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APPLICATIONS OF AIRBORNE THERMAL INFRARED SCANNERS TO ENGINEERING PROBLEMS

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ABSTRACT

This paper presents an overview of some of the types of engineering problems that have been investigated through the use of the airborne thermal infrared scanner in the last several years. The successful use of thermal infrared scanners in providing data to solve some of these engineering problems promises to open new prospects for the operational use of this remote sensing technique as an engineering tool. Special techniques for the determination of leaks in underground fluid transfer systems and seepage through dams and dikes are illustrated.

INTRODUCTION

This paper discusses how thermal infrared (TIR) remote sensing technology can be successfully used by photogrammetrists and civil engineers as a complementary and unique airborne survey tool. Many valuable applications provide new data for interpretations and offer new service opportunities pertinent to civil engineering tasks. Important principles, operational considerations, and procedures are reviewed. Most important is the discussion on how this tool is successfully employed on an operational basis for a broad variety of survey applications. To evaluate the TIR survey potential, the application must be defined consisely in light of the thermal process and properties of the subject. The success of the thermal survey mission, however, is judged by the interpretability of its imagery product. Required here is an understanding of key principles of detection, what is detected, and proper mission planning. Application examples of interest to this audience are used to demonstrate how these factors are integrated for successful TIR survey missions.

PERSPECTIVE

TIR technology development started in the 1950's for the military to detect the thermal manifestation of matter and display this property relative to its thermal background. The military's interest was the ability of a TIR scanning system to detect and image remote thermal anomalies and features camouflaged for low reflected light contrast, or hidden by low levels of reflected light.

Important civilian application for this technology became evident in the 60's when its potential for terrain mapping was recognized. In 1968, the government declassified systems not exceeding certain thermal and spatial resolution standards.

The 70's witnessed the gradual transfer of the remote sensing of heat to scientific and engineering applications. Two significant technological refinements of military system designs made this transition to civilian applications viable: 1) The recording of the TIR detector signal on magnetic tape. The signal could, thereby, be electronically optimized and manipulated, after acquisition, to generate the desired image qualities. 2) The incorporation of calibrated thermal reference sources. This feature transformed a system capable of imaging relative temperature differences into a radiometrically stable and quantitative imaging radiometer.

SIMPLE PHYSICS - (Basic Principles)

At absolute zero (0°K or -273°C) all motion of atoms and molecules in matter is frozen. As temperature is increased, the random motion of particles produces collisions and accelerations. This internal heat or kinetic temperature is converted to radiant energy.

All materials at a temperature above absolute zero radiate energy in a characteristic and quantitative manner that depend on the temperature and emissivity of the material. Emissivity (ε) represents the efficiency of a material's surface in radiating energy. Our skin will sense radiated heat that is emitted energy traveling as electromagnetic radiation (EMR). We call this energy thermal infrared and define it to be that region of the electromagnetic spectrum with wavelengths (λ) longer than reflected infrared and visible EMR, but shorter λ than microwave and radio EMR, Figure 1. We refer to a specific region or band of TIR by identifying its λ range. By convention λ is measured in terms of micrometers ($1\ \mu m = 1 \times 10^{-6} m$).

EMR may be transmitted, absorbed, emitted, scattered, and reflected. The interaction between EMR depends on atomic, molecular, size, and surface property of matter. Smoother surfaces have lower emissivity values than rough surfaces of the same composition. Many atmospheric gases such as ozone, water vapor, and carbon dioxide absorb radiation in the TIR region. Figure 1 shows two TIR wavelength regions where the atmosphere is most transparent to TIR. These are called TIR transmission windows. The 3 to 5 μm window represents the shortest TIR λ range in common use.

Hot matter (450°C) radiates more energy in this region than at longer λ. If heat or molecular action is increased further, it will become visible to the eye or influence photographic emulsion. The second window, from 8 to 14 μm, is the region of peak radiation of matter at ambient earth temperature. This window is the λ region which offers the greatest variety of TIR remote sensing applications potential.

Heat travels from one place to another by three mechanisms: conduction, convection, and radiation. Solar radiation is the principle source of thermal energy radiated from the ground. Solar radiation varies in duration and intensity depending on the time of day and season. Figure 2 illustrates a typical heating and cooling cycle of a variety of surface cover types. Local topographic orientations modify this diurnal effect.

