N72-21357

Technical Report RSC-22

REMOTE SENSING IN HYDROLOGY: A SURVEY OF APPLICATIONS WITH SELECTED BIBLIOGRAPHY AND ABSTRACTS

compiled by

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October 1971

supported by
National Aeronautics and Space Administration
NSG-239-62

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ABSTRACT

The purpose of this document is to demonstrate remote infrared sensing as a water exploration technique. Various applications are described, demonstrating that infrared sensors can locate aquifers, geothermal water, water trapped by faults, springs and water in desert regions. This document is intended to stimulate the awareness of the potentiality of airborne IR sensors as a water prospecting tool.

Also included is a selected bibliography with abstracts concentrating on those publications which will better acquaint the hydrologist with investigations using thermal remote sensors as applied to water exploration.

REMOTE SENSING IN HYDROLOGY

INTRODUCTION

Within the last decade, there has been as increasing awareness of the need for the exploitation of our diminishing resources, especially the increasing demand for more water. Because of the inadequacy of the current surface exploration techniques for groundwater, for future demands [1] airborne remote sensing applications using "thermal infrared" detectors have been explored as a potential water prospecting tool. In an aerial remote sensing survey, it is well documented that vast areas can be examined more rapidly and cheaper in terms of a square mile cost, than land survey [2]-[13]. Aircraft are not limited by topographic obstacles, and thus survey an area much faster than land based reconnaissance by man and vehicles. Airborne sensors obtain a large overview, permitting recognition of features which are difficult and sometimes indistinguishable on the ground. This is especially true in remote sensing application of thermal infrared detectors to groundwater prospecting.

FUNDAMENTALS OF REMOTE THERMAL SENSING

The Infrared region of the electromagnetic spectrum was first observed in 1800 by Sir William Herschel [14],[15].

Since this discovery, man has utilized infrared techniques in observation of various thermal radiation characteristics within our environment. The term infrared refers to that portion of the electromagnetic spectrum with frequency less than visible light but greater than that of the microwave region [14]. The frequency range of the infrared spectrum is from 3×10^{11} Hz to approximately 3×10^{14} Hz, or a wavelength range from 1000 μ (microns) to 0.75 μ.

In applying infrared detection to remote sensing the transmission characteristics of the atmosphere in the infrared region are critical. Infrared radiation above 14 μ wavelength is generally absorbed by molecules in the atmosphere. Between 0.75 μ and 14 μ, infrared radiation transmits only in certain wavelength bands called atmospheric "windows" [14]. Near, middle, and far infrared refer to portions of this 0.75-14 μ region, while extreme infrared refers to that above 14 μ.

To detect characteristics of a remote terrain target, only measurements in the atmospheric windows are of use. The energy-frequency relationship of the detected infrared radiation is the signature of the remote target and might be used to distinguish it from other possible targets. Thus, the measurement of the infrared radiation spectrum of a target can obtain important information about the physical nature of it. Measurement of the entire infrared spectrum is not always necessary, since measurement in one frequency window may adequately describe the important characteristics of the target. For example, infrared radiation is highly dependent upon target temperature in the 8-14 μ window, providing the basis for remote temperature measurements. For the detection and evaluation of the amount of groundwater, another window may be more suitable. The physical characteristics of the ground will change as the amount of water present increases and the change will cause a change in the level of the infrared (IR) radiation detected. Being able to correlate a change in the IR characteristics with the change in physical characteristics of the ground as related to groundwater is all that is necessary to remotely detect the presence of groundwater.

SURVEY OF APPLICATIONS

Aquifers. Lovering and Goode [16], and Cartwright [17] suggest that the change in surface signature with the presence of groundwater is the result of the high specific heat of the water, causing a shallow aquifer to act as a heat sink or as a heat source that influences the near surface temperatures to a measurable extent. This perturbation in the geothermal gradient will cause a marked effect on the temperature variations of the surface. Cartwright [18] states that the maximum effective depth of an aquifer to cause a surface anomaly is about 33 to 66 feet. Cartwright [17] made seven field surveys in Illinois over known shallow alluvial and glacial aquifers, all of which revealed surface anomalies. He found that detecting surface anomalies offers a rapid, inexpensive and reliable means of locating shallow aquifers. Cartwright also used thermistors to measure the anomalies which were as much as 2° C cooler than the adjacent material.

The same type aquifers that Cartwright surveyed in Illinois, extend eastward into Indiana where Carr and Blakely [49] searched for similar sand and gravel groundwater aquifers. By using near-surface thermistors like Cartwright used, Carr and Blakely were able to detect higher diurnal temperature changes in clay till than in outwash sand and gravel. The survey of sand and gravel aquifers in Indiana reflected the results obtained by Cartwright, in which the presence of shallow aquifers produce a cooling effect at the ground surface.

Chase [20] undertook a study to determine the applicability of IR photography and thermal IR imagery to near-surface evaluation. The survey was prompted by a deficiency of groundwater in the prairie lands of southern Alberta, Canada. Chase found IR sensors a valuable tool for such studies, as it detected soil moisture variation, soils of high salt content, and shallow subsurface drainage. Canal seepages were traced by soil moisture and salt content. Chase concluded that IR black and white photography was found to be of little help in groundwater studies in the prairie environments.

One might refer to the previously described heat sink effect when considering some of the anomalies Strangway and Holmes [21] encountered in a program of infrared investigations. Their studies were made in the southwestern United States where vegetation cover is a minimum and in the early spring so that residual effects from solar heating would be a minimum. Most of their work was conducted just before sunrise in order to reduce solar effects.

While surveying the Arizona Basin and Range province, they encountered known fault zones which showed well-defined breaks with the downthrown side of the fault appearing cold. An explanation for such a feature is that the faults are trapping the groundwater aquifers, and the accumulation of groundwater produces the heat sink effect.

Geothermal. The earliest utilization of geothermal energy for industrial power was at Lardarello, Italy in 1904 [23]. Domestic and industrial heating by natural steam was initiated in Iceland in 1925 [24], and over 40% of its population now live in houses heated by natural steam [25]. Recently, geothermal power production has been taken up in New Zealand, Iceland, Japan, Chile, El Salvador, Turkey, U.S.S.R., and the U.S.A. There is a growing interest in this source of energy.

Largely ignored in the United States while other countries pioneered its development, geothermal energy is gaining interest because of growing power shortages, increasing air pollution from fossil fuel plants and the possible danger of nuclear power plants. The only geothermal power plant in the United States is the Geysers, Sonoma County, in northern California. The Geysers is considered to be the third largest geothermal water supply in the world [23].

During an infrared survey in the vicinity of Safford, Arizona, Strangway and Holmes found that the apparent temperature was extremely high from the base of one mountain to another. This feature was so repeatable and diagnostic that they paid special attention to it. A temperature profile was recorded across the valley by drilling test wells, which revealed that the valley is underlain by hot water which has a temperature of 150° F at 419 feet below the surface. This appears to be a heat rise revealing the potential usefulness of infrared detectors for geothermal water. Strangway and Holmes made a survey over the Lordburg, New Mexico area in order to compare the infrared profile with Kintzinger's [22] ground temperature data, since this area is underlain by hot water. The infrared profile was identical to the ground data profile.

The thermal water detected by infrared sensors in the Lordsbury, New Mexico and Safford, Arizona, areas offer reservoirs of heated water which could possibly permit steam to be conducted to the surface where it could be used as a source of energy. Searching for thermal anomalies, Moxham applied IR detectors to six volcanoes in the Cascade Range [27]. The volcanoes were: Mt. Rainier, Mt. Adams and Mt. St. Helens, Washington and Mt. Shasta, Cinder Cone and Lassen Peak, California. His IR survey revealed the detection of geothermal energy being released at the ground surface. Moxham also located geothermal water at Crater Lake, Oregon, using IR detectors.

