Surface and Subsurface Exploration by Infrared Surveys

R. V. MATALUCCI, U. S. Air Force Institute of Technology, and
M. ABDEL-HADY, School of Civil Engineering, Oklahoma State University

This paper summarizes some of the basic principles related to infrared radiation and demonstrates various applications of infrared photography and imagery to surface and subsurface exploration and terrain analysis for highway construction and other engineering projects. Major conclusions from this study are the following: (a) IR photography and imagery highlight variations in soil texture, composition, and moisture that may not usually be recorded by conventional photography; (b) the chlorophyll effect allows IR photography to assist in the appraisal of cultivated land for right-of-way acquisitions; and (c) hidden subsurface conditions and geological features that are of greatest importance during highway site selection and design can be exposed with IR instrumentation—features such as muck pockets, underground cavities, volcanic and hydrothermal activities, subsurface drainage systems, and buried utilities and conduits. With further research in the techniques used for remote sensing in the infrared, surface and subsurface exploration and drainage studies for construction of highways, airports, and other projects may be greatly facilitated.

•IN THIS advancing technological age, there is indeed a requirement for detecting and identifying various objects and conditions in the universe from remote locations. Because our natural remote sensors—our eyes, our ears, our skin—are surprisingly limited in acquiring and recording information about a remotely situated area, it has been necessary over the years to develop measuring devices to supplement them. These measuring devices, better called "remote sensors," detect and record energy that is either emitted or reflected from objects that would otherwise not be revealed through the human senses. As research in the area of remote sensing of environment continues, techniques are beginning to provide otherwise unobtainable information about the world around us.

One of the most useful regions on the electromagnetic spectrum for remote sensing, in terms of engineering application, is the infrared. It has been established that although not detectable by the human eye, all objects having temperatures above absolute zero emit infrared radiation. In addition, an object receives infrared radiation from the sun, reflects a portion of it and absorbs the rest. The latter portion can then be emitted. If a sensing device is appropriately positioned to detect the emittted or even reflected infrared radiation, an identification of some objects could be possible through application of some basic laws of physics and radiation.

It is the purpose of this discussion to summarize some of the basic principles related to infrared radiation and review various applications of infrared photography and imagery to surface and subsurface drainage and terrain analysis for highway construction.

NATURE OF INFRARED

Infrared is an electromagnetic radiation whose spectrum band falls between that of visible light and the microwave region. It is a form of "heat" radiation, but this significance appears less prominent today than it was at the time of its discovery by

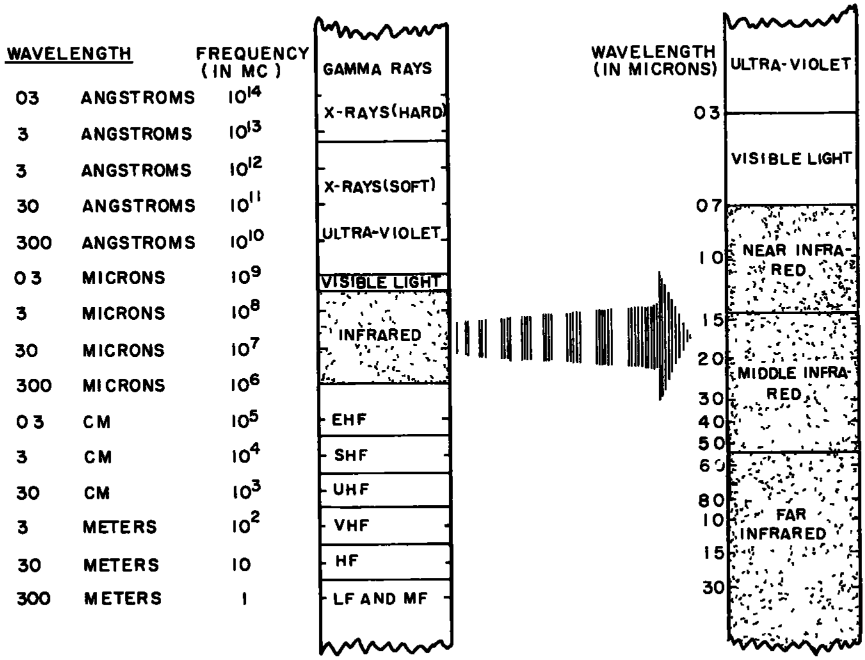


Figure 1. Electromagnetic spectrum: infrared occupies the spectrum band between visible light and microwaves.

Herschel, in 1800. In any event, today infrared (IR) is most generally applied to electromagnetic energy whose wavelength lies between 0.7 and 1000 microns (0.7×10^{-4}cm to 1000×10^{-4} cm). This energy can be reflected from, absorbed by, or emitted by objects of the universe.

Considering IR as a form of electromagnetic radiation, Figure 1 shows its domain in the electromagnetic spectrum. The customary units for wavelengths in the various regions are angstrom, micron, or centimeter as shown (1 micron = 10^{-4} cm, 1 angstrom = 10^{-8} cm). 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.

