Detection of nonmetallic landmines using microwave-enhanced infrared thermography

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Abstract: *Nowadays detection of the landmines is mostly based on electromagnetic induction. This method, however, is useless for the low metal containing, plastic devices. The microwave-enhanced infrared thermography, which can detect plastics as well as the explosive material itself, can be an alternative for the metal detectors. In this paper we present the theoretical foundations of this technique and some experimental methods that have been provided.*

Keywords: *landmines detection, microwave heating, active IR thermography.*

1. Introduction

Hundreds of thousands of people was killed or injured by anti-personnel mines (APMs) and anti-vehicle landmines (Mines Other Than Anti-Personnel Mines - MOTAPMs). Only in 2007, Landmine Monitor [2] identified 5.426 casualties caused by mines, explosive remnants of war (ERW), and victim-activated improvised explosive devices (IEDs). Most of the victims was civilians (Fig. 1).

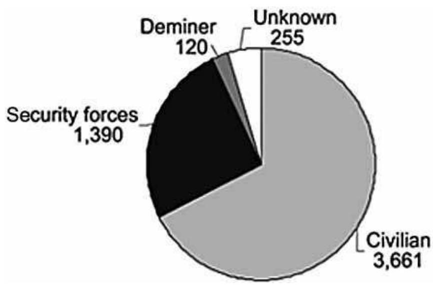

Fig. 1. Casualties in 2007 by civilian/military status [2].

These facts show how important is to develop new, efficient methods of detection and neutralizing the landmines. Today still the most popular method of detecting landmines is, invented during II World War, scanning the area with the metal detector. Nowadays the metal detectors are sensitive enough to detect almost every mine that contains metal, but subsequently they yield about one thousand false positives for every mine. Furthermore this method can not be used to detect low-metal containing devices. The special trained dogs (Explosive Detecting Dogs - EDDs) are often used to detect explosives [2]. Although it is proven that animal can sense the odour emanated by explosive material, this method has lots of disadvantages: dog can't operate itself, operator has to control animal and understand its signs entirely – the long, expensive training is needed; odours permeate from concealed objects in unpredictable ways, which means that dogs can not locate the mine properly; when there are many mines or explosive items in close proximity, the animals can become confused and may be unreliable. Alternative ways of landmine detection, that are currently under development, focus on variety of physical and chemical properties of these devices. For example nuclear quadrupole resonance (NQR) detects some kinds of explosives (RDX, Tetryl) by collecting resonance signal from stimulated nuclei; by thermal neuron analysis (TNA) large concentrations of nitrogen can be detected; fluorescent polymer detection is based on observations of chemical reactions which occurs between fluorescent polymers and specific chemicals – it can detect even very low concentration of explosives [2].

The method of infrared detection, which we would like to present, is based on inducing temperature difference between the soil and landmine, which can be observed with the thermographic camera. To induce temperature difference, different types of radiation can be used (sunlight, lamps, etc.), but due to its properties, it seems that microwave radiation is most interesting. The main advantage of this method is that microwave source causes volumetric heating of the soil rather than heating the only the surface and relaying on conduction to spread the heat to the buried landmine. In effect the time needed to receive observable thermal signature of the landmine is greatly decreased using microwave illuminator. However, there are many factors which may disturb the detection: weather conditions, other objects presence (rocks, wood branches, etc.), soil moister etc.. These factors have to be taken into account during the detection itself and during post detection image processing [3-5, 8-10].

In this paper we present theoretical foundations of microwave-enhanced infrared thermography, as well as the experimental methods and results that have been received by groups of scientists from Canada, USA and France [8-10].

