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Preface

This study was conducted for the U.S. Army Corps of Engineers (USACE) under Army Direct funding, Program Element Number 622144A, Project BN87, Task 812. The technical monitor was Dr. Jay Clausen.

The work was performed by the Biogeochemical Sciences Branch (Mr. David B. Ringelberg, Acting Chief) of the Research and Engineering Division (Dr. George Calfas, Chief), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, the Deputy Director of ERDC-CRREL was Mr. David B. Ringelberg, and the Director was Dr. Joseph L. Corriveau.

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The Commander of ERDC was COL Teresa A. Schlosser and the Director was Dr. David W. Pittman.

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Modeling of a Multi-Month Thermal IR Study

^J ABSTRACT

Inconsistent and unacceptable probability of detection (PD) and false alarm rates (FAR) due to varying environmental conditions hamper buried object detection. A 4-month study evaluated the environmental parameters impacting standoff thermal infra-red (IR) detection of buried objects. Field observations were integrated into a model depicting the temporal and spatial thermal changes through a 1-week period utilizing a 15 minute time-step interval. The model illustrates the surface thermal observations obtained with a thermal IR camera contemporaneously with a 3-d presentation of subsurface soil temperatures obtained with 156 buried thermocouples. Precipitation events and subsequent soil moisture responses synchronized to the temperature data are also included in the model simulation. The simulation shows the temperature response of buried objects due to changes in incoming solar radiation, air/surface soil temperature changes, latent heat exchange between the objects and surrounding soil, and impacts due to precipitation/changes in soil moisture. Differences are noted between the thermal response of plastic and metal objects as well as depth of burial below the ground surface. Nearly identical environmental conditions on different days did not always elicit the same spatial thermal response.

1. INTRODUCTION

The environmental phenomenological properties responsible for thermal variability evident in the use of thermal infrared (IR), (0.7 – 1300 μm) sensor systems is not well understood. This lack of understanding is manifested in a poor probability of detection (PD) and elevated false alarm rate (FAR) when using IR for buried object detection. Understanding the variables comprising the thermal variance and associated IR signature would be invaluable in improving the signal-to-noise ratio for buried object detection using IR sensors.

The U.S. Army has been testing a variety of sensor systems (IR, seismic, acoustic, radar, and electromagnetic) for detecting buried objects and has amassed a significant library of data. It has also spent the last several years developing and testing a diversity of computer algorithms incorporated into automatic target recognition (ATR) software to improve buried object detection. However, these efforts do not yet consistently meet the desired performance, i.e. confidence at the three nines level. We hypothesize the undesired performance is the lack of consideration in the detection algorithms for the impact of soil and atmospheric phenomenological properties on sensor performance.

The Army needs techniques for rapidly assessing within a large spatial area the location of soils disturbed by buried-object emplacement. Coupling of wide area assessment technologies, such as IR signatures, magnetic fields, or other spectroscopic sensor modalities on areal platforms, with novel geospatial statistical methods is a means to effectively evaluate large spatial areas for soil disturbances. Our approach uses mid- and long-wave IR imagery for detecting soil disturbances. For example, modern thermal sensors are capable of detecting thermal differences on a fraction of a Celsius degree. However, a common problem for practical use of this technology is the unacceptable rate of false positive detections, which requires substantial time-consuming human intervention to assess the validity of the detection.

2. BACKGROUND

Historically, electromagnetic sensor systems have been utilized to detect buried ferrous objects. However, buried objects are made out of other materials (e.g., plastic, wood) as well as metal. Recent military conflicts have increased interest in other sensor modalities (e.g., thermal IR hyperspectral imagery, seismic, acoustic, and ground penetrating radar (GPR)). These sensor modalities are principally operated independently. However, there is increasing interest in the sensor application community for fusing multiple sensor systems into a single comprehensive platform allowing for complimentary integrative analysis [1]. Additionally, using autonomous unmanned aerial vehicles (UAVs) or unmanned ground platforms (UGVs) could allow for quickly characterizing an area at standoff distances.

The goal of new detection methods is to detect all constructs of buried objects, such as plastic, metal, or wood, in any type of soil, weather, or extenuating condition. Bello [2] states no optimal procedure yet exists and current methods perform inconsistently, depending on the environmental conditions and object material. The best method should be able to detect the object instantaneously with few false alarms [3].

