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Microwave Enhanced IR Detection of Landmines using 915 MHz and 2450 MHz

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14. ABSTRACT
As a continuation of previous studies in microwave enhanced infrared (IR) detection of landmines at DRDC Ottawa, additional experiments were performed using a microwave source at 2450 MHz to illuminate buried inert antipersonnel and antitank landmines. Further experiments were performed for the first time using a microwave device at 915 MHz with an open waveguide. Infrared detection was accomplished using a FLIR A20M IR camera in the 8-12 mm region. An investigation of this method was done by examining mine signatures made up of two components: the microwave interference on the surface of the sand caused by the superposition of incident and reflected microwave beams, and the microwave absorption by the mine and sand causing a temperature difference to be thermally conducted to the surface of the soil. Results are presented for a wide variety of experimental arrangements. An attempt at simulating various minefield conditions was explored. Some of the surfaces examined above buried mine targets include smooth, moist, hand brushed, very uneven, and raked soil. Introducing clutter on the surface of the soil such as pebbles, rocks, leaves and wood has also been studied. Many of these parameters impeded the detection process. Thus, this method is not an allencompassing solution to mine detection but may improve IR methods in circumstances such as dark or cloudy weather. Outlined recommendations concerning future scientific studies into the proposed method may refine microwave enhanced IR imagery.

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Abstract

As a continuation of previous studies in microwave enhanced infrared (IR) detection of landmines at DRDC Ottawa, additional experiments were performed using a microwave source at 2450 MHz to illuminate buried inert antipersonnel (AP) and antitank (AT) landmines. Further experiments were performed for the first time using a microwave device at 915 MHz with an open waveguide. Infrared detection was accomplished using a FLIR A20M IR camera in the 8-12 μm region. An investigation of this method was done by examining microwave absorption by the mine and ground. The difference in absorption creates a temperature gradient thermally conducted to the surface of the soil that appears on the mine signatures. Results are presented for a wide variety of experimental arrangements. An attempt at simulating various minefield conditions was explored. Some of the surfaces examined above buried mine targets include smooth, moist, hand brushed, very uneven, and raked soil. Introducing clutter on the surface of the soil such as pebbles, rocks, leaves and wood has also been studied. Many of these parameters impeded the detection process. Thus, this method is not an all-encompassing solution to mine detection but may improve IR methods in circumstances such as dark or cloudy weather. Outlined recommendations concerning future scientific studies into the proposed method may refine microwave enhanced IR imagery.

Resumé

Dans la foulée d'études antérieures de RDDC Ottawa sur la détection de mines terrestres par imagerie infrarouge (IR) assistée par micro-ondes, d'autres expériences ont été menées à l'aide d'une source micro-ondes à 2450 MHz pour illuminer des mines antipersonnel et antichars inertes enfouies. D'autres expériences encore ont été faites pour la première fois à l'aide d'un dispositif micro-ondes à 915 MHz avec un guide d'ondes ouvert. La détection IR a été effectuée au moyen d'une caméra IR FLIR A20M fonctionnant dans la plage de 8 à 12 μm. On a étudié cette méthode en examinant l'absorption de micro-ondes par la mine et le sable qui, grâce à la conduction thermique, produit une signature sous forme d'une différence de température à la surface du sol. Les résultats sont présentés pour un large éventail de configurations expérimentales. On a tenté de simuler diverses conditions de champ de mines. On a examiné entre autres les surfaces de recouvrement de mines suivantes: sols peu accidentés, sols humides, sols balayés à la main, sols très accidentés et sols raclés. L'impact de foullis de sol dû à des cailloux, des roches, des feuilles et du bois, a également été étudiée. Plusieurs de ces paramètres gênaient la détection. Cette méthode n'offre donc pas une solution globale pour la détection des mines, mais elle peut améliorer les techniques IR dans certaines conditions, particulièrement par temps sombre ou nuageux. Les recommandations présentées pour la conduite de futures recherches scientifiques sur la méthode proposée pourront contribuer au perfectionnement de l'imagerie IR assistée par micro-ondes.

Executive summary

Statistics show that every year, 110 million mines kill approximately 12 000 people and limit the use of land for cultivation purposes in 64 countries around the globe. Unfortunately, the present methods of landmine detection have unsatisfactory detection rates, high false alarm rates and are time consuming. This paper describes a remote-sensing method relying on microwave enhanced IR imagery, which involves illuminating a buried landmine with microwave energy and detecting its thermal signature at the soil surface. Microwave illumination was accomplished with two separate novel magnetron assemblies using both 2450 MHz and 915 MHz. To the authors' knowledge, this is the first experimental study reporting results from using an open waveguide configuration at 915 MHz for this detection method. The experimental results presented in this report demonstrate the method's usefulness in detecting metallic and non-metallic antipersonnel or antitank mines in a reasonable amount of time.

Clutter, soil moisture content, solar heating effects and wind seem to affect the thermal signature of the mine. Although preliminary results indicate that this method shows promise to improve existing IR methods in certain circumstances such as dark or cloudy weather, it is not an all-encompassing solution to mine detection. The authors believe that further studies recommended in this report could drastically improve this detection method and a new tool for landmine/UXO detection could be realised. Recommendations include studies with this technique for different conditions including soil and weather conditions, waveguide and camera positioning, illuminating power densities, frequencies of illumination and detection, and evaluation of data processing techniques to eliminate clutter and noise from IR images.

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Sommaire

Les statistiques montrent que tous les ans, les 110 millions de mines enfouies dans 64 pays tuent environ 12 000 personnes et limitent l'exploitation de terres pour la culture. Malheureusement, les méthodes actuelles de détection des mines terrestres présentent des taux de réussite insatisfaisants, des taux de fausses alarmes élevés et de longs délais d'exécution. Le document décrit une méthode de télédétection par imagerie IR assistée par micro-ondes. Cette méthode consiste à illuminer une mine terrestre enfouie, à l'aide de rayonnements micro-ondes, puis à détecter sa signature thermique à la surface du sol. L'illumination par micro-ondes a été réalisée au moyen de deux nouveaux ensembles magnétrons séparés fonctionnant à 2450 MHz et à 915 MHz. À la connaissance des auteurs, il s'agit de la première étude expérimentale à présenter les résultats de l'exploitation d'une configuration de guide d'ondes ouvert à 915 MHz pour cette méthode de détection. Ces résultats démontrent l'utilité de la méthode pour la détection de mines antipersonnel et antichars métalliques et non métalliques dans des délais raisonnables.

Le clutter, le degré d'humidité du sol, le réchauffement solaire et le vent semblent influer sur la signature thermique de la mine. Selon les résultats préliminaires, la méthode étudiée s'avère prometteuse comme moyen d'améliorer les techniques IR existantes dans certaines conditions, surtout par temps sombre ou nuageux, mais elle n'offre pas une solution globale pour la détection des mines. Les auteurs estiment que les études ultérieures recommandées dans le rapport pourraient apporter des améliorations radicales à cette méthode, et qu'un nouvel outil de détection de mines terrestres/UXO pourrait être réalisé. Ces recommandations comprennent l'étude de la méthode dans différentes conditions, incluant les conditions de sol et météorologiques, le positionnement du guide d'onde et de la caméra, les densités de puissance d'illumination, les fréquences d'illumination et de détection, ainsi que l'évaluation des techniques de traitement de données utilisées pour éliminer le clutter et le bruit des images IR.

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1. Introduction

It is currently estimated that there are 110 million antipersonnel (AP) and antitank (AT) mines planted in the soil of 64 countries around the globe. It is an understatement to say that the global landmine problem poses a threat to the people of these countries. Statistics show that approximately 12 000 people are killed while thousands more are injured by landmines every year [1]. It has been the goal of many non-governmental and peacekeeping organizations, such as The Canadian Red Cross [2], to clear minefields and destroy stockpiles. The recent international treaty to ban the use of AP mines by most countries has promoted support to develop improved methods of demining. For this reason, research is being done to find fast, simple, inexpensive and reliable ways to improve or replace the present methods of demining.

Today, the most common method for detecting and neutralizing various types of buried landmines is by the use of manual probing. This method is dangerous, time consuming and laborious. A second approach for detecting mines utilizes standard electromagnetic induction techniques first introduced before World War II to detect metal buried in the ground. A high false alarm rate is associated with this technique due to random pieces of metal often found in a typical minefield. A second issue associated with metal detection is that some mines contain little to no metal, thus creating an additional undetected hazard for the deminer. The most promising new techniques for landmine detection to date include: ground penetrating radar (GPR) [3], passive IR remote sensing [4], thermal neutron activation (TNA), radiometry [5], chemical detection, as well as other electromagnetic [6] and acoustic [7] techniques. Amongst these novel technology driven methods, passive infrared imaging has the advantage of being easy to use, is relatively inexpensive and has a remote-sensing capability.

Passive IR imaging has been studied and is currently used for military minefield detection operations such as the improved landmine detection system (ILDS) [8]. This method detects infrared energy given off by solar heating effects to generate a thermal signature at the surface of the soil. This is explained well by Simard [4]. The mine signature is produced due to the difference in heating rates between a buried landmine and the surrounding soil. It is dependant on the amount of solar illumination, variations in soil temperature, soil type, surface clutter, moisture content of the soil and the depth of the landmine. On a cloudy or foggy day, a mine signature may be non-existent. To improve the accuracy of the mine signature in passive IR detection systems, microwave enhanced IR illumination has been examined [9-13]. One advantage of this method is that microwave radiation causes volumetric heating rather than only heating the surface of the soil and relying on conduction to spread the heat to the buried landmine. The time required to sufficiently heat the landmine and thus produce a thermal IR signature is greatly decreased using microwave illumination.

To the authors' knowledge, enhanced microwave detection has not been thoroughly studied, though available results indicate that this method has advantages over passive IR imaging [9-13]. Results have already been obtained by Khanna et al. [9] from illuminating actual buried AP landmines with a 5 kW microwave source at a frequency of 2450 MHz. As a continuation of the previous study, the present work includes the proposed method for mine detection using a new 2450 MHz arrangement. This report also includes an experimental study that uses a continuous wave, 915 MHz, 5 kW magnetron as the illuminating source. To the author's knowledge, this is the first time a 915 MHz source is used in microwave enhanced IR detection of landmines. Two reasons for utilizing 915 MHz in particular are that 915 MHz is an Industrial Scientific & Medical (ISM) microwave frequency with magnetrons being produced by industry worldwide and there is an increase in microwave penetration of the soil at this lower frequency as well as a decrease in the amount of absorption from the soil and mine components. Additional differences with the original work done by Khanna et al. [9] include an attempt at examining the effects of using various power densities and a more detailed study into the variation of physical parameters. It should be emphasized that the present investigation is a proof of concept study and mainly experimental in nature.