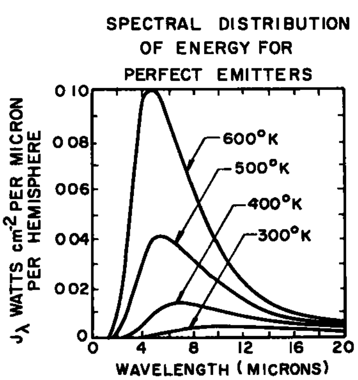


Figure 2. The effect of body temperature on intensity and wavelength of infrared radiation.

Infrared Radiation

At temperatures above absolute zero (absolute zero in degrees Kelvin equals -273 degrees Centigrade), all objects continuously radiate electromagnetic energy as a result of their atomic and molecular motion. The total amount of emitted radiation increases with the object's absolute temperature and reaches a peak at a certain wavelength. With increasing temperatures, the peaks are reached at progressively shorter wavelengths (Fig. 2). The earth, having an average temperature of 300 K, has an emission curve that peaks near 10 microns and gradually decreases toward the microwave region. This permits the detection of emitted radiation of terrestrial bodies in a broad region of wavelengths in the infrared band. The sun, by the same token, peaks in radiant power around 0.5 microns, which permits easy detection of reflected light with conventional photographic equipment.

Two fundamental laws set forth the relationships of Figure 2. The first is Wien's displacement law, which states that the wavelength at which peak radiation occurs equals a constant K divided by the object's absolute temperature in degrees Kelvin ($\lambda = K/T$). The second is the Stefan-Boltzmann Law, which states that the total radiation from an object is equal to the product of the fourth power of its absolute temperature, a constant, and an emissivity factor E ($W = E\sigma T^4$). The emissivity factor is the ratio of an object's radiation to that of an equivalent "blackbody." A blackbody is an object that absorbs all radiation that strikes it without any reflection. The factor, therefore, depends on the material and its surface properties. The emissivity factor for a mirrored surface, for example, would be about 0.05, while for lamp black 0.95. Finally, since total radiation or radiant emittance is expressed as the radiant energy emitted per second per square centimeter of surface area, energy per second is power; hence, emittance is usually measured in watts per square centimeter.

There are several other laws of radiation that in varying situations take on a complicated form. These become more applicable in the quantitative analysis of emittance, absorption, and reflectance characteristics of different objects. A discussion in this area is beyond the scope of this paper. Nevertheless, from some of the principles already presented, the basic strategy for detecting infrared radiation becomes relatively clear.

Each object in nature has its own unique property of reflected, emitted, or absorbed radiation. These properties, once identified, can be used to distinguish one object from another, or obtain information about shape, size, and other characteristics. Furthermore, if the spectral characteristics of an object are known, an appropriate detector can be selected to make the desired measurement.

The best known thermal source of IR radiation is the sun. Here, approximately 40 percent of the sun's energy is in the form of IR heat radiation. Variations in the quantity of radiation can obviously be attributed to the changing distance from the earth, water vapor and particles suspended in the atmosphere, and irregularities in the sun itself.

Atmospheric Absorption of IR

The atmospheric path between source and object, object and detector, or source and detector imposes severe limitations that must be considered. The atmosphere is, of course, far from being a pure substance. It is a mixture of oxygen, nitrogen, water (vapor, liquid, or solid), carbon dioxide, rare gases, and the suspended particles generally classified as haze, smog, or dust. Any radiation passing through the atmosphere could be either scattered, absorbed, or reflected by suspended particles before being finally transmitted.

A typical transmission spectrum of the atmosphere is shown in Figure 3. The darker areas are the regions in which transmission is almost completely blocked by H_2O vapor, CO_2, or a combination of other gases. The remaining regions are referred to as "infrared windows" in which the absorption is slight. Absorption by water vapor virtually closes the atmosphere beyond the 25 micron wavelength to the start of the microwave region, where the absorption of the IR is so complete that for practical purposes the atmosphere is considered opaque. As a result of this natural phenomenon, if transmission of radiation is required through the atmosphere, it would be necessary to channel the wavelengths within the infrared windows.

INFRARED DETECTION AND RECORDING

Infrared radiation can be detected and presented in image form by two methods: photography and imagery. First, IR can be presented by photography using film that is sensitive to reflected IR radiation. Second, IR can be presented by radiometry or imagery with electronic devices that are sensitive to emitted IR radiation and that produce an electrical signal proportional to the incident IR radiation. Both methods

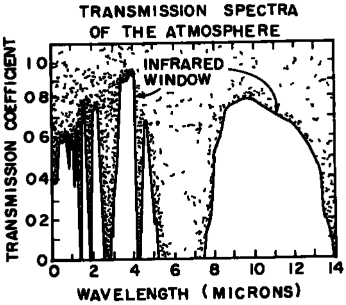


Figure 3. Atmospheric absorption of infrared energy as a function of wavelength: atmosphere is opaque to IR except in the "windows" shown.

can provide a visible photograph of the area in question, providing the latter utilizes a device that converts the IR emission to an electrical signal, which is further converted to light that exposes a photographic film and records an IR image.

