Controlled field experiments of wind effects on thermal signatures of buried and surface-laid land mines

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ABSTRACT

Thermal signatures of buried land mines depend on a complex combination of environmental conditions, soil properties, and properties and burial depth of the land mine. Due to the complex nature of the problem most modeling and experimental efforts to understand thermal signatures of land mines have focused on the effects of one or a few variables. Of these variables, the effect of wind speed has received little attention in modeling and experimental studies. In this contribution we discuss the role of wind in the generation of thermal images and we present results of field experiments at the outdoor land mine detection test facility at New Mexico Tech. Here, several anti-tank and anti-personnel land mine simulants have been buried in sand, loam, and clay soils. During the measurements the environmental and soil conditions were continuously monitored using a fully equipped weather station and using probes for measurements of soil temperature and soil water content.

Keywords: land mine test lane, thermal infrared, detection, climatic conditions, wind speed

1. INTRODUCTION

Infrared technology uses diurnal temperature variations to detect anomalous surface temperatures above buried mines or resulting from surface-laid mines. The thermal signature of a buried or surface-laid mine is a function of many different parameters in the atmosphere, the soil and of the mine itself. Because of this complexity a comprehensive model for the prediction of thermal signatures does not exist and the large variability in performance remains unexplained [1]. Because of these drawbacks infrared technology is currently not applied in the field of humanitarian demining and chances are slim that this will change in the near future [2]. However, the technique holds promise for the detection of surface-laid land mines and buried anti-vehicle mines, provided that the underlying basic phenomena and the effects of variable soil and environmental conditions are better understood.

Predicting the thermal signature ($\Delta T = T_{surface,\ mine} - T_{surface,\ no\ mine}$) of a buried landmine requires knowledge of the heat flux into the soil, the thermal properties of the landmine, the soil above the landmine and of the soil surrounding the landmine. Several papers discuss the underlying physical principles of the processes that cause temperature perturbations at the surface caused by subsurface anomalies [3,4,5,6,7]. Inherent to the cyclic nature of the incoming solar radiation, the thermal signatures of underground anomalies follow a cyclic pattern. Due the nature of heat propagation into the soil and its dependency on soil thermal properties (heat capacity, thermal conductivity, which in turn depend on the type of minerals, porosity, and water content) the cyclic pattern of temperatures above an anomaly may experience a time shift [5]. To make matters more complicated, the strength of the thermal signature and the phase shift of the signal are also affected by the (thermal) properties of the land mine [8] and by the burial depth of the land mine [3,9,10].

Intuitively, we know that the strength of the thermal signature decreases with increasing burial depth, which is confirmed by both modeling and experimental studies. However, the phase shift is also a function of the burial depth. The thermal signature of a land mine buried close to the soil surface will experience its maximum temperature contrast with the background (its undisturbed surroundings) at a time close to the maximum incoming radiation [7,9], while the

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maximum rate of change of thermal signatures may occur around sunset and sunrise [5,11]. Thermal signatures of deeper buried mines experience a phase shift [3,7,9]. Using a simple one-dimensional analytical solution for the temperature propagation through homogeneous and layered soils the effect of burial depth of a landmine on the thermal signature can be shown (Fig. 1).

Due to the complex nature of the problem most modeling and experimental studies focus on the effects one or a few variables involved. Of these variables, wind speed and its variability has received remarkably little attention. Wind speed affects the convective transport of heat between the surface and the atmosphere [4,12] and has an effect on the temperature of the surface. Also, because under natural conditions wind speed is never constant over long periods of time, wind variability has a potential effect on thermal camera images. Several publications acknowledge the relevance of wind speed for thermal imaging of land mines [1,11,13,14]. However, to date no systematic field experiments studying the effects of variability in wind speed on thermal images of land mines have been performed. The objective of this contribution is (1) to discuss the role of wind in the generation of thermal images and (2) to present the results of field experiments at the outdoor land mine detection test facility at New Mexico Tech.

