*AN OPTIMUM MULTISENSOR
APPROACH FOR DETAILED
ENGINEERING SOILS MAPPING*

VOLUME I

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Highway
Research
Project*

*PURDUE UNIVERSITY
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by

H.T. RIB

Progress Report

AN OPTIMUM MULTISENSOR APPROACH FOR
DETAILED ENGINEERING SOILS MAPPING

To: Dr. G. A. Leonards, Director
Joint Highway Research Project

December 19, 1966

From: H. L. Michael, Associate Director
Joint Highway Research Project

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The attached two volume report entitled "An Optimum Multisensor Approach for Detailed Engineering Soils Mapping," completes Phase A of the project entitled "Annotated Aerial Photographs as Master Soils Plans." This report was prepared by H. T. Rib, Graduate Instructor in Research under the direction of Professor R. D. Miles.

The report recommends an optimum multisensor system for performing detailed engineering soils mapping. The system was evaluated from a study of available sensors and the data obtained in the ultraviolet, visible, infrared and microwave portions of the electromagnetic spectrum. Some aspects leading to automatic interpretation techniques were also evaluated.

Respectfully submitted,

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DETAILED ENGINEERING SOILS MAPPING

by

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ABSTRACT

Rib, Harold T., Ph.D., Purdue University, January 1967. AN OPTIMUM MULTISENSOR APPROACH FOR DETAILED ENGINEERING SOILS MAPPING. Major Professor: Robert D. Miles.

This research study investigated the potential of available types of remote sensing systems for the evaluation of soils and soil conditions for the purpose of developing an optimum multisensor approach for detailed engineering soils mapping. Other objectives of the study were: (1) to investigate the value of quantitative measurements on aerial photography and imagery for assistance in interpretation; and (2) to perform a limited study to determine which parameters would be of value to measure at the time of flights.

Three test sites were selected which contained a variety of land forms and soil units. A total of nine flight programs were obtained over the test sites during the period from May 1965 to June 1966. Coverage was obtained with various types of aerial films (color, color-infrared, color negative, black-and-white panchromatic and black-and-white infrared), a multiband camera, a radar sensor (K-band), infrared sensors (far infrared), and a multichannel sensor (ultraviolet through far infrared). All of these types were not obtained in any one flight program, but generally several combinations were obtained at one time. Daytime and nighttime imagery were also obtained during one flight.

The field investigations included field radiometer readings (taken during last two flight programs), soil moisture content measurements, and resistivity surveys. Ground photographs were taken during aerial flights to record the conditions existing at flight time. Meteorological data were also collected during flights. The resistivity surveys were performed to add to the existing information known about the test areas. The remainder of the data were used to help evaluate the influence of various parameters on the data collected.

Quantitative aspects of the project included performing continuous scans with reflection and transmission densitometers, to determine if typical density patterns existed for various land forms. Attempts were also made to prepare isotonal maps. Densitometers were used to prepare normalized response curves from multichannel data. A system was also developed which determines the Munsell color notation on aerial photographs based on densitometer readings with four filters. Based on this color measuring system a method was developed to prepare isochromal maps (maps showing areas of uniform colors).

Major conclusions obtained in this study include: (1) the optimum multisensor system for detailed engineering soils mapping is a multichannel sensor (minimum of seven bands in ultraviolet through far infrared) obtained simultaneously with medium scale color aerial photography; (2) alternate systems depending on availability of equipment and security restrictions are color and color-infrared photography and infrared imagery obtained simultaneously, or color and color-infrared photography obtained simultaneously; (3) spectral response curves obtained by normalizing multichannel data has great potential

for differentiating between various soils and soil conditions automatically; (4) typical patterns for various land forms are not obtained by densitometric scans - influence of various parameters results in more variations within land forms than between them; (5) the technique of determining Munsell notations by means of densitometer readings is a simple, rapid method whose accuracy (for the intended purpose) is commensurate with other color measuring systems; and (6) field measurements found to be of greatest value in evaluating the photography and imagery include field radiometer readings, ground photographs taken at the time of flight and meteorological data.

CHAPTER 1

INTRODUCTION

The utilization of aerial photographic interpretation techniques for the evaluation of engineering soils was developed in the early 1940's at Purdue University. Information on soils was obtained from the interpretation of black-and-white aerial photographs taken at a scale of approximately 1:20,000. The use of these photographs and techniques have been in developing information on soils which were of value predominantly in the early stages of an engineering project. The application of aerial photographic interpretation in performing the final detailed soil survey necessary for many engineering projects has been limited to outlining the broad soil boundaries and planning the field exploration program. The detailed final soil survey is performed in most cases by extensive field exploration programs (148)(169).¹

The limited use of aerial photography in detailed soils mapping may be attributed to several main factors:

1. The small scale of the readily available photography;
2. Inability to obtain special photographic coverage at desired scale for the particular study;
3. Large scale photography, when available, not necessarily flown for the purpose of the study or at the desired scales;

¹Number in parenthesis refers to references in bibliography.

4. Lack in some cases of significant tonal contrasts between significantly different engineering soils as indicated on the normally used panchromatic photography;
5. Inability to determine the reasons for some of the tonal differences present on the photography due to lack of knowledge of the various parameters and their effect on the final tones; and
6. Lack of skilled photo interpreters to perform the detailed study.

Since most of the costs involved in a detailed engineering soil survey are incurred in the field exploration and investigation stage, methods which will decrease the costs or which will develop more complete and useful information at the same cost would be beneficial. Several recent studies have proposed techniques for the use of supplementary information in order to optimize the field exploration phase. These techniques include the use of geologic and pedologic literature, aerial photography as well as a more extensive use of geophysical exploration (93)(109)(133). Some work has also been done in the study of large scale photography and the use of various types of films and filter combinations. In addition, limited work in the evaluation of engineering soils and associated areas of earth sciences (agriculture, geology, forestry) has been accomplished using other portions of the electromagnetic spectrum other than the visible (e.g., infrared, radar). These investigations have indicated that further study into the use of various types of films, filters and other sensors (e.g., infrared, radar), offer great promise in performing detailed engineering soils

mapping projects.

Purpose and Scope

The principal objective of this study was to evaluate the potential of available types of remote sensing systems in order to develop an optimum multisensor approach for detailed engineering soils mapping. Secondary objectives of this study were: (1) the development of an optimum system for detailed soils mapping utilizing only the equipment normally available to highway organizations; (2) to investigate the value of quantitative measurements on aerial photography and imagery to determine their usefulness in the interpretation of the images and in preparing detailed soils maps; and (3) to make a limited study of what parameters would be of value to measure at the time of aerial flights to assist in the interpretation of the images.

Multisensor flights are much more complex undertakings than the normal aerial photographic flight. To properly evaluate and utilize the results of a multisensor mission, it is necessary to understand what the various sensors measure and what parameters influence the sensors and the final results obtained from these sensors. Chapters 2 and 3 discuss these factors. Chapter 2 discusses basic energy considerations, regions of the electromagnetic spectrum available for remote sensing, and the types of sensors available. Chapter 3 discusses the parameters affecting the various sensors used in multisensor projects; the results obtained by previous investigators in evaluating the parameters and in the application of the various sensors in engineering and related fields; and the various factors to consider in a multisensor approach and evaluation of the results obtained.

The remaining chapters of this study discuss the project area, the study approach, and the results and conclusions obtained. Chapter 4 discusses the study approach, describes the test areas, the exploration and measurement program, and the flight program for this project. Chapter 5 discusses the qualitative evaluation of the project data and the conclusions obtained, and Chapter 6 discusses the quantitative aspects of the project study and the conclusions obtained. Chapter 7 gives the overall conclusions of the study and lists recommendations for further studies.

This study is the first phase of a research project entitled "Annotated Aerial Photographs as Master Soils Plans" initiated in the Civil Engineering Department of Purdue University. It is being performed as a Joint Highway Research Project (JHRP) and is cooperatively sponsored by the Indiana State Highway Commission and the Bureau of Public Roads.

Photographic support for the study has been furnished by the Indiana State Highway Commission. Multisensor coverage of the test areas have been accomplished by, (1) the Avionics Laboratory, Wright-Patterson Air Force Base, (2) the Infrared and Optical Sensor Laboratory, Institute of Science and Technology, University of Michigan, and (3) Intermountain Forest and Range Experiment Station, Northern Forest Fire Laboratory, U.S. Forest Service.

Note: Since this report will contain colored photographs which do not reproduce satisfactory detail on microfilming, the color negatives will be filed in the Joint Highway Research Project files in the Civil Engineering Department of Purdue University. Copies of the colored photographs can then be ordered from this office upon payment of appropriate charges.

CHAPTER 2

ELECTROMAGNETIC SPECTRUM CONSIDERATIONS IN MULTISENSOR APPROACH

Remote sensor systems available for inclusion in a multisensor program are of two basic types: (1) force field sensors, e.g., gravimeters and magnetometers; and (2) electromagnetic systems, those capable of detecting and recording electromagnetic energies. For remote sensing from aircrafts at altitudes normally flown, the force field devices are little used. Lancaster and Feder indicate that although airborne magnetometers are common for some types of reconnaissance work, they suffer because of drastic reduction in resolution with increased operational altitudes and also have problems with ambient noise. With respect to gravimeters, intensive research is in progress directed primarily at achieving stability in the airborne mode and improved aircraft velocity component monitoring (85). Therefore, multisensor programs generally emphasize the electromagnetic spectrum.

The electromagnetic spectrum classifies (according to wave length or frequency) all energy that moves with the constant velocity of light in an harmonic wave pattern (26). Figure 1 shows a segment of the electromagnetic spectrum and the various regions delineated. Sharp boundaries do not exist between the regions, but rather smooth transitions occur. This figure also indicates the various sources of energy

FIGURE 1. ELECTROMAGNETIC SPECTRUM AND FACTORS INFLUENCING MULTISENSOR ANALYSIS. (COURTESY AMERICAN SOCIETY OF PHOTOGRAMMETRY)(26)

available in the electromagnetic spectrum, the types of interactions that occur, and the types of detectors available for sensing in the various regions. It is noted that the visible band, until recently the only part available to the interpreter, uses only a minute portion of the spectrum.

Basic Energy Considerations

An understanding of basic energy considerations is necessary to the understanding of the basis for a multisensor approach. The discussion on this subject will necessarily be brief. Further details can be obtained from the excellent article on this subject in Photogrammetric Engineering, September 1963 (26).

Electromagnetic radiation is composed of collections of photons (discrete units or "quanta" of energy). When a photon of any specific energy strikes the boundary of an aggregation of matter, a number of interactions are possible which may result in changes in the vibrational, rotational or translational energy levels of the matter. Since mass and energy are conserved according to basic physical principles, the energy can either be:

1. "Absorbed," giving up its energy largely into heating the matter;
2. "Emitted," or more commonly re-emitted by the matter as a function of temperature and structure at the same or different wavelength;
3. "Scattered," or deflected away and ultimately lost by absorption or further scatter; or

4. "Reflected," or returned unchanged to the medium (26).

From basic energy considerations the energy of a photon is

$$E_p = hf = hc/\lambda \quad (2.1)$$

where

E_p = the energy of any photon (ergs)

f = the frequency of the wave motion, in cycles per second

c = the velocity of wave motion (3×10^8 meters per second for all electromagnetic waves in vacuo)

λ = the wavelength in meters

h = Planck's constant (6.62×10^{-27} erg-sec)

This equation shows that photon energies and wavelengths are related, i.e., higher energy photons have shorter wavelengths and lower energy photons have longer wavelengths. Since absorption, emission, scattering and reflection of electromagnetic energy by any particular kind of matter are selective with regard to wavelength, and are specific for that particular kind of matter depending primarily upon its atomic and molecular structure, this leads to a very important application in multisensor analysis. By observing the reaction of matter to these phenomena throughout the electromagnetic spectrum, we can in principle identify the material of interest (26).

The type of interaction and the band of the spectrum involved is related to the energy of the photon (refer to Figure 1 - Interactions). In the high frequency short wavelength regions the energy of a photon increases beyond the binding energies of molecules or even atoms, and individual collisions with such photons result in dissociation or violent disruption of matter. As one progresses up the spectrum, the interactions shift from reaction within atoms to reactions within molecules. Here energy changes produce electron shifts affecting the "bonding" of atoms within the molecule as evidenced by changes in the

ultraviolet and visible band; changes in vibrations of atoms within the molecule as evidenced in the near and middle infrared band; and changes in the "rotational energy" of the molecule as a whole in gases and liquids as evidenced in the infrared and microwave regions. At the low frequency end (radio), photon energies are low, and wavelengths are large compared to atomic distances, so that no permanent structural adjustments occur (26).

Energy Propagation, Sources and Detectors

In order for a remote sensing system to operate effectively within any specified region of the electromagnetic spectrum, the following factors must be considered:

1. An energy source must be available which will provide photons having the proper energies and hence the proper wavelengths;
2. A collection of matter (target) which will interact with photons in this range must be present;
3. An energy detector which is sensitive to photons in this range must be available;
4. The propagating medium between detector and target will transmit photons in this range; and
5. One must have an energy filter which will exclude unwanted photons to which the detector is sensitive, while transmitting the desired ones (26).

Atmospheric Transmission

In remote sensing from aircraft, the atmosphere is the main medium through which radiation is transmitted. In special cases, such as the interpretation of submerged objects, the transmission properties of water in addition to the atmosphere are of interest (24, p. 93).

The atmosphere is a turbid medium composed of a mixture of gases in which are suspended a wide variety of particles distributed over a great range of sizes. The gases present in greatest abundance in the earth's atmosphere are nitrogen (N_2), oxygen (O_2), water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO), and ozone (O_3) (84). The suspended particles present in the aerosol include varying amounts of smoke, fumes, dust, salt particles, water droplets and minute living organisms (118). As a result of the presence of these gases and aerosols, any radiation passing through the atmosphere is selectively absorbed by the gases and scattered by the aerosols depending on the energies or wavelength distribution of the radiation. This attenuation can be described by the equation

$$I = I_o e^{-k_e d} \quad (2.2)$$

where

I = Intensity of emergent radiation

I_o = Intensity of incident radiation

k_e = extinction coefficient (due to absorption and scattering)

d = path length in the atmosphere

The amount of attenuation encountered is variable and at any given location is dependent upon: (1) The concentrations and distribution

of the gases and aerosols making up the atmosphere; (2) meteorological conditions, particularly in the lower atmosphere where the water-vapor, gaseous and aerosol content may vary continuously; and (3) time of year, time of day and altitude.

Absorption. Absorption occurs at selected wavelengths in the atmosphere depending on the type of gaseous molecules encountered. The amount of absorption or conversely atmospheric transmission (Percent Transmission = 100 - Percent Absorption) as well as the types of interactions involved (translation, rotation, etc.), causing the absorption in various parts of the electromagnetic spectrum are shown in Figure 1. A more detailed rendition of atmospheric transmission for a portion of the spectrum is shown in Figure 2 which extends from 0.5 microns to 25 microns. Table 1 lists the kind and degree of absorption occurring throughout the electromagnetic spectrum.

As is evident from Figures 1 and 2 and Table 1, the atmosphere is relatively impenetrable to radiation due to absorption phenomena below about 0.3 microns and between 15 and 1000 microns. In the range from 0.5 microns to 15 microns, there are numerous absorption bands due to the presence mainly of CO_2 and H_2O in the atmosphere. There are also relatively clear areas (little to no absorption) in this region called "windows" where radiation is effectively transmitted through the atmosphere (e.g., 0.3-1.35 μ , 1.95-2.5 μ , 3.3-4.2 μ , 8-14 μ). These windows are evident in Figure 2. In addition, the region above 1000 microns is relatively free for transmission of radiation. Thus one can readily see, that in the multisensor approach from an aircraft, the various sensors used will essentially be limited to these clear transmission areas or "windows."

NOTE: TRANSMISSION OF 1000 FOOT HORIZONTAL AIR PATH AT SEA LEVEL,
5.7 MM PRECIPITABLE WATER, 79°F. TEMPERATURE.

FIGURE 2. EXAMPLE OF SPECTRAL TRANSMISSION
OF ATMOSPHERE.

Table 1. Absorption Bands of the Atmosphere

Wavelength Region	Kind and Degree of Absorption
X-ray 0.003 to 0.03 μ	Complete absorption because of (a) short wavelength in relation to size of atmospheric particles and (b) very high photon energy with consequent high probability of interaction with atmospheric matter.
UV 0.03 to 0.13 μ	N ₂ and O ₂ electronic bands and associated continua; almost complete absorption.
0.13 to 0.22 μ	O ₂ electronic bands; almost complete absorption.
0.22 to 0.30 μ	O ₃ electronic bands; strong absorption.
0.30 to 0.40 μ	No specific absorption bands; Rayleigh scattering troublesome.
V and Photographic IR 0.40 to 1.0 μ	few absorption bands except for water band at 0.9 μ ; good transmission.
Near IR ^a 1.0 to 20 μ	many rotational - vibrational bands, throughout the region, of H ₂ O and CO ₂ ; electronic O ₂ at 1.06 and 1.27 μ .
Far IR ^a 20 to 1,000 μ	many rotational lines, principally H ₂ O; strong absorption.
Microwave 1mm to 10cm.	widely spaced pure rotational lines, many clear windows.
Radiofrequencies 10cm (+)	almost complete transmission.

^a - zones of infrared, (i.e., near, far) are arbitrary. Those shown here are as reported in reference (26). The more common divisions of the infrared are: near ~ 0.7 - 1.5 μ , middle ~ 1.5 - 5.6 μ , far ~ 5.6 - 1000 μ (54). (Courtesy American Society of Photogrammetry) (26).

Scatter. As was previously mentioned, scatter is predominantly caused by the presence of particles in the atmosphere. The type and amount of scatter that occurs depends on: (1) the size, number and distribution of the particles present; (2) the wavelength of the radiation; and (3) the energy level of the particle. The size of particles that may be found in the atmosphere may range from 10^{-6} to 10^{-1} cm. (117). The size of the particles has a great effect on the type and amount of scatter that occurs. This effect is as follows:

1. Much smaller than the radiation wavelength, Rayleigh scattering occurs;
2. Comparable in size to the radiation wavelength, Mie scattering occurs; and
3. Much larger than the radiation wavelength, non-selective scattering occurs.

In Rayleigh scattering the amount of scattering is inversely proportional to the fourth power of the wavelength.

$$S = C_1 \lambda^{-4} \quad (2.3)$$

Therefore, for a given particle size the smaller the wavelength the greater the scatter. This effect is the cause of the blue appearance of the sky in the daytime. The blue portion of the spectrum of sunlight being of a shorter wavelength is scattered much more than the red portion; thus producing the blue appearance of the sky.

Rayleigh scattering does not change the energy of the individual photons, nor does it erase any spectral signal. What it does is alter the direction of photon paths, selectively, according to wavelength. However, by scattering the photons from spectral signals it makes it

difficult to distinguish the desired object from the general background. Rayleigh scattering is especially pronounced for particles of molecular size.

Mie scattering applies to particles of larger size up to several microns in effective diameter. Application of the Mie scattering theory to atmospheric scattering is far more complicated than for Rayleigh scattering. It involves the classification of particle size and index of refraction by statistical methods (54). A general relationship governing Mie scattering which is applicable to atmospheric aerosol in the visible and near infrared regions takes the form of

$$S = C_2 \lambda^n \quad (2.4)$$

where the exponent n , which is a function of particle size, varies between -4 and a small positive number (118).

For the larger size particles such as fog and clouds, geometrical theories which have been given by Wiener and Bricard and others provide satisfactory results (117). In this size, the scattering is non-selective, that is, the scatter is independent of the wavelength of the radiation; thus for example the white appearance of fogs.

Figure 3 shows how these theories can be used to calculate the extinction coefficient of droplets of various sizes throughout the ultraviolet, visible and a portion of the infrared spectra. It is seen that for very small particles, the extinction in blue light is much greater than in red. This is not true for the larger particles. For very large particles, there is practically no change in the extinction coefficient within the region plotted (26).

Another form of scattering which is present but relatively small

(COURTESY AMERICAN SOCIETY OF PHOTOGRAMMETRY) (26)

FIGURE 3. EXTINCTION COEFFICIENT (for a density of one particle per cm³ of atmosphere).

in extent is "Raman" scattering. In this type of scatter there is no elastic rebound between the molecule and the photon as in the case for Rayleigh scattering. On contact, the photon impinging may give up energy to a molecule in the vibrational or rotational manner, and raise the molecule to a higher vibrational or rotational energy state. Conversely, it may gain energy if the target molecule was in a higher state at the moment of collision. Thus, the photon in addition to being scattered has taken on the signature of the scattering molecule. This effect commonly occurs in the ultraviolet and visible regions. The importance of the "Raman" effect is that it may give molecular information in cases where none is readily available from normal IR molecular spectroscopy (26).

The various scattering factors of the atmosphere are very important to multisensor applications. The types and sizes of the particles in the atmosphere will determine which region of the spectrum one would have the most success in obtaining information; or conversely, whether information can be obtained at all in the regions of interest under given atmospheric conditions. For example, if haze is the primary atmospheric condition (particle sizes usually of the order of 3 or 4 tenths of a micron), then by referring to Figure 3 one can see as one progresses toward the infrared region, the extinction coefficient decreases. However, if fog conditions exist where the size of the water droplets are much larger (radius from about 2 to 25 microns), then one can see from Figure 3 that there is little difference in the extinction coefficient as one progresses from the visible through most of the infrared region. A relatively long wavelength radiation would

be required to satisfactorily penetrate fog.

Path Length. Another factor of importance in atmospheric attenuation is the path length or the distance that the radiation has to travel in traversing the atmosphere. This effect is quite evident from equation (2.2). The greater the path length "d," the greater the attenuation. This effect however is not always continuous in the atmosphere as one might expect from this equation. For example, most of the gas molecules are concentrated in the extreme lower layers of the atmosphere, but most of the ozone is at high levels; thus, leading to a non-linear change in attenuation with increase in altitude.

Summary of Atmospheric Effects. From the discussion of the various effects of the atmosphere on the transmission of radiation, it is clearly evident that these effects will greatly decrease the extent of the electromagnetic spectrum available for remote reconnaissance. The atmospheric effect essentially divides the spectrum into four areas:

1. Gamma ray region. - affect of attenuation is essentially uniform across this band but does not exclude possibility of discerning information;
2. X-Ray to approximately 0.3 microns in ultraviolet. - the effects of absorption as well as Rayleigh scattering essentially eliminates this region of the spectrum;
3. From approximately 0.3 microns in the ultraviolet to about 1 mm. (end of infrared region). - there is selective absorption by the gaseous molecules in the air which limits the application of various sensors to specific regions or "windows." The use of these regions or "windows" are further

limited by the presence of aerosols which may be either selective or non-selective depending on the size of the particles. This latter factor is highly variable, depending on location, season, time of day, altitude, etc.;

4. Microwave and Radio regions. - relatively few absorption areas - almost complete transmission.

Energy Sources

Now having some conception of the areas of the spectrum available for remote reconnaissance applications based on the atmospheric transmission properties, one can look at the sources of radiation available within these specified regions. Figure 1 indicates the general sources of radiation available for remote reconnaissance. These may be divided into "passive" or natural sources and "active" or artificial sources. In "passive" sources, the radiation energy occurs naturally, either by radiation emitted by the material itself (e.g., radioactivity) or by reflection or reradiation of energy originating in some natural source (e.g., reflection of sun's radiation). In "active" sources, the radiation is produced by artificial methods (e.g., radar, maser, x-ray). Since "passive" sources are the primary sources of radiation for multisensor analyses, an understanding of their origin and their application to remote reconnaissance is important.

"Passive" Sources. All matter at temperatures above zero degrees Kelvin radiates electromagnetic energy, so that all matter is in a sense, a "source." As mentioned previously in the discussion of basic energy considerations, all matter consists of particles in harmonic motion, and each particular collection of matter (i.e., any object) has definite

resonance frequencies of vibration, rotation and translation. Any incident radiation which strikes this object at these resonance frequencies is absorbed to varying degrees. If all the incident radiation is completely absorbed by the object it is called a "black body." Conversely, the radiation emitted by a black body at any given temperature is the maximum possible. A black body is therefore an idealized or perfect absorber and radiator of radiation, at all temperatures and for all wavelengths.