Walker evaluated IR imagery taken during a survey of southeastern Oregon and discovered several geothermal areas. His imagery coincided with several areas containing hot springs. He attributed the energy source as a result of underground heat being convected to the surface by thermal spring waters [30].

Because of the large variety of geothermal anomalies in Yellowstone National Park, Wyoming, IR investigations have centered around this area [31]-[35]. All of the IR investigations reveal successful applications of IR sensors to various thermal anomalies. The largest geothermal field in the world was detected at Cerro Prieto, in Baja California on an extension of the San Andreas fault system [23].

Infrared investigations have discovered large supplies of geothermal waters for domestic heat on the Kamchata Peninsula Siberia, U.S.S.R. [36]. Geothermal water is a most valuable source of heat in the colder regions of the world. Parker located geothermal water in Antarctica and Friedman discovered new supplies in Iceland [28]. Moxham and Alcarez detected geothermal water at Taal Volcano, Philippines (37).

It is apparent that any structure showing a geothermal surface signature should be easily detected by IR sensors.

Faults. Wallace and Moxham [38] traced 200 miles of the San Andreas fault system in the Carrizo Plain area of California, using 8-13 μ band infrared imagery. They were able to detect vegetation differences along the fault zone. The heavier vegetation was found to be related to variations in soil moisture caused by the water barrier characteristics of the fault zone. Also identified on the imagery were offset sediments of ancient stream channels. Imagery obtained just before sunrise was considered most useful in their fault studies.

Saunders [39] detected infrared lineaments caused by fault controlled groundwater discontinuities of a basin area in Nye County, Nevada using 8-14 μ infrared imagery.

Sabins [40] located faults covered with alluvium in an infrared survey of Indio Hills, California. The faults were expressed on the imagery as temperature anomalies related to blockage of groundwater. These temperature anomalies consisted of patches and streaks of colder ground aligned parallel with the fault trace, and were recognized only on the infrared imagery.

In another survey by Sabins [41], soil moisture variations were detected in sedimentary bedrock of the Imperial Valley, California, using 8-14 μ imagery. This suggested the possibility of finding groundwater in deserts. The moisture located was believed to be blocked by a fault causing the water to be trapped in the bedrock.

<u>Arid regions</u>. An examination of the literature reveals that little has been done to apply infrared sensors to arid regions in search of water. An excellent arid hydrogeologic study by Wermund [42], demonstrates the capability of IR sensors in locating groundwater in such terrains. His survey extended over four arid areas in the western United States:

Railroad Valley and Las Vegas Basin, Nevada, Death Valley, California, and the Hueco Mountains of Texas. Results of the study show that infrared imagery data, in the 8-14 μ region, contains signatures of near-surface water concentrations in all these areas. However, the probable cause of this surface anomaly is the effect of perched water. The perched water lens cannot exist over 30 feet below the surface in order to cause this anomaly.

Wermund also found springs and faults in the various areas due to the surface expressions detected by the IR sensors.

Springs. All coastal countries lose groundwater to the ocean, by springs or seeps. If 5% of this groundwater loss were intercepted and recovered, the additional water supply in this country would raise the standard of living and possibly cause population shifts.

Lee [43] collected infrared data on four different missions using 3-5.5 μ and 8-14 μ regions. Shoreline springs and seeps were detected around Mono Lake, California. Lee empirically derived quantitative correlation methods, derived from a study of image anomalies from seven springs, and estimated the discharge rates of eleven other springs using imagery data.

In an IR investigation of the same Mono Lake area, Friedman [44] concluded that convective heat loss from fractures heated by epithermal solutions, detected on night and pre-dawn imagery, provided a means for outlining the surface configuration of the thermal anomalies associated with the hot springs and fumaroles of the area.

Hunn and Cherry [45], using 8-14 μ imagery, detected groundwater discharge from springs along the shore of Florida. The aquifer discharging these springs is the source of groundwater supply for central Florida.

Fischer [46] used an IR detector in the 4.5-5.5 μ region to locate the discharge of groundwater at sea level around the Island of Hawaii. He claims to have located 219 shore line springs around the island. Laltman [47] discovered several springs as a side benefit during a geologic IR survey of Mount Niltany, Pennsylvania. Stingelin [48] not only located springs using IR detectors, but was able to trace their drainage pattern to the Bear Meadows Bay, in Pennsylvania.

CONCLUSION

Thermal infrared measurement techniques have been shown to be applicable in the location of areas of probable groundwater occurence in those cases where the groundwater would directly affect the surface temperature. Groundwater occurrences in near surface aquifers (at a depth of less than 30-60 feet) have been shown to cause surface temperature anomalies in certain soil types within sensitivities of remote thermal sensors. Groundwater heated by geothermal energy has been detected by remote sensing techniques, whereas limited investigation of arid regions indicate the detectability of perched water at depths of less than 30 feet. Surface groundwater appears to be the most readily detectable.

The application of remote thermal infrared sensing to hydrology has occurred only within the past ten years and the maximum potential of this technology as a hydrologists tool has not been completely realized. Various applications to hydrology have been described to stimulate the awareness of the potential of airborne thermal infrared sensors as a useful water prospecting tool.

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A SELECTED BIBLIOGRAPHY WITH ABSTRACTS

This document consists of a bibliography with abstracts of current publications on thermal sensor applications to water prospecting. The primary objective of this document is to concentrate those publications that will better aquaint hydrologists with a new water exploration technique-remote (thermal) sensors. All publications present data obtained from investigations using thermal sensors applied to water exploration or as a by-product of other investigations.

An overview of this literature may assist in formulation of the potential effectiveness of thermal sensors as a tool for finding an adequate water supply for present day demands.

Each of the references is cross-indexed using different key words, as well as by the geographical area in which the intestigation occurred, the purpose being for maximum retrieval of articles dealing with a particular subject and/or area. The references are indexed according to assigned numbers within each alphabetical letter grouping, and each includes the letter followed by three (3) numerical digits (i.e. B100).

B100

Blinn, J.C., Quade, J.G., Chapman, P.E., and Brennan, P.A., "Multispectral Remote Sensing of an Exposed Volcanic Province", Jet Propulsion Laboratory Technical Memorandum 33-453, California Institute of Technology, Pasadena, June 15, 1970.

During July of 1968 a mission was flown, for a second year, over a volcanic province at Mt. Lassen National Park, in support of the NASA Earth Resources Program. Day and night flights were completed with the following instruments operating satisfactorily: two 9-in. by 9-in. metric cameras with black and white and color IR film, an 8-14 μm IR scanner, four microwave radiometers operating at 8.9, 15.8, 22.2, and 34.0 GHz and a 13.3-GHz radar scatterometer.

Four ground stations were manned during the flights to monitor ground temperatures and moistures. These data were used in conjunction with ground-based radiometers operating at 1.4, 9.3, 13.7, and 37.0 GHz. Prior to the overflights, extensive ground studies (terrametrics), utilizing standard geologic and geophysical techniques, were performed. Some of these studies were reported in greater detail in JPL Technical Memorandum 33-405; however, those pertinent to this report and studies completed this year are reported herein.

Data from the aircraft and ground-gased sensors are presented with the relative merits of each sensor discussed along with recommendations for their application.