This report is organized into sections as follows. Section 2 provides the theory behind transmission at the air-ground interface, including the reflection coefficient, skin depth and power density, for the two frequencies of interest. Section 3 describes the experimental set-up and apparatus, providing the method used to carry out experiments at both frequencies. Section 4 presents the results obtained from the experimental data. A summary of the experimental trials are arranged in tables with corresponding IR images in Annex A. Section 5 provides recommendations for future work on microwave enhanced IR imagery and Section 6 provides conclusions to this study.

2. Reflection and transmission at the air-ground interface

There are two theoretical factors that explain the thermal image detected at a soil surface [9]. The first factor is associated with interference. The incident microwave beam will be reflected at the soil/mine interface and will interfere with the incident beam in the volume between the surface of the soil and the surface of the buried mine. Interference patterns create high and low electromagnetic field strengths, which lead to hot and cold regions in the soil volume surrounding the mine resulting in a thermal signature. This phenomenon was not readily seen with the current study's apparatus. The second factor is associated with absorption. The mine and the soil will absorb microwave energy at different rates due to their variation in dielectric properties. These heating rates will be conducted to the surface of the soil and produce a temperature difference seen by the IR camera. The thermal mine signature on the surface of the soil is composed of both of these components. The interference due to the mine occurs almost immediately after HPM illumination and the absorption of microwave energy by the mine occurs after a short time delay. This delay is dependant on many parameters involved including power density of the illuminating microwaves, differences between dielectric constants of the mine body and surrounding soil, weather conditions and soil moisture content. Since we are primarily concerned with the absorption process, relevant theoretical aspects such as the reflection coefficient and the skin depth are now examined.

2.1 Reflection coefficient

Von Hippel [14] has evaluated dielectric properties of different plastics and soils at different frequencies and moisture contents. The complex permittivity of a material

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{1}$$

is represented by a real and imaginary part, where ε' is the dielectric constant and ε'' is the loss factor of the medium. Microwave heating is determined by the dielectric loss tangent

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \tag{2}$$

It is the ratio of the imaginary permittivity to the dielectric constant at a given frequency [13]. The higher the loss tangent a material has, the more microwave energy it can absorb. Table 1 indicates the relative dielectric constant ($\varepsilon'/\varepsilon_0$) and the dielectric loss tangent ($\tan\delta$) for three frequencies in dry sand. These values are provided by Von Hippel's table of dielectric materials [14] and are used throughout this section.

Table 1. Relative dielectric constant and dielectric loss tangent for certain frequencies in dry sand.

Frequency (MHz)	10	300	3 000
tanδ	0.016	0.0100	0.0062
$\varepsilon'/\varepsilon_0$	2.55	2.55	2.55

Table 2. Linearly interpolated values for the dielectric loss tangent and the relative dielectric constant of the two frequencies.

Frequency (MHz)	915	2450
tanδ	0.0091	0.0070
$\varepsilon'/\varepsilon_0$	2.55	2.55

At an interface between two media, media 1 and media 2, an electromagnetic wave traveling from media 1 will partially reflect back to media 1 and partially transmit through to media 2. At normal incidence, the reflection coefficient R is given by

$$R = \frac{\sqrt{\frac{\varepsilon_1}{\varepsilon_2}} - 1}{\sqrt{\frac{\varepsilon_1}{\varepsilon_2}} + 1} \tag{3}$$

The dielectric loss tangents, tanδ, for the two frequencies of interest were linearly interpolated from the measured values of Table 1. The calculated values are indicated in Table 2. Using these values, the modulus of the complex reflection coefficient was calculated to be 0.229864 for 915 MHz and 0.229855 for 2450 MHz. Since the difference between these values is approximately 9×10^{-6}, it can be concluded that there is no appreciable difference in the reflection coefficient of the two frequencies.

2.2 Skin depth

The attenuation factor, α, is given by

$$\alpha = \frac{\omega}{c}\left[\frac{\varepsilon'}{2\varepsilon_0}\left[\sqrt{\left(1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2\right)}-1\right]\right]^{1/2} \tag{4}$$

where ω is the angular frequency of the electromagnetic radiation, ε_0 is the dielectric constant of free space and c is the velocity of light. The skin depth (the inverse of the attenuation factor) represents the distance through which the field strength drops to 1/e of its original value or approximately 36.8%. Using Table 2, the skin depths were calculated for the two frequencies as shown in Table 3. The fact that 915 MHz has a larger skin depth was the original rationale for the procurement and testing of its respective magnetron assembly.

Table 3. Skin depths and reflection coefficients of the two frequencies.

Frequency (MHz)	915	2450
Reflection coef.	0.229864	0.229855
1/ α [m]	7.2	3.5

2.3 Transmitted power density

In order to calculate the approximate power density at a distance R from a waveguide illuminating at a certain frequency, one can follow the analysis provided by Balanis [15]. If the distance R from the open waveguide to the air/soil satisfies

$$R \geq \frac{2D^2}{\lambda} \tag{5}$$

then the interface is located in the far-field (Fraunhofer) region. This fact allows for a simple calculation of the power density involved. In (5), λ is the wavelength of the microwave energy and D is the largest dimension of the waveguide aperture. The wavelength can be calculated from the relation

$$\lambda = \frac{c}{\nu} \tag{6}$$

where c is the speed of light and ν is the frequency of the microwaves. Using ν = 915 MHz and $c = 3\text{x}10^8$ m/s, the wavelength is calculated to be 32.79 cm. The largest dimension (diagonal) of the WR975 waveguide aperture is 27.7 cm. Inputting these dimensions into (5) yields the result that the far-field begins when R equals approximately 47 cm. The distance from the waveguide to the surface of the sand is 38 cm. Given that the dominant fields for the TE_{10} mode are located near the centre, it can be approximated that the air-ground interface is in the far-field region. Using ν = 2450 MHz and the largest dimension of the WR340 waveguide D = 9.35 cm, the far-field distance is calculated to be 15.23 cm. Comparing this with the waveguide height of 15 cm, it can also be approximated that the air/ground interface is in the far-field region.

Based on the assumption that the sand under the waveguide is in the far-field region, the radiated power density, W_T, for any antenna at a distance R with a directivity D_T and transmitted power P_T, is given by

$$W_T = \frac{P_T D_T}{4\pi R^2} \tag{7}$$

We estimated the transmitted power to be 4.3 kW for 915 MHz and, as stated earlier, the distance R was equal to 38 cm. The directivity of a waveguide aperture on an infinite ground was used for convenience and is given by

$$D_T = 0.81 \frac{4\pi ab}{\lambda^2} \tag{8}$$

where a is the longest side of the rectangular waveguide aperture (a = 24.38 cm) and b is the smallest (b = 12.38 cm). Replacing variables with their representative values results in a microwave power density of 0.69 W/cm² at the surface of the sand for the 915 MHz frequency set-up.

An identical analysis of the power density for the 2450 MHz experimental set-up produced an estimated microwave power density of 0.90 W/cm² at the surface of the sand. The waveguide dimensions used were 8.636 cm by 4.318 cm and the estimated transmitted power used was 1 kW. This power density is smaller than the power density used in previous studies, estimated to be 1 to 3 W/cm².

The power density at different depths in the sand is proportional to the power density at the surface of the sand multiplied by $e^{-2\alpha z}$, where α is the attenuation and z is the depth. The transmission coefficient is neglected because it is almost identical for both frequencies. Therefore, it is useful to define the quantity

$$S = W_T \, e^{-2\alpha z} \tag{9}$$

and examine its behaviour as a function of depth in sand for the 915 MHz and 2450 MHz experimental arrangements. The power quantity in (9) is shown in the graph of Figure 1, indicating that the 2450 MHz experimental set-up has a higher power density at the surface of the sand but decreases faster as the depth of the sand increases. The difference in power density is due to i) the difference in radiated power (4 times larger at 915 MHz than at 2450 MHz) and ii) the difference in waveguide height (2 times larger at 915 MHz than at 2450 MHZ) and spot size. It will be seen in Section 4 that for the given fixed parameters in this study, the higher density of the 2450 MHz assembly seemed to result in a higher quality IR image. If the power densities were identical for the two frequencies, the difference in attenuation would be negligible within a few centimetres. This is a fact to be considered for AP mines, which are typically buried 1-5 cm. Antitank mines, typically buried 10-20 cm, may be better detected with a lower frequency at the same power density.

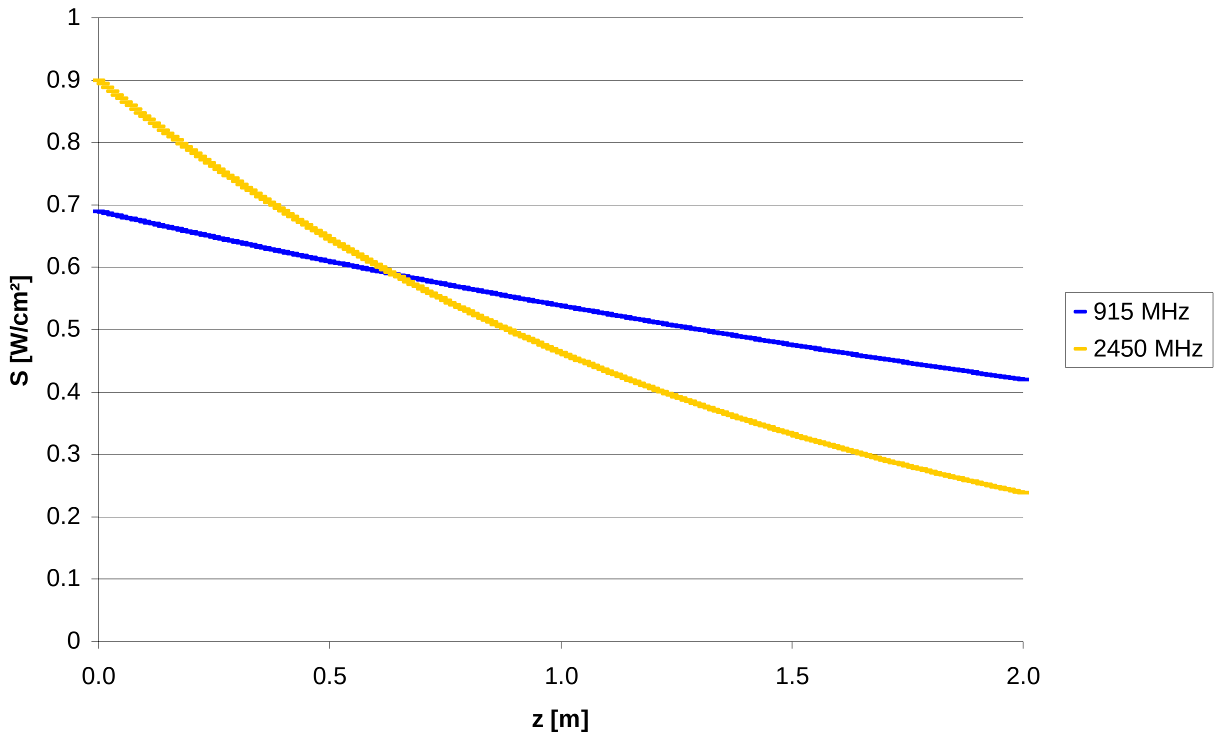

Figure 1. The quantity S at 915 and 2450 MHz frequencies for soil depths of up to 2 m.

