SUBSURFACE DRAINAGE MAPPING BY AIRBORNE INFRARED IMAGERY TECHNIQUES

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Infrared (IR) radiation can be considered one of the most useful regions of the electromagnetic spectrum for remote sensing for engineering purposes. Within the past years, there has been increasing awareness of the potential application of IR imagery techniques for many practical purposes. It should be possible to exploit economically the special problem solving capabilities of this technique. In addition to the limitations of ground exploration methods, cost of these methods is steadily increasing. It may turn out that economics will be the catalyst that accelerates the use of remote sensing, including IR imagery technique, for solving various engineering problems. Hidden subsurface conditions that influence planning and design of engineering structures can be exposed with IR instrumentation. The location of subsurface muck pockets, entrapped moisture in natural slopes, underground cavities and conduits, and subsurface drainage systems can all be exposed with IR imagery.

Remote sensing of the earth's environment has been and continues to be one of the most valuable aspects of this nation's vast aerospace program. In addition to the immeasurable military benefits of high altitude and space reconnaissance, civilian applications of various remote sensing devices have begun to pay real dividends. With high altitude aircraft and satellites, surveillance systems can gather data from large geographical areas and relay this information back to the earth in fractions of seconds. This information benefits not only the military, but many civilian agencies as well.

In engineering construction as well as military operations, one of the most important aspects of terrain is its effect on the planning or behavior of structures, or on the movement of vehicles.

Obstacles which would significantly influence the planning, design or construction of these structures or would affect the trafficability of the area, are usually (but not always) obvious and easily identified from maps or conventional aerial photographs. However, some terrain elements or characteristics such as soil's physical properties, subsurface features or even camouflaged surface features are less susceptible to accurate analysis by conventional means. Because of the difficulty of physical access to certain areas, remote means of assessing terrain characteristics may be not only highly desirable but essential. The NASA Earth-Orbital Experimental Program exemplifies the interest in remote sensor geoscience data aquisition.

Remote sensing is the measurement of properties or characteristics of an object without the measuring device actually coming into physical contact with the object. The results may be quantitative, as the height of a structure, or qualitative as in the case of detecting pollution of a stream or locating a subsurface drainage channel. This remote measurement can be accomplished by electromagnetic radiation and force fields. In this paper, discussion will be limited to the use of techniques utilizing electromagnetic radiation in the infrared range.

NATURE OF INFRARED

Infrared (IR) is an electromagnetic radiation whose spectrum band falls between that of visible light and the microwave region. Considering IR as a form of electromagnetic radiation, Figure 1 shows its domain in the

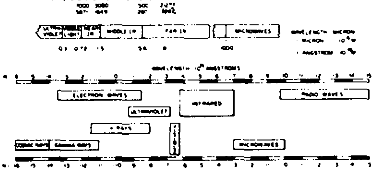

FIGURE 1. Position of infrared radiation in the electromagnetic spectrum.

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electromagnetic spectrum. The customary units for wavelengths in the various regions are angstrom, micron or centimeter. The IR domain is further divided into near, middle and far infrared, whose limits have been arbitrarily defined by the different types of detection devices used to record them.

The atmospheric transmission and absorption characteristics of the electromagnetic energy in the IR range are of primary importance in infrared remote sensing techniques. Attenuation of radiation is produced by absorption and forward scattering by different gases and suspended particles in the atmosphere, e.g., carbon dioxide, water vapor, clouds and fog. This effect is not constant across the infrared spectrum as "*windows*" or areas of peak transmission are present ($\approx$80% transmission). The two primary "windows" considered for remote sensing or infrared imaging are at 3-5 and 8-14 microns. The most important "window" concerning the terrain reconnaissance for civilian and military purposes exists at 8-14 microns, the region of maximum terrain emission and minimum natural reflection. The "*window*" then is defined as a range of wavelengths of least attenuation across the infrared spectrum.