Interest in IR thermography as a sensor modality has increased in the past decade. Thermal IR is based on the concept that the thermal signature of soil is altered by objects buried at shallow depths, regardless of material type [4]. The technique measures surface-emitted electromagnetic energy in the IR radiation band, also known as thermal radiation. Materials differ in thermal capacities, resulting in different heating and cooling rates and associated infrared emissions [5]. Buried-object detection using IR depends on the object's thermal signature being different than the surrounding soil. The deeper the object is buried, the more important it becomes to understand the soil signature and how it is affected by soil texture, water content, and other factors [6, 7] since the signal weakens with increasing depth. Other environmental factors investigated include diurnal cycles and meteorological properties ([5, 8, 9]. However, the mechanism of heat and moisture transfer contributing to contrasts in thermal variance where objects are buried remain unclear and unquantified [10].

3. METHODS

The study was conducted at the Cold Regions Research and Engineering Laboratory (CRREL) Hanover, NH in an area devoid of brush and trees, eliminating shadow effects. This study consisted of a 3.05×3.05 m test plot, containing twenty-five 61×61 cm cells. A test plot was scraped with a surface excavator to remove the surface vegetation, exposing bare ground consisting of mineral soil to simulate a typical unsurfaced road. On 6 October 2016, we buried four objects at the test plot (Figure 1) following guidelines in [11]. A small excavation was made to a depth sufficient to cover the buried object with 5 cm of soil. The removed soil was placed on plastic next to the hole and then used to cover the object with the excess removed from the site.

Figure 1. Spatial locations of buried objects, disturbed soil, white body panel, Fiducials, and control areas for the CRREL 3.05 x 3.05 m test plot.

A meteorological station as well as upward and downward looking radiometers to record incoming and reflected solar radiation were located approximately 50 m south of the plot. The meteorological station records air temperature (approximately 1 m above the ground), precipitation, wind speed and direction, barometric pressure, and relative humidity. Soil temperature was measured at five locations within the plot using a string of thermocouples installed at six depth intervals of: 0.0, 5.1, 15.2, 30.5, 45.7, and 61.0 cm below ground surface (bgs) (Figure 2). Six calibrated Campbell Scientific CS655 sensors were installed at two locations (Figure 2). These sensors measure temperature, volumetric water content, bulk electrical conductivity, and relative dielectric permittivity. Two Campbell Scientific CS616 water content reflectometers were also installed, one location in the test plot and one location just northeast of the plot (Figure 2). Volumetric water content was measured at one location in the test plot with a Delta-T PR2 soil moisture probe that had sensing elements at 10.2, 20.3, 30.5, 40.6, 61.0, and 91.4 cm bgs (Figure 2). Data acquisition on 15-minute intervals and synchronized to the collection of the IR camera images began on 30 August and continued to 31 December 2016. In addition, one time analysis was made of the surface roughness, soil particle size, density, and chemistry.

Figure 2. Subsurface instrumentation emplacement.

Figure 3 is post disturbance high resolution (300,000 points/second) LIDAR image collected at 1,550 nm of the test plot. The image indicates the soil disturbance in terms of changes of topography as a result of object burial was kept to a minimum with the site being relatively flat. The elevated area corresponding to the White Body panel is evident in the upper left as is excess soil left above the rectangular metal and rectangular plastic objects, disturbed soil, and round plastic object (Figure 1). In these locations there appears to be 1 to 2 cm of excess soil as compared to the topography prior to object placement.

Figure 3. Surface topography of the test plot post-object emplacement.

The plot was imaged using a FLIR (Forward Looking IR) Systems Inc. camera (model A300), hereafter referred to as FLIR, with the Scout III 240 lens. The field of view is $24 \times 18^\circ$, which covers the entire 3.05 x 3.05 m plot. The camera's resolution is 320 x 240 pixels with a spatial resolution of 25 μm for the 24° lens using an uncooled microbolometer. The camera provides fully radiometric 16-bit real-time video to a computer.

The FLIR camera outputs the intensity of the received radiation (energy per unit area per time). Raw intensity data is converted to temperatures using either the FLIR software or by using the FLIR-supplied metadata and external tools. The FLIR camera output temperatures must be corrected for background radiation and emissivity difference effects to obtain a sensible heat temperature that equals the physical temperature. Before the camera was used, it was calibrated against measured soil temperatures and “white” and “black” bodies equilibrated to the surrounding atmosphere, and in some cases soil surface temperature using a two-step process.

