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Characterizing optical properties of disturbed surface signatures

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ABSTRACT

The burial of objects disturbs the ground surface in visually perceptible ways. This project investigated how such information can inform detection via imaging from visible through mid-infrared wavelengths. Images of the ground surface where objects were buried were collected at multiple visible through mid-infrared wavelengths prior to burial and afterward at intervals spanning approximately two weeks. Signs of soil disturbed by emplacement change over time and exposure in the natural environment and vary in salience across wavelengths for different time periods. Transient cues related to soil moisture or illumination angle can make signatures extraordinarily salient under certain conditions. Longpass shortwave infrared and multi-band mid-infrared imaging can enhance the signature of disturbed soils over visible imaging. These findings add knowledge and understanding of how soil disturbances phenomena can be exploited to aid detection.

Keywords: buried objects, disturbed soils, SWIR, Mid-IR

1. INTRODUCTION

The remote detection of buried explosive threats is not mature. A reliable method for the remote detection of buried objects would significantly enhance the capability to U.S. forces facing these threats in theaters around the world. Optical remote sensing techniques have demonstrated some promise for detection but are challenged in many ways, in part because of the assumptions inherent in detecting a that surface has been disturbed, and from that inferring the presence of a buried object. Many actions unrelated to burying can disturb the earth's surface, and there are several mechanisms by which a disturbed surface can be rendered difficult or impossible to distinguish from an undisturbed surface. Although several optical methods have shown considerable promise not one alone or in combination with others has yet proven robust.

Disrupting a soil alters many parameters that have direct and indirect effects on its optical and thermal properties. These properties include the particle size distribution and shapes of the grains that compose the soil as well as the roughness of the surface to include the number and shape of rock shards and soil aggregates. Sometimes there are changes in the larger scale topography, the composition or moisture content. This is especially true if a subsurface soil horizon is mixed with the material exposed at the surface. These differences will evolve with time in complex ways, not just gradually trending to background conditions, and can even invert with respect to the original surface conditions.

Previous work has demonstrated that visual cues of disturbed soils exist at many wavelengths[1-6]. We report progress made in further documenting the phenomena of soil disturbances for detection purposes. Prior work has shown that certain optical signatures of temperate well-developed soil disturbances produced by landmine emplacement persist for several months in well-developed soils during winter months[1]. Results identified visual cues that characterize the signatures, their changes over time and exposure to the natural environment, as well as contrasts in the perceptual salience of signatures on the bandwidths sampled over time. Recent laboratory and field investigations have furthermore demonstrated that signatures of disturbed moist soils can be more salient at Shortwave Infrared (SWIR) wavelengths than at Visible (Vis) or Thermal Infrared (TIR) under a wide range of illumination conditions.

In this paper we explore the Vis – Mid-Infrared (MIR) properties of temperate soils under summer conditions. A field study was performed on the grounds of The Johns Hopkins University Applied Physics Laboratory to characterize physical and optical phenomena related to burial of improvised explosive devices (IEDs). Soil disturbances of interest included the ground spoor (footprints) left by personnel emplacing the targets, vehicle tracks, and the surface disturbance resulting from the burial of simulated IEDs. These consisted of 5-gallon plastic pails filled with ammonium nitrate prills emplaced according to TTPs used by enemy forces in current combat theaters.

The goals of the current effort were to generalize and extend these findings to IEDs and test under different weather conditions. The simulated IEDs were buried in sandy-clay soil at a secure test site during the summer. Imagery was collected before and after target emplacement over a two-day period and again two weeks later. Disturbed and surrounding undisturbed surfaces were sampled using instruments spanning the Vis – Mid-IR (Table 1). Results show (a) changes for better and worse in signature salience over time within bands (b) contrasts in salience across bands within time periods, and (c) enhanced signature salience under certain illumination conditions for specific wavelengths. Discussion addresses phenomenological bases of results and their methodological implications for efforts to exploit the optical phenomena of disturbed soils to detect buried explosive hazards

