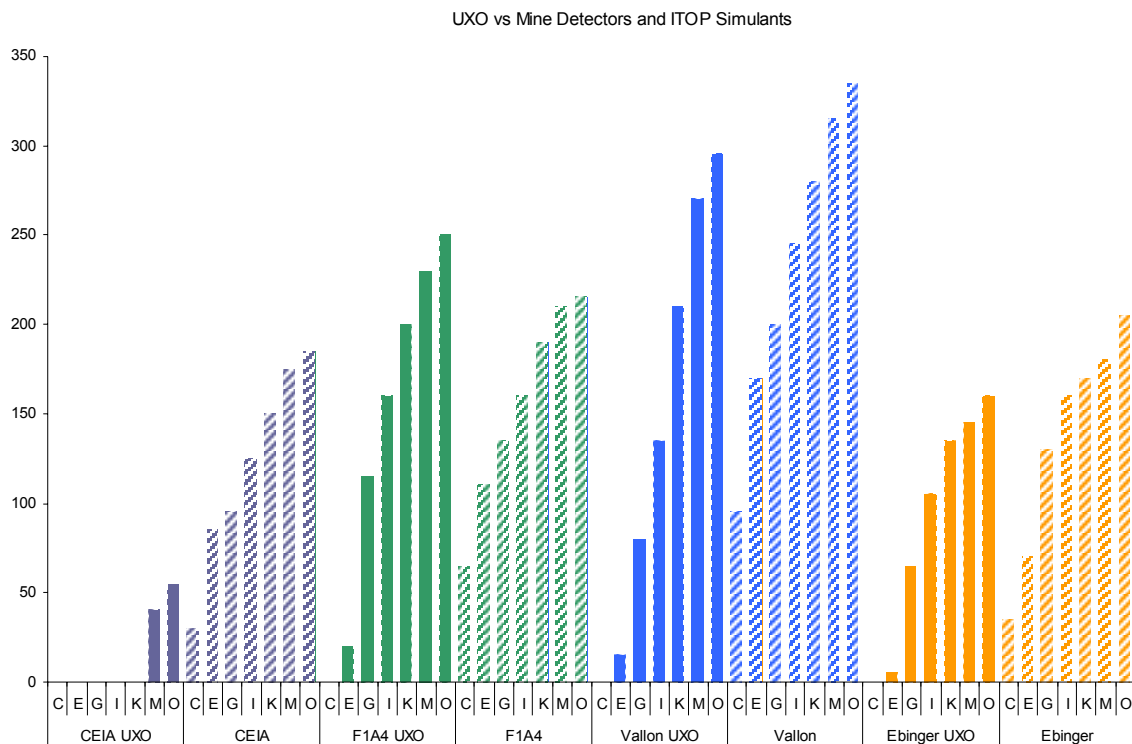
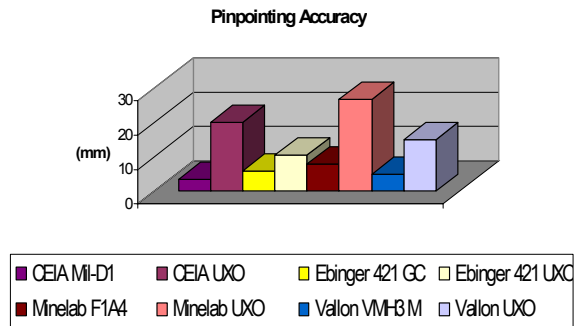


Figure 27 very clearly demonstrates the reduced sensitivity of the UXO versions against the basic metal detector. The ITOP simulants have an increasing metal content in alphabetic order. The letter “I” stands for known minimum metal mines as M14, PMA-2, and Type 72. The simulants do not simulate exactly the metal content of those named mines but the response to metal detectors is similar as those mines. Those simulants are still too small to make the UXO detection capabilities to detect bigger metal amounts deeper obviously. Only the F1A4 UXO is better as the basic version to the larger ITOP simulants – this confirms also the results from the graph before where the full lines of the UXO version cross the lines of the basic detector quite early.

Fig.: 28 Search size and Pinpointing



pinpointing accuracy. The latter under lab conditions for detectors is below 10 mm and for UXO detectors between 10 to 30 mm (Fig. 28).