The first step involved verifying that the FLIR software was correctly converting the raw image radiance data files to temperatures using Ex-ifTool (a UNIX program) to extract the emissivity and reflected apparent temperature from each radiance file (3 separate 8-bit band intensities or a composite 24-bit value in *.jpg format). These parameters were then input into MATLAB's FLIR software development kit, which enables post processing of FLIR imagery to calculate the associated temperatures. These values were then compared to those calculated using the proprietary FLIR software. The second step compared the calculated temperatures against several external probe reference temperatures using the buried thermocouples and black and white bodies.

The thermal IR surface soil images generated on 15 minute intervals were stitched together using MATLAB to create a temporal model of the site from the period of 7 to 15 October 2016. A 3-d model of the subsurface soil temperature was also created using the soil thermocouple sensors as well as a plot of the mean surface and subsurface soil temperature. All three figures were incorporated into a video showing the spatial and temporal variability of soil temperatures. The buried objects were present during the period of time selected. More details on the experimental setup can be found in Clausen et al. [12].

4. RESULTS

A comparison of the surface soil spatial temperature variability is shown in (Figure 4) for three days (25 to 27 September 2016 at 1700 hours prior to object placement. Each of the images in Figure 4 were obtained at 1700 hours when the sun angle was 8° above the horizon corresponding to minimal incoming short-wave IR (SWIR) and long-wave IR (LWIR). Each day had similar environmental conditions and similar air temperatures prior and during image collection (Table 1). What is notable is that the mean and range of FLIR measured surface soil temperature is different each day and unexpected. As presented in Table 1, 27 September started out foggy with morning rain giving way to sunshine around noon. Yet, the surface soil temperatures are hotter than 26 September where the maximum air temperature was two degrees higher and 25 September where it was sunny all day. Further the distribution of temperatures is spatially heterogeneous and the pattern of distribution is different each day. However, there are temperature patterns that appear spatially in the same locations, e.g. cool cluster circled at the bottom of images Figures 4a and 4b or hot cluster circled in the upper left of Figures 4a, 4b, 4c.

Figure 4. Comparison of pre-object placement thermal IR images for 4a) 25 September, 4b) 26 September, and 4c) 27 September 2016.

Table 1. Summary of weather conditions for Figure 3.

Variables	25 September	26 September	27 September
Time of Day (hr)	1700	1700	1700
Sun Angle (°)	8	8	8
Air Temp. (°C) @ 1700 hour	24.0	28.3	24.6
Wind Speed (m/sec) @ 1700 hour	0.4	0.5	0.5
Max Air Temp & Time (°C @ hr)	25.9 @ 1430	29.6 @ 1500	27.6 @ 1400
Weather Conditions	Sunny	a.m. fog then sunny	a.m. fog & rain then sunny

Against this backdrop pre- and post-object emplacement thermal images were compared for 6 October 2016. The pre-emplacement image was collected at 0100 and the post object emplacement at 2355 (Figure 5). The weather conditions were dry at the time of object placement and two days prior. The air temperature was 8.1°C at 0100 and 8.2°C at 2355 and the wind was calm at both times. Image collection occurred at night so there is no incoming SWIR or LWIR. In these images it is apparent that the degree of spatial variability, clustering of elevated and lower surface soil temperatures, is reduced post emplacement despite disturbing less than 10% of the total plot area. Further, the

objects emplaced beneath the subsurface, the disturbed soil, and White Body are visible as areas of colder temperatures as compared to the surrounding soil. In Figure 5b, the seven buried objects/disturbed areas are noted are as follows; 1) White Body panel, 2) disturbed soil with no object, 3) buried round plastic object, 4) buried rectangular metal object, 5) buried round metal object, 6) buried rectangular plastic object, and 7) location of where surface vegetation (individual weeds) were burned using a blow torch. Object 5 is 1/10 the size of objects #3, 4, and 6. All object emplacement and site disturbance was completed by 1400 hours on 6 October.

Figure 5. Comparison of 5a) pre-object and 5b) post object placement thermal images for 6 October 2016.