2. METHODOLOGY

2.1 Site Preparation and Instrumentation

The tests were conducted in a secured facility in central Maryland during later July and early August, 2010. The site consisted of hardpacked bare earth accessed by a gravel road. The soil of central Maryland is dominated by ferric clays, and at this location, also had significant clasts of schist and other metamorphic rocks, which added mica grains to the soil. There was little organic plant material in the soil at this site. The buried objects were plastic 5-gallon buckets completely filled with fertilizer prill (Figure 1). For each buried object, the holes were approximately 21-25” in diameter, with loosened soil and unearthed clasts spread nearby due to the digging and movements of the personnel. Targets were buried with an overburden of approximately 5”-6” of soil. The disturbed surfaces were smoothed with shovels after the holes were filled to decrease the salience of the disturbance. No precipitation was recorded for the three days preceding object emplacement. However, the night after emplacement, approximately 0.1” of rain fell. Between the 10 days between the July and August measurements there was significant rainfall that significantly altered the surface expression of the buried simulants. No precipitation was recorded for five days leading up to the August data collection and the top and subsurface soil were dry.

Table 1. Instrumentation.

	Instrument	Measurement
Visible Color	Nikon D70 SLR	Visible RGB imaging
Hyperspectral Vis-SWIR	ASD FieldSpec Pro	Spectral profiler 0.35 – 2.5 μm
SWIR multiband	SUI Goodrich MSX-320	Imaging @ 0.9 - 1.7 μm
Mid-Infrared 2-band	2-band MCT detector	Imaging @ 4 and 4.5 μm

The remote sensing instruments (Table 1) acquired data of the emplaced target periodically throughout each day of observing. Additional observations were made of the adjacent gravel road and sites of disturbance within it. The instruments were co-located in the bed of a covered vehicle, protected from the elements and secured, enabling them to remain in place during each data collect. The instruments were approximately 20’ from the targets, with the base of the instruments approximately four feet above ground level and sensor heads approximately eight to nine feet above ground level. The visible color camera is a Nikon D70 SLR with an effective 6.1 megapixel resolution. The hyperspectral Vis-SWIR point spectrometer is an ASD FieldSpec Pro point spectrometer with a spectral range of 0.35 μm to 2.5 μm, a 3 nm resolution from 0.35 μm to 1 μm, and 10 nm resolution at longer wavelengths. A biconical reflectance apparatus was used with artificial illumination and requires touching the surface with the sample probe. A diffuse halon reflectance plate provided a background measurement from which relative reflectance could be derived after correcting for the minor spectral variations in the halon. This approach is not subject to spectral variations associated with

Figure 1 Day 1. 07/28/10. Example buried object and surrounding undisturbed soil. Visible salience enhanced due to higher moisture content of th recently subsurface soil.

changing illumination and thus provided consistent results enabling the direct comparison of various soils without the need for photometric correction. The SWIR camera is a Goodrich SU-320M camera with a 320 x 240 pixel InGaAs array. It obtained images both in a longpass filtered mode in which only illumination from ~ 1.55 – 1.7 μm was collected, and in its unfiltered broadband mode in which light from ~ 0.9 to 1.7 μm was collected. Although about a factor of 9 lower spatial resolution than the Nikon SLR, the SWIR images were able to spatially resolve major features. The Mid-IR imager uses a liquid-nitrogen cooled dual-band 256 x 256 pixel HgCdTe array designed and built to sense two wavelengths at each pixel, bracketing the telluric CO_2 absorption with bands at ~ 3.8 – 4.2 μm and ~ 4.5 – 5 μm. The shorter band is sensitive to both reflected sunlight and thermally emitted radiation, while the longer wave band is dominated by thermally emitted radiation under the conditions of these field experiments. The mid-IR images were each corrected separately to radiance and the longwave image was corrected for bad pixels through a nearest-neighbor iterative replacement.