It is hypothesized that for a given type of soil found in landmine fields around the globe, an ideal frequency of illumination could be found analytically and experimentally in order to optimize the detection of buried objects. Judging from the skin depths in Table 3 and the experimental results described in Section 4, it is speculated that the optimal illuminating frequencies of interest will fall between 500 MHz (skin depth of about 19 m) and 10 GHz (skin depth of about 1.7 m). Finding commercial off the shelf (COTS) tuneable magnetrons could pose a significant problem if one was so inclined to experimentally carry on the present work. As outlined in Section 5, further studies in the present body of work could lead researchers to the best possible way of using this method in actual military and humanitarian detection scenarios.

3. Experimental method

The present work represents a first real time experimental procedure for microwave illumination and IR detection using a 915 MHz high power microwave source. As in the previous study conducted at the then Defence Research Establishment Ottawa (DREO) [9], the primary goal was to obtain accurate experimental data while varying parameters under laboratory and near field-like conditions to further evaluate the suitability of microwave enhanced IR imagery for mine detection. There are key differences between the present and previous study. The variations that are worth mentioning include the utilization of a vastly different microwave and waveguide assembly working at 915 MHz, the use of a new and more compact 2450 MHz system, and the use of a newly acquired IR camera. The current study used an A20M infrared camera manufactured by FLIR Canada. All experimental methods are described in the following section and results are outlined in Section 4.

The experimental methods for the illuminating frequencies of 915 MHz and 2450 MHz were similar. In preparation for a typical experiment, a mine was buried under the centre of an open ended waveguide to allow for symmetrical coupling and was left buried in the sand for a minimum period of time (anywhere from a few hours to overnight) to allow the mine to be in thermal equilibrium with the surrounding sand. The sand was contained inside a wooden box for insulation purposes and to help minimize the effects of normal environmental changes (eg. higher humidity, hot to cool temperature changes, etc…). At the time of burial, care was taken to place the mine at the desired depth. Care was also taken to position the IR camera at approximately the same location each time and the focus was manually adjusted before each experiment. IR images were normally saved one minute before, every minute during microwave irradiation for a minimum of fifteen minutes and a few minutes after microwaves were turned off.

A few series of trials were devoted to determining the temperature differences associated with the experimental arrangements using fibre optic temperature probes buried in the sand under the respective waveguides (WR975 for 915 MHz and WR340 for 2450 MHz). The temperature was recorded at depths of 1 or 3 cm under the surface of the sand.

An 8-12 µm ThermoVision ™ A20M IR camera was used to produce pictures of thermal signatures of mines and measured temperature to an accuracy of ±2°C. In most experiments, an automatic adjust feature was utilized before taking IR images. It should be noted that this step did not necessarily result in obtaining an optimal image. As explained in more detail in a subsequent section, it is recommended that any future work concerning the subject at hand include extensive image processing in order to optimize this method of detecting and identifying buried objects in a potential landmine field.

Although every effort was made to ensure that parameters were identical in order to compare experimental results, unavoidable fluctuations in sand conditions, weather conditions and slight variations of the angle of the IR camera occurred during normal experimental procedures.

3.1 Buried targets

A variety of buried objects were used in the experiments to verify that detection and identification could be obtained using the current method. Three inert antipersonnel landmines were used. They were all fabricated with hard green plastic and all had distinctive circular or rectangular shapes. All metal was removed from the inert AP mines in the demilitarization process and wax was added to simulate the explosive material used in actual mines. An inert version of a FFV 028 antitank mine was also examined in various experiments. The inert AT mine was circular and, for the most part, was comprised of aluminum. Antipersonnel mines were buried from 1 to 5 cm in the soil and the antitank mine between 5 and 15 cm. Other objects of interest included a polypropylene cylinder and an aluminum cube. The polypropylene puck was originally used to act as a mine surrogate because it was made of a dielectric material that simulated the plastic often found in common AP landmines. The aluminum cube was fabricated strictly for use as a 5 cm dimensional reference. Objects used during the experiments are shown in Figure 2. Properties of militarized versions of the mines used for this study are listed in Table 4.

Figure 2. Different types of AT and AP mines, and other objects used in the experiments.

Table 4. Properties of landmines simulated in the experiments.

PROPERTY	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 of Explosive	TNT	TNT	Tetryl	RDX / TNT
Mass of Explosive	200 g	70 g	35 g	4 kg
Length	14.0 cm	–	–	–
Width	7.0 cm	–	–	–
Height	3.0 cm	6.1 cm	3.6 cm	12.0 cm
Diameter	–	6.8 cm	10.3 cm	25.0 cm

3.2 915 MHz experiments

A 5 kW magnetron operating at 915 MHz was used as the microwave source for this portion of the experiments. The WR975 waveguide was positioned at a height of 38 cm from the sand surface and the IR camera was located 1.6 meters away from the waveguide. Figure 3 shows a sketch of the experimental set-up inside a tent located outdoors. A digital picture is provided in Figure 4.

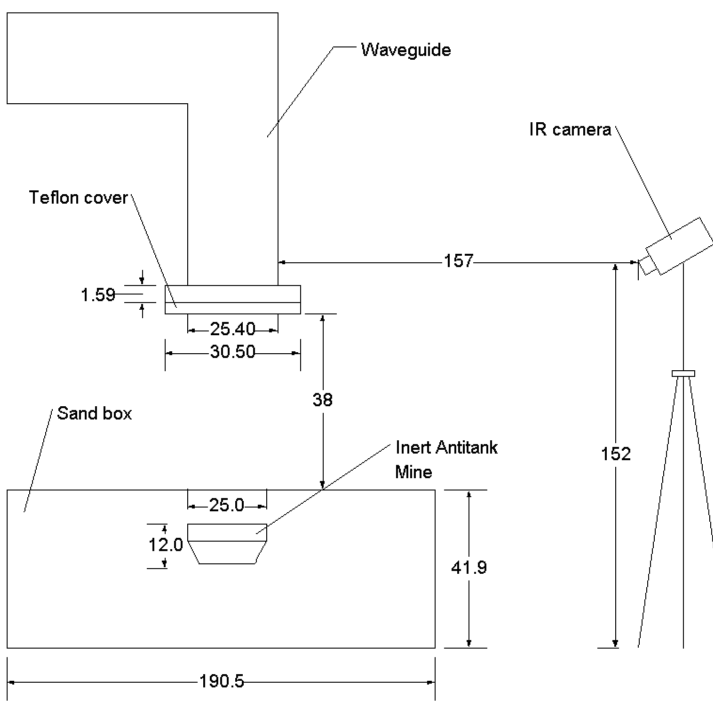

Figure 3. Model of 915 MHz experimental set-up, dimensions in cm.

Figure 4. 915 MHz frequency experimental arrangement.

3.3 2450 MHz experiments

In the previous studies, a 5 kW source at 2.45 GHz was utilized [9]. A standard gain horn, located approximately 50 cm above the ground, was used for high power beam shaping. It was desired to look at an alternate approach for the same frequency in the current study. Rational for furthering this work was to try to a) incorporate the neutralization apparatus (see Section 4.2) as a detection device and b) attempt to engineer a more practical working assembly for the Canadian Forces. The approach in this study consisted of using a 42 cm length of WR340 waveguide with a 1.1 kW magnetron as the microwave source. The physical set up is shown in Figure 5. The waveguide was directly connected to a magnetron that was cooled by a fan. The waveguide height was manually adjusted and tested at several heights between 5 and 30 cm above the soil in order to achieve a seemingly ideal arrangement for detection. It was decided that buried landmines were best detected when the spot size was greater than the size of the landmine. A final distance of 15 cm off the surface of the soil was found to yield the best IR images of buried objects.

Figure 5. 2450 MHz frequency experimental assembly.

3.4 Radio frequency radiation hazard

A radiation hazard (RADHAZ) survey was conducted for the two radiating microwave detection apparatus. The microwave detectors used are shown in Figure 6 and were made by General Microwave Corporation (Raham Radiation Hazard Meter Model 495 and RF Radiation Badge Model 60A-1). They are typically used as measurement tools for RF workers so that they do not expose themselves to fields greater than those outlined in Health Canada's Safety code 6. As detailed in that document, the exposure of 1 mW/cm^2 over a 6-minute interval is the limit for anyone in the public domain. This power density was measured at a radius of 6 meters from both detection assemblies.

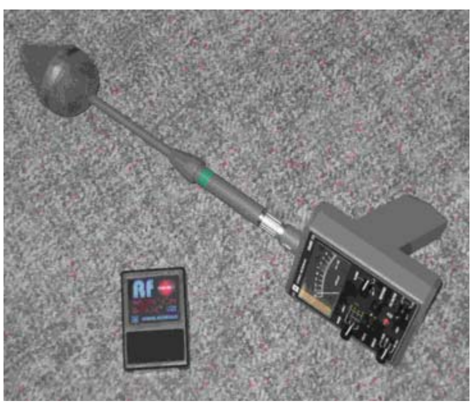

Figure 6. RF field measurement devices.

4. Experimental results

A list of experimental results using enhanced microwave IR imaging with 915 MHz and 2450 MHz microwave sources for illumination are shown in Table 6 and 7 respectively in Annex A. The tables provide a summary of the experiments, including information such as the weather conditions outside the tent, soil conditions, mine burial depth, type of mine, whether the mine was deemed distinguishable or not and references to IR pictures taken during the experiment. While some of the IR images are included in the main body of this paper, the majority of the IR images listed in Table 6 and 7 are included in Annex A. It should be noted these IR images might have been altered using Microsoft Photo Editor in order to make the mine signature more distinguishable. No images in this study were enhanced in a sophisticated manner. It is stressed that in the opinion of the authors, more work concerning IR image processing is required in order for the current method to be utilized in a real mine clearing operation.