2. Theoretical foundations of microwave-enhanced infrared thermography

2.1. Theory of microwave heating of soil and plastic materials

2.1.1. Dielectric properties of the materials

The dielectric properties of material have been extensively investigated in the literature [3-6]. It has been established that there are mainly two physical phenomena which are responsible for the microwave heating of materials. For lower microwave frequencies the ionic conductivity is the most important cause of the material heating. The temperature increase in this case is due to energy transfer via conductive currents. The currents can flow through the material due to the movement of ionic components of the material (such as salts etc.). This loss mechanism can be described by the value of the loss parameter $\frac{\gamma}{\omega\varepsilon_0}$, where γ indicates the electric conductivity, ω is the angular frequency of the electromagnetic radiation and ε_0 indicates permittivity of free space. For higher frequencies (i.e. above 3000 MHz) the effect of mechanism of ionic conductivity becomes negligible, and the energy absorption is primarily due to the existence of dipole molecules which tend to re-orientate in presence of microwave field. In this case the loss mechanism is due to inability of the polarization to follow the extremely fast field alternations. This re-orientation loss mechanism can be described by the relative loss factor term ε'', which is the imaginary part of complex dielectric permittivity. The microwave heating can be described by the value of dielectric loss tangent

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} ,$$

where ε' indicates the real part of complex dielectric permittivity. The dielectric loss tangent is a function of frequency, and describes the ability of material to absorb the microwave energy: the higher is its value, the more energy can be absorbed by the material.

In case of plastic material the mechanism of heating is caused by the rotation of the dipoles in the plastic construction and by the displacement effect in the plastic chain caused by the electric field. The frictional effects cause energy absorption in the material. Due to their viscoelastic behavior, plastic materials can be divided into two groups: the materials with high loss factor, which have the highly polar structure and the materials with low loss factor, which have low polarity structures. The typical materials used as the landmines' casings are bakelite, rubber, polypropylene and polyethylene, all of these materials have rather low value of dielectric loss tangent, i.e. in the range 0.0001 ÷ 0.001.

The loss mechanism in soil is dependent on the variety of contributions. In Fig. 2 we present the schematic representation of different factors of the loss mechanism in function of frequency. The most important factors are: ionic conductivity described above and bound and free water relaxation.

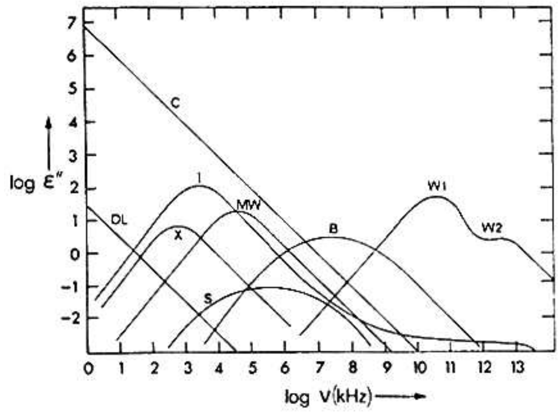

Fig. 2. Schematic representation of loss mechanism in function of frequency. C - ionic conductivity; DL - charged double layers; I - ice relaxation; X - crystal water relaxation; MW - Maxwell-Wagner; B - bound water relaxation; W1 - principle relaxation of free water; W2 - secondary relaxation of free water; S - surface conductivity. [5]

Water is present in the moist soil in variety of forms: it can be free liquid water, the molecules of water chemically bounded with the soil molecules, and in low temperatures – ice. Since the water molecules can be considered as the dipoles, the re-orientation loss mechanism will occur.

The soil is a highly heterogeneous material, from the electromagnetic point of view it is a four-component dielectric mixture, containing air, bulk soil, and water in free and bound form. In general the dielectric constant of the soil is a function of frequency, temperature, moister content, bulk soil density and texture. The dielectric loss tangent of soils varies form 0.1 ÷ 1.