AIRBORNE INFRARED IMAGERY

Interpretation of aerial photographs taken by means of visible light is a well-developed art. Visual photography has been extended slightly into the infrared region by use of special films but most infrared radiation cannot be directly photographed. To extend the application of aerial reconnaissance techniques beyond the visual and near IR ranges, infrared thermal imaging techniques using optical-mechanical line scanning systems in the 3-5 and 8-14 micron spectral regions have been widely applied in the past couple of years toward the solution of environmental problems. Since relaxation of stringent military security regulations in early 1968, a marked increase has occurred in operational infrared imaging surveys for nonmilitary terrain, hydrological and land use purposes. Prior to 1968, thermal imaging surveys were more or less restricted to services offered by manufacturers and by research-oriented groups such as National Aeronautics and Space Agency, U.S. Geological Survey and Air Force Cambridge Research Laboratory. While current unclassified systems remain far behind the state-of-art in infrared imaging technology, they are adequate for specific applications in scientific studies. It is the purpose of this paper to discuss some of the useful applications of this technique in the field of Civil Engineering and particularly in mapping subsurface drainage systems and structures.

TECHNIQUE OF OBTAINING INFRARED IMAGERY

All objects in nature emit infrared radiation as long as they are above absolute zero temperature (−273 C). This radiation arises from the thermal agitation of the charged particles of which all material is composed. The ability of a target to radiate infrared is determined by the temperature of the target and its surface conditions; this is measured by emissivity. As the temperature of a body increases, the vibration amplitudes and frequencies of the atoms and molecules composing the body also increase. Thus the radiation of infrared from a heated body increases with the temperature. The total radiation is roughly proportional to the fourth power of the absolute temperature, so any small change of target temperature will cause marked increase in the amount of radiant energy emitted by the target.

Because the terrain is not photographed directly by airborne IR sensors, the term "IR imagery" is used to describe the final photograph obtained. Aircraft can be employed for taking infrared image as involved in taking normal aerial photographs. The airborne IR sensing equipment is flown over the terrain in straight parallel lines. A scanning device such as a rotating mirror, Figure 2, scans the terrain in continuous

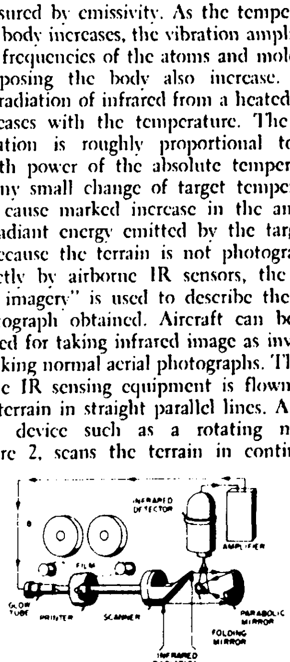


FIGURE 2. Basic elements of the airborne infrared image recording system.

strips perpendicular to the line of flight. The image from the mirror strikes an element sensitive to IR radiation, and the signal from the sensitive element is electronically amplified and produces a visual image on a cathode ray tube or a glow tube. A final photographic record is made by the glow tube or from the cathode ray tube. The scanning mirror sweeps an angle on either side of the vertical and an image is recorded which in the most part is an oblique view of the terrain.

CHARACTERISTICS OF INFRARED IMAGERY

The photographic tone of an object sensed by infrared imagery equipment is primarily a function of the intensity of the object's infrared radiation emission, which depends upon the object's emissivity and temperature.

Infrared imagery may be obtained during the day or night. If an IR image is obtained during daytime, the total radiation including visual will be sensed, unless all radiation other than IR in the desired range is filtered out. At nighttime only IR radiation is sensed. The most difficult adjustment an engineer or military analyst familiar with ordinary and classical forms of aerial photographs must make when studying infrared imagery is the realization that he is not seeing objects by reflected light. The experience of the human eye is in sensing objects by reflected light, but the eye has no experience in sensing objects by their infrared radiation. The photo-analyst in this case must be trained to realize that, in infrared imagery, he is looking at objects whose photographic tone is a function only of their emissivity and temperature. The infrared image then is a function of emitted radiation, not reflected, radiation.

Because infrared imagery looks at the terrain in a new range of the electromagnetic spectrum, many features not ordinarily visible to, or difficult to detect by the human eye, or by conventional means of aerial photography will be apparent. Herein lies the great potential value of this new technique.