As predicted in the section containing the theoretical analysis, the effectiveness of this method was found to be experimentally dependent on factors such as soil moisture content and illuminating power density. The calculated power densities are included in this report to act as a guideline for where to begin a more rigorous analysis. The ideal power density required would have no chance to induce a current on the buried mine fuse, thus detonating the mine, but would give the best IR image for detection purposes. Experiments that involved large amounts of surface moisture, clutter and very uneven sand resulted in poor recognition of the buried mine. The following paragraphs outline detailed results for specific experiments conducted in the current study.

Results show that moisture content altered the effectiveness of the method due to the microwave absorbency properties of water. Moisture that was spread uniformly throughout the sand or solely on the sand surface hindered the rate of detection of a buried mine. Figure 7 shows a series of IR images of a mine buried in sand with uniformly spread moisture. The images show a clear mine signature before microwave radiation that becomes difficult to recognize as heating progresses. The first image from the right reveals that a layer of moisture spread throughout the soil above a buried object may aid passive or microwave illumination detection immediately after illumination begins. As time passes, the moisture in the soil will absorb the microwaves, thus “whiting out” the buried object in an IR image. Figure 8 shows IR images of a mine buried under a lightly moistened sand surface where the mine is difficult to recognize. These results can be explained qualitatively in terms of the difference in rate of heating of the mine and surrounding soil as well as the loss of the thermal signature of the mine due to various heat loss mechanisms in the soil.

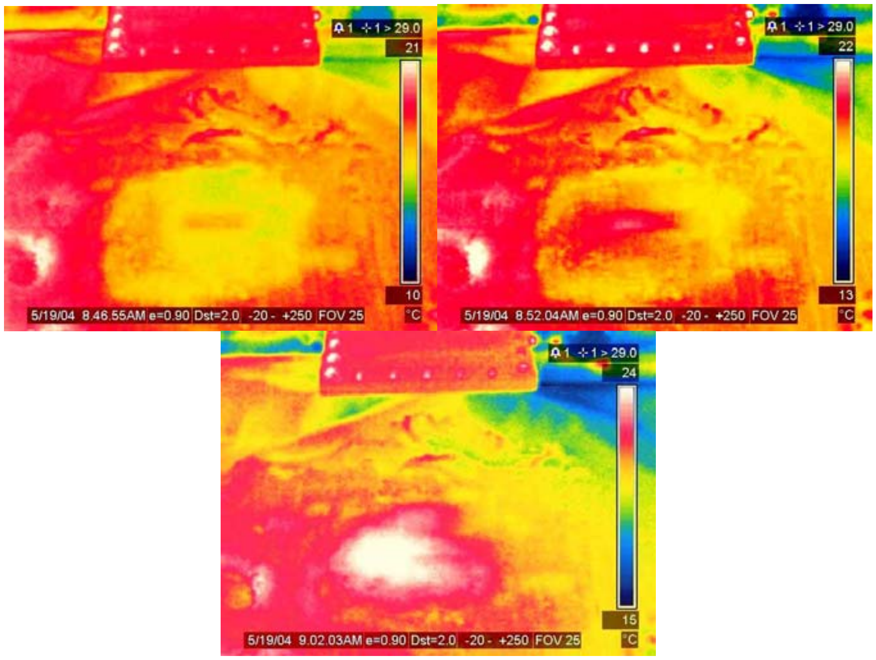

Figure 7. 0, 5 and 15 minutes of 915 MHz microwave heating. PMA 1 buried 1 cm under uniformly moistened sand in sunny weather.

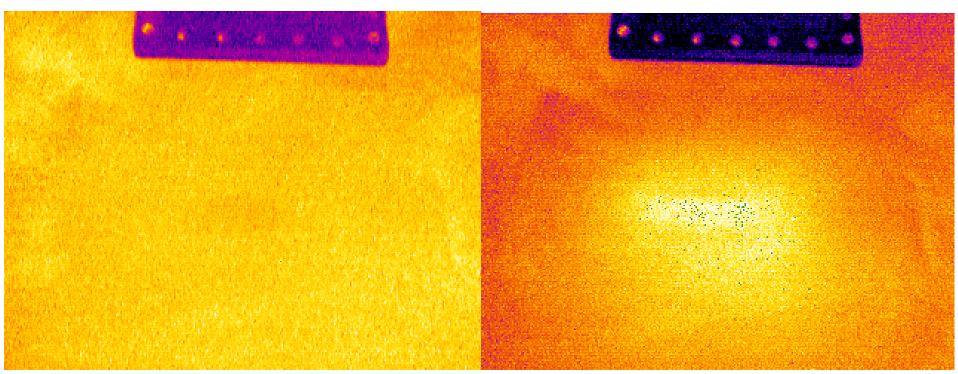

Figure 8. 0 and 6 minutes of 915 MHz microwave heating. PMA 1 buried 1 cm below a slightly moistened sand surface.

The addition of clutter on the soil surface or buried in the sand beside the mine obviously interrupts the regular process of illumination and detection. Experiments with clutter on the surface of the sand such as rocks, leaves or uneven soil resulted in producing thermal signatures of the clutter alone as shown in Figures 15, 19-28 in Annex A. Consequently, the detection of a buried mine was prevented under the extreme case tested in these particular experiments. As stated in Section 5, further studies are recommended in whether or not complex signal processing could help in this scenario.

Weather conditions that affected the experiments were direct sunlight, humidity and wind. All three circumstances had the ability to influence the thermal signature viewed by the IR camera. Direct sunlight added unwanted heating effects to the surface of the sand and wind played havoc with the IR image by convection cooling of the surface of the sand. Once again signal processing may eliminate these types of effects.

Table 5 contains a summary of both favourable and ineffective weather and soil conditions found during the present study.

Table 5. Results in various soil and weather conditions.

Soil		Weather	
Ineffective	**Successful**	**Ineffective**	**Successful**
moist layer on surface	dry	direct sunlight	indirect sunlight
very uneven	even	moist, damp	dry
inhomogeneous	homogeneous	windy	calm

One parameter that may have contributed to better IR images was the fact that the 2450 MHz system had a faster heating rate. The graph in Figure 9 shows the heating rates of the two frequencies. During microwave illumination, the temperature of the sand was recorded every second at a 1 cm depth for 15 minutes. Measurements were done in dry sand with no clutter or mines. The slopes of the heating runs for the two frequencies show that the 2450 MHz heating run had a higher heating rate. This corroborates the theory outlined in Section 2, which showed that the absorption of microwaves would be higher at 2450 MHz.

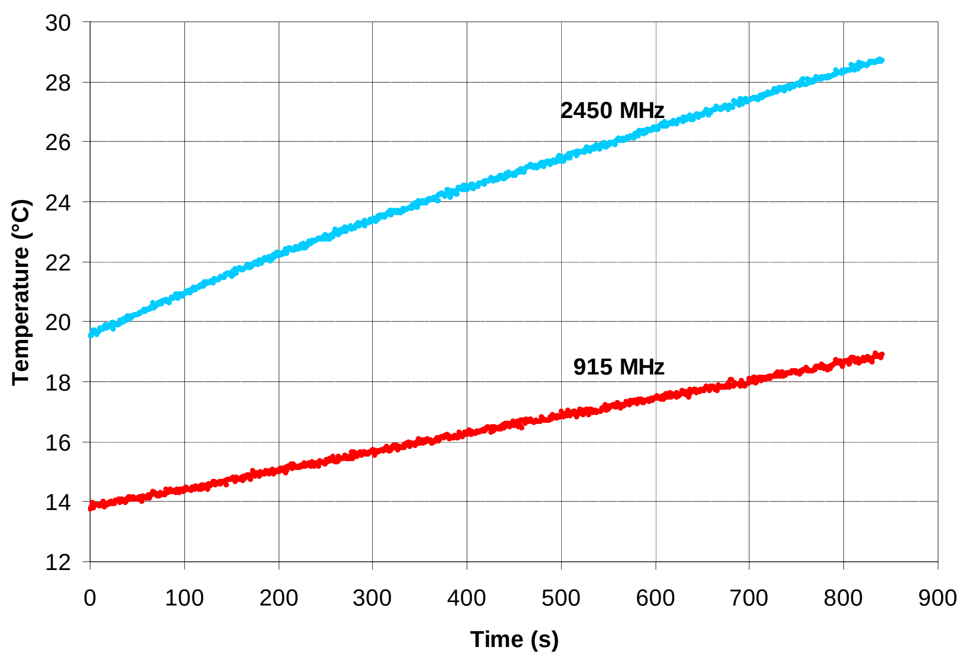

Figure 9. Heating rates of the two frequencies measured 1 cm under dry soil with no mine or clutter.

Additional parameters such as microwave spot size, frequency of illumination, penetration depth and power density all play important roles in this detection problem. For the cases considered, the IR images shown in the present work demonstrate that the 2450 MHz setup is more optimal for mine detection. As outlined in the recommendations Section, a more rigorous study into the optimal arrangement could be performed.

4.1 915 MHz experimental results

The main focus for the current study was to examine the use of 915 MHz as the illuminating radiation. To date and to the best of our knowledge, this particular experiment has not been reported in the open literature. A plethora of experiments were conducted in order to attempt to simulate actual minefield situations. Detailed results of laboratory conditions in which the sand was smooth, moist, hand brushed, very uneven, or raked are listed in Annex A. Other experiments included items on the surface of the soil such as pebbles, rocks, leaves and wood.

An initial experiment consisted of illuminating a mine buried in soil that had a smooth dry surface without clutter. Results show that the mine was recognized in approximately five to ten minutes (see Figure 10). The first indication of an object in the sand occurred four minutes into the experiment. This particular test was a “proof of concept run” that showed that the new system could work in ideal laboratory conditions.

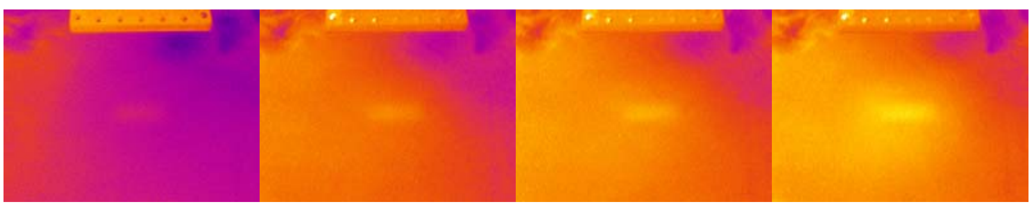

Figure 10. PMA 1 in cloudy weather. Images are several minutes apart.