2.1.2. Microwave penetration

It can be shown [3] that the attenuation factor is given by:

$$\alpha = \frac{\omega}{c}\left[\frac{\varepsilon'}{2\varepsilon_0}\left[\sqrt{1+\left(\frac{\varepsilon'}{\varepsilon''}\right)}-1\right]\right]^{1/2},$$

where ω is the angular frequency of the electromagnetic radiation, c is the speed of light. The inverse of the attenuation factor, skin depth, represents the distance on which the field strength drops to $1/e$ of its original value. The power loss in dB/cm can be expressed as follows:

$$P = -0{,}086859\cdot\frac{\omega}{c}\left[\frac{\varepsilon'}{2\varepsilon_0}\left[\sqrt{1+\left(\frac{\varepsilon'}{\varepsilon''}\right)}-1\right]\right]^{1/2}$$

The part of electromagnetic wave which is traveling from media 1 to media 2 (in our case the wave is initially traveling through the air and then impinges the soil) is partially reflected back to the media 1. The reflection coefficient for air/soil interface can be written as follows:

$$R = \frac{1-\sqrt{\varepsilon_2}}{1+\sqrt{\varepsilon_2}},$$

where ε_2 indicates the dielectric permittivity of the soil. Tab. 1. shows the skin depths and reflection coefficient for two frequencies of microwave radiation

Tab. 1. The reflection coefficient and skin depth for two frequencies of microwave radiation. [9]

Frequency [MHz]	915	2450
Reflection coefficient R	0.229864	0.229855
Skin depth [m]	7,2	3,5

Active IR thermography

The active infrared thermography needs the external source of energy (in our case the microwave generator. Different active thermography methods are presented in Fig. 3) to induce the temperature difference between the soil and the landmine [7].

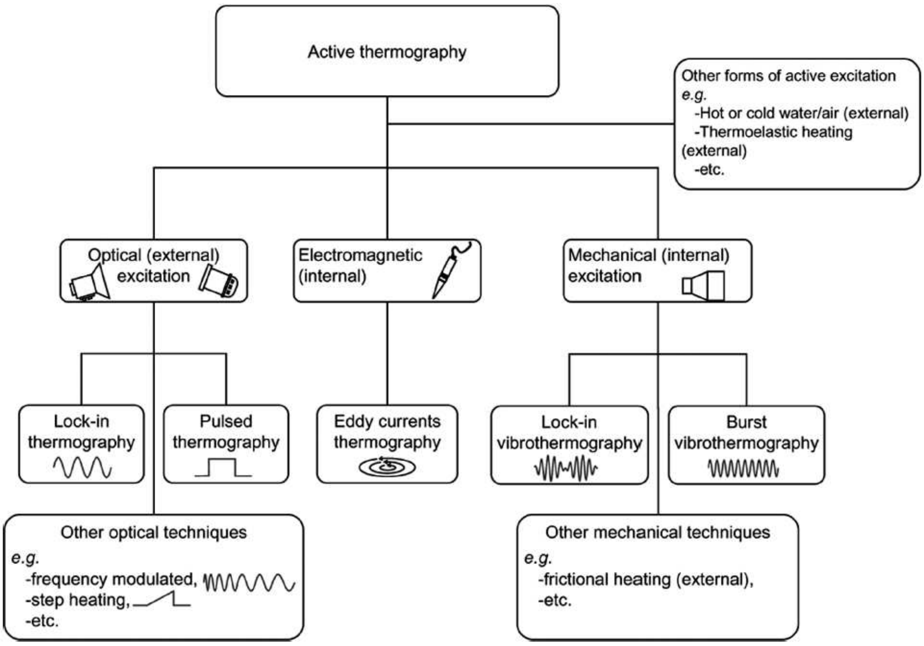

Fig. 3. Methods of active thermography. [7]

There are different methods of active thermography, the most popular are: lock-in thermography, pulsed thermography and step heating thermography. The details of these methods are discussed below.

- **Lock-in thermography** – in this method the wave is excited sinusoidally on the tested surface using optical or electromagnetical device. The main property of this method is a fact, that temperature changes are observed only at the frequency of excitation, we get the phase images which show color-coded the time delays due to heat transportation.
- **Pulse thermography** – the specimen is reflected by short, i.e. (2 ÷ 15) µs, pulses of energy by optical or electromagnetical device. The synchronization unit is used to control the time between the heat pulse and recording of the thermal image of the specimen.
- **Step heating thermography** – is based on heating the specimen for a certain period of time, and observe the received thermal image for the whole process of relaxation.

