Low frequency radar for buried target detection

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Abstract The detection and mitigation of unexploded ordnance (UXO) is recognised to be a serious global issue. Many millions of landmines have been deployed in recent conflicts, with few records of what has been laid and where. As well as landmines, other types of UXO include unexploded shells, mortar bombs and missiles, scatterable mines fired from mortars or artillery or dropped from aircraft or helicopters, and cluster munitions. Not only do such weapons cause injury and death to innocent civilians, but also they deny the use of substantial areas of land for agricultural and other economic purposes, which may be critical in countries where the threshold of poverty is already low. Ground-penetrating radar (GPR) is one of a family of sensors that may be used to detect UXO. In addition, GPR may also be used to detect other classes of target such as Improvised Explosive Devices (IEDs), weapons caches, and tunnels; further applications of GPR include archaeology, forensics, and the detection of buried pipes and cables. The purpose of this chapter is to present an account of the principles of ground-penetrating radar and their use in detecting buried UXO.

Key words: landmines, unexploded ordnance, radar, impulse radar

1 Historical background

The history of landmines goes back a long way. The Emperor Caesar used pits, arrays of stakes, and devices called caltrops to impede the progress of the Gauls in the

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siege of Alesia in 52 BC [5]. Similar devices were used in the battle of Bannockburn (1314) and the Wars of the Roses (1455–85). After the discovery of gunpowder in the 13th century explosive charges were used in siege warfare.

This led to the development of the fougasse – essentially an underground cannon, placed forward of a defensive position to shower rocks and debris over a wide area.

The naval mine was developed and used during the American Civil War (1861). In both the American Civil War and the Boer War, electrically-operated fougasses and mines were laid, as well as pressure-operated landmines. In the First World War, British engineers tunnelled under the German trenches and laid huge explosive charges [4]. Anti-personnel mines were not much used, but with the introduction of the tank in September 1916, anti-tank mines were soon introduced, initially improvised from shells.

In the Second World War, both Anti-tank (AT) and Anti-personnel (AP) mines were extensively used, especially by the Germans. Considerable advances were made in mine technology, and in the technology of mine detection and mine clearance.

1939	108,100
1940	102,100
1941	220,900
1942	1,063,600
1943	3,414,000
1944	8,535,500

Table 1 Numbers of the German anti-tank Tellermine deployed in the Second World War [7].

The table above indicates that the Germans kept careful records of the number, and indeed the locations, of mines that they laid. However, whilst in post-WWII conflicts mines have been used extensively, armies have not necessarily been so careful in marking and recording the location of minefields.

Of the 48 countries in Africa, more than half are known to be mine-affected. There are minefields in North Africa that remain from WWII. In Zimbabwe (formerly Rhodesia) there are an estimated 1.5 million landmines, some of which have been laid at random and only 10% of which have been removed. Somalia, South Africa, Rwanda, Chad, Angola and Mozambique are also heavily affected.

Afghanistan and Cambodia are two of the most mine-infested countries of the world. In the Korean War (1951–53) some ten different countries made use of anti-personnel mines. Some fields were so thick with AP landmines that they were a constant threat even to those that laid them. In the Vietnam War entire villages were surrounded by landmines, hand laid or dropped from the air, and no records were kept of the mines laid. In Cambodia, humanitarian groups have demined areas just to have them remined again. Cambodia has more amputees as a percentage of the population than any other country in the world.

In Bosnia–Herzegovina, an estimated 3–6 million mines still remain uncleared. Some maps were kept and have been turned over to the UN. In WWII landmines were not used extensively in Europe until the end of the war. Minefield clearance is still being undertaken in countries such as Belgium, while in France land is still contaminated by landmines.

In El Salvador in 1980–1991, mining was done without any charting, so many of the original mine-layers were recruited for the demining operations. In a one-month conflict in 1995, tens of thousands of landmines were laid down on the borders between Ecuador and Peru. Some efforts have been made to demine the area, but about 6,000 mines still remain. In the Falklands War (1982) extensive use of anti-personnel mines was made by the Argentine forces. Some clearance programmes were established, but were short-lived due to heavy casualties on demining units, so the minefields still remain.

