MID/THERMAL IR REMOTE SENSING

FY82 RTOP #677-21-21 SUMMARY REPORT

by

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OBJECTIVES:

In order to effectively utilize information derived from the mid to thermal infrared (mid/thermal IR) region of the electromagnetic spectrum (0.76μm-14μm), research needs to be conducted dealing with the basic factors associated with land covers that influence mid/thermal IR reflectance and emissivity. Fundamental to such research is an understanding of the relationships between the life processes or physical state of a land cover and the phenomena that are measured in the mid/thermal IR region. Upon increasing our knowledge of these relationships, data collected in this region of the spectrum can be used to augment studies of a larger scope, thus contributing to our comprehension of complex global interactions. The objective of the project described in this document is to conduct such relational research using both aircraft - and spacecraft - acquired mid/thermal IR data, augmented in certain instances by ground based studies. As a direct result of the analysis of information collected, our knowledge of fundamental relationships between land covers and their associated mid/thermal IR spectral properties will be extended.

The major thrust of this research project will be directed toward vegetated land covers, but soils and other land covers will also be examined. Two areas of interest will be investigated in this project. The first, based on the mid IR (0.76-3.0μm), will have as its goal the determination of relationships that exist between leaf water content and data recorded by Earth-orbiting satellites. The second area of interest deals with thermal studies, (3.0-14μm), and will focus on the estimation of plant temperature, which is not an end in itself, but rather an initial point from which other studies requiring a knowledge of temperature can begin.

This document summarizes work conducted during FY82 on NASA RTOP 677-21-21, task #1, Mid IR/Thermal IR Sensing of Land Cover Types, (literature review and design of the experiment). Beginning in FY83, this study is continued on RTOP 677-21-28, task #1.

BACKGROUND:

It appears that initial research into the spectral properties of land covers was directed, to a large degree, at gaining an understanding of the interaction between green plants and light, particularly in the area of photosynthesis. As early as 1862, Simmler recognized that light striking a plant leaf was either reflected (which occurs mostly at the outer epidermal surface), absorbed by internal plant cell constituents (mostly the chlorophyls) after first having penetrated the outer leaf surface, or scattered internally and subsequently exiting through either leaf surface. Unfortunately, as pointed out by Mestre (1935), much early work (such as Simmler) was prevented from evolving to any great degree not by the lack of sufficient analysis of such things as the distribution of solar illumination of a plant leaf, as might be expected, but rather by the "inability to make the requisite measurements" of internal absorption, etc.

Technological advances led to the ability to make initial (although somewhat "coarse") measurements, and plant physiologists and photobiologists used the new instruments to further their understanding of plant/light interactions. An exceptional summary of "state-of-the-art" analysis conducted by fellow scientists using several "new" devices is presented by Mestre (1935). However, even with the improvements made to measurement devices (e.g. vacuum type photoelectric cell with vacuum tube amplifier, Ulbricht sphere, etc.), spectral measurements were restricted to the absolute wavelength (and energy) sensitivity of the devices used (generally between 0.43-0.85μm although some photographic type systems were able to reach 1.2μm (Harrison, 1929, 1934)). Thus, at least in a broad sense, the mid/thermal IR regions were only dealt with on a broad theoretical basis (if at all), as the routine measurement capability required to collect the necessary data (at required resolution) was yet lacking. This situation existed at least through 1946 for most researchers (Rabideau, et. al. 1946).

Further improvements made to measurement devices resulted in an increased interest in spectral research in the 1950's. Billings and Morris (1951) used a Beckman DU quartz spectrophotometer to make reflectance measurements of plant leaves of numerous species in 0.025μm intervals from 0.04-0.08μm, and in 0.05μm intervals from 0.8-1.1μm. A $MgCO_3$ block was used as a reference standard. Their results agreed in general with those of earlier researchers. Deviations between the results obtained and those of earlier studies were attributed to the "inferior" characteristics of previous instruments used. Billings and Morris (1951) also state "In general, the (reflectance) curves for green leaves all have similar shapes, varying principally in magnitude." Thus, as early as 1951, it was quantitatively demonstrated that plant leaf spectral characteristics vary with species and with the environment in which plants occur, and Billings and Morris (1951) allude to the use of this variability to discern differences between major plant groups.