Many mathematical relationships describe the behavior of EMR. Of the various equations that are used in thermal radiation calculations, the following are most important.

Wien's Displacement Law: The wavelength of maximum emittance is proportional to a physical constant divided by its radiant temperature in degrees Kelvin.

$$\lambda \text{ max} = \frac{2897.9 \ \mu\text{m } (^{\circ}\text{K})}{\text{T } (^{\circ}\text{K})}$$

Stefan-Boltzmann Law: The total energy emitted by a blackbody is proportional to the fourth power of its absolute temperature.

$$E \sim T^4 \qquad W = ST^4 \qquad S = 5.67 \times 10^{-12} \text{ Watts cm}^{-4} \ {}^{\circ}\text{K}^{-4}$$

A blackbody (BB) is a theoretical material which is a perfect emitter and absorber of TIR. No energy is reflected. The emissivity coefficient of a BB is perfect or 1. Emissivity represents the efficiency of a material's surface to radiate energy. No material is a perfect BB. The emissivity of "graybodies" have values between 0 and 1.

Emitted energy in the TIR λ range is related to four internal properties of materials.

A. Thermal Conductivity - The measure of the rate at which heat will pass through a material; conduction is the transfer of heat through molecular action. $\frac{\text{cal}}{\text{cm}\cdot\text{sec}\cdot{}^{\circ}\text{C}}$

B. Thermal Capacity - The ability of a material to store heat. $\frac{\text{cal}}{\text{gram}\cdot{}^{\circ}\text{C}}$

C. Thermal Inertia - A measure of the thermal response of the material to temperature changes. $\frac{\text{cal}}{\text{cm}^2\sqrt{\text{sec}}\cdot{}^{\circ}\text{C}}$

D. Thermal Diffusivity - The rate at which a temperature can be transferred between the surface and interior of a material. $\frac{\text{cm}^2}{\text{sec}}$

(Sabins, 1978)

Refer to Table 1 for data on geologic materials.

Most natural materials have fairly high emissivities (coefficients close to 1) in the TIR region. Kirchhoff's Law states the ratio of radiant emittance to absorptance is the same for all bodies. At thermal equilibrium, emissivity is equal to absorptance; therefore, high emissivity indicates high absorptance. It follows that detected thermal induced radiation is basically a surficial phenomenon. Conditions below the surface (density, conduction, convection, heat flow, moisture content, etc.), as well as atmospheric conditions such as wind, humidity, solar radiation, etc., affect the detected temperature of the surface.

THE TECHNOLOGY

To detect a given object or surface by thermal infrared means, it must have a radiation characteristic that differs from its surroundings, i.e., a different temperature or emissivity. TIR line scanners are devices capable of sensing this thermal radiation. Emitted temperature differences of 0.2°C are routinely detectable. Special purpose systems can discriminate differences measured in hundredths of a degree. TIR at the most useful wavelengths cannot pass through glass and cannot be recorded directly by film emulsion. Thus to detect and image this EMR, reflective optics and a quantum detector, analogous to one silver halide crystal, are employed in airborne systems. The detector has an electrical output which changes proportional to minute variations of the incoming TIR radiation. A rotating mirror allows the detector to look at the ground scene in a sweeping motion perpendicular to the flight line. Its electrical output is amplified and recorded on magnetic tape or recorded directly on a moving film strip via a CRT tube trace of each scan line on the ground. A gyroscope provides a roll stabilizing signal for the start of each line. The forward progression of the aircraft and film speed adjustment provides the contiguous scan lines of the image. The final product is a photo-like image. The pattern of gray tones, which may be color-coded, represent radiant temperature-emissivity differences rather than reflected differences from a surface. By convention, light tones represent warm areas of higher radiation levels, and dark tones represent cool areas on photographic print. Quantitative scanners compare the incoming TIR signal relative to two precisely calibrated and stable thermal reference sources. They are adjusted to bracket the temperature range of interest. Each scan line the TIR signal is compared to the references; therefore, each signal level, gray tone, or color represents the same radiation levels, or temperature, throughout the image.

The diagrams of Figure 3 show the important geometric relationships and operational parameters of a typical line scanner system.

