Ground Penetrating Radar for Buried Landmine and IED Detection

David J Daniels

Abstract Detection of landmines using electromagnetic induction (EMI) techniques is well established and a range of metal detectors is commercially available. Recent developments using dual sensor technology combining EMI and ground penetrating radar (GPR) have enabled improved discrimination against small metal fragments to be demonstrated in live minefields. Reductions of up to 7:1 compared with the standard metal detector have been achieved in the field by hand held systems such as the UK-German MINEHOUND/VMR2 system and the US AN/PSS-14 (formerly HSTAMIDS: Handheld Standoff Mine Detection System).

Stand off vehicle based radar systems are now being trialled in realistic conditions. Airborne systems have also been trialled, but as yet have some way to go to deliver useful performance. These three distinct modes of operation pose fundamentally different challenges in terms of the physics of propagation and the radar system design and will be discussed.

End user expectations in terms of performance are challenging and at present only the hand held detectors are approaching these needs. This chapter reviews the high-level performance requirements from an OA perspective in order to set the performance envelopes of the radar designs. We also address the fundamental challenges in terms of propagation, proximity to the ground surface; ground topography and signal to noise and signal to clutter bandwidth of operation with reference to both close in and stand off landmine and IED detection. A review of the performance of GPR systems at the higher TRL levels is provided.

A key issue in comparing the published results of controlled trials relates to statistics of the depth of cover, the soil propagation characteristics, and the type of landmine, the sample size, the physical placement of the landmine as well as the characteristics of the clutter. This chapter will also highlight the future engineering challenges to achieve not only detection but recognition and identification using GPR.

Key words: Landmine detection, radar, ground penetrating radar

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Introduction

Landmine detection using electromagnetic induction (EMI) techniques (commonly termed metal detector (MD)) is well established and a range of these devices is commercially available. Recent developments using dual sensor technology combining EMI and ground penetrating radar (GPR) have enabled improved discrimination against metal fragments to be demonstrated in live minefields and reductions of up to 7:1 compared with the standard metal detector have been achieved in the field by hand held systems such as MINEHOUND [3] and AN/PSS-14 [5]. These systems have reached the stage where they are being produced in large numbers.

Stand off vehicle based radar systems are now being trialled in realistic conditions. Airborne systems have also been trialled, but as yet have some way to go to deliver useful performance. These three distinct modes of operation pose fundamentally different challenges in terms of the physics of propagation and the radar system design and will be discussed in this chapter.

End user expectations in terms of performance are challenging and at present only the hand held detectors approach these expectations. This chapter will review the high-level performance requirements from an OA perspective in order to set the performance envelopes of the radar designs. We also address the fundamental challenges in terms of propagation, proximity to the ground surface; ground topography and signal to noise and signal to clutter bandwidth of operation with reference to both close in and stand off landmine and IED detection.

A review of the performance of GPR systems at the higher TRL levels will be provided as well as an introduction to the various algorithmic approaches to the classification of landmines. A key issue in comparing the published results of controlled trials relates to statistics of the depth of cover, the soil propagation characteristics, and the type of landmine, the sample size, the physical placement of the landmine as well as the characteristics of the clutter. We highlight the future engineering challenges to achieve not only detection but recognition and identification using GPR.

Background

Landmines can be either buried or laid on the surface of the ground or buried flush with the surface of the ground. They are emplaced by a variety of techniques, including being scattered on the surface by vehicles or helicopters. Thus landmines may be found in regular patterns, or in irregular distributions. Where environmental conditions result in soil erosion and movement caused by rain over several seasons the landmines may be lifted and moved to new locations and can be covered or exposed. Landmines are encountered in desert regions (i.e. Somalia, Kuwait), mountains (i.e. Afghanistan, El Salvador), jungles (i.e. Cambodia, Vietnam) as well as urban areas (i.e. Beirut, former Yugoslavia).

In general, most pressure sensitive landmines are not designed to operate when buried deeply. In these circumstances the overburden ground material acts as a me-

Fig. 1 UK Army landmine detection 1945 (Photo: IWM).

chanical bridge and inhibits triggering of the detonator mechanism and also reduces the force of the explosion. This fact is often taken into account in the specification of performance for a mine detector. For example a hand held mine detector should be able to detect AT landmines at depths up to 300 mm and AP Landmines at depths up to 100 mm with spacing between the detector head and ground surface of up to 100 mm. Users of vehicle based close-in landmine detectors prefer a greater ground clearance, although very successful operation of EMI arrays has been achieved with very close (proximal) ground clearance. Landmines can also be encountered at depths well beyond the range of most detection systems due to movement of the soil. Mine detection systems can be employed in several different roles: for close-in hand-held detection, for vehicle mounted standoff detection or as a remote sensor mounted on low flying fixed or rotary wing aircraft. These are mostly synthetic aperture radars (SAR).

The variety of environmental conditions in which landmines can be found is enormous. Minefields are not only neat ordered rows of landmines in flat deserts but can also be found among the debris of burnt out buildings and post-conflict urban and rural environments. Clearly, mine detection equipment has to be designed to work in a wide range of physical environments and the statement of operational requirements issued by end-users will reflect this need. Detection equipment must be able to be operated in climatic conditions, which range from arid desert, hillside scree to overgrown jungle. Ambient operating temperatures can range from below 20°C to 60°C. Rain, dust, humidity and solar insolation all must be considered in the design and operation of equipment. The transport conditions of equipment can

Fig. 2 Sappers learning mine detecting and clearance methods at the Royal Engineers School of Mine Warfare, Middle East 1942 (Photo: IWM).

be arduous and these as well as man-machine interface issues are vitally important to the design of detectors.