An aircraft can be employed for taking IR photography and imagery as involved in taking normal aerial photographs. In IR photography, a camera is used to photograph a large area of the terrain from a single perspective point, whereas in imagery, a radiometer is used that scans the terrain from side to side as the aircraft moves forward. The former method photographs the image of the reflected IR radiation, and the latter produces an image that is similar to a photograph but whose tone is related directly to the IR radiation emitted in the form of heat by the terrain.

In general, therefore, IR photography is similar to normal panchromatic photography except that IR radiation is recorded on an IR-sensitive film while panchromatic radiation is recorded on a visible light-sensitive film. Furthermore, panchromatic and IR photography are both involved with reflected radiation. Infrared imagery, on the other hand, is a heat-measuring system that records IR radiation emitted from the object and is, therefore, a function of the object's emissivity and apparent temperature.

The following table offers a brief comparison of IR photography and imagery:

Photography	Imagery
Records reflected radiation.	Records emitted radiation.
Recording is directly on IR-sensitive film.	Recording is an electric signal converted to light that exposes the film and produces an IR image.
Can only record up to about a 0.9 micron wavelength unless film is shielded from the emission of the camera.	Can record all IR wavelengths except those restricted by the atmospheric absorption bands.
Usable in daytime or when some other source of IR radiation is available instead of the sun.	Usable preferably at night unless filtering devices are employed to eliminate ambient reflected radiation.
Reflection qualities of objects are measured.	Apparent temperature and emissivity of objects are measured.

SURFACE AND SUBSURFACE EXPLORATION AND DRAINAGE STUDIES BY AERIAL INFRARED SURVEYS

Surficial Earth Features

Aerial photography provides a reliable and efficient means of mapping terrain features of many areas. This method is further enhanced by the development of instruments for remote sensing in the IR region. Photographing an area in the infrared region in no way provides a complete image from which accurate identification of objects can be made. Instead, the infrared provides a new dimension to aerial photography where, in correlation with panchromatic photographs, more details about objects can be determined. Quite often, one portion of the desired information is best obtained in one region of the electromagnetic spectrum, while other portions require sensing in other regions of the spectrum. This consideration is often referred to as "multiband spectral reconnaissance" and it has several specific applications.

Colwell (4) illustrates the use of this method as a means of distinguishing between grass, concrete, asphalt, and soil surfaces from an examination of aerial photographs. Figure 4 shows the relative light reflectance of the four surfaces with respect to wavelength. For example, note that a grass surface has the lowest reflectance below 450 millimicrons and the highest reflectance above approximately 720 millimicrons. Consequently it is necessary to select appropriate bands in order to obtain photographic tonal characteristics that would permit differentiation between the four surfaces. The selection of a film sensitive to a specific wavelength where the greatest reflectance difference between surfaces exists provides the best tonal contrast. In this situation, the best tonal contrasts appear to lie at the 400 millimicron and 800 millimicron wavelength regions.

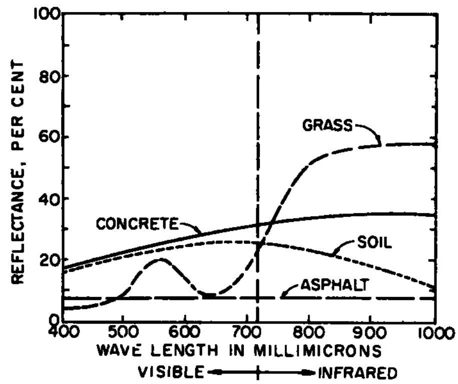


Figure 4. Light reflectance of surface materials [after Colwell (4)].

Figure 5 is a comparison between visible and IR photographs. Both were recorded during a summer day while using an IR detector for the one and a visible light detector for the other. The IR photograph represents primarily reflected IR solar energy, while the visible is the result of reflected sunlight. Note the difference in the appearance of the stream, vegetation, road, and cultural features on the IR.