The relationship between the radiation intensity, spectral distribution, and temperature of a black body is shown in Figure 4. This figure shows that as the temperature of the black body increases, the intensity of the radiant energy emitted increases rapidly. In addition, it is seen that the radiation peaks shift to shorter wavelengths as the absolute temperature is increased. These peaks can be predicted by the Wien's Displacement Law.

$$\lambda_{(\text{peak})} \cdot T = \text{Constant} = 2897 \text{ micron-degrees} \quad (2.5)$$

Using this law, one can determine the peak wavelength (one of maximum intensity) for the radiation of objects of interest. For example:

$$1. \text{ Sun, } T = 6,000^{\circ}\text{K, } \lambda_{(\text{peak})} = \frac{2897}{6000} = \underline{.48 \text{ microns}};$$

$$2. \text{ Average Terrain, } T = 300^{\circ}\text{K, } \lambda_{(\text{peak})} = \frac{2897}{300} = \underline{9.6 \text{ microns}}.$$

Actually, there are no true black bodies in nature although some objects come very close. The efficiency at which an object absorbs and radiates energy as referenced to that of a black body is termed "emissivity factor" or generally, just "emissivity." The emissivity of a black body is unity. Objects with emissivities less than unity are

FIGURE 4. BLACK BODY SPECTRAL EMITTANCE AT VARIOUS TEMPERATURES.

called "gray bodies."

The amount and spectral characteristics of the energy emitted by an object depend upon the absolute temperature of the object (degrees Kelvin) and also upon its nature and surface finish. A highly polished surface such as a silver-or aluminum-surfaced mirror is an extremely poor absorber and radiator of energy; its emissivity is close to zero. In contrast, a surface coated with lampblack is a highly efficient absorber and radiator of energy; its emissivity is close to unity. The emissivity of most objects is generally not constant over all frequencies; and accordingly, must be determined for various regions of the spectrum.

The fundamental relationship for the total radiated energy from a body into a hemisphere at absolute temperature T and emissivity ϵ is expressed by the Stefan-Boltzmann law

$$W = \epsilon \sigma T^4 \quad (2.6)$$

where

W = total radiant emittance in watts/cm²
 ϵ = emissivity factor of gray body
 σ = Stefan-Boltzmann constant = 5.673×10^{-12} watt/cm²-deg⁴
 T = absolute temperature in degrees Kelvin

If the radiating surface is a plane and a perfect diffuser, then the radiant intensity emitted for all wavelength intervals varies as the cosine of the angle between the line of sight and the normal to the surface according to Lambert's law of cosines. Thus if the total radiant emittance of the source is W , then the radiant intensity (J) received at a detector is

$$J = \frac{WA}{2\pi d^2} \cos \theta \quad (2.7)$$

where

A = area of emitting source, cm²
 d = distance from source to detector (line of sight), cm
 θ = angle between a normal to the surface of the source
 and the detector, degrees

It will be noted from this equation that the intensity of the radiation received is inversely proportional to the square of the distance between the source and the detector (known as inverse square law).

The amount of energy radiated by a "passive" or natural source and the region of the spectrum over which it radiates primarily depends on the temperature of the source. The main and most intense natural source available for remote reconnaissance is the sun. Being at a very high temperature (equivalent to a black body temperature of approximately 6000°K), it radiates enormous amounts of energy throughout the visible, and portions of the ultraviolet and infrared regions. Figure 5 shows generalized spectral distribution curves for solar energy measured above the atmosphere and at the earth's surface. The amount of solar energy reaching the surface of the earth depends on many factors some of which are:

1. Variation of the amount of heat energy radiated from the sun;
2. Attenuation by the atmosphere; and
3. Path length through the atmosphere - function of time of year, altitude of sun, and altitude of object.

Figure 6 shows the variation of the altitude of the sun versus time of the year and time of the day at a specific latitude. From this

FIGURE 5. SPECTRAL DISTRIBUTION OF SOLAR ENERGY.

FIGURE 6. VARIATIONS OF SOLAR RADIATION WITH ALTITUDE AND TIME.

figure one can estimate the effect of time of the year and day on the path length (e.g., as altitude of the sun decreases, path length increases).

As the solar radiation impinges upon the surface of the earth it is either absorbed or reflected to various degrees. Therefore, its value for remote sensing is twofold. It is an excellent source for illuminating the surface of the earth when one wishes to accomplish remote reconnaissance of the earth by use of reflected light. As noted in Figure 5, solar energy is obtained in the region from about 0.3 microns to 3.5 microns with a peak at about 0.5 microns. Thus, reflected sunlight is available for multisensor applications in all of the visible region, a portion of the ultraviolet range, and a portion of the infrared region where "windows" are available in the atmosphere.

The second point of value of solar radiation is the effect of the absorbed portion of the solar radiation. The various objects on the earth, by virtue of their having absorbed energy from the sun are emitting radiant power. The natural terrain, a primary area of interest in soils studies, has an average temperature of 300°K by virtue of its heating by the sun. This temperature results in a radiant power peak at about 9.6 microns and a low, broad radiant power distribution extending from about 5 to 25 microns. Fortunately, this band includes the 8-14 micron atmospheric window, making possible the sensing of the terrain features by virtue of their emitted radiation.

Emitted radiation can also be studied in the microwave region where there is little atmospheric attenuation. In this region the emitted energy is low, but generally it is approximately proportional

to the temperature to the first power ($W \propto T$)(31). This trend can be anticipated from Figure 4 where it is seen that at longer wavelengths the curves are approximately parallel to each other.

Other "passive" sources of radiation besides the sun and the natural terrain (heated by the sun) include atmospheric sources (gaseous molecules and aerosols) and other celestial sources (the moon and the stars). These latter celestial sources are negligible with respect to terrestrial illumination or emission factors.

The atmosphere behaves like a secondary source of radiation by virtue of the scattering, reflection, absorption and reemission of primary radiation due to illumination from both celestial and terrestrial sources. Atmospheric radiation can be considerable in the ultra-violet and visible range due to scattering and reflection. Clark has indicated that the contribution of sky radiation at midday is approximately 12.5 percent of the total radiation; in mid-morning and afternoon about 20 percent; and near sunrise and sunset, it is greater than the direct light from the sun (21). The effect of atmospheric radiation can be useful in some areas (e.g., it illuminates the shadows) and detrimental in others (e.g., it adds a general uniform background infrared radiation which tends to equalize overall radiation and decrease or eliminate the differences one is searching for).

Another possible "passive" or natural source of potential value in remote reconnaissance is the natural radioactive emission of various materials. The portion of the spectrum where this is effective is the "gamma ray" region. Analysis of this for a multisensor approach from an airborne platform however is still in the experimental stage (82).

"Active" Sources. "Active" or artificial sources which can be used from an aerial platform and which are applicable to the "windows" or zones of transmission of the atmosphere include cavity resonators for the radar-microwave region, electronic circuits (e.g., oscillating dipole source) for radio-frequency region and "maser" and "laser"¹ energy sources for very narrow regions of the spectrum (26). Except for the radar applications to remote reconnaissance the other "active" sources are in the experimental state (6)(140).

Energy Detectors

Knowing the type of energy sources available for remote reconnaissance and the regions of the spectrum or "windows" where these energy sources will successfully penetrate the atmosphere, methods of recording the energy are required. Energy detectors are needed which are sensitive to the radiation in the desired regions of the spectrum. In addition, energy filters are required which will exclude unwanted radiation to which the detectors are sensitive, while transmitting only the desired range.

Figure 1 indicates the type of detectors which are available throughout the electromagnetic spectrum. At this stage, due to the various reasons previously mentioned, the regions available for sensing include: (1) the near ultraviolet (0.3-0.4 microns); (2) the visible (0.4 to 0.75 microns); (3) portions of the infrared region where "windows" are available; and (4) the radar region.

¹"Maser" - stands for microwave amplification by stimulated emission of radiation. Substitute term "light" for "microwave" and have "laser."

Detectors in Ultraviolet Spectrum. Detectable ultraviolet extends from 0.29 - 0.40 microns. Within this region, less than two percent of the total solar radiation is available compared with approximately 50 percent in the visible region (180). In addition, because Rayleigh scattering has a large effect at these wavelengths, the information content generally received is not as great as in other bands.

Two types of detectors are available for ultraviolet detection. These are, aerial photographic film filtered to exclude everything but the ultraviolet region, and photomultiplier tubes with appropriate filtering. Olson and Cantrell indicate that one problem with the photographic method is that conventional lenses absorb all radiation below about 0.32 microns; thus, requiring replacement by special lenses. Filters such as Wratten 18A and Corning 7-54 are normally used to limit the transmission to 0.40 microns or less (136).

Detectors in Visible Spectrum. Photographic films are the most widely used and most thoroughly developed type of detectors in remote sensing from the air. They have been used for many years dating back to the first photograph taken from a captive balloon by Gaspard Felix Tournachon in 1858 (24). There are many types of aerial films available today. These films cover the spectrum from the near ultraviolet (0.3 microns), through the visible and into the near infrared to about 0.9 microns. In addition to broad coverage, this region can be subdivided into narrow spectral bands by the use of appropriate film-filter combinations. The various types of film and film-filter combinations will be discussed in more detail in the next chapter.

There are several other types of detectors which are sensitive in

the visible region such as photomultipliers, cadmium sulphate and cadmium selenide detectors; however, these are used only in special multisensor equipment and are not too common. They can not duplicate the detail or resolution that can be obtained on normal photographic films. More details on these types of detectors can be obtained in the book by Kruse, et al. (84 - p. 417).

Detectors in Infrared Spectrum. Due to the many absorption bands in the infrared region, detectors have to be selected that have peak response in the regions of atmospheric transmission. The field of detectors in the infrared is very specialized and beyond the scope of this study. The following discussion therefore will be general and limited to the common detectors used in the infrared. More details can be found in references (66) and (84).

Figure 7 shows the range of application of some of the typical detectors used as well as their operating temperatures. The ordinate D^* indicates the detectivity characteristic of the detector in terms of the intrinsic properties of the material of which it is made (66). The detectors normally used in infrared sensing are indium antimonide (InSb) cooled with liquid nitrogen for use in the regions from 2-5.5 μ , and mercury-doped germanium (Ge: Hg) cooled with liquid helium for use in the 8-14 micron wavelength band. Since these detectors have some sensitivity below 3.5 microns, filters are required to eliminate the reflected sunlight if imagery is taken during the day.

Detectors in Radar Spectrum. An "active" source of energy is utilized in the radar spectrum as opposed to "passive" sources which are used in the spectra previously described. The portion of the radar

FIGURE 7. SPECTRAL DETECTIVITIES FOR TYPICAL INFRARED DETECTORS.

spectrum utilized depends on the frequencies or wavelengths generated and transmitted by the radar set. The common frequencies utilized in radar sensors are shown in Table 2.

Table 2. Radar Frequency Bands (172)

Designation	Frequency Limits megacycles	Wavelength cm.
P	225-390	133.3-76.9
L	390-1,550	76.9-19.3
S	1,550-3,900	19.3- 7.69
C	3,900-6,200	7.69- 4.84
X	6,200-10,900	4.84- 2.75
K	10,900-36,000	2.75- 0.83
Q	36,000-46,000	0.83- 0.65
V	46,000-56,000	0.65- 0.54

The detector in a radar system consists essentially of the antenna system; thus the sensitivity or resolution of the final product depends on antenna characteristics. The antenna length determines beamwidth which in turn affects the resolution that can be obtained. It is necessary to employ an extremely long antenna to obtain a very narrow beam in order to refine the detail. The use of long antennas does not lend itself to scanning procedures such as are used in the Plan Position Indicator (PPI) system. In order to use these long antennas they are mounted so they can point to either side of the aircraft and the terrain is scanned in strips. This latter system is called Side-Looking Airborne Radar (SLAR) and is the type most commonly used in recent years for interpretation purposes.

Summary

It is seen from the basic energy considerations that when a photon of any specific energy strikes the boundary of an aggregation of matter, it is either absorbed, emitted, scattered or reflected. These properties are selective with regard to wavelength and are specific for a particular object depending primarily upon its atomic and molecular structure. This concept leads to the possibility of a multisensor approach for the identification of a material, an object, or a target of interest. This type of approach is standard practice in some laboratory analysis of materials. For example, in clay mineralogy various analyses are performed such as electron microscopic study, x-ray diffraction, differential thermal analysis, chemical analysis, and infrared spectrophotometry. The results of these various tests which are essentially measuring different properties of the material are used to identify the material.

The multisensor approach is more difficult to apply from an aerial platform. Remote reconnaissance from the air requires consideration of (1) basic energy properties of the target, (2) the sources of energy available, (3) the effects of the propagating medium between the detector and the target, and (4) the types of detectors and filters available for detecting the object of interest and excluding undesirable information. In addition to the forementioned, there are other factors which make it difficult to apply a multisensor approach to remote reconnaissance from the air. Some of these factors include:

1. The sampling area covered from the air is much larger than for a laboratory specimen; therefore, the problem of homogeneity is more

prevalent. In many cases there is an averaging effect from several materials;

2. In a real environment there is never a perfect absorption-reflection interaction;

3. Determining the spectral composition of emitted radiation is a problem to the observer because, added to the signal that is emitted by the target, there is some radiation contributed by the propagating medium itself. Thus one may have photons of equal energy from different materials returned to the detector and there is no way to separate this information;

4. The intensity of the radiation falling on the detector is a function of the inverse square of the distance along the path from the energy source to the detector (see equation 2.7 page 23). This imposes the requirement for either strong sources, short distances, sensitive detectors, or some compromise of these three factors; and

5. Distortion and degradation of information is introduced by the detection and subsequent display systems.

These five factors tend to degrade the amount and quality of the target information that is obtained and make it more difficult to identify the target. Moreover, it is difficult or impossible to assess the extent to which the information has been degraded by these factors. The multisensor approach, nevertheless, offers a means of identifying certain gross targets of interest and offers some potentials for the remote reconnaissance for detailed soils analysis.

The regions of the electromagnetic spectrum available for remote sensing from an aerial platform are limited by (1) atmospheric

transmission, (2) sensors available for aerial reconnaissance, and (3) availability of suitable detectors and energy filters. A brief description of each band of the electromagnetic spectrum and its potential use follows:

1. Gamma ray - This region is a possible source of information and natural occurring gamma rays from terrain materials are available for passive airborne detectors. Detectors for this region have been developed; however, their use is still in the experimental stage and definite results with the equipment are still to be demonstrated;

2. X-Ray - This region is unavailable at present. The probability is very low for passive x-rays being present from natural radioactive decay or solar induced reradiation. To equip an airborne platform with an active x-ray device would require a lot of power and there would be a large probability of interaction with atmospheric matter;

3. Ultraviolet - There is only a small region available because of atmospheric absorption. Within this available region, there is only a very small percentage of solar radiation available for illumination. Greatly limited by meteorological conditions and limited to daylight hours;

4. Visible - Completely available for passive remote systems. Only limitations are meteorological conditions and generally limited to daylight hours. Under special conditions sensing can be accomplished at night when artificial sources of light are utilized (e.g., flares);

5. Infrared - Absorption by various constituents of the atmosphere limit this region to several "windows". In the "windows" existing below 3.5 microns (e.g., 0.75-1.35 μ , 1.95-2.5 μ ,) one is mainly sensing

reflected sunlight from the target. In the "windows" existing above 3.5 microns (4.4-5.0 μ , 8-14 μ) one is sensing the energy emitted by the target. Various types of detectors are needed depending on the bands being sensed. Aerial cameras and special aerial photographic film can be used up to approximately 0.9 microns. Infrared scanners and special detectors are used above 0.9 microns (e.g., InSb to 5.0 μ , Ge:Hg in 8-14 μ band). Meteorological conditions also limit sensing in this range; however, not limited to daylight conditions.

6. Microwave (Radar) - Completely available for active remote systems. Various frequencies or wavelengths can be utilized in the radar band for sources of energy. The most common radar bands available are X-band and Ka-band. Passive systems in the longer wavelength microwave region are also possible; however, work in this area is mainly in the research stage. Meteorological conditions have a lesser effect in this region, being negligible except for heavy rains and snows;

7. Audio and Radio - Both passive and active sensors are being used in this range. Their use to date has been in special airborne geophysical work where they are used to search for buried mineral deposits (82). Application of these sensors in a multisensor approach has been limited and is in the research stage.

CHAPTER 3

MULTISENSOR APPROACHES AND PREVIOUS INVESTIGATIONS

The apparent similarity of the geometric appearance of imagery obtained from the photographic camera to those obtained from other sensors (e.g., infrared and radar) is striking. This is evident in Figure 8. For example the geometric appearance of the roads, streams and fields have similar geometric shapes on all three sensor images. Because of these similarities, some aerial photographic interpreters are tempted to apply the techniques used for analyzing normal visual photography to interpreting the images obtained by these other sensors. However, if they apply these techniques to interpret items which do not have typical two-dimensional geometric shapes such as soils, vegetative cover, moisture conditions, geology, etc., the interpreters can be grossly misled. This is what would intuitively be expected when one considers the energy relationships and forms of radiation recorded by these various sensors as described in the previous chapter. In the visible region, we are dealing with the reflection of sunlight and skylight from the surface of materials back to the camera (passive sensing system). Infrared sensing generally deals with the reflection characteristics of materials below approximately 3.5 microns or with emission properties of materials above 3.5 microns (also a passive system). Finally, radar deals with the amount of the transmitted signal of given frequency reflected back to the antenna (an active

B & W PHOTOGRAPH

RADAR IMAGERY

INFRARED IMAGERY

FIGURE 8. SIMILARITY OF APPEARANCE OF VARIOUS SENSORS.

system). Each of these sensor systems are reacting in a different portion of the spectrum and therefore are affected by different interactions of matter with energy in these various bands. Thus one would not expect to receive similar results from the same surface in all these regions. This raises the questions as to what extent can the usual aerial photographic interpretation techniques be applied to the interpretation of "imagery" obtained by the other sensors, and what other techniques must be utilized to interpret these images?

An understanding of the basic principles of photo interpretation as applied to visual photography is necessary to evaluate whether the techniques of photo interpretation utilized for visual photography can be used in the other sensor areas. In addition, one must understand the parameters that affect the procurement and interpretation of visual photography as well as the parameters that affect the collection of data in the other sensors. To discuss these various techniques and parameters, this chapter will be divided into four main subdivisions:

1. Photographic Interpretation in the Visible Region;
2. Imagery Interpretation in the Infrared Region;
3. Imagery Interpretation in the Microwave Region; and
4. Multisensor Approach.

In addition to discussing the techniques and parameters affecting each region, a separate review of literature will be made for each of the subdivisions to indicate the accomplishments and latest trends prevalent in each. The literature review will not only include the application of these sensors for interpreting soils, but will include some discussion on the application of these various sensors in the

earth sciences (e.g., agronomy, geology, forestry) as well. These latter reviews are included for two main reasons. First, information on soils is not directly observable on the photography or imagery, but is interpreted by deduction and inference based on the evaluation of certain pattern elements. Therefore, any technique or features observed that increase the interpretability of the pattern elements should also, theoretically, increase the probability of interpreting soils information. Second, the techniques developed for interpreting information in the other fields might be applicable for obtaining information about soils and were included for background information.

One final point with respect to the literature review is that of the terminology encountered. In the literature there is a general confusion in the use of the terms "multiband" systems, "multispectral" systems and "multisensor" systems. These terms are often used interchangeably, but in actuality are often not the same. In this report, "multiband" systems will be limited to those systems sensing several bands of one spectral region, "multispectral" systems are those sensing more than one region of the spectrum, and "multisensor" systems are those using more than one type of sensor to sense various portions of the spectrum. Typical multiband systems are those which utilize multiple cameras or multiple lenses and special film-filter combinations, or multiple detectors or frequencies in order to divide the region being sensed into smaller bands. These are not considered multisensor systems in this report. Multispectral systems may or may not be a multisensor system depending on whether or not one type of sensor is being used to sense more than one region of the spectrum (e.g., use of

photographic films sensitive in the near ultraviolet, the visible, and the near infrared), or two or more different types of sensors are being used to sense different regions of the spectrum. For this report, the former system is not considered a multisensor system while the latter system is considered both a multispectral and multisensor system.

Photographic Interpretation in the Visible Region

The technique of the interpretation of visual aerial photographs for engineering purposes has been adequately described in many reports; for example, Miles (120)(121), Belcher (10)(24, chapt. 6), and Lueder (98). The fundamental assumptions on which the photo interpretation technique is based, are well summarized by Miles, et al. (121,p. 19) and are as follows:

- "a. The aerial photograph is a record of the results of long-time natural and man-made processes which are reflected on the photograph as surface features.
- b. The surface features on the airphoto can be grouped together to form patterns that are characteristic of particular environmental conditions.
- c. The environmental conditions and their reflected airphoto patterns are repetitive; that is, similar environments will produce similar airphoto patterns while different environments will usually produce different patterns."

The application of these basic assumptions is not straightforward but requires judgment, experience and skill on the part of the interpreter in deduction (analysis) and induction (synthesis) in order to make legitimate inferences and predictions from the details seen on the photograph. The detail and quality of information interpreted from a given set of photographs varies among interpreters and depends on their knowledge of the given area, experience and skill.

Specific methods of approach or techniques for interpreting the photograph have been developed. A technique widely used in engineering is based on the study and evaluation of the terrain elements that collectively produce the patterns recognizable on aerial photographs. The pattern elements which are used to evaluate surface and subsurface conditions are: (1) topography; (2) drainage; (3) erosional features; (4) vegetation; (5) photographic tone; and (6) cultural features. Each of these elements are usually studied independently by stereoscopic examination and then by means of converging evidence, the interpreter would arrive at the interpretation of the pattern or images. Since all of these elements are directly interrelated, Miles has proposed a grouping into two basic items: elements of "form" and elements of "tone of gray." Under "form" are considered the elements of topography, drainage and erosion. Items considered under the elements of "tone of gray" include the values and textures (related to land use and vegetation), and the tones (related to materials)(120).

Based on the study of the elements of the aerial photographic pattern and the fundamental assumption previously stated that these photo patterns are repetitive in nature, various basic land forms¹ have been recognized and correlated (e.g., sand dune, alluvial fan, limestone plain, etc...). Because many land forms have typical pattern elements, systematic approaches and keys have been developed to assist in their identification. An example of such a key is included in the

¹Land form. - defined as the repetitive expression of the topography of the earth's surface, including relief and slope, that reflects the geomorphic processes involved in its development as well as the parent material type of which it is composed (120).

report by Belcher, et al.(11). To a limited extent, the systematic approach has made it possible for persons with limited background and experience to identify many land forms and make general interpretations.

Parameters Affecting Interpretation of Visual Photography

The previous paragraphs have generally indicated the importance of the interpreter (i.e., his background, education and skill) in photo interpretation of visual photography. The same situation can be applied to the interpretation of imagery obtained by the other sensors. Removing the factor of the interpreter, that is, assuming qualified interpreters are available for interpretation of the imagery obtained by each of the sensors, it is important to know the effect of other parameters on the interpretation of visual photography.

The parameters that affect the elements of the aerial photographic pattern fall into four main areas. These are:

1. Natural phenomena;
2. Properties of the target material;
3. Characteristics of the collection, processing and viewing systems; and
4. Human factors

The discussion of these parameters will be confined to just those factors that affect the aerial photographic pattern at any given period of time for which photographic coverage may be obtained. It is not the intent here to discuss long term changes that occur due to natural or man-made causes and their effect on the landscape or the aerial photographic pattern obtained.

Natural Phenomena. Included under natural phenomena are the effects of meteorological conditions, climatic conditions, sun altitude and angle, as well as location and topographic position of the target material. A brief description of these factors and their effects on the interpretation of visual photography follows:

(a) Meteorological conditions include haze, clouds, gases, and other aerosols. The effects of these factors were discussed previously under atmospheric transmission (page 10). They determine the ability to obtain interpretable photography; therefore, they affect all the pattern elements.

(b) Climatic conditions such as the presence of different climatic zones and their seasonal influences largely affect the vegetative growth present at any time of year and the moisture conditions of the soil. They influence the elements of tone and culture present on the photographs in any given area and at any given time.

(c) Sun altitude and angle affect the amount of illumination on the target of interest and the amount and type of return (i.e., specular or diffuse) reflected back to the camera. This especially affects the tonal elements.

(d) Location and topographic position of the target material in any given climatic environment can have a significant effect on the final tones, vegetation, and culture present. For example, the same target material located on a dry upper slope will appear different on the photography than if it were located in a low wet area: The low wet area will appear darker. In addition, the vegetation and culture may be different at the two locations and thus result in different patterns on the photography.