MISSION SCHEDULE

Night-time imagery is preferred whenever possible in order to record true thermal emittance properties without solar reflectance and shadow effects. Filtering is mandatory during the daytime, especially when using sensors sensitive in the middle infrared range (3-5 micron window). Of course, there are many other environmental and sensor parameters to be considered when the best schedule for image data collection is selected. But, it is always desirable to obtain the image when peak periods of emission exists, a fact pertinent to such applications discussed in this paper. Early evening or immediately after sundown, when the earth's surface is at highest relative terrain emission with absence of reflection, appears to be an appropriate time for imagery collecting. This adds to the value of such technique as a means of night aerial reconnaissance with no visible light needed. In other reconnaissance problems, it may be desirable to collect imagery during daytime, since shadowing may enhance terrain or target definition.

VARIATION OF INFRARED EMISSIVITY OF GROUND SURFACE DUE TO VARIATION OF DEPTH TO GROUND WATER TABLE

A special set-up was designed and built by the School of Civil Engineering at Oklahoma State University to study the effect of changing the depth to ground water table on the infrared emissivity of the ground surface. Also, the object was to study the pattern and the periods of maximum variances in emissivity which in turn indicate the most favorable time for image data collection in the field to produce maximum contrast on the image between areas of high water table and others of relatively lower water table. The apparatus consisted of a 10 inch square inner box, 4 feet, 2 inches high, to hold the soil and a 17½ inch square outer box, 4 feet high, to hold the water. The outer box had a 20 inch square base plate affixed to the bottom with built-up strips 10 inches square for the inner box to rest in. The inner box was made in one-foot sections for ease of cleaning and tearing down after each experiment was completed. The inner box had 12 quarter-inch holes, three on each side, at every one-foot level to allow passage of the water into the soil as the water level changed. The apparatus was constructed from plexiglass for ease of making and having a watertight system.

Two types of soil, sand and silty clay, were dried, sieved and stored in 30 gallon galvanized barrels. The boxes were placed outdoors and the inner boxes were filled with soil. When placing the soil in the inner box, it was tamped every six-inch lift in order for all five boxes to have approximately the same density. This was done to eliminate the variable of density of soil on its emissivity. The outer boxes were then filled with tap water to the 0 ft, 1 ft, 2 ft, 3 ft, and 4 ft levels. This same procedure was followed with both sand and silty clay soil.

The boxes were left outdoors overnight before readings were begun to allow the soil temperature to come into equilibrium with the ambient temperature and for the capillary rise to occur. Infrared emissivity was measured on the surface of soil mass during day and night, using IR (PRT-5) radiometer sensitive in the range of 8-14 microns of the far infrared range of the spectrum (Figure 3).

FIGURE 3. Water table set-up during IR emissivity measurements.

When evaporation of the water brought the water level below the desired level, water was added to the outer box to keep it at the same level throughout the test. The boxes were covered with plastic sheets when it rained to keep the soils from becoming wetter than would be natural from the levels of the water table. Energy was measured over a period of one week for each type of soil tested and readings were taken eight times every day.

Test results indicated that variations of depth to ground water table caused both silty clay and sand to produce the same pattern of emittance over a 24 hr period. Their peak emittances occurred between 2:00 p.m. and 6:00 p.m., and their lowest emittances occurred at predawn (5:00 a.m. to 6:00 a.m.). The maximum variance in the emittances due to different levels of water table also took place between 2:00 and 6:00 p.m. for both soil types, with the 4 ft level causing soil surface to have the highest emittance and 0 ft level (water level at surface of soil) having the least emittance of radiant energy. There was an inversion in the amounts of emittances given off by the soils between 12:00 midnight and 6:00 a.m. with the highest energy being emitted by the 0 ft level (water level at surface of soil) and the least energy being emitted by the 4 ft level of both soil types.

These variations in emittances on the surface of the ground resulting from different levels of the ground water table were due primarily to the diverse thermal characteristics of air and soil-water system. Water takes the place of air in soil voids as the soil becomes moist. Since water has a specific heat of 1.0 and air has only .000306, water has great influence on the ability of the soil to be warmed and cooled. For this reason, the maximum variance in emittance between the different levels of the water table occurred in later hours of the day and early evening since more solar energy was needed to raise the temperature of water than is needed to raise that of the soil. Also, as the water table gets closer to the surface of the ground, more cooling effect was produced by evaporation from the surface, resulting in lower infrared emissivity during the warm period of the day.