The large majority of civilian casualties are caused by anti-personnel landmines, which come in a wide variety of types. Many are designed only to maim. The blast type anti-personnel landmine will cause a traumatic amputation to a foot or leg, often injuring the other leg and genitals as well. Fragmentation land mines are far more deadly. Some models shoot hundreds of metal fragments in an arc that reaches out 50 metres. Other types spring into the air when triggered and then explode at waist level. Anti-personnel mines can be buried in the ground or placed on the surface and can be set off by pressure, trip wire, remote control or sensors. They can be laid by hand, dropped from airplanes or spread by artillery. Many are made of plastic, which means they cannot be located by metal detectors during clean-up operations. Mine clearance has come a long way since the procedures adopted in the Second World War as shown in Figures 1 and 2.

Anti-vehicle mines are less numerous but more powerful. A mine that can disable a tank will destroy a civilian vehicle and kill its occupants. These mines usually cannot be detonated by a person's body weight alone, although when they are fitted with an anti-handling device they become anti-personnel weapons. Anti-vehicle mines are a particular threat to humanitarian aid workers who must travel roads before they have been systematically cleared.

Fig. 3 A woman deminer working for MAG excavating anti-personnel mine in Battambang province in Cambodia (Photo: MAG).

Types of Landmines

In terms of detection techniques, landmines can be classified into several groups. These are metallic landmines, minimum metal landmines and non-metallic landmines. The latter type is in a minority and cannot be detected with the metal detector, in contrast to the metallic and minimum metal landmines. In addition to conventionally manufactured landmines there are numerous examples of other versions, which fall in the category of improvised explosive device (IED). These are often not buried and hence are not landmines. The Geneva International Centre for Humanitarian Demining (GICHD) provides a useful introduction to types of landmine [7]. Other sources of information on landmines can be found on the US Department of Defense CD Minefacts © which contains details of over 675 landmines as well as the US Department of Defense, Naval Explosive Ordnance, CD Ordata which is a guide to UXO identification or many of the websites of Mine Action Centres and Non-Governmental Organisations NGO's. Some examples of typical landmines are shown in Figures 4 and 5.

These landmines are generally detectable with standard metal detectors but the completely non-metallic mine, though rarely encountered, can only be detected using a radar based detector. The French 1947 AT shown in Figure 6 has been found in Southern Lebanon and is constructed from bakelite and uses a glass based chemical detonator. Mines that are flush buried are a major problem as can be seen in Fig-

Fig. 4 Various anti-personnel blast landmines (Photo: GICHD).

Fig. 5 TM-57 metallic landmine and TM-62 P2 minimum metal antitank landmines (GICHD).

Fig. 6 Examples of the French 1947 AT landmine in Southern Lebanon (Photo: Bactec).

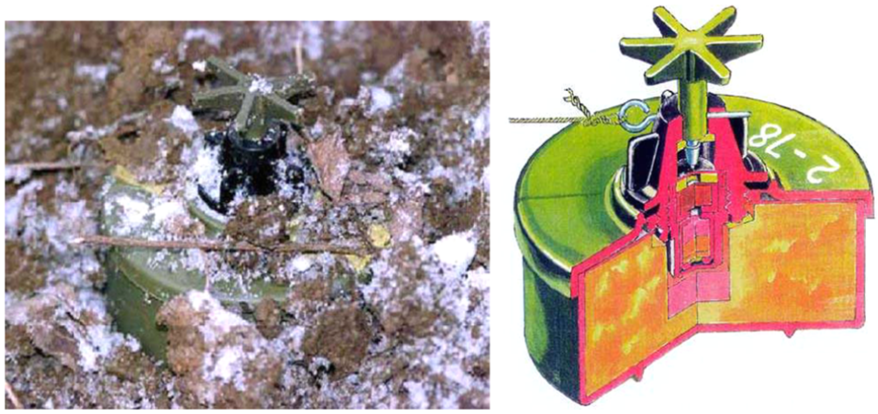

Fig. 7 PMA2 AP landmine in Bosnia (photo: D J Daniels) and internal construction (ORDATA).

ure 7, which shows the detonator just above the surface of the ground. The search techniques must allow for this situation, as too close an approach is inadvisable.

It is very important to understand the physical construction of landmines as this has a major influence on their radar cross-section (RCS). Some minimum metal landmines are substantially solid explosive, but others have significant air gaps and these enhance the radar scattering cross-section of the landmine. Landmines such as the PMD-6 and PFM-1 are asymmetric and this affects the polarisation characteristic of the RCS as well as causing differences between the centres of detection of radar and a MD.

Performance requirements

The key performance factors of the specification of a landmine are its probability of detection (PD) and its probability of false alarm (PFA). For a hand held system the requirement is to achieve a PD = 1 and PFA = 0. The threshold between the populations of true/false reports can be plotted as a sensitivity/specificity graph and generates a receiver operating characteristic (ROC) curve. A typical example is shown in Figure 8 which plots true positives against true negatives in a sample population.