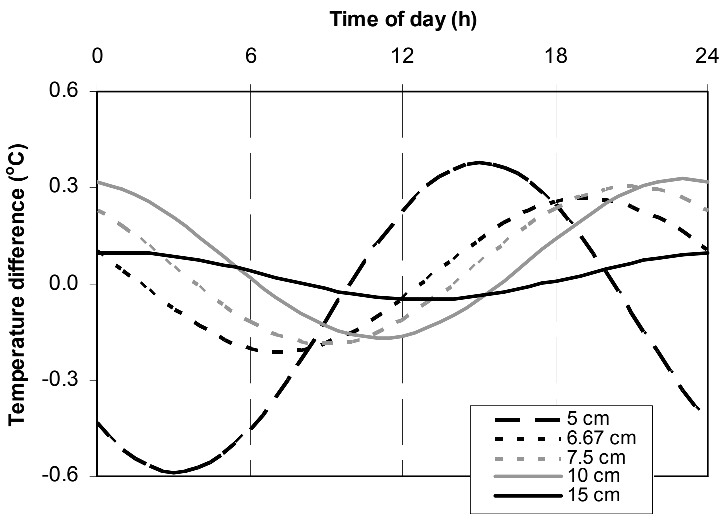

Fig. 1. Model results showing the thermal signature for mines composed of TNT buried at different depths in dry sand using a model by [12], adapted by [9].

2. THEORY

The temperature of the soil surface is a function of different sources of electromagnetic radiation. Short wave solar radiation is the driving source but the amount of radiation available at the soil surface may vary due to reflection and adsorption in the atmosphere and reflection at the soil surface. In the soil, heat can move upwards or downwards, but typically is directed downwards during the day, while the soil loses heat during the night. Convective and advective processes transport latent heat away from and to the surface. Figure 2 is a schematic presentation of the processes involved.

Ignoring the negligible component of diffusive transport, the heat balance at the soil surface can be described as [4]:

$$q_{soil}(t) = q_{sun}(t) + q_{rad}(t) + q_{conv}(t)\,,$$

where q_{soil} is the soil heat flux [J/m^{2}s]. The term q_{sun} is the incident solar radiation minus the atmospheric absorption and reflection, and the surface albedo. The second term q_{rad} represents the long-wave heat from the atmosphere to the surface minus the long-wave radiation emitted by the soil.

The term q_{conv} is the sensible heat that is transported from or to the soil surface by convection or advection and can be expressed as [14]:

$$q_{conv}(t) = h_c\left(T_0(t) - T_a(t)\right),$$

where T_a is the temperature of the air at the soil-air interface and T_0 is a reference temperature. The convective heat transfer coefficient, h_c, is given by:

$$h_c = \frac{C_a k^2 \phi U_a}{\left(\ln\left(z_a / z_0\right)\right)^2}.$$

Here, C_a is the volumetric heat capacity of air, k is Von Karman's constant (0.4), ϕ is a factor related to the Richardson number, and U_a is the wind speed at reference height z_a [14]. It follows that convective losses increase when wind speed increases [12].

In recent literature one paper is presented that specifically addresses the effects of wind speed of thermal signatures of buried land mines [14]. In this model, thermal signatures of buried land mine, which has the thermal properties of TNT, are calculated for four different constant wind speeds. The results show that an increase in wind speed decreases the strength of thermal signature, but does not cause any phase shift. No literature examples are known about the effects of short-term wind variability (i.e., on the order of tens of minutes or hours) on thermal signatures.