To attempt to understand what may be occurring it was decided that more than single IR snapshot images was needed. Consequently, a period of time following object emplacement was selected for more detailed analysis. Figure 6 depicts the diurnal change in thermal response for each 15 minute interval from 7 to 15 October of the surface soil above three of the buried objects, a disturbed area with no object emplaced, and a control area with no soil disturbance as compared to the average temperature of entire undisturbed area of the test plot. As shown in Figure 6 it was partly sunny on 7 October, raining 8-9 October, sunny 10-12 October, rainy 13 October, and partly sunny 14 October. The greyed area in Figure 6 is the interval of night time. The largest thermal response was observed for the buried rectangular plastic object (#6 in Figure 5b), during the day time with a maximum temperature difference of 4 to 7°C as compared to the average temperature of the surrounding undisturbed soil. The rectangular metal object (#4 in Figure 5b) had the second largest thermal response followed by the round plastic object (#3 in Figure 5b) and the disturbed area (#2 in Figure 5b). The smallest IR measured temperature change was observed for the undisturbed control areas. These observations should be borne in mind when watching the model simulation of the data in Video 1.

Figure 6. Difference in surface soil temperature between the average temperature (°C) of the undisturbed plot area and buried objects for the period 7 to 15 October 2016.

A model simulation depicting the data presented in Figure 6 is shown in Video 1. The video starts at 0630 on 7 October and continues until 15 October at 0600. As the simulation proceeds it is apparent that the spatial thermal pattern changes throughout the 24-hour cycle and is different from day. Some of the day to day difference are the result in changes in environmental conditions. For example, the overall temperature change and spatial thermal variability is muted on 8 and 9 October due to a precipitation event. As discussed in [13] the thermal response on cloudy, partly cloudy, sunny, and raining days is statistical different with sunny days having a higher maximum spatial variance resulting in larger temperature contrasts between the buried objects and surrounding soil. This observation is evident in Video 1. Conversely, rain resulting in increasing soil moisture decreases the maximum spatial variance and increases the spatial range resulting in little contrast between the buried objects and the surrounding soil.

Video 1. Thermal model of FLIR Surface temperatures, 3-d subsurface soil temperatures, and mean subsurface soil temperature for the period 7 to 15 October on 15 minute time steps: <http://dx.doi.org/doi.number.goes.here>

The data used to generate Video 1 was analyzed to determine the percent visibility of the metal objects as compared to the plastic objects. The analysis shows that during the period of study and the conditions at the CRREL test plot that the highest percentage of plastic object detection occurred between 1200 and 1800 (Figure 7a). This is a result of the plastic objects heating faster than the surrounding soil manifesting as higher temperature anomalies in the FLIR imagery. In the case of metal, there was no optimum viewing window although there is a period of higher visibility degradation which occurs between 0600 and 1200. During this period the metal objects have cooled and their temperature is equivalent to the surrounding soil. It takes several hours of thermal loading before the metal object temperature increases faster than the surrounding soil making them visible. Even then, metal objects are only visible up to about 70 percent of the time.

During the precipitation event overall object visibility percentage decreases for both plastic and metal objects for most 3 hour blocks of time during the 24-hour cycle (Figure 7b). For the plastic objects visibility remains above 80% between 1200 and 1500 hours. In contrast, the visibility of the metal objects is significantly degraded with an expansion of the less than 50% response from 0000 to 0600. Note, the visibility drops below 5% between 0600 and 1200 for the metal objects. Analysis of the visibility of the objects as a function of soil moisture is depicted in Figures 7c, 7d. When the soil moisture is low, less than 19%, the visibility of the plastic objects is above 80% for all hours except 1800 to 0000 (Figure 7c). The overall visibility of the metal objects is lower with the poorest visibility between 0600 and 0900. Contrast this with Figure 7d which depicts object visibility when soil moisture is greater than 21%. Visibility of the plastic objects is reduced to less than 80% except for 1200 to 1500 hours whereas the metal objects visibility drops below 50% from 0000 to 1200 and 1800 to 2100 hours and between 50 to 80% for the remaining hours.

Figure 7. Percent overall visibility and during rain events and moisture content of <19 and >21% of buried and metal objects for the period 7 to 15 October 2016.

