UCRL-JC-113695
PREPRINT

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This paper was prepared for submittal to the
SPIE
Orlando, Florida
April 12-16, 1993

April 2, 1993

SEP 03 1993

OSTI

Lawrence
Livermore
National
Laboratory

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Dual-band infrared capabilities for imaging buried object sites

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ABSTRACT

We discuss dual-band infrared (DBIR) capabilities for imaging buried object sites. We identify physical features affecting thermal contrast needed to distinguish buried object sites from undisturbed sites or surface clutter. Apart from atmospheric transmission and system performance, these features include: object size, shape, and burial depth; ambient soil, disturbed soil and object site thermal diffusivity differences; surface temperature, emissivity, plant-cover, slope, albedo and roughness variations; weather conditions and measurement times. We use ground instrumentation to measure the time-varying temperature differences between buried object sites and undisturbed soil sites. We compare near surface soil temperature differences with radiometric infrared (IR) surface temperature differences recorded at $4.7 \pm 0.4 \mu\text{m}$ and at $10.6 \pm 1.0 \mu\text{m}$. By producing selective DBIR image ratio maps, we distinguish temperature-difference patterns from surface emissivity effects. We discuss temperature differences between buried object sites, filled hole sites (without buried objects), cleared (undisturbed) soil sites, and grass-covered sites (with and without different types of surface clutter). We compare temperature, emissivity-ratio, visible and near-IR reflectance signatures of surface objects, leafy plants and sod. We discuss the physical aspects of environmental, surface and buried target features affecting interpretation of buried targets, surface objects and natural backgrounds.

1. INTRODUCTION

1.1 Background and technical approach

Previous applications of a precise airborne temperature survey developed at LLNL for imaging and detection of underground and obscured object sites depicted heat flow anomalies which produce distinguishable surface temperature differences from:

- geothermal aquifers under 6 to 60 meters of dry soil, ^{1,2}
- cemetery walls, trenches and a building foundation under 80 cm of asphalt and debris, ³
- buried mines, rocks and objects under 1 to 15 cm of disturbed sand, soil, or sod, ³⁻⁶
- sea ice thicknesses varying from 5 to 50 cm. ^{7,8}

In 1989, LLNL began a DARPA funded program under the name of TEMPS (Temperature Evaluated Mine Position Survey). ⁴⁻⁶ The TEMPS method used two, selectively filtered, thermal infrared images to locate buried mine sites. These sites had thermal and emissivity-related signatures unlike those associated with surface object clutter. In January, 1991 we successfully demonstrated the dual-band infrared (DBIR) concept using helicopter overflights to image a cluttered field site with 6 buried surrogate mines at Byron California. In March, 1991 we flew over the Yuma Arizona Army Proving Grounds. We successfully imaged the sites of all 36 live mines buried under a layer of cleared sand 1 to 15 cm thick. ⁶ Following these successes, the Laboratory was asked to evaluate recent advances in multisensor imaging, image processing and sensor fusion techniques. These techniques were expected to provide a more robust, all-weather system, which would be better able to distinguish buried mine sites from clutter sites.

1.2 Dual-band infrared (DBIR) concept and physical principles

The dual-band infrared (DBIR) concept which we describe below has proven to be useful for image interpretation of certain types of buried mine fields. It exploits a property of Planck's radiation law that applies for emitted radiation from a surface at temperature T (Kelvin), near T_0 (typically 288 K or 15 °C). For surface temperatures within about 20 °C of T_0 , the radiant emittance is proportional to surface emissivity (ϵ_λ) times (T/T_0) raised to the power of $50/\lambda$, at wavelength λ in μm . ⁹

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1.3 DBIR image ratios used for temperature map

The short wavelength band (SWB) image at 5 μm and the long wavelength band (LWB) image at 10 μm , are ratioed to produce a temperature map as follows:

$$\text{SWB} / \text{LWB} = (\epsilon_5) / (\epsilon_{10}) \cdot (T / T_0)^5 .$$

The temperature map enhances surface temperature differences for different surface materials. It is insensitive to surface emissivity variations for typical natural surfaces which have nearly the same emissivity at 5 μm and 10 μm .^{2,6}

1.4 DBIR image ratios used for emissivity-ratio map

Also, we produce an emissivity-ratio map using image ratios which cancel out the effect of surface temperature:

$$(\text{LWB})^2 / (\text{SWB}) = (\epsilon_{10})^2 / (\epsilon_5) = \epsilon .$$

The emissivity-ratio map enhances the emissivity-ratio differences between natural surface materials and surface object clutter. It depicts objects with the same (or very different) surface emissivity ratios at the same (or very different) values, grey scale (or color-coded) levels, which are independent of their surface temperature.