3. Experimental methods and results

In this section we will present the experiments which have been provided by the groups of scientists form the Canada (H. Mende, B. Dej, S. Khanna, R.Apps, M. Boyle and F. Addison) , USA (T. Shi, G. O. Sauermann, C. M. Rappaport, and C. A. DiMarzio) and France (D. Balageas, M. Lemistre and P. Levesque). There were several approaches to the problem: the experiments concerning soil heating using 915 MHz or 2.45 GHz magnetron were provided, the theoretical modeling was presented for dual-frequency microwave excitation and using of the EMIR® method for the landmine detection was discussed.

3.1. The Canadian experiments

In [8] we can find the description of experimental method using both 915 MHz and 2.45 GHz magnetrons for soil heating. The experimental arrangements are presented in Figs. 4 and 5.

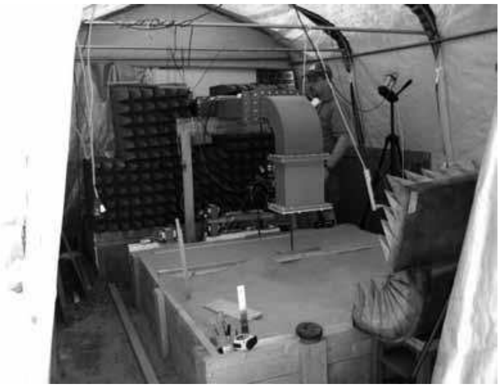

Fig. 4. The experimental arrangement for 915 MHz frequency. [8]

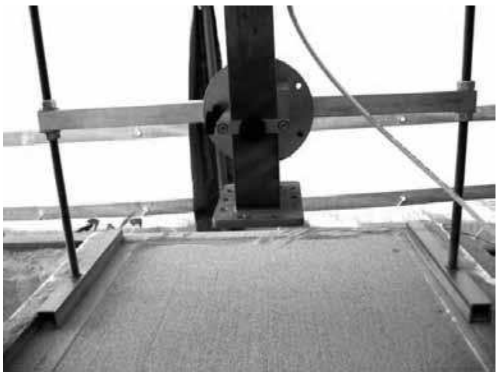

Fig. 5. The experimental arrangement for 2450 MHz frequency. [8]

For the experiments using 915 MHz frequency the 5 kW magnetron was used. The standard WR975 waveguide was positioned at a height of 38 cm from the sand surface and the IR camera (8 ÷ 12) µm ThermoVision ™ A20M IR camera) was located 1.6 m away from the waveguide. The radiation source for the experiments using 2.45 GHz frequency was 1.1 kW magnetron. Standard, 42 cm long, WR340 waveguide was positioned 15 cm above the sand surface.

As a specimens the landmines' surrogates were used, the properties of models are shown in tab. 2. Three small antipersonnel landmines (PMA 1, PMA 2, PMA 3) were used, as well as one antitank mine FFV 028. In process of demilitarization all metal content was removed from AP mines and due to its dielectrical properties the paraffin wax was used as a model of explosive material.

Tab. 2. The properties of landmine models used in experiments. [8]

Property/landmine	PMA 1	PMA 2	PMA 3	FFV 028
Type	AP	AP	AP	AT
Shape	rectangular	circular	circular	circular
Metal content	low	low	low	high
Type and mass of explosives	TNT/ 200 g	TNT/ 70 g	Tetryl/ 35 g	RDX/TNT/ 4 kg
Length [cm]	14	-	-	-
Width [cm]	7	-	-	-
Height [cm]	3	6.1	3.6	12
Diameter [cm]	-	6.8	10.3	25

The experiments have been provided in open field in various weather conditions. The effectiveness of landmine detection was dependent on the number of factors as it shown in tab. 3.

Tab. 3. Experiment effectiveness due to soil type and weather conditions. [8]

soil		weather	
ineffective	successful	ineffective	successful
moist layer on surface	dry	direct sunlight	indirect sunlight
very uneven	even	moist, dump	dry
heterogeneous	homogenous	windy	calm

The results of the experiment, presented in the form of pictures weren't enhanced in the sophisticated manner, the authors claim that there is a need of more work concerning IR image processing. The sample of experimental results is presented in Figs. 6 and 7.