Fig. 1 A minefield in the Falkland Islands.

Over 175 million landmines have been deployed since the end of World War 2, including more than 65 million since 1980. Mines are seen by warring factions as attractive weapons as they are relatively cheap to acquire, easy to lay and invariably have a devastating effect on the target. They differ from most other weapons, however, by remaining active in the ground long after hostilities have ended. They lie in fields and woodlands, alongside roads and footpaths, and in villages creating a humanitarian problem – with social, economic and environmental dimensions. Anti-personnel landmines are designed to maim rather than to kill, since a wounded combatant is more trouble to an army than a dead one. Not only do such weapons take their toll on victims and families, but the presence of landmines in and around communities, on roads, in farmland, and near rivers and wells prevents the productive use of land, water and infrastructure for development.

The term ‘minefield’ conjures up an image of flat open countryside, in which rows of anti-tank and anti-personnel mines have been carefully laid, surveyed and recorded, and which are bounded by minefield fences marked with white tape and red warning triangles. In reality the situation is quite different. Minefields are often laid in a hurry by poorly trained and ill equipped armies; mines are rarely laid according to a pattern; booby traps may have been set up; and the area may be scattered with other forms of unexploded ordnance (UXO), from small items such as phosphorus grenades, to artillery shells and missiles containing a deadly cocktail of explosives and fuel.

In some situations the ground may be contaminated by scatterable mines fired from mortars and artillery, or dropped from helicopters and aircraft. It is estimated that two million tons of bomblets were dropped from US aircraft on Vietnam, Laos and Thailand in the 1970s, aimed at disrupting movement along the Ho Chi Min Trail. The bomblets were anti-personnel devices designed to explode on impact with the ground, although it is now assessed that 25% failed to explode and they remain an ongoing hazard to communities.

Of more recent concern is the use of cluster munitions. These are small weapons – often no larger than a small cola can – containing a powerful explosive charge. They are packed into containers and dropped from aircraft or fired from artillery systems. Cluster munitions have a high failure rate; more than 20% fail to detonate on reaching the ground and remain hazardous until they are cleared. Large numbers were dropped in the Balkans, Afghanistan, Iraq, and more recently in the Lebanon.

So after the guns fall silent, and when the mines and UXO no longer have a military purpose, the battlefield remains dangerous, and explosive remnants of war have a major impact on communities attempting to recover from years of conflict.

2 The role of technology

Over 1,000 square kilometres of land have been cleared of mines and UXO since the start of modern humanitarian demining in the early 1990s. In its 2007 report, the international NGO Landmine Monitor estimates some 140 square kilometres were cleared in 2006, as well as over 310 square kilometres of UXO and other explosive remnants of war. This is a remarkable achievement, and is a significant improvement on clearance rates of a decade ago. But a massive challenge remains, and will continue for many more years – long after international interest and funding has moved on to address other issues and humanitarian concerns.

There is a pressing need to find smarter ways of clearing landmines and UXO. This can be achieved in three ways: first, by improving the quality of the information on the threat and its impact, and from this improved information to prioritise better the use of clearance teams; second, by developing new survey and clearance procedures; and third, by developing and deploying better equipment, including improved sensors.

Over the past 15 years there has been substantial interest in finding a technical 'silver bullet'. These ideas have included experimental prodders (with acoustic sensors to detect the presence of metals and plastics), improved handheld metal detectors, nuclear quadrupole detection, X-ray backscatter, vapour and chemical analysis detectors, laser detection, the use of animals and insects, infrared detectors and exploiting other parts of the electromagnetic spectrum including ground penetrating radar (GPR).

Indeed, following the Falklands conflict of 1983 the British Government funded considerable research and development into smarter ways of locating and neutralising the landmines which scattered the islands, many buried in peat or scree which would prove difficult to detect and clear using conventional metal mine detectors and prodders. This work was halted in 1986 when it was clear that the systems being proposed could not achieve the substantial improvements in clearance rates being demanded by the British Government.

Notwithstanding this absence of a 'silver bullet' there is still a need to find and apply better technologies to demining.