The IR pictures from a typical experiment with a PMA 1 in cloudy weather are shown in Figure 10. A comparison can be made with IR images of the same mine in warm, sunny weather shown in Figure 11. At zero minutes, the mine is seen due to solar effects and the image is improved as the mine is illuminated with microwave radiation. Thermal signatures of all three demilitarized antipersonnel mines used in the study as well as a surrogate antitank mine are shown in Figures 15-32 in Annex A.

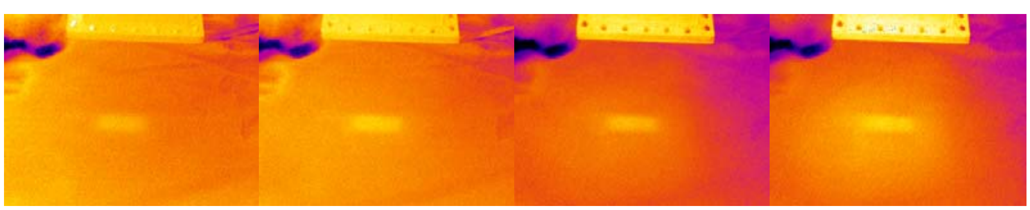

Figure 11. 0, 3, 7 and 10 minutes of heating. PMA 1 buried 1 cm deep in sunny weather.

4.2 2450 MHz experimental results

A separate low power microwave (LPM) neutralization assembly (shown in Figure 4) using standard magnetrons from common microwave ovens at 2450 MHz was also utilized in the current study for two main reasons. One aspect includes the continuation of the previous work [9]. The second rationale behind using such a physical arrangement was that it was conceived that if a mine could be detected and identified with such a system, perhaps at a different power setting or physical distance away from the buried object, the detection unit could then be used as a neutralization device. The concept could be dubbed "The Landmine Seek and Destroyer". The neutralization study is still in the works as of the date of publication of this report (the end of 2004) and the interested reader is advised to search for publications summarizing results of that work sometime in the near future.

Once again, an initial test consisted of illuminating a buried mine in smooth sand without clutter, and this resulted in recognizing the mine in approximately three to six minutes. A first indication of an object in the sand occurred three minutes into the experiment. An optimal arrangement was studied by performing experiments with a few different waveguide heights, with and without a horn, and all are listed in Table 7 of Annex A.

Thermal images taken by an IR camera of a buried PMA 2 are shown in Figure 12 and 13. A visual comparison of these mine signatures with the heating spot is contained in Figure 14 and reveals that there is very little to distinguish between a mine signature and a thermal image with no mine. For this and other reasons, recommendations are made for further studies in IR image processing in order to maximize the effectiveness of this method. Figure 13 shows a clearer image of the PMA 2 taken in the same experiment as in Figure 12. This was accomplished by manually adjusting the temperature range on the IR camera from a 27ºC to 38ºC range to a 31ºC to 53ºC range. As it is readily shown, even a simple adjustment significantly improves the image.

It should also be noted that the spot size of this particular 2450 MHz assembly was much smaller than the 915 MHz version. It is not clear at this point as to which spot size would be optimal for buried object detection. One could argue that a larger spot size might cover more area and perhaps with the correct power density would be better than such a confined arrangement as shown in Figure 14.

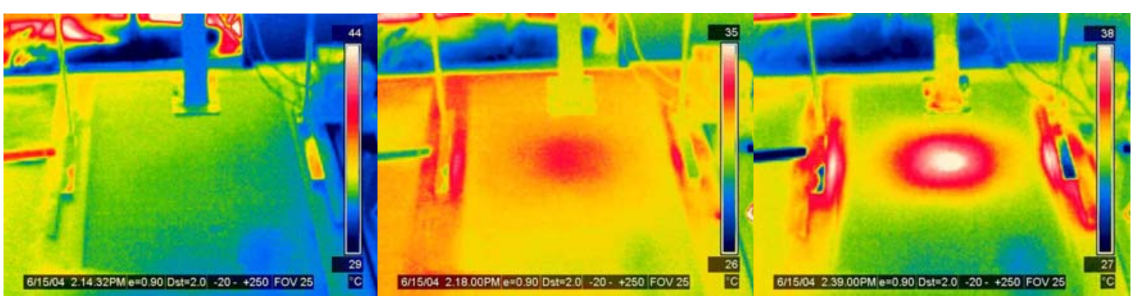

Figure 12. 0, 3 and 13 minutes of 2450 MHz microwave heating. PMA 2 buried 1 cm deep.

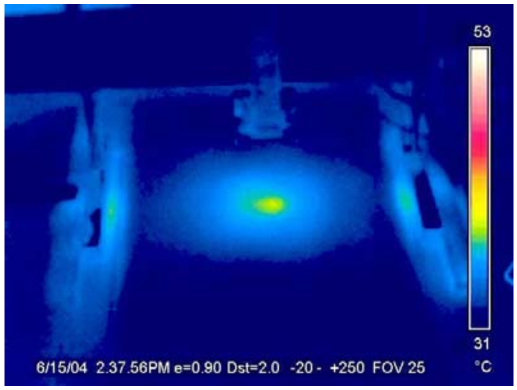

Figure 13. 23 minutes of 2450 MHz microwave heating. PMA 2 buried 1 cm deep. Temperature range on IR camera changed.

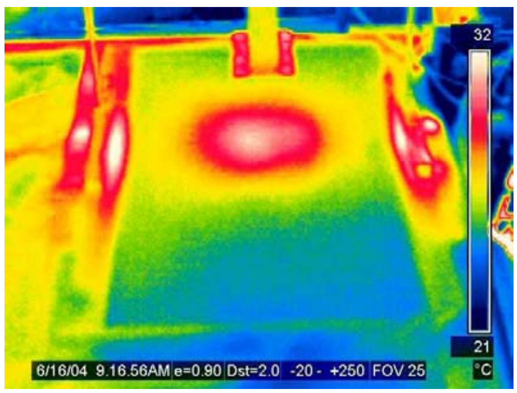

Figure 14. 15 minutes of 2450 MHz microwave heating. No mine.

5. Recommendations

Further studies are recommended in microwave enhanced IR imagery. Improved results may be found with rigorous testing of different parameters. To fully understand the problem at hand, parameters that could be studied include soil and weather conditions, waveguide and camera positions as well as different illuminating power densities.

The first recommendation is to optimize the position of the IR camera with respect to the unknown buried object of interest. The ideal position could be found by conducting studies into the best angle, height and distance for viewing. This distance is necessary to protect the camera from the illuminating microwaves and to allow for a discreet field of vision.

The second recommendation is to find the optimal orientation of the waveguide that will produce an efficient and effective detection arrangement. Parameters that could be evaluated include angle of incidence, height of the waveguide above the buried object and whether or not to use a horn or other antenna. Microwave illumination intensities could be studied in order to find field strengths that allow for superior IR imagery. At the same time, field strengths should not induce currents on landmine or UXO, causing unwanted detonation. Continued numerical and experimental studies along these lines could find the most favourable arrangement for this method of detecting and identifying buried objects.

This method could also be improved by optimizing frequencies of illumination and detection. The frequency range of detection should be varied with a calculated range of illuminating frequencies. Since antipersonnel mines are typically buried up to 5 cm, one could calculate the highest possible illuminating frequency for penetration at that depth, as described in Von Hippel [14], and correlate it to the viable frequencies of interest. As stated in Section 2, for practical purposes, the optimal frequency of illumination will probably be found in the region between 500 MHz and 10 GHz. Finding commercial off the shelf (COTS) tuneable magnetrons could pose a significant problem if one was so inclined to experimentally carry on the present work.

Studies in image processing are also recommended. This processing could include adjusting the temperature range for clearer mine signatures, eliminating background noise such as the sun or wind as well as eliminating clutter such as rocks or leaves. A possible method is to subtract a function of the thermal image near the beginning from a thermal image at the end of the high power microwave illumination. This would remove the illumination pattern of the source and reduce the effect of clutter on the surface. The image processing work could potentially be an excellent MSc, or MEng thesis project. Supervised university or college students could carry out recommendations made at a relatively low cost to any party interested in finding novel demining detection techniques.

Once the ideal parameters mentioned in the previous paragraphs are determined, proper engineering of components and apparatus would be required for a deployable detection device. Engineering design would include many factors such as remote capability (possibly autonomous), size and mobility to name a few.

6. Conclusions

This paper describes advances in experimental work concerning the potentially powerful remote-sensing method of detecting buried landmines using microwave enhanced IR imagery. To the authors' knowledge, using 915 MHz to illuminate buried objects and then detect signatures with an IR camera is unique in its approach. In the current study it was shown that under favourable weather and soil conditions, this method has the capability of producing a recognizable mine signature by measuring temperature differences at the soil surface of a buried mine. Many parameters may impede this type of detection process as described in the results. This method is not an all-encompassing solution to mine detection but may help passive IR methods in certain circumstances where enhanced microwave imagery would be required or desired such as in semi autonomous night time demining activities or cloudy weather.

The present study utilized two distinct experimental arrangements. In the two apparatus examined, the resulting IR images demonstrated that the 2450 MHz setup was more optimal for mine detection. As outlined in Section 4, it was a more successful arrangement due to a resulting ideal combination of particular parameters such as the microwave spot size and power density.

Although this work is an extension of the previous study by Khanna et al. [9], it is the authors' opinion that this study is still fairly preliminary. Future work has been outlined and discussed in the previous section. As concluded in the earlier study, we suggest that continued studies into finding false alarm rates, detection sensitivity and detection rates for this method could be explored. It is still conceivable that this method, in conjunction with a microwave neutralization technique, could be used to seek, identify and destroy landmines.

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Annex A Summary of experimental results

Table 6. Synopsis of experimental results using 915 MHz microwave frequency.