It will be noted that for a true positive or PD value of 1 incurs a true negative or PFA of 0.4. The closer the ROC curve is to a step function the lower the PFA for a PD equal to 1. The ROC curve is used as a means of evaluating detector performance or aspects of the performance of a detector. It should be noted that where human decision-making is involved the ROC curve could also be used to assess both equipment and human performance. Given a certain spatial density of landmines the chance of survival can also be determined. In the case of vehicle-based systems that provide route clearance this is an important parameter. For example, if a mine den-

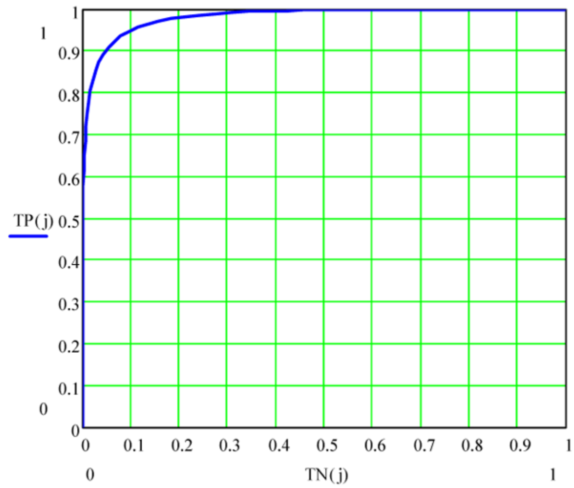

Fig. 8 Receiver operating characteristic.

sity of 1 per km along a route 4 m wide is assumed, then for a sensor PD of 0.9, the land mine detection system has a 60% probability of encountering a landmine explosion within 10 km, on the basis of a probability of explosion of 0.5 for each of the mines encountered. The implications of this are that the attrition rate of such systems will be high and the vehicle protection and cost and replace-ability of the sensors and vehicle drive train are important system parameters.

The density of mines, PD and PFA of the sensor system fundamentally determine the rate of advance of vehicle-based systems in the following ways. The density of mines clearly affects the number of potential encounters, the PD affects the chances of the vehicle being damaged by a landmine as well as the time spent in neutralising the landmine and the PFA affects the time spent in clearing false alarms. Typical example values are that the rate of advance is limited to a maximum of 11 kph for 1 mine per km of a 4 m wide swathe, assuming a sensor probability of detection of 0.9. The effect of clutter is to reduce this speed even further. For a situation with 0.1 mines per km and 100 items of clutter per km, a system probability of detection = 0.9 and PFA of 0.01, the maximum speed that a vehicle could advance would be 10 kph. Only an improvement in the probability of false alarm to 0.001 would enable the vehicle to increase significantly its rate of advance.

GPR for Landmine Detection

Ground penetrating radar (GPR) is an electromagnetic technique which is used to measure the range and position of landmines buried within the ground or dielectric material. The energy radiated by a GPR system occupies a frequency band of a

Table 1 Relative dielectric constants of explosives.

Substance	Name	Relative Dielectric Constant
TNT	2,4,6-Trinitrotoluene	2.70
Detasheet	PETN	2.72
PETN	Pentaerythritol tetranitrate	2.72
Comp B	RDX TNT	2.90
Octol	HMX TNT	2.90
Tetryl	2,4,6-Trinitrophenyl-N-methylnitramine	2.90
Semtex-H	RDX-PETN	3.00
HMX	Cyclotetramethylene-tetranitramine	3.08
Comp C-4	RDX	3.14
RDX	RDX Hexahydro-1,3,5-trinitro-1,3,5-triazine	3.14
AN	Ammonium nitrate	7.10
NG	Nitroglycerin	19.00

decade or more from several hundred MHz up to several GHz with commensurate wavelengths of 1m down to 10cm in air but appropriately reduced by the dielectric constant of the ground. The wavelengths are therefore the same order of magnitude as the dimensions of the landmine and are very different from conventional radar systems where the landmine dimensions are much larger than the wavelength of the incident radiation. The typical average radiated power, integrated over the band of interest, may be on the order of a few tens of milliwatts, but the power per Hz may be as low as picowatts. For landmine detection it is important that the radiated power is lower than that required to initiate some types of fuse. The loss of the soil is often measured as a propagation loss in dB m^{-1} and is dependent on the conductivity of the soil and the frequency of operation. At 1 GHz it is possible to encounter attenuation losses of many tens of dB m^{-1}. Some GPR systems are operated so that the landmine, which is within a lossy dielectric, may be only a few wavelengths from the aperture of the antenna. The total path losses within a few wavelengths may be as much as 100 dB depending on the material. As GPR systems do not have a total loop gain much in excess of 120 dB the designer has a major challenge to detect landmines signatures within very short ranges of typically 20 ns.

Additionally GPR can be operated so that the antenna is very close to the ground surface and landmine such that the energy transfer is predominantly either induction or quasi-stationary (the near field), or can be operated such that the energy transfer is in the far field region. GPR encounters extremely high levels of clutter at short ranges and this as well as signal/noise ratio is its major technical challenge. All these aspects pose special design problems for GPR, which is described in detail by Daniels and Curtis [3]. The landmine is surrounded by soil, which is a lossy dielectric whose relative dielectric constant depends mainly upon the water content. Typically the relative dielectric constant of the soil varies from 3 in dry sand to greater than 16 in wet and waterlogged soils.

The explosive used in landmines is typically nitrogen based with a relative dielectric constant between 2.7–3.5, ammonium nitrate being the exception as shown in Table 1. Landmines can also be found in fresh water, which has a relative dielectric constant of approximately 80, but a very low loss tangent, hence it is quite feasible to detect landmines in fresh water or soils saturated in fresh water, which also has the benefit of increasing impedance contrast. Salt water on the other hand completely attenuates radar signals. It should be noted that the ground and surface are quite likely to be inhomogeneous and contain inclusions of other rocks of various size as well as man-made debris. Thus the signal to clutter performance of the radar is likely to be an important performance factor. Clutter may be regarded as any radar return that is not associated with the wanted landmine and needs to be defined with respect to a particular application.

Scattering of electromagnetic energy from a landmine results from the impedance differences of the landmine compared with the host material. Canonical targets such as cylinders, which are similar to landmines, have well understood free space scattering characteristics that will be modified by the dielectric of the soil. The mine may have a number of scattering centres, each with their own angular radiation pattern and, in the case of plastic landmines, the internal structure of the mine may generate additional scatterers. Most minimum metal landmines may be considered as multiple layered dielectric cylinders, each interface causing a reflection, the impact of the small internal metallic fuse being minimal. A simple transmission line model representing the case where the angle of incidence is equal to the angle of reflection can simulate the time domain signature of the latter.