Properties of the Target Material. Properties of the target material which affect elements of the aerial photographic pattern include the spectral reflectance properties, the contrast of the target material to its surroundings, and other physical characteristics of the target material. All of these items affect the element of photographic tone and to a lesser degree the appearance of cultural elements.

(a) Spectral reflectance properties are basic properties of the target material based on its molecular makeup and modes of vibration. The amount of reflectance from the surface (or brightness) of the target material depends on the angle of incidence of the light striking the surface and the surface properties of the target. In addition, the spectral reflectance of a target material is not constant but varies with wavelength. Since the wavelength of light in the visible region is small compared to the size of particles it impinges on, the reflected portion is scattered specularly (mirror-like) or diffusely (in all directions) from the surface of the target and does not penetrate. Thus the reflected light returning to the camera indicates only the reflectance properties of the surface of the target and not the subsurface conditions. Figure 9 shows examples of spectral reflectivity curves for several different target materials. This property as well as the type of reflection determines the relative brightness of the tone that one would see in black-and-white photography or the color of the target as it would appear in color photography.

(b) Contrast of the target material to its surroundings affects its interpretability. The degree of contrast that appears on the final photograph not only depends on the previously mentioned spectral

FIGURE 9. TYPICAL SPECTRAL REFLECTIVITY CURVES.

reflectance properties of the target and the surroundings but also on the size of the target, the ability of the camera, film and processing system to reproduce differences in tone, the scale of the photography, the degree of magnification on viewing, and the capabilities of the human eye in differentiating slight tonal changes on the photograph.

(c) Physical characteristics of the target which affect the elements seen on the photograph include the uniformity or variability of the target material, and the texture of the target material. The uniformity or variability of the target material, for example soils or vegetative cover, will affect the final tonal rendition on the photograph. Uniform target materials (where all other factors are the same) have uniform tones on the photograph while variable materials have variable tones. The same effect would apply to the texture of the target material (i.e., texture of soil, texture of leaves, texture of surface of object, etc...). Variations in texture between target material and surroundings are observed as variations in photo elements because of the difference in response of the various textures to radiation, moisture conditions and cultural practices.

Characteristics of Collection, Processing and Viewing Systems. Included in this group are the characteristics of the camera-carrying vehicle, the camera, the film-filter combination, the scale of the photography, processing effects and viewing systems.

(a) Camera-carrying vehicle factors include vehicle speed, altitude, vibration and rotational stability. The combination of vehicle speed, altitude and camera characteristics are significant factors in the origin of image motion which produces blurring of the target and

decreases the interpretability of the target. Vibration of the vehicle during exposure can greatly limit the quality of the photographic image; however, with present day stabilizers this is no longer a critical problem. Rotational instability covers the effects of roll, pitch and yaw deviations from straight line flight. This effect is not as critical as in photogrammetry; however, it will affect the ability of the interpreter to properly orient the photographs for interpretation purposes. These factors affect the image quality of the photograph; therefore, affecting all the elements of the aerial photographic pattern.

(b) Camera characteristics of importance include the focal length, the lens characteristics and format dimensions. The focal length of the camera together with the flight altitude determine the scale of the photography. Focal length is also an important factor in vertical exaggeration of relief. At a given scale of photography, the shorter the focal length, the greater is the vertical exaggeration of relief: an important factor in aerial photographic interpretation. Lens characteristics of importance include the quality of the lens and its correction for the different distortions (e.g., spherical aberration, coma, astigmatism, chromatic aberration, etc...). These factors affect the resolution or amount of detail obtained on the film and the uniformity of light distribution over the whole photograph. The speed of the lens (i.e., the largest lens opening that can be obtained) is an important consideration in determining the exposure. Format dimensions determine the area covered per photograph; therefore, the number of photographs needed to cover a given area.

(c) Scale of the photography is controlled by the altitude of

the aircraft and the focal length of the camera. The scale affects the area of coverage per print as well as the amount of minute detail that can be interpreted. This in turn can affect the interpretability of all elements of the aerial photographic pattern.

(d) Film-filter considerations include the spectral sensitivity, speed, and graininess of the film, spectral transmission of the filter, the spectral reflectivity of the targets of interest and the scattering effect of the atmosphere. The choice of a film-filter combination for any project is actually a compromise of the above factors. Faster films are usually desired because they allow smaller aperture openings which give better overall light distribution. Faster films are more grainy and result in decreased resolution or detail that can be recorded. A film-filter combination is selected so as to give maximum response in the area of the spectrum where the targets of interest have maximum reflectivity. Special filters are used to reduce or eliminate the region of the spectrum where haze is more prevalent (blue portion of the spectrum). This increases the quality and detail of images obtained. Figure 10 shows the spectral sensitivity of some typical aerial films. The choice of proper film-filter combinations can "enhance" or increase the contrast between the target of interest and its surroundings and make it easier to identify and interpret. This feature is effective in increasing the interpretability of all the photo elements, especially the photographic tonal contrast.

(e) Exposure that a film requires is dependent mainly on the amount of light which finally reaches the film and the speed of shutter required to keep image motion to a minimum. Many of the factors which

(a) TYPICAL BLACK-AND-WHITE FILMS

(b) TYPICAL COLOR FILMS

After KODAK Data Sheets (39)(40)

FIGURE 10. SPECTRAL SENSITIVITIES OF TYPICAL AERIAL FILMS.

affect this have already been discussed such as speed of aircraft, altitude, amount of light present, contrast or brightness range of subject, the speed of the photographic film, and type and number of filters placed in front of lens. Also of importance is the aspect angle between the camera and the target. This also affects the amount of illumination received. Improper selection of exposure can drastically affect interpretability of all the photo elements on the photograph. The presence of image motion blurs the photographic images and decreases interpretability. Overexposed or underexposed film cause the loss of considerable detail on the photograph and decreases interpretability.

(f) Processing factors such as developing time, temperature and type of developer, length of exposure, spectral characteristics of light source, type of paper used and method of printing cause wide variations in the final photograph. Any large errors in exposure of the film can not be corrected; however, slightly overexposed or underexposed film can be corrected in the printing process. Figure 11 shows the influence of various processing factors on the final density of the photograph. As can be seen with the same range in exposure, a large variation in density can be obtained. Further variations in density from the original film to the final print can be induced by addition of special chemicals (e.g., reducers, intensifiers); however, this is beyond the scope of normal photographic processing of aerial film and will not be pursued any further. More details on this can be found in the book by Mees (112). In correcting for improper exposures, automatic dodging equipment may be used. This produces prints with a more normal range of tones, but in the process, there may be a loss of information.

(a) VARIATION DUE TO
DEVELOPING TIME

(b) VARIATION DUE TO
TYPE OF DEVELOPER

(c) VARIATION DUE TO
TYPE OF PAPER USED

(d) VARIATION DUE TO
GRADE OF PAPER USED

After KODAK Data Sheets (39)(41)

FIGURE II. INFLUENCE OF VARIOUS PROCESSING
FACTORS ON FINAL PHOTOGRAPHIC
DENSITY.

Extreme tonal variations which are present on the negative due to certain special conditions of reflectivity of target materials at the time of exposure may be subdued in the printing process causing the loss of the absolute tonal differences between the objects. In printing color photographs, the proper selection of light source is important to insure that the light source of the printer will cover the spectral range exposed on the film. The photo element most affected by the processing factors is the photographic tone.

(g) Viewing system's ability to increase the interpretability of the photographs depends on the amount of magnification possible by the viewing system, the type of film viewed, and the original scale of the photography. The amount of magnification possible would depend on the type of viewer available. For example, the type of viewers available vary from the simple lens stereoscopes with a 2x or 4x magnification factor to the zoom type stereoscopes with a 2.5x to 40x magnification factor. The ability to magnify the photograph increases the interpretability of certain targets up to a point. This point is determined by the graininess of the photograph viewed, and the original scale of the photograph. This relationship is not linear, that is, a twofold increase in magnification does not increase interpretability two times. The type of film viewed is important as some film types are more grainy than others and therefore can not be enlarged as much.

Human Factors. Beside the factors of background, experience and skill previously discussed, human factors include the stereoscopic acuity of the interpreter and his color perception. Other factors of consequence which are a function of the physiological state of the

individual include stimulants, fatigue, mental depression, distracting noises, unsatisfactory illumination, uncomfortable viewing position and improper humidity and ventilation of work area (173). The effect of these physiological factors are difficult to evaluate but can be controlled and will not be considered further in this discussion.

(a) Stereoscopic acuity of the interpreter is largely a function of binocular vision capabilities and the presence of eye defects or deficiencies such as astigmatism, presbyopia, anisometropia and heterophonia (173).² The capability of binocular vision is an absolute necessity in photo interpretation. There is also variability among individuals with binocular vision in their depth-perception and visual acuity (ability to distinguish fine details) and thus their stereoscopic vision capabilities. Stereoscopic capabilities are necessary for the evaluation of the topographic element; especially the determination of micro-features. It is also of great assistance in the study of the drainage and erosion elements as well as evaluation of cultural elements.

(b) Color perception is of no consequence in the normal interpretation of black-and-white aerial photographs; however, it is a critical factor in the study of color aerial photography. Color blind individuals are limited when studying color photography.

²"Astigmatism" - rays from a single point of an object fail to meet in a single focal plane.

"Presbyopia" - difficulty of accommodation and recession of the near point of vision.

"Anisometropia" - unequal refractive power in the two eyes.

"Heterophoria" - insufficient action of one or more of the three pairs of eye muscles so that one eye tends to deviate from the correct direction.(173, p.518)

Summary of Parameters. The number of parameters affecting the acquisition of visual aerial photography are numerous. In the discussion of these parameters, it has been noted that some parameters influence all the interpretation elements while others influence only certain elements. The main effects of these various parameters on the photo elements are summarized in Table 3. The subdivision of the elements of the aerial photographic pattern used is that proposed by Miles (120).³ Table 3 indicates that almost all the parameters affect the element of tone and texture; a very important element in the evaluation of engineering soils.

Recent Approaches in the Evaluation of Aerial Photography

The previous discussion on the various parameters and their influence on the interpretation elements indicates the importance of controlling or evaluating some of the parameters in the procurement and interpretation of aerial photography. Until recently, aerial photographic interpreters have had little or no control over the planning or procurement of the aerial photographic coverage needed for their projects and very few were able to obtain aerial photography flown specifically for their projects. The interpreters had to utilize the existing black-and-white aerial photography flown for the U.S. Department of Agriculture, the U.S. Geological Survey, or other agencies who made their photography available (1) (179). This factor limited the amount of information

³The subdivisions shown in Table 3 are based on the system discussed by Professor Miles in his course at Purdue University, CE 567 "Engineering Uses of Aerial Photography." It is an elaboration of the basic system mentioned in his paper, "A Concept of Land Forms, Parent Materials, and Soils in Airphoto Interpretation Studies for Engineering Purposes" (120).

Table 3. Major Effects of Parameters on Interpretation Elements of the Aerial Photographic Pattern

Parameter	Elements of Form ³			Elements of Tone and Texture ³		
	Topography	Drainage	Erosion	Soils and Rocks	Culture	Vegetation
Natural Phenomena						
Meteorological conditions	X	X	X	X	X	X
Climatic Conditions	-	-	-	X	X	X
Sun altitude and angle	-	-	-	X	X	X
Location and topographic position	X	X	X	X	X	X
Properties of Target						
Reflectance properties	-	-	-	X	X	X
Contrast with surroundings	-	-	-	X	X	X
Uniformity and texture	-	-	-	X	X	X
Collection, Processing and Viewing System						
Camera-carrying vehicle	X	X	X	X	X	X
Camera	X	X	X	X	X	X
Scale of photography	X	-	X	X	X	X
Film-filter combination	-	-	-	X	X	X
Exposure	X	X	X	X	X	X
Processing	-	-	-	X	X	X
Viewing	X	-	X	X	X	X
Human Factors						
Stereoscopic capabilities	X	X	X	-	X	-
Color perception	-	-	-	X	X	X

that the interpreter was able to extract from the photography, without field checking.

In recent years, interpreters in several disciplines have attempted various approaches in an effort to evaluate or control more of the parameters affecting the aerial photography. These efforts have been directed towards increasing the amount of information that could be extracted from the photography and decreasing the amount of field checking required. Some of the approaches utilized include:

1. Study of color photography;
2. Spectral reflectance studies of the target materials;
3. Selection of special film-filter combinations;
4. Spectrazonal studies;
5. Image enhancement;
6. Measurement of certain parameters at time of flight;
7. Efforts to quantitize information on photo elements.

Methods of investigating these approaches have not been confined solely to aerial surveys, but have included the study of the problem in the laboratory under controlled conditions and the study of the problem on the ground. The method of investigation will be indicated in the review of these approaches since it has a direct bearing on the type of results obtained and its applicability to aerial survey methods.

Study of Color Photography. Numerous investigations utilizing color aerial photography of all types (e.g., color positive transparencies, color negative, color-infrared) have been performed by various groups in different disciplines. In all studies, color photography was

compared to the normally used black-and-white panchromatic photography and in some cases to other types, such as black-and-white infrared photography.

Several investigators have reported on the use of color photography for soils and materials studies. Chaves and Schuster (20) utilized color photography in the location of sources of construction materials in Yellowstone National Park in Wyoming. The author assisted in a portion of this survey and noted the value of the color photography in not only locating the source of material but also in indicating to some degree the predominant minerals present in the deposit (e.g., obsidian sands, siliceous sinter or heterogeneous glacial gravels and sands). This factor was useful in that it made it possible to evaluate the deposits further as to their suitability for construction purposes. A similar indication of the possibility of separating deposits of different mineral compositions was reported by Minard (123) who showed that sand deposits of two different geologic ages could readily be separated by their color tones on the color photography. Other reports in this area include the work done by Ohio State University (133), U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) (177) and the work by Stallard and Biege (165). In the Ohio study it was indicated that color aerial photography was valuable in delineating earth slumps and differentiating the lithology of earth slopes. The report by CRREL concluded that the infrared-color aerial photography was superior for bounding water areas and differentiating clear water versus water laden with silts. The work by Stallard and Biege found color aerial photography valuable in certain phases of road condition surveys, and

material surveys and concluded that color photography was most useful in areas where the detection and mapping of material source were dependent on tonal patterns.

In other areas of engineering the advantages of color photography have been similarly demonstrated. In mapping of coastal waters by the U.S. Coast and Geodetic Survey, Smith (163) has indicated that by using color photography, navigational aids such as lights, beacons and buoys which could not be distinguished on black-and-white photography could readily be distinguished on color photography; thus, decreasing the amount of ground surveys needed. He also indicated that with color photography, underwater formations could be interpreted down to depths of 60 to 70 feet in the Caribbean. This is much greater than depths of penetration reported for black-and-white photography. Strandberg (167) has indicated that both natural and infrared-color aerial photography are very valuable for water quality analysis. Infrared color photographs were used to evaluate such factors as the operating efficiency of trickling filters in sewage plants. Color photographs were used to note the location of pollutant effluents, an indication of dissolved oxygen levels in the streams and the location of sulfuric acid drainage areas.

Several researchers have reported on studies in the use of color photography in the field of pedology (soil science). Dominguez (24, chapt. 5, Append. A) indicated in his mapping project of a wildland area in California that color photography showed superiority over black-and-white photography in instances where soil or vegetation colors were of primary importance in identifying the soil boundaries. Simakova (159),

in mapping pedologic soils in the Caspian lowlands in Russia similarly indicated the desirability of the use of color photography for soil scientists because of the high interpretive quality of the photographs obtained.

In the field of Geology, Fischer (48)(24,pages 293-294) has shown specific examples of how color photography assisted in differentiating bedrock of different lithology which were indistinguishable on black-and-white photography. Steiner (166) reports similar conclusions were indicated by Russian scientists.

Extensive studies of color photography have been reported in the fields of forestry and botany. Heller, et al.(59) has shown statistically that the accuracies in the interpretation of various individual tree species were significantly higher on color photography than on comparable panchromatic film. Steiner in his review of aerial photographic interpretation in the Soviet Union has indicated that results of studies by several researchers in the Soviet Union have shown the superiority of color film for such factors as separation of deciduous and coniferous trees with greater accuracy, observation of details in the understory vegetation and indicating areas of dead trees and wind damaged stands. Significant advantages have also been noted for the use of color-infrared films and the two layer spectrazonal films used in U.S.S.R. (166). Living vegetation having a higher reflectance in the photographic infrared region (0.75μ to 1.0μ) appears as "red" on the infrared color film, and in most cases appears in the red color family on the spectrazonal film. These red or reddish tones make it very easy to differentiate the living vegetation. This feature has influenced

several investigators to indicate a preference for this type to all others for mapping vegetated areas and distinguishing dead vegetation from living vegetation (4),(177),(119). Other spectacular results which are distinct on the infrared-color and spectrazonal photography include the identification at an early age of the presence of diseased crops and trees [Colwell (23)], surveying areas infected by the Siberian silk-moth [Steiner (166)], and imaging algae present at some depth below the surface of the water [Strandberg (167)]. Some of these features are noticeable on black-and-white infrared photography but are not as distinct.

Reports by several other researchers (9),(25),(105),(170) have compared color photography to black-and-white photography as well as comparing different types of color photography. These investigators merely listed the advantages and disadvantages of these various films.

The general advantages of the use of color photography over black-and-white photography for photo interpretation purposes; other than the specific examples already mentioned include:

1. All reports in all disciplines indicated that it was easier and faster to interpret color aerial photography because of the natural appearance of the objects; that is, a much more positive identification could be made. This was especially valuable to inexperienced interpreters who could more easily recognize an object when it appeared in its natural color than in a shade of gray,

2. Many objects or targets which have the same tones in black-and-white photography are distinctly different in color photography;

3. Differences in contrast between the target and the background

are greater on color photography than on black-and-white photography because of the larger number of color tones reproduced on the color photography. The presence of greater contrast leads to greater probability of identification. This factor is shown in Figure 12 which is based on the work of Blackwell (13). This curve shows the probability of detecting a small, light-toned circular stimulus as a function of the contrast between that stimulus and the illuminated viewing screen upon which the stimulus is cast. Thus a slight increase in relative contrast of objects can greatly increase the probability of picking out the object from its background. This would explain why it was possible to identify the lights, signals and buoys on color photography but not on the black-and-white photography in the example reported by Smith (163);

4. The three layers and two layers present on the color and spectrazonal films respectively offer the opportunity for color enhancement and selective printing to emphasize the differences between various targets of interest;

5. Color film has a relatively fine grain therefore can be magnified more without serious loss of detail.

The major disadvantages and limitations of color photography mentioned in the literature include the following:

1. The cost of color photography has been stated by many investigators as the main limiting factor in its use. Estimates of costs in comparison to conventional black-and-white photography has ranged from 10 to 30 percent more to as great as 3 to 5 times as much. The variation in figures depends on whether one is comparing the additional cost based on the overall project cost (the former estimate) or whether one

After BLACKWELL (13)

FIGURE 12. PROBABILITY OF DETECTION VERSUS RELATIVE CONTRAST.

compares just the direct cost of film, processing and printing (the latter estimate). Since the largest factor in the cost of aerial photography is the cost of operating the aircraft it would seem that the only reasonable way to make a comparison is based on the overall costs;

2. Exposure latitude is more restrictive in color film which may on occasion cause difficulties in obtaining proper exposures in a high contrasting landscape. Overexposure causes a washing out of the colors and a loss of details; while underexposure results in loss of details in the shadows and darker colored areas;

3. Investigators have indicated that more limited exposure latitude available would further limit the amount of flying time available during the year and during the day below that normally acceptable for black-and-white photography. An additional factor affected by flying conditions is that color films are very susceptible to haze effects as altitude above the terrain increases (i.e., obtain an overall bluish color tint). This is not a problem at lower altitudes. Swanson (170) of the U.S. Coast and Geodetic Survey has commented on this item and states:

"Experience indicates that when cloud and aerial haze conditions are satisfactory for panchromatic aerial photography they are also satisfactory for color photography. There is a relatively rare marginal haze condition under which more satisfactory photography can be taken through the use of the standard yellow or minus-blue filter generally used for panchromatic photography. However, if this same filter is used for color photography under the same meteorological conditions, minus-blue or two-color aerial photography will be produced which is superior to panchromatic photography both in ground resolution and interpretability."

4. Color balance and quality of the color film vary from one lot to another. Even with the close controls practiced in manufacture,

color films will vary because of the complex interactions between the three emulsion layers. The film manufacturers generally recommend or provide the specific corrective filters required for best possible color balance;

5. Color requires closer control during processing, more costly chemicals, and the need for more complicated handling procedures;

6. It has been indicated by several investigators that the lack of true color reproductions of the objects was a limitation. No film made today can truly reproduce the natural colors occurring in nature (81),(170); but this should not be considered a limitation. The tones on color photographs are certainly closer to the true colors than the shades of gray shown on black-and-white photography;

7. Color film storage requirements are more critical than for black-and-white. In addition, although the dyes used in color film are the best available, their color permanence cannot be warranted; thus they are susceptible to change with time. Also condensation on the transparency may encourage fungus growth on the gelatin layers (9).

8. If the type of color film used is a reversal type then one is faced with the need of special viewing equipment in the office and field to view the color transparency. The light source on the viewing equipment has to produce light covering the full spectrum. This generally is not as great a problem in the office as in the field. The need to carry a portable light source around greatly hampers maneuverability in the field. Also since the transparency is the only print, any loss of or damage to a transparency would be very unfortunate since it could not be replaced. To make color prints from the transparency for field

use is very costly.

9. Color film is not as readily available as ordinary panchromatic films as the manufacturers do not maintain as great a stock.

In the discussion of limitations it was assumed that a suitable camera was available for the flights; that is one with a color corrected distortion free lens. If a suitable camera is not available this would also be a limitation on the quality of the photographs obtained.

In sundry discourses on the use of color photography various comparisons have also been made on the advantages and limitations of using color reversal film versus color negative film (107),(184). Table 4 summarizes the comparison of both types of films.

Spectral Reflectance Studies of Target Materials. The efforts of researchers in this area are twofold. First, they are attempting to use the spectral reflectance information of target materials to plan systems or flight programs to enhance the contrast between the target material of interest and the background. Second, they are attempting to explain by means of spectral reflectance data what tones or colors a particular material will have on the photograph as well as to obtain a "signature" for the target material in question; that is, particular wavelengths in the spectrum that are diagnostic for the particular material.

The spectral reflectance studies of natural objects by researchers are not limited to the visual spectrum alone. Since solar radiation irradiates the surface from approximately 0.3 to 3.5 microns (Figure 6 page 24) and systems are available which can sense energy in this region, some investigators have collected spectral reflectance data into the near infrared regions in addition to the visible.

Table 4. Comparison of Reversal Color and Color Negative Films (107)(184)

Process	Reversal Type	Color Negative Type
Exposure	<ol style="list-style-type: none"> 1. Proper filters must be chosen at time of flight to correct for color balance, vignetting effect and haze conditions. 2. Faster film speeds available. 	<ol style="list-style-type: none"> 1. Larger exposure latitude as filters for color correction and vignetting not necessary during flight. 2. Films presently available not as fast as the reversal types.
Processing	<ol style="list-style-type: none"> 1. Process directly into a positive film thus laboratory procedures simpler and less costly. 2. Can view the transparency directly to see natural colors. No additional processing necessary. 3. Limited ability to correct for improper exposure. 	<ol style="list-style-type: none"> 1. Can correct for errors in exposure as well as correct color balance and vignetting effect. 2. Do not obtain a positive from the film during processing. Need additional processing to obtain a positive for viewing; therefore, more costly.
Reproduction	<ol style="list-style-type: none"> 1. Since processing produces a positive it is not necessary to make prints. Resolution of transparency greater than that of copies made from color negative or the transparency itself. 2. Since the transparency is the only copy available it is usually desirable to make copies for field use. Cost of prints from transparencies more expensive than from color negatives. 3. Has a narrower range for color adjustments. 	<ol style="list-style-type: none"> 1. More flexible. Either color prints, diapositives or black-and-white prints can be made from the color negatives. 2. Cost of color prints less than from reversal type. 3. Adjustment of color tones can be accomplished during printing. 4. After use, negatives can be safely stored.