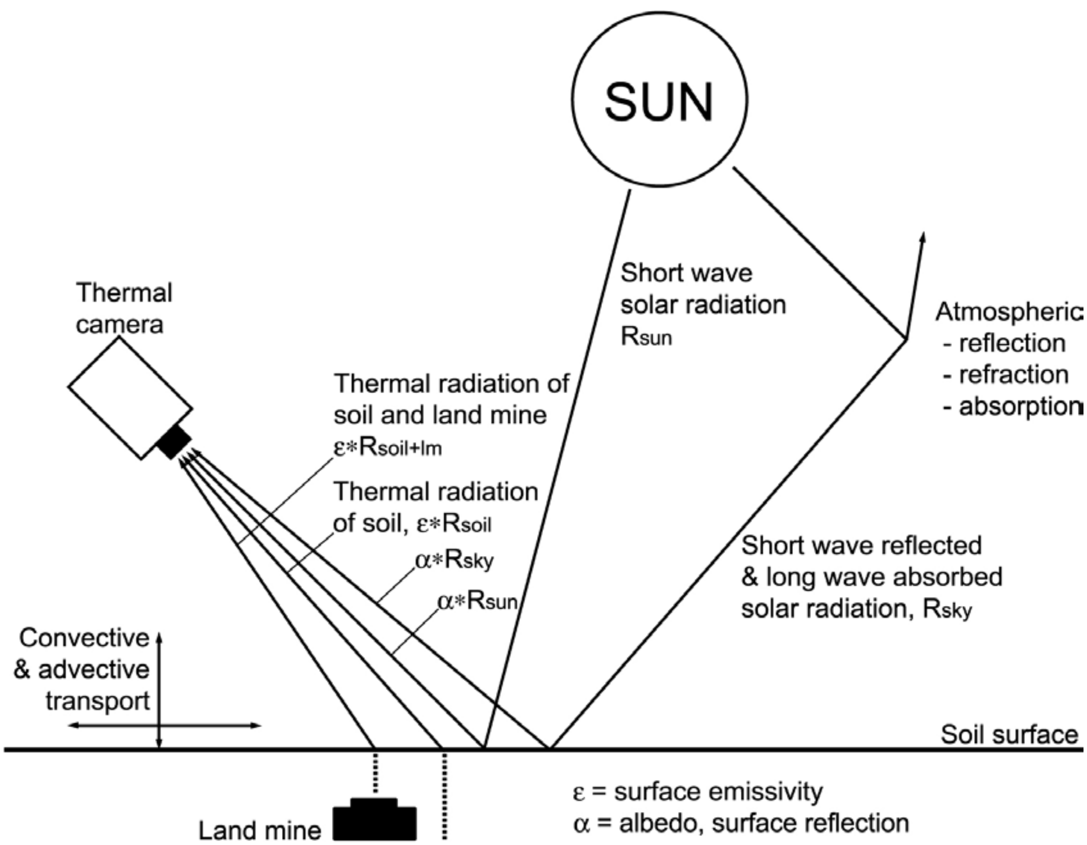

Fig. 2. Schematic diagram of processes involved in thermal imaging of the soil surface.

3. EXPERIMENTAL SETUP

3.1 Land mines and material

Measurements were performed in a loam soil at an outdoor test site on the campus of New Mexico Tech in Socorro, New Mexico. At this test site several low-metal anti-tank and anti-personnel land mine simulants are buried in 2×2×1 meter wooden test boxes that are filled with sand, loam and clay sediment (Fig. 3). In the test boxes the soil temperature and the soil water content are continuously monitored at various depths in homogeneous soil and above and below the buried land mines. Also, the environmental conditions are monitored using a weather station. More about this test site can be found in an accompanying paper [15].

In each of the test boxes 2 nonmetallic anti-tank (AT) mine simulants were buried with their top at 0.05 meters depth (Fig. 4a). These mines are composed of Dow Corning 3110 RTV silicon rubber and have been designed to simulate a Netherlands landmine of type NR26 [16] (Fig. 5a). Four anti-personnel (AP) mine simulants were buried at the surface, and at 0.02, 0.04, and 0.06 meters depth (Fig. 4a). These mines have been manufactured by New Mexico Tech using silicon rubber and a plastic casing and have a 2.5 cm air gap (Fig. 5b). Each test box is equipped with 8 sensors for soil moisture measurements and 8 sensors for measurements of soil temperature (Fig. 4b). One sensor of each was placed at 0.02m depth above the AT mine simulant. Four sensors of each were placed below the AT mine simulant at 0.2m, 0.3m, 0.4m, and 0.5m depth. Three sensors of each were installed at 0.02m, 0.2m, and 0.5m depth in undisturbed soil away from the land mine simulants. The sensors are connected to a datalogger to allow continuous monitoring of the conditions.

Fig. 3. Overview of the NMT land mine detection test facility showing clay (foreground), loam (middle), and sand test pits.

3.2 Weather station

The weather station for monitoring of atmospheric conditions is equipped with a net radiometer, a sonic anemometer, a rain gauge, a thermocouple, a hygrometer, and a scintillometer. The net radiometer measures the difference between incoming and outgoing short- and long-wave radiation. The sonic anemometer measures turbulent fluctuations of wind speed and speed of sound on three nonorthogonal axes; data that are used to obtain the horizontal wind speed. The thermocouple measures the air temperature, while the hygrometer measures the atmospheric water vapor. The data from the anemometer, the hygrometer, the thermocouple, and the net radiatiometer, plus an estimate of the soil heat flux, can be used to calculate the evapotranspiration rate. The tipping bucket rain gauge measures precipitation at 0.01 inch increments. The scintillometer measures atmospheric turbulence, heat flux and crosswind over a large distance of several kilometers.