Authors

C100

Cantrell, John L., "Infrared Geology", Photogrammetric Engineering, Vol. 30, pp. 916-922, 941, 1964.

In the not too distant future geologists and, in particular, photogeologists will have a new remote tool--infrared imagery--to aid in solving geologic reconnaissance problems. By comparing airborne infrared imagery with aerial photography, unique information can be obtained about the earth's surface features.

The military is continually developing infrared imaging systems for surveillance and target acquisition purposes; but only recently have geologists discovered the value of these systems for their purposes.

Interpreters of infrared imagery for geologic purposes must be fully aware of the physical phenomena involved in generating infrared imagery. They must recognize the fact that infrared imagery is created primarily by emitted energy and not reflected energy as in conventional photography.

Author

C200

Carr, Donald D. and Blakely, Robert F., "Temperature Variation at a Depth of 30 cm in Clay Till and Outwash Sand and Gravel", Proceedings of the Fourth Symposium on Remote Sensing of Environment, Univ. of Michigan, Ann Arbor, pp. 203-214, April 1966.

The near-surface (30 cm) temperature variation of soils with parent materials of clay till and outwash sand and gravel was investigated by the Indiana Geological Survey with a thermistor probe having a sensitivity of 0.05° C. The site studied was a 10.3-square-kilometer (4-square-mile) area in central Indiana underlain by glacial drift of Wisconsin Age.

Temperatures measured at 30 cm varied considerably within both the soils of clay till and outwash sand and gravel, so that it was impossible to distinguish between the lithologies by temperature alone. However, diurnal temperature changes were found to be consistently higher in the clay till than in outwash sand and gravel. The mean diurnal change in temperature for clay till at a depth of 30 cm ranged from 2.18°F in May to 0.32°F in December; in outwash sand and gravel it was 0.48°F in May and 0.03°F in December.

The delineation of bodies of sand-size and gravel-size material from bodies of clay-size material by temperature change holds promise as an exploration tool. Sand and gravel are important mineral products that are used in large quantities mainly by the construction industry. Also, these materials form excellent reservoirs for ground water. Indiana has several types of areas containing sand and gravel deposits that could be used to study near-surface temperature variation.

Authors

C300

Cartwright, Keros, "Temperature Prospecting for Shallow Glacial and Allurial Aquifers in Illinois", Illinois State Geological Survey Circular 433, 1968.

Theoretical considerations of the thermal properties of glacial and alluvial deposits in Illinois suggest that a shallow aquifer might form a heat sink (or source) that would influence the temperature effects on the soil of heat originating at the land surface and within the crust. If shallow aquifers are nonuniformly distributed laterally, and if their effects on the temperatures of surface soil can be measured and distinguished from other factors that affect soil temperature, a possible exploration method for shallow aquifers is suggested. A positive (warm) anomaly would be expected over such aquifers in the winter and a negative anomaly in the summer. The size of the anomalies is dependent upon the thermal properties of the overburden, temperature difference between the surface and aquifer, and the depth of burial of the aquifer.

An electronic thermometer, utilizing a thermister at the end of an aluminum-tipped stake and a transistor-amplified bridge circuit, was used to measure soil temperatures at a depth of about 18 inches in seven areas in Illinois where shallow aquifers were known in some detail. The data from these surveys, presented here, show maximum anomalies of about 2^{o} C over the aquifer. Surveys were made both in summer and winter; summer anomalies generally are of a greater magnitude than winter anomalies.

Soil differences, vegetation, and ice in the soil also affect the soil temperatures. The effect of vegetation in the summer can be as great as the anomaly produced by an aquifer. Frozen soil tends to eliminate anomalies, but this effect can be partly overcome by taking readings at a greater depth. In general, however, field data show close agreement between the location of shallow aquifers and thermal anomalies.

Author

C400

Cartwright, Keros, "Thermal Prospecting for Ground Water", Water Resources Research, Vol. 4, No. 2, pp. 395-401, April 1968.

Theoretical consideration of the thermal properties of unconsolidated deposits suggests that a shallow aquifer might form a heat sink that influences and modifies the temperature effects of heat originating at the land surface and within the crust. The unconsolidated water-yielding deposits apparently are not of the same temperature as the material surrounding them. If the shallow aquifer is nonuniformly distributed, it should produce a temperature anomaly in the surface soil. The size of the anomaly resulting from a shallow aquifer would depend on the thermal properties and thickness of the overburden and on temperature differences between the surface and the aquifer. (Key words: Geophysical investigations; ground water)

Author

C500

Chase, M.E., "Airborne Remote Sensing for Groundwater Studies in Prairie Environment", Canadian Journal of Earth Sciences, Vol. 6, pp. 737-741, 1969.

A deficiency of groundwater in an area of prairieland in southern Alberta prompted a survey by airborne remote sensors. Panchromatic and black and white true infrared photography coverages were obtained and studied, but were found to be of limited value. An infrared scanning survey, using the 2.5-5.6μ band was flown at the same time and found to be more informative. Conditions of ground truth were not ideal, making the results less conclusive than desired. Till covers most of the area, with lake deposits in the eastern section. Soil moisture changes were registered on the imagery, but the depths of overburden to which these changes were recorded on the surface are unknown, due to the condition variations between the time of the survey and the drilling. Vegetation, surface water, soil moisture, and saline sloughs were found to have the strongest thermal signatures. Problems encountered in the survey are discussed and recommendations to eliminate them are given.

Author

C600

Colwell, Robert N., "Uses and Limitations of Multispectral Remote Sensing", Proceedings of the Fourth Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, pp. 71-91, April 1966.

Some enthusiastic proponents of multispectral remote sensing herald it as the means by which virtually all of man's data-gathering problems, both terrestrial and extra-terrestrial, can best be solved. However, certain high-level decision-makers feel that such optimism is not justified. They assert that little or no information of vital importance has been found to be better derivable through multispectral remote sensing than through any of several other, less sophisticated means. Consequently they are of the opinion that the continuation of a vigorous research and development program in this area is unwarranted. Perhaps both groups need to examine more carefully, and in more specific terms, the uses and limitations of multispectral remote sensing. This paper undertakes such an examination through the use of both specific examples and analytical discussions of the various factors governing remote sensing. It is hoped that the approach used here will help to place in better focus both the enthusiastic claims and the pessimistic criticisms, thereby assisting the reader in formulating his own opinion relative to the potential usefulness of multispectral remote sensing.

Author

C700

Colwell, Robert N. and Olson, Don L., "Thermal Infrared Imagery and Its Use in Vegetation Analysis by Remote Aerial Reconnaissance", Proceedings of the Third Symposium on Remote Sensing of Environment, Univ. of Michigan, Ann Arbor, pp. 607-621, October 1964.

In recent years it has become acutely apparent that from both the military and civil standpoints, there is a need for some rapid, accurate and economical means of analyzing vegetation.

This paper will consider the various kinds of useful information which military and civil experts can obtain regarding vegetation from the use of a thermal infrared mapping system which operates in the 7-15 micron band. Special emphasis will be placed on the value of this imagery when used in conjunction with imagery obtained in the visible, near infrared, and near ultraviolet portions of the electromagnetic spectrum.

Authors

E100

Estes, J.E., "Some Applications of Aerial Infrared Imagery", Annals of the Association of American Geographers, Vol.56, No. 4, pp. 673-682, 1966.