PROBLEM DEFINITION AND APPLICATION EVALUATION

Assessing the potential for successful applications of TIR remote sensing techniques requires a concise definition of thermal and spatial features to be imaged relative to thermal processes, operational conditions, and TIR principles. Direct applications are those where the detection, quantification, and mapping of heat distribution are of interest. Indirect applications are those where the apparent radiation temperature of a surface, relative to that of its surroundings, will be used as an indicator of conditions related to the survey objective. Examples of the former are fire detection through smoke or below ground, heat loss, and measurement of thermal effluents; of the latter are geotechnical applications where relative heat capacity and/or conductivity can be used to interpret density, moisture content, and water dynamics as indicators of subsurface conditions. In both cases, the correct interpretation of the measurements depends upon knowledge of the physical characteristics of the material and the understanding that the thermal effect imaged and measured is a property of the surface only, but is influenced by internal and external parameters. Examples of TIR applications to engineering problems are used to demonstrate how successful TIR surveys are conducted.

HEAT LOSS SURVEYS

DATA ACQUISITION - The objective of a heat loss survey is to obtain an image which can be interpreted with confidence to assess the heat retention efficiency of a structure. A structure is subject to internal and external thermal loads. To image heat lost from the inside, the cumulative effect of solar heating must be allowed to reradiate before meaningful TIR data acquisition.

Line scanner geometry, aircraft altitude, and recording medium determine imagery scale. Up to 4X enlargement of a film record can be made without loss of spatial detail. Ambient ground temperature should be 2°C or less (with lower dew point) for best thermal contrast. Sky conditions must be clear or uniformly overcast; surface winds not exceeding 10 km/hour. High wind will cause "smear" along the boundaries between features of different radiation temperature. Trees, snow cover, and standing water will attenuate or absorb thermal emission. The best time of acquisition is between several hours after sunset to predawn. A daytime aerial photo taken within one day of a TIR survey is helpful to the client and provides the interpreter with a visual comparison standard for interpretation of the thermal TIR data.

Imagery interpretation must be based on the following relationships and principles:

A. Spatial resolution on the surface is determined by the altitude of the aircraft and each apparent temperature is the average value of one IFOV.

B. The recorded radiation temperature is a function of all of the physical parameters discussed above as modified by the intervening atmosphere.

C. Metalic surfaces reflect the thermal irradiance of the night sky, approximately - 60°C on a clear night, therefore, appear black.

D. Heat is dissipated by radiation, conduction, convection, and ventilation, so that the TIR survey measures only heat lost by radiation.

SEEPAGE THROUGH DAMS & DIKES - The TIR survey objective is to detect anomalous soil moisture conditions and water seepage on the face of an earthen retention structure and in front of its toe. Standing water is usually represented as a light tone on a nighttime image, due to its high heat capacity as compared to surrounding soil, rock, or vegetation materials. The thermal contrast of flowing water depends on its temperature difference relative to adjoining surficial material. The thermal contrast of moist soils depends on the rate of evaporation and its heat capacity. Damp ground is usually represented as darker gray tone, relative to adjoining dry soil during the day and has the opposite appearance at night due to the much higher heat capacity of wet soils compared to dry soils.

The predawn TIR image and daytime photo comparison of Ill. 1 shows clearly the merit of thermal detection of seeps and soil moisture vs. tonal contrast due to reflected light. This imagery was acquired predawn from 600m AGL. Ground temperature was -2°C with 6Km/hr surface wind and a clear sky. TIR data were recorded on magnetic tape for laboratory playback and imagery production. The continuous tone analog data displays wet areas and probable seeps as light tonal features or warm, relative to dry soils. Thermal reference sources of the line scanner were used to calibrate and level slice the imagery into eight tonal levels between 24°F and 36°F. The six gray levels represent 2°F temperature increments. This quantification of radiant temperature permits the analysis of soil temperature across the face of the dam and below the dam. Finer sets of isolevels were produced bracketing only the temperature variations of the seepage areas. This allowed a comparison of seep temperature to know ground water springs, the surface temperature of the impoundment, and the discharge; thereby, interpretation progressed to probable seep sources.

BURIED PIPELINE LEAK DETECTION - Breaks in underground steam or fluid transfer pipelines are detected using TIR scanner imagery on an operational basis. Many have been subsequently verified by excavation. Heat or moisture will produce thermal anomalies on the ground. Their combined affect will be imaged, given the proper ground and survey conditions.