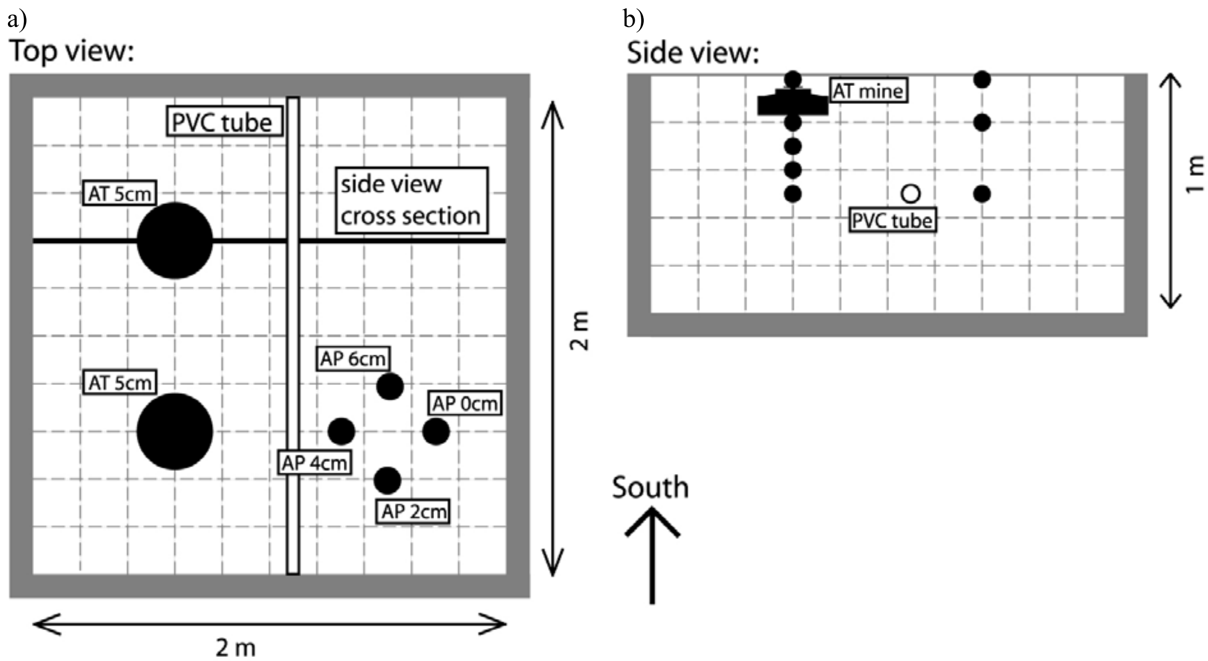

Fig. 4. Layout of the test boxes. a) Top view, showing the location of the different land mines and PVC tube buried at 0.5 meter depth. c) Side view, showing the location of the PVC tube (open circle) and the locations of the temperature and time domain reflectometry sensors (black circles).

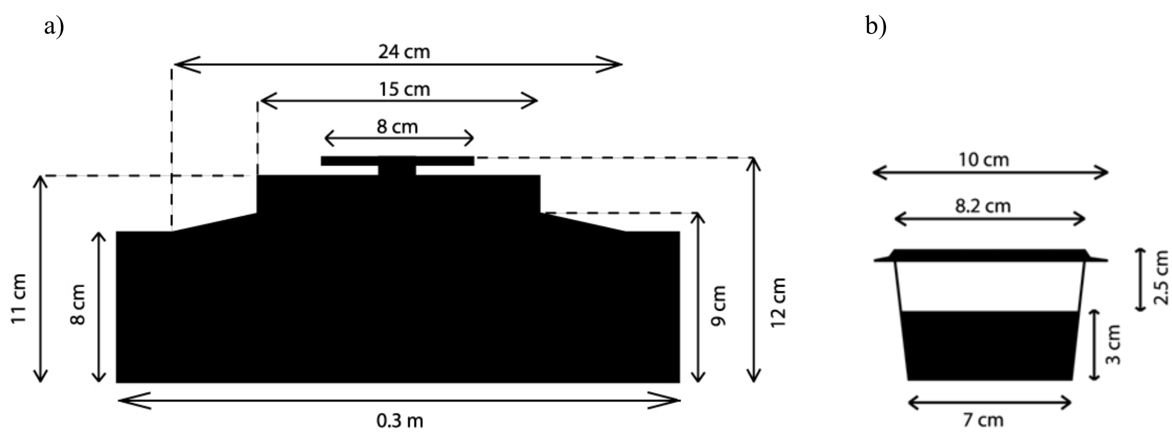

Fig. 5. Schematic pictures of the buried land mine simulants; a) AT land mine; b) AP land mine.