3 The operational needs

In 2000/01, the Geneva International Centre for Humanitarian Demining (GICHD) was invited by the United Nations to establish a priority list of operational needs that could benefit from improved equipment, processes and procedures. The GICHD's Study of Global Operational Needs [14] which was carried out in partnership with Cranfield University identified a number of generic operational needs and equipment requirements. The purpose of the study was to give guidance to research and development, and provide the user and donor communities with the means to assess more effectively the benefits and cost of technology to mine action programmes. The ultimate aim of the study was to encourage the design, development and manufacture of safer, better and more cost-effective equipment.

The findings and recommendations of the study are still relevant today. Of the 12 capability areas identified by the study two were considered as potentially benefiting greatly from better equipment: the close in detection of landmines, and systems which could more accurately determine the outer edge of mined areas. In particular, the study recommended that such equipments should not only have improved detection accuracy but a much lower rate of false alarms – which leads to inefficiency and can result in complacency of the deminers.

One area of technology where there have been demonstrated improvements in mine detection accuracy and false alarms is in the application of Ground-Penetrating Radar (GPR).

4 Fundamentals of Ground-Penetrating Radar

GPR has been developed over the past couple of decades as a means of detecting buried targets such as landmines. Other applications include the detection of buried utilities such as pipes and cables, as well as archaeological and forensic applications. The technologies also have some similarities to those used for through-wall radar detection and imaging [1, 13], foliage penetration (FOPEN) radar, and for glaciological sounding [12].

Fundamental to all of these applications are the propagation characteristics of electromagnetic radiation through materials such as soil and concrete and at the boundary between air and such materials, and how these characteristics depend on frequency and on material properties. In general it can be appreciated that a lower frequency may give lower propagation loss than a higher frequency, but will in general give poorer resolution, both in range and in azimuth.

Daniels [8] has provided a comprehensive account of the design factors in Ground Penetrating Radar and examples of systems and results. He states that 'GPR relies for its operational effectiveness on successfully meeting the following requirements:

- efficient coupling of electromagnetic radiation into the ground;
- adequate penetration of the radiation through the ground having regard to target depth;
- obtaining from buried objects or other dielectric discontinuities a sufficiently large scattered signal for detection at or above the ground surface; and
- an adequate bandwidth in the detected signal having regard to the desired resolution and noise levels.'

Table 2 shows the losses for different types of material at 100 MHz and 1 GHz. This shows that the loss is relatively low for dry materials, but that the loss increases substantially with moisture content. It also shows how the losses increase with frequency. However, it should also be understood that the attenuation of an acoustic signal decreases with moisture content, so acoustic (sonar) sensors may in a sense be considered complementary to radar sensors. Fusion techniques to optimally exploit the strengths of both types of sensor may therefore be of interest [11].

Daniels also presents a taxonomy of system design options. The majority of systems use an impulse-type waveform and a sampling receiver, processing the received signal in the time domain. More recently, however, Frequency-Modulated Continuous Wave (FMCW) and stepped frequency modulation schemes have been developed, which allow lower peak transmit powers. Both types of system, though, require components (particularly antennas) with high fractional bandwidths, which are not necessarily straightforward to realise.

Material	Loss at 100 MHz	Loss at 1 GHz
Clay (moist)	5–300 dB m^{-1}	50–3000 dB m^{-1}
Loamy soil (moist)	1–60 dB m^{-1}	10–600 dB m^{-1}
Sand (dry)	0.01–2 dB m^{-1}	0.1–20 dB m^{-1}
Ice	0.1–5 dB m^{-1}	1–50 dB m^{-1}
Fresh water	0.1 dB m^{-1}	1 dB m^{-1}
Sea water	100 dB m^{-1}	1000 dB m^{-1}
Concrete (dry)	0.5–2.5 dB m^{-1}	5–25 dB m^{-1}
Brick	0.3–2.0 dB m^{-1}	3–20 dB m^{-1}

Table 2 Material loss at 100 MHz and 1 GHz [8] (© IET, 2004).