GPR system design can be classified into two classes. Systems that transmit an impulse and receive and process the reflected signal from the landmine using a sampling receiver can be considered to operate in the time domain. Systems that transmit individual frequencies in a sequential manner or as a swept frequency and receive the reflected signal from the landmine using a frequency conversion receiver can be considered to operate in the frequency domain. Handheld GPR systems use separate, man-portable, transmit and receive antennas, which are placed just above the surface of the ground and moved in a known pattern over the surface of the ground under investigation. This generates, in real time, data or an image. By systematically surveying the area in a regular pattern, a radar image of the ground can be built up. Alternatively, the GPR may be designed to provide an audible warning of landmine presence while the antenna is moved. Vehicle based or airborne systems use much larger arrays of antennas to illuminate a swathe of the ground surface ahead of the platform and rely on the movement of the vehicle to create the data, which may be processed using SAR techniques.

The GPR image of a landmine is very different from its optical image because the wavelengths of the illuminating radiation are similar in dimension to the landmine. This results in a much lower definition in the GPR image and one that is highly dependent on the propagation characteristics of the ground. The beam pattern of the antenna is widely spread in the dielectric and this degrades the spatial resolution of the image, unless corrected. Refraction and anisotropic characteristics of the ground may also distort the image. For some longer-range systems, synthetic aperture processing techniques are used to optimise the resolution of the image.

Unprocessed GPR images often show “bright spots” caused by multiple internal reflections within the landmine as well as a distortion of the aspect ratio of the image of the landmine caused by variations in the velocity of propagation. Symmetrical targets, such as spheres, cause migration of the reflected energy to a hyperbolic pattern. Radar images can be processed to compensate for these effects and this is usually carried out off-line. A radar can be designed to detect specific landmines by means of polarised radiation. This chapter considers the practical limitations of radar for detecting buried landmines. The types of radar considered are those in which the antenna is very close to the ground surface (proximal operation), radar systems whereby the antenna is operated a few wavelengths from the surface of the ground and finally radar systems whereby the antenna is many wavelengths from the surface of the ground (stand-off operation).

There is an extensive literature on radar methods for landmine detection and a variety of sophisticated modelling and processing methods have been applied to the problem. However the ill-posed nature of operation in real soils has meant that few of these techniques have proved robust when moved from the laboratory to the field and simpler methods have often proved more reliable.

Attenuation

Electromagnetic waves propagating through soil incur an attenuation loss given by

$$L_a = 8.686 \cdot 2 \cdot R \cdot 2\pi f \sqrt{\left(\frac{\mu_0 \mu_r \varepsilon_0 \varepsilon_r}{2}\left(\sqrt{(1+\tan^2\delta)}\right) - 1\right)}$$

where

f = frequency in Hz
$\tan d$ = loss tangent of material
ε_r = relative permittivity of material
ε_0 = absolute permittivity of free space
μ_r = relative magnetic susceptibility of material
μ_0 = absolute magnetic susceptibility of free space
R = range in metres

The graph in Figure 9 shows the two-way attenuation loss in dB m^{-1} plotted against frequency for a material with a relative dielectric constant of 9 and loss tangents of 0.1 to 0.9 in steps of 0.3 respectively. As the frequency is increased from 1 GHz to 5 GHz, the attenuation loss for a soil with a loss tangent of 0.3 increases from 20 dB to 100 dB.

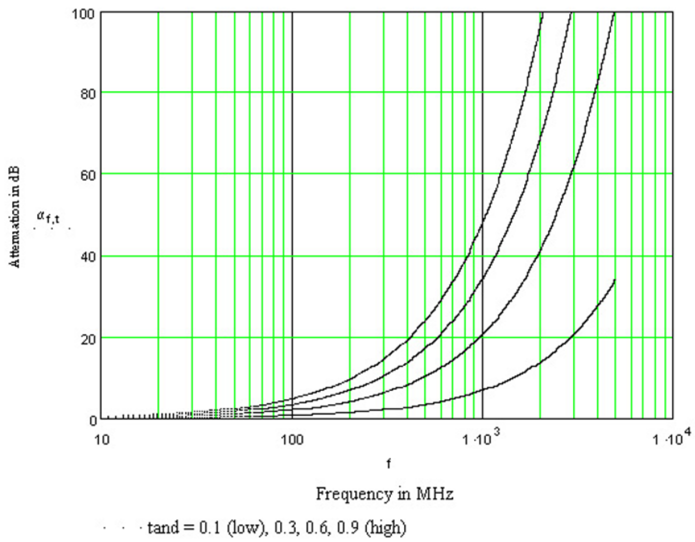

Fig. 9 Material losses in dBm-1 plotted against frequency in Hz for values of tan*d* of 0.1 to 0.9.

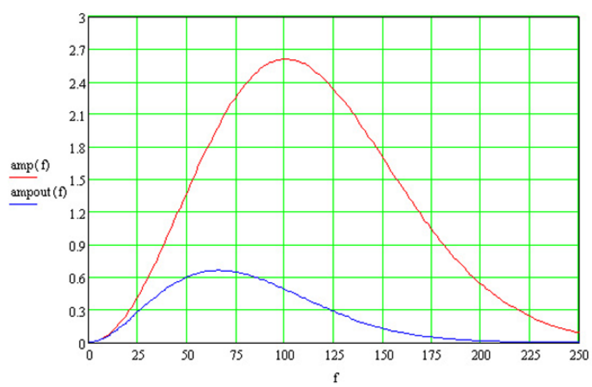

Fig. 10 Spectrum of transmitted and received signals after passing through lossy ground.