3.3 Infrared camera

We used a ThermaCAM SC3000 infrared (IR) camera manufactured by FLIR Systems Inc., Sweden, for measurement of the apparent temperature of the soil surface above and away from the buried land mines (Fig. 6). This IR camera has a spectral range from 8 to 9 µm with thermal sensitivity of 0.03 °C at +30 °C. It uses a quantum well infrared photon detector. The camera was placed on a tripod at 2 meters height at the northern side of the loam test box. The raw thermal IR images were analyzed using the software provided by FLIR, and using standard spreadsheet programs.

Fig 6. Picture of the FLIR thermal infrared camera at the New Mexico Tech land mine detection test facility.

4. RESULTS

We present the results of measurements on February 18, 2004, when we took thermal IR images of the loam test plot, and measured the wind speed and air temperature. All measurements were collected at 10 minute intervals from 9 AM to 6 PM. In Fig. 7 four thermal IR images of the loam test plot are shown. The buried AT mine simulant shows up as a warmer spot in the lower left of the images (especially Fig. 7c). The surface-laid AP mine simulant is clearly visible as a colder (dark) spot in the lower right of the images (except Fig. 7d). The AP mine simulant buried at 2 cm is well visible around noon as a warmer spot to the lower left of the surface-laid mine simulant (Fig. 7b). See Fig. 4a for reference.

The air temperature during the day varied about 8 ^{o}C (Fig. 8a). The apparent temperature of the soil surface in the test box showed a larger variation and increases from –7.5 ^{o}C in the early morning hours to 30 ^{o}C around 1PM. After 1 PM it gradually decreases to around 6 ^{o}C at 6PM (Fig. 8a). The 10-minute average wind speed varies significantly during the measurement period. It is around 1 m/s during the early morning and increases to values around 5.5 m/s after which it gradually decreases in the late afternoon (Fig. 8b). Figure 8c shows the wind speed is positively correlated with the air temperature, test box surface temperature, and the temperature of the surface-laid mine simulant. This is merely a result of the fact that the wind speed experienced a cyclic pattern and was highest on the middle of the day, and lower around sunrise and sunset (Fig. 8b).