This paper, by showing various applications of infrared imagery, is intended to stimulate thinking among geographers toward the potentiality of airborne infrared imaging systems as geographic research tools. By making use of the capabilities of airborne infrared systems the research will gain valuable supplemental information which in many cases is unattainable from conventional aerial photography. The geographer interested in earth science investigations will find infrared imaging systems quite valuable in the determination of certain geological formations and structural features. Hydrographic features, owing to the variation in land-water heat capacities, show quite well on most infrared imagery. Certain types of vegetation may be differentiated more readily in the infrared, than in the visible, portion of the electromagnetic spectrum. Other applications to archeological research, rural applications such as wildlife inventories, and urban investigations, such as computer studies are also suggested. High resolution infrared radiometers are already being used to great advantage in meteorological studies from orbital altitudes. By applying infrared imaging devices in their research geographers, while gaining valuable supplemental information, may provide data useful in systems development. At present, the geographer may find it difficult to apply infrared sensor to his research because of the relative expense of the system or U.S. Department of Defense security classification of the imagery, but he should be prepared to employ this new tool as more infrared imagery is declassified and more systems come into use.

Author

E200

Estes, John E., "Some Geographic Applications of Aerial Infrared Imagery", Proceedings of the Fourth Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, pp. 173-181, April, 1966.

This paper, by showing various applications of airborne infrared imagery is intended to stimulate thinking among geographers toward the potentials of airborne infrared imaging systems as geographic research tools. Examples of the ability of airborne infrared imagery to aid investigations of rural and urban land use, climatology, physiography, resource development, and others are shown. By utilizing the capabilities of airborne infrared systems the researcher will gain valuable supplemental information which in many cases is unattainable from conventional aerial photography.

The geographer, in turn, by making use of this tool may be able to aid in infrared systems development. There is still much research to be done on the capabilities and limitations of infrared and the trained geographer can make a significant contribution.

At present academic and professional geographers may find it difficult to apply infrared sensors to their research because of the relative expense of the system or the U.S. Department of Defense security classification of the imagery. However, as more imagery is declassified and more systems come into use geographers should be prepared to employ this new research tool.

Author

F100

Fischer, William A., Davis, Dan A., and Sousa, Theresa M., "Fresh-Water Springs of Hawaii from Infrared Images", U.S.G.S. Hydrologic Atlas - 218, 1966.

Measurements indicate that the ocean waters surrounding the island are commonly warmer than the ground water discharging into them, thus suggesting that spring discharges are located the contrast of the thermal patterns in the nearshore waters.

The infrared images, obtained in the course of these investigations show numerous features that contrast in apparent temperatures with the surrounding ocean. The pattern of these features and their thermal contrast with adjacent ocean waters suggest that they result from the spring discharge of fresh, relatively cool or relatively warm ground water into the ocean.

S.W.S.

F200

Friedman, Jules D. and Williams, Richard S., Jr., "Infrared Sensing of Active Geologic Processes", Proceedings of the Fifth Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, pp. 787-801, April 1968.

A literature review indicates that the most numerous and definitive examples of detection of active geologic processes on the earth's surface by airborne infrared line-scanning techniques have been of volcanic and geothermal activity. Several geothermal fields and more than 22 volcanoes, in various stages of activity and repose, have been surveyed by infrared techniques. Infrared imagery has been obtained of two active effusive, eruptions (Etna and Surtsey) and two active pyroclastic eruptions (Irazú and Taal). The active processes which give rise to post-eruptive and inter-eruptive thermal anomalies are manifested by radiant emission associated with convective heat transfer from crater or vent areas, convecting fracture or fault systems, porous scoriaceous rocks which emit convective thermal currents, primary and secondary fumaroles, solfataras and steam vents, and various forms of related hydrothermal activity. The main contributions of the infrared imagery have been the spatial depiction of the relationship between intensity of thermal emission and structure, the recording of time-dependent changes in emission and the documentation of previously unrecorded hydrothermal activity and changes in hydrothermal systems during repose periods.

A specific case history of an infrared survey over an active effusive eruption at Surtsey, Iceland, is given. Infrared emission from the volcano was recorded in part concurrently by an airborne and a satellite infrared system between 19 August and 3 October, 1966. Ground and lava temperature measurements and volumetric lava outflow data allow a comparison between total thermal energy yield and radiant emission recorded by the satellite system; the Nimbus HRIR recorded radiant emission at a level of about 4% of the estimated total thermal yield. Aerial infrared imagery and derivative isoradiance maps and thermal profiles of Surtsey reveal that lava cauldron activity and incandescent lava flows in Surtur I were responsible for the major part of the radiant emission. Secondary thermal anomalies outline subsurface lava courses emanating from Surtur II, as well as fracture patterns, collapse features, pressure ridges and vent structures related to effusive flows of 1965. The final stages in the history of Surtsey's satellite pyroclastic volcano Jólnir were recorded prior to its destruction by wave action.

Authors

G100

Gawarecki, S.J., "Infrared Survey of the Pisgah Crater Area, San Bernardino County, California: A Geologic Interpretation", U.S.G.S. Technical Letter NASA-99, 71p, 1969.

Infrared imagery in the 8-14 band to the Pisgah Crater area has provided useful geologic information to complement data obtained from ground studies and from aerial photography. Thermal contrasts representative of those found through the diurnal cycle were acquired during three of six flight periods: at about 2000 (post-sunset), 0400 (pre-sunrise), and 1200 (midday). The largest amount of information on geologic thermal parameters from a single imaging period was obtained from the imagery flown shortly after sunset. Among the geologic features shown on imagery of one or more flight periods were basalt flow contacts where the adjacent flows differed in surface character, distribution of pyroclastics and their alluvial derivatives on the flows, collapsed lava tubes, fissured areas, detail of the Pisgah fault, zonation within Lavic dry lake, active drainage on a alluvial fan, and moist areas suggestive of ground water conditions.

Author

H100

Honea, R.B. and Prentice, Virginia L., "Selected Bibliography of Remote Sensing", U.S. Geological Survey-NASA-129, 35p, September 1968.

Publications pertaining to the geographic applications of remote sensing techniques are presented in a four-part bibliography. The first part included publications that provide an overview of the field and its geographic applications, while more technical publications are listed in the second part. Publishers and prices of the latter list are included. Part III contains documents relating to land use classification and analysis, and Part IV is a selected bibliography of data handling and automatic data processing techniques used in remote sensing. References in each part are listed alphabetically according to author.

M.W.R.

J100

Jones, Natalie E. and Leestma, R.A., "Bibliography of Remote Sensing of Resources", Corps of Engineers, U.S. Army, Fort Selvoir, Virginia, NASA-CR-93738, 40p, 1966.

References on remote sensing of resources that appeared in the open literature between January 1960 and June 1966 are presented alphabetically according to author. A subject index lists article disciplines, spectral fields, radar uses, and photographic techniques.

Authors

K100

Kuhl, Arthur D., "Color and IR Photos for Soils", Photogrammetric Engineering, Vol. 36, No. 5, pp. 475-482, May 1970.

A quantitative method measured the accuracy of interpreting soil characteristics from black-and-white, infrared, and color aerial photos of selected sites in Onondaga County, New York. These sites represent a diverse set of soil forming conditions, soil parent materials, and several types of vegetative cover. Color and infrared photos were better than black-and-white photos in interpreting soil drainage and slope.

Author

L100

Lattman, Lawrence H., "Geologic Interpretation of Airborne Infrared Imagery", Proceedings of the Second Symposium on Remote Sensing of Environment, Univ. of Michigan, pp. 289-293, 1963.

Modern airborne infrared (IR) imagery allows the photogeologist to view the earth's surfaces in a vast new range of the spectrum. This imagery is a function of the energy emitted from, not reflected by, the terrain object. As this energy is a function primarily of the object's emissivity and temperature, the photogeologist must retrain himself to interpret terrain features in a new aspect.