Buried pipeline systems present considerable variability in terms of line size, proximity of lines, topographic position, type, and depth of cover. Imagery should be interpreted using information on line size, spacing, insulation characteristics, backfill material, depth of burial, and line temperature information.

GEOTECHNICAL AND SITING SURVEYS

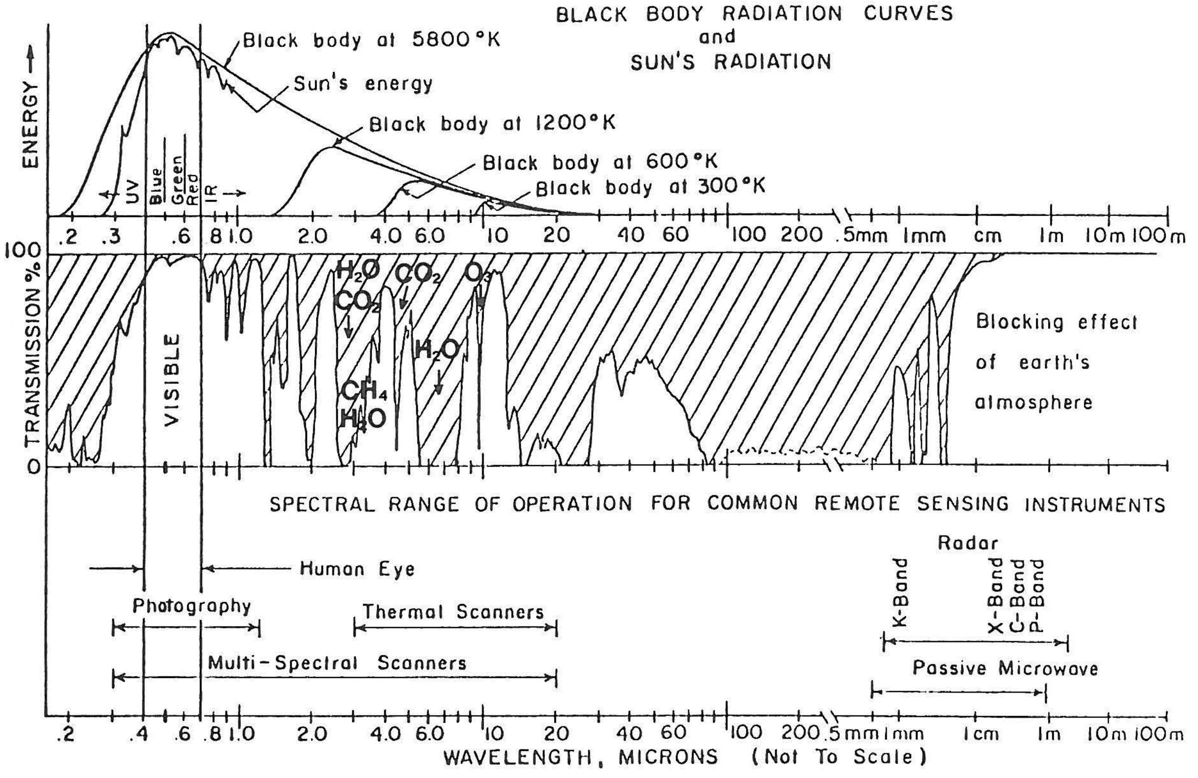
TIR surveys in areas with sparse vegetation and thin soil cover provide optimum conditions for obtaining detailed imagery of near surface bedrock structure. Imagery of areas covered by thin soils underlayed by faulted and fractured bedrock or a limestone/dolomite sequence display structural features which can be interpreted faster and cheaper using TIR remote sensing than by any other survey method. Major linears, which were not resolved on reflected light and near IR imagery, have been imaged with TIR scanner systems even in temperate areas.[1] Some such linears have been verified to be faults by seismic methods and proposed nuclear power plant sites were relocated.

The Florida Department of Transportation[2] has demonstrated the successful application of nighttime TIR imagery interpretation to locate solution features and sink holes. Over 70% of the anomalous thermal areas interpreted to be probable sink holes were verified by subsequent borings.