5 Imaging and Resolution

We can establish some of the fundamental relations for the resolution of an imaging system. In the down-range dimension resolution Δr is related to the signal bandwidth B, thus

$$\Delta r = c/2B \tag{1}$$

where c is the velocity of propagation. High resolution may be obtained either with a short-duration impulse or by a coded wide-bandwidth signal, such as a linear FM chirp, a step-frequency sequence or a pseudo-random digital code, with the appropriate pulse compression processing. A short-duration impulse requires a high peak transmit power and instantaneously-broadband operation; these requirements can to some extent be relaxed in the case of pulse compression.

The rapid increase of attenuation as a function of frequency through most materials (Table 2) demands a low radar frequency. However, high range resolution demands a high bandwidth (equation 1). Thus ground-penetrating radars will in general have a high fractional bandwidth:

$$B_F = \frac{f_h - f_l}{\frac{1}{2}(f_h + f_l)} = \frac{B}{f_C} \tag{2}$$

where f_h and f_l are, respectively, the upper and lower frequencies of the radar signal. By convention, a radar with a fractional bandwidth of greater than 25% is characterised as ultra-wideband (UWB) [20]. In the case of an impulse-type radar f_l will tend to zero, so it can be seen from equation 2 that such radars are inherently ultra-wideband.

The cross-range resolution is complicated by the fact that in many cases the target (at range r) will lie within the near-field of the antenna, i.e.

$$r < \frac{2d^2}{\lambda} \tag{3}$$

where d is the aperture dimension and λ is the wavelength. In the far-field, though, the cross-range resolution is determined by the product of the range and beamwidth θ_B. The beamwidth is determined by the value of d and thus the cross-range resolution Δx at range r is given by

$$\Delta x = r\,\theta_B \approx \frac{r\lambda}{d}. \tag{4}$$

As most antenna sizes are limited by practical considerations, the cross range resolution is invariably much inferior to that in the down range dimension. However, there are a number of techniques that can improve upon this. All of these are ultimately a function of the change in viewing or aspect angle. Thus in the azimuth (cross-range) dimension the resolution Δx is related to the change in aspect angle $\Delta\theta$ as follows:

$$\Delta x = \frac{\lambda}{4\sin(\Delta\theta/2)}. \tag{5}$$

For a linear, stripmap-mode synthetic aperture, equation 5 reduces to $\Delta x = d/2$, which is independent of both range and frequency. Even higher resolution can be obtained with a spotlight-mode synthetic aperture, steering the real-aperture beam to keep the target scene in view for a longer period, and hence forming a longer synthetic aperture.

Realistic limits to resolution may be derived by assuming a maximum fractional bandwidth of 100%, and a maximum change in aspect angle of $\Delta\theta = 30^\circ$ (higher values than these are possible, but at the expense of complications in hardware and processing). These lead to $\Delta x = \Delta r = \lambda/2$. In the last year or so results have appeared in the open literature which approach this limit.

Figure 2 shows that range resolution may be achieved by different methods. In (i) the transmitted signal is an impulse waveform in the time-domain. This requires specialised hardware to generate the high-voltage impulse in the transmitter and to sample the echo in the receiver. In (ii) the transmitted signal is a linear FMCW sweep and the received echo is deramped and processed in the frequency domain. The requirements for the peak transmit power and the digital sampling and processing rate in the receiver are considerably relaxed, but the technique does introduce range sidelobes. These can be lowered by the usual weighting techniques, but nevertheless the sidelobes from the direct transmit to receive antenna coupling or the strong ground echo may mask target echo features. Similar comments apply to (iii), in which the transmitted signal is a stepped-CW waveform, and (iv) in which it is a pseudo-random biphase- or polyphase-modulated carrier. In both cases the echo is digitised and processed with a matched filter (correlator) in the receiver. In practice the vast majority of GPR systems are of the impulse type.

In contrast, holographic imaging techniques may be used with CW or quasi-CW signals, giving high spatial resolution by exploiting spatial bandwidth rather than frequency bandwidth.