Run #	Mine Type	Burial Depth (cm)	Parameters of Sand	Weather Conditions	Comments	Reference Figure #
1	PMA 1	1	hand leveled, leaves and wood	sunny	distinguishable within 5 minutes	15
2	none	0	Phenolic board	cloudy, 25°C	spot size changed 8°C in 10 minutes	
3	none	1	Aluminum cube	sunny, 16°C	distinguishable cube before microwaves on	
4	none	1	Bakelite (Phenolic puck)	sunny, 10°C	distinguishable within 5 minutes	16
5	none	1	Polypropylene	sunny, 22°C	warmed up slower than soil	
8	none	1	Delrin	sunny, windy, 15°C	distinguishable within 6 minutes	17
9	PMA 3	1	no wax in mine	cloudy, damp, windy, 13°C	distinguishable within 4 minutes	18 a)
10	PMA 1	1.25	no wax in mine	sunny, 13°C	not found within 15 minutes	
11	PMA 1	1	fixed	sunny, windy, 18°C	distinguishable before microwaves on	9
12	PMA 1	1	animal tracks	foggy, damp, 7°C	slightly distinguishable within 20 minutes	19
13	PMA 1	3	fixed	sunny, 10°C	distinguishable within 15 minutes	
14	PMA 1	3	thin mist sprayed	sunny, 5°C	not found within 22 minutes	
15	PMA 1	1	thin mist sprayed	sunny, 1°C	distinguishable within 6 minutes	8
16	PMA 1	1	hand brushed	cloudy, damp, 4°C	not found within 20 minutes	20
18	PMA 1	1	raked	cloudy, high winds, 2°C	slightly distinguishable within 11 minutes	21
19	none	–	fixed	cloudy, windy, 8°C	spot about the width of waveguide	
21	PMA	1.1	4 rocks buried,	rainy	not found within 15	22

	2		rough		minutes	
22	FFV 028??	8	fixed	cloudy, dry, 3°C	distinguishable within 10 minutes	
23	PMA 3	3	fixed	thunderstorms, 18°C	distinguishable within 14 minutes	18 b)
24	PMA 1	1	moisture throughout	sunny, 18°C	not found within 25 minutes	7
25	PMA 1	1	hand brushed	cold, drizzly, 12°C	distinguishable within 5 minutes	23
26	PMA 1	1	very uneven	cloudy, drizzly, 15°C	not found within 30 minutes	24
27	PMA 1	1.5	raked	cloudy, moist, 13°C	distinguishable within 12 minutes	25
28	PMA 1	1	pebbles on surface	cloudy, 18°C	distinguishable within 17 minutes	26
29	PMA 1	1	large rocks on surface	sunny, 16°C	not found within 30 minutes	27
30	PMA 1	1	leaves	cloudy, windy, 13°C	not found after 15 minutes but seen when leaves uncovered	28
32	PMA 1	1	rocks buried	cloudy, moist, 14°C	not found within 15 minutes	
33, 39	FFV 028	10	fixed	sunny, mild winds, 14°C	distinguishable within 15 minutes	29 b)
35	none	–	fixed	sunny, 13°C	8cm by 7cm spot to the left of the waveguide	30
36	PMA 3	1	large rocks on surface	sunny, mild winds, 18°C	very difficult to recognize mine	
37	none	2, 5, 6	rocks buried	sunny, mild winds, 15°C	only 2 rocks visible, similar to mine signature	
38	none	1,7	wood buried	sunny, mild winds, 19°C	only 1cm deep wood appeared, similar to mine signature	
48	FFV 028	15	fixed	partial clouds, 17°C	distinguishable within 5 minutes	29 a)
49	FFV 028	15	mine to right	sunny, 27°C	distinguishable within 5 minutes	
50	FFV 028	5.5	fixed	sunny, mild winds, 17°C	distinguishable within 2 minutes	
53	FFV 028	8	fixed	sunny, 24°C	distinguishable within 5 minutes	29 c)
55	none	–	fixed	cloudy, 13°C	temp probe at 1cm	

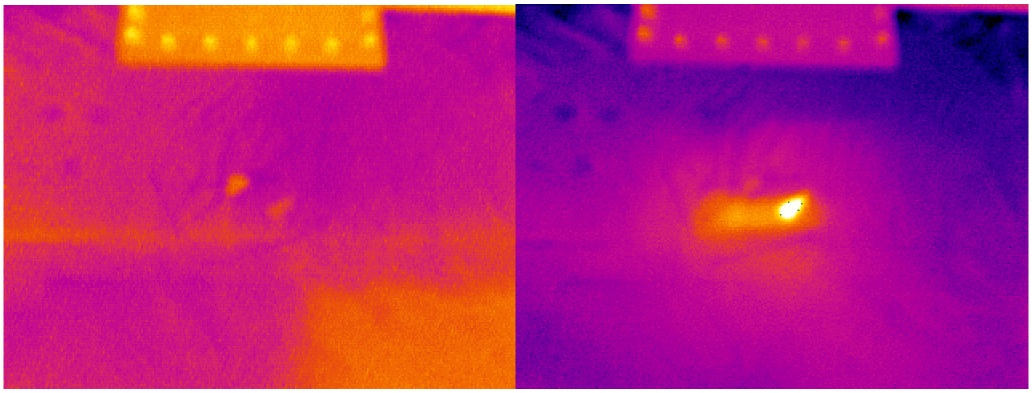


Figure 15. 0 and 15 minutes heating. PMA 1 buried 1 cm below hand-leveled sand with wood and leaves.

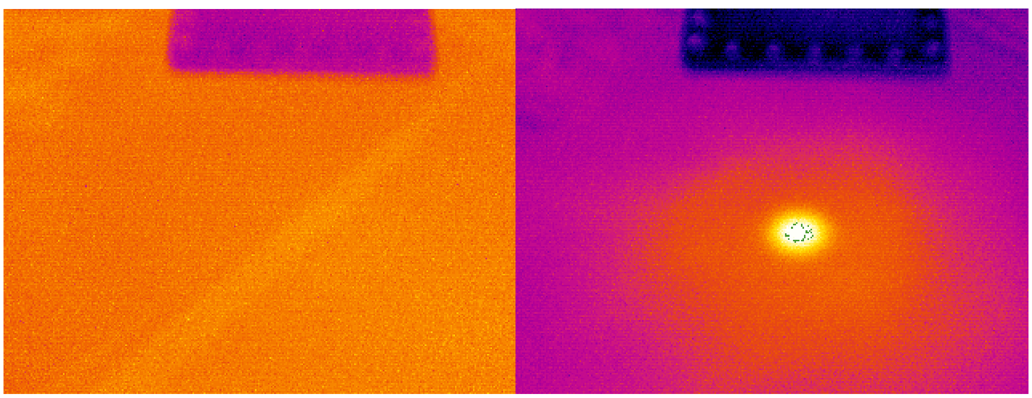


Figure 16. 0 and 5 minutes heating. Phenolic puck buried 1 cm deep.

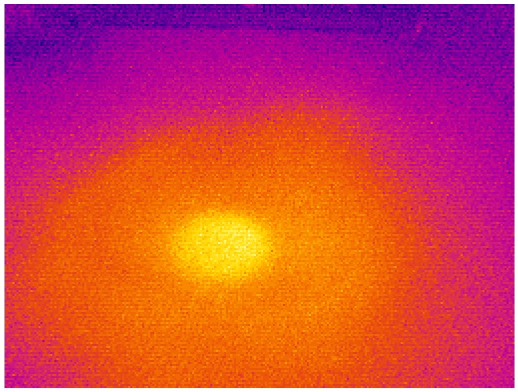
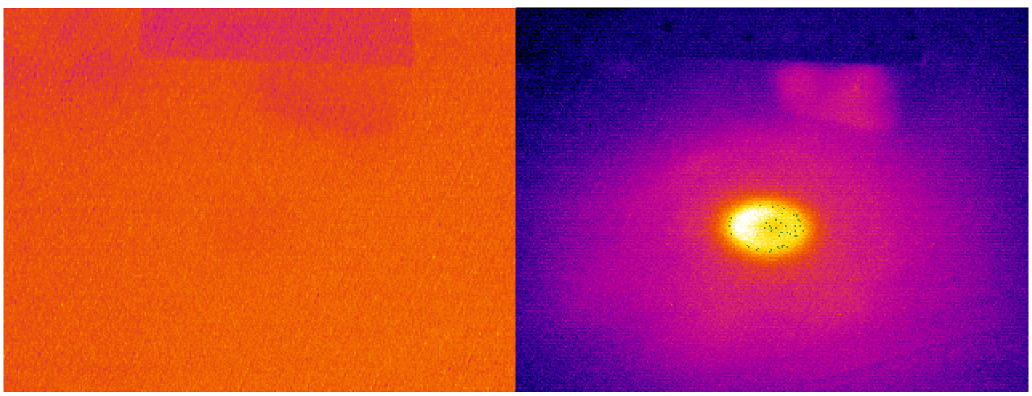
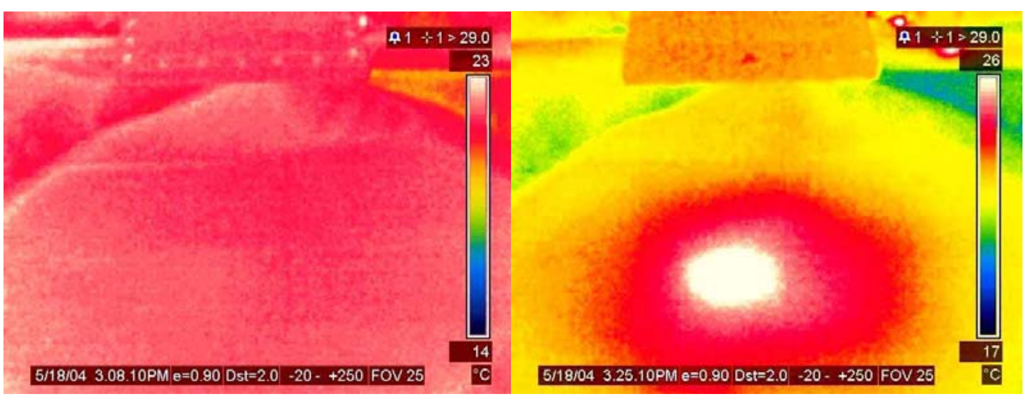


Figure 17. 15 minutes heating. Delrin buried 1 cm deep.



a)



b)

Figure 18. PMA3 buried at different depths. a) 0 and 15 minutes heating. 1 cm. b) 0 and 15 minutes heating. 3 cm.