This fact further explains the inversion of emittances which occurred at night. The greater moisture content in the soil results in a higher heat capacity because of the higher specific heat of water. Since heat capacity is the ability of a material to hold heat, the more saturated the soil is, the longer it will hold heat. Furthermore, the drier soils cool faster than the wet soils and, therefore, the emitted energy becomes less.

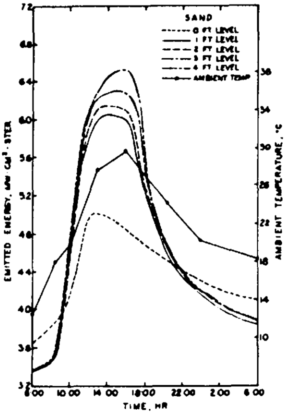


FIGURE 4. Emitted energy of sandy soil for changing depth to water table.

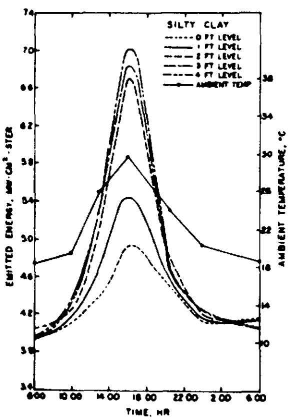


FIGURE 5. Emitted energy of silty clay for changing depth to water table.

This results in the inversion of emittances in the later hours of the night. Typical test results for both sand and silty clay are shown in Figures 4 and 5.

This experiment indicated clearly that differences in depth to ground water table within the range used in experiment (0-4 ft) was detectable by ground surface infrared emissivity measurements in the 8-14 micron range. This was particularly true during late hours of the afternoon and early evening.

FIELD APPLICATIONS

The following examples show some valuable applications of the IR thermal imagery techniques in revealing surface and subsurface ground moisture variations. They also show the capabilities of this technique in exposing some of the hidden subsurface conditions and features which may not be obtained by other conventional aerial reconnaissance techniques. Such information can be very important in site selection for engineering structures, as well as for agricultural and military purposes.

Example 1

Figure 6-a shows a standard black and white aerial photograph of a field area at the University of California campus (Davis, California). In this field, a wet stream channel was completely buried by filling it with the same type of soil as in the surrounding terrain. As can be seen from the photograph, the buried stream channel is hardly visible on the surface. Figure 6-b shows an infrared image (in the 8-14 micron wave band) taken over the same area in Figure 6-a. In this image, the buried stream channel shows with distinct outline and with a light tone in contrast to the darker tone of the surrounding area. The image was recorded late at night which explains the lighter tone (higher emissivity) of the wet fill in the buried channel. It is because of the higher specific heat of the wetter soil in the buried stream channel that it remained warmer late at night while the surrounding drier area was cooling off at a more rapid rate.

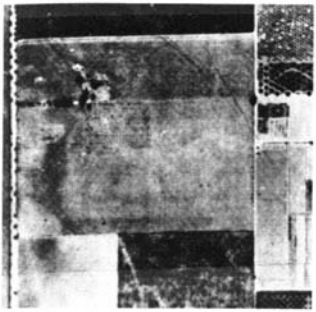


FIGURE 6-a. Standard aerial photograph in the visible spectrum of a buried stream channel.

FIGURE 6-b. Infrared image of the same area in Fig. 6-a showing a distinct outline of the buried stream channel.

This example demonstrated in a controlled test area how the difference in ground moisture content may cause a thermal anomaly to exist on ground surface and would produce this sharp tonal contrast in an image form recorded in the 8-14 micron infrared range. One should carefully note, however, that this thermal anomaly and maximum variances in emissivity, which permit the best delineation in imagery between areas of different ground moisture contents, may occur only over a short period of time during the day or night. During the remaining period, there may not be enough difference in emissivity to cause a sharp tonal contrast between the two situations. Therefore, the schedule of the mission should be carefully planned in correlation with the thermal characteristics of the situations involved. Time of recording should be carefully selected when maximum emissivity differences exist between the target or situation to be delineated and the surrounding area.