Investigators in South Africa[3] have published very impressive and conclusive results for geotechnical studies based upon TIR line scanner imagery interpretations. Sinkholes, pinnacles, faults, fractures, joints, potential water well sites, borrow pit areas, and impoundment site suitability studies have been successfully interpreted from TIR imagery of many localities underlayed by near surface dolomite. They stress the importance of much additional information obtainable from TIR imagery and the complementary benefit of combining thermal geologic interpretation with photogeological interpretations. Typically they perform TIR surveys predawn between 300m and 3000m altitude. The majority of missions are flown in the dry season when vegetation cover is sparse. Surveys are not conducted immediately after rainfall. However, judicious timing after precipitation may enhance interpretation of soil permeability, potential aggregate reserves, and ground water regimes.

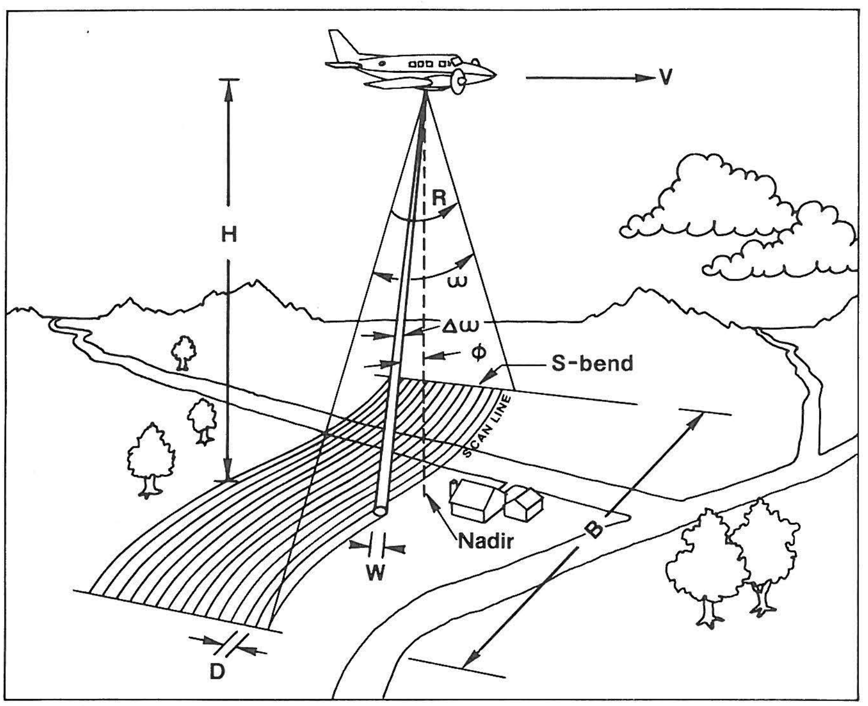
Illustration 2 shows a spectacular application, personal communications, and (op. cit.) capable of saving vast sums of money and potentially lives was demonstrated in South Africa by chance. The imagery was analyzed after acquisition only for equipment related R&D purposes. However, it clearly showed two anomalous dark-tone high moisture bands on the median of a divided highway cut on a steep slope. Six months after acquisition, the slope failed precisely along the most prominent thermal linear. Remedial measures (possibly dewatering and slope toe abutment) along the second anamaly have reportedly been undertaken.

Figure 1.



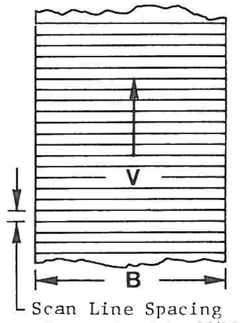
The electromagnetic energy spectrum (from Sherz and Stevens, 1970).

Figure 3.



R = Scan Mirror Rotation
V = Ground Speed
ω = FOV (Total Field of View)
Δω = Spatial Resolution in mrad. (str. rad.)
H = Altitude
D = Scan Line Spacing
B = Swath Width = 2 [H TAN ω/2]
W = IFOV (Inst. Field of View = mrad. x H)