In order to be able to properly evaluate the spectral reflectance data reported in the literature and see how it can be applied, an understanding of the parameters affecting the spectral reflectance data obtained is necessary. Many of the parameters which affect the final tones on the aerial photograph (Table 3 page 55) are equally important in obtaining the spectral reflectance properties of target materials; however, since this information is largely obtained by means of spectrophotometers, the parameters previously mentioned for collection, processing and viewing, and human factors in general do not apply. The parameters of natural phenomena, and properties of the target material certainly apply. In addition the relationship of aspect angle of the measuring instrument to the target and the properties of the instrument itself are important. The general effects of natural phenomena and properties of the target material were briefly discussed previously. However, to fully understand the effects of these two parameters on the spectral reflectance properties of the target material, a more complete discussion is needed.

The properties of the target material include its composition, surface roughness, structure, uniformity and variation of composition with time. These properties are important in the effect they have on the spectral reflectance of the material. The basic spectral reflectance curve obtained is largely controlled by the composition of the material; that is, the curve will display characteristic regions where energy reaching the material will be absorbed, reflected, emitted and scattered. This factor is demonstrated by the spectral reflectance curve shown in Figure 13 which is typical for many common leaves. In

the visible region it is noted that there is a peak in the green range (0.55μ) due to high reflection from the chloroplasts in the leaf while there is little reflection in the blue and red region because light in these regions is largely absorbed by chloroplasts and used in photosynthesis. In the photographic infrared region however, there is a much larger reflection because the solar energy is highly reflected by the spongy mesophyll within the leaf (28).

Although the composition of the target material is important in determining the spectral reflectance curve, spectral reflectance characteristics are further modified by other factors such as surface roughness, structure and uniformity. The wavelength of light in the visible and near infrared region is small in comparison to the size of the particles encountered and is scattered by the surface layer. Penetration is practically negligible, a matter of several angstroms in the visible to tens of microns in the infrared except in the case of water where in the visible range penetration is deeper (5). Therefore, the surface configuration or roughness is important in the type of reflection that results. If the surface is smooth (e.g., a water surface) it will reflect light specularly (mirror-like), while if it is rough (e.g., sands) it will reflect the light diffusely (equally in all directions). Most materials in nature have a mixed reflection; that is they have both diffuse and specular components. This aspect is best illustrated by preparation of an indicatrix of diffusion⁴ for the target

⁴Indicatrix of diffusion represents graphically in the form of polar diagrams the radius vectors corresponding to the amounts of energy reflected in each direction. The nature of the indicatrix of diffusion depends on the angle of incidence of the light flux and on the angle at which the instrument for registering the reflected light flux is positioned (150).

material. Figure 14 shows typical indicatrices of diffusion. The arrow indicates the position of the photometer for registration of the reflected light flux and the various angles shown indicate the variation in angle of incidence of the light flux. Figure 14a shows the indicatrix of diffusion for a material of predominantly diffuse reflection; Figure 14b that for a material of predominantly specular reflection; and Figure 14c that characteristic for most common materials which have some degree of both. The importance of this factor is that the amount of reflection obtained from the target material will thus depend not only on its composition but also on the nature of its surface roughness and the viewing angle.

The uniformity of the target material, its size and structure on a macro scale can also have a significant effect on the spectral reflectance properties. For example, in laboratory measurements on samples, the field of view is very small and the area studied is in the order of one inch square. In field measurements, the field of view is much larger and measurements are from sample areas in the order of one to tens of square feet. Spectral reflectance measurements from the air, involve target areas, possibly hundreds of square feet or more in size. One should not expect to obtain similar reflectance properties for a target material from viewing a small sample in the laboratory to viewing an extensive area composed of this material from the air unless the material was very uniform in composition, texture and overall macro structure. This occurrence is not normally encountered in nature. Figure 15 shows reflectance curves for a typical fir leaf measured in the laboratory (113), a coniferous forest (fir) viewed from the ground

FIGURE 13. EFFECT OF PROPERTIES OF TARGET MATERIAL ON SPECTRAL REFLECTANCE OBTAINED.

FIGURE 14. TYPICAL EXAMPLES OF INDICATRICES OF DIFFUSION FOR VARIOUS MATERIALS.

and a coniferous forest (fir) viewed from the air (83). The values shown are relative as the intent is only to show the trend. There is less total reflectance obtained from the air, as included in the field of view are the leaves, the branch structure and shadows. These items are not included in laboratory measurements.

In addition to the above factors, spectral reflectance characteristics of the target material are also influenced by changes in the composition of the target material with time. For example, the reflectance properties of trees would vary with the season and those of soils would vary with moisture content. Figure 16 shows some typical spectral reflectance curves indicating the effects of variation of composition of the target material with season (Figure 16a) and with moisture content (Figure 16b). The effect of moisture is to make the material act like a diffusely reflecting material of low reflectance; however, when moisture content reaches the point where free water is on the surface, then it acts as a specular material.

Natural phenomena which influence spectral reflectance properties include angle of incidence of the sun, presence of haze, clouds and other particles, and climatic conditions. The influence of the angle of incidence of the sun can have as great or greater an effect on the spectral reflectance characteristics obtained for a target material as the effect of the properties of the target material itself. Figure 17 indicates the influence of the angle of incidence of the sun on the spectral reflectance curves for two materials. Measurements were made on samples under field conditions and taken from the same position at different times of the day (150). The angle of incidence of the sun has

FIGURE 15. EFFECT OF TYPE OF MEASUREMENT ON SPECTRAL REFLECTANCE.

(a) EFFECT OF SEASON

(b) EFFECT OF MOISTURE

FIGURE 16. EFFECT OF VARIATION OF COMPOSITION OF TARGET MATERIAL ON SPECTRAL REFLECTANCE.

little effect on diffusely reflecting materials, such as the loose sand; however, it can be quite a significant factor for specular materials or materials with significant specular components such as the carbonate sandstone sample. This factor would also be readily apparent on the indicatrices of diffusion such as those shown in Figure 14.

Dust, haze and other particles in the air have practically no effect on the spectral reflectance at low altitudes but at higher altitudes they will attenuate the amount of solar energy irradiating the target in the visible and photographic infrared region. Haze, which causes more scatter in the blue region of the spectrum than the other regions can cause some change in the spectral reflectance characteristics of the target material which reaches the spectrophotometer. Clouds, however, can greatly change the spectral reflectance curve of the target material and this change would be erratic, changing only where the clouds or cloud shadows cover the target material. Figure 18 shows the effect of difference in amount of cloud cover on spectral reflectance properties.

The effect of aspect angle, the third main area affecting the spectral reflectance information obtained from the target material is somewhat similar to the effect of angle of incidence of the sun and can have just as great an influence. For a given position of the sun, the amount of light reflected from the material would depend on the properties of the material and the angle of viewing. This effect is quite frequently noticeable on adjacent photographs. On one photograph a field looks light and the next photograph the same field looks dark. This result is not due to change of angle of incidence of the sun, but

FIGURE 17. EFFECT OF ANGLE OF INCIDENCE OF SUN ON SPECTRAL REFLECTANCE.

FIGURE 18. EFFECT OF CLOUD COVER ON SPECTRAL REFLECTANCE.

due to a different aspect angle. For a diffusely reflecting material on a flat surface there would be little to no change of reflectance properties due to aspect angle. However, aspect angle is very critical for specular and partially specular materials and for diffuse materials with rough textured surfaces or varying surface configurations where shadows are present. This factor is illustrated in Figure 19 where for a diffusely reflecting material with considerable macro relief there is a change in spectral reflectance as the aspect angle is changed. No figure is shown to indicate the difference in spectral reflectance for specular materials with different aspect angles but a large difference would naturally be expected. This effect is often evident on adjacent photographs containing the same body of clear water. On one photograph it appears dark (low reflectance) and on the adjacent one it appears light (high reflectance) because the aspect angle is proper to obtain specular reflections.

The parameters of the instrument can also cause some variations in the spectral reflectance curves obtained for a given material. In measurements made over the years various spectrographs and spectrophotometers have been utilized by various researchers both in the laboratory, in the field and from the air. Not all were of the same accuracy or covered the same spectral range. With spectrograms, photographic plates are used and the information is obtained in the form of differences in densities on the film. Therefore, variables due to exposure time, photographic materials, processing, densitometric readings and reduction of data all can affect the final spectral reflectance curve obtained. With spectrophotometers there are possible variations or errors due to

FIGURE 19. EFFECT OF ASPECT ANGLE ON SPECTRAL REFLECTANCE.

maladjustment of the instrument such as inaccuracies in wavelength scale, zero and 100 percent scale points, slit width, stray energy errors and inertia errors (78). With both types of instruments there is the need for proper checking of calibration against a known source (primary source usually magnesium oxide). Taking these factors into account and with proper calibration of these instruments and care in reduction of data, reliable readings can be obtained.

Due to the many parameters affecting the spectral reflectance characteristics of a given target material, it would be exceedingly difficult to obtain spectral signatures for materials so that they can be positively identified from aerial spectral curves or on aerial photography. It does not seem likely that this goal can be achieved by spectral measurements made in the laboratory or on the ground in situ and only partial success would be expected by measurements from the air. The application of spectral reflectance data to planning flight programs to enhance the contrast between the target of interest and the background is more encouraging since absolute data is not necessary. Only information on relative differences is needed. For this application, aerial spectral measurements are desirable; however, significant trends can be obtained from ground measurements and in some cases from laboratory measurements. Care has to be used in applying these data and some consideration should be given to those parameters which affect the spectral reflectance properties but which were not accounted for in the measurements.

Extensive collections of spectral reflectance curves have been obtained over the past thirty or more years. The majority of these were

measurements of vegetation. Very little has been done on spectral reflectance measurements of soils. Aerial spectral reflectance data have been reported by Romanova (150), Krinov (83), and Schimpf and Aschenbrenner (156). Romanova was successful in performing an aeropetrographic survey in the Northwestern Caspian region where she mapped sand deposits of different mineralogical composition. This was accomplished by statistically correlating the characteristic aerial spectral reflectance curves and results of laboratory measurements of the samples obtained from the various deposits. This is the only published report that the author is aware of where a diagnostic signature for a particular material was obtained and successfully utilized to identify the target material. This was obtained however under very restrictive conditions which included measuring the spectral reflectance properties of diffusely reflecting materials on essentially a horizontal surface (top of barchan dunes) in a desert environment between the hours of 10:00 AM and 2:00 PM on a clear day taken from a very low altitude (10-20 meters) and a chosen flight direction to avoid shadows from the plane. In addition, three points were chosen for study for each sand type and the average spectral reflection curve for these points were used (150). It is evident that in the choice of target material, location, time and altitude, many of the parameters which could cause variations in spectral return were negated (e.g., effect of angle of incidence, aspect angle, aerosols, clouds, etc...). Even with many of the parameters essentially controlled, extensive sampling and statistical analysis of the data were necessary. This report indicates the possibilities of obtaining diagnostic spectral reflectance data for

certain target materials.

Penndorf (141) made a comparison of the aerial spectral reflectance data obtained by Krinov and Schimpf and Aschenbrenner to ground measurements made by Krinov of a similar target material. These curves are reproduced in Figure 20. It is interesting to note that spectral curves of a similar target material obtained by two different investigators in different areas taken at different altitudes and made years apart have a somewhat similar appearance. The effect of target composition uniformity and structure are also evident in this figure. The spectral reflectance curves obtained from the ground and the air are somewhat similar for the meadow which has a more uniform texture and structure than for the fir forest whose texture and structure change significantly depending on the aspect angles measured from. However, if the curves for the meadows were analyzed by the technique used by Romanova, they would also be significantly different. This example offers some encouragement in indicating that ground measurements, under certain conditions, can be used to estimate the aerial reflectance characteristic of a target material.

Extensive field measurements of materials in situ have been made by Krinov (83) and the U.S. Army Research and Development Laboratories (139). Krinov had also made considerable measurements in the laboratory as have Keegan et al. of the National Bureau of Standards (74)(76) and Olson (134). Krinov made extensive measurements during the periods 1932 to 1937 and again in 1942. Using various spectrographs, he made a total of 10,316 measurements, over nine thousand of which were field measurements taken in the region 0.4 to 0.65 microns. He also made a limited

FIGURE 20. COMPARISON OF RESULTS BY DIFFERENT INVESTIGATORS FOR SIMILAR TARGETS.

number of infrared field measurements (total of 218) in the region 0.7 to 0.9 microns. His field measurements utilized solar radiation for the illumination of the target materials. The U.S. Engineer Research and Development Laboratory (ERDL), in their field measurements, used artificial light instead of solar radiation to irradiate the test site. They used a field spectrophotometer covering the range 0.25 to 2.0 microns in two bands. Spectral reflection properties of target materials were measured in situ at various locations within the United States. Instrument stability was greatly influenced by temperature conditions; therefore, most of their measurements were made in early morning or late evening. Both Krinov and ERDL reported only the data they collected. No attempt was made to evaluate or draw conclusions from the data as to spectral signatures for different materials or to predict tones or colors of objects on photographs.

The National Bureau of Standards performed a series of laboratory spectral reflectance studies on various natural and man-made objects and color film transparencies taken of these objects. Their data were collected on a recording spectrophotometer and covered the range from 0.4 microns to 1.06 microns in two bands. By comparing spectral reflectance curves for the natural objects and for color film transparencies of the objects, they concluded that the spectral reflectance curves and colors of the objects as they appeared on various transparencies of different exposures were not the same as that for the original object. Olson (134) also performed laboratory studies using a spectrophotometer to measure the reflectance properties of freshly picked leaves of various types. His studies indicated that the relative

reflectance of leaves of various trees were not constant but varied during the growing season. In fact, it was demonstrated that tonal relationships could actually reverse during the growing season. Therefore, Olson cautioned against utilizing general differences in spectral reflectances between different species as being absolute and invariant.

Additional spectral reflectance curves have been published in various articles. Of note are the works of Colwell (23)(27) and Ray and Fischer (147). They obtained laboratory spectral reflectance curves for various target materials for the purpose of planning flight programs to exaggerate the contrast between the object and its background or to develop systems to enhance the object so that it can be more easily interpreted. Their work will be discussed in more detail in the next subsection.

Film-Filter Combinations, Image Enhancement and Multiband Studies.

All three of these approaches are different yet they have the same goal; to make the target of interest easier to identify and interpret. To accomplish this aim all three methods rely to some degree on spectral reflectance data to choose regions of the spectrum where this condition can be most successfully accomplished. The difference between these three methods is basically the approach used to accomplish the goal.

(a) In film-filter combination studies, a selection is made of existing or specially made film or film types and certain filter combinations. This selection is made to either narrow the visible spectrum down to a desired region where the target of interest has the maximum contrast with the background, or to select various film types which are sensitive in different parts of the spectrum and investigate the

response of the target on these various film types. This latter type has also been referred to as "spectrazonal" studies. The choice of the region of study and film-filter combination to use is usually based on the evaluation of the spectral reflectance curves of the target and its background.

(b) Image enhancement, attempts to increase the contrast between the targets of interest and the background by special laboratory processing techniques or by viewing techniques. Standard film and filter combinations are normally utilized for these studies. Spectral reflectance curves are sometimes utilized in these studies as a guide to the selection of the processing or viewing system to use.

(c) Multiband studies are different from the above two approaches in that various portions of the spectrum are subdivided into smaller segments which are photographed or imaged simultaneously. The systems used to obtain multiband coverage in the visible and photographic infrared regions include photographic systems (e.g., nine-lens cameras developed by University of Michigan and Itek Corporation), and optical-mechanical multisensor systems (e.g., University of Michigan multi-channel detector)(95)(124). In the multiband approach, once the photographs or imagery are obtained, the methods utilized to study the data are similar to one or both of the other approaches. The photographs or images can be scanned to select for further study the band where the contrast between the target and the background is greatest (but not necessarily the optimum contrast possible), or several of the bands can be combined by various processing or viewing techniques to enhance the target information desired. Another use is to make normalized spectral

reflectance graphs showing the relative reflectance between various targets as they appear in the various bands.

The approach of comparing various film types in an effort to determine the type that offers the greatest contrast or interpretability of the target of interest has been discussed in detail for the case in which color photography was evaluated (see pages 56 to 65). Just a brief review will be added in this section on the work of those investigators who compared only the standard black-and-white panchromatic and infrared photography.

Several of the advantages of black-and-white normal infrared photography (using a Wratten 89 B filter) and "modified" infrared photography (using a Wratten 12 filter) over panchromatic photography indicated in the literature include the following:

1. Delineating shore line boundaries of bodies of water
[Meier (113), Spurr (164)];
2. Delineating wet areas and seepage zones [CRREL (177)];
3. Tracing stream courses overhung by hardwood trees
[Colwell (27)];
4. Penetrating haze (if particle size small) [Clark (21)];
5. Camouflage detection [Clark (21)];
6. Separating healthy vegetation from diseased vegetation
[Colwell (23)]; and
7. Distinguishing coniferous trees from deciduous trees
[Haack (53), Hildebrandt (60), Spurr (164)].

Many of these advantages have also been noted for color-infrared photography.

The approach used by various investigators in studying the various film types available (i.e., black-and-white, color) has been to determine which particular film type was best for obtaining information relevant to their field of interest. From the various results indicated, it is seen that no one film type has been found that gives all the desired information.

The approach of evaluating spectral reflectance data to select a particular film-filter combination that will increase the contrast between the target and its background is opposite to the previous method of studying various film types. In this approach the region of the spectrum evaluated is narrowed down to the region of interest as far as is possible with the selection of specific film-filter combinations. Dr. R. N. Colwell has been the leading proponent for this method of approach and has published several articles and a movie film illustrating its value (22) (23) (24) (27, chapt. 2). Several of the examples in the publications demonstrate the success of this method for improving the contrast between rock outcrops and soil cover, diseased and non-diseased vegetation, different species of trees, and an example differentiating between grass, cement, asphalt and soil. Walker also included examples in his paper demonstrating the use of reflectance data to choose film types for showing maximum contrast for targets of interest and the increase in contrast of an object that can be obtained by selective filtering techniques (185). In the work of the above authors, spectral reflectance data were obtained from laboratory measurements.

Personnel at Ohio State University (133) have investigated film-filter combinations. As part of the study, various aerial film-filter

combinations were compared over a chosen test site to evaluate which combination showed the greatest sensitivity to moisture differences in the soils. With the types investigated (panchromatic film with Wratten No. 29, No. 55 and no filter; infrared with Wratten No. 29 filter) it was concluded that the panchromatic film without a filter gave the most definite expression of moisture variations. In this study no spectral data were obtained on the test soils to assist in the choice of filter. The limited spectral data available in the literature for similar type soils were used as a guide.

Poley (144), reported a somewhat different approach, but with the same goal in mind, that of increasing the contrast of the target material. His approach was that of rejection-filtering. His reasoning was that differences in certain surface-color tones between the target and the background may not be strong enough to register as distinctly different gray tones on the normal unfiltered black-and-white aerial photograph. The tone registered on the photograph would be that due to the object with the largest reflectance (i.e., dominant color) and the tone of the other would not be distinguished. His technique required the use of a filter which would reject the main color, allowing the lower reflecting surface to register on the film. This technique resulted in appreciable contrast enhancement where before there was a featureless gray-tone region. The choice of the rejection-filter is arrived at through spectral reflectance studies.

It is evident from the examples discussed in the literature that the choice of film-filter combinations based on laboratory reflectance measurements can be successful in certain cases in increasing the

contrast of the target of interest and its background. This condition should increase the probability of detection of the target. However, there are several major limitations that have to be considered when this approach is utilized.

1. Although some examples demonstrate that the contrast can be increased, because of the many parameters and complex interactions between them one can never be quite sure that the desired results will be achieved. Conditions may be such as to even cause reversals. Close control will be required on as many parameters as possible thus further restricting the conditions under which the aerial photography can be obtained. This can increase the cost of obtaining the desired photography.

2. There is a limitation on the minimum spectral reflectance band width which can be obtained with available filter-film combinations. Walker in his study indicated the minimum band width was between 50 and 70 millimicrons (185).

3. This technique may be of value if one desires to search for a given object or a limited number of objects; however, if information is desired for numerous objects, or if area surveys are necessary, this technique would not be satisfactory. The use of a particular film-filter combination limits the spectrum to a narrow band width which may cause the loss of valuable information present in other regions.

In the technique of image enhancement as a method for increasing the contrast between the target material and its background several different approaches have been reported in the literature. The approach used by Ray and Fischer (147) was that of using color transparencies as

an intermediate product to produce black-and-white prints by means of selective filtering. Colorimetric and densitometric measurements were made on the color transparency to determine the range of the spectrum where the target information had the greatest contrast with the background. Utilizing this information, a filter was then chosen through which to make the black-and-white print to obtain the region of greatest contrast of the target material, in their case, between different types of rocks. A somewhat similar approach was reported by O'Neill and Nagel (137). They also used color photography as the basic source of information but instead of making black-and-white prints using selective filters they built an instrument called the "diachroscope." This instrument increases the visibility of an object whose hue is different than that of the background by providing colored light as the background for viewing. In addition colored filters including liquid filters can be used to obtain the spectrum range desired for viewing. The choice of filters or lighting to use is based on a study of the spectral reflectance curves for the target and its background.

A further method of image enhancement considered is the use of selective filters placed in the viewing system during the interpretation phase. Judd (72) considered the system for viewing transparencies by placing the filters between (1) the eye and the color film or (2) between the color film and the light source. He indicated that the first system provided somewhat better chromatic adaption while the second system provided better freedom from bad effects of optical imperfections of the colored filter. For this latter reason he recommended the second system.

The main advantage of image enhancement is that the full spectrum range is collected on the photography and any narrowing of the range desired for contrast enhancement is accomplished from the data collected by subsequent processes. This technique is better suited to area surveys or projects where it is desirable to delineate several targets. Some additional advantages are that more filter possibilities are available, more manipulation in laboratory and viewing procedures are possible, and longer exposure times are possible to obtain greater enhancement of image contrast. As an example, the U.S. Naval Photographic Interpretation Center in Maryland has an instrument that can electronically enhance small differences in tones and then outline constant tonal values electronically (48).

A disadvantage of this method is the increased cost involved in film, equipment and laboratory processing. A multilayer film which is sensitive to different portions of the spectrum is necessary (e.g., color film, spectrazonal film). Panchromatic film with or without filters can not be used by itself. An additional disadvantage is that in the process of enhancing the target of interest through laboratory or viewing techniques additional variables are being introduced which may cause differences in tones to occur that are not due to natural occurrences.

The simplest form of multiband analysis is that where three exposures of panchromatic film are made simultaneously with each film exposure having a different filter (e.g., red, blue and green filters). In this method the spectrum is divided into segments by the filters used. Subsequent analysis for contrast enhancement is similar to the

processes previously described for image enhancement. The three photographs can be processed or viewed together to form a color photograph or in any combination to obtain the contrast desired. Work of this type has been reported by Winterberg and Wulfeck (190). A somewhat similar technique was utilized to obtain color photography of the moon's surface. In this case, exposures using different filters were taken in sequence instead of simultaneously (175).

Yost and Wenderoth (188) and Lohse (94) in addition used infrared photography and had four bands of information to work with. Yost and Wenderoth used a special camera that had four lenses and exposed all four bands simultaneously on a single strip of film. To view these bands they used a special viewer which has four separate optical and lighting systems. Each individual system has two lamps which control brightness and saturation respectively. In the printing process each of the emulsions was developed to the same apparent gamma (straight-line slope of log exposure-density curve, see Figure 11) so as to give similar contrast conditions. Lohse's work similarly used four bands but the enhancement of the target is accomplished by complicated processing techniques. Their photography was largely obtained by hand held 4 X 5 cameras.

Other multiband systems reported which cover the visible and the photographic infrared include the nine lens camera system developed by the University of Michigan and described by Lowe et al. (96), and the nine lens system developed by Itek Corporation and described by Molineux (124). The system developed by the University of Michigan consists of a converted 4 X 5 speed graphic camera with nine separate matched lenses

which take nine simultaneous exposures of the same ground area. The camera uses 1-N spectroscopic glass plates. A system of selective filtering over each lens is used to cover the range from 0.32 to 0.89 microns in eight steps plus one lens covering the whole spectrum (i.e., near ultraviolet, visible and near infrared). The system developed by Itek is different than the one developed by Michigan. The Itek camera also has nine separate matched lenses which take nine simultaneous exposures; however, it varies in that it is exposed on three separate rolls of 70 mm. film, two panchromatic and one infrared, to cover the range from 0.4 to 0.9 microns. Figure 21 indicates the bands covered by the nine lenses superimposed on the sensitivity curves for the two types of film used in this camera. Image enhancement techniques are used to prepare color prints from the multiband photographs. Any combination of three negatives can be selected to enhance the color range desired.