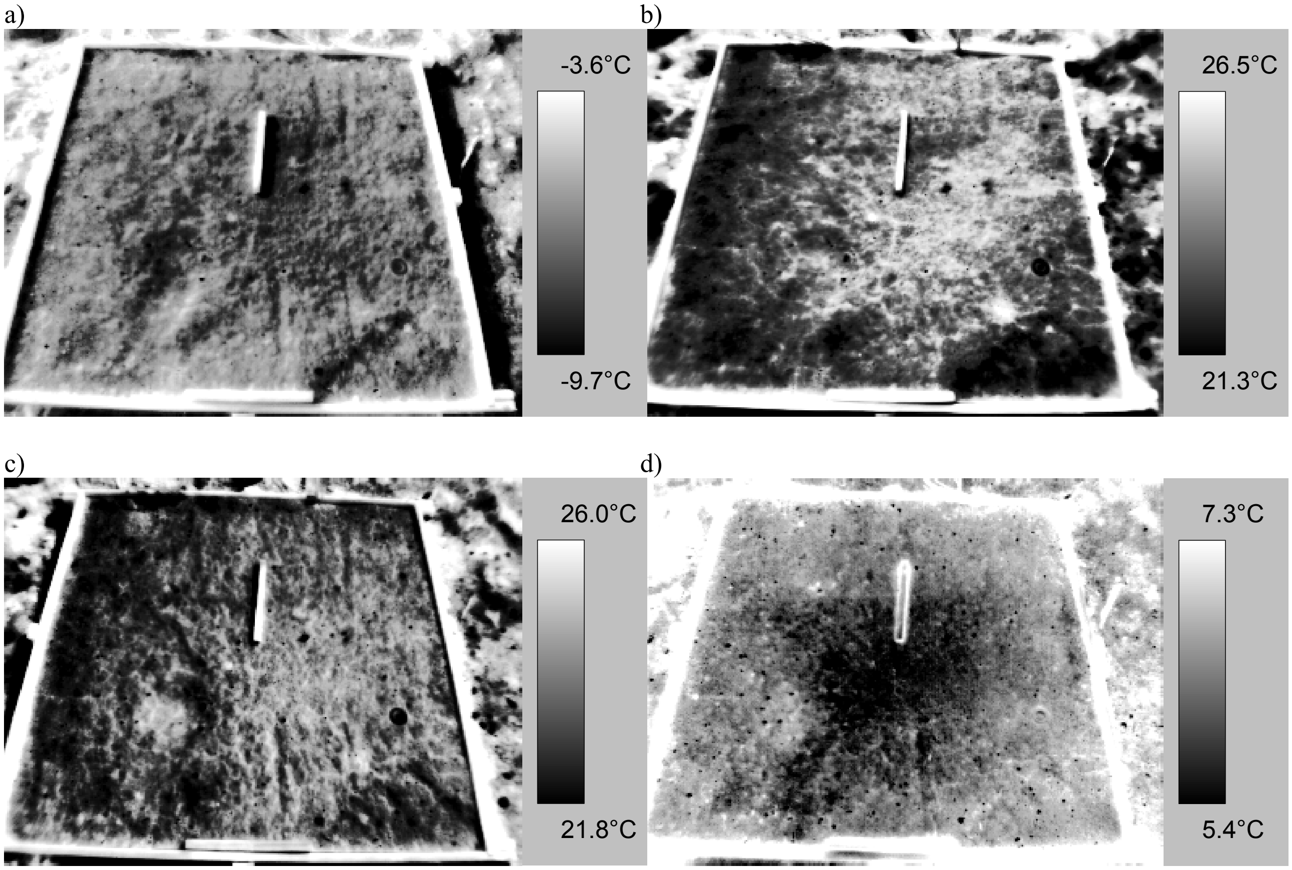

Fig. 7. Thermal infrared images of the loam test on February 18, 2004. a) 6 AM, b) noon, c) 3PM, d) 6PM. The vertical bar in the middle of the plots, and the horizontal bar in the bottom of the plots are 50 cm long rods for scale.

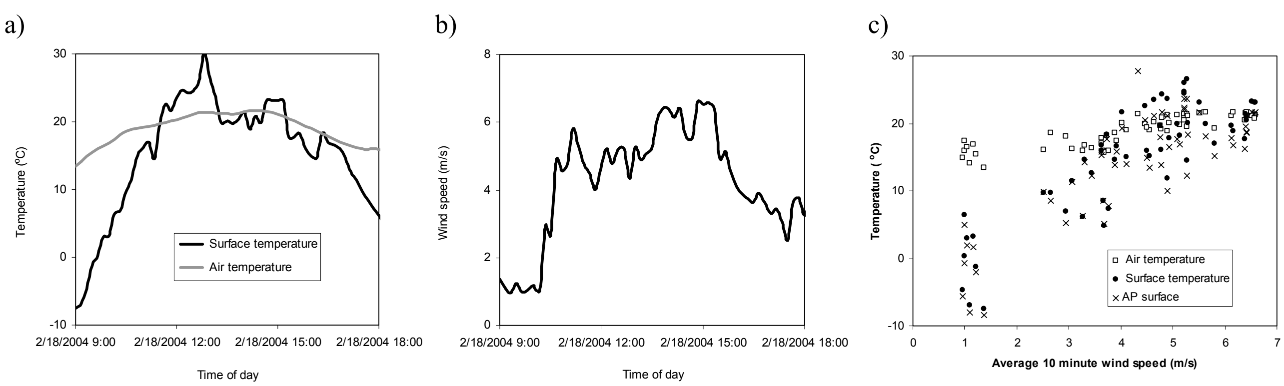

Fig. 8. a) Time series showing variation in surface temperature and air temperature at 2 meters height. b) Time series showing variation in average wind speed. For both plots the measurements were averaged over a 10 minute period. c) Plot showing the correlation between the average wind speed measured over a 10 minute interval and the air temperature, test box surface temperature, and the temperature of the surface-laid anti-personnel land mine simulant.