During daylight hours when the short wave IR (SWIR) is > 750 watts/m² the plastic objects have the highest visibility from 1200 to 1800 hours whereas the metal objects are visible between 64 and 45% of the time (Figure 8a). When it is cloudy during daylight hours with SWIR < 500 watts/m² there is a drop in visibility to the 4 to 15% range for the plastic objects. In contrast, the visibility of the metal objects decreases significantly to < 50% between 0900 to 1500 with the greatest decrease between 1200 to 1500 (Figure 8b).

Figure 8. Percent visibility during 8a) sunny days with short wave SWIR > 750 watts/m² and 8b) cloudy days with SWIR < 500 watts/m² for the period 7 to 15 October 2016.

Review of Video 1 and Figure 6 indicates the round metal object (#5 in Figure 5b) thermal response is generally lost in the background noise of the soil thermal variability. One reason for this is that this object is 1/10 the size of the other buried objects and consequently doesn't have a large thermal capacity to store heat. However, careful analysis indicates the round object is consistently visible at very limited times of the day. Figure 9 shows soil temperature response from a short time period that is illustrated in Figure 6 from 1800 hours on 10 October to 1800 hours on 11 October. There is roughly one hour each day where this object has enough thermal contrast that it is visible and this

occurs between 0850 and 1000 each day. However, the IR image (inset to the right), which has been masked from 18.9 to 19.2°C, indicates the object can easily be lost in the natural background noise if the location of the object was not known.

Figure 9. Thermal response of buried objects (inset left) from 10 October at 1800 hours to 11 October at 1800 hours and thermal IR of test plot (inset right) on 11 October at 0935.

5. CONCLUSIONS

The thermal response for the buried objects varied by the size/mass and material. Thermal response for the rectangular plastic object was more apparent than for the round plastic object. For the rectangular metal object, the response was similar to the plastic objects; but for the round metal object, there was no visible response. The lack of thermal response from the small round metal object is likely a function of the thermal mass being insufficient to manifest a significant differential response as compared to the surrounding soil. Initial qualitative analysis suggests surface thermal spatial patterns are a function of incoming solar radiation, air temperature, subsurface- soil temperatures, and moisture content.

During periods of high solar input the surface soil located directly above a buried object heats more rapidly than the surrounding soil creating a temperature differential with the surrounding undisturbed soil. The size/mass and material of the buried object affects the thermal capacity as well as rate of thermal loading. Plastic objects absorb more thermal energy more quickly than metal objects resulting in greater temperature differentials with the surrounding soil. This contrast results in improved visibility for a longer period of time for plastic versus metal buried objects. Conversely, plastic objects during an absence of solar thermal loading cool more rapidly than metal

objects and both cool faster than the surrounding soil. Very small objects such as the small metal object have insufficient thermal capacity to create a temperature differential with the surrounding soil. Consequently, small buried objects are more difficult to see due to the inability to differentiate the response from background noise.

One of the observations from viewing the spatial data is that the soil surface temperature is not constant throughout the study area at any given point time. The surface soil temperature is distributed heterogeneously, i.e. there are clusters of elevated and lower temperatures, with values ranging by as much 9°C across the test plot. This heterogeneous distribution of surface soil temperatures was apparent prior to object emplacement and continued after object emplacement. Further, complicating the situation is that the surface soil temperature is not constant throughout a 24-hour cycle. The diurnal solar loading results in a peak and trough fluctuation in average soil temperature response each day across the entire plot. However, the temporal changes does not result in a consistent thermal response within the test plot, i.e. the location of clusters of elevated and lower temperatures changes as does the magnitude of thermal response. The heterogeneity of the surface soil temperatures is analogous to noise. The spatial distribution and magnitude of this noise is constantly changing throughout a 24-hour period.

Consequently, comparing two different days with identical environmental conditions for a given time of day does not produce the same spatial thermal response. In some instances, the difference in average thermal response can be explained by changes in solar input due to cloud cover, changes in air temperature, or precipitation events changing the soil moisture content. However, the heterogeneous distribution of soil temperature, i.e. clustering, appears unpredictable. This is not problematic for seeing larger buried objects but for small objects with poor thermal conductivity the thermal noise makes the objects invisible. We continue to pursue identification of the phenomena responsible for the variability in surface soil temperatures at the scale of buried objects of interest.

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