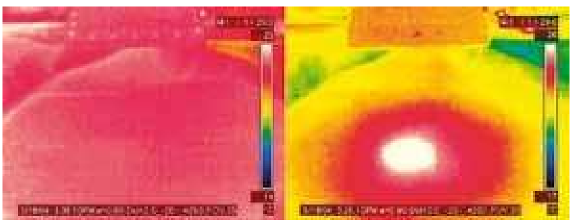

Fig. 6. Result of 0 min (left) and 15 min. (right) of 915 MHz microwave heating. PMA 3 buried 3 cm deep. [8]

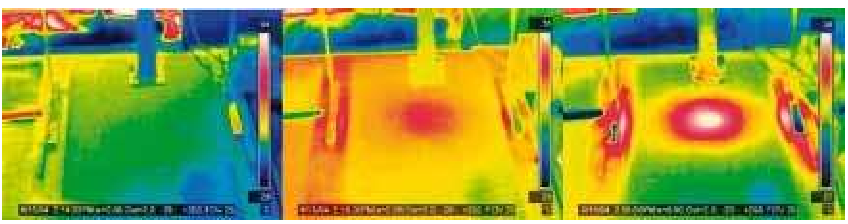

Fig. 7. Results of 0 min. (left), 3 min. (middle) and 13 min. (right) of 2450 MHz microwave heating. PMA 2 buried 1 cm deep. [8]

3.2. The dual-frequency technique

In [9] the improvement of MEIT (Microwave Enhanced Infrared Thermography) was presented. The dual-frequency method has the potential to detect buried objects under the rough surface at depths greater than with the presented earlier, single frequency method. Authors presented 2-D computational model simulating real-world landmine detection. The ground roughness was simulated by parameter σ. The results show that this method minimizes the clutter introduced by an irregular surface, and can lead to better detection of buried objects.

In this approach, the soil is heated by two sources of different frequencies (i.e. 915 MHz and 1115 MHz) in two consecutive heating cycles. The incident radiation field is modified by the surface clutter and is scattered by the underground object. Since the modification of the incident wave caused by the clutter does not change with the frequency (Fig. 8) and the scatter field associated with the target (mine) does, by subtracting the two radiation fields the clutter effects can be substantially suppressed and a signature of the mine can be obtained. Practically this method can be divided into few steps:

1. Heat the soil with the radiation source of the first frequency and take IR signatures of the rough surface and the landmine.
2. After cooling-down of the ground, use the other illumination frequency and repeat the process described in point 1.
3. Process obtained data by subtracting the amplitudes of two signatures obtained during first two steps.

To compare single- and dual-frequency method, the ROC curves were used. As it is shown in Fig. 8, for the smooth surface both methods work well, but the situation changes when we consider more rough surfaces: the dual-frequency method is significantly better.