Film is S-bend Corrected & Rolls Stabalized Continuous Film Strip



Scan Line Spacing Determined by V/H
Scale is H dependent

Table 1

Thermal properties of geologic materials and water at 20°C

Geologic materials	K Thermal conductivity, $cal \cdot cm^{-1} \cdot sec^{-1} \cdot °C^{-1}$	ρ Density, $gm \cdot cm^{-3}$	c Thermal capacity, $cal \cdot gm^{-1} \cdot °C^{-1}$	k Thermal diffusivity, $cm^2 \cdot sec^{-1}$	P Thermal inertia, $cal \cdot cm^{-2} \cdot sec^{-1/2} \cdot °C^{-1}$
Basalt	0.0050	2.8	0.20	0.009	0.053
Clay soil (moist)	0.0030	1.7	0.35	0.005	0.042
Dolomite	0.0120	2.6	0.18	0.026	0.075
Gabbro	0.0060	3.0	0.17	0.012	0.055
Granite	0.0075 0.0065	2.6	0.16	0.016	0.052
Gravel	0.0030	2.0	0.18	0.008	0.033
Limestone	0.0048	2.5	0.17	0.011	0.045
Rhyolite	0.0055	2.5	0.16	0.014	0.047
Sandy gravel	0.0060	2.1	0.20	0.014	0.050
Sandy soil	0.0014	1.8	0.24	0.003	0.024
Sandstone, quartz	0.0120 0.0062	2.5	0.19	0.013	0.054
Serpentine	0.0063 0.0072	2.4	0.23	0.013	0.063
Shale	0.0042 0.0030	2.3	0.17	0.008	0.034
Tuff, welded	0.0028	1.8	0.20	0.008	0.032
Water	0.0013	1.0	1.01	0.001	0.037

*Source: From Janza (1975, Table 4.1).

Emissivity of representative samples of various materials determined in the 8 to 12 μm wavelength region

Material	Emissivity, ε
Granite	0.815
Feldspar	0.870
Granite, rough	0.898
Quartz sand, large grains	0.914
Dolomite, rough	0.958
Asphalt paving	0.959
Concrete walkway	0.966
Water, with a thin film of petroleum	0.972
Water, pure	0.993

*Source: Buettner, K. J. K., and C. D. Kern, Journal of Geophysical Research, v. 70, p. 1333, 1965, copyrighted by American Geophysical Union.

In the 8 to 12 μm region, polished metal surfaces have very low emissivities of about 0.06, but a coat of flat black paint increases the emissivity to about 0.97.*

It is important to note these are laboratory measurements. In the field, ε is averaged over one IFOV by a line scanner. Similar ε ranges could be measured by soil types and grain size.

*Adapted From Sabins, 1978

Figure 2.
DIURNAL THERMAL CYCLE

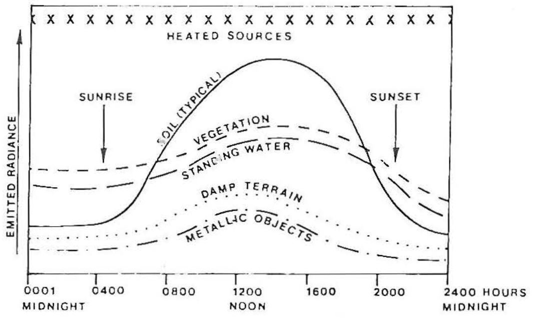


Illustration 1. Daedalus Enterprises, Inc.