3. RESULTS AND DISCUSSION

Generally, the variability we have observed in the salience of IED signatures over time and across imagery captured in different bands suggest a general approach to both advancing our fundamental knowledge and understanding of disturbed soil phenomenology and exploitation of these phenomena. Similarly high temporal and spectral variability was observed in a longitudinal study[2] which captured visible color, SWIR, and TIR images of buried mine signatures over a period of months. Beyond our studies, several independent studies have demonstrated that imagery at various bands can identify disturbed soils. Noting that a comprehensive review of the literature is needed to appropriately guide investigation, the question shifts from “Can “X” detect disturbed soils?” to “When does “X” work?” “When” implies here a temporal component as well as related environmental conditions. Operationally, this implies sampling at regular intervals using a suite of imagers operating at selected bands as well as measurements of variables in the natural environment (soil and meteorological) that change over time. Where reliable correlations can be found between signature salience and environmental variables can guide narrow the search for causal factors and at the same time identify and predict the conditions particular imagery sources are most effective for detecting soil disturbances of interest for various purposes. Imaging at multiple bands simultaneously would also allow exploration of which combinations/fusions of bands yield the greatest signature salience/detectibility.

3.1 Vis-SWIR spectral measurements

For transmissive minerals, such as most silicates and carbonates, finer grain powders are more reflective than coarse particles (e.g. 6). In general, this effect is a result of the fact that the total distance light travels through smaller particles is less than for larger particles before being scattered back to be detected, and thus not as much light is absorbed. Vis-SWIR measurements of quartz sand, carbonate sand, and mixture of sands confirm this occurs at those wavelengths where the materials are reflective and thus scattering [3]. Thus, reflectance in the Vis-SWIR can be sensitive to grain-size variations. However, natural surfaces are rarely flat nor are of a uniform composition or grain size, and thus exhibit other reflectance variations that often dominate over grain size effects. Even in the laboratory, it is essential to ensure a granular surface is flat and there are no shadows if one is attempting to make measurements comparing the reflectance properties of materials of different grain sizes. Any noticeable surface roughness will inherently result in surface darkening (unless at very low phase), working in opposition to intensity variations associated with grain size[1]. Consequently, Vis-SWIR field measurements of disturbed soils, which are assumed to have a greater amount of small grains then do undisturbed soils, do not consistently show a higher reflectance than undisturbed soils, and often are darker due to the presence of shadows and to the excavation of organic and other darkening material from the subsurface.

Reflectance spectra of various soils were obtained in-situ (Figure 2). Because the measurement approach was robust against photometric effects and shadows, the reflectance is a function of composition and grain size. However, there is no clear relationship between reflectance and disturbed soil other than a reddening in the Vis-NIR region in a spot disrupted by a vehicle. Figure 2 demonstrates that these soils are likely rich in iron bearing clay, with ferric iron causing the redness at visible wavelengths and a small band near 900 nm, and evidence for significant clays comes from the presence and existence of a deep 2.2-µm band that is a weak harmonic in clay minerals. The clay is red and dark and would be spectrally distinct from most rocks– the later not having a strong 2.2-µm band and being bright at all wavelengths. However, the existence or absence of a 2.2-µm band will not be a reliable metric as all surfaces will often have small amounts of clay or other alteration minerals on its surface inducing this feature.

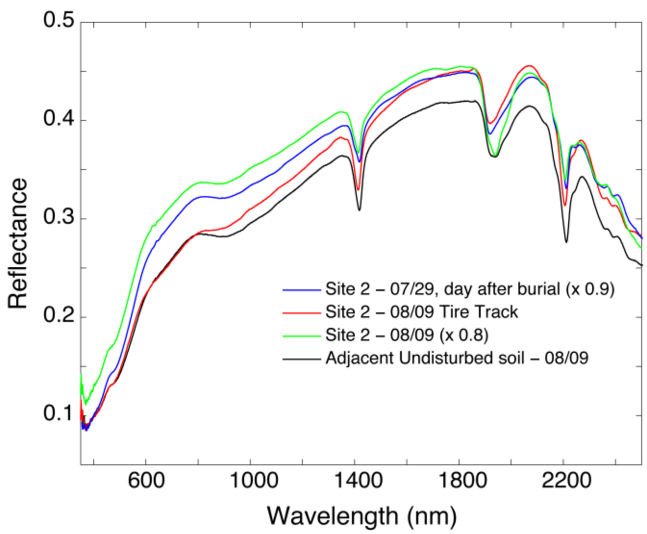

Figure 2. Field Vis-SWIR reflectance spectra of site from Figure 1. Not scaled.