Example 2

Infrared imagery in the 8-14 micron range is also used to display subsurface water channels which may otherwise be somewhat obscured by overburden or vegetation. In flat terrain, dark toned areas in an infrared image recorded in the early evening, are usually expressions of higher ground moisture content. Figure 7 reveals a striking subsurface drainage feature that was not displayed by a visual photograph or visual examination of the ground surface.

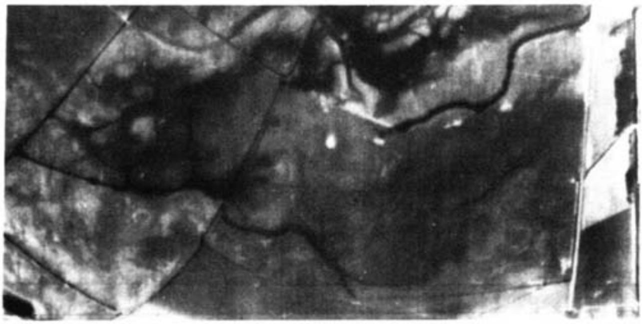


FIGURE 7. Infrared image of terrain near Walley's Spring (Nevada) showing a subsurface moisture system.

The benefits to be gained from the use of IR imagery for locating underground drainage more reliably during site selection for engineering projects or construction are considerable. The question which always arises here is "To what depth will the subsurface ground moisture produce significant thermal patterns on the surface and thus allow tonal contrasts to be produced in thermal imagery?" In answer to this question, we should realize first that the capabilities of modern imagery systems makes it possible to record differences in terrain emissivity resulting from thermal anomalies as low as I C from an altitude of over 20,000 ft. Secondly, the lack of basic research in the area of soil IR emissivity and the great number of factors which influence the radiating power of the earth's surface materials tend to complicate the problem.

Factors affecting soil emissivity may be divided into two general groups, *intrinsic* and *external*. Intrinsic factors are those contained in the soil, e.g., specific heat of soil and soil water system, soil suction pressure, capillary rise of ground water table, soil density, radiating power, heat absorption, nature of surface, etc. External factors consist of the meteorological elements, e.g., air temperature, sunshine, barometric pressure, wind velocity, humidity, precipitation, etc. Some of these impart energy to the soil and thereby raise its emissivity while others tend to take away energy from the soil and thereby lower its emissivity. These opposing factors are in operation all the time, but some are predominant over the others at different times. Therefore, in terrain reconnaissance, a thermal imagery taken at any time under field conditions may be considered to be the sum or resultant of the effects of these contrasting factors. All these factors will have to be considered and analyzed to be able to obtain the optimum time and environmental conditions which will allow *maximum differences in emissivity* (or maximum contrast in field imagery) to be produced with the variations of depth to ground water.

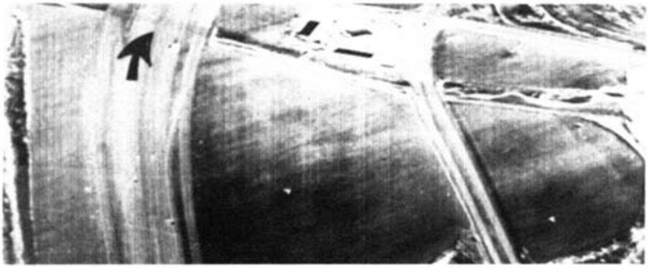


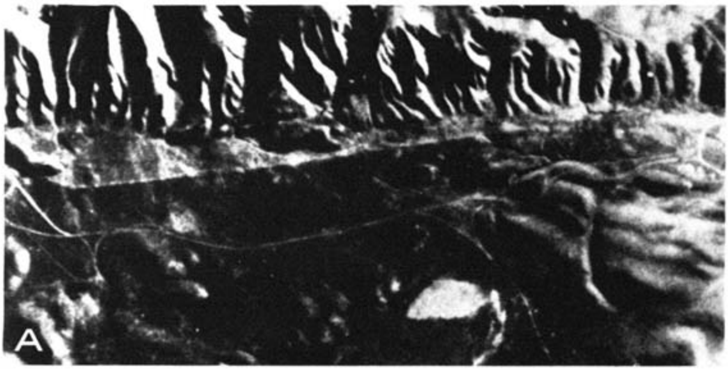
FIGURE 8. Infrared image for a stretch of Interstate 35 near Dallas, Texas. Arrow indicates location of a subsurface buried conduit.