2. RATIONALE FOR PRESENT STUDY

2.1 Transition from previous studies

The present study reviews the results of the helicopter proof-of-principle demonstration^{3,6} conducted over a grass-covered field with buried (surrogate) mines and surface clutter. It shifts emphasis away from the sole use of IR images to distinguish buried mine sites from surface object clutter. It focuses on the combined use (where applicable) of coregistered visible, near IR and thermal IR images. These images are used to characterize the signatures of surface-cleared buried mine sites (without surface object clutter). Also, they are used to study the multispectral signatures of diverse surface objects (including U. S. and foreign mines).

2.2 A better understanding of subsurface detection and analysis

For the most part, the capabilities of infrared imaging for subsurface detection and analysis are poorly understood. This study addresses how the environment, measurement conditions, target geometry and heat transfer properties associated with buried objects and their surroundings affect image interpretation. Specifically, we characterize the physical nature of buried object signatures. Our goal is to develop realistic selection rules to be used as guidance for automatic target recognition.

2.3 Characterization of near-surface soil property differences

Our procedure is to quantify thermal contrast from surface and near-surface soil property differences (temperature, emissivity, reflectance, shading, plant-cover, wetness, thermal diffusivity and roughness); measured at different times; for varied targets (metal, plastic, surface and buried) and target geometries (size, shape, and depth); under changing weather conditions (wind velocity and cloud cover) and for different sensor responses (spectral peak and band width).

We measure temperature differences between buried object sites, filled hole sites (without buried objects) and undisturbed soil sites (without surface objects). Also, we compare temperature and emissivity signatures (derived from selective DBIR image ratios) with surface reflectance signatures (derived from multispectral visible and near-IR image differences) for a variety of surface objects surrounded by sod.

2.4 Collection and analysis of coregistered multispectral image data

We used a (12.5 m high) tower platform and gravel road to collect multispectral image data allowing direct comparisons of coregistered ultraviolet (UV), visible, near IR, thermal IR, CO₂ laser-IR and ground-penetrating radar images. This paper focuses on the results of passive dual-band thermal-IR image data. This data appears to have best characterized buried mine site

signatures (e. g., for plastic-cased mines in dry, weathered sand). In addition, we direct attention to the results of coregistered multispectral visible, near-IR and thermal-IR image data which according to our recent investigations have best characterized surface mine site signatures (for U. S. and foreign-Country mines laid on wet sod, amidst leafy plants and other objects).

2.5 Characterization of buried and surface object signatures

This paper evaluates DBIR spatial, spectral, thermal, emissivity and temporal signatures used in combination with visible and near-IR reflectance signatures. These signatures were used to detect the sites of time-weathered, surrogate mines buried in a dry, surface-cleared, sand pit; and paint-camouflaged surface mines surrounded by wet sod, leafy plants and other objects. A complementary paper: "Sensor feature fusion for detecting buried objects" ¹⁰ follows this paper. It describes the results of advanced signal processing, automatic target recognition and clutter rejection algorithms developed to classify buried mine sites in surface-cleared areas and to determine the probability of true and of false detections.

3.0 PROCEDURE

3.1 DBIR system used for signature characterization

The Agema 880 DBIR camera system and Burst Recording Unit (BRU) digital processor records daytime and nighttime thermal images at two filtered IR wavelength bands (near 5 μm and 10 μm). These thermal IR images provide a measure of the apparent temperatures for the surfaces they image. These images are partly emitted surface radiation, which relates to the surface temperature, and partly reflected sky radiation which relates to the cooler sky temperature. The apparent surface temperature equals the true surface temperature when the surface emissivity is equal to one (i.e., when there is no reflected IR component) and the surface is referred to as an ideal blackbody surface. When the surface emissivity is less than one (but equal in value at IR camera wavelengths centered near 5 μm and 10 μm) the surface behaves as a greybody surface.