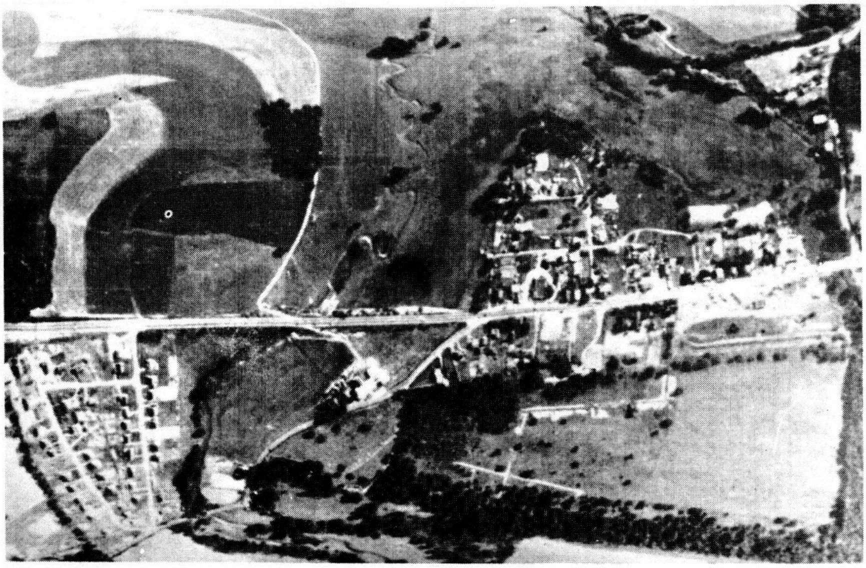
From a study of IR and visible photographs and IR imagery, plowed and unplowed fields can be distinguished. The plowed field would be expected to have higher emission if more of the solar energy is absorbed and subsequently emitted at the surface. A plowed or scarified surface would, therefore, usually appear lighter in tone on an IR image because of the higher emission (Fig. 6). Much of this phenomenon, however, depends on soil composition, density, surface texture, and moisture, which have been known to sometimes reverse expected tonal contrasts.

This same correlation assists in estimating various soil parameters. The configuration, physical state, and trafficability of surficial materials can be ascertained to a great extent simply by interpretation of the tonal contrasts and other features that may appear on an IR photograph or image. Besides comparing IR photographs obtained in daylight with conventional aerial photographs, nighttime IR imagery adds a new dimension that assists in identifying surficial properties.

An important fundamental principle that arises in the discussion of IR photography of vegetation is the "chlorophyll effect." In essence, this effect is usually explained by stating that chlorophyll is transparent to IR. As such, the internal tissues of leaves are permitted to reflect IR radiation. When leaves are diseased, however, the internal structure collapses and reflectance of IR decreases. As a result, vegetation will photograph lighter in IR if healthy and darker if diseased (Fig. 7). IR photographs, therefore, could be well used by right-of-way departments in appraising the value of citrus groves, crops, and other cultivated lands.

Geological and Subsurface Exploration

The geological interpretation of aerial photographs for identifying various landforms, rock types, and erosional features and for mapping joints and faults is a well-developed discipline. The location of these and other types of geological structures that may exert major influence on site selection for highway construction and other engineering



(a) Panchromatic Aerial Photograph.

(b) Infrared Aerial Photograph.

Figure 5. Comparison of visible and near infrared photographs of the same area taken on a summer afternoon (courtesy of HRB-Singer, Inc.).

projects can be greatly enhanced by infrared surveillance. Within recent years, the development of IR aerial surveys has provided a means of obtaining geological and subsurface information that was not possible with conventional photography. Much of the additional detail that IR provides is due to the different specific heats and thermal conductivities of the materials associated with the geological formation.

Recent IR imaging instruments have made possible the investigation of subsurface anomalies associated with volcanic regions of Hawaii (6). The aerial extent and relative intensity of the subsurface thermal activity were mapped. From the IR image,

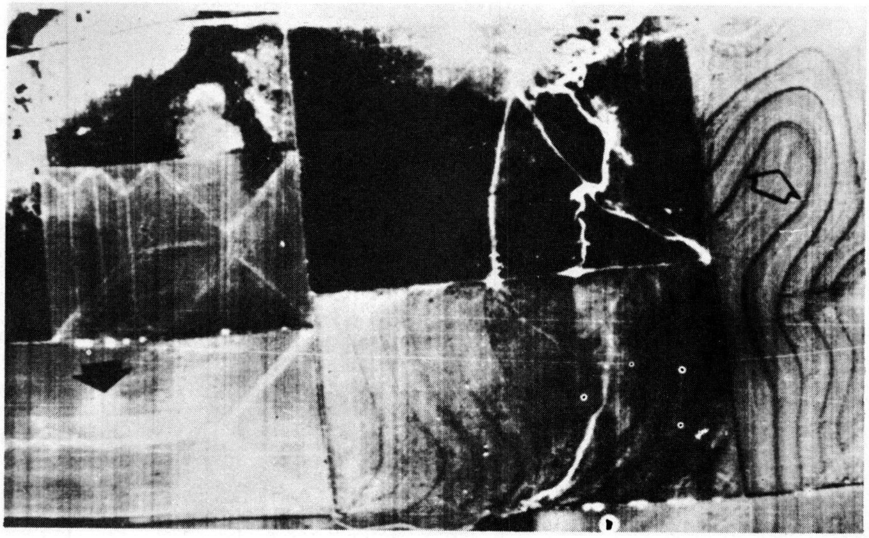


Figure 6. IR image of farmland near Dallas, Texas, reveals a tilled field and contour ridging (courtesy of Texas Instruments, Inc.).

it was possible to locate volcanic thermal patterns and structural features that were not observed on conventional aerial photographs. The degree and extent of thermal activity in many of the areas surveyed were obtained at various periods, and changes were noticed. The causes of a continuous increase in degree of intensity in some areas are not always known, but one could speculate that increasing subsurface activity of some type could be imminent. Airborne IR sensing instruments could be used periodically to monitor subsurface thermal activity in volcanic regions.