Example 3

Recently, infrared imagery has been used for civilian and military reconnaissance purposes to reveal subsurface hidden or forgotten conduits and features in a particular area. The Science Service Division of Texas Inst. recorded the image appearing in Figure 8 for a stretch of Interstate 35 near Dallas, Texas. Image was recorded in the early evening at the 8-14 micron range. It can be seen that the buried conduit exposed on both sides of the road is still visible and detectable through the full width of the Interstate highway as if the pavement structure is transparent. This may give a wrong impression that the infrared imagery techniques allow a penetration of the surface to reveal some of the subsurface features; however, this is not true. It is the existence of this subsurface structure underneath the pavement which caused the pavement temperature at the surface above the location of the structure to be slightly different from the surrounding pavement area. This caused a difference in surface emissivity which allowed the detection by the IR imagery technique. Detection by airborne technique.

without setting a foot on the ground, of such hidden or buried structures and other features, especially at night with no visible light, makes this technique a very valuable one for both civilian and military purposes. Of course, there is a limit of depth beyond which no effect of the buried structure will be detected by thermal anomalies on the surface and no detection by this method would be possible. This depth depends on

FIGURE 9. Infrared image showing location of a pipeline in a terrain near Death Valley, Calif.; arrows indicate location of buried sections of pipeline ➚, pipeline right-of-way ⬆, pipeline exposed at valley crossing ⇧.



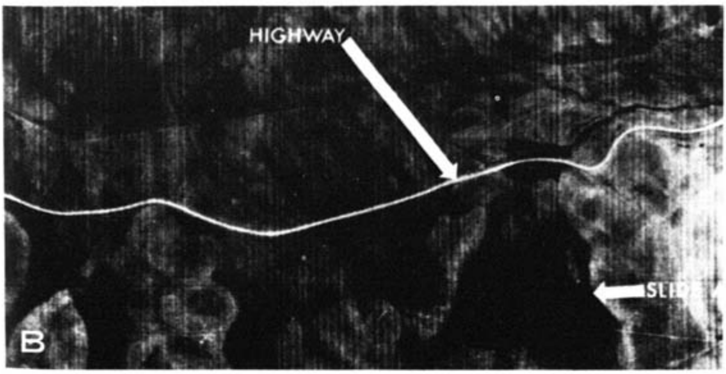


FIGURE 10. Comparison of visible and infrared image of a landslide prone area near a highway. A— STANDARD AERIAL PHOTOGRAPH. Standard aerial photograph gives few clues to the presence of landslide-prone areas. B— INFRARED IMAGE. Dark areas identified on the photograph by arrows represent soil that has moved as landslides toward the upper portion of the photograph. Difference in tone results from moisture trapped in the slide soil.

many factors such as the size, type and nature of the structure as well as characteristics of overburden.

Early this year, the Florida State Road Department investigated the possibility of detecting near-surface underground voids and cavities in limestone areas of the state with IR imagery. In a recent pilot surveying, using a Bendix LN-1 sensor filtered to 3.7-5.5 microns, subsurface wet muck pockets were located that were previously overlooked in the soil survey.

Example 4

Figure 9 shows an infrared image (8-14 microns) for a pipeline in the Death Valley, California area. Although the image was recorded at night with no visible light used, it shows with amazing clarity the pipeline right-of-way, the exposed sections of the line when it crosses the valleys and more amazingly, the location of the buried sections of the pipe.

Example 5

Figure 10 shows a comparison of standard aerial photograph and infrared image in the 8-14 micron of a terrain along a highway. The dark area indicated by the arrow in the image is a landslide prone area. The natural slope in this location has a high amount of moisture entrapped in it which actually caused the soil on the slope to move as a landslide toward the upper portion of the photograph. This is a fairly good example to show how this entrapped moisture in the slope at this particular location did not show on the surface in the standard aerial photograph. It did, however, cause a thermal anomaly on the surface of the ground which allowed a detection and clear delineation in the infrared image. This application can be of significant value to highway engineers for landslide studies.

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