A photogeologic interpretation of an IR image of Mt. Nittany, Pennsylvania, reveals that shale may be distinguished easily from sandstone and that valleyside springs are more clearly shown than on conventional aerial photography. As more IR imagery becomes available, more geologic information will undoubtedly be obtained from this medium.

Author

L200

Lee, Keenan, "Infrared Exploration for Shoreline Springs at Mono Lake, California, Test Site", Proceedings of the Sixth Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, pp. 1075-1087, October 1969.

Remote sensing methods offer the potential for rapid aerial exploration for water resources. This research investigated one aspect of this potential, namely the ability of a non-classified, airborne infrared scanner to detect and evaluate shoreline springs. Infrared data were collected on four different missions using the Bendix scanner operating in the 3-5.5 μm and 8-14 μm windows. The test site contained numerous fresh water springs of various temperatures and rates of flow which discharged around and under Mono Lake. Mono Lake is a large saline lake and was therefore analogous to a marine situation.

Shoreline springs and seepage can be detected by this scanning system. Springs discharging a fraction of a liter/sec (few gpm) have been recognized on imagery, and under favoring conditions springs can be detected where there is no temperature difference between the spring water at its discharge point and the surface of the open salt water. Sublake fresh water springs normally are not apparent on imagery except under special conditions.

The volumetric discharge from shoreline springs at Mono Lake can be estimated from infrared imagery if air temperature at ground-level is known. Empirically derived quantitative correlation methods, derived from a study of imagery anomalies from 7 springs, estimated the discharge rates of 11 other springs using imagery data. These methods apply to small streams as well as to shoreline springs.

Author

L300

Llaverias, Rita K., "Bibliography of Remote Sensing of Earth Resources for Hydrological Applications", U.S. Geological Survey, Washington, D.C. Technical Letter NASA-134, 75p, 1968.

This preliminary bibliography was prepared to acquaint hydrologists with the basic literature involved in this field. Some of the references concern specific hydrologic topics or specific remote sensing methods. Other references on vegetation mapping and geology were included so that the reader can find information on the selection, processing, and use of remote sensing data in these cognate fields. A number of meteorological references were included because in many remote sensing applications, especially from earth orbital satellites, atmospheric effects must be taken into account in interpreting the views of the earth.

Author

M100

Matalucci, R.V. and Abdel-Hady, M., "Surface and Subsurface Exploration by Infrared Surveys", Remote Sensing and Its Application to Highway Engineering, Highway Research Board Special Report 102, pp. 1-12, 1969.

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.

Author

M200

McLerran, James H. and Morgan, Joseph O., "Thermal Mapping of Yellowstone National Park", Proceedings of the Third Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, pp. 517-530, October 1964.

In April 1961 infrared imagery was obtained over Yellowstone National Park. The purpose was to conduct a preliminary study of the usefulness of infrared imagery over terrain with natural high-temperature contrasts, and to determine if subsurface thermal anomalies could be imaged if they are not evident by surface hydrothermal features.

This paper presents imagery from several areas of the Park and demonstrates that infrared sensing is useful for mapping hydrothermal features. The results from this study indicate that new studies should be conducted using new state-of-the-art infrared scanners and detectors.

Authors

M300

Miller, Lee D., "Location of Anomalously Hot Earth with Infrared Imagery in Yellowstone National Park", Proceedings of the Fourth Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, June 1966, pp 751-761.

Infrared imagery of Yellowstone National Park acquired under a program described in the "Third Symposium on Remote Sensing of Environment" was used on the ground in the Park to locate several anomalously hot earth and not as hot water or steam. Only one of the approximately dozen such areas encountered had been previously specifically noted by individuals frequenting these areas of the Park. Interactions between the anomalously hot earth and the surrounding vegetation including tree cover will also be noted.

Author

M400

Moxham, R.M., "Aerial Infrared Surveys in Water Resources Studies", U.S.G.S. Technical Letter NASA-74, 21p, April 1967.

New types of infrared line scanning radiometers record very small relative variations in earth surface radiance. This permits thermal patterns to be mapped in great detail, especially in surface waters. The technique has been useful in finding the location of ground-water discharge into marine coastal waters and in studying the circulation and diffusion of natural waters, and of liquid discharge from industrial plants.

The quantity and spectral distribution of infrared radiance from natural surfaces is a function of temperature and emissivity. As emissivity of water is nearly unity, radiance variations are due chiefly to temperature variations. The infrared line scanner, carried in a aircraft, generates a photograph-like image whose gray scale is a measure of the infrared radiance of land and water surfaces along the flight path.

Author

M500

Moxham, R.M. and Alcaraz, Arturo, "Infrared Surveys at Taal Volcano, Philippines", Proceedings of the Fourth Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, pp. 827-837, April 1966.

After being dormant for 54 years, Taal Volcano erupted violently on September 28, 1965. An elongate, southwest-trending explosion crater formed on the southwest flank of the volcano. The water of Lake Taal, which surrounds the volcanic island, flowed into the explosion crater, forming a narrow inlet. Infrared scanner (8-14 micron) surveys, made about two weeks after eruption ceased, show relatively little thermal activity on the southern part of the island, except for the high temperatures of water issuing from the new cinder cone at the head of the inlet. Two other principal areas of abnormal thermal activity were defined: 1) a fumarole area which has been active for many years on the north flank of the volcano's main (1911) crater and 2) anomalies around the summit and on the southeast flank of Mt. Binintiang Malaqui on the northwest tip of the island. Historical records indicate Mt. Binintiang Malaqui last erupted in 1707. Though some hot springs and fumaroles were previously known here, the infrared surveys indicate the thermal activity at this crater may be more widespread than previously supposed. No thermal evidence of a postulated southwest-trending rift zone across the island was found.

Authors

M600

Myers, Victor I., "Thermal Infrared for Soil Temperature Studies", Photogrammetric Engineering, Vol. 35, No. 10, pp. 1024-1032, October 1969.

Seasonal remote sensing flights by NASA and the University of Michigan were made over an area of alluvial soils. Detailed soil surveys were related to thermal infrared imagery in a manner which shows that surface soil temperatures can be indicative of subsurface soil conditions. The warming and cooling of soil depends on many factors. The specific soil characteristics that most influence heat transfer and storage are water content, size of soil particles and pore space. The time of diurnal and the season can be important factors in conducting remote sensing missions. Thermal infrared sensing gives a qualitative indication of soil water in approximately the top 50 cm. of bare soil. The magnitude of diurnal temperature oscillations can also be an indicator of soil moisture content. Thus thermal imagery can be valuable for management of farm resources. The investigation described is intended as initial evidence that soil characteristics influence the thermal regime of soils in a manner that can be helpful to the soil surveyor.

Author

M700

Myers, V.I., Wiegand, C.L., Heilman, M.D., and Thomas, J.R., "Remote Sensing in Soil and Water Conservation Research", Proceedings of the Fourth Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, pp. 801-811, April 1966.

This paper describes the application of remote sensing to certain soil and water problems. Aerial mapping of soils and vegetation using optical and thermal techniques is now possible, but the physiological characteristics and environmental factors affecting optical and thermal characteristics are largely unknown. Studies are now underway to establish the factors affecting remote sensing.

Spectrophotometry as applied to agricultural and desert vegetation is discussed. Spectrophotometer curves serve mainly to establish the pure optical phenomena of plants unaffected by extraneous conditions. It is important to recognize that other factors such as crop geometry and background soil conditions influence the signal from vegetated areas. An example of the relationships is presented.