The subsurface and near-surface hydrothermal activity in Yellowstone National Park was recorded with IR sensing instruments (13). The image presented high-temperature features such as hot springs and geysers, warm rivers, and above-normal ground temperatures. Various thermal patterns were observed where hot springs discharged into lakes. Many of the hot springs at the lake bottoms had not been previously located. The imagery presented demonstrated the usefulness of IR sensing for mapping hydrothermal features, especially in areas too remote to be otherwise charted.

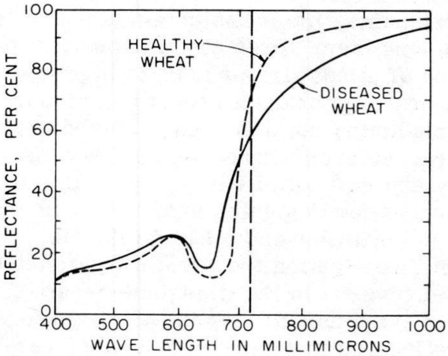


Figure 7. Light reflectivity of wheat leaves [after Colwell (4)].

Although discontinuities in rock and soil masses can usually be mapped using conventional aerial photography, the tonal differences are at times more pronounced on IR imagery. To illustrate this application some investigations made by the Science Service Division of Texas Instruments, Inc., are shown in Figures 8 and 9. Some of the distinction between the different materials could have been attributed to the different types of vegetation supported by each, but much more contrast is evident on IR imagery due to the thermal qualities of the rock and associated soils.

Although the surface and subsurface drainage pattern in Figure 9 is distinct, the tonal contrast between adjacent soil types, which expresses different thermal characteristics, is evident. Thermal variations are a function of specific heats

Figure 8. IR image of Mt. Pisgah near Hector, Calif., reveals a cinder cone of higher thermal property and a clear contact between lava flows ; the lighter tone at the center of the image is indicative of a relatively warmer material (courtesy of Texas Instruments, Inc.).

and thermal conductivities of the two lava flows in Figure 8 and of soil materials in Figure 9. Thermal patterns on IR imagery indicate variation in ground moisture and in the mineralogy and chemistry of the materials.

Infrared imagery is also used to display stream valleys and subsurface water channels that may otherwise be somewhat obscured by overburden or vegetation. Dark-toned areas within the stream valleys on IR imagery are usually expressions of higher ground moisture content. There is, however, the strong possibility that the dark-toned stream valleys do not actually represent moist areas. At times, valleys are filled with colder air that cools the surface in this area more than the surface of the higher land and results in darker tones on IR imagery.

Figure 10 reveals a striking subsurface drainage feature that is not displayed by a visual photograph. Vegetation many times suggests greater surface or subsurface moisture conditions at particular areas. However, vegetation alone does not provide a completely reliable means of exposing hidden drainage systems. The benefits gained from the use of IR imagery for locating underground drainage more reliably during highway site selection and construction are considerable.

The Science Services Division of Texas Instruments, Inc., has obtained much IR imagery for near-surface terrain analyses. Among them, three striking photographs reveal subsurface cultural features that could be of utmost importance to highway engineers. Figure 11 reveals the location of a drainage channel beneath an airport runway; Figure 12 exposes the location of a buried pipeline, and Figure 13 shows the location of a buried conduit. Many other cultural features whose location is vital for highway planning can usually be more distinctly exposed with IR imagery. Futhermore, considerable time could be saved in making surveys for designing highways if IR instruments were used to detect lost or forgotten buried utilities and other facilities.

The Florida State Road Department has been investigating the possibility of detecting near-surface underground voids, caves, and caverns in the 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, muck pockets were located that were previously overlooked in the soil survey (19). Further research to determine the type of IR instrument and wavelength bands most suitable for detecting underground voids and muck pockets will undoubtedly provide a valuable tool for the highway engineer.