3.2 DBIR filters designed to minimize reflected solar light near 4 μm

Sensor measurements were recorded at several times during the day and night using the Agema 880 DBIR Camera System. This system had a short wavelength InSb detector with a filtered wavelength interval of 3.3 to 5.0 μm which was used at night, and 4.4 to 5.0 μm which was used during the day, in order to cut out reflected solar light below 4.4 μm . It had a long wavelength Hg-Cd-Te detector with a filtered wavelength interval of 9.7 to 11.6 μm which was used both night and day, since variations from reflected solar light and the humidity are not detectable near 10 μm .

3.3 Detection of heat flow anomalies which characterize buried mine sites

At certain times during the day and night, buried object sites which transfer heat differently from their surroundings have surface temperatures which differ from their surroundings. Thus the thermal transport properties of a buried mine, covered by disturbed surface materials, produce a heat flow anomaly. This heat flow anomaly often causes both daytime and nighttime surface temperatures directly above buried mines to differ from the ambient value. Buried mine sites are typically warmer by day and cooler by night than undisturbed soil sites. Unlike surface object sites, sufficiently weathered buried mine sites are expected to have the same emissivity (and surface reflectance properties) as undisturbed soil sites. Typically, buried mine sites shortly after burial have very different surface reflectance properties than their surroundings. This difference usually disappears with time as a result of wind gusting and heavy rains.

3.4 Meteorological station and measurements

The test sites were instrumented with a meteorological station which measured the air temperature, humidity, wind velocity, net surface solar radiation flux, shallow subsurface heat flux, soil moisture, soil temperature profile and soil thermal conductivity. The digital data were recorded at 1 minute intervals, averaged and tabulated during five consecutive days at intervals of 15 minutes.

3.5 Soil temperature and thermal diffusivity measurements

Thermistor probes were used to measure true contact temperature data (within 0.1 or 0.2 $^{\circ}\text{C}$) at several locations in a one meter deep sand pit. Each probe measured the soil temperature 1 cm below the surface, and 10 cm below the surface. The probes were located at three undisturbed soil sites, within a filled hole, and above a buried surrogate anti-tank mine.

Thermistor data were recorded on a custom-made computerized data logger which stored 16 channels of data, collected at consecutive 1 minute intervals, during a period of five weeks, without down-loading the data. The thermistor temperature-difference measurements allowed comparisons with DBIR surface temperature-difference measurements. In addition, they provided an *in situ* determination of soil thermal diffusivity which varies (predictably) with soil moisture.

3.6 Multispectral visible and near-IR sensor instrumentation

A camera system spanning the ultraviolet (UV), visible and near-IR wavelengths was demonstrated by scientists Ned Witherspoon and John Holloway from the Coastal Systems Station (CSS) in Panama City, Florida. The CSS scanner used a CCD camera to view images through one of two synchronized filter wheels which provided six different (50 nm wide) band passes from the near UV (400 nm or 0.4 μm) to the near IR (900 nm or 0.9 μm). The images were taken in NTSC standard video and recorded on video tape providing calibrated black and white or color-coded coverage which extended beyond the region of normal human vision. The CSS scientists provided reflectance calibration standards and a variety of foreign and U.S. surrogate mines which were placed atop sod in Area 3. Also, SAI Corporation scientists, Larry Acton and Mike Griggs provided aluminum plates coated with various Army (camouflage) paints.

4. FIELD DEMONSTRATION SITES

4.1 Byron, California grass-covered field demonstration site ⁶

Using the helicopter-borne Agema 880 DBIR camera system, we imaged a grass-covered field site in Byron, California, with buried surrogate mines surrounded by surface object clutter. ⁶ In Figure 1, we see the aerial photo (a), and IR images centered near 5 μm (b) and 10 μm (c). We note in (b) and (c) that images of natural surfaces (shown as blue and green) appear alike, whereas images of man-made surface objects (shown as yellow and red) appear different at 5 and 10 μm . The demonstration produced a temperature map in (d) and an emissivity-ratio map in (e). These maps clearly depicted four centered surface markers, spaced 3 m apart, and weighted aluminum perimeter strips (9.1 m on-a-side by 5 cm wide) and scattered debris.