There are two other effects which appeared with the change from a mine detector to an UXO detector. The first one is the increased power consumption, i.e. reduced battery life. The excitation current for the same field is linearly increasing with the loop diameter. But also linearly is increasing the coil inductance, which means that the supply voltage should also be increased. In a result, the power consumption is approximately proportional to the loop area. The second issue is the

## 4.9 New technical features

### Changes and tendencies

Metal detectors have within ten years drastically improved in capabilities and design. The designs have gone from a detector that had to be assembled after it was taken from its case, to a “one piece” detector that can be instantly deployed; from not having GC to “must be” with GC, and sensitivity has also increased markedly. Other development concerns the interface with the user and the possibility to adjust the detector to specific local conditions by having access to the software. The operator has the choice for the latest models to receive information in audible, visual form but also via vibration of the handle. These changes have made the metal detector, after the human being, the only tool on which humanitarian demining relies completely. After machines and animals (dogs, rats) have been used, the deminer and metal detector are still in charge of the final investigation of the area.

Could more information useful to the deminer be obtained from metal detectors by advanced signal processing? Detectors today typically use only one or a few samples of the signal or a limited number of frequencies. Without a doubt, developments in modern digital electronics allow the possibility for far more processing to be done on-board the detector, without an unacceptable increase in weight. The real limit, in fact, is the signal quality of the signature obtainable from the target and the mathematical bounds on what can and cannot be extracted [ref. Tantum and Collins]. The possibility of being able to discriminate between targets of different shape and material and to say something about the target depth is still the subject of active research. [ref. HuMin/MD 2005, SPIE Conferences especially Sessions 5 and 6 EMI I and II in 2005 and Sessions 1 and 2 EMI I and II in 2006 ].

During the development of HD, many attempts have been undertaken to develop detection methods using techniques other than low-frequency electromagnetic induction. Different promising sensor techniques and physical principles were thoroughly investigated, unfortunately without coming to a cheap and easy usable field solution until now. The most promising candidate today is a detector in which a metal detector is combined with ground-penetrating radar (GPR) in a single hand-held device. Systems from the US, UK, and Japan are in the development stage. Challenges in designing such a device include the reduction of mutual interference between the two sensors and the signal fusion. The GPR has advantages: it can establish if the signal comes from a metal fragment or a mine-like body but can also easily be influenced by environmental conditions especially soil moisture. In practice, the metal detector serves as the main detection sensor while the GPR is more a confirmation tool. Dual-sensors

have still to undergo further field testing before employment in humanitarian clearance operations. The costs of such a combined detector are above twice that of the normal metal detector so the crucial question which must now be answered, and is being very actively investigated, is: do dual-sensors deliver enough improvement in safety and efficiency to justify their higher price?

Having been involved in the test and evaluation of dual sensors, what is missing in our opinion is the parallel development of a light easy useable GPR that could be added as another clearance tool to the already quite voluminous tool box of the deminer. Then every metal detector in use could be extended by the new technique and the same advantage for reducing false alarms by GPR would broadly be available at a much lower price [ref.Pike].

## 5 Conclusions

### *General*

Today, a great deal of detailed information about tests of equipment for humanitarian demining is publicly available from sources such as the ITEP website, GICHD, JMU - MAIC, CCMAT, the NGO's and last, but not least, from our own archives at the JRC. With this information, we were able to review the results of metal detector trials and make overall statements about the development of the technology.

Metal detectors used in humanitarian demining employ diverse technical solutions and come to similar results. Detectors from different manufacturers achieve broadly similar levels of sensitivity under favourable conditions, and only testing in extreme conditions reveals limitations in one respect or another. Although the sensitivity of detectors has increased, there are still problems in detecting the common, well-known and massively used low-metal-content mines Type72 (China) and PMA-2 (FRY), under complicated soil conditions, to the IMAS default clearance depth of 130 mm. In connection with this it is important that the clearance organisations are aware about the ground compensation capability of the detectors they deploy.