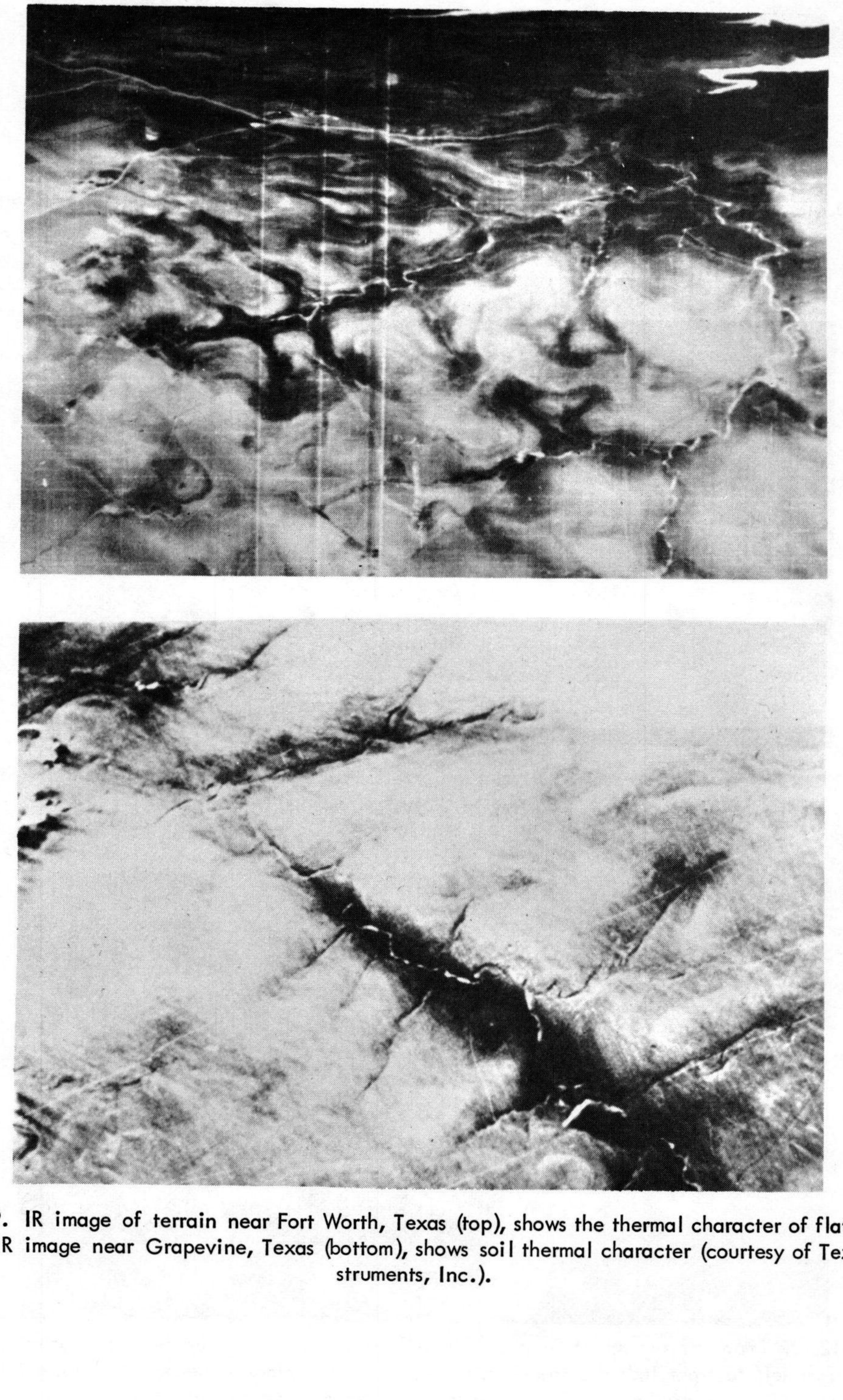


Figure 9. IR image of terrain near Fort Worth, Texas (top), shows the thermal character of flat-lying strata; IR image near Grapevine, Texas (bottom), shows soil thermal character (courtesy of Texas Instruments, Inc.).

Figure 10. IR image of terrain near Walley's Spring, Nevada, expressing a subsurface drainage feature (courtesy of Texas Instruments, Inc.).

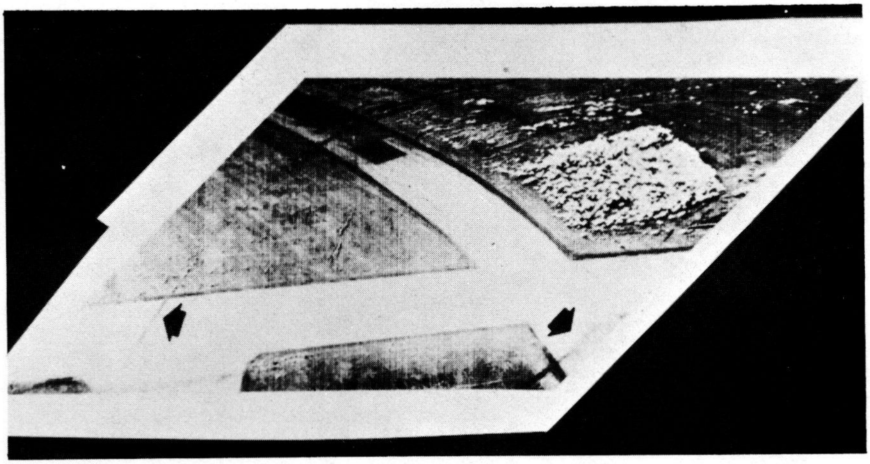


Figure 11. IR image of airport runway; arrows indicate location of existing subsurface drainage channels (courtesy of Texas Instruments, Inc.).