In radar tomography the observation of an object from a single radar location can be mapped into Fourier space. Coherently integrating the mappings from mul-

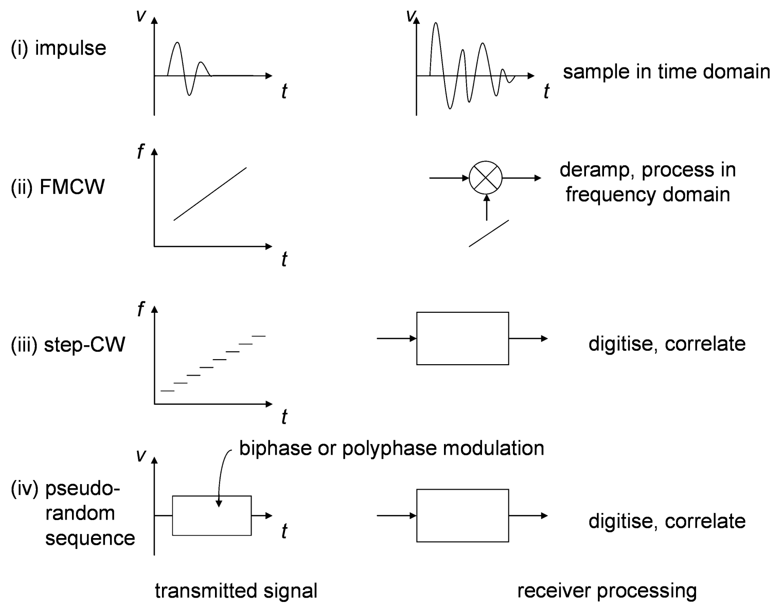

Fig. 2 Form of transmitted signal and receiver processing for different GPR system options. Note that the time axis of (i) is of considerably shorter duration than those of (ii), (iii) and (iv).

tiple viewing angles enables a three dimensional projection in Fourier space. This allows a three dimensional image of an object to be constructed using conventional tomography techniques such as wavefront reconstruction theory and backprojection where the imaging parameters are determined by the occupancy in Fourier space. Complications can arise when target surfaces are hidden or masked at any stage in the detection process. This shows that intervisibility characteristics of the target scattering function are partly responsible for determining the imaging properties of moving target tomography. In other words, if a scatterer on an object is masked it cannot contribute to the imaging process and thus no resolution improvement is gained. However, if a higher number of viewing angles are employed then this can be minimised. Further complications may arise if (a) the point scatterer assumption used is unrealistic (as in the case of large scatterers introducing translational motion effects), (b) the small angle imaging assumption does not hold and (c) targets with unknown motions (such as non-uniform rotational motions) create cross-product terms that cannot be resolved.

Finally, image processing techniques (including singularity expansion methods, wavelet transforms, pattern recognition techniques and neural networks) may be used to reduce the effect of clutter and enhance targets. In general these attempt to exploit prior knowledge of the nature of the targets and of the background noise and clutter.

As an example of the results that can be achieved, Figure 4 shows images of a buried antipersonnel mine at a depth of 15 cm, showing both the original image and

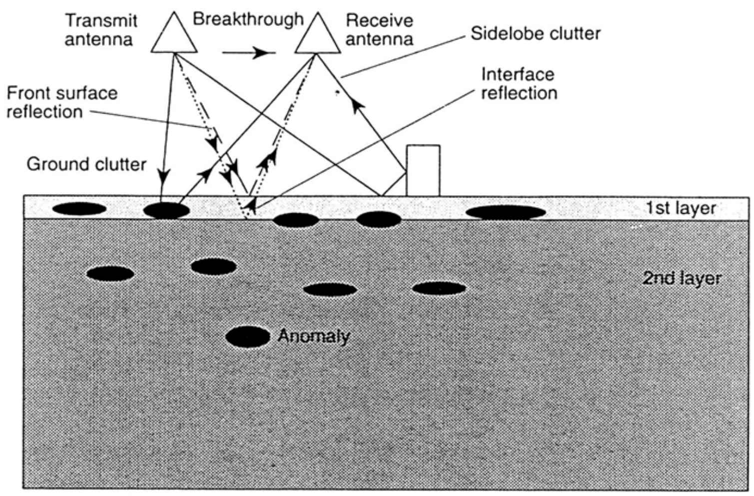

Fig. 3 Physical layout of Ground Penetrating Radar system [8] (© IET, 2004).