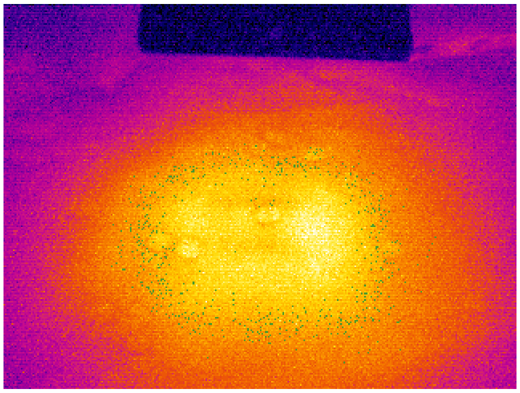


Figure 19. 20 minutes heating. PMA 1 buried 1 cm deep in damp weather.

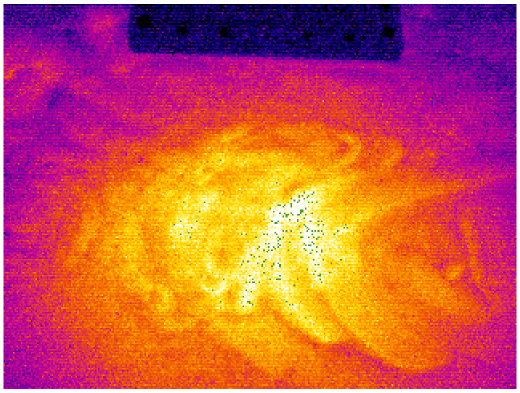


Figure 20. 20 minutes heating. PMA 1 buried 1cm below hand brushed, damp sand.

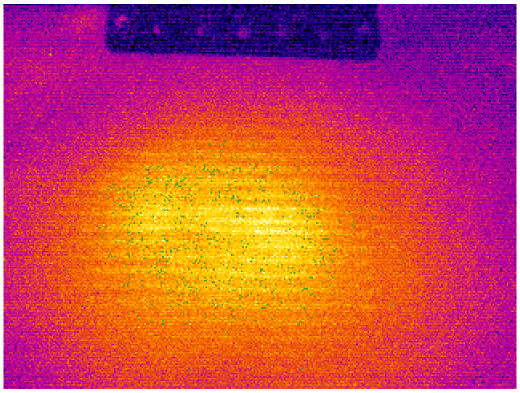


Figure 21. 18 minutes heating. PMA 1 buried 1 cm below raked sand.

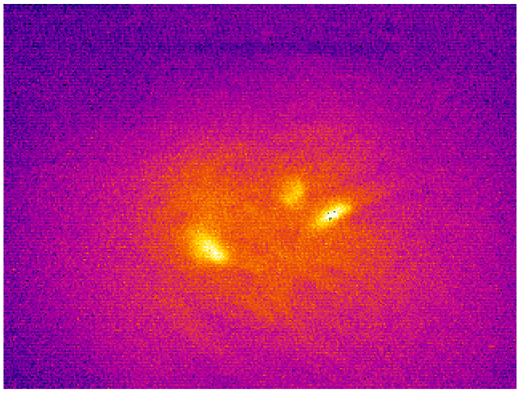


Figure 22. 11 minutes heating. PMA 2 buried 1.1 cm below rough sand surface with 4 rocks.

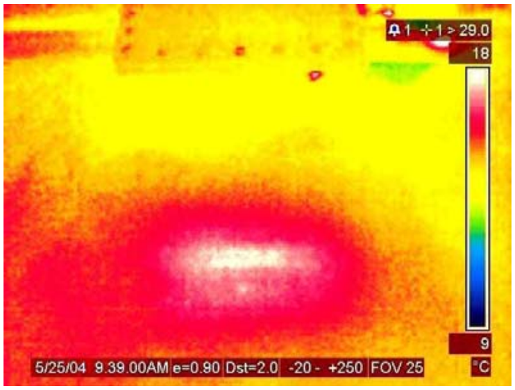


Figure 23. 15 minutes heating. PMA 1 buried 1 cm below hand brushed sand.

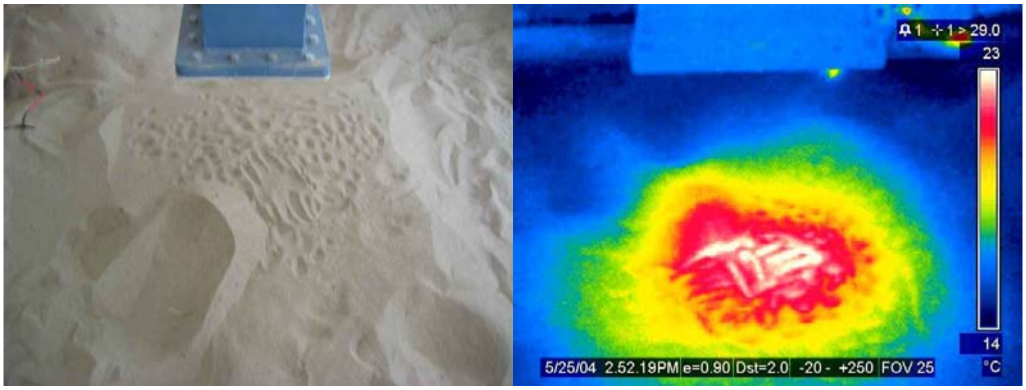


Figure 24. 30 minutes heating. PMA 1 buried 1 cm below uneven sand. The optical picture is a side profile.

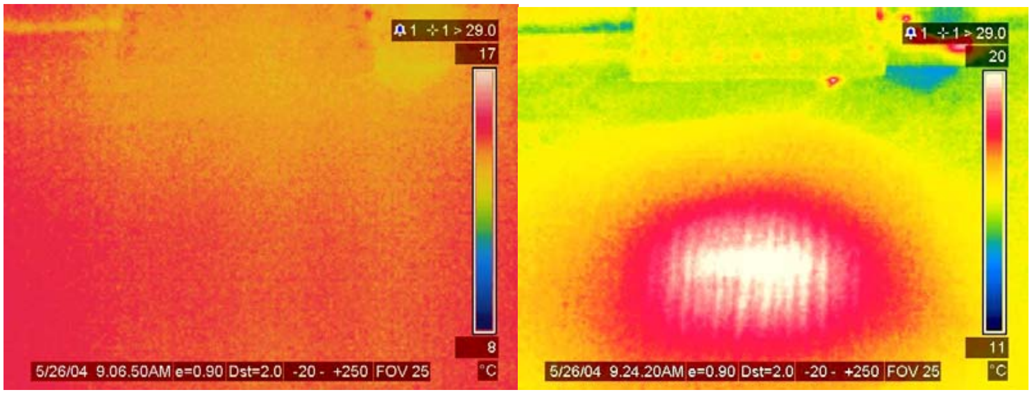


Figure 25. 0 and 17 minutes heating. PMA 1 buried 1 cm below raked sand.

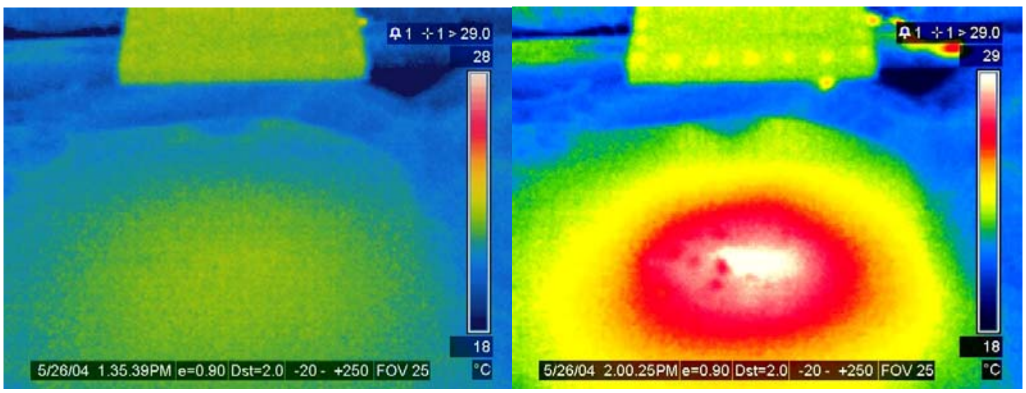


Figure 26. 0 and 25 minutes heating. PMA 1 buried 1 cm under pebbles on sand.

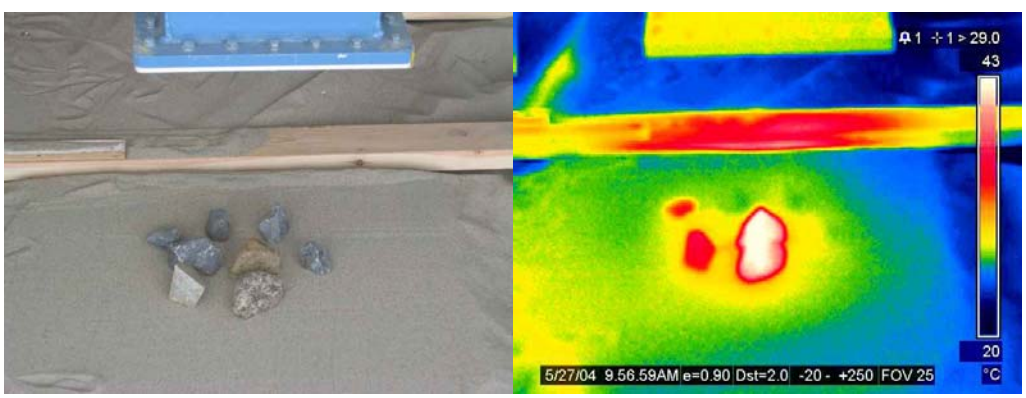


Figure 27. 17 minutes heating. PMA 1 buried 1 cm below rocks on sand.