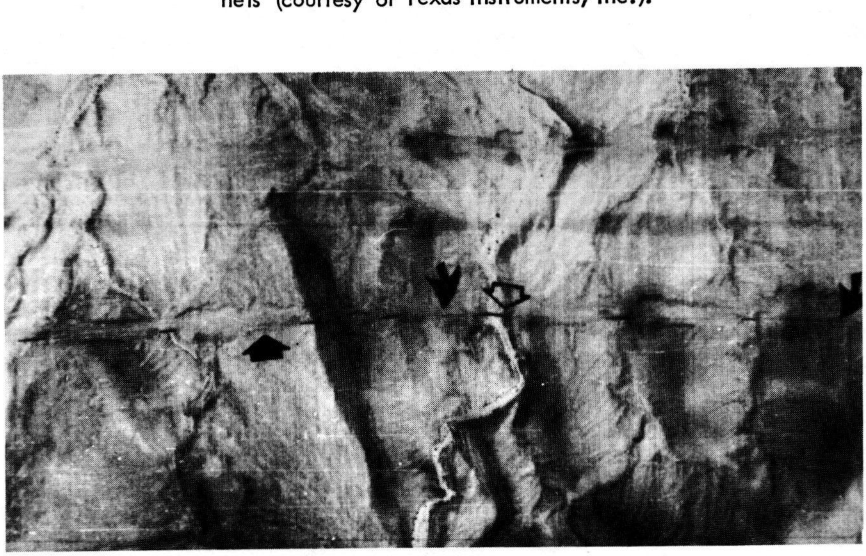


Figure 12. IR image of terrain at Death Valley, Calif., exposing the location of a buried pipeline; arrows from left to right indicate the pipeline right-of-way, pipeline beneath terrain, and pipeline exposed at stream crossing (courtesy of Texas Instruments, Inc.).

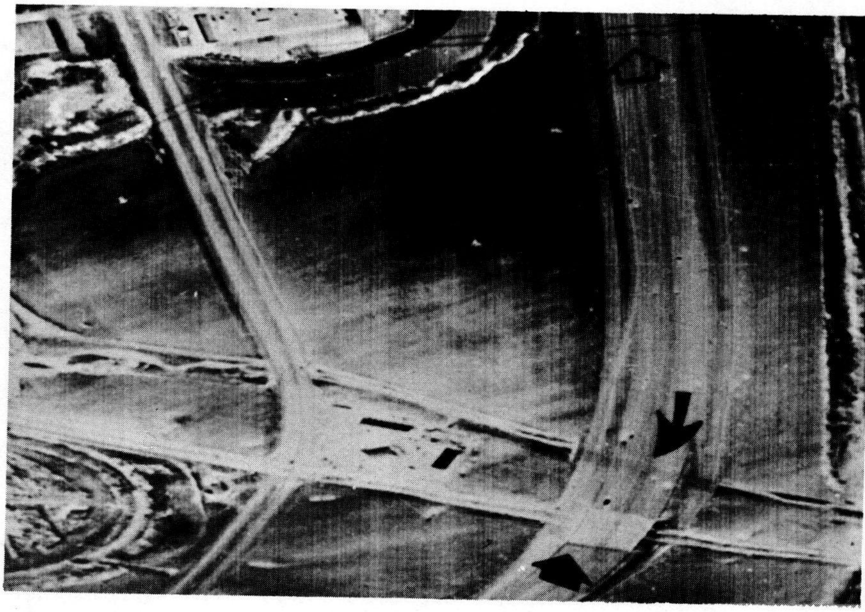


Figure 13. IR image of an industrial area of Dallas, Texas, showing highway overpass , power transmission lines , and subsurface conduit (courtesy of Texas Instruments, Inc.).

The application of IR instruments for detecting cavities under edges of concrete pavements is also promising. The advantage in detecting these cavities before pumping develops or actual failure takes place, both from a safety and maintenance standpoint, is obvious.

CONCLUSIONS

Infrared radiation, which lies between visible light and microwaves, can be considered one of the most useful regions of the electromagnetic spectrum for remote sensing for engineering purposes. Within the past few years there has been an increasing awareness of the potential applications of IR surveys for many practical purposes. Numerous investigations are presently being conducted by private and governmental agencies that are expanding IR sensing techniques into many areas of highway engineering.