the results after image processing techniques have been used to enhance the target. The mine was buried at a depth of about 5 cm at an angle of about 30 degrees, in dry sand. In the raw image the mine target is barely evident, but after deconvolution processing, in which the impulse response of the instrument is deconvolved from the radar data [8], the improvement is clear. The third image shows the result of applying Kirchhoff migration processing to the image, which in this case is less successful. These show that, under the right conditions and with the use of appropriate algorithms, significant enhancement is possible.

6 MINEHOUND

MINEHOUND is a prototype low-cost, man-portable detector developed for humanitarian demining purposes by ERA Technology, for the UK Department for International Development (DfID). It consists of an ultra-wideband GPR and a metal detector, with the output presented to the operator in audible form, and the signature varies in a characteristic way as the detector is moved over a buried object. Trial results are reported in [8].

7 The *Mineseeker* Project

Another example of an advanced radar system for detection of abandoned UXO is the Mineseeker project [22]. The Mineseeker Foundation has the support of some

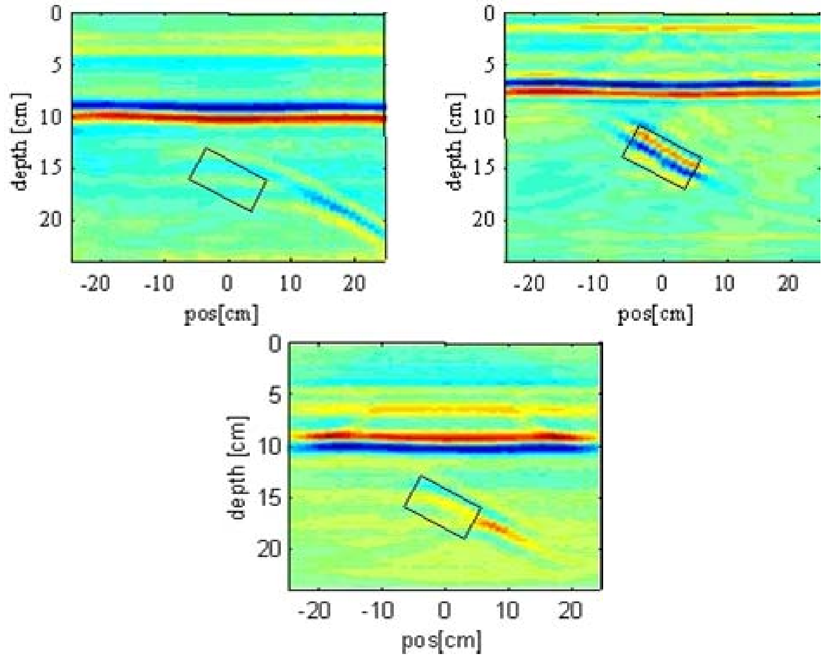

Fig. 4 Oblique antipersonnel mine at an angle of 30 degrees: (a) B-scan of raw data; (b) after migration by deconvolution; (c) after Kirchhoff migration [8] (© IET, 2004).

Fig. 5 The MINEHOUND instrument (left), under test in Sarajevo (right) [8] (© IET, 2004).

high-profile patrons, and represents a not-for-profit joint venture between the Lightship Group and QinetiQ. The concept uses an ultra-wideband synthetic aperture radar (UWB SAR) developed originally by engineers from DERA Malvern (now QinetiQ), and gimbal-stabilised electro-optic sensors operating in the visible and 3–5 micron IR bands, mounted on an airship platform. The airship has the particular merits of being mobile, stable, low-cost and with long endurance, as well as the ability to carry a substantial payload.

The pulse generator and high-speed digitiser subsystems used in the UWB radar were developed by Kentech, the UWB antennas by researchers at Dundee University, and the synthetic aperture processing and target signature analysis algorithms by Applied Electromagnetics Inc.

Fig. 6 The Mineseeker airship (© Mineseeker Foundation, 2001).