Features like ground compensation and interface to the user do have differences in quality but, generally speaking, many of the differences are questions of style connected with the policy of the manufacturer. Taking the example of sensitivity adjustment, most manufacturers allow the operator either full control with a continuous adjustment knob or some control with a limited number of switch positions, but Minelab Pty. Ltd. exclude *all* features by which the operator can change the sensitivity without the knowledge of the supervisor. Another example is Ebinger Prüf- und Ortungstechnik GmbH standing by their modular approach, where interchangeable parts are to be assembled, resisting the trend to one-piece designs followed by other manufacturers. It is not the place here to discuss the pros and cons. At the end, the results are metal detectors which are widely used in HD from different manufacturers.

Good effective trials should enable a demining organisation to make sense of all the available models and decide which one is most suitable for its purposes. All the trials we reviewed here had two general objectives: to compare the capabilities under specific local conditions and to short-list the detectors that came closest to the requirements. With the IPPTC trial, for the first time an overview of currently available COTS detectors was given, later updated by the STEMMD trial, this time making use of the CWA standardised test methods. The STEMMD Mozambique trial collected a considerable amount of empirical data, which include the reaction of the available detector fleet to real mines, simulants and balls and also to seven types of soil. These data should allow comparison to other countries, with some more analysis.

The implementation of the CWA in STEMMD and other recent trials showed that the full set of tests requires much effort and can only be routinely repeated by a programme with the capacity

of ITEP. Since the IPPTC test, 12 new or updated metal detector models have come onto the market, and it is expected that this pace of development will continue. A strategy is required to make most efficient use of the international resources available to keep the information about new development updated. Neither the lab trial nor the field reliability trial can be dispensed with. The lab trial enables one to obtain the best understanding of the intrinsic capability of the detector but the blind test is the only way to unite all factors influencing the entire detection system consisting of the human being, the metal detector, and the environment. We have found that conducting lab tests with many detectors at once does not lead to efficiency savings because it is impractical to have many detectors switched on simultaneously so they must be warmed up one by one. Conversely, running field trials with only small numbers of detectors is inefficient because of the fixed cost of organising each campaign, recruiting and transporting staff etc. We would propose the following strategy:

- 1) All new models should undergo lab tests by ITEP one by one as they come onto the market.
- 2) Statistically-based blind reliability tests of all available COTS models should be timed for each publication of the GICHD detector catalogue.
- 3) Specific trials focused on targets or scenarios of particular interest, or new devices under development, would also be conducted by individual demining organisations or regional groups or manufacturers, with the assistance of ITEP.

The efficiency of such a scheme hinges on whether the results of centralized testing can be applied by field operators to their own specific detection problems. If not, one would have to conclude that only specific focused trials are valuable. But, as demonstrated in the more recent trials, it is now possible to recommend detectors which have generally superior ground compensation and will be able to work under difficult ground conditions successfully. Admittedly, for practical purposes it is not yet possible to calculate the detection ability for a given target under given ground conditions, but the analysis of the results of the trials, together with knowledge of the factors influencing detector performance, enables one to achieve a degree of prediction. The balance of evidence and the overall trend of recent trials suggest that this can be developed in the future. Mathematical or/and simulation solutions may well have something to offer. Furthermore, general properties such as handling, battery life, the effect of temperature and suitability of head size and shape for broad classes of target certainly do not need to be re-assessed by every MAC in an in-country trial. Overall, therefore, we believe that the balanced strategy outlined above makes sense.

#### *The human factor in test campaigns*

The more sensitive part of the deminer-detector combination is the deminer, who works in a high-stress environment. Any possible effort has to be undertaken to build up and to increase his confidence level with the detector used. The reliability trials gave some examples of the value of training and practice in this direction. Test and evaluation methods used to compare detector qualities could also be used to investigate such human factors.

It must also be recognised that the human factor does limit the achievable reproducibility and precision in testing the detectors. Although one could, for example, work always with electronically recorded signals, in practical use it is the reaction of the operator which really constitutes a detection.