The metallic surface objects had temperature and emissivity ratios which differed markedly from those of the surrounding soil. Daytime temperature images of warmer than ambient picture elements (pixels) at buried mine and clutter sites (f), soil pixels (g) and their logical intersection showing warm soil pixels (h), when combined with the image of texture-segmented regions (i) identified all six buried surrogate anti-tank mine sites (j) with two false detections (see arrows) from a squirrel tunnel site (top, center) and a coiled electrical cable site (top, left).^{3,6}

4.2 Yuma, Arizona Army Proving Grounds cleared-sand field demonstration site ⁶

In Figure 2, we see processed daytime 10 μm IR images from helicopter overflights of the Yuma Proving Grounds cleared-sand field test. This test identified 100% (8 of 8) of the buried live mine sites with 15 cm of sand cover shown amidst tire track and disturbed soil images in (a). We set apparent temperature thresholds just below the warmer than ambient mine site values in (b) and removed thermal clutter from time tracks and the edge of a dry creek bed in (c). The open circles have been added to show the mine sites. The processed 5 μm images (not shown) identified 88% (7 of 8) of the buried live mine sites.

4.3 Implications of field demonstrations

In Figure 1(e), most natural surfaces had the same surface emissivity at 5 and 10 μm causing their images to appear alike on the apparent temperature maps shown in 1(b) and 1(c). In striking contrast are the emissivity-ratio map images of specular (highly-reflective) manmade surfaces shown in 1(e). The weighted aluminum strips (along the perimeter of the grass-covered field enclosing six buried, surrogate, anti-tank mines) have very different emissivity ratios from those which represent natural ground cover. Also, their apparent LWB temperatures in 1(c) are as much as 10-40 °C lower than their apparent SWB temperatures in 1(b). We exploited these image differences to reject clutter which tended to mask the buried mine sites.

The combination of temperature maps and emissivity-ratio maps is most useful for rejecting sites with surface object clutter. At the Byron site, surface objects, debris, and disturbed ground presented a major problem for image interpretation. There were 110 texture-segmented regions in Figure 1(i) derived using LLNL-developed computer vision and target recognition techniques to classify objects in the images.^{3,6,10} The use of temperature and emissivity-ratio maps allowed us to tag all six of the buried surrogate anti-tank mine sites by removing the mask from clutter and limiting our false buried mine site detections to two as shown in Figure 1(j).

5. LLNL TOWER DEMONSTRATION SITE

5.1 Cleared, sand-filled pit with buried surrogate mines

Using a 12.5 m tower platform, we conducted sensor characterization tests of a surface-cleared, sand-filled pit with buried mines (Area 2B) from December 1991 through August 1992. The Area 2B sand-filled pit is 1 m deep, 4.9 m or 16 feet on-a-side, and 3.0 m south of the tower. The cleared sand had three disturbed (filled) hole sites across the center and nine buried

Figure 1. Daytime aerial photo (a) and apparent temperature images taken with IR wavelengths near 5 μm (b) and 10 μm (c) of a grass-covered field with buried surrogate mines (under 1-10 cm soil) and surface object clutter. In (b) and (c), natural surfaces (shown as blue and green) appear alike, whereas manmade surface object clutter sites (shown as yellow and red) appear different. Images from the temperature map (d) and emissivity-ratio map (e) identify warm pixels (f), soil pixels (g) and warm soil pixels (h). The intersection of warm soil pixels (h) with texture segmented regions (i), located all six buried mine sites (j) with two false detections (see arrows).

Figure 2. Processed daytime apparent temperature images taken with IR wavelengths near 10 μm (a) of a cleared sand field with buried live mines (under 15 cm of sand) and thermal clutter from tire tracks, the perimeter of a dry creek bed and disturbed sand. The clutter was removed by locating warmer than ambient sand sites near the centers of buried mine sites and rejecting thermal clutter with different spatial properties. The open circles are added to clearly show the mine sites.