3.2 SWIR imaging

SWIR imaging of disturbed and undisturbed soils was obtained throughout the 2 two-day periods spanning a two-week period, with observations obtained the day of and the day after emplacement (July 28-29), and again nearly two weeks later (Aug 9-10). Observations from the day after emplacement demonstrate that SWIR imaging in the 1.5-1.7-µm region is sensitive to smaller amounts of soil moisture (which darken the surface) than are observations at visible wavelengths (Figure 3), confirming prior observations of disturbed soils at SWIR wavelengths[1]. However, after thorough drying, signature salience was poor at both SWIR and Visible wavelengths. This result is consistent with previous interpretations of observations under moist conditions that suggested SWIR imaging, especially at the longer wavelength portion of its spectrum (1.5-1.7 µm), is more sensitive to soil moisture and can be used in some cases to infer soil disturbance[3]. This result also demonstrates that efforts to disguise soil disturbance by smoothing over a surface can be effective at SWIR as well as at visible wavelengths.

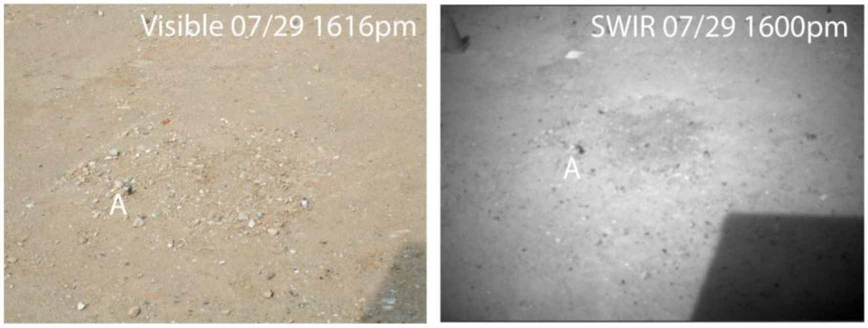

Figure 3. July 29, the day after emplacement. Light rain the night before. Ground is dry in visible image but significantly darker (wet) in SWIR. The 'A' delineates a reference stake. After fully drying, salience was poor in both visible and SWIR.

However, areas of surface disturbance that have not been intentionally disguised are tractable with SWIR imaging. The continued observations over this two-week period demonstrate that shadows cast by roughened surfaces at these SWIR wavelengths are more salient than those cast at visible wavelengths. Imaging at SWIR wavelengths can improve the ability to detect disturbed terrain, under certain viewing conditions. First suggested in prior field observations, these observations confirm this effect, as salience gradually diminishes as the sun's illumination decrease in phase (moves behind the observer and cast shadows diminish). Figure 4 compares visible color imaging obtained by the Nikon camera to that of the lower spatial resolution imaging of a gravel road that has patches of clay soils. Despite being hampered by the almost 9x lower spatial resolution, areas devoid of gravel are readily apparent in the SWIR images, especially when spectrally curtailed to the longest wavelengths to which the camera is sensitive (1.5 – 1.7 μm). Salience in the visible image is hampered by distraction from excess information, or clutter, that is not relevant to detecting disturbed soil, or in this case, to a lack of gravel. For instance, the eye is naturally drawn to the green and brown vegetation on the left side of the image, as well as to shadows, and the color variations between the gravel and clay. At SWIR wavelengths, the gravel reflectance inverts and is darker than the soil or the vegetation. This blandness in the broadband, unfiltered SWIR image emphasizes the reflectance difference between the dark gravel and brighter soil, however, the bright vegetation continues to be distracting. Utilizing the longest wavelengths available in SWIR imaging (1.5- 1.7 μm), the vegetation also darkens, so that the only highly reflective surfaces are dominated by the smooth, clast-free clay soil, thereby emphasizing the areas of disrupted gravel in the road. In contrast, at SWIR wavelengths and especially at the longer wavelengths of SWIR, many materials (such as grasses – green and brown, rocks, and other surfaces tend to have similar, somewhat low, reflectance[1]. Green vegetation tends to be dark due to the presence of water, whereas brown vegetation is dark at this wavelength due to the lack of chlorophyll. Other than the broad absorption due to water, there are few other geologic materials that absorb at these wavelengths. Thus, surface reflectance is inordinately affected by illumination conditions as well as surface texture. In Figure 4, the sun is in front of the observer and shadowing is prevalent. The SWIR observations strongly emphasize the shadows because there is little other reason for a reflectance change. In the visible, however, there are many variations in the scene, and furthermore the visibly bright stones forward scatter a significant portion of the sunlight. With this light allowed to travel forward, shadows are softened, and obvious surface anomalies are disguised. Even as good as the salience is in the SWIR, under these illumination conditions, better spatial resolution would likely be a significant improvement. The contrast difference in the visible and