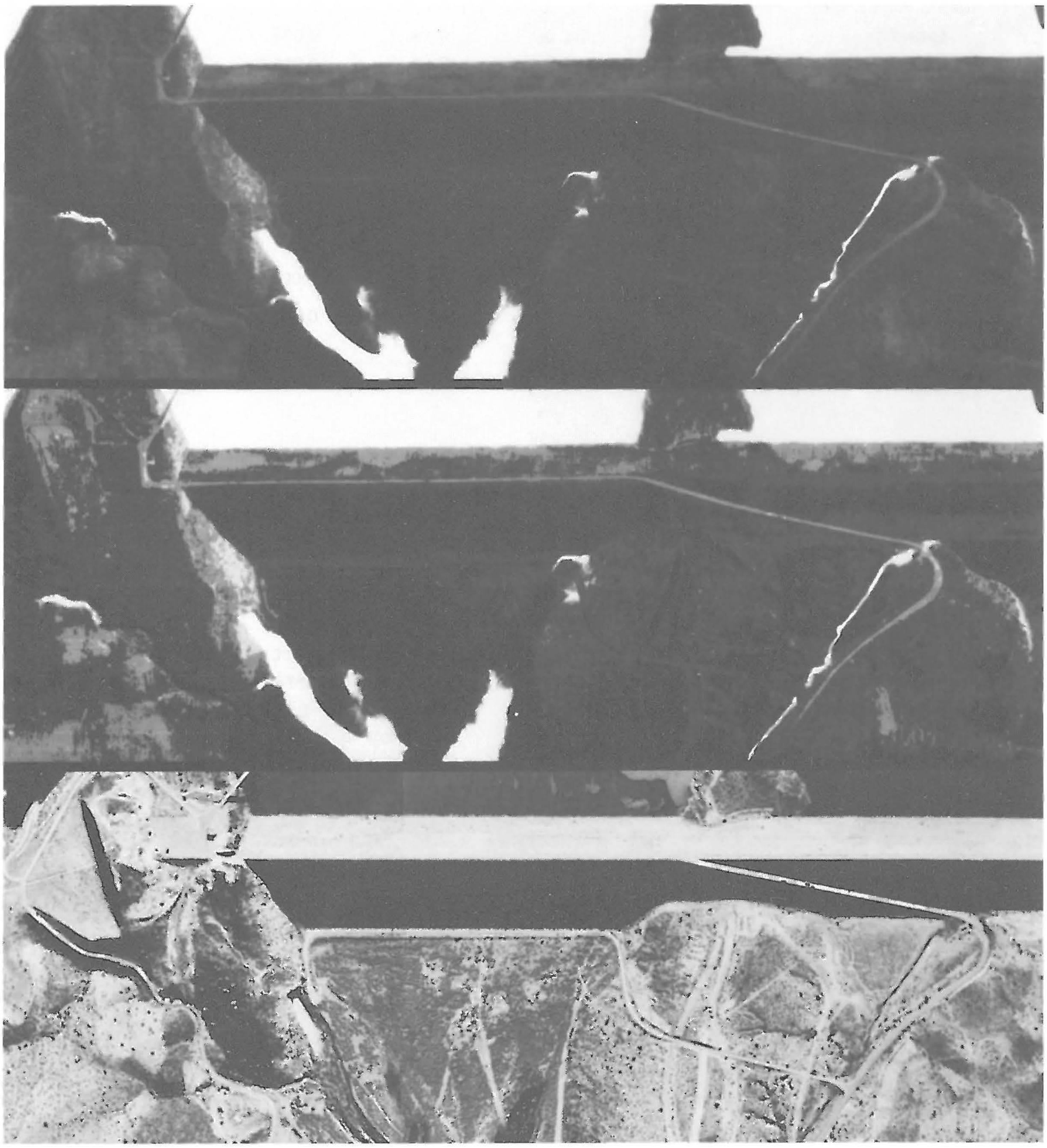
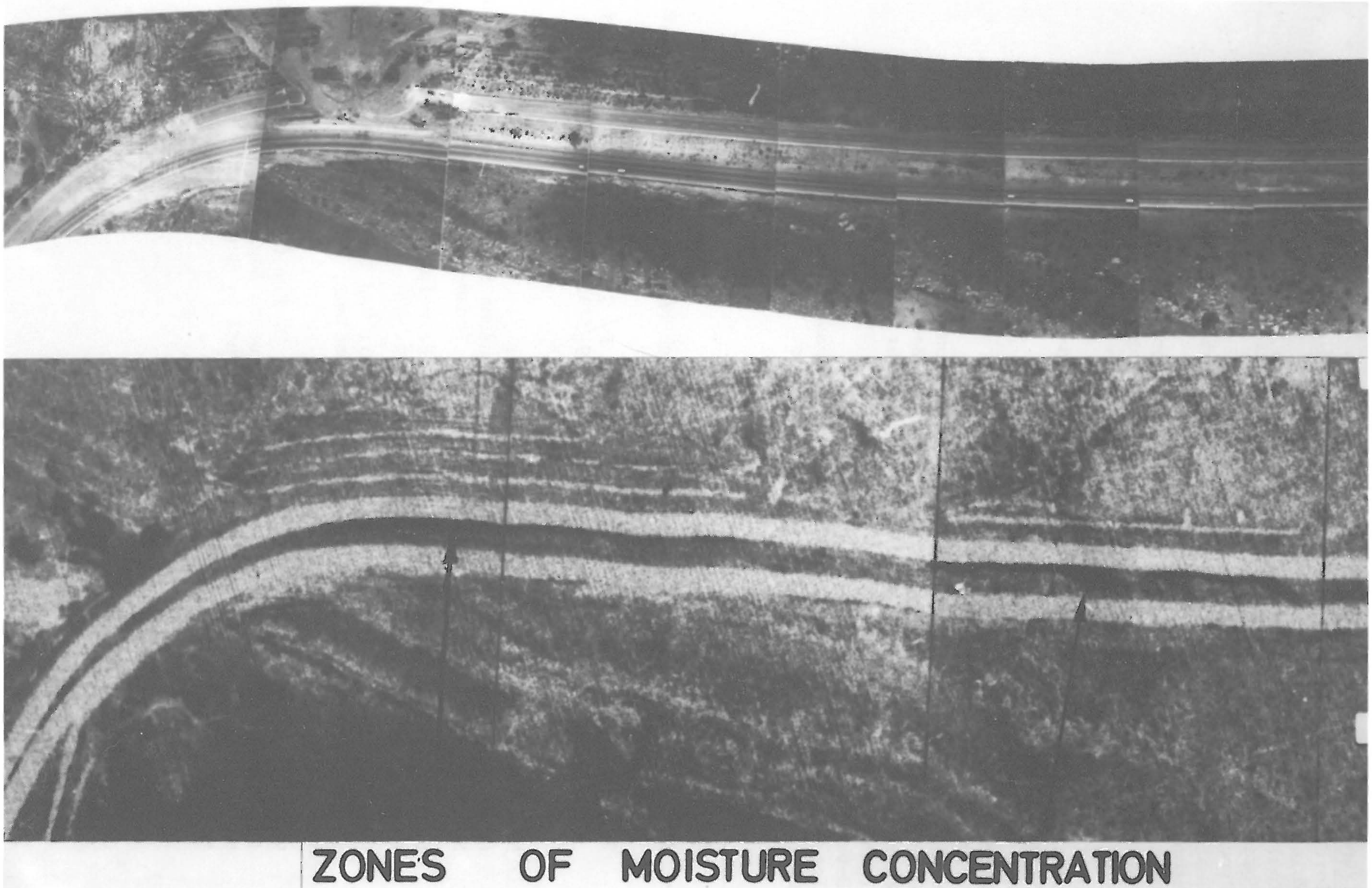