The effect on the spectrum of typical radar is shown in Figure 10 which shows the peak of the spectrum shifted to lower frequencies and the higher frequencies considerably reduced.

Coupling energy into the ground

Buried mines pose a difficult detection problem for radars and their performance is strongly influenced by the ground conditions. For close-in operation the efficiency of the coupling process is high but this is not the case for standoff radar systems since, where lossy materials are involved, complex angles of refraction may occur. With vertical polarisation at incidence angles less than the Brewster angle, transmission losses at the air/ground interface are relatively small but at larger incidence angles than the Brewster angle the losses increase more rapidly. Hence to maximise the operating range the radar should be mounted as high off the ground as is possible. Thus for a given height, the performance of the radar will be set by the relative dielectric constant of the ground. In addition to the problem of coupling energy into the ground the effective cross section of all landmines decreases when they are buried. Measurements and modelling suggest that under conditions of negligible attenuation losses, as are expected in very arid ground or for shallow burial depths, metal landmine to clutter ratios are expected to be degraded on burial by approximately 10 dB. Under the same conditions the cross section of plastic mines is reduced by a larger factor because of reduced dielectric contrast between the mine material and the surrounding soil, so that, in wet sandy soils, plastic mines are more readily detected than in dry conditions. However plastic mines are subject to substantially smaller burial losses in dry sand when they contain air voids. This is beneficial for detection as plastic mines generally contain such voids to allow movement behind the pressure plate. The radar system must have at least a 20 dB signal to clutter ratio to detect buried landmines in all weather conditions. Thus in order to detect buried plastic landmines with air voids the corresponding signal to clutter ratio for surface-laid metal landmines must be better than 12 dB for dry conditions and 18 dB for wet conditions.

Depth resolution

For traditional radar systems it is accepted that two identical targets can be separated in range if they are 0.8 of a pulse width apart. Essentially range resolution is defined by the bandwidth of the received signal and in this context it is the bandwidth of the received signal which is important, rather than that of the transmitted signal. The earth material acts as a low pass filter, which modifies the received spectrum in accordance with the electrical properties of the propagating medium. A receiver bandwidth in excess of 500 MHz and typically 1 GHz is required to provide a typical resolution of between 5 and 20 cm, depending on the relative permittivity of the material. Where interfaces are spaced more closely than one half wavelength the reflected signal from one interface will become difficult to resolve with that from another. It should be noted that the normal radar criteria for range resolution is less appropriate for the case of a weak target adjacent to a strong target and there is no accepted definition of resolution for the case of unequal size targets.

Plan resolution

The plan resolution is defined by the characteristics of the antenna and the signal processing employed. In general radar systems (apart from SAR) require a high gain antenna to achieve an acceptable plan resolution. This necessitates a sufficiently large aperture at the lowest frequency to be transmitted. To achieve small antenna dimensions and high gain therefore requires the use of a high carrier frequency, which may not penetrate the material to sufficient depth. When selecting equipment for a particular application it is necessary to compromise between plan resolution, size of antenna, the scope for signal processing and the ability to penetrate the material. Plan resolution improves as attenuation increases, provided that there is sufficient signal to discriminate under the prevailing clutter conditions. In low attenuation media the resolution obtained by the horizontal scanning technique is degraded, but only under these conditions do synthetic aperture techniques increase the plan resolution. Essentially the ground attenuation has the effect of placing a "window" across the SAR aperture and the higher the attenuation the more severe the window. Hence in high attenuation soils SAR techniques may not provide any useful improvement to radar systems. SAR techniques have been applied to GPR, but very often in dry soils with low attenuation.

A key feature of non-contacting ground antennas is their illuminating footprint. As a landmine radar image is effectively the convolution of the antenna footprint with the landmine radar spatial cross section, the landmine image becomes blurred. This effect increases with antenna to ground spacing and eventually results in landmines with small radar cross-section (AP mines) becoming vanishingly small.

Plan resolution actually improves as attenuation increases, assuming that there is sufficient signal to discriminate under the prevailing clutter conditions. In low attenuation media the resolution obtained by the horizontal scanning technique is degraded, but under these conditions the use of advanced signal processing techniques becomes feasible. These techniques typically require measurements made using transmitter and receiver pairs at a number of antenna positions to generate a synthetic aperture or focus the image. Unlike conventional radars, which generally use a single antenna, most GPR systems use separate transmit and receive antennas in what has been termed a bistatic mode. SAR techniques typically require measurements made using transmitter and receiver pairs at a number of antenna positions to generate a synthetic aperture or focus the image. Unlike conventional radars, which generally use a single antenna, most landmine radar systems use separate transmit and receive antennas to provide receiver isolation. The GPR community refer to this as a bistatic mode, although actually the antenna system is closely spaced and mobile. This is different from the traditional radar community that associates the term bistatic with large separations.

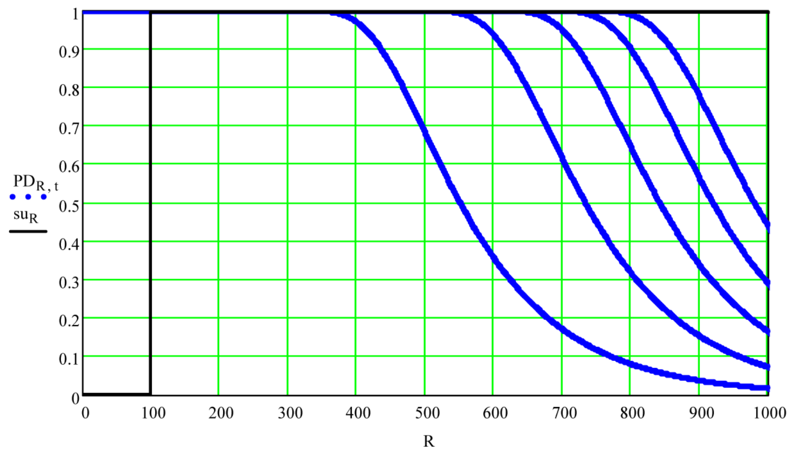

Fig. 11 Probability of detection of dielectric cylinders 10 cm to 50 cm at 1 GHz.