Figure 3. Typical nighttime (from about midnight to predawn) (a, b, c, and d) and daytime (from about mid-morning to mid-afternoon) (e, f, g, and h) 10 μ m IR apparent temperature images of a cleared sand-filled pit with buried surrogate mine sites and filled hole sites. The layout of buried surrogate mine types, depths and filled holes as shown in Figure 4. The units are in degrees Celsius.

Figure 4. The layout and legend for the Area 2B sand-covered surrogate mine and hole sites viewed with multispectral sensors from a 12.5 m high tower

Figure 5. A photograph of the Area 3 sod-covered soil plot with inert surface mines, painted metal plates, ceramic reflectance standards and other objects.

surrogate mine sites with 1, 5, or 10 cm of sand cover. Nighttime (from about 2400 to 0620 hours) and daytime (from about 1040 to 1410 hours) 5 and 10 μm DBIR images depicted buried surrogate mines covered by cleared sand. For representative 10 μm IR images, see Figure 3. For the layout of buried surrogate mine types, depths and filled holes, see Figure 4.

5.2 Sod covered by inert mines and surface object clutter

Also, using the same tower, we conducted sensor characterization tests of a square soil plot covered by sod (Area 3). This Area 3 sod-covered soil plot is 4.9 m on-a-side and 3.0 m west of the tower. The sod is partly covered by a grid (with spacings at 0.61 m or 2 feet) of surface objects, including calibrated ceramic plates used as spectral reflectance standards and inert U.S. and foreign mines (provided by Ned Witherspoon and John Holloway), leafy plants, painted and unpainted metal plates (provided by scientists Larry Acton and Michael Griggs from SAI Corporation), metallic fiducial markers and assorted types of clutter (see Figure 4).

6. SIGNATURES OF CLEARED SAND WITH BURIED SURROGATE MINES

6.1 Thermal signatures

The surface thermal signature from weak heat flow anomalies at buried mine sites can be used to locate buried mine sites, and hence buried mine fields. This thermal signature, measured by the DBIR imaging and processing system, is a surface temperature difference at the mine site (relative to surroundings). It results from alteration of the ground thermal transport properties where the mine is layed. This alteration is due both to the presence of the mine and the disturbance of the soil resulting from having buried the mine.

6.2 Temperature difference signatures

Figure 6 shows the April 8, 1992 Area 2B cleared sand temperature-differences, versus time, for a mine site (where a hole has been dug and filled with a surrogate mine) relative to the average of three undisturbed reference sites. We used thermistor probes to take temperature differences in sand at 1 and 10 cm below the surface. Figure 7 applies to a hole site (where a hole has been dug and filled without a surrogate mine). We used DBIR images to measure mine site and hole site surface temperature differences. These sites had DBIR surface temperature differences confirmed by thermistor probe measurements. Their values lay typically between the respective site temperature differences measured for the near-surface air (1 cm above) which is not shown and the near-surface soil (1 cm below) the surface.

6.3 Thermal diffusivity signatures

Soil thermal diffusivities were measured *in situ* from the thermistor probe data for the upper 10 cm sand layers (in Area 2B) above a surrogate mine ($0.0121 \text{ cm}^2/\text{s}$), within a filled hole site ($0.0046 \text{ cm}^2/\text{s}$) and at three undisturbed sand reference sites ($0.0058 \text{ cm}^2/\text{s}$, with a standard deviation of $0.0004 \text{ cm}^2/\text{s}$). The three reference sites were separated by 30 to 60 cm from the centers of surrogate anti-tank mine sites.

Figure 6. Time-varying temperature differences between mine sites and undisturbed soil sites comparing thermistor data with DBIR image data.

Figure 7. Time varying temperature differences between filled-hole sites and undisturbed soil sites comparing thermistor data with DBIR image data.

6.4 Temporal (time-dependent) signatures

After 2130 hours, on April 7 and before 0630 hours on April 8, calm night air thermistor-probe temperature differences above mine and filled hole sites, were typically -1.5 ± 0.5 °C relative to reference temperatures; whereas, the respective sand temperature differences were typically -2.5 ± 0.5 °C. Calm nights were best for distinguishing mine and filled hole sites from background, mainly because there was very little thermal noise. Mine sites were, on the average, about 0.2 °C cooler, at their centers than hole sites, when measured at 2300 to 0100 hours. Figure 2 nighttime images (top row) show mine sites better than daytime images (bottom row).