Figure 4. Salience is strongly wavelength dependent. Longpass SWIR diminishes information content from parts of the scene unrelated to disturbance so that the disturbance or other anomalies are emphasized.

SWIR arise from different phenomena. At visible wavelengths, the clay soil is distinguished from the bright gravel by a color as well as brightness difference which are due to different compositions.

Salience, even at longpass SWIR wavelengths, is strongly dependent on viewing geometry. Figure 5 demonstrates the strong dependence the SWIR imagery has on solar illumination direction. When the sun is behind the observer, shadows are minimized and the more uniform reflectance between the stones and the soil in the SWIR return making the detection of disturbed locations difficult, but still more effective than in the visible. In the SWIR, the green vegetation remains dark due to the absorption of light by the moist soil (not standing water) and is not strongly photometric.

Figure 5. Illumination geometry strongly affects the salience of a disturbed gravel road. Illumination trends left-to-right, from high phase (looking into the sun), high sun, to low phase (sun behind observer). Higher phase observations have more shadows and enhance surface roughness, especially in absence of other sources of brightness differences.

3.3 Mid-IR measurements

Mid-IR measurements are similar to the thermal infrared in that emitted heat is detected. However, at shorter wavelengths in the mid-IR, a significant component of reflected sunlight can be present. Because the measured illumination will be a combination of both emitted heat and reflected sunlight, properties that only affect either reflected light or thermal emitted radiation will all be factors affecting the signal to potentially be leveraged together for increasing the salience of the disturbed soils. For instance, the spectral properties of the soils in the mid-IR are similar to the spectral properties in the SWIR in that there is significantly more volume scattering than there is in the TIR. Because of this, mid-IR reflectance spectra exhibit a consistent relationship between grain size and reflectance regardless of composition, with finer-grained surfaces having a higher reflectance. But macroscopic roughness will usually result in significant shadowing at all but the low sun angles (Figure 2) controlling the reflectance in the mid-IR and likely swamping any reflectance changes caused by grain size variations.

The mid-IR images at each wavelength are each a mosaic of two images because the field of view of any single image was not sufficiently large to cover, for instance, an entire site of disturbed soil and each image was independently contrast stretched to reduce the seam between the images when stitched together. For freshly disturbed soil, shadowing and thermal emission contribute significantly to the salience and the disturbance is quite salient in both reflected sunlight as well as thermal emission (Figure 6). The 4.5-5-μm image is dominated by thermal emission with the entire area of disturbance dominated by thermal emission and generally warmer than the undisturbed terrain. This is due to the lower bulk thermal conductivity decreasing the ability of the surface to cool by transferring its heat into the subsurface and in part by the rough surface being less efficiently cooled by a convective breeze. The low-lying areas between clasts tend to be warmer than their peaks, which are cooled by circulating air. Vegetation is the coolest, appearing the darkest. Peripheral to the main disturbance is soil that has been lightly disturbed by the actions of personnel emplacing the simulants. Where its thermal properties have not been significantly altered, the surface appears bland and mottled in thermal emission. Small clasts and low laying topography are at a more or less uniform temperature which significantly degrades the ability of thermal imaging to detect small scale features or disturbances that only affect the top surface and do not alter the bulk thermal properties of the soil.