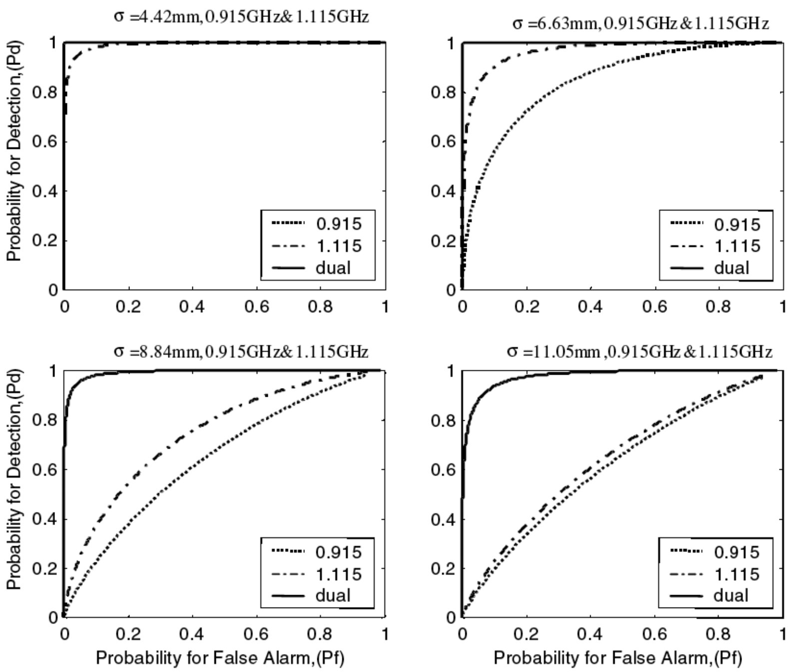

Fig. 8. ROC curves for single- and dual-frequency with increasing surface roughness σ, and depth d = 4 cm. [9]

3.3. EMIR® method

In [10] we can find another approach to the problem of detecting the landmines using microwave enhanced thermography. The EMIR® (ElectroMagnetic-InfraRed) method (which is often used in different NDT experiments) also uses the microwave generator as the source of radiation for the active thermography, but additionally between the generator and the soil a photothermal transducer is placed under the form of an electrically conductive thin film (Fig. 9). The camera can now monitor the thermal field on the film directly, and not the field produced on the surface itself. In this case the complex three-dimensional process of thermal diffusion inside the observed system has no influence on the measurement.

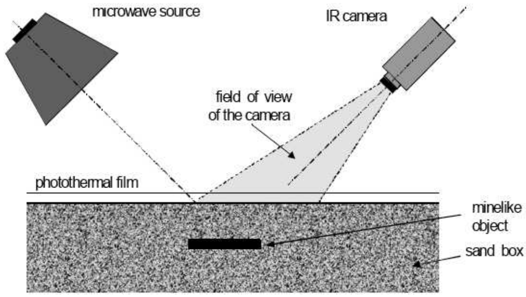

Fig. 9. The EMIR® method. [10]

In the experiment the 2.45 GHz horn with maximum power of 150 W was used as a microwave generator. As a specimens the minelike object were used: 10 mm thick and (100 ÷ 200) mm diameter disks made of plastic and metal. The AGEMA 880 LW camera (thermal sensitivity of 35 mK rms for one single image) was used to observe thermal filed. The experiment arrangement is presented in Fig. 10. Some samples of the results are presented in Fig. 11.

Fig 10. The experiment arrangement. Left: mine surrogates are lying on the sand's surface. Right: minelike targets are embedded and the surface is covered by photothermal film. [10]

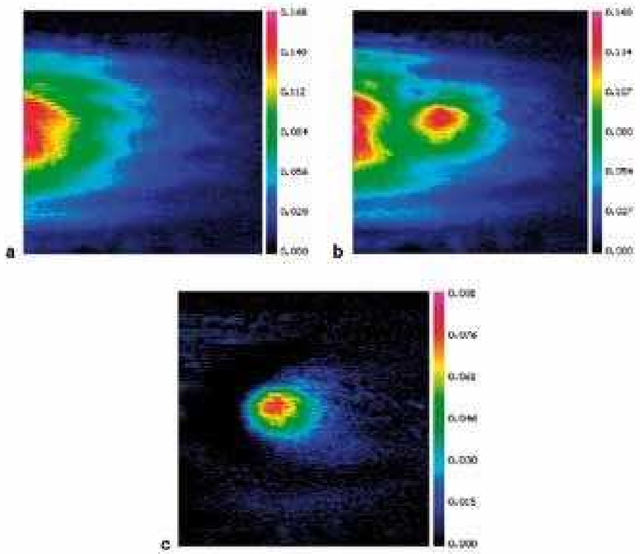

Fig. 11. Detection of a metallic mine (100 mm diameter) located at 50 mm depth in dry sand by the EMIR® technique at 2.45 MHz. a) Image of the soil without mine simulant; b) image of the soil with a mine simulant; c) EMIR differential image showing the mine position and size. [10]

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