Figure 3 nighttime images (top row) show mine sites better than daytime images (bottom row). There are two apparent reasons for this, namely: air temperature variabilities and thermal clutter. On clear calm days, from 0900 hours to 1500 hours, near-surface air temperatures above mine and filled hole sites, relative to reference sites, were typically cooler by -4 ± 1 °C and more variable than the respective near-surface sand temperature changes. Ridges and small animal tracks or depressions produced significant thermal clutter in loose sand which masked the sites of buried mines and filled holes. We note that daytime 10 µm IR apparent temperature images of buried mine sites were identified in natural weathered sand (see Figure 2).

6.5 Spatial signatures

The spatial signatures seen on thermal images of buried surrogate mine sites (aged from late December 1991 to early April 1992) had approximately twice the diameter, and four times the area, of the surrogate mines originally buried in the Area 2B sand-filled holes. This suggests the occurrence of heat transfer from the sides of the surrogate mines. In April, we saw no evidence of sand spoils which had been apparent shortly after the mines were buried. The respective diameters of mines, hole boundaries and thermal images were approximately 30, 40 and 60 cm for anti-tank and 15, 25 and 30 cm for anti-personnel mines.

6.6 Emissivity signatures

We do not consider emissivity signatures for the cleared sand pit with buried surrogate mines in Area 2B, since there are no surface object clutter sites expected to have emissivity-ratio signatures which differ from their surroundings. There is "thermal clutter" associated with depressions in the loose sand which form shadows and as such have different apparent surface temperatures. These apparent surface temperature patterns, when viewed on judiciously scaled SWB and LWB images, look alike.

6.7 Implications of buried mine site signatures

Interpretation was difficult for daytime apparent temperature images of Area 2B loose sand, weathered during a period of three months. Surface temperature differences (for sand-buried mine sites and sand-filled hole sites) were warmer than ambient by 1 °C to 3 °C. Images of sand-buried mine sites and filled-hole sites had about the same size, shape and thermal contrast as mounds or depressions made by rabbits and squirrels in loose sand. Interpretation was easier for nighttime apparent temperature images after the Area 2B sand pit was smoothed to eliminate animal tracks.

Buried mine site and filled hole site signatures were more evident for other surface materials, namely: Area 1, 2A and 2C (which were surrounded by naturally compacted clay soil). We recorded daytime and nighttime radiometric images for these areas. These images are considered in detail elsewhere.¹⁰ There are visible (reflected light), thermal (emission) and possible emissivity-ratio signature differences which distinguish disturbed from undisturbed (compacted) clay soil. Because the undisturbed soil was compacted, animal tracks were less visible, and sufficient weathering (to remove the obvious differences in albedo or surface reflectance properties for mine sites buried during late March) had not taken place. The recently disturbed clay-soil daytime and nighttime burial sites had not had time to show the effects of rain and gusts of wind. However, their signatures were clearly evident on the DBIR (SWB and LWB) apparent temperature images.

Cleared areas (which exclude Area 3) have less thermal clutter. As such, there is no need to remove sites in the DBIR images associated with surface object clutter. Thus it is not necessary to use emissivity-difference (or emissivity-ratio) signatures which distinguish between natural surfaces with the same emissivities and manmade surfaces with very different emissivities at detected SWB and LWB wavelengths near 4.7 and 10.6 µm. It is expected that separation of buried mine sites from surface object clutter, particularly for metal objects, will require use of both temperature-difference and emissivity-difference (or emissivity-ratio) signatures, based on the previously reported analyses of the Byron CA test site.

7. SIGNATURES OF SURFACE OBJECT SITES

Emissivity-ratio signatures

A photograph of the Area 3 site with sod, covered by surface-objects, is shown in Figure 4. The surface objects included painted and covered metal plates (top two rows), calibrated ceramic plates used as spectral reflectance standards (third row from top), U.S. and foreign mines (bottom three rows) and metallic fiducial markers at the corners of the small (2 feet on-a-side) and large (12 feet on-a-side) areas. When the respective temperature-difference scales were adjusted, the cleared sod images at $4.7\text{ }\mu\text{m}$ and $10.6\text{ }\mu\text{m}$ looked alike, whereas the surface object images had subtle differences related to their respective emissivity ratios at $4.7\text{ }\mu\text{m}$ and $10.6\text{ }\mu\text{m}$.