The thermal signature of a (buried) land mine is defined as the temperature above the land mine minus the temperature of the soil surface surrounding the land mine. Thus, a positive thermal signature means that the surface temperature above a land mine is higher than the surface temperature of its surroundings. We determined the mean apparent temperature of the soil surface above the land mines by averaging the temperature within a circle with a radius that equals ~75% of the radius of the respective AT and AP mines. We determined the mean apparent temperature of the soil surface away from the mine for an area enclosed by two concentric circles surrounding the mine.

Figure 9 is a plot of the change in thermal signatures for the different land mine simulants in the test plot. The surface-laid AP mine simulant has a strong negative thermal signature, which is mainly a result of its contrasting color. The white surface of this mine has a higher albedo than the loam soil and causes a large part of the solar radiation to reflect. The other (buried) mine simulants all have a positive thermal signature during most of the day. The AP mine buried at 2 cm depth has a strong positive thermal signature, which reaches it peak between noon and 1 PM, after which it rapidly decreases. The other mine simulants have less strong thermal signatures. The thermal signature of the AT mine simulant buried at 5 cm depth experiences a time shift of approximately 2.5 hours.

To study the possible effects of the variability in wind speed on the thermal signatures we plotted these variables in Fig. 10. These plots indicate there may be a negative correlation between the two variables for the surface-laid mine and a small positive correlation between thermal signatures and wind speed for the buried mines (Fig. 10a). However, the variation in wind speed is not normally distributed (see Fig. 8b), and there is a positive correlation between wind speed and air and surface temperature (Fig. 8c). We believe this may affect the correlations in Fig. 9a. Figure 9b shows the scatter plots for the thermal signature and wind speed for the time frame between 11 AM and 4 PM, when the wind speeds fluctuates around a constant mean of approximately 5.5 m/s. For this situation, there seems to be a small negative correlation between the two variables for the AP land mine stimulant buried at 2 cm depth. For the other land mines there appears to be no correlation.

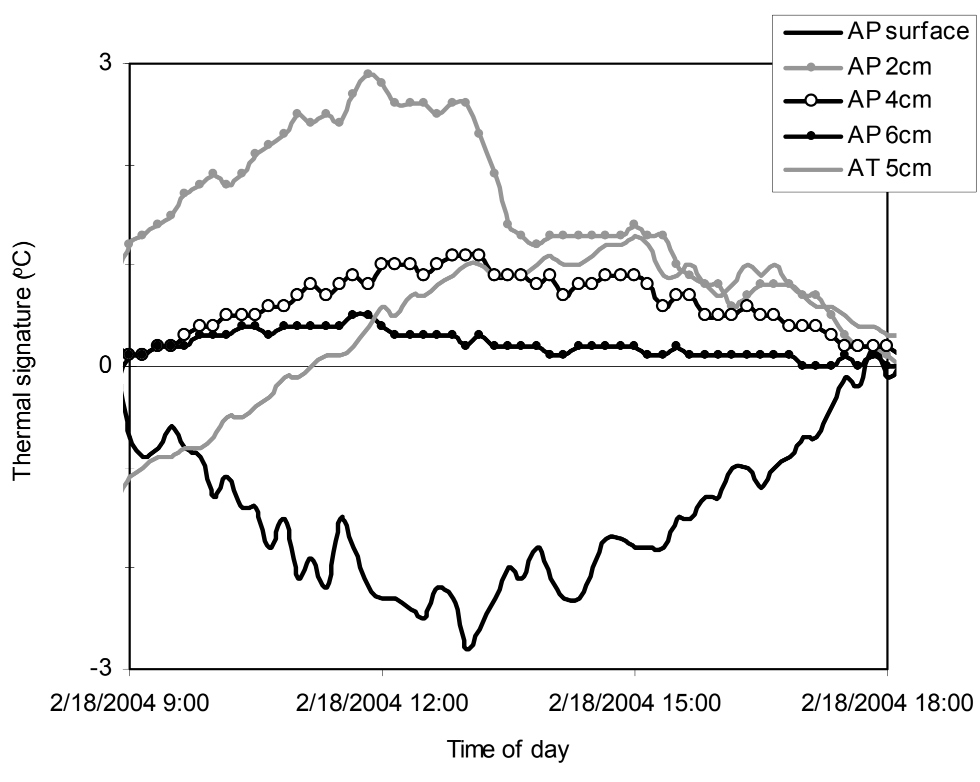

Fig. 9.Time series of thermal signatures for different land mine simulants at the New Mexico Tech land mine detection test facility.