The use of various crops as indicator plants for detailed detection of subsoil moisture and salinity conditions, using Kodak Ektachrome infrared aerial film is described.

The measurement of plant-leaf temperatures as a method for studying energy budgets of agricultural areas, for estimating soil moisture, and for detecting the occurrence and extent of soil salinity is discussed.

The potential of multispectral remote sensing for soil surveys is discussed. Certain past limitations in the application of color aerial photography to soil surveying may be surmounted using microwaves, low-frequency radar, infrared thermometry, and sensing in other portions of the electromagnetic spectrum.

Authors

P100

Parks, Sewell, Hilty, and Buckner, "Multispectral Photography in Agriculture", Remote Sensor Utilization for Environmental System Studies, University of Tennessee, Contract No. F19628-69-C-0116, pp. 21-23, December 1969.

The general scope of the research is to assess the used of multi-spectral photography in agriculture to determine its potential for rapidly inventorying large areas. Agricultural test plots are located at Ames Plantation, West Tennessee; Holtson River area, just east of Knoxville; John Sevier Reservoir area, Northeast Tennessee; Cherokee Wood Lot, Knoxville; and the Oak Ridge Forest, Oak Ridge, Tennessee. Both multispectral aerial photography and corresponding ground data are being obtained at these sites. Specifically, remote sensing procedures are being developed and evaluated for reliability in:

1. Identification of plants as to species (crop plants forests, weeds, etc.) and maturity.
2. Detection of disease and insect infestation in plants.
3. Identification of major soil series.
4. Evaluation of soil and plant moisture conditions.

Authors

P200

Pierce, Kenneth L., "Evaluation of Infrared Imagery Applications to Studies of Surfacial Geology-Yellowstone Park", U.S.G.S. Interagency Report NASA-93, 34p, May 1968.

Infrared imagery, in the 3-5 micron band, was obtained during afternoon and post-sunset hours of August 1966 by the H.R.B. Singer Corporation on contract to the U.S. Geological Survey. Analysis of these data reveals that known thermal features such as hot and cold springs, glaciers and snow fields and lakes are readily identified on day and night images but that areas of known "hydrothermal" alteration are not detectable by the system employed.

Surficial deposits such as talus and frost rubble are generally light toned but commonly darker than outcrops warmed by solar radiation. Sharp contrasts were noted between forest and grassland areas. Attempts were made to use the imagery in mapping surficial deposits in several areas but results were variable due to the overriding effects of outcrop-forest-grassland contrasts. Recommendations for future missions are presented.

Author

P300

Pratt, W.P., "Infrared Imagery of Lordsburg-Silver City Area, New Mexico", Manned Spacecraft Center, NASA, Houston, Texas, NASA-71, 17p, 1968.

Nighttime infrared imagery of the area between Lordsburg and Silver City, New Mexico, indicates numerous applications for studies of geology and hydrology of desert regions. Tertiary volcanic rocks consisting of flows and welded tuffs show good tonal contrasts within themselves. Precambrian granites and gneisses appear mottled. Water courses appear as dark streaks, cold water springs as dark patches, and water standing in ponds and reservoirs is bright in contrast to the darker (cooler) surrounding materials.

Author

R100

Rib, Harold T. and Miles, Robert D., "Multisensor Analysis for Soils Mapping", Remote Sensing and Its Application to Highway Engineering, Highway Research Board Special Report 102, pp. 22-37, 1969.

The potential of available remote sensing systems for evaluation of soils and soil conditions was studied and an optimum combination of sensors for analyzing soils was sought. To investigate the various sensors, nine flight coverages were obtained over three controlled test sites during a 13-month period. Coverage was obtained with various aerial films (color positive, color infrared, color negative, black-and-white panchromatic, and black-and-white infrared), a multiband camera (9 lens), radar sensors (K-band), infrared sensors (far infrared), and a multichannel sensor (ultraviolet through far infrared). Not all combinations were obtained in any one flight program; however, several combinations were obtained during each flight. The major conclusion was that the optimum system for delineating and mapping soils was a multichannel sensor flown simultaneously with an aerial mapping camera taking natural color photography. Of the aerial film types investigated, natural color was the most useful single film type.

Authors

R200

Rohe, Donald L., "Potential uses of Color Infrared Photography in Mosquito Control", California Vector Views, Vol. 17, No. 2, pp. 7-11, February 1970.

This article describes and provides directions for uses of Infrared Film, and discusses the potential uses in mosquito control by detecting soil moisture.

S.W.S.

S100

Sabins, Floyd F., "Infrared Imagery and Geologic Aspects", Photogrammetric Engineering, Vol. 33, No. 7, pp. 743-750, 1967.

Structural and stratigraphic interpretations can be made from nighttime infrared scanner imagery in the Indio Hills. The younger, undeformed alluvium covering the valleys images distinctly cooler than the older, deformed sedimentary bedrock of the hills. The bedrock consists of two distinctly different stratigraphic-radiometric units. The poorly stratified unit is relatively featureless on the imagery, whereas the well stratified unit has a distinct pattern of alternating warmer and cooler bands that correspond to outcrops of sandstone and siltstone beds respectively. A concealed trace of the San Andreas fault is revealed on the imagery by a cold anomaly apparently related to blockage of groundwater. Other faults and folds are imaged by offsets and strike changes in the patterns of the stratigraphic-radiometric units.

Author

S200

Sabins, Floyd F., Jr., "Thermal Infrared Imagery, and Its Application to Structural Mapping in Southern California", Geological Society of America Bulletin, Vol. 80, pp. 397-404, March 1969.

Thermal infrared imagery is obtained by airborne scanning devices that detect thermal radiation from the earth's surface and record it as an image in which bright tones represent relatively warm temperatures. Scanners sensitive to wavelenghts between 8 and 14 microns span the radiant power peak of the earth at 9.7 microns and coincide with an atmospheric "window."

An example of 8 to 14 micron nighttime infrared imagery from the Imperial Valley, California, is interpreted and compared with aerial photographs of the same area. In this monotonous-appearing desert terrain, the imagery exhibits greater contrast and geologic detail than the photography. On the imagery, deformed Tertiary sedimentary bedrock (relatively cool) is distinguished from Holocene windblown sand cover (relatively warm).

Of especial geologic interest is a faulted plunging anticline in flat terrain. It is obscure both on aerial photographs and to a ground observer. On nighttime infrared imagery, however, the fold is clearly shown by the outcrop configuration of the individual siltstone and sandstone strata comprising the structure. Apparently the radiometric temperature differences between strata are sufficient to outline the fold on the imagery. The obscure expression of the fold on aerial photographs may be due to insufficient contrast in light reflectance between the different strata.

Author

S300

Simonett, David S., "Land Evaluation Studies with Remote Sensors in the Infrared and Radar Regions", U.S. Geological Survey Contract No. 14-08-0001-10848, University of Kansas, 17p.

This paper reviews the literature, especially of the last two years, dealing with remote sensor evaluation of surface and shallow sub-surface characteristics, employing remote sensors in the infrared (1.5μ-14μ) and radar (0.5cm-100cm) regions. Imaging and non-imaging sensors are examined to assess their current status and possible value in 1) assisting in the mapping of natural plant communities, 2) deriving hydrologic parameters, 3) discriminating among broad land use, crop type and, to a lesser degree, crop state, 4) delineating soil and geomorphic units, and 5) estimating soil moisture. Possible applications of these remote sensors in reconnaissance-scale evaluation of natural resources are considered. The paper leans heavily on unpublished and limited-circulation studies sponsored by the National Aeronautics and Space Administration, U.S.A.