7.2 Temporal (time-dependent) signatures

Area 3 daytime and nighttime (see Figure 8) images depict temperature-related and emissivity-related signatures for cleared sod and sod covered by surface objects. These signatures characterized various surface object sites. By understanding the characteristics of surface object sites, we are less likely to identify such sites as buried mine sites when they occur amidst, or surround a buried mine field. During daytime, most surface object sites had different temperatures (mostly warmer) and emissivities (some warmer, some cooler) than cleared grass. During nighttime, most surface objects had different temperatures (mostly cooler) but the same emissivities as the moist sod, because the images were taken when the surface objects were also covered by moisture.

7.3 Temperature and emissivity-ratio maps

Area 3 images are shown in Figure 8. The top three rows have seventeen surface objects approximately 30 cm on a side, whereas the bottom three rows have six surface mines of comparable size and six which are 10 or 15 cm on a side (see Figure 5). In Figure 8 we see the respective daytime (top, left to right) and nighttime (bottom, left to right) LWB apparent temperature images scaled in degrees Celsius (a) and (e); the SWB apparent temperature images (b) and (f); the temperature maps (c) and (g); and the emissivity-ratio maps (d) and (h).

7.4 Interpretation of surface object site signatures

Note the striking differences between temperature and emissivity-ratio signatures both during the day and night. During the day, most surface objects, corner metallic fiducials and all large mines are warmer than the ambient dry sod (b); whereas, daytime emissivity ratios for most surface objects range from lower values to higher values than the values for dry sod, while metallic fiducials and large mines all have lower values than the ambient dry sod (f). At night, most surface objects, including a few mines, were cooler than the wet sod (d). However, dew-covered surface objects had about the same emissivity ratios as wet sod, apart from the corner metallic fiducials (h). These fiducial markers had a small warm light bulb at their centers.

The daytime (top row) and nighttime (bottom row), LWB (left) and SWB (right) Area 3 temperatures (in Kelvin) were calculated using Planck's Radiation Law for a blackbody surface. These apparent temperatures were compared with the temperature maps obtained from SWB/LWB intensity ratios described above. The comparison is shown in Figure 8. The temperature map shows the warmer than ambient soil corner fiducials both day and night, whereas the reverse is true for the apparent daytime SWB and LWB and nighttime LWB temperatures which do not take into account emissivity effects.

7.5 Daytime and nighttime temperature and emissivity-ratio differences

The Area 3 temperature spreads in Figure 8 are typically $30\text{ }^{\circ}\text{C}$ during the day and $2\text{ }^{\circ}\text{C}$ at night. Hence, in practice, there is little difference between the daytime and the daytime minus nighttime temperature maps. Not much additional data for Area 3 surface objects was learned by taking the daytime minus nighttime temperature maps.

Similarly, not much additional data was learned by taking the daytime minus nighttime emissivity-ratio signature for surface objects covered by dew. We note the sharp contrast on the daytime emissivity-ratio map for square (2.5 cm on a side) steel fiducials at the corners of 60 cm on a side sod squares. Emissivity-ratio maps highlight surface metallic objects to a much greater extent than single band images centered at $10.6\text{ }\mu\text{m}$.

7.6 Multispectral UV, visible and near-IR signatures of surface objects

In Figure 9, representative multispectral data for Area 3 are imaged in (a) at 500 nm ($0.5 \mu\text{m}$), in (b) at 700 nm ($0.7 \mu\text{m}$) and in (c) at 900 nm ($0.9 \mu\text{m}$). These images are compared with image differences (c) - (a) in (d); (b) - (a) in (e); and (c) - (b) in (f). These surface reflectance images suggest greatest contrast for surface mines surrounded by wet sod in (f). We note that where leafy plants mask surface mines at positions shown in Figure 5, the image differences shown in (d) and (f) enhance the contrasting reflectance values between plants, soil and surface mines.