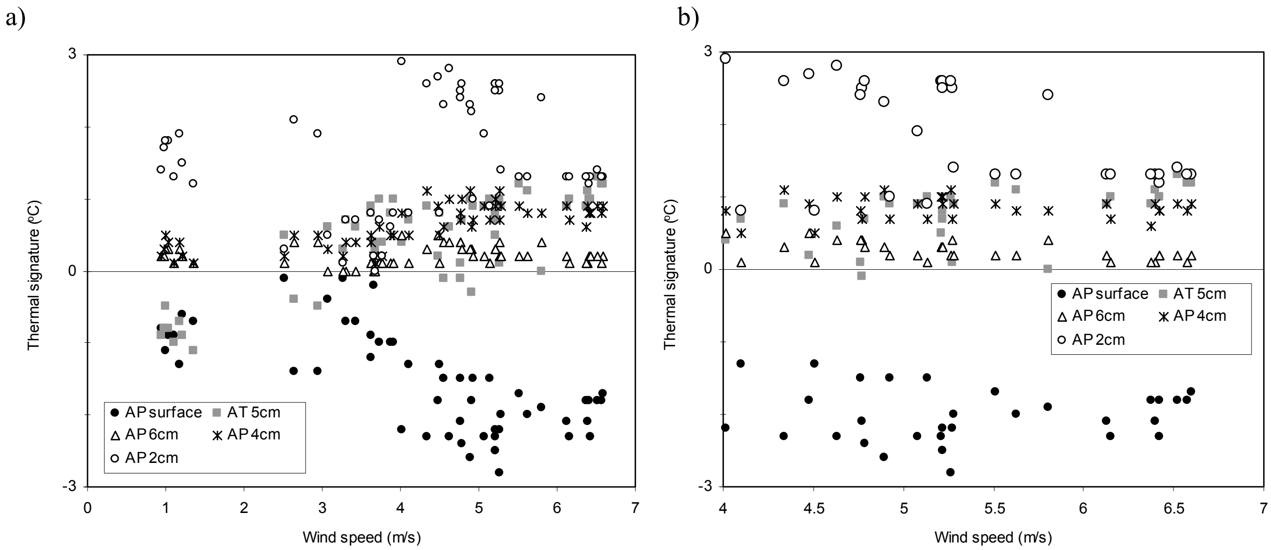

Fig. 10. Plots showing the correlation between the 10-minute average wind speed and thermal signatures of all the land mine simulants buried in the loam soil; a) the full data set; b) for the time frame between 11 AM and 4 PM.

5. DISCUSSION

The thermal signatures of land mines are controlled by a wide range of variables in the atmosphere (net solar radiation, wind), in the soil (soil thermal properties, water content), and of the land mine itself (material and explosive, burial depth). In all this complexity the effects of wind have hardly been studied. Using a simple energy balance model it can be shown that a higher wind speed causes an increase in convective transport of heat from the surface. This, in turn causes a decrease in thermal signatures [14]. However, the effect appears to be small. No effect of wind on the phase shift of the thermal signatures was detected. The situation of advective transport of heat to the surface (in the case of a wet soil) has not yet been studied.

In this paper we have shown results of experiments studying the effects of short-term wind speed variability (10-minute average wind speed) on thermal IR images of a series of buried and surface-laid AT and AP land mine simulants. Based on theory, a smaller thermal signature is expected for higher wind speeds because the wind attempts to even out the existing temperature differences at the surface. The results from our experiments are non-conclusive. Although a small correlation seems to be present between wind speed and thermal signature for some land mines, it seems that in most cases the short-term variability in wind speed does not affect the thermal signatures.

A more extended study in which each of the variables is singled out by avoiding cross-correlations between wind speed, time of day, incoming solar radiation, and surface temperature, is needed to fully understand the effects of wind speed on surface temperature in general and thermal signatures in particular. For this we plan to look more in depth into surface energy balance models and perform controlled measurements in the laboratory to study the effects of wind speed (without cyclic variation in radiation). Also, we plan to expand our experimental dataset with measurements during night time, for periods of advective rather than convective transport of latent heat, and during periods with a larger variability in wind speeds.

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