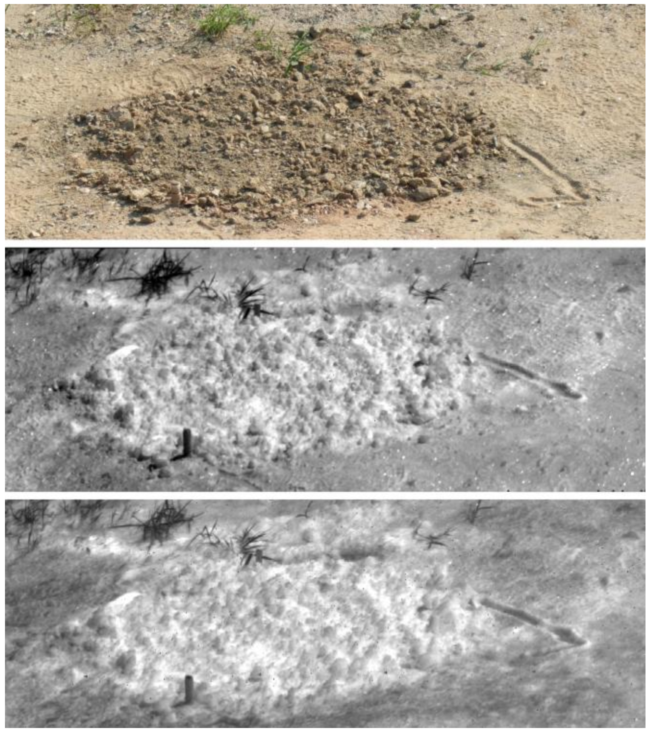

Figure 6. Soil imaged immediately after disturbance. From top to bottom: visible, 3.8 - 4.2 μm, 4.5 – 5 μm. High phase (viewing into sun), providing significant shadows for increased salience in visible and at the shorter mid-IR band. Note the generally softer appearance of the longer band IR image compared to the shorter wavelength IR image, specifically the foot prints in the upper right are apparent in the top two images but less salient in the bottom. Scale: the images are foreshortened and are ~ 3 feet in each direction.

The shorter wave mid-IR image (3.8-4.2 μm) also contains a significant thermal component. However, the interclast regions are neither consistently brighter nor darker than the clasts due to a complex interaction of brightness variations associated with shadows and the presence of thermally emitted radiation. Small-scale roughness including overlapping tread patterns in the right foreground of the disturbance are salient at this wavelength due to significant shadowing resulting in reflectance variations that are perceptible above the thermally emitted component. The presence of shadowing in the shorter wavelength mid-IR and resulting salience of patterns provides this mid-IR band with the appearance of greater spatial resolution than is present in an image dominated by only thermal emission.

The synergy of combining reflected sunlight and thermal emission is more evident in the detection of disturbed soil for which imaging at wavelengths relying entirely on reflected sunlight is ineffective (Figure 7). The signature of the buried prill container in both mid-IR bands is dominated by the thermal emission from the surface. However, the salience in the shorter mid-IR band is further increased by the perceivable variation in topography and size distribution of clasts. It is interesting to note that an anomalous distribution of clasts is not sufficient to robustly differentiate this site from the surrounding undisturbed terrain in visible and SWIR images (also see figure 3), but that this secondary information, when added to thermal emission, presents a compelling image of an anomalous surface. This is likely due to the recognition of sharp light and dark patterns superimposed on a less familiar background of more smoothly mottled dark and bright. The spatial variations in brightness can be immediately interpreted as clasts and topographic variations, which at the most are present as mottling in the image of thermal emission.