Illustration 2 - Courtesy of Spectral Africa (Pty.) Ltd.; R. P. Viljoen and T. D. Feuchtwanger



SYNOPSIS OF WIDEBAND TIR IMAGERY APPLICATIONS

Forest Fire Surveys, Smoke and Cover Penetration
Volcanic Activity and Geothermal Surveys
Coal Refuse Dump and Insite Coal Fire Surveys
Power Line Fault Surveys
Process Temperature Surveys and Refineries
Heat Loss from Industrial and Urban Areas, Urban Analysis
Microclimate and Airmass Dynamics Studies
Detection of Ancient Cultural Features, Archeology
Geotechnical Studies, Siting, Routing, and Hazard Surveys
Sink Hole Detection, Karst Topography Surveys
Near Surface Aggregate Surveys
Fault and Fissure Surveys, Moisture Anomaly Delineation
Slope Failure Susceptibility Studies
Dam and Dike Integrity Surveys
Pipeline Surveys, Buried and Exposed
Crop Moisture, Stress and Irrigation Studies
Soil Moisture Aquifer Recharge Area Definition
Ground Water Discharge to Surface and Water Bodies
Thermal and Sewage Effluent Discharge to Water Bodies
Tidal and Current Studies
Detection and Delineation of Oil Spills
Ice, Permafrost, Glacial, and Snow Covered Coast Line Studies
Census and Behavior Studies of Hidden Mammals

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[1] Daedalus Enterprises, Inc.

[2] Florida Department of Transportation, Tech Memo No. 1, 1972, and Tech Memo No. 5, 1972, by Tom Griepentrog.

[3] Spectral Africa (Pty.) Ltd., D. Warwick, P. G. Hartopp, R. P. Viljoen, Q.Jl Engrg. Geol., 1979, Vol. 12, pp. 159-179.

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