Basic parameters of the radar sensor are listed in Table 3 [22];

Range resolution	5 cm
Azimuthal resolution	0.5 m
Instantaneous bandwidth	$>$ 3 GHz
Frequency range	200 MHz to over 3 GHz
Pulsewidth of impulse waveforms	$>$ 100 psec
Peak power	1 MW

Table 3 Basic parameters of Mineseeker UWB SAR (© Mineseeker Foundation, 2001).

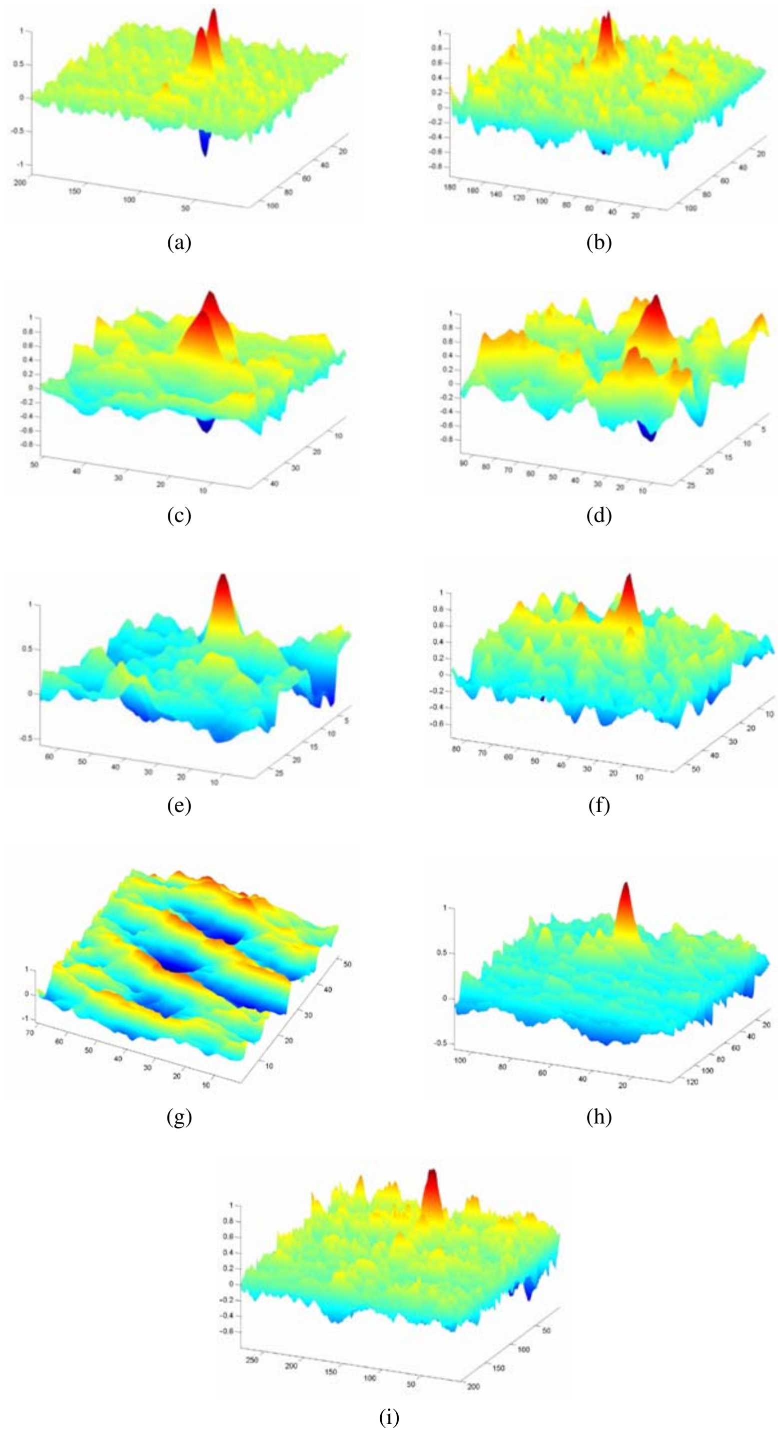

Fig. 7 Signatures of different targets obtained in trials with the Mineseeker UWB SAR: (a) surface-laid calibration sphere, HH polarisation; (b) surface-laid mortar round (inert), VV polarisation; (c) surface-laid RBL755 cluster bomb sub-munition (inert), VV polarisation; (d) above-ground PMR2a stake mine (inert), VV polarisation; (e) buried TMM1 metal anti-tank mine (inert), VV polarisation; (f) buried RBL755 cluster bomb sub-munition (inert), HH polarisation; (g) buried mortar round (inert), VV polaristion; (h) buried handgrenade (live), VV polarisation; (i) buried PMR2a (live), VV polarisation (© Mineseeker Foundation, 2001).

It has been demonstrated in trials that different mine targets have characteristic signatures, so different mine types may be distinguished from each other and from other false alarm debris (Figure 7). These examples also show the information that may be obtained from the polarimetric signatures of mines and other UXO, though in practice the additional hardware complication of a polarimetric radar makes these techniques very difficult.

MINESEEKER's coverage rate (in terms of location and delineation) of more than 100 square metres per second is claimed, in contrast to 20 to 50 square metres per day by manual demining.

The preceding are just two examples of practical GPR systems; many more are described in [8].

8 Management of humanitarian demining programmes

Whilst the emphasis here has been on the technology used to detect and neutralise landmines and other UXO, equal prominence should be given to the management of demining programmes, since even the most sophisticated technology is of little use unless deployed in a systematic and properly managed way.

Fig. 8 Mine Action.

Work over more than two decades at the Defence College of Management and Technology, Shrivenham (part of Cranfield University and of the Defence Academy of the United Kingdom, and led by Alastair McAslan) has developed programmes in the management of humanitarian demining, and earlier this year received the Queen's Anniversary Prize for Higher and Further Education, from Her Majesty the Queen, for this work.

'The management of mine action at the national level is, essentially, about ensuring that programmes, projects and day-to-day mine action activities are carried out effectively, efficiently and safely. This involves defining the requirements through assessment missions and site surveys, prioritising requirements, developing plans, securing funding, implementing projects and confirming that the requirements have been met' [17].