A very extensive camera system covering only the visible range of the spectrum is that developed by the Cornell Aeronautical Laboratory (32). It is a multiple camera system that contains ten narrowband cameras which selectively record the spectrum of interest; four oblique cameras which view the ground from a variety of angles; one panoramic camera which gives large-area coverage; and two others which provide conventional color and black-and-white coverage.

The advantages of multiband systems are: (1) they afford a means of studying the tonal relationships of target materials of interest in several distinct portions of the spectrum; (2) they allow comparisons to be made between data of each band or any combination of bands; and

LENS NO.	BANDWIDTH (mμ)	LENS NO.	BANDWIDTH (mμ)
1	400 - 500	6	670 - 720
2	450 - 510	7	700 - 810
3	520 - 550	8	810 - 900
4	550 - 600	9	Full sensitivity range of IR film

After MOLINEUX (124)

FIGURE 21. EXAMPLE OF NINE LENS MULTIBAND CAMERA SYSTEM.

(3) they obtain a general indication of the spectral reflectance properties of the target materials under the actual flying conditions. In addition, the advantages indicated for image enhancement also apply to multiband systems.

There are several disadvantages encountered in the use of a multiband system. First the cost of obtaining the data is significant and the access to equipment is limited. There are a limited number of groups in the country that presently are capable of obtaining the multiband coverage. For an organization to develop its own capabilities of obtaining multiband data would be extremely costly. In addition, with the accumulation of data from three or more different bands, data extraction and analysis becomes a more difficult problem as the amount of data to analyze is greatly increased.

Measurement of Parameters at Time of Flight. Because of the numerous parameters affecting the appearance of target materials on photography, it would be expected that attempts would be made to determine some of the conditions existing at the time of the flight. This has not been the case for photo interpretation projects confined to the visible and photographic infrared spectrum except in a few cases for special research projects.

As indicated previously, until recently, photo interpreters have utilized existing photography in their work; therefore, there was no opportunity to measure any parameters at the time of flight. Their only recourse was to determine what weather conditions existed at the time of flight in the general area and to try to evaluate the effects of some of the parameters by field checking. In the field checking, the

only thing the interpreter could do was to try to correlate the conditions shown on the photography to the conditions existing at the time of the field check. In most cases this was not too successful as the photography was several years old and changes had occurred in the land use, culture and in some cases even the drainage and topography. However, the general land form features were still present and could be correlated.

Where photography was flown specifically for interpretation purposes some attempt has been made to measure the effect of some of the parameters. The measurement of spectral reflectance properties during the flight has been accomplished by Romanova (150). Her work has previously been discussed. Other parameters investigated include the effect of moisture content on the tonal patterns and the possibility of predicting the moisture content from the tonal patterns on the photograph. Altschaeffl (2) in his research project collected moisture samples at the time of flight from various soils which could be recognized and distinguished on panchromatic aerial photographs. At the same time he noted the vegetative conditions and surface soil color at the sampling sites. Transmission density readings were made on the aerial photographic negatives obtained during the flight at the locations which most accurately represented the ground test locations. Statistical analysis of the data correlating density readings to moisture contents indicated that only about 30 to 60 percent of the variation in density readings could be attributed to variations in soil moisture content. Winkler (189) also studied the effect of moisture contents on final tonal patterns. His study was basically a laboratory study where he

prepared samples of different types of soils at different moisture contents and then photographed them outdoors at noon time with a sheet film camera using four different types of film (panchromatic, infrared, ektachrome and infrared color). The moisture contents were determined immediately after the pictures were taken and film densities were measured on the negatives or transparencies. Comparisons of tones with densities in this study also indicated that no direct correlation between densities and tones could be made. Trends were evident that showed a change in density with increasing moisture up to approximately the plastic limit of the material. After this, there was a slight reversal in trend. It is evident from these two studies that direct relationship of density and moisture content can not be made. Too many parameters influence the final tones present on aerial photographs.

Other endeavors to measure or evaluate some of the parameters affecting the final target image include attempts to relate tones on the photograph to the true color of the object. Lohse (94) as well as several other investigators have photographed color control panels in conjunction with the photographing of other targets in attempts to relate final tones to color of objects. This approach is useful in color and multiband photography in noting the appearance of the colors on color photography and relative tonal patterns in the different regions of the spectrum in multiband photography. One additional item utilized by some investigators which does not come under the field of measurements but which is actually more of a control item, is that of photographing a standard color and density wedge on each roll of color film. This procedure assists in controlling the development of the

color rolls so that the colors produced will be as close to natural color as is possible.

It is seen that very little has been done in the way of measurement of parameters during flight time so as to assist the photo interpreter in interpreting the various pattern elements evident on the photography. All previous attempts have only indicated trends or shown what parameters will affect a certain photo element.

Efforts to Quantitize Information on Photo Elements. The speed with which multiple film types, multiband, and multisensor data can be acquired and the increase in the amount of data to be analyzed are rapidly exceeding the interpretation capabilities of present methods for analyzing and integrating the information content. As more and more researchers are investigating information collected by these forms of data gathering systems, it has become increasingly evident that in order to handle this mass of data, there is a need for developing some method for automatically analyzing the aerial photography and imagery.

Several researchers have investigated this problem and have tried to develop systems for automatic interpretation. The search for diagnostic spectral reflectance data is one of the approaches; however, as indicated previously, this has not been too successful. Other approaches include scanning of aerial photography by densitometers, microdensitometers, flying spot scanners and electric optical fourier analyzers and other optical-electronic systems. All of these items are essentially based on scanning the tonal patterns present on photography.

The use of densitometry has been reported by Carr, et al. (17), Ray and Fischer (147), Fischer (48), Hackman (55), and Doverspike

et al. (38). In the studies reported by Carr and his associates and Fischer and Ray, readings were obtained with a point reading densitometer whose aperture openings could be varied from 1 mm. to 4 mm. With this type of instrument, variations in film densities on a transparency or negative, or variations in reflection from the surface of a positive print are measured. Carr et al. made point by point straight line traverses across three different desert land forms at three different aperture openings (1 mm., 2 mm., and 4 mm.). They indicated that the effect of increasing aperture openings was to smooth out the amount of variations in tones obtained; that is, there is a larger tonal averaging effect with larger apertures. Although some differences in patterns were noticed between land forms, no diagnostic pattern could be identified. Fischer and Ray (147) similarly made straight line traverses over several land forms except they constructed a device so that a continuous scan could be taken. They also demonstrated that differences in patterns (i.e., frequency and magnitude of tonal changes) were obtained for different land forms. However, these patterns were significant only for the photographs scanned and not diagnostic for the land forms studied. Fischer (48) also studied the effect of scanning color transparencies with the use of different filters (red, blue, and green). By comparing the relative amount of light transmitted through the various filters he was able to map geologic contacts between two different rock types. This latter work was actually a form of image enhancement. Hackman (55) using the same densitometer prepared an isotonal map of a portion of the moon from a series of traverses on the transparency. Doverspike et al. (38) made measurements on color aerial 70 mm. films

both with a normal densitometer (the same instrument as that used by Fischer) and with a microdensitometer in order to determine the feasibility of automatic interpretation of various land use classes (e.g., water, hardwood forest, concrete highway, etc.). The preliminary study with the densitometer indicated that the aperture size was a significant factor and that accuracy of the data improved as the aperture size was decreased from 4 mm. to 1 mm. Even at the 1 mm. aperture size the reliability of results did not exceed 25 per cent. Effect of aperture size as well as the identification of various land uses were studied with a microdensitometer. In the study, scans were made using three different filters (blue, green, red). Statistical analysis of resulting data on effect of aperture size indicated that although the density decreased asymptotically as aperture size increased, no improvement in land use discrimination could be ascribed to changes in aperture. With regard to the differentiation of the various land use classes, the authors concluded that the measurements of color densities alone did not offer a solution to differentiating land uses on color aerial photographs.

Other work in microdensitometry or microphotometry as it is called in Russia has been reported by Gospondinov (52). He discusses the technique developed for analyzing the traces obtained and methods for possibly identifying various soils by preparation of keys based on trace characteristics. No actual examples or projects are cited to indicate the success of this technique.

Attempts at automatic interpretation of photography with the use of flying spot scanners to electronically scan the photographs have been reported by Rosenfeld (151) and Latham (86). In this method, as in the

previous methods, one is basically working with differences in density of the films as a method for distinguishing various land uses. The size of the spot scanned as indicated by Latham (86, p. 19) can be as small as one micron in size. Rosenfeld in his report (151) indicated that by his procedure he was able to distinguish automatically between certain basic terrain types such as urban residential areas, cultivated fields and hydrographic features; however, he was unable to automatically differentiate between industrial areas and wooded areas. In addition, the work reported on was limited to the study of only two examples of each terrain feature as present on two aerial photographs.

Another electro-optical system is that described by Brody and Ermlich (14). In their analysis they used an Electric Optical Fourier Analyzer in which one-dimensional Fourier transforms of photographic positives or negatives are analyzed. They also evaluated two-dimensional Fourier transforms. By studying the presence or lack of presence of periodicity in the patterns for natural and man-made objects, they indicated that they could differentiate between these types of objects by means of the Fourier spectra. Their paper presents results obtained from the study of only two aerial photographs.

All of the above projects attempted to discriminate between various patterns encountered in the normal terrain. In addition, in most of the projects reported above, extensive work and interpretation is still required of the photo interpreter. More completely automatic systems in which pattern recognition and decision making are built into the machine are described by Hawkins and Munsey (57) and Murray (129). Because of the complexity of naturally occurring target materials, these

systems were developed initially just to identify objects with simple geometric patterns. Each of the systems described by these investigators has a different approach to the method of locating and identifying the simple geometric shapes. The reports indicate that generally these systems can find a particular object with a fair degree of accuracy when it is uncluttered by background; however, the incidence of false alarms can be quite high. When the object of interest is located in a background with a lot of clutter, the accuracy of detection decreases.

It is apparent that, at least at the present time, automatic interpretation is not a reality. Practically all of the techniques investigated depend on some form of scanning of photographic tones or densities on the photographs. The various parameters affecting photographic tone have to be evaluated or at least considered in any sort of automatic interpreting system. For the various systems described, only a few of the parameters affecting photographic tones were evaluated and a very limited number of samples were studied. The results indicated that, for the limited areas studied, relative differences between various target materials were evident, but no diagnostic patterns were obtained because of the limited sampling. Practically all investigators indicated that some additional factor had to be evaluated in conjunction with variation of photographic tone, if the possibility of automatic interpretation was to be realized.

Imagery Interpretation in the Infrared Region

The bands or 'windows' available in the infrared region for remote sensing, are roughly thirty times greater in extent than that available in

the visible region of the spectrum. Thus, the probability of obtaining diagnostic signatures for particular target materials is accordingly increased. The infrared region is concerned with reflected and emitted radiation below about 3.5 microns and exclusively with emitted radiation above this wavelength. The previous discussion included information on the photographic infrared region so that a discussion on photographic sensors will not be repeated.

In the infrared region, as was also true for the visible region, the wavelength of the radiation is small compared to the size of surface particles; therefore, the radiation is essentially scattered by the surface of the target material and does not penetrate very deep. Thus, the images seen on the infrared imagery are a function of the surface properties or subsurface properties which influence surface features.

An investigation of sensors and interpretation in the infrared region involves information about equipment, techniques, capabilities and applications that are "classified" and not readily available. The author has reviewed some of the classified literature; however, any reference made to classified reports in this study are strictly limited to those sections which were specifically noted as "unclassified" material. It can be appreciated that any reference to accomplishments in these fields can only be made to those reported in the "open" literature and thus, may not be an indication of the latest state of the art.

Elements of the Infrared Pattern

In order to be able to properly compare interpretation in the infrared region with that in the visible region, it is necessary to

know what elements make up the pattern and their importance in the interpretation.

Infrared imagery is obtained by a line scanning technique in which the area of interest is scanned in narrow strips normal to the line of flight. The forward motion of the aircraft is utilized in progressing from strip to strip (see Figure 22a). The width of the scanned strip in the direction of flight is a function of the altitude of the aircraft above the terrain, the instantaneous angular field of view, and the ground speed. A basic requirement of this technique is that the line-scan rate be high enough to provide at least contiguity of the scanned strips of the scene. The expression for determining the scan rate is:

$$\eta = \frac{v}{h\alpha} \quad (3.1)$$

where

η = line-scan rate - lines/sec.

v = ground speed - ft./sec.

h = aircraft altitude - ft.

α = instantaneous field of view - radians (56)

The difference in the method of obtaining infrared imagery compared to the normal method for obtaining the visual aerial photography (see Figure 22b), results in significant differences in the final product used by the interpreter. The major differences between the final products of these two systems, excluding differences due to the form of energy being sensed, include the following items.

1. In normal aerial photography, stereoscopic coverage is obtained over the test area, while for infrared imagery a continuous line scan is obtained. Therefore, no stereoscopic coverage is obtained for the imagery.

(a) SIMPLE LINE-SCANNING TECHNIQUE

(b) NORMAL AERIAL PHOTOGRAPHIC TECHNIQUE

FIGURE 22. COMPARISON OF TECHNIQUES FOR OBTAINING INFRARED IMAGERY AND NORMAL AERIAL PHOTOGRAPHY.

2. Image distortion due to motion in normal aerial photography is generally negligible; however, for infrared imagery, it can be quite significant. Referring to Figure 22a, it can be seen that as a line-scan is made, the aircraft is moving forward; thus, there would be displacement of straight lines normal to flight direction from the start of a line scan to the end of the line scan. This will affect the appearance of geometric shapes and linear trends on the imagery. Derenyi and Konecny (36) have indicated that distortions due to these factors under certain conditions can be several times the size of the object scanned.

3. The resolution of aerial photography is much greater than that which can be obtained on infrared imagery. The scan-lines on the imagery are much farther apart and are themselves wider than the narrowest lines that can be resolved by normal aerial photography. The resolution is dependent upon the electronic system rather than the resolving power of the film. Thus, the amount of information that can be stored in aerial photography is much greater than that on infrared imagery.

4. Large scale coverage can be obtained for aerial photography but not for infrared imagery. As seen from equation 3.1 for a given scanner system the minimum altitude is controlled by ground speed and scanning rate. The maximum scanning rate is a function of the equipment design.

It is evident that not all of the elements utilized to interpret aerial photography can be applied to interpret infrared imagery. Since stereoscopic coverage is not obtained in the usual infrared scanning,

none of the elements of surface form (i.e., topography, drainage and erosion) can be evaluated directly. The only possibility of evaluating these elements is through any differences that may occur in the tonal patterns on the imagery associated with these features. For example, if there is a difference in temperature between the streams and the terrain, the drainage pattern would be evident. The pattern elements of tone and texture however are present and thus are the predominant elements which make up the infrared imagery pattern. The influence of image distortion, resolution and scale will affect the amount of detail that can be interpreted from the imagery.

The elements of tone and texture are the only ones which can be utilized to interpret infrared imagery. The factors producing these elements are different for infrared imagery than for normal aerial photography (i.e., heat emission in infrared and light reflectance in visual); therefore, the techniques and diagnostic pattern elements used to interpret visual photography are not applicable to the interpretation of infrared imagery. In order to properly evaluate infrared imagery, it is necessary to understand what parameters affect the tonal patterns observed on the imagery.

Parameters Affecting Interpretation of Infrared Imagery

In this discussion, an attempt will be made, as far as possible, to group the parameters into the same categories as those listed for the visible region. This will facilitate direct comparisons between factors and effects in the different regions. It will be assumed that qualified interpreters are available for the interpretation of the infrared imagery.

In daytime infrared imaging, the sensor is essentially measuring solar reflectance below 3.5 microns, and emitted radiation above 3.5 microns. It is expected that the same parameters would not influence the final tonal images obtained in the two regions in a similar manner. In nighttime imagery, the effects in both regions should be similar. The discussion that follows will be limited to the parameters that affect emitted radiation. The parameters affecting solar reflectance (daytime, below 3.5 μ) are similar to those reported for the visible and photographic infrared region (pages 42 to 52).

The parameters which influence the pattern elements observed on the infrared imagery can be grouped into three main areas. These are:

1. Natural phenomena;
2. Properties of the target material; and
3. Properties of the collection, processing and display systems.

Natural Phenomena. Included under natural phenomena are the effects of meteorological conditions, climatic conditions, the surface heat balance and that of location or topographic position.

(a) Meteorological conditions include presence of haze, clouds, aerosols, wind, gases, etc... The effects of these factors were discussed previously under atmospheric transmission (page 10). It is evident from this discussion and Figure 2 (page 12), that the absorption characteristics of the atmosphere are critical in this region. It is due to this factor that infrared sensing is limited to just a few "windows" in the infrared region. The presence of haze and other small particles in the atmosphere has less effect on the attenuation of the radiant energy in the infrared region as compared to its effect in the

visible region (refer to Figure 3 page 16). The influence of wind however, is much more critical in the infrared region. Since the tonal differences which are recorded are due to differences of emitted radiation between various target materials, the presence of wind could either eliminate any differences that are present due to cooling causing uniform tones or else it could cause a "smearing" or spreading out of emitted radiation so that it covers areas where differences are not actually present. The effect of scattered clouds is to cause shadows which cool areas on the ground, thus portraying darker tones on the imagery which are not related to actual target material characteristics. If cloud cover is extensive, it prevents the sun from heating the terrain. The terrain then remains at a fairly constant temperature and differences in target materials would not be evident. Meteorological conditions can thus have a great effect on the tonal patterns present on imagery. Micro-meteorological conditions or conditions close to the target material surface are equally important. Such factors as shading of surface by trees and plants, local evapotranspiration from the surface, presence of dew, temperature inversions, etc..., all can have an effect on the final tones recorded on the imagery which may not be indications of differences of target materials. Therefore, it is evident that meteorological conditions have a greater influence on infrared imagery than on visible or near infrared photography.

(b) Climatic conditions such as presence of different climatic zones and seasonal influences on such items as the vegetative cover present at any time of year, and the moisture conditions of the soil, will greatly influence the tonal pattern present on the imagery. The

influence of moisture or precipitation is to even out any differences in temperature occurring between different materials thus resulting in more uniform tones on the imagery.

(c) Surface heat balance varies continuously during the day and night affecting the tonal patterns obtained. During the day, direct solar radiation and some sky radiation raise the total surface temperature. The amount of solar radiation obtained varies with sun angle, sun altitude and season of year (see Figures 5 and 6 page 24). Evaporation and convection phenomena tend to lower the temperature during the day; however, these effects are generally small compared to the incoming solar radiation. The effect of heat balance during the day is toward raising the temperature of the surface and increasing its emitted energy. The heat balance at night is the reverse. The factors tending toward cooling the surface such as effective outgoing radiation, radiation absorbed by the atmosphere and to a small extent evaporation, are larger than the factors tending to heat the surface such as back radiation from the atmosphere and convection. Therefore, due to heat balance phenomena, the tonal pattern for different target materials will be continuously changing during the day and at different amounts depending on the properties of the target materials.

(d) Location or topographic position of the target material in the terrain will also be a significant factor on the final tonal image. For example on daytime imagery of similar materials on north and south facing slopes, the south facing slope would appear brighter. Similarly, for comparable materials, one located on a dry upper slope and the other in a low wet area, the material in the low area would appear as a darker tone on the imagery.

Properties of the Target Material. Equation 2.6 (page 22) indicates that the amount of energy emitted by a material depends on the temperature of the material and its emissivity. Thus the basic properties of the target material which influence the amount of heat that can be absorbed, the efficiency at which it is absorbed and the amount of rise in temperature that occurs will influence the amount of radiation emitted and thus the brightness of the tone on the imagery. Other factors which will also affect the tonal pattern on the imagery include the contrast of the target material to its surroundings and its uniformity or variability.

(a) Basic properties of the target material include emissivity, heat capacity, thermal conductivity and surface to volume ratio. These properties depend on its molecular makeup and modes of vibration. The emissivity of a material is not constant but varies with wavelength and temperature. The emissivity indicates how efficient an absorber and emitter the material is, or how close it approximates a black body. Emissivity is a property of the surface of the material and is affected by anything which can change the surface physically. Spectral emissivity curves for various typical target materials are shown in Figure 23. These were obtained in the laboratory by measurement of spectral reflectance (15).⁵ Figure 24 illustrates some typical examples of the variation of emissivity with wavelength and temperature. These curves were also determined from laboratory spectral reflectance data (101). These curves are comparable to the spectral reflectance curves used in the visible

⁵By applying Kirchhoff's Law (emissivity = 1 - reflectivity) where the material is impermeable for the wavelengths of concern (15). Thus emissivity is determined from spectral reflectance readings in the region of interest.

After BUETTER et al. (15)

FIGURE 23. TYPICAL EXAMPLES OF SPECTRAL EMISSIVITY CURVES.

(a) VARIATION WITH TEMPERATURE

(b) VARIATION DUE TO MATERIAL TYPE

AFTER LYON (101)

FIGURE 24. TYPICAL EXAMPLES OF VARIATION OF EMITTANCE WITH TEMPERATURE AND MATERIAL TYPE.

and near infrared region. They will similarly indicate the relative brightness of tone that will appear on the imagery. The other properties of the material, that is, the heat capacity, thermal conductivity and surface-volume ratio will also have an effect on the relative brightness of the target's tone on the imagery. In general terms, the heat capacity is an indication of the amount of heat needed to raise the temperature of the material, the thermal conductivity a measure of the rate at which the heat can be transferred to and from the material, and the surface-volume ratio is some indication of the surface exposed to the radiation to the volume of material which has to be heated before there is a rise in temperature of the material. The effects of these items on the final infrared image are best illustrated by an example. Asphalt has a high heat capacity; however, its tone on an infrared image would vary depending on where it was placed and the time of day. Asphalt on a roof would appear hotter or brighter than an asphalt road during the day. The reason for this is that the road, being connected to the earth, has a large heat sink or volume where it can transmit the heat absorbed; thus, it will heat up less than the asphalt placed on the roof. The reverse is true at night. Now the road will appear hotter or brighter on the imagery because it has stored up more energy during the day and will lose it slower at night than the asphalt on the roof.

(b) Contrast of the target to its surroundings will affect the interpretability of the target. This feature will depend on the temperature differential and/or emissivity differential of the target material to its surroundings as well as on the size of the target, the scale of the imagery and the properties of the scanning and display system in

reproducing the differences in tones present. Tonal contrasts are not as sharp in imagery as on photography as the boundary represents temperature differentials which are actually in a state of flux (energy flow is present across the boundary). Thus the thermal region is far "fuzzier" than the visible region (68). Therefore, for an image to be interpretable, the relative contrast must be much greater or the size of the object much larger than the equivalent case in the visible range.

(c) Uniformity or variability of the target material being evaluated will also affect the final tonal patterns present on the imagery. Materials with uniform physical properties will absorb and emit radiation uniformly and produce a uniform tone on the imagery. Whereas, variable materials will produce variable tones on the imagery.

Properties of the Collection, Processing and Display Systems.

Included in this group are the properties of the sensor-carrying vehicle, the sensor unit, the detectors used, auxiliary equipment, the scale of the imagery, processing effects and type of display systems used.

(a) Sensor-carrying vehicle factors include vehicle speed, altitude and vibration and rotational stability. The combination of vehicle speed, altitude and scanning rate are significant factors in determining the amount of image distortion and blurring obtained. The effects of vibration and rotational stability are similar to those described for visual photography (page 46). An additional factor in infrared sensing is that because of the auxiliary equipment needed, a larger airplane is usually required.

(b) Sensor unit and detector characteristics of importance include the angular field of view of the scanner, its optical resolution,

the dwell time per element or scanning rate, and the spectral response of the detector, its sensitivity and its response-time constant (56). The angular field of view and the altitude determine the scale of the imagery, while scanning rate, optical resolution and response time of the detector affect image sharpness. An additional factor is the aspect angle from target to the sensor. As shown by equation 2.7 (page 23), the amount of energy received by the sensor depends on the aspect angle and its distance from the target material. Thus as aspect angle changes from the normal, there is a decrease in the amount of radiation energy received at the detector and results in darker final tonal images. Detector response and sensitivity also affect the spectral response characteristics of the system. Typical examples of detectors and their responses under given conditions are illustrated in Figure 7 (page 30). As noted in this figure, the detectors have to be cooled to very low temperatures thus requiring special containers called "Dewars" with the additional problems of handling and supply of these special cooling liquids. An additional factor affecting final tonal patterns is the type of material used for viewing windows in the sensor units and their transmission characteristics. Details on this phase is beyond the scope of this report. More information on this topic can be obtained in the book by Holter et al. (66, chapt. 6).