Frequency of operation

The most basic model for assessment of signal level is derived from the far field radar range equation, which does however have limitations with respect to correct representation of the actual operation of very short-range system. However, it does enable a first order assessment of expected signal levels. In the absence of any clutter whatsoever in the ground and assuming a complete removal of the front surface reflection it is possible to calculate the probability of detection as a function of landmine range and landmine size. This is shown in Figure 11. The family of curves represents the probability of detection versus range for dielectric cylinder of diameters 10 cm to 50 cm in increments of 10 cm, working from left to right.

The signal to noise ratio (SNR) of the radar receiver is 14.6 dB and the mine signal is 6 dB greater than the SNR. A frequency of 1 GHz was used with a landmine $e_r = 2.2$, a soil relative permittivity e_r of 9 and ground attenuation of 27 dB m^{-1} at 1 GHz. The antenna to ground spacing is 10 cm. The smallest cylinder can be detected at a depth of cover of 25 cm. At 3 GHz the radar performance as a function of range is considerably reduced as the attenuation has increased to 82 dB m^{-1}.

Landmine scattering characteristics

Scattering of electromagnetic energy results from impedance differences in the landmine compared with the host material. Canonical landmines such as cylinders have well understood radiation characteristics as described by Skolnik [10], that can be modified for the dielectric of the soil. The mine may have a number of scattering centres, each with their own angular radiation pattern and in the case of plas-

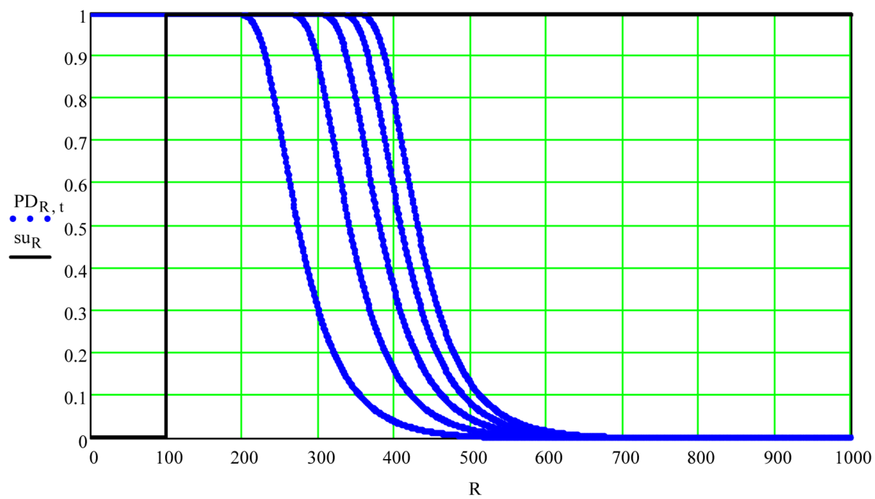

Fig. 12 Probability of detection of dielectric cylinders 10 cm to 50 cm at 3 GHz.

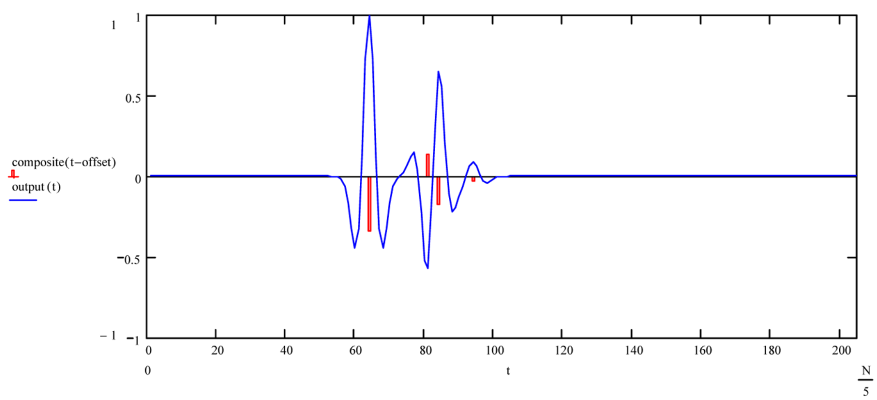

Fig. 13 Simulated time domain signature of a buried landmine simulation.

tic landmines the internal structure of the mine may generate additional scatterers. Most plastic landmines can be considered as multiple layered dielectric cylinders, of which each interface causes a reflection. A simple transmission line model representing the case where the angle of incidence is equal to the angle of reflection can simulate the time domain signature of the latter. The first reflection is due to the ground surface and the subsequent reflections are due to the landmine air void and explosive. The depth of cover of the mine is 10 cm and it is 10 cm in thickness.

For comparison the time domain signatures of various landmines buried at 5 cm are shown and it can be seen that the simulation most closely resembles the VS50 in shape. On the horizontal scale 10 samples equals 0.25 ns and the vertical scale represents relative amplitude.