To process images in Figure 9, we obtained a normalized reflectance value by dividing each image by the mean value for all the pixels within the image. We then calculated the mean value and standard deviation for representative background sod surfaces. This mean value was subtracted from the normalized image reflectance values. The resulting difference was divided by the standard deviation for sod backgrounds. We displayed a range of values which applied to over 95% of the image pixels.

8. SUMMARY AND CONCLUSIONS

Interpretation of thermal IR imagery is often fraught with ambiguities. These ambiguities result from the difficulty to interpret heat transfer differences for surface and near surface materials (such as surface objects, ground cover, soil layer, buried objects, vegetation); the buried object layer size, shape and depth; the environmental conditions; the measurement procedure; the presence or absence of surface object clutter and the IR system performance.

Figure 8. Area 3 respective daytime (top, left to right) and nighttime (bottom, left to right) apparent temperature images in degrees Celsius at $10 \mu\text{m}$ in (a) and (e) and $5 \mu\text{m}$ in (b) and (f). Temperature maps in (c) and (g) and emissivity-ratio maps in (d) and (h) show images scaled to the mean value for background sod, in units of standard deviations for background sod, showing surface objects which include inert mines, painted metal plates, and ceramic reflectance standards surrounded by sod.

To overcome these interpretative hurdles, we first identify the time-varying thermal signatures which relate to the volumetric properties of surface and near surface materials. We then consider the surface reflectance properties (albedo in the visible and near-IR; one minus the emissivity in the thermal IR). Can these be characterized in the ultraviolet (UV), visible, near-IR and thermal IR portions of the electromagnetic spectrum? If so, can algorithms be developed that do this effectively as well as automatically?

To this end, we present results of Area 3 studies with coregistered data for painted metal plates, ceramic reflectance standards, European, Russian and U.S. mines, metal fiducials and clutter surrounded by wet sod. Our goal here is to evaluate the combined capabilities of the UV, visible, near-IR and dual-band thermal IR for distinguishing surface object clutter in the absence of buried mines. Daytime visible and near-IR imagery can help to find sites which represent surface disturbances or objects. When these sites coincide with the positions of thermal clutter, they provide a valuable aid in identifying, and removing, images that otherwise might be confused with a buried mine site.

The first step in detecting buried mine sites should be to remove the effect of clutter, vegetation and surface mines. This is accomplished by defining the scale of the image displays to enhance contrast with backgrounds for multispectral visible and near-IR surface object images by day and surface emissivity differences by day or night. What remains after removing surface objects by their spectral signatures should be natural soil. The soil pixels have a gaussian distribution of emissivity variations.

The temperatures of buried mine sites are significantly warmer than ambient soil temperatures during daytime, and significantly cooler than ambient soil temperatures at night. For dry sand sites, additional "thermal" clutter may be confused

Figure 9. Area 3 normalized surface reflectance images collected with multispectral visible and near-IR data for inert mines obscured by leafy plants at 500 nm (a), 700 nm (b) and 900 nm (c) compared with multispectral difference images (c) - (a) in (d), (b) - (a) in (e) and (c) - (b) in (f). The images are relative to the mean value for background sod, in units of the standard deviation for background sod. Contrast between mines and grass appears greatly improved in (d) and (f).

with buried mine signatures during the day (e.g., from animal tracks, ruts or depressions in the sand), making interpretation of buried mine sites during the day extremely difficult (see Figure 3). However, IR images of natural sand (such as was present at the Yuma Proving Grounds test) under different environmental conditions, and with different types of thermal clutter (such as tire tracks, a dry creek bed and larger disturbed sand areas than mine site areas), identified daytime thermal signatures of buried live mine sites with 15 cm of sand cover (see Figure 2).

9. ACKNOWLEDGEMENTS

This work was performed by LLNL under the auspices of DOE contract number W-7405-ENG-48 for the DoD DARPA/BRDEC/Marine Corps Countermining Program, ARPA order number 7180-01. The authors acknowledge the field support efforts of Brad Burdick, Mervyn Lawrence and Charles Dingus, the multispectral visible and near-IR measurements taken by Ned Witherspoon and John Holloway and the overall support of Arthur Toor, Mark Eckart, David Fields, Suzanne Lake, Milt Finger, and Satish Kulkarni.

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