(c) Display and processing systems used by various groups are different. Consequently, the final tonal images obtained will be affected by the system utilized in obtaining the infrared imagery. The radiation falling on the detector is converted to electrical signals where it is fed to a tape and/or some display unit such as cathode-ray

tube, globar or crater lamp or other visible energy source. Photographic film is then pulled across an exposure slit at a rate proportional to the forward speed and altitude of the aircraft resulting in a strip film presentation (16)(56). Thus, the linearity and dynamic range of the display equipment is important. Morgan (126) has indicated that, "...infrared remote sensing techniques are available which permit measurement of radiation fluctuations corresponding to temperature fluctuations of the order of 0.01° Centigrade...." Since the range of temperature present in any scene may be quite large ($50-75^{\circ}\text{C}$), the linear response of the film to this range is critical. If it were desirable to distinguish between target materials at temperature differences as close as 0.01°C , then large temperature differences between objects would be lost. If however, it were desirable to distinguish between large differences in temperature, small differences would not be present. A critical operation at the time of flight on the final imagery obtained is the gain setting or range covered that is set by the equipment operator who monitors the incoming information. To obtain all the information desirable, it may be necessary to make several passes over the area of interest with different gain control settings at each pass. The control of the processing of infrared imagery on film is much less than for equivalent visual photography. Thus, there can be wide variations in gray tones of the imagery due entirely to processing factors. When the data is collected on tape, more control can be maintained in the exposure and processing stage. In fact, with tape, small increments of the signal can be printed at a time to give maximum differentiation of temperature differences.

Investigations of Infrared Imagery

There have been a number of approaches used in the study and evaluation of imagery obtained in the infrared region in several different disciplines. These efforts may be grouped into four main approaches:

1. Multiband and multisensor comparisons.
2. Spectral radiation studies of target material.
3. Measurements of parameters at time of flight.
4. Quantitative measurements on imagery.

Multiband and Multisensor Comparisons. Since the only pattern elements discernible on infrared imagery are those of tone and texture and only limited interpretation has been accomplished in this area, diagnostic pattern elements have not been developed to assist in the identification of the various land forms from the infrared imagery. Therefore, additional coverage, usually visual aerial photography, is normally obtained simultaneously with infrared imagery coverage in order to determine the basic land forms. Thus, most projects utilizing infrared imagery are using a multisensor approach. Multiband imagery is obtained in addition when coverage is obtained in several different regions of the infrared where atmospheric windows are available (e.g., 1-1.4 μ , 4.5-5.5 μ , 8-14 μ).

Infrared imagery can not be used as a primary source for identification of various land forms. The main value is that of adding convergent evidence to help explain certain features in the visible range, or of adding additional evidence not possible to determine from visual aerial photography. The approach used by most interpreters is to compare the infrared imagery to the conventional photography and report

what assistance or additional information was furnished by the infrared imagery. Most of the papers published on this subject list particular examples in which infrared imagery was of value. In reviewing these works, it must be realized that these examples are definitive for a particular location at a given time. By varying any of the numerous parameters which affect the tonal patterns obtained, the final results can be completely changed.

Since infrared sensors are very sensitive to thermal differences (vary as T^4), it would be expected that research with this technique would be utilized to evaluate areas where known thermal differences are present such as, gas or steam fissures, hot springs, areas of active volcanic activities or forest fires. In addition to differences due to temperature, differences due to such factors as emissivity, heat capacity, and thermal conductivity will cause differences in tonal patterns on infrared imagery and attempts are being made to investigate these factors. Most disciplines are interested in the natural terrain as the target material. The temperature normally encountered in terrain features (approximately 250° - 350° K) peak at about ten microns, it would be expected that the 8-14 micron band would be the band most utilized in the studies.

Hirsch (61)(62) has reported great success with the use of infrared sensors in evaluating forest fires. The infrared sensor was able to penetrate the dense smoke around the fire (which is not possible with visual photography) so as to indicate the perimeters of fires and to locate spot fires outside the main fire perimeters. This was possible because of the temperature differences prevailing. McLerran and

Morgan (111) and Miller (122) in studies in Yellowstone Park have indicated that hydrothermal features such as geysers, hot springs and areas of hot earth both previously mapped and unmapped were clearly shown on the imagery. Robinove (149) also indicated similar success by U.S. Geological Survey personnel in mapping hydrothermal features in Yellowstone and Hawaii as did Moxham (127) for work done by the Geological Survey in the Philippines. Slavecki (162), has shown examples of how infrared sensors can be used to detect burning coal refuse fires. Some of the fires were not evidenced on the surface, but were burning below the surface.

Infrared detection of temperature differences is not limited to very high temperature and temperature differentials. This technique has also been used successfully to detect smaller temperature differences and in regions of very low temperatures. McLerran (110) has shown examples where some crevasses in ice not discernible on normal photography could be detected on the infrared imagery. He also indicated however that crevasses are not always detected by infrared imagery as environmental factors such as wind could erase the surface thermal contrast. Also in this environment, Poulin (145) indicated that the land-ice boundary not discernible on normal photography, could be differentiated on infrared imagery.

Temperature differences due to water or moisture conditions have also been successfully detected even when vegetation overhangs and hides the stream from direct view. During the day, the temperature of water is usually cooler than the surrounding terrain so water is apparent as a darker tone. During the night the reverse occurs. Cantrell (16)

shows some examples of infrared imagery showing various drainage patterns. He also shows an example of how thermal patterns in a lake used by a power plant for cooling purposes can indicate the efficiency of the plants cooling operations. Strangway (168) has demonstrated a case where the presence of hot waters fifty feet below the surface resulted in an anomalous bright pattern on the imagery. No surface expression of this hot water was present. Lattman (87) has shown an example where springs on valley sides could be differentiated due to thermal differences.

In the area of vegetation interpretation Gates (49), Colwell and D. L. Olson (28), C. E. Olson, Jr. (135) and Hoffer et al., (64)(65) have published results of work in the infrared region. Gates (49) has indicated that all plant surfaces have a long wave emittance of 0.95 or larger, hence plants are nearly black body radiators. He has also indicated that conifers are always cooler than the deciduous trees during midday for the same environmental conditions; however, at night, the reverse is true. Colwell and D. L. Olson (28) have indicated that generally most fully illuminated deciduous leaves during midday were 3 to 5 degrees warmer than the surrounding sunlit ground while those in the shade at the same time were 3 to 5 degrees cooler. However, they also indicated that other factors could influence these relative temperatures such as whether the location was on a north or south facing slope or what background the leaves are imaged against. The above studies were based on analyses in the 8-14 micron band. C. E. Olson, Jr. (135) has studied both nighttime and daytime infrared imagery in the 4.5 to 5.5 micron band. He concluded that for differentiating between different

types of vegetation it was best to study daytime imagery. This is because the difference in transpiration rates of the different plants cause differences in moisture stresses which correspondingly cause differences in temperature and emissivity. Plants under high stress should appear lighter on the imagery. In his study, Olson attempted to differentiate between various vegetation and land use classifications present on the imagery. Accuracy after field checking and final interpretation varied from about 85-90 percent for differentiating cultivated versus non-cultivated, and wooded versus non-wooded. His accuracy for differentiating between various crops varied from 65 percent for soybeans to 95 percent for alfalfa. Differentiation of brush versus pasture and identification of different tree species were much poorer (30-45 percent). Hoffer et al., (64)(65) also worked in the area of differentiation between various crop types. In their work they studied multisensor as well as multiband imagery covering the region from the near ultraviolet to far infrared in attempts to find diagnostic patterns for the various crops. Although distinct patterns differentiating between various crops were obtained at given periods of time, they indicated that these patterns were not diagnostic for the particular crops studied but varied due to such factors as (1) relative size and maturity at time of flight (2) soil type, moisture content, and relative amounts of soil and vegetation observed, and (3) geometric configuration of the crop. This last item is an especially important factor on the final tones obtained and is one of the most difficult to evaluate in terms of energy budget. Both Hoffer and Gates have emphasized the variability of tones possible due merely to differences in crop geometry

and aspect angle of viewing (49)(65).

Very little work has been reported in the open literature on the use of infrared imagery for evaluation of soils and bedrock conditions. Hoffer and Miller (64) in their multisensor, multiband studies of vegetation also noted that certain soil conditions could be distinguished because of tonal reversals in the different bands. Differentiation between light colored, dark colored and wet soils were indicated. Lattman (87) has indicated specific examples where tonal patterns on the infrared imagery made it easier to differentiate between sandstone and shale bedrock. There was no one reason for this difference, but it was ascribed to several factors such as difference in vegetative cover, moisture conditions and thermal conductivities of the two rocks. Wallace and Moxham (186) in the study of the San Andreas fault system in the 8-14 micron band indicated that the fault was clearly evident over most of the 200 mile length flown. Several other features were also identified on the imagery including ancient offset segments of stream channels, landslide terrain and various soil and bedrock units. An example included indicated how a particular shale formation was clearly distinguished from adjacent beds, some of which were also shale formations.

It should be realized that the examples reported by the various investigators are not applicable to all conditions, environments or times. They are indications of specific items that the investigators were able to differentiate at that particular time, place and condition. Any attempts to apply their conclusions under other conditions can cause gross errors in interpretation. An example of how variable the

various parameters are and how the time and environment can be more critical than the actual differences in target materials is evident when one notes the recommendations of various investigators as to the best time for obtaining the imagery. Wallace and Moxham (186) indicated that the two hours before sunrise was the best time for differentiating soils and rocks. Cantrell (16) indicates that generally the best time for obtaining signature of different rock types is immediately after sundown although he indicated daytime imagery was desirable since the shadowing enhanced terrain definition. Strangway (168) indicated a preference for obtaining imagery in early spring before sunrise when vegetation cover and solar heating were at a minimum. For vegetation differentiation C. E. Olson (135) recommends midday as the best period.

It is apparent that there is no one time suitable for every application, or even for any one application. Many factors have to be evaluated. The only possible way to arrive at a satisfactory solution is by taking the imagery at several periods of the day, or by taking field radiometer readings of the target materials of interest to determine their daily change and even their seasonal changes if necessary.

Spectral Radiation Studies of Target Materials. In an effort to obtain diagnostic signatures for various target materials, researchers have obtained spectral radiation curves in the infrared region. Laboratory and field measurements have been performed, but no infrared aerial measurements have been reported in the open literature. Lyon and Patterson have indicated that equipment has recently been constructed for airborne operation (102).

Laboratory IR spectroscopy is not new but dates back to the

nineteenth century (e.g., Rubens and Nichols work in 1897)(54). Its use as a quantitative tool for analysis of the composition of rocks or soils has been little utilized until recently (101). The laboratory technique for determining the emissivity values from the surface of the target materials of interest is that of measuring the spectral reflectance from polished surfaces of infrared opaque materials. For these conditions, scatter and transmission are negligible, and the emissivity is determined from Kirchhoff's law (absorptivity = $1 - \text{reflectivity}$), where emissivity equals absorptivity under thermal equilibrium conditions (101). These types of measurements can be used to determine the variation of emissivity with wavelength for a given temperature. Since spectrophotometers, sensitive in the infrared region are used, the parameters discussed for spectrophotometers on page 75 are for the most part also applicable to infrared spectrophotometers. The only additional factor to consider is that due to the properties of the prism used in the infrared instrument to scan the infrared region.

Laboratory emissivity determinations on various polished rock and mineral samples have been reported by Lyon (101) and Buettner et al.,(15). Typical examples of the data reported by these investigators are presented in Figures 23 and 24, pages 110 and 111 respectively. Figure 23 demonstrates the variation of emissivity with wavelength for some typical minerals. Figure 24 shows the variations occurring in the radiant energy emitted with variations in temperature and materials. The curves in Figure 24 are compared to the black body curve for the given temperature.

Regions of departure from the black body curve or reststrahlen⁶ effects are significant and diagnostic for different materials. It is known that various materials exhibit reststrahlen effects at specific wavelengths (101).

The spectral reflectance technique described is applicable only for hard rock specimens that can be polished. A laboratory technique which can be used on loose soil samples has been reported by Davis et al., (34) and Shockley et al., (158). They measured the amount of radiant energy reflected from the surface of specially prepared compacted soil samples. The spectrophotometer used was capable of covering the range from 0.25 microns in the ultraviolet to 5.0 microns in the infrared. However, the work reported was for that in the infrared region. They did not attempt to determine the emissivity of the soil samples but evaluated the effect of various soil parameters on the infrared reflectance obtained. The soil parameters investigated included the effects of moisture content, dry density and grain size for different types of soils. Results obtained indicated that pertinent soil parameters such as moisture content, grain size and soil type could be identified through changes in amount of infrared energy detected. Data showed that the percent of radiation reflected decreased as the moisture content increased and that inflection points occurred at the optimum moisture content. (See Figure 25). Laboratory measurements of infrared reflectance at a particular wavelength indicate the possibility of determining either the type of soil or its moisture content if either one of these properties are known. Wavelengths

⁶ Reststrahlen - defined by 3rd. Edition of Van Nostrand's Scientific Encyclopedia (182) as "residual radiation." This results in a sharply increased reflectance or decreased emittance at the reststrahlen wavelength.

After SHOCKLEY et al. (158)

FIGURE 25. EFFECTS OF MOISTURE CONTENT ON INFRARED RADIATION REFLECTANCE.

were chosen which were particularly sensitive to moisture changes. These wavelengths were naturally the ones where maximum absorption by H_2O occurs (e.g., 1.4μ , 1.75μ , etc...). This feature is satisfactory for laboratory or even possibly field investigations but not for airborne measurements. The radiation to be recorded from an aerial platform has to pass through the atmosphere where at these chosen wavelengths the radiation is absorbed. This study confirmed that the radiation measured is that from the surface. No penetration occurs. The effect of density differences per se would not be significant other than for effects due to differences in the amount of water present in the surface layer. This may vary with density.

Field infrared measurements have been reported by Lyon and Patterson (102) and Eisner, et al., (42). Both groups of investigators are attempting to develop diagnostic signatures for various target materials by developing emittance curves similar to those plotted in Figure 24. As field measurement techniques are still fairly new, sufficient data has not been collected to determine if these emittance curves are diagnostic for various materials under all conditions, or if the various parameters previously mentioned would cause significant changes in the curve. The initial work by Eisner, et al., (42) on beach sands indicates there are some changes in the emittance curve due to differences in moisture, time of day, and amount of cloud cover. Based on this limited data, it would seem that the various parameters would influence the final emittance data. Therefore, in order to predict type of material or the final tonal pattern present on the imagery obtained from airborne platforms, airborne spectroscopic data would be needed.

Measurement of Parameters at Time of Flight. The elements of tone and texture and not of form are available for the interpretation of infrared imagery. Since there are numerous parameters affecting tone and texture, any one of which can cause unexplainable tonal reversals, it is even more important to measure some of the parameters during flight time for infrared imagery than for visible photography.

Lancaster and Feder (85) show some examples of some of the support information or measurements which are desirable at the time of flight. These include measurements of micrometeorological data such as air temperature (dry and wet), wind direction and velocity, relative humidity, cloud cover and precipitation data; recordings of gain settings of the infrared scanner as some indication of the radiation or effective temperature of known target materials; and the placement of thermal boards having electrically variable thermal emission for calibration purposes. The measurements supply information about local ground conditions as well as radiation emittance relationships between various materials so that they can be related to tones on the imagery. Sufficient control is available making it possible to reproduce and relate the maximum radiation differences obtained to the maximum tonal differences available on film.

The report by Lowe, et al., (96) also includes examples of measurements made during imagery flights. Micrometeorological measurements were also made. These include measurements of incoming and outgoing solar radiation, humidity, wind velocity and vertical temperature profiles which included temperature readings in the subsurface, near the ground as well as within and above the vegetation canopy. Radiometric

readings were taken in the 8-14 micron band of selected target materials throughout a 24 hour period to show the relative emittance changes of these various materials and to help choose the best time of day for obtaining the infrared imagery.

Although there is a general need for measurements of parameters during flights where infrared imagery is obtained, the majority of the reports published indicated that no measurements of parameters were made. The approach used was the same as that which has been used for many years for the interpretation of aerial photography, no measurements are made at the time of flight. The imagery is interpreted and the influence of various parameters evaluated by comparison to standard aerial photography and by field checking of the project area.

Quantitative Measurements on Imagery. Very little work has been reported in this area, although this is being investigated to a greater extent at present. Ory (138) describes a system of a dual channel line-scanning imaging system where on one channel the conventional line-scan image is registered, while on another channel, signals above or below a selected intensity level are recorded. This system is proposed so as to facilitate delineating areas of certain terrain features as wooded areas, streams and lakes, and road systems and thus make it easier to inventory or enhance these features. The problem with this type of system is that of the delineation of the specific terrain feature. Because of the numerous parameters affecting the radiation received at the imaging system, it would be very difficult to obtain a signal which is diagnostic for a particular terrain feature. At the specific level chosen, the areas shown would most likely include some areas of different

terrain features and exclude some areas of the terrain feature desired.

McLerran and Morgan (111) have included a map in their report which delineates apparent temperature differences based on differences in film density of the imagery as recorded on photographic film. This study was based on imagery obtained over Yellowstone National Park where differences in tonal pattern may well be related to differences in temperatures because of the presence of thermal active features in the park.

England and Morgan (43) have proposed a technique for calibration of the final imagery which employs quantitative radiometric measurements in combination with special electronic processing of magnetic tape recorded infrared scanner signals and densitometric readings of film densities for corresponding scan lines. This technique of recording the signals on tape in lieu of or at the same time as it is recorded on film is becoming more common. With this technique, film prints can be prepared at a later date from the tape. Either the whole range, or selected portions of the signal recorded on the tape, can be printed on the film. This offers a greater potential for making quantitative measurements than the other methods described; however, there is no guarantee that the targets of interest can be segregated by printing out only selected signal levels.

Imagery Interpretation in the Microwave Region

The microwave region is generally considered to be that region of the electromagnetic spectrum lying approximately between 1 millimeter and 1 meter. As noted in Figure 1 (page 6) this region is largely free from major atmospheric absorption. Compared to the regions of the spectrum available for visible and infrared sensing, the microwave region offers a vast zone for remote sensing.

Remote sensing in the microwave region is accomplished with both active sensors (radar) and passive sensors (radiometry). The discussion in this section will be largely on radar since it has been studied in greater detail and is more readily available for multisensing projects. The work being done with microwave radiometry is still in the research stage. A discussion of this sensor is included in this section because it is of potential value for remote sensing studies. In addition, microwave radiometer units are now installed in some multisensor aircraft and may be more readily available in the near future (30) (114).

An investigation of sensors and interpretation in the radar region, as is true for the infrared region, involves "classified" information. Since only reference to "unclassified" information can be made, the information may not necessarily be an indication of the latest state of the art.

Elements of the Radar Pattern

Two basic types of scanning systems are presently utilized in obtaining radar imagery. In the first type Plan Position Indicator (PPI), scans are obtained by rotating the antenna at a steady rate through a 360° circle. The sweep lines on the PPI are synchronized with the antenna so that the final display on the cathode-ray tube shows both range and azimuth of all reflecting objects. During one antenna revolution, the aircraft moves a relatively short distance, so that it is feasible to obtain a large percentage of overlap between successive scans. Each reflective object appears on adjacent scans; therefore, stereoscopic examination and measurements from PPI radar are possible. This type of radar display was used initially when techniques were developed for interpretation of terrain features from radar imagery. It is little used at present because

the broad antenna beamwidths of this type result in relatively poor quality imagery for detailed interpretation of terrain features (173).

In the second type of radar system Side-Looking Airborne Radar (SLAR), the antenna employed is either extremely long so as to obtain a narrow beam and therefore more detailed imagery, or a synthetic or "coherent" system is used which provides a greatly extended effective antenna length through data processing. Two antennas are simultaneously operated and scan a large swath of ground normal to the flight path of the aircraft. The forward motion of the aircraft is used to scan the area of terrain desired. Unlike the infrared scanning system, with a SLAR scanning system, an area underneath the aircraft approximately equal in width to the altitude of the aircraft cannot be scanned thus leaving a blank strip. The aircraft has to fly off to the side of the area of interest in order to obtain coverage. Stereoscopic radar imagery can be obtained with SLAR systems by either flying parallel flight lines which cover the same target area or by flying the same flight line at two different altitudes as illustrated in Figure 26 (8). Further details on radar stereoscopy are beyond the scope of this report. More information on this subject can be found in the book by Levine (92).

The relative reflectance of electromagnetic radiation from the target material back to the detector is of concern in radar as with visual photography. There the similarity ceases. There are several major differences between the final products of these two systems. In radar systems, the antenna is both the transmitter of the energy and the receiver of the return reflections from the target material so that the aspect angle or depression angle of the antenna to the target material is important. If the target material surface is smooth to the

(a) PARALLEL FLIGHT LINES

(b) DIFFERENT ALTITUDES

After RAYTHEON/AUTOMETRIC (8)

FIGURE 26. METHODS FOR OBTAINING STEREO-
SCOPIC RADAR IMAGERY WITH SLAR
SYSTEMS.

radar wave, specular (mirror-like) reflection is obtained which will be reflected away from the antenna unless the depression angle is 90 degrees. If the surface is rough textured to the radar wave, diffuse reflection is obtained and a signal is returned to the antenna. In visual photography, the source of the energy (the sun) and the collection system (the lens) is not the same. The aspect angle of the lens and sun to the target material is important. This factor can be controlled to some degree by planning the mission for certain hours of the day and at given flight directions. Therefore, reflections from specular surfaces can more readily be received in visual photography than in radar imagery.

A second major difference is that the wavelengths of the radar frequencies are much longer than in the visible region. They are approximately the same size as the particles they are striking; therefore, long radar wavelengths may penetrate the surface and reflect information from the sub-surface. This is in contrast to that in the visual and infrared spectra where except for unique conditions, only surface reflections or emissions are obtained. In addition, as Rydstrom (154) states: "Because a surface with roughness on the order of one-half the wavelength of the impinging energy is smooth to that energy, the surface acts as a specular or mirror-like reflector. Rougher surfaces act as diffuse reflectors. Therefore, many more surfaces are smooth to radar energy than they are to visible light energy. Thus similar materials could easily appear at different brightnesses of tones in the two regions."

Additional differences are those of image distortion, resolution and scale. Image distortion due to instrument factors and scanning techniques can be quite significant. This will affect the appearance

of geometric shapes, linear trends and the reliability of positioning of terrain and cultural features on the imagery. The resolution of aerial photography is much greater than that obtained by radar systems. The resolution of the radar system depends on the beamwidth of the radar and the frequency utilized. These factors produce a much poorer resolution than that available on film. Therefore, the amount of information that can be stored in aerial photography is much greater than that on the radar imagery. The scale of imagery obtained by the presently available "unclassified" radar systems or those commonly used in multi-sensor coverage is very small. For example, the majority of the "unclassified" radar imagery reported in the open literature is at a scale of 1:400,000 (8). Some larger scales were also shown but none that even approached the capabilities of aerial photography.

The same techniques used to interpret visual photography can not be used to interpret radar imagery because of the differences noted above. As indicated previously, stereoscopic radar imagery is possible although the procedure for obtaining true stereoscopic radar is still in the developmental state. In all the reports on interpretation of radar imagery reviewed, only one report (8) included a few stereoscopic images. At the present stage of development reported, interpretation of radar imagery is essentially performed on monoscopic imagery. Thus the elements of surface form (i.e., topography, drainage and erosion), can not be directly evaluated stereoscopically. Because of the nature of radar, large topographic breaks and principal drainage ways are evident on the imagery due to the presence of radar shadows, displacements of topographic highs and sharp tonal changes. Microfeatures such

as gullies, hummocky topography, and dunes can not be discerned (5). As a result of unidirectional illumination of the terrain by radar, if the beam angle is low, small differences in surface slopes which are not discernible on aerial photography are imaged as tonal changes on the imagery (154). It is apparent that more information on surface form is available on radar imagery than is available on corresponding infrared imagery, but not as much as is available on visual photography.

The elements of tone and texture present on radar imagery are therefore the main elements of value in the interpretation of radar imagery. The subdivisions into various shades of gray are not as numerous as in the other two sensor systems. Generally, only three relative tones are recorded. These are bright, medium and weak. Some additional assistance is afforded by topographic expression and drainage pattern.