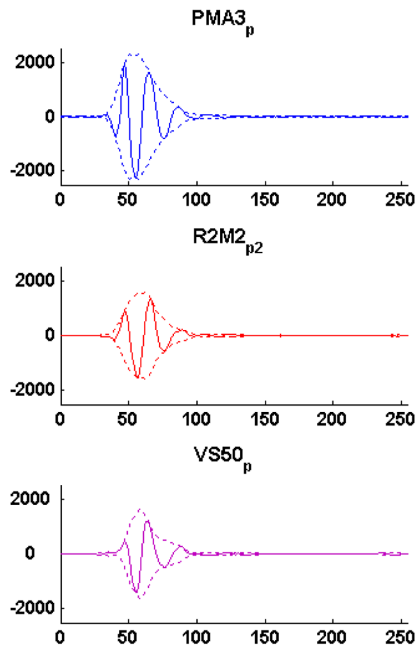

Fig. 14 Time domain signatures of buried mines taken with radar transmitting 1 ns duration impulses.

If the metallic landmine is at an angle to the plane of the surface the peak response may well be to one side of the actual physical position of the landmine. This is particularly critical for hand held radar systems. Other aspects of the radar cross section of landmines are concerned with the relative contributions of specular reflection, diffraction off discontinuities, travelling waves including direct illumination running wave, creeping wave on metal, trapped guided wave on dielectric as well as the contribution due to resonant scatterers, which are a combination of discontinuities that allow the echo to build up. Much effort has been applied to accurate modelling, as described by Streich and Van der Kruk [11].

Clutter

A major difficulty for operation of GPR systems is the presence of clutter within or on the surface of the material or in the side and back lobes of the antenna and sources of surface clutter. These has been modelled by Firoozabadi et al. [6]. Clutter is defined as sources of unwanted reflections that occur within the effective bandwidth and search window of the radar and are present as spatially coherent reflectors. Animal burrows and cracks in the ground are examples of features that will cause reflections. Careful definition and understanding are critically important in selecting and operating the best system and processing algorithms. Clutter can completely obscure the buried landmine and a proper understanding of its source and impact on the radar is essential. A key issue is the effect on the radar of variations in the topography of the ground surface caused by potholes or ruts. Methods of processing the radar signals that adjust the delay time to the front surface to "flatten it" will actually distort the radar signature of buried landmines. Abrupt discontinuities can also cause multiple reflections, which become superimposed on later arriving reflected energy. Such "interference" will be extremely difficult to remove. Radar systems should not provide indications on the following small sources (small being defined as not exceeding a surface area of 1.5 cm^2):

- Small metal fragments,
- Shrapnel,
- Spent bullet and cartridge cases,
- Ground topographical variations less than 3 cm in any dimension,
- Puddles of water up to 15 cm diameter,
- Tufts of grass up to 5 cm in diameter and 5cm high,
- Rocks, stones less that 5 cm in maximum dimension,
- Animal burrows less than 5 cm diameter,
- Cracks and fissures in ground less than 1.5 cm in width.

Vehicle Based Radar Systems

Vehicle based systems have been developed that use arrays of antennas and generate 3-D data, which is then processed to provide a rolling map of detections. The signal and image processing options for vehicle based landmine detection are more extensive because the radar and its platform generate 3-D data. In general vehicle based systems concentrate on anti-tank landmines because it is difficult to achieve adequate cross range resolution at realistic budgets. Options for signal and image processing include image inversion and synthetic aperture techniques for image enhancement principal component analysis (PCA) and independent component analysis (ICA) techniques and hidden Markov models. ERA Technology developed a 4 m wide antenna close-coupled GPR system for the UK Minder CAP programme as shown in Figure 15. Against minimum metal mines buried up to 17.5 cm it achieved a PD of 0.77. It should be noted that during these trials 80% of the on-road AT mines were buried low metal (TMA4, Type72) and the maximum depth of burial was 17.5 cm. The most common depth of burial was 6" (15 cm) and approximately 65% of the mines were buried with a depth of cover greater than 10 cm. Using the trial results we get an extended estimate of GPR performance for off ground radars based on an average PD = 0.8 against a depth of cover of 10 cm and for proximal GPR systems with an average PD = 0.8 against a depth of 17 cm. It can be seen that the depth performance of the proximal GPR is greater because of the improved

Fig. 15 UK Minder CAP programme countermine system.

coupling and reduced range-spreading losses. Although a number of developmental vehicle-based GPR systems have been trialled and reported on over the last 5 years, even the most extensively reported NIITEK radar system has yet to move into production.

Handheld Radar Systems

Recent developments using hand held dual sensor technology combining electromagnetic induction EMI and ground penetrating radar (GPR) have enabled improved discrimination against metal fragments to be demonstrated in live minefields. Reductions of up to 7:1 compared with the standard metal detector have been achieved in the field by hand held systems such as MINEHOUND [3] shown in Figure 9 and AN/PSS-14 [5]. Handheld landmine systems are more limited in the signal processing algorithms that can be applied because they usually only have a single transmit-receive antenna pair and with only a few exceptions do not form an image. Research into landmine discrimination based on the analysis of A-scans by means of complex resonances, wavelets, time-frequency characteristics, neural networks, fuzzy sets, Gaussian mixture models, order statistics and template matching, has been carried out. Methods based on time-frequency characteristics are reported

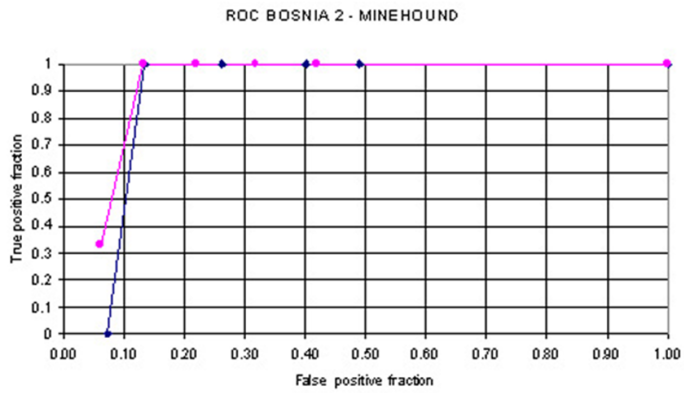

Fig. 16 ROC curve for MINEHOUND for trial in Bosnia.