Author

S400

Shilin, B.V., Guser, N.A., Miroshnikor, M.M., and Karizhenski, Ye. Ya., "Infrared Aerial Survey of the Volcanoes of Kamchatka", Proceedings of the Sixth Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, pp. 175-181, October 1969.

The results of the IR survey of some of the volcanoes of Kamchatka permit us to reach the following conclusions.

1. The IR survey is a new and effective method of studying volcanic sources, which permits us to obtain important data regarding their structure. IR survey may be the only method of studying active volcanoes, which are unapproachable to ground measurements.

2. The most important value of IR surveys as compared to ground thermal measurements, aside from its speed and better detail is the possibility of obtaining a truly current thermal map of a volcanic source.

3. Repeated IR surveys of volcanic sources are practically the only effective method for recording the changes of the thermal field of a volcanic source. The periodic surveys of the volcanoes will probably permit the prediction of the periods of activization through the changes in the intensity of the thermal radiation. Therefore, the establishment of a systematic watch over volcanoes with the aid of IR surveys can be of large scientific and economic value.

4. The IR surveys of volcanic sources is best conducted in the evening and nighttime, when the interference from solar heating is absent and the true thermal map of the volcano can be recorded. However, the feasibility of obtaining such data is strongly contingent on the safety of the night flights.

5. The maximal information about the structure of the volcanic source can be obtained only through concurrent interpretation of aerial photographs and IR imagery.

6. The most urgent direction in the improvement in the interpretation of IR surveys of volcanoes should be the development of methods of quantitative analysis of the data. This can be accomplished through assigning relative intensity gradients to thermal objects with the help of radiometry.

Authors

S500

Shockley, W.G., Knight, S.J., and Lipscomb, E.B., "Identifying Soil Parameters with an Infrared Spectrophotometer", Proceedings of the Second Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, pp. 267-274, October 1962.

The Terrain Analyzer Project of the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, is aimed at exploiting the electromagnetic spectrum as a means of identifying and quantifying those elements of the terrain that have an effect on military operations. In the initial studies emphasis will be placed on soil trafficability elements. The first phase of the project will be to examine the feasibility of the general principles by carefully controlled studies in the laboratory using infrared and radar. Upon valid proof of the feasibility of the principles under laboratory conditions, the studies will be extended to field conditions (phase two); and if the principles are further demonstrated to be feasible in the field, the third and final phase, that of developing the instruments and techniques for use under actual combat conditions, will be undertaken. Results of controlled laboratory tests using an infrared spectrophotometer to determine the relationships between the quantity of infrared energy reflected from prepared soil samples and variations in the soil parameters will be discussed.

Authors

S600

Smedes, Harry W., "Geological Evaluation of Infrared Imagery, Eastern Part of Yellowstone National Park, Wyoming and Montana", N.S.G.S. Interagency Report NASA-83, pp. 1-46, December 1968.

Infrared images covering more than 475 flightline miles were studied (Figure 1). Evaluation of the imagery was made by visual comparison of the relative intensities of different features shown on positive prints of the imagery; by comparing the same features on daytime and night imagery; and by checking features with one or more of the following: 1) Conventional black and white aerial photographs at a scale of about 1:37,400; 2) color pictures (transparencies) which were taken from the ground and from helicopter in flight; 3) geologic maps at 1:62,500 and 1:125,000; 4) topographic maps at 1:62,500; and 5) radar imagery.

The results from this study will be discussed in general qualitative terms. This qualitative approach stems from the lack of data available on emissivity of the surface materials in the area. The study was also designed to compare several types of visual data (photographs or images) to determine

whether geologic features could be identified by comparison and contrast among the various kinds of data. For the comparative study, absolute values of emissivity are not important.
Author

S700
Strangway, D.W. and Holmer, R.C., "Infrared Geology", Proceedings of the Third Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, pp. 293-319, October 1964.

Bear Creek Mining Company has conducted several months of airborne infrared work in an attempt to detect patterns related to geology or the presence of oxidizing sulphides. The results encountered have shown that certain microclimatological effects are very important. Among these are the hill effect shown by small topographic features bathed in warm air under thermal inversion conditions. Major faults are evidently reflected in some cases as are areas of subterranean hot water. These observations have been confirmed by ground temperature measurements in holes 2-3 feet deep.

The feasibility of using microwave systems has also been inestigated. Some limited experiments on the absorption of microwave energy by sand and water mixtures indicate that such measurements would be useful.
Authors

S800
Stringelin, Ronald W., "An Application of Infrared Remote Sensing to Ecological Studies: Bear Meadows Bog, Pennsylvania", Proceedings of the Fifth Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, pp. 435-438, April 1968.

Comparative analysis of infrared line scan imagery and panchromatic photography of the newly established (1967) national landmark, Bear Meadows Bog, Centre County, Pennsylvania, reveals thermal tonal signatures that may be correlated with existing vegetation patterns and specific ground conditions. Summer and wintertime imagery are compared and the response of ericaceous and coniferous vegetation to trans-freezing temperatures studied. Strongest wintertime signals were being emitted by Rhododendron maximum L. which is concentrated along the margin of the bog. The location and distribution of the low ericaceous shrub Chamaedaphne calyculata (L.) Moench var. angustifolia (Ait.) Rehd. may be traced on the imagery. Drastic changes in the emitted signal from the bog are recorded for nights with sub-freezing air temperatures. A loss of the strong emitted signal from the ericaceous vegetation is attributed to the minimal absorbance of solar radiation during the day due to the curled attitude of the leaves. Such an attitude was acquired as a physiological reaction to the intense cold. Coniferous trees, however, continued to emit a warm signal with the large pines and hemlocks providing strong returns. During both seasons detailed delineation of vegetational communities under daylight imaging conditions appears inferior to nighttime imaging. Early evening flights on nights with temperatures above freezing appear to be optimum for vegetational studies.

Author

W100

Wallace, R.E. and Moxham, R.M., "Use of infrared Imagery in Study of the San Andreas Fault System, California", U.S. Geological Survey Prof. Paper 575-D, pp. D147-D156, 1967, U.S. Geological Survey Technical Letter NASA-42, 14p, June 1966, Proceedings of the Fourth Symposium on Remote Sensing of Environment, Univ. of Michigan, Ann Arbor, April 1966.

Infrared imagery (in the 8 to 13 micron band) of the San Andreas fault system in the Carrizo Plain area of California shows that the fault can be clearly traced over most of about 200 miles flown. Variations in soil moisture caused by the water-barrier characteristics of the fault zone, as well as vegetation differences related to soil moisture and microtopography, are factors influencing visibility of the fault in the IR imagery. Also identified on the imagery and useful in analyzing offset on the fault are (1) offset segments of ancient stream channels disrupted by movement on the fault, (2) landslide terrain, and (3) numerous soil and Tertiary bedrock units. Imagery obtained 1-2 hours before sunrise in considered most useful for the fault studies.

Authors

W200

Walz, F.A., "Multidiscipline Remote Sensing Research for Hydrology and Agriculture", Journal of Remote Sensing, Vol. 1, No. 4, pp. 11-18, August/September 1970.

Remote sensing is now emerging from a potential science to an operational reality. The need for remote sensing techniques in many different disciplines has been demonstrated.

Principles of handling data and dissemination of useful information to users have been advanced but not proven. The influences of extraneous sources of variation on sensor measurement and data processing appears to be a major problem.