Parameters Affecting Interpretation of Radar Imagery

The parameters which influence the elements of the patterns as evidenced on radar imagery can be grouped into the three main areas. These are:

1. Natural phenomena;
2. Properties of the target material; and
3. Properties of the transmission, collection, processing and display systems.

The discussion of these parameters will be limited to SLAR radar systems as this is the type used almost exclusively at present. Similarly as for the other sensors, it will be assumed that qualified interpreters are available.

Natural Phenomena. Natural phenomena include the effects of meteorological conditions, climatic conditions and location or topographic position.

(a) Meteorological conditions such as presence of haze, aerosols, wind, clouds, etc..., have very little if any effect on radar imagery. Windborne sand and dust can attenuate radar signals, but their occurrence in sufficient quantities to affect radar operation is relatively rare (47). Wind can have an affect in that it can change the reflectance characteristics of some target materials such as bodies of water and vegetation by changing their aspect angle with respect to the radar transmission. Radar signals will penetrate all but the very dense clouds. Light precipitation has no effect on radar, but heavy precipitation, snow and sleet will attenuate the radar signal. Radar is independent of natural illumination and less influenced by weather conditions than the other two sensors; therefore, it is possible to obtain radar imagery round-the-clock and almost under all weather conditions.

(b) Climatic conditions such as presence of different climatic zones and their seasonal influences on such items as the vegetative cover and the moisture conditions of the soil will greatly influence the tonal patterns present on the imagery. This effect would be more critical on radar tonal patterns than on other sensors. For example, the moisture content of the target material would have a direct influence on the type of reflectance (specular or diffuse) and the amount of penetration by the radar signal.

(c) Location and topographic position of the target material

can influence the tonal pattern present on the imagery. As with other sensors, the effect of moisture differences in the material due to differences in location, is important. The location and topographic position can be more critical in radar than other sensor types due to the shadow effect. Radar signals are unidirectional; therefore, they can only illuminate those objects which are directly on a line of sight from the antenna. If the signal intercepts a topographic high, the signal is reflected back and all target materials which lie behind the topographic high along the line of sight will not be seen by the radar system. This is somewhat analogous to the shadow effect in visual photography; however, in visual photography scattered radiation from the sky can illuminate target materials located in the shadows so that with proper film-filter selection, some information in the shadows can be obtained. This is not the case for radar.

Properties of Target Material. Numerous parameters affect the radar return or "back-scatter" from the target materials back to the antenna and thus the relative brightness of the target material on the imagery. Among these are the physical and chemical composition of the target material, the orientation of the target material relative to the radar signal, and the contrast of the target material to its surroundings.

(a) Physical and chemical composition of the target material considered includes molecular make-up, surface roughness or texture, geometry of the target material, dielectric constant, temperature, moisture content, salinity, and the uniformity or variability of the target. As indicated previously, surface roughness or texture is an important factor in the type of reflectance that occurs. The amount of

diffuse reflectance or back-scatter increases with increase in surface roughness or texture for a given radar frequency. It also increases as radar frequency increases (i.e., wavelength decreases). The amount of back-scatter obtained for a given surface is also a function of the depression angle of the radar transmitter. For rough surfaces large back-scatter is obtained for all depression angles, but for smooth surfaces, the amount of back-scatter increases as depression angle approaches 90 degrees. Figure 27 shows the difference in the amount of back-scatter received at the antenna in decibels for various target materials with varying surface roughness as a function of the depression angle. Measurements were made by Goodyear Aircraft Corporation using an X-band (3 centimeter) radar (51). The geometry of the target materials or the relationship of the surfaces of target materials to each other or to the base on which the target is located has a strong influence on the intensity of energy returned. Assuming a specular surface, the only time a signal return is received by the antenna is when it is normal to the object surface. At any other angle there is no return and the object appears dark on the radar imagery. However, if the geometric relationships are such that a dihedral reflection surface oriented at 90 degrees to the radar beam is present (see Figure 28a) or if a trihedral reflection surface is present (three surfaces mutually perpendicular--see Figure 28b) a signal is returned to the antenna and a tonal pattern is present on the radar imagery (154). This factor of geometric conditions can cause a small feature such as a creek, which would normally not be identifiable, to stand out sharply due to bright tones on the imagery. The factors of dielectric constant, temperature,

(COURTESY AMERICAN SOCIETY OF PHOTOGRAMMETRY) (173)

FIGURE 27. VARIATION OF BACK-SCATTERING COEFFICIENTS AT X-BAND.

FIGURE 28. EFFECT OF GEOMETRIC RELATIONSHIPS ON BACK-SCATTERING.

moisture content and salinity not only have an effect on the amount and type of back-scatter, but also, for a given frequency, affect the amount of penetration by the radar wave into the ground. Several investigators have indicated that for a given frequency in the radar band, the depth of penetration varies inversely with the relative dielectric constant " ϵ_r "⁷ (35)(153)(168). Thus the penetration in dry soils with relative dielectric constants in the order of 2 to 10 (6)(73) is much greater than that in water where the relative dielectric constant varies from 78 to 87 depending on salinity and temperature (6). Wet soils have dielectric constants between these two values depending on the moisture content. The actual amount of penetration also depends on the wavelength of the radar utilized, increasing with increasing wavelengths. In addition to the above factors, the uniformity or variability of the target material, especially in the case where the surface is rough textured to the radar signal, will affect the tone and textural pattern of the radar imagery. Uniform materials would produce a uniform tonal pattern on the imagery and variable materials, variable tones.

(b) Contrast, size and orientation of the target material have a significant effect on the tonal patterns seen on the radar imagery. The contrast of the target material depends on the physical and chemical properties of the target material relative to that of the surroundings, the size in relation to the scale of the imagery and orientation relative to the radar beam. The scale of radar imagery is very small; therefore, the object size will be a factor in its differentiation

⁷Relative dielectric constant " ϵ_r " equals the dielectric constant of the material in question divided by the dielectric constant in free space. It is a dimensionless term (35).

from the surroundings and its interpretability. Spacing between objects and orientation is also important. It has been indicated that two objects can be resolved in the radar's range direction if they are separated by a distance greater than one-half the pulse length of the radar signal (154). This factor is also affected by the wavelength of the radar. For a given antenna and pulse length, the resolvable area becomes smaller as the wavelength is decreased (33). The effect of orientation is equally important in that certain objects oriented normal to the flight direction can act as dihedral or trihedral reflectors and thus give a bright return. This accounts for the identification of small features such as creeks and the presence of bright returns from buildings which are oriented normal to the flight direction but low returns from similar buildings oriented parallel to the flight direction.

Properties of the Transmission, Collection, Processing and Display Systems. This section is limited to a discussion of some of the major parameters that affect the tonal patterns of radar imagery as have been reported in the literature. Discussed are the factors of the sensor-carrying vehicle, the sensor equipment and antenna characteristics, auxiliary equipment, and the processing and display systems used. The field of radar and equipment design is quite complex and beyond the scope of this report.

(a) Sensor-carrying vehicle factors of importance for the sensor-carrying vehicle include stability and size. Excessive turning, yaw, pitch and roll can cause image distortions. Turning causes a compression of the imagery on the side toward the turn and stretching of the imagery on the opposite side. Yaw, a change in heading by the aircraft, causes

the antenna beam to illuminate the same terrain area twice producing a double image. Pitch or a sudden movement of the nose of the aircraft can result in either failure to scan an area or redundant scanning of an area. Roll or dipping of wings during flight can cause an uneven illumination of the area being scanned (8). Most radar systems can compensate for certain amounts of these erratic motions. Larger size aircraft are required for radar systems than for the other systems because of the size of the antennas required and the amount of auxiliary support equipment needed. The factors of vehicle speed and altitude range are also of some importance in the choice of the radar systems that can be utilized in a particular vehicle.

(b) Transmission and collection system factors of importance include the radar frequency, pulse width, size and characteristics of the antenna, angle of incidence, wave polarization, distance to target, and power of the transmitter. The frequency of the radar signal, its pulse width and the antenna characteristics are critical factors in the resolution and sensitivity of the system. The amount of penetration obtained for a given target material is a function of the radar frequency. The lower the frequency, the greater the penetration. For a given target material, the magnitude of the signal received by the antenna (or brightness of the tone on the imagery) is affected by the radar frequency, antenna characteristics, angle of incidence, wave polarization, transmitter power, and distance to the target. The relationships of these factors are demonstrated in the equation for the power of the received signal (P_r) (173 Chapt. XXI).

$$P_r = \frac{P_t G_m^2 \lambda^2 \sigma}{(4\pi)^3 R_s^4} \text{ Watts} \quad (3.2)$$

where

P_t = transmitted peak power

G_m = maximum antenna power gain

λ = wavelength of the radar signal

σ = back-scattering coefficient

R_s = slant range

More detailed discussion of these factors are found in references (8)

(33) (125) (153) (161) (173 Chapt. XXI).

(c) Processing and display of the energy returned to the antenna as well as equipment adjustment and settings can also affect the final tones appearing on the radar imagery. In the typical recording system, the signals received at the antenna are imaged on a cathode-ray tube and pictures are taken of the tube. Leonards (89) has indicated that the system components of the cathode-ray tube and film cannot record with equal discrimination all signal levels received at the antenna. Whether the film records the maximum difference between high or low intensity signals depends on the setting of the instrument. Thus for radar imagery, as was the case for infrared imagery, a critical operation at the time of flight on the final imagery obtained is the instrument settings. Besides the setting of the range of coverage by the film, other equipment settings relative to altitude, drift, and film speed are important. For example, improper setting of the altitude control can cause a change in the extent of the blank area obtained on the imagery or distort part of the imagery; improper drift setting will cause distortion of the images; and improper ground speed setting can

also cause distortion of the images recorded from the cathode-ray tube (8).

Investigations of Radar Imagery

Investigations into the applications of radar imagery for the interpretation of terrain conditions have been conducted in a laboratory type setup, in the field on target materials in situ, and from the air. Radar sensors are active systems and the power transmitted and returned can be readily measured; thus, actual quantitative measurements can be obtained. The measured quantities include the signal level return " γ " (decibels), the back-scattering coefficient " σ " (decibels), and the relative dielectric coefficient " ϵ_r ". Although actual values are obtained, they are still dependent on numerous parameters, the significance of which can not be distinguished or separated from the final value. Even though relative differences have been noted between certain target materials under certain conditions, no diagnostic characteristics have been noted for any given material. It is also not uncommon for values of different materials to overlap (refer to Figure 27 page 139).

Extensive laboratory radar studies have been conducted by the U.S. Army Engineer Waterways Experiment Station. Work on phases of this project has been reported by Nikodem (132), Davis et al.(35), Lundien (99) (100), and Texas Instrument Co. (172). For this project, a special fifty foot high arched structure was constructed on which radar antennas mounted on a track could traverse the arch. Various angles of incidence were utilized. For most tests, a 90 degree angle of incidence was used. Samples including soils of various types, densities and moisture contents as well as various vegetation types were placed in special containers

below the center of the arch. Four radar frequencies were utilized in the study which included the following:

1. K_a - band, 34,543 mc/sec, 0.87 cm.;
2. X - band, 9,375 mc/sec, 3.21 cm.;
3. C - band, 5,870 mc/sec, 5.10 cm.; and
4. P - band, 297 mc/sec, 101 cm. .

The primary objectives of the study were to determine if terrain material moisture contents for the top 18 inches of soil could be measured by reflectance techniques and if the penetration by radar frequencies was useful for obtaining an approximation of near-surface water-table depths (35)(99)(100). Results of the studies led to some of the following conclusions.

1. Standard pulsed radar sensors can provide information that permit an estimate of the moisture content of deep homogeneous soils. They cannot provide information to predict the depth of surface water, presence of ground water or depth to ground water. Water density can be determined by determining the relative dielectric constant " ϵ_r " of the sample material as shown in Figure 29. This relationship appears independent of type of soil material. The relative dielectric constant is determined from measurements of variations of reflected power versus depth in soil and the relationship is,

$$\epsilon_r = \frac{c^2}{f^2 \lambda^2} \quad (3.3)$$

where

c = speed of light in free space

f = radar frequency

λ = wavelength of radar wave in material

FIGURE 29. RELATIONSHIP BETWEEN RELATIVE DIELECTRIC CONSTANT AND MOISTURE CONTENT.

Figure 30 indicates an example of the determination of " λ ", the wavelength of the radar wave in the soil. The presence of these oscillations also indicates the depth of penetration of the radar wave. Lack of oscillations indicates no penetration of radar wave.

2. Long wavelength radar waves (P-band) will reflect from a subsurface soil-water interface or layered systems. This indicates the possibility for measuring the depths of layered materials with specially designed radar systems operating at P-band frequencies (e.g., mono-pulse radar system, FM radar system or variable-frequency radar system). The shorter wavelength radar waves (C-band or shorter) do not appear to be as effective as P-band for measuring depth of layered materials.
3. Depth of penetration was affected by moisture content. As moisture content increased, depth of penetration decreased.
4. P-band results are not influenced as much by various heights of vegetation as are those for the other three bands. This suggests that the shorter wavelength radar systems could be used to measure vegetative parameters, while the longer wavelength radar systems (e.g., P-band) could be used to analyze soil conditions below the vegetation.

Barringer, et al. (7), has also recently reported on some laboratory type measurements of radar reflectivities and attenuation on various rock types under conditions of dehydration and high vacuum. These studies provided design parameters for the development of a special satellite-borne

FIGURE 30. TYPICAL EXAMPLE OF DETERMINATION OF RADAR WAVELENGTH IN SOIL.

radar unit adapted to measuring layering effects.

An extensive field radar measurement program has been conducted by Cosgriff et al.(180). Measurements were made with K-band and X-band radar systems mounted on a boom attached to a truck with a constant 20 foot slant range distance maintained. The results of this study led to the determination of some of the fundamental parameters that affected the radar signal return. These have already been discussed. Some of the conclusions indicated in this report relative to terrain features include:

1. Seasonal changes which vegetation covered terrain undergo have a highly significant effect on the terrain return measured. This change is dependent mainly on the moisture content of the vegetation. The change was more pronounced at K_a -band (35 kmc), than at X-band (10 kmc) or K_u -band (15.5 kmc) frequencies.
2. Water on relatively smooth surfaces tends to lower the return while water on vegetation covered surfaces may increase the return.
3. The magnitude of signal return " γ " from a smooth surface terrain using horizontal polarization is less than the return from the same surface using vertical polarization. Thus using vertical polarization the range of radar can be increased by a factor of about two. However horizontal polarization may be preferable if it is desired to achieve maximum contrast between rough and smooth surfaces.

Meyer (116) reported on a field project for the sensing of ice and snow thickness using high-resolution monocyde VHF radar. Measurements were made on the ground and from a helicopter at 280 feet. He indicated that ice and snow thickness could readily be measured by visual data reduction to accuracies in the order of 1 centimeter. The break between the measured layers were based on the ratio of the dielectric constants of the materials.

Several investigators have reported on the interpretation of aerial radar imagery. These include a group with Raytheon/Autometric (3), Rouse et al.(153), Morain and Simonett (125), Rydstrom (154), Fischer [(as reported in (173 Chapt. XXI, pp. 1027-1030))] and Feder (46). The report by the Raytheon/Autometric group is an extensive evaluation of the potentials of "unclassified" SLAR systems for geoscience purposes. Two "unclassified" radar systems were studied. These include the AN/APQ-56 (K_a -band, 0.86 cm) and the AN/APQ-69 (X-band, 3.2 cm). The following is a brief summary of some of the major conclusions reported in the study.

1. It is possible to delineate major drainage systems from these radar systems; however, the complete pattern is not always present in its entirety. By tracing the principal drainage elements first and determining their flow directions, it is possible to prepare a cohesive drainage network. Mapping drainage is significantly easier in mountainous areas than in low-relief plains.
2. Cultural features identified in the radar mosaic did not approach the anticipated level of interpretation.

Considerably more cultural detail could have been extracted if equipment gain settings were lowered.

3. Land use information on a reconnaissance-level can be extracted from the radar imagery.
4. With the exception of mountainous areas, it appears that radar imagery is suitable for generalized mapping of vegetation at regional scales.
5. Radar provides a fairly accurate medium for the interpretation of geological structure and lithology in mountainous regions. In plains and basins it is a good adjunctive tool. Regional physiographic units can be clearly and accurately identified and delineated but micro-terrain features are not generally distinguishable. Included in the geology section is a table indicating levels of K_a -band energy returns. Some examples include: (a) weak returns - sand, silt, clay, shale, marl, chalk; (b) moderate returns - gravel, glacial drift, limestone, diabase, basalt; and (c) strong returns - sandstone, granite, rhyolite, gneiss and schist.
6. Key sea ice features commonly associated with formation, growth, drift and disintegration are readily identified on the radar imagery. The all-weather capabilities of radar make it an excellent tool for periodic coverage of areas to provide means of detecting changes in direction and rate of movement of sea ice floes.
7. Surficial materials can generally not be interpreted directly from radar imagery. They are interpreted by deduction and

inference techniques based on the interpretation of other features such as geology, physiography drainage, land use and vegetation (same technique as utilized in the interpretation of soils on aerial photography).

Rouse et al. (153), also reported on the use of radar for geoscience investigations and demonstrated its value for delineating geologic structure in the Faulkner County area in Arkansas. In this area, the effect of rock type on signal return was of less significance since most of the sandstones and shales were covered with soil and moderate to heavy vegetation. These factors greatly influenced the strength of the signal returned since an X-band radar unit was utilized. Also included in this report was an example of a regional vegetation map of Jackson Hole, Wyoming derived from radar imagery. This map compared favorably with a similar type vegetation map of the area previously prepared.

The investigations by Fischer (173 pages 1027-1030), Feder (46) and Rydstrom (154) also demonstrated some applications of radar imagery in the field of geology. Fischer indicated that the materials studied in his project area (New Mexico) could be placed into three main groups by virtue of their signal return intensity. These were in order of decreasing brightness: (1) igneous rocks and drifting sands; (2) ferruginous sandstone; and (3) limestone, siltstone, gypsum and soils. In the test area, the limestone could not be differentiated in all cases from the residual soils. Fischer also showed that some structural features visible on the radar imagery were either unobservable or visible only with difficulty on the conventional photograph. Feder showed

examples where information on structural and lithologic differences not readily identifiable on aerial photography were noticeable on radar imagery. An example of PPI radar clearly showed the presence of a fault which was not easily discernible on aerial photography as there were no topographic or drainage anomalies present. Another example of SLAR imagery distinctly differentiated oil shale beds from chalk beds in a series of interbedded shales and chalk. The shale showed a bright return in contrast to the low return of the chalk beds. The distinction between these beds was not as evident on the aerial photography. Rydstrom postulated that the object geometry was the single most important cause of the return energy intensity, while that caused by the type of material was subordinate. He demonstrated this by showing areas where high signal returns were received from naturally occurring materials such as limestones and some lavas. These materials weather into blocks whose surfaces form corner reflectors thus giving a high return (see Figure 28 page 139). Other investigators studying similar materials indicated that limestones and lavas had low to moderate returns (8) (173 page 1027).

It is interesting to note that the various geologic studies discussed generally indicated different levels of return for similar geologic materials (e.g., limestone). This demonstrates the difficulties of arriving at diagnostic tones for any particular material on the radar imagery. There are too many parameters influencing the final tones.

The work by Morain and Simonett (125) deals with the use of radar imagery obtained with a K_a -band radar unit for the preparation of vegetation maps over several climatic environments. Results of the study

indicated that it was possible by means of tonal and textural comparisons combined with basic geographic knowledge of the study area to:

- (a) prepare regional or reconnaissance vegetation maps; (b) delimit vegetation zones as they vary with elevation and also delineate the altitudinal timber line; (c) trace burn patterns of previous forest fires; and (d) identify species from inference in areas characterized by near monospecific stands. In some of these studies both horizontally polarized transmitted and return signals (HH) and horizontally polarized transmitted signals and vertically polarized return signals (HV) were analyzed. Differences between these two types of polarized imagery have indicated the possibilities of obtaining more information from the study of both types than from the study of one type alone. Preliminary results indicated differences between HH and HV made it possible to more readily distinguish between forested and non-forested boundaries. In the study of the various areas, quantitative measurements of probability density curves for representative vegetation types, as indicated by film densities, were prepared in an attempt to aid in the separation and mapping of various vegetation types. Some distinct differences between vegetative types were noted, but further studies of this technique are required.

From the discussion of the investigations reported on radar applications in the "open" literature, it is apparent that at present, measurements of the parameters affecting the imagery are not performed during aerial flights. The approach used for the interpretation of aerial radar imagery by the various investigators is the same as that used for the interpretation of infrared imagery and aerial photography. In this

approach, no measurements are made during the time of the aerial flight. The imagery is then evaluated and attempts are made to determine the influence of the various parameters by comparison to standard aerial photography and/or by field checking of the project area.

Some efforts to evaluate some of the parameters or to increase the amount of information extracted from the radar imagery are in progress or have been proposed. In an effort to evaluate the effect of rock type, size, and depth of burial on radar returns, a radar geology test area was constructed by the Corps of Engineers in 1965 at Wilcox Playa, Arizona (178). In this project area various materials of various gradations such as sand, quartzite, basalt, limestone, copper ore, rhyolite, granite, and back fill were placed in 100 feet by 100 feet by nine inch patches at varying depths of burial from 0 to 24 inches. Corrugated steel sheets 40 feet by 40 feet were also buried at various depths in the test area. This test site is available to all researchers wishing to obtain coverage of this site for research purposes. No reports on overflights over this test area have been made yet.

In another approach, several researchers have suggested the use of variable-frequency radar measurements (6) (35). Since the amount of back-scatter and the depth of penetration varies with different frequencies and different target materials, this technique offers a means of determining the textures of target materials, and depth to the water-table and discontinuous subsurface layers.

Microwave Radiometry

The field of passive microwave radiometry is the least developed of the relatively new sensor techniques. In some respects passive

microwave equipment resembles infrared equipment, and in other respects it is akin to active radars. The physics is infrared physics; the instrumentation is generally radar equipment.

Comparison to Infrared Systems. Microwave sensing in many ways parallels infrared. An appreciation of some of the similarities and differences is necessary in order to evaluate the conditions or applications where each would be most beneficial.

(a) Both systems employ electromagnetic radiation emitted by materials. This radiation is a function of the material's absolute temperature, the wavelength of reception and the emissivity of the materials. As noted in Figure 4 (page 21) and equation 2.6 (page 22) the total amount of energy emitted from an object in the infrared region is proportional to the emissivity and to the fourth power of its temperature. In the microwave region, the total amount of energy emitted is proportional to the emissivity and the temperature to the first power (31). This would be apparent if the curves in Figure 4 were extended out to the microwave region. Also evident would be that the amount of energy emitted in the microwave region would be correspondingly less. Nevertheless, even though the power emitted and temperature effects are much greater in the infrared region, the sensitivity of the units which can be used in the microwave region are much greater; therefore, these factors compensate to allow equivalent operation in both regions.

(b) Each technique receives the radiation as a random noiselike energy which must be integrated so that the output is smoothed to reduce fluctuation peaks. In each the amount of smoothing time required is inversely related to the bandwidth of the receiving system. The detector

noise temperature is presently much better for microwave receivers than for the infrared receiver. This factor offsets the naturally higher bandwidths available for infrared detectors making the temperature resolution about equal for both systems (63).

(c) The angular resolution of each system is dependent upon the aperture of the antenna or lens used for reception. In each, optical relationships are involved since the energy is propagated in a nearly straight line, ray-like fashion.

(d) The attenuation of the atmospheric constituents for microwave is much lower than for infrared. No principal component attenuates microwave at wavelengths above 1.8 centimeters (63).

(e) The emission of electromagnetic energy from terrain objects is not entirely a surface related phenomenon. As wavelength increases, the energy contribution of the underlying depths becomes sizable, thus allowing long wave radiometry a capability of determining conditions at depths of several centimeters in reasonably solid materials and meters for loose materials having a lower dielectric constant and/or lower conductivity (63).

(f) Similar to infrared sensors, the main element for the interpretation of microwave radiometry is that of tone and texture. The elements of surface form can not be directly evaluated because there is no stereoscopic coverage in this region. However, all the parameters which affect the tone and texture pattern on infrared imagery are not applicable to microwave radiometry. In addition, since the instrumentation and frequencies are the same as those of radar, some of the parameters that affected the radar tonal pattern will also affect the microwave radiometry.