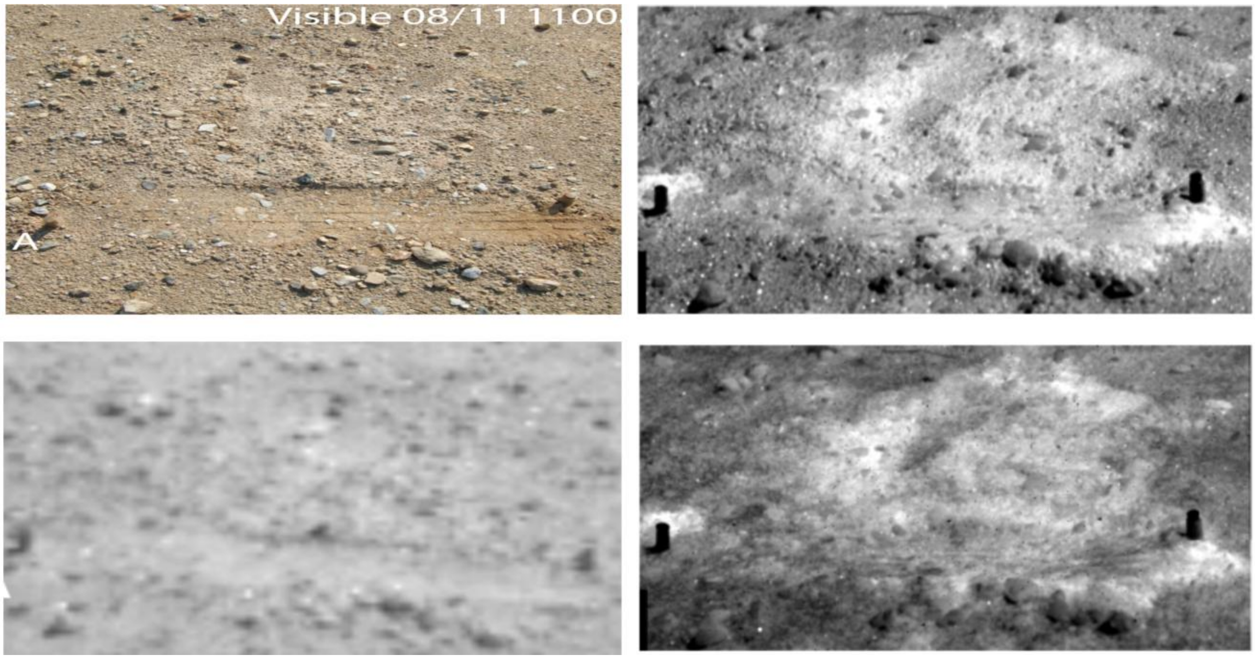

Figure 7. Site 2, Aug 11. Visible, SWIR, and 2 bands of mid-IR. Despite a high phase angle (viewing into the sun) the salience of the area of burial in the visible and SWIR are poor due to the surface structure having been 'reset' by rainfall. The salience in the SWIR is further degraded by low spatial resolution compared to the other images. Salience is greatest for the 3.8-4.2-μm mid-IR band for which the thermal signature is enhanced by the addition of spatial texture present from shadowing.

4. CONCLUSIONS

The optical salience of buried objects, such as mines or IEDs, is affected by factors such as size of object, method of emplacement, soil and moisture conditions during and subsequent to emplacement, solar illumination, temperature, and the optical wavelengths selected for observation. The surface disturbance caused through the burial of an object alters the grain size, surface roughness, and possibly composition of the soil. While laboratory measurements suggest that grain-size effects in the reflected solar spectrum could potentially be diagnostic of disturbed soils, in practice this proves impractical because shadows at multiple scales dominate. Despite the absence of a detectable optical effect due to variations in grain size, multi-band mid-IR imaging and possibly narrow band SWIR (1.55 - 1.7 μm) imaging appear to be potentially effective means for detecting the disturbance associated with buried mines. The high salience of the optical cues in the SWIR are likely a result of multiple small scale shadows cast by the clasts and agglomerations in the disturbed soil. Soil moisture may contribute to this effect. The high salience in multi-band mid-IR is likely a result of a synergy between reflected solar illumination and thermal emission. Small scale surface roughness and topographic variations that affect the reflected signal in the shorter wavelength mid-IR imaging augments the thermal signature of the soil disturbance, providing topographical and effectively higher spatial resolution information than is available from images of only thermal emission.

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