Fig. 17 MINEHOUND dual sensor landmine detector.

by Wong et al [13], Lopera et al [8], as well as Daniels et al [4] who showed the feasibility of discriminating between AP landmines and typical false landmines on a small data set.

The AN/PSS-14 hand held detector trialled in Angola [5] reports the following results for probability of detection using experienced operators at a 90% confidence level (CL) range with a false alarm rate of 0.23 m^{-2} to 0.28 m^{-2}. The trials carried out in Bosnia, Cambodia and Angola using the MINEHOUND detector [3] reported a ROC curve as shown in Figure 16. The ROC curve relates to over 1069 encounters in live minefields of which 7 were actually mines. It should be noted that the trials did not test the MINEHOUND in a blind test, but compared the MINEHOUND with the CEIA MIL D1 metal detector, which was used first. The MINEHOUND does not currently incorporate mine classification algorithms.

Assessment of radar performance

There is an potentially overwhelming body of literature on GPR for landmine detection and an approach for its assessment is to consider the comparability of the data, the maturity of the technology, the feasibility of implementing the proposed algorithm and, most importantly, the performance in terms of the probability of detection and the probability of false alarm.

There are a number of fundamental issues that govern the probability of detection. Both propagation parameters as well as the radar cross-section define the fundamental system performance as discussed by Daniels [2].

In comparing published results relating to controlled trials, it is critical to know the statistics of the depth of cover, soil propagation characteristics, type of landmine, the physical placement of the landmine as well as the characteristics of the clutter. In the case of field trials in, or close to, live minefields it is more difficult to gather such information; however, a statistically based approach may be a realistic alternative. In reviewing published receiver operating characteristic (ROC) curves the statistics of the sample should be known in order to understand the confidence that can be placed in any data. Simonsen [9] provides a useful treatment of sampling statistics as applied to landmine data. Clearly any assessment of the performance of algorithms should also state the confidence limits that apply to ROC curves. However if the sample size is known, it is relatively straightforward to determine bounds. Simonson notes that 39 or more mines are needed to ensure at least an 80% chance of detecting a difference when the two systems have detection probabilities of 0.90 and 0.60, respectively.

Voles [12] considered this issue and showed that based on a Poisson distribution, even if no mines were missed by a sensor in a test of 100 then at the 95% confidence limit the highest value of probability of detection that can be claimed is 97%. Voles also showed that to achieve a 99.6% probability of detection at a confidence level of 95% would require a test of 750 mines and none should be missed.

Future development of radar

The main challenge for hand held radar is the further reduction in the rate of false alarm. At present the EMI detector encounters around 200 false targets to every AP mine. The current generation of dual sensor detectors reduces the ratio to around 5:1. If robust classification techniques can be developed that reduce the ratio down to around 30:1 the efficiency improvement in humanitarian operations will be even greater.

Vehicle based radar has to achieve orders of magnitude performance improvement to enable route clearing military operation to proceed at speed. A total system performance of a probability of detection better than 0.99, with a probability of false alarm less than 10^{-4}, is called for if route clearance at convoy speeds is to be achieved. Humanitarian clearance may tolerate speed reduction but still requires high detection rates. This applies to both stand off and close in GPR systems.

Airborne radar is an enormous technical challenge. However a new generation of unmanned airborne vehicles may provide suitable platforms for the close in GPR systems if ground skimming can be achieved. This would allow reconnaissance vehicles to run ahead of convoys and would reduce the need to mine protect vehicles.

Summary

- GPR systems for landmines have a loop gain on the order of 120 dB, which sets their order of magnitude performance.
- The radiated power is limited by licence restrictions and EMC considerations as well as the need to avoid detonation of certain types of fuses.
- Most path losses are such that penetration is limited to 50 cm depth of cover for most GPR systems.
- The propagation losses decrease as the fourth power of range to landmine for far field conditions.
- The propagation losses may decrease at lower rates depending on the landmine dimensions for near field boundary conditions.
- The received signal may be augmented by induction and quasi-stationary contributions for landmines within the near field.
- The attenuation losses in materials rapidly increase with frequency, which means that most systems will receive frequencies in the range 300 MHz to 1.5 GHz. The use of transmitted frequencies above 2 GHz is unlikely to provide useful performance in real world conditions and will severely limit depth performance.
- The attenuation losses in materials will reduce the effectiveness of multi-look antenna arrays by effectively putting a window taper across the array.
- At 1 GHz the total losses in typical soils mean that, in ideal conditions, detection ranges of 20–30 cm are feasible.
- In dry soils the dielectric contrast between the soil and mine reduces and this can make the detection of mines with minimal air voids more difficult.

- Most GPR systems will achieve optimum performance in terms of range when the antennas are operated in close proximity to the ground. As the antenna to ground spacing increases, the antenna radiation pattern results in reduction of the received signal from small landmines and increased vulnerability to clutter from free space sources.
- Rough surfaces, ruts, potholes etc. degrade the signal to clutter ratio and reduce the system performance.
- The angular response of mines that are tilted relative to the ground surface may not be co-incident with their physical position and this should be considered when neutralising.
- Stand off SAR radar systems have fundamental limits to performance at shallow grazing angles, which constrains their forward look range to between 10 and 20 m.

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