Parameters Affecting Microwave Radiometry. As indicated above, it is seen that some of the parameters affecting the tonal patterns on both infrared and radar imagery will affect the tones on imagery obtained by microwave radiometry. The major parameters include the following:

1. Emissivity
2. Temperature
3. Angle of incidence
4. Surface roughness
5. Polarization
6. Frequency
7. Relative dielectric constant
8. Equipment factors

Studies in the microwave region indicate that the emissivity of target materials also vary with wavelength (or frequency) as was demonstrated in the infrared region (see Figure 27, page 110). Conway and Sakamoto (31) illustrate this condition with an example for water. Water has an emissivity of about 0.05 at low microwave frequencies and a value of approximately 0.3 at 70 kmc. Comparing these values to the emissivity of water in the infrared region which is about 1.0, it is apparent that different tonal patterns would be present for water in the two types of imagery. These differences are not only true for water but for other materials as well. An additional factor to consider, is that in addition to differences in emissivity for the same target material, it must be remembered that the emissivity which affects the tonal pattern in the microwave region also depends on the emissivity values of subsurface layers if a layered system is present. The amount of

subsurface emissivity which will affect the microwave imagery in turn depends on other factors such as the frequency of sensing, the relative dielectric constant of the surface layer, the surface roughness, the angle of incidence at which the surface is observed, and the type of polarization.

The signal received at the antenna consists of two components: a steady state or d-c component ($\epsilon_a T_a$) and point-to-point variations in energy ($\epsilon_e T_e + r_e T_s$). These are illustrated in Figure 31. The steady state component is a characteristic of the antenna while the point-to-point variations provide the vast majority of the information obtained by microwave radiometers. This latter component is composed of the radiation emitted by the target material ($\epsilon_e T_e$) and the incident energy striking the target material which is reflected up to the antenna ($r_e T_s$). The source of incident energy in the microwave region is normally the sky which is generally quite low in its emission temperature (T_s) (63).

Another important consideration is that the temperature received at the antenna may be influenced by the angle of incidence of the impinging radiant energy. Figure 32 illustrates the difference in apparent temperature between various materials (for horizontal polarization) and their dependence on the incidence angle.

Equipment factors of importance include antenna characteristics, bandwidth, and receiver characteristics. As indicated for radar systems, the antenna size and beamwidth affect the resolution of the system. Also, the lower the frequency (longer the wavelength) the greater the depth from which information is received for a given material. Conway, et al.(30) indicate that the bandwidth is determined by the scan rate

FIGURE 31. RADIATION FROM TERRESTRIAL OBJECTS.

After CONWAY et. al. (30)

FIGURE 32. VARIATION OF APPARENT TEMPERATURE AS A FUNCTION OF ANGLE OF INCIDENCE.

and antenna beamwidth. If scan rate is increased or antenna beamwidth narrowed, the bandwidth is increased. The bandwidth in turn is an important parameter affecting the amount of power received at the antenna and the temperature sensitivity of the radiometer. These relationships as shown by Hodgkin (63) are:

$$P_r \sim T'_b B, \text{ and } \delta T \sim \frac{TF}{(B\tau)^{\frac{1}{2}}}$$

where

P_r = power received

T'_b = apparent temperature⁸

B = bandwidth

δT = temperature sensitivity

T = temperature, degrees Kelvin

F = input noise factor

τ = integration time constant

Both F and τ are parameters of the radiometer which directly affect its temperature sensitivity. Hodgkin indicates that receivers can now be constructed which would provide a capability of $\delta T = 0.03^\circ\text{K}$.

Other parameters listed under the infrared and radar parameter discussions such as seasonal changes, location and topographic position, contrast with surroundings, uniformity and variability, moisture content and properties of the processing and display systems would also influence the final tonal images of the microwave imagery.

⁸ Apparent temperature is defined as the temperature at which a perfect black body radiator would radiate the same amount of energy (31).

Investigations of Microwave Radiometry and Potential Applications.

Very little has been reported in the use of microwave radiometry for remote reconnaissance of natural terrain features. Conway et al.(30), performed aerial test flights with a K_u -band gradient radiometer where terrain maps were prepared. The repeatability of maps produced under varying climatic and diurnal conditions were checked by flying over a number of targets several times under a variety of conditions (e.g., day, night, clear, rain, snow). The maps were correlated to aerial photography and topographic maps. The comparisons indicated that the maps were repeatable under a wide range of conditions. Also shown was that areas containing water surfaces which were resolvable with the radiometer beamwidth were easily correlated to both topographic maps and photographs because the land-water boundaries had a large temperature differential. No significant advantages of this sensor were indicated. Skiles, et al. (160), compared aerial infrared imagery and microwave radiometry (operated at X-band frequency) obtained simultaneously over a test area. A comparison of the microwave and infrared terrain data was shown in the paper. Similarities of patterns were noted for both types over certain general terrain features but no attempt was made in the paper to discuss the reasons for the differences or the potential value of microwave systems. Pascalar and Sakamoto (140) demonstrated the application of microwave radiometry for determining the thickness of an ice layer under laboratory conditions. Chalfin and Ricketts (18) conducted experiments with a 3.2 mm. microwave radiometer. They concluded that in general, the gross features corresponded very closely to visual photography of the same area. However imagery taken in heavy

fog showed the scene almost as clearly as when taken in clear weather; whereas, visible and near-infrared photography showed practically nothing.

Some potential applications of radiometry have been listed by Hodgins (63) and Vivian (183). Some of these include:

1. Determination of soil moisture contents as related to temperatures. Surface temperature could be determined by infrared sensors and deep soil penetration by microwave sensors.
2. Crop cover density could be measured after certain correlations had been determined for similar crop varieties. Also, it might be possible to measure plant growth by adjusting the received wavelength into the oxygen resonance region.
3. Water, land, and ice have widely differing apparent temperatures. Measurements can be made by aircraft survey even through heavy overcasts. Some of the possible applications include differentiation of land-water boundaries, iceberg surveillance, measurement of ice thickness and crevasse detection.
4. Measurements of differences in subsurface earth strata would be possible with long wavelength radiometry.
5. Sea or lake water temperatures could be measured by using infrared sensors for surface temperatures and the microwave sensor for its ability to penetrate to depths of a few wavelengths.

Although some of the previously mentioned applications and potential applications can be accomplished to some degree with other sensors, the field of microwave radiometry offers another region of the spectrum for the analysis of the properties of various target materials. As indicated in the discussion of factors affecting microwave radiometry, the reaction of materials to this form of sensing is different than in the other regions of the spectrum. Thus it offers another link in the overall multisensor technique of analyzing the reactions of matter to radiation in different portions of the electromagnetic spectrum as a means of identifying the material. As previously stated, this technique is still in the developmental and research stage.

Multisensor Approaches

The discussion in this chapter has been on the sensor systems available for remote reconnaissance, the parameters that affect pattern elements on the final photography or imagery used for interpretation, and a summary of sensor applications in various fields. Additional items to be considered in a multisensor approach are:

1. What factors to consider in choosing the sensors for use in a multisensor project; and
2. What types of multisensor systems are available.

Factors to be Considered in Multisensor Approach

The factors that need to be considered in planning a multisensor project include the following items:

1. Purpose
2. Economics

3. Time
4. Personnel
5. Equipment availability
6. Techniques of handling and interpretation
7. Security
8. Area accessibility

It is not possible to discuss all possible ramifications of these items in planning and carrying out a multisensor project. Naturally, at any given time or for any given project, any one of the factors may be controlling; however, ultimately all factors have to be considered.

In a multisensor approach for military reconnaissance purposes the main goal is to obtain information on military targets and terrain conditions in as short a time as possible, at any time of the day or year, and in inaccessible areas. In many cases, the targets of interest are not stationary but are continuously shifting positions. The problem of costs, although important, is not as critical as in civilian applications. Also, there are no problems of security limitations as to the availability of information critical to the project. The most recently developed equipment is generally available for achieving the project goals. In actual military conditions, the areas of interest are inaccessible and the number of qualified interpreters available are limited. Therefore, the development of equipment and techniques for military projects are aimed toward utilizing all the sensors possible and taking as many simultaneous measurements as possible. This results in the collection of a large amount of data. Reliance on automatic data collection, reduction and interpretation techniques is thus an important part of the

military approach. This approach is a very costly one.

The goals or approaches for civilian projects are different than those for military projects; therefore, the emphasis of some of the factors is different. Economics or cost becomes a prime factor in most civilian projects. This can limit the number and type of sensors that can be utilized as well as the amount of simultaneous measurements that can be made and the amount of auxiliary automatic data collection and reduction equipment that can be used. The emphasis on "time" in most civilian projects is not on obtaining the information as quickly as possible or at any time of the day or night, but on obtaining the information at the proper time of the day and season of the year. In addition, the project area is usually accessible; therefore, evaluation of parameters can be carried out before, during, or after the flight program. Major problems with civilian projects as compared to military projects are those of security and availability of equipment. Only a few organizations in the United States are capable of obtaining multisensor coverage and the equipment used by these organizations is "classified"; therefore, all the imagery obtained is classified. In order to obtain the imagery for evaluation, the civilian groups have to have a security clearance and the "need to know". The availability of "unclassified" infrared and radar sensors is very limited. To the author's knowledge there is only one "unclassified" infrared sensor system which has been developed recently⁹, and two "unclassified" radar sets (48). These systems are not the latest state of the art.

⁹The Bendix Corporation has recently announced the development of an "unclassified" thermal mapping and infrared imagery system. Specifications indicate the standard unit can only scan in the 2-5.5 micron range. Special modifications and accessories, which they indicate are available, are needed to scan in the 8-14 micron range (12).

The differences in the goals of the various disciplines within the civilian field (e.g., agriculture, engineering, forestry, geology, etc.) will also determine what factors are of importance in the choice of multisensor units. For example in the type of work reported by Hirsch for forest fire surveillance (61)(62), time is an important factor and the main type of sensor needed is an infrared sensor. This equipment has to be available for use on short notice and at any time of the day when the need arises. In comparison, for a multisensor project evaluating vegetative cover, (e.g., type of crop or tree species) other factors are of importance. Time of the year is the important factor as vegetation differences are continuously changing and it may be desirable to have multisensor coverage several times during the year so as to coincide with the peak differences for various vegetation types (see Figure 16a(page 72)). The need for multisensor coverage several times during the year makes the project very costly; thus, economics is an important factor. In addition, since a considerable amount of data are accumulating for each flight, and from the several flights made during the year, the problem of data handling and interpretation also becomes an important factor.

These examples indicate just a few of the possible variations in approaches and the influence of the various factors and demonstrate a very important point. The results or conclusions obtained in any multisensor project will definitely be influenced by the goal of the project, the approach taken and the influence and limitations imposed by the various factors. Therefore, care should be taken in attempting to apply the results reported by an organization in one field of endeavor into

another field of endeavor, or attempting to apply the results obtained by one data collection system to a different system of data collection.

Types of Multisensor Systems Available

The author does not presume to know or be aware of all the airborne multisensor systems presently available or in the developmental stage. The purpose of this section is to describe some of the systems presently available, the type of sensors utilized and the final form of the data obtained for interpretation. In addition, some discussion will be included on the differences of approach of some of the systems and the cost factor for obtaining multisensor coverage.

Multisensor systems of all types and complexities from the simpler sensor systems to the multisensor, mutispectral, and multiband combinations have been developed by various groups. Examples of less complex multisensor systems have been reported by Valovcin (131), Ory (138) and Conway, et al. (30). Valovcin described the system developed by the Air Force Cambridge Research Laboratories which is mounted in a U-2 aircraft. It is composed of a Barnes Infrared Radiation Thermometer scanning in the 7.5-13.5 micron region, a 70 mm. camera mounted slightly in front of the radiation detecting unit to determine the field of view of the detector, and a panoramic camera to obtain horizon-to-horizon display. The unit described by Ory is the HRB-Singer Reconofax system which is a dual-channel, electro-optical scanner which can scan from the ultraviolet to the far infrared. Both channels of this system can be utilized in the same region, one scanning the complete region and the other utilized to discriminate certain levels of the signal, or they can be utilized in two different regions of the spectrum. The system

reported by Conway et al., senses in the microwave and visual regions. It consists of a microwave radiometer, a bore sight camera to obtain the field of view of the antenna and a K-17 visual camera, all mounted in a B-25 aircraft.

More complex multisensor systems have been developed by various groups. Some examples of these include the systems developed by (1) the Air Force Avionics Laboratory at Wright-Patterson Air Force Base in Ohio, (2) Texas Instrument Incorporated in Texas, (3) the National Aeronautics and Space Administration (NASA) in Texas and (4) the Infrared and Optical Sensor Laboratory, Institute of Science and Technology of the University of Michigan. The Avionics Laboratory system contains side-looking radar (K-band), a two spectrum electro-optical scanner that can scan the infrared region and the visible region and two T-11 aerial cameras. This system is mounted in a Convair 440. The Texas Instrument group has a B-25 aircraft in which is mounted an infrared scanner, side-looking radar, two aerial cameras and two hypersensitive radiometers (89). In addition, an airborne gamma ray spectrometer has recently been added (92). The NASA group has equipped several planes, one of which is a Convair 240A. It contains a microwave radiometer, metric camera system, multi-band camera system, an ultraviolet imager, a recon IV imaging IR, redop scatterometer and doppler chirping radar (5a). The University of Michigan group has recently completed a new multisensor system which is mounted in a DC-3 aircraft (143). It contains a multichannel detector scanning the spectrum from the near ultraviolet through the visible to the far infrared obtaining simultaneous coverage of all the bands scanned in these regions. Photographic cameras and a multiband camera are also

included in this system.

From the description of these various multisensor systems it is evident that each group essentially has its own approach as to the type of equipment utilized and the type and amount of data obtained. The multisensor systems require the use of large planes which accordingly are costly to outfit and operate, making the collection of multisensor data much more costly to obtain compared to the standard aerial photography.

The ideal multisensor system is one which obtains simultaneous coverage of the test area with the various sensors, at the same scale, the same detail, and on the same format. This is to facilitate the comparison of the imagery between various sensors as well as to facilitate handling of any data and measurements made on the imagery. This latter item is becoming an important factor as these systems generate a lot of data in a short time and handling and analyzing all the data becomes a difficult and time consuming effort. Many of the systems described above obtain simultaneous coverage by two or more sensors. Although all of the final imagery may be on film, for almost all these systems, they are not at the same scale, they do not show the same amount of detail and they do not have the same format. In fact, in sensor systems in which side-looking radar is included, there is no coverage obtained by the radar sensor directly below the aircraft: a region which contains the maximum information for other sensor systems. These items increase the difficulty of interpreting and comparing the imagery obtained by the various systems. Also, it makes it difficult to compare measurements (e.g., densitometric measurements) made on the various films. This is not true for the new

system developed by the University of Michigan group. Their multi-channel detectors which generate imagery from the near ultraviolet to the far infrared in many bands, obtain simultaneous coverage of the test area at the same scale, on the same format and with about the same detail. This facilitates direct comparisons and measurements between the various channels (143).

Next to the availability or access to groups who can fly multisensor coverage, the type of sensors available, and the security problem, the factor of cost of obtaining the multisensor coverage is a very important item. In fact, for the usual photo interpretation projects in the engineering field, the cost factor alone would eliminate any chances of obtaining multisensor coverage. The purchase price and operating costs of the larger multi-engine aircraft; the cost of the sensor equipment, auxiliary equipment and modification and installation costs; and the increase in the number of support personnel needed make it exceedingly costly and difficult for any group but those of the larger organizations or those sponsored by large military contracts to outfit their own aircraft. The cost of obtaining this coverage from an organization with multisensor capabilities, is much greater than the cost of obtaining the usual aerial photography. For example, the cost of obtaining normal aerial photographic coverage is approximately \$20 to \$40 an hour of flying time including aircraft, personnel and camera costs.¹⁰ The costs for multisensor coverage varies from \$100 to \$1,000 per hour depending upon type of aircraft and performance characteristics required (157).

¹⁰ Estimates based on project costs for photographic coverage performed by the Indiana State Highway Commission.

Investigations of Multisensor Imagery

In the interpretation or evaluation of infrared, radar and microwave radiometry the imagery is compared to normal aerial photography since the only pattern elements available for the interpretation of these sensors are tone and texture. Thus, an estimation of the value of these sensors is usually based on how much corroborating or additional information they furnish compared to the aerial photography.

Although several reports have been written on the potential of infrared, radar and microwave sensor systems, very little has been written showing results of actual comparisons of these systems. One such study was recently reported by Meier et al. (114). This multisensor project was conducted over the South Cascade Glacier in the State of Washington. From a preliminary comparison of panchromatic, color, color infrared and multiband photography (from the nine-lens Itek camera); infrared imagery; and side-looking radar; the following conclusions were indicated:

1. Near-infrared is the most effective in distinguishing snow from ice and old firn; whereas, short-wavelength visible light may be better for distinguishing moraine from ice;
2. Color infrared film shows more detail than color or individual narrowband photographs both on the glacier and on adjacent moraines; and
3. Crevassed areas, moraines, and other linear structures show up clearly on radar imagery, with parallel-polarized images (i.e., HH or VV) generally superior to cross-polarized ones. Also, gross textural differences between ice, snow and surrounding bedrock are apparent even when both are covered with a thin snow layer.

Other multisensor studies which compared three or more sensors have been performed, but these are of a classified nature and results are not readily available.

Summary of Approaches Applicable to Soils Evaluation

Discussions in this chapter have indicated in detail the parameters affecting the final pattern elements for each sensor and have included examples of the application of these various sensors in engineering and in several other disciplines (e.g., geology, forestry, agriculture). The broad scope of the literature review was intended to not only demonstrate what had been accomplished with the various sensors for the interpretation of engineering soils, but also to indicate the applications and techniques developed in other fields which might be applicable to engineering soils analyses. As a summary to this chapter, a listing is included, for each type of sensor, indicating those conclusions demonstrated by various investigators which will assist in engineering soils analyses. Unless otherwise stated, the conclusions are based on comparisons made with the standard black-and-white panchromatic film.

Visual and Photographic Infrared Sensors. Several different techniques have been demonstrated as being of assistance for the interpretation of soil and soil conditions. These include: (1) the use of color photography; (2) the selection of particular film types, film-filter combinations, image enhancement and use of multiband photography; and (3) the use of spectral reflectance measurements.

The preference of color photography for the interpretation of soils has been noted for the following reasons:

1. Many more tones can be differentiated on color than on black-and-white photography and a greater contrast exists between target materials. These factors make soil differences more distinct;
2. The more natural appearance of the terrain makes it possible to make a more positive identification of various features; and
3. Color film has a finer grain making possible greater magnification for the same scale and thus, more details can be interpreted on the color.

Various investigators have indicated examples of how the selection of film type, or film-filter combination, or use of multiband photography, together with image enhancement techniques have assisted in interpreting soils and soil conditions. Some reasons for the value of this technique for interpreting soils and examples include:

1. By the proper selection of film type, film-filter combinations or by image enhancement it has been shown that the contrast of various materials and conditions can be increased with respect to the surroundings. This increase of contrast increases the possibilities of interpreting the material and makes soil differences more distinct;
2. Due to the molecular make-up of various materials, they will react with radiation in different ways throughout the spectral region. By the proper choice of film-filter combinations, regions of the spectrum can be selected where large differences in materials of interest exist. This

increases ability to interpret the various materials. The problem here is determining these regions where maximum contrast of the materials of interest exist; and

3. In the comparison of film types presently available various investigators have indicated that aerographic infrared, or color infrared films increase the interpretability of drainage conditions (i.e., drainage patterns, wet zones, seepage zones, etc..) and vegetation patterns, both of which can aid in determining soil conditions.

Spectral reflectance measurements of various target materials have been shown to be of value in obtaining information assisting in determining soil and soil conditions. Some examples of these include:

1. Various investigators have shown that different spectral reflectance curves are obtained for different materials and these curves can be utilized to differentiate between materials. However, as indicated in the discussion of these matters, there are numerous factors that affect these curves so that diagnostic curves for any particular material can not be obtained. Their value is indicating relative differences between materials under the given testing conditions;
2. Laboratory spectral reflectance curves have been shown to be of value in certain cases for determining the film-filter combination that will show the greatest contrast between materials of interest; and
3. Aerial spectral reflectance measurements together with sampling of the various materials present enabled an investigator

to differentiate between sand deposits of different gradations and mineralogical composition. It was only applied to sand deposits under specific conditions. It was not shown that it could be applied to materials other than sands.

Infrared sensors. Very little has been reported regarding the value of infrared sensors for the interpretation of soil or soil conditions. Due to the effect of the various parameters on the final imagery, only specific examples are given in the open literature. No general conclusions can be stated because under different conditions, the results could be reversed or negated. Therefore, the following examples only indicate specific cases where the infrared was of assistance. Any attempt to generalize can cause gross errors in interpretation.

1. Specific examples have been shown where differences in certain rock types were determined on the imagery. Where these are present, differences in soil types could be correlated to the differences in the rock types.
2. Evaluation of multiband and multisensor photography and imagery indicated that tonal reversals occur which make it possible to differentiate between wet soils, dark colored soils, and light colored soils.
3. The difference in temperature of terrain features due to moisture conditions has been used very successfully for determining several terrain features such as drainage patterns, large seepage zones and differences in various materials due to moisture conditions. The contrasts in patterns caused by these features, in many cases, can be

correlated to differences in soils and soil conditions. It must be remembered however, that because of small scale, and image distortions due to scanning techniques, precise boundaries and accurate drainage patterns can not be determined on the imagery.

4. Laboratory infrared spectroscopic reflectance measurements have indicated relationships between reflectance, soil types and moisture contents. These relationships have been found to be especially sensitive in the regions of maximum water absorption. Results have indicated that by determining two of these features, the third one can then be evaluated. These relationships have not been determined as yet in the field or from the air.
5. Laboratory and field spectroscopic reflectance measurements also have been reported for various rocks, minerals, and soils. By determining variations of emissivity or emittance with wavelength, differences between various materials are evident due to their reststrahlen effects. For rocks and minerals, these curves are fairly typical although there are some parameters that can affect the final curves obtained. For the measurement of soils in the field, variations in the typical curves were noted for such factors as moisture content, time of day, and cloud cover. Thus these curves are not diagnostic for the materials, but only indicate relative differences between materials at a given time and under given conditions.

Microwave Sensors. Sensors in this field include both active radar sensors and passive microwave radiometry. No results have been reported in the open literature indicating the value of microwave radiometry for determining any features that would assist in evaluating soils or soil conditions. Various examples are reported for radar imagery which are of assistance in determining soil and soil conditions. Most of the conclusions reported for radar imagery, as was the case for infrared imagery, were reported for specific examples and any attempt to generalize from the specific cases can be misleading. The following are some examples indicating how radar imagery can be of assistance in determining soils and soil conditions:

1. A laboratory type installation has shown that the depth of penetration of radar waves for a given angle of incidence depends on the frequency of the wave, and the moisture content or relative dielectric constant of the target material. Moisture contents were found to be directly related to the relative dielectric constant for a given frequency, and were essentially independent of soil type [Figure 29 (page 146)]. Thus an indication of dielectric properties of soils and hence, their moisture contents may be possible with the use of certain radar frequencies;
2. Various investigators have reported results of the evaluation of tonal patterns present on radar imagery as related to bedrock and soil conditions. For a given test area, differences in strength of signal return as related to brightness of tone on the imagery enabled the investigator to separate

different bedrock and soil conditions. However, no general conclusions can be obtained from these studies as reports for similar materials from different areas indicated different relative tonal pattern relationships;

3. It has been reported that radar provides a fairly accurate indication of geologic structure, lithology and major drainage systems in mountainous regions. These features are not as distinct in areas of low relief. In addition, various investigators have indicated that differences in vegetation and vegetation patterns can also be determined for given areas of study. Therefore, by determining these features in a given area, some indications of soils and soil conditions can be inferred. It must be remembered that because of the small scale, the presence of radar gap, and radar shadows as well as image distortions, precise boundaries for these various elements can not be determined on the imagery; and
4. Because surface texture and geometry directly affect the signal return at a given frequency, several investigators have proposed the technique of determining these features by noting the change in amount of signal return received for different frequency radar waves at a given aspect angle. This procedure has not been tried as yet in actual practice, but in the laboratory set up, various frequencies have been used and differences in reflected patterns noted.