The feasibility of applying remote sensing research results in traditionally "tough" areas has proven of value.

Author

W300

Wermund, E.G., "Remote Sensors for Hydrogeologic Prospecting in Arid Terrain", Remote Sensing Inc., Houston, Texas, 28p, 1970.

An examination of remote sensing literature shows that little has been done to apply newer remote sensors to water prospecting. Hydrologic and geothermal principles indicate that heat sensitive remote sensors like the infrared line scanner and the microwave radiometer have useful potential in arid hydrogeologic studies. An experimental test is described in which results of remote sensing are presented for four arid areas in the western United States; Railroad Valley and the Las Vegas Basin in Nevada, Death Valley in California, and the Hueco Mountains in Texas. In the test the primary remote sensors are the infrared line scanner, 8-14 microns, and a 13.7 Ghz microwave radiometer; color and color infrared photography is a secondary sensor. The altitude best for hydrogeologic data collection is examined.

Results of the study show that infrared color photography is sensitive to changes in plant communities reflecting concentrations of near surface water. 8-14 micron infrared and 13.7 Ghz microwave radiometer data contain signatures of near-surface water concentration. This data with hydrologic and geologic extrapolation lead to rapid prospecting of arid regions for indications of groundwater reserves.

Author

W400

Winkler, E.M., "Relationship of Airphoto Tone Control and Moisture Content in Glacial Soils", Proceedings of the Second Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, pp. 107-113, October 1962.

Airphotos frequently show light tones on high points of morainal systems but darker tones in depressions which are primarily caused by different soil moisture contents. Experiments were conducted on the ground with glacial soils at different water contents. The relationship between the tone of airphotos and the water content of soils was established with the following commerical aerial films: Super XX-Aerographic, Infrared-Aerographic, Aero-Ektachrome, Aero-Ektachrome Camouflage Detection (Infrared color). The densities of the developed films were measured on the negatives with a standard Weston Photographic Analyzer (densitometer).

Results obtained from ground experiments did not match the density-moisture proportions from actual airphotos which were believed to exist. The film densities rose approximately proportional to the moisture contents up to near the Atterberg Plastic Limit of the soil, but sharply decreased again towards the Atterberg Liquid Limit.

Darker tones through concentration of organic matter in terrain depressions and rapid drying of wet soil in thin sheets on the surface in contrast to darker wet soil below do not permit the calculation of moisture contents from presently available photographic emulsions.

Author

W500

Wolfe, Edward W., "Geologic Evaluation of Remote Sensing Data-Site 157, Anza-Borrego Desert, California", U.S. Geological Survey Inter-agency Report NASA-144, pp. 1-61, February 1969.

Remote sensing data were obtained at site 157 in May 1968. This paper describes previously obtained geologic data as well as the obtained remote sensing data. The Anza-Borrego Desert is located west of the Imperial Valley, Southern California, an area of high temperatures and extremely arid.

This paper describes the data collected using an Ultraviolet Scanner, Black and White and False Color Photography, Multiple-Filtered Color Infrared Photography, Multispectral Photography, Thermal Infrared (8-14 micron) Imagery and a Microwave Radiometer.

Continuously recorded near-surface temperature data were collected (1) on gypsum outcrop and a small allurial fan at the north end of Split Mountain, (2) on allurial deposits of two different ages and on sandstone bedrock in Vallecito Wash, (3) on the allurial fan at the mouth of Indian Gorge and on the adjacent allurial deposits at its margin, and (4) on granitic bedrock and allurium in Indian Valley.

It was found that Thermal inertia, reflectivity, and slope angle are factors that influence nighttime 8 to 14 micron radiance. Thermal inertia increases with an increase of moisture content.

S.W.S.

W600

Wolfe, Edward W., "Geologic Evaluation of Thermal Infrared Imagery, Caliente and Temblor Ranges, Southern California", U.S.G.S. Interagency Report NASA-113, pp. 1-27, September 1968.

Thermal infrared (8 to 13 micron) imagery was obtained in the Caliente and Temblor Ranges and Carrizo Plain, southern California, in the pre-dawn and post-sunrise hours of June 18, 1965. Field observations; measurements of moisture and specific gravity of the regolith, and radiation temperatures; and comparison with geologic maps and aerial photographs lead to the following conclusions:

1. The specific gravities of surficial materials (usually not bedrock) influence tonal densities in the pre-dawn imagery.
2. Geologic interpretation of tonal density patterns is complicated by topographic, atmospheric, and vegetative effects on pre-dawn radiation.
3. Geologic features such as outcrop patterns and some faults are recognizable in the infrared imagery as well as in aerial photographs. The sensitivity of the system to microclimatic anomalies may be valuable in aiding recognition of some geologic features with subtle topographic expression.
4. Local radiative anomalies, previously suggested to be caused by the occurrence of ground water at shallow depths, may be caused by nighttime entrapment of cold air in poorly drained, topographically low areas.
5. Post-sunrise imagery is dominated by the preferential warming of slopes exposed to the early morning sun and resembles low sun angle photographs.

Author

W700

Wolfe, Edward W., "Thermal IR for Geology", Photogrammetric Engineering, Vol. 37, No. 1, pp. 43-52, 1971.

Thermal infrared (8 to 13 micrometers) imagery was obtained in the Caliente and Temblor Ranges and Carrizo Plain, southern California, in the predawn and post-sunrise hours of June 18, 1965. Field observations, measurements of moisture and specific gravity of the regolith, and radiation temperatures, and comparison with geologic maps and aerial photographs lead to the following conclusions:

1. The specific gravities of surficial materials (usually not bedrock) influence tonal densities in the pre-dawn imagery. Hence areas underlain by sandy alluvium, sandstone, or conglomerate (high specific gravity)

tend to be brighter in pre-dawn imagery than areas underlain by shale, mudstone, or diatomite (low specific gravity).

2. Geologic interpretation of tonal density patterns is complicated by topographic, atmospheric, and vegetative effects on pre-dawn radiation.
3. Geologic features such as outcrop patterns and some faults are recognizable in the infrared imagery as well as in aerial photographs.
4. Post-sunrise imagery is dominated by the preferential warming of slopes exposed to the early morning sun and resembles low-sun-angle photographs.

Author

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VOLCANIC WATERS

B100, C100, F200, G100, M100, M500, S400

INDEX OF GEOGRAPHICAL AREAS OF INVESTIGATIONS

B100	Nevada
C100	California, Nevada, Texas
C200	Indiana
C300	Illinois
C400	Illinois
C500	Canada
C600	California
C700	California, Michigan
E100	Amazon, California, Congo, Hawaii, Pennsylvania, Sudan, Texas
E200	Amazon, California, Congo, Hawaii, Pannsylvania, Sudan, Texas
F100	Hawaii
F200	Iceland
G100	California
K100	New York
L100	Pennsylvania
L200	California
M100	California, Nevada, Texas, Wyoming
M200	Montana, Wyoming
M300	Wyoming
M500	Negros Island, Luzon Island, Philippines
M600	Texas
M700	Texas

P100	Tennessee
P200	Wyoming
P300	New Mexico
R100	Indiana
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W300	California, Nevada, Texas
W400	Indiana, Georgia, Michigan
W500	California, Washington
W600	California
W700	California

The REMOTE SENSING CENTER was established by authority of the Board of Directors of the Texas A&M University System on February 27, 1968. The CENTER is a consortium of four colleges of the University; Agriculture, Engineering, Geosciences, and Science. This unique organization concentrates on the development and utilization of remote sensing techniques and technology for a broad range of applications to the betterment of mankind.