'Resilience' may be defined as understanding the risks to nations and organisations from factors as diverse as terrorism, natural disasters, health pandemics and IT fraud, and hence firstly being able to minimise the risks and effects, and secondly ensuring that the organisation is able to recover as quickly as possible. Demining therefore represents one specific aspect of Resilience.

Fig. 9 Developing national management capabilities consists of training national managers in mine-affected countries to run mine clearance programmes for themselves.

In March 2008 Cranfield University launched an MSc course in Resilience [23], aimed at professional managers who wish to apply rigorous academic thought to practical problems in their sector, and to acquire the necessary knowledge and skills to analyse threats and build resilient organisations and systems. The course includes an elective module of Managing Post Conflict Challenges, which has been designed for national and international managers operating in mine-affected countries. Students on the course include graduates of the University's national mine action management training programmes.

9 Conclusions

All of the foregoing has attempted to show first of all the extreme nature of the UXO detection and disposal problem. Many millions of landmines and other types of ordnance have been deployed in conflicts, with few records of what has been laid and where. Not only do such weapons cause injury and death to innocent civilians, but also they deny the use of substantial areas of land for agricultural and other economic purposes, which may be critical in countries where the threshold of poverty is already low.

Low-frequency ground-penetrating radar represents one of a number of sensors that may be deployed to detect such targets. It is important to understand the strengths and weaknesses of radar techniques for these purposes, and the synergy with other types of sensor. Under favourable (i.e. dry) ground conditions and at relatively low radar frequencies penetration to significant depths can be obtained. However, low frequencies are unable to support wide radar bandwidths, so it is difficult to obtain high resolution at the same time as significant penetration.

Whilst such sensors must always respect the laws of physics, improvements in RF hardware, in digital processing hardware and in processing algorithms mean that steady advances will continue to be made. One promising area is in the complementarity of other types of sensor and hence of data and image fusion techniques to better exploit the strengths of each.

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