It is of great value in highway planning to identify surface materials reliably and rapidly. IR photography and imagery highlight variations in soil texture, composition, and moisture that are not usually recorded by conventional photography. The chlorophyll effect allows IR photography to assist in appraising cultivated land for right-of-way acquisitions. The additional information that IR techniques provide about surface conditions can greatly reduce highway construction costs.

Hidden subsurface conditions and geological features that influence highway planning and design can be exposed with IR instrumentation. The location of muck pockets, underground cavities, volcanic and hydrothermal activity, subsurface drainage systems, and buried utilities and conduits is of utmost importance during highway site selection. IR sensing in many instances can expose these items, which are usually omitted during normal exploration surveys or drainage studies. The application of IR sensing for mapping boundaries of rock formations and soil types cannot be overemphasized.

Although experience in the geological interpretation of imagery and photography may appear to be somewhat limited at present, it is evident that valuable surface and subsurface information not noticeable on visible aerial photographs may be displayed using IR. This potential method of gathering such information should not be overlooked and its value in preliminary investigations is obvious. With further research in the techniques used for infrared remote sensing, surface and subsurface exploration and drainage studies for construction of highways, airports, and other projects may be greatly facilitated.

ACKNOWLEDGMENTS

The writers gratefully acknowledge the cooperation and assistance given by HRB-Singer, Inc.; Texas Instruments, Inc.; and the U. S. Geological Survey. The literature and information pertaining to remote sensing with infrared furnished by them and permission for reproduction of photographs were a great aid in the preparation of this paper.

The writers wish to thank Prof. O. Mintzer, Ohio State University, and Mr. J. H. McLerran, CRREL, U. S. Army, for their critical review of this paper and for their many helpful suggestions.

REFERENCES

1. Cantrell, J. L. Infrared Geology. Photogrammetric Engineering, Vol. 30, No. 9, p. 916, Nov. 1964.
2. Chaney, L. L. Earth Radiation Measurements by Interferometer From a High Altitude Balloon. Proc. Third Symposium on Remote Sensing of Environment, Feb. 1965, Univ. of Michigan, p. 225-245.
3. Clark, W. Photography by Infrared, Second Edition. John Wiley and Sons, New York, 1946.
4. Colwell, R. N. Some Practical Applications of Multiband Spectral Reconnaissance. American Scientist, Vol. 49, p. 9-36, March 1961.
5. Feder, A. M. Let's Use More of the Electromagnetic Spectrum. Trans. Gulf Coast Assn. of Geological Societies, Texas, Oct. 1964.
6. Fischer, W. A. and Moxham, R. M. Infrared Surveys of Hawaiian Volcanoes. Science, Vol. 146, No. 3645, p. 733-742, Nov. 6, 1964.
7. Gates, D. M. Characteristics of Soil and Vegetated Surfaces to Reflected and Emitted Radiation. Proc. Third Symposium on Remote Sensing of Environment, Feb. 1965, Univ. of Michigan, p. 573-600.
8. Harris, D. E., and Woodbridge, C. L. Terrain Mapping by Use of Infrared Radiation. Photogrammetric Engineering, Vol., 30, No. 1, p. 134-139, 1964.
9. Jamieson, J. A. Infrared Physics and Engineering. Inter-University Electronics Series, McGraw-Hill Book Co., New York, 1963.
10. Kinsman, F. E. Non-Contact Sensors, Across the Electromagnetic Spectrum, for Geoscience Purposes. Texas Instruments, Inc., Dallas, April 1964.
11. Kruse, P. W., McGlauchlin, L. D., and McQuistan, R. B. Elements of Infrared Technology. John Wiley and Sons, New York, 1962.
12. Martin, A. E. Infrared Instrumentation and Techniques. Elsevier Publishing Company, Amsterdam-London-New York, 1966.
13. McLerran, J. H., and Morgan, J. O. Thermal Mapping of Yellowstone National Park. Proc. Third Symposium on Remote Sensing of Environment, Feb. 1965, Univ. of Michigan, p. 517-530. (Reprinted by the Am. Soc. of Photogrammetry in "Selected Papers on Remote Sensing of Environment," July 1966.)
14. Molineux, C. E. Aerial Reconnaissance of Surface Features With the Multiband Spectral System. Proc. Third Symposium on Remote Sensing of Environment, Feb. 1965, Univ. of Michigan, p. 399-421.
15. Ory, T. R. Line-Scanning Reconnaissance Systems in Land Utilization and Terrain Studies. Proc. Third Symposium on Remote Sensing of Environment, Feb. 1965, Univ. of Michigan, p. 393-398.
16. Robinove, C. J. Remote-Sensor Applications in Hydrology. U. S. Geological Survey, Washington.
17. Simon, I. Infrared Radiation. D. Van Nostrand Co., Princeton, 1966.
18. Strangway, D. W., and Holmer, R. C. Infrared Geology. Proc. Third Symposium on Remote Sensing of Environment, Feb. 1965, Univ. of Michigan, p. 293-320.
19. Personal communication from the Florida State Road Department.