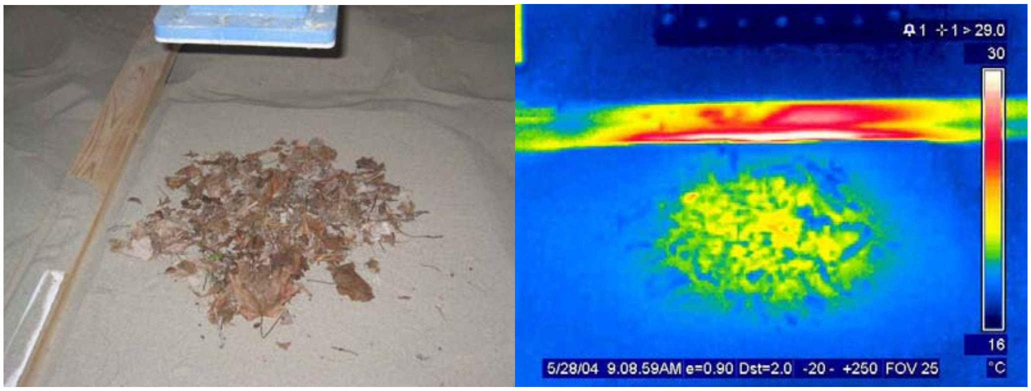
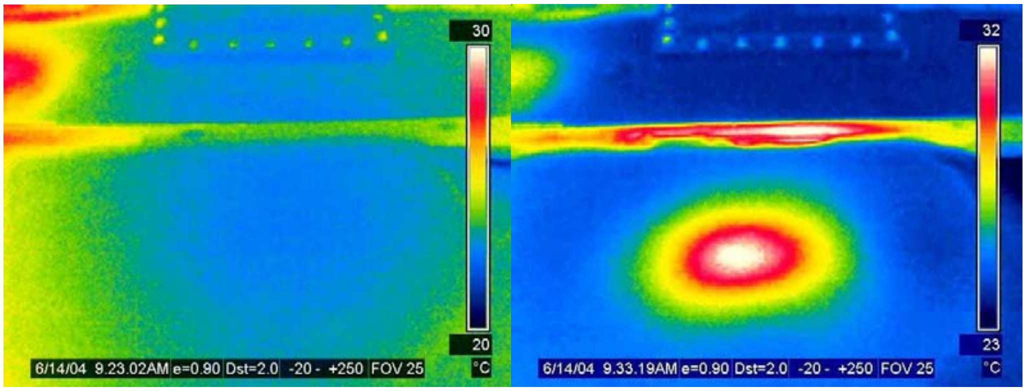
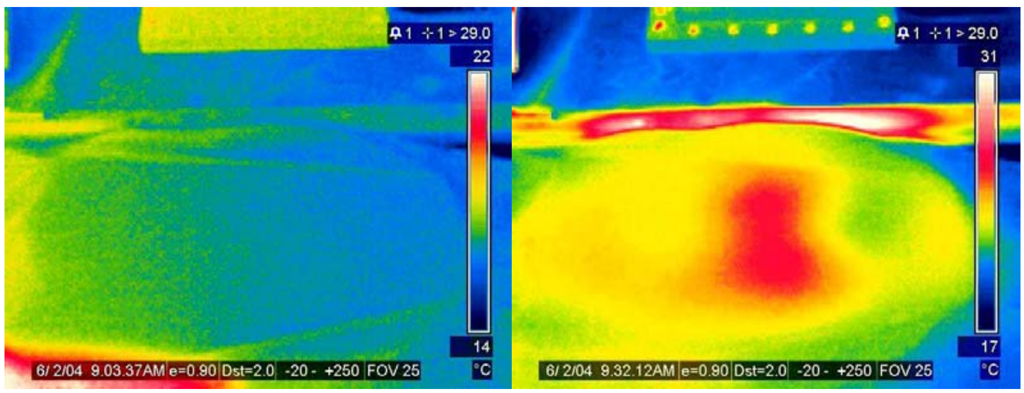


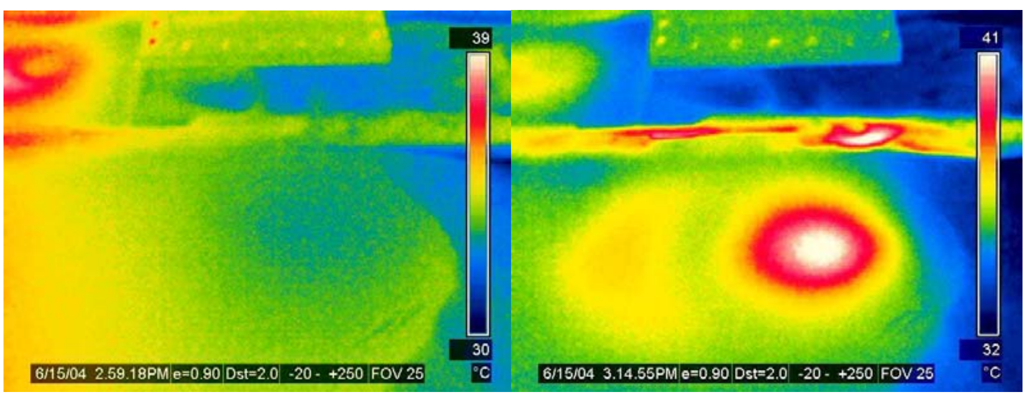
Figure 28. 15 minutes heating. PMA 1 buried 1 cm below leaves on sand.



a)



b)



c)

Figure 29. FFV 028 antitank buried at different depths. a) 0 and 8 minutes heating. 15 cm. b) 0 and 19 minutes heating. 15 cm. c) 0 and 15 minutes heating. 8 cm.

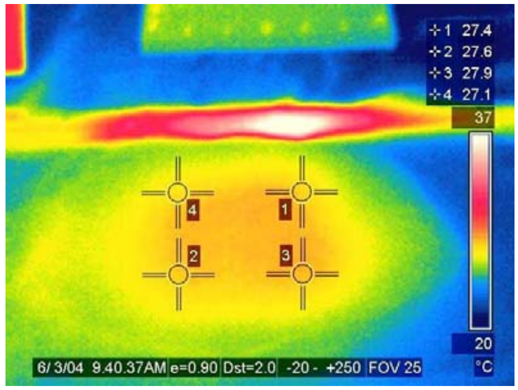


Figure 30. 20 minutes heating in sunny weather. No mine.

Table 7. Synopsis of experimental results using 2450 MHz microwave frequency.

Run #	Mine Type	Burial Depth (cm)	Height of Waveguide (cm)	Weather Conditions	Comments	Reference Figure #
40	none	–	44	sunny, few clouds, 26°C	power density too low	
41	none	–	30	humid, windy, 22°C	2 spots close together	
42	none	–	30	humid, windy, 24°C	with horn, still seeing 2 spots	
43	PMA 1	1	30	humid, windy, 25°C	with horn, mine distinguishable within 15 minutes	
44	none	–	15	sunny, 18°C	with horn, spot size small	
45	PMA 1	1	15	sunny, 22°C	spot less circular, mine distinguishable within 10 minutes	31
46	PMA 1	1	15	sunny, 22°C	mine is offset and was buried at same time	
47	PMA 1	1	15	cloudy, humid, 16°C	can see the mine before illumination, mine offset	
51	PMA 3	1	15	sunny, mild winds, 18°C	mine distinguishable within 5 minutes	32
52	PMA 2	1	15	sunny, mild winds, 24°C	mine distinguishable within 10 minutes	12, 13
54	none	–	15	sunny, 16°C	spot size larger than those created by mines	14
56	none	–	fixed	sunny, 16°C	temp probe at 1cm	

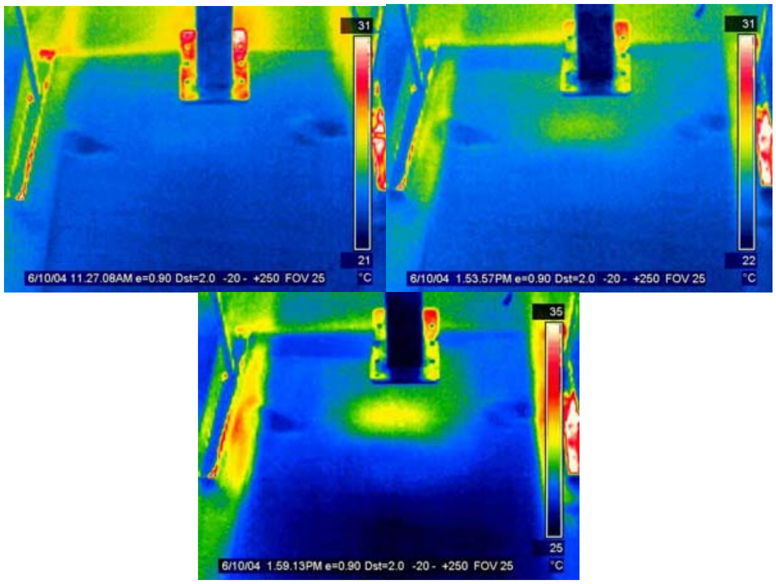


Figure 31. 0, 3 and 8 minutes of 2450 MHz microwave heating. PMA 1 buried 1 cm deep.

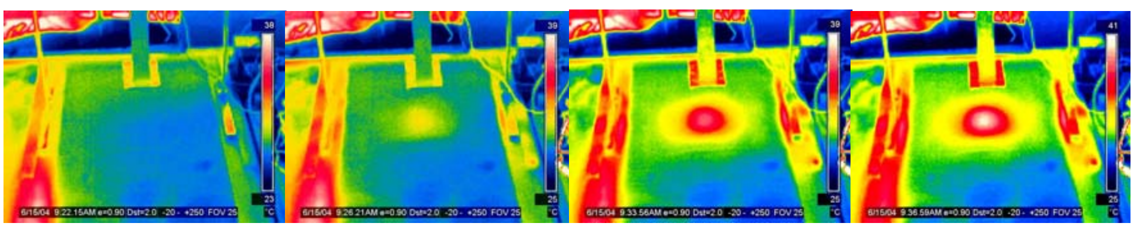


Figure 32. 0, 4, 8 and 11 minutes of 2450 MHz microwave heating. PMA 3 buried 1 cm deep in sunny weather.

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As a continuation of previous studies in microwave enhanced infrared (IR) detection of landmines at DRDC Ottawa, additional experiments were performed using a microwave source at 2450 MHz to illuminate buried inert antipersonnel and antitank landmines. Further experiments were performed for the first time using a microwave device at 915 MHz with an open waveguide. Infrared detection was accomplished using a FLIR A20M IR camera in the 8-12 mm region. An investigation of this method was done by examining mine signatures made up of two components: the microwave interference on the surface of the sand caused by the superposition of incident and reflected microwave beams, and the microwave absorption by the mine and sand causing a temperature difference to be thermally conducted to the surface of the soil.

Results are presented for a wide variety of experimental arrangements. An attempt at simulating various minefield conditions was explored. Some of the surfaces examined above buried mine targets include smooth, moist, hand brushed, very uneven, and raked soil. Introducing clutter on the surface of the soil such as pebbles, rocks, leaves and wood has also been studied. Many of these parameters impeded the detection process. Thus, this method is not an all-encompassing solution to mine detection but may improve IR methods in circumstances such as dark or cloudy weather. Outlined recommendations concerning future scientific studies into the proposed method may refine microwave enhanced IR imagery.

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landmine detection, high power microwave heating, IR, infrared, thermal imaging, remote sensing