#### *Importance of knowledge about soil properties collected during test and evaluation projects*

The soil is still the main influencing factor on detector performance. Trials without the measurement of the soil properties are of reduced value because the main factor directly influencing the detector was not included in the assessment. The effect of soil influence, especially the magnetic susceptibility and its frequency dependence can render detectors unusable. In this area one finds the biggest differences between detectors, and the improvement in recent years has been significant. Detectors without GC may be used only in areas with

benign magnetic soil properties. Values of frequency dependence of the magnetic susceptibility above  $6 \times 10^{-5}$  SI units are the recommended limit for their employment. Use of non ground-compensating detectors in such conditions may create danger. The collection of soil properties during impact/technical survey should be seriously considered by the authorities for mine action standards because it can in advance prevent a decision to use inappropriate detectors. A good example concerning the magnetic properties of soil data was the creation of maps reflecting those properties in BiH. A quite complete map about those properties is now available and may help in the planning of detector employment in the regions of the country.

#### *In-air versus in-soil measurements*

Here the results of the trials, especially IPPTC, BAM/JRC and the Mozambican STEMMD trial, brought the authors to the following conclusion.

*“In-air measurements do not always correspond well to the results measured with the same setting in soil. This finding should be further verified, because it has serious consequences: the air sensitivity measurements cannot be used to predict detector performance in soil. If this statement is verified, it would mean that the in-air measurements with detectors set-up for soil have no sense and should be excluded from the CWA.”*

#### *Reliability*

The reliability tests need a careful assessment of the statistics during their planning, to understand what level of confidence can be achieved. The main interest is not in the simulation of conditions during real clearance operations but in the obtaining of valid data for the comparison of the detectors. The POD should be planned to be at a level that delivers comparable results (0.5 to 0.8).

The FAR in practice maybe considered as a combination of ground effects, ground metal contamination, electronic noise and human factors influencing the detectors' intrinsic capabilities. Depending on the local situation one or the other part of this combination may have increased influence on the detection results.

#### *Control of detector settings and state during trials*

Some detectors with a continuous sensitivity adjustment have extremely delicate adjustment near to the maximum sensitivity point – moving the knob a millimetre may change the detection capability by centimetres. This makes the setting hard to reproduce, record or keep stable during a test.<sup>17</sup> Sensitivity, soil compensation and EMI filter settings at which an automatic detector locks are usually not indicated, so that one cannot always be sure what the state was during test. Exactly what happens on manipulating a sensitivity knob may not be obvious. In some cases, changing the sensitivity does not simply change the gain of the electronics. An example is the AN 19, whose “sensitivity” knob changes in fact the sampling time, which may result in significant change in the relative sensitivities to different shaped targets. With the exception of such issues, and of course the battery state, the detector's own properties are usually reasonably stable during a test.

#### *Stability of environment during trials*

Environmental factors such as the vegetation, ground conditions and EMI are normally stable during a test. The great exception is of course the weather, which may certainly affect the detector and, in a reliability trial, may also affect the operator.

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<sup>17</sup> This can be considered a true design flaw, not just a nuisance for testing, since the sensitivity setting is also critically important in use.

### *Normal and UXO detectors*

The use of UXO detectors should only be allowed where no threat of mines exist. The increase of the search head size has six effects in comparison to a normal metal detector

- large targets can be detected at greater depths
- sensitivity to small targets decreases, the smallest targets may no longer be detected
- the false alarm rate decreases
- the rate of ground-coverage increases
- the power consumption increases, shortening the battery life
- pinpointing is not as precise



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- [QinetiQ Trial](#)
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- [IPPTC field Trial](#)
- [UN Afghan Trial](#)
- [UNMAS Trial in Bosnia](#)

## General Sources of Trial Information:

International Test and Evaluation Program in Humanitarian Demining

<http://www.itep.ws/>

Geneva International Centre for Humanitarian Demining

<http://www.gichd.ch>

James Madison University Mine Action Information Centre

<http://maic.jmu.edu>

EUDEM 2 network database

<http://www.eudem.vub.ac.be/>

Canadian Centre for Mine Action Technologies

<http://www.ccmata.gc.ca/>

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I to XI, 1996-2006 [www.spie.org](http://www.spie.org)

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CROMAC – Croatian Mine Action Centre

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## Contact Details of Manufacturers

### Metal Detector Manufacturers

Adams Electronics International Ltd.  
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<http://www.adamsinc.com>

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## **Suppliers of Magnetic Instruments for measuring soil properties**

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<http://www.agico.com/>

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