In a study which followed, Gates and Tantraporn (1952) used a Perkin-Elmer infrared spectrometer Model 12C, equipped with NaCl prisms, to determine the reflectivities of the leaves of numerous deciduous trees and shrubs in the 0.9-3.0μm region (mid IR). For measurements between 3.0μm and 25μm, a Baird infrared spectrophotometer with NaCl or KBr prisms was employed. In both cases, a Globar was used as the infrared radiation source. To quote from that study:

"The reflectivity of leaves in the infrared beyond 2.0μm is generally small, being less than 10 percent for an angle of incidence of 65°, and less than 5 percent for an angle of 20°. The reflection takes place principally at the outer epidermal surface, with about one fifth or less of it contributed by the epidermal-palisade boundary. The upper surface reflects more than the lower, old leaves more than young, and the shade leaf more than the sun leaf. For each of these, the inverse is true in the visible. The structure of the leaf surface and the covering by the cuticle appear to be the factors determining the reflectivity. The transmissivity of leaves is zero in the infrared beyond 1.0μm, although the transmissivity of the clear epidermis is 40 percent or more." The significance of the study conducted by Gates and Tantraporn (1952) lies in the fact that the spectral variability of plant leaves of differing species was established in the thermal IR, which is well beyond the limits of the mid IR (< 3.0μm).

By the mid-50's, research in areas other than vegetation/light interactions had begun. As a classic example, Kislovskii (1959) calculated the electro-magnetic properties of water and ice from about 2.2μm to the radio-region of near 1.7mm, including both the mid and thermal IR regions. His spectral curves for water and ice still form the basis of ongoing studies and represented state-of-the-art analysis for his time.

The next major advance in instrument technology resulted in albedo (reflection) measurement devices which were capable of being placed in low-flying aircraft or earth orbiting spacecraft. However, unlike measurements made in the laboratory at close proximity to the target, data collected by such "remote" instruments contained errors induced by altitude, motion of the aircraft, and the type of sensor being used, as well as perturbations which result from the non-uniformity of the intervening atmosphere.

Aircraft motion and altitude related errors can be quantified, as shown by Dutton (1962), who developed mathematical relationships between actual albedo associated with a target and the values recorded by various radiation sensors. In addition, weighting functions for modifying output data values are presented for both narrow and wide beam (angle of look) devices overcoming, in part, sensor induced errors. Bauer and Dutton (1962) extended the sensor analysis, showing how a "beam" sensor might be calibrated to a hemispherical device. Errors related to the atmosphere were minimized in both studies by operating the aircraft at very low altitudes.

With the development of sensors capable of accurately measuring mid/thermal IR radiation, research in these areas began to accelerate. It appears as if two parallel lines of study developed, one line keying on mid IR (0.76-3.0μm), and another aimed at thermal IR (3.0-14μm).

PAST RESEARCH: MID IR

Interest in the mid IR region is based at least in part on the fact that on a clear day more than 50 percent of the sun's radiation which reaches the earth's surface is contained in the infrared beyond 0.76μm (Gates & Tantraporn, 1952), with a vast majority falling in the 0.76-3.0μm region (Gates, 1966). Thus, with so much incident solar radiation in the mid IR region, a uniform change in the percent of energy reflected would result in a much greater (and hence more easily detectable) shift in the spectral response in the mid IR than in the visible region. With early measurement devices this was a particularly significant consideration.

The level of technology has also had an impact on research in the mid IR, since it was historically easier to construct devices that could make measurements in that region (compared to the thermal IR region). Thus, with measurement devices becoming more readily available and able to make measurements more precisely, researchers worked in this region in ever increasing numbers.

Another factor which leads to the high interest in the mid IR region is related to a target's physiological or chemical response to radiation with wavelengths between 0.76 and 3μm. In this respect, the nature of some of the earliest work performed in the mid IR region were investigations of plant reflectance. The study by Mestre (1935) cites numerous earlier studies of the reflectance of plants in the visible and near IR (out to ∽ 0.85μm in this case). It was deduced that the characteristic green-leaf reflectance curve in the visible was dominated by the absorption of incident radiation by plant pigments, the most significant of which are the chlorophylls. Thus, in the region between 0.4-0.7μm, leaf reflectance of incident radiation is quite low, frequently less than 10 percent with a peak reflectance (near 5%) at about 0.55μm (Figure 1) (Knipling, 1970). This accounts for the green color of leaves as seen by the human eye.

At wavelengths longer than about 0.7μm, and out to about 1.3μm, reflectance of a typical green leaf increases dramatically, with values of 50 percent being common. This high reflectivity is due primarily to differences which exist between the refractive indicies of hydrated cell walls and the intercellular air space in plant leaf tissues (Mestre, 1935; Gausman, 1974). Then, owing primarily to absorption by water in the intercellular spaces, (Allen & Richardson, 1968; Allen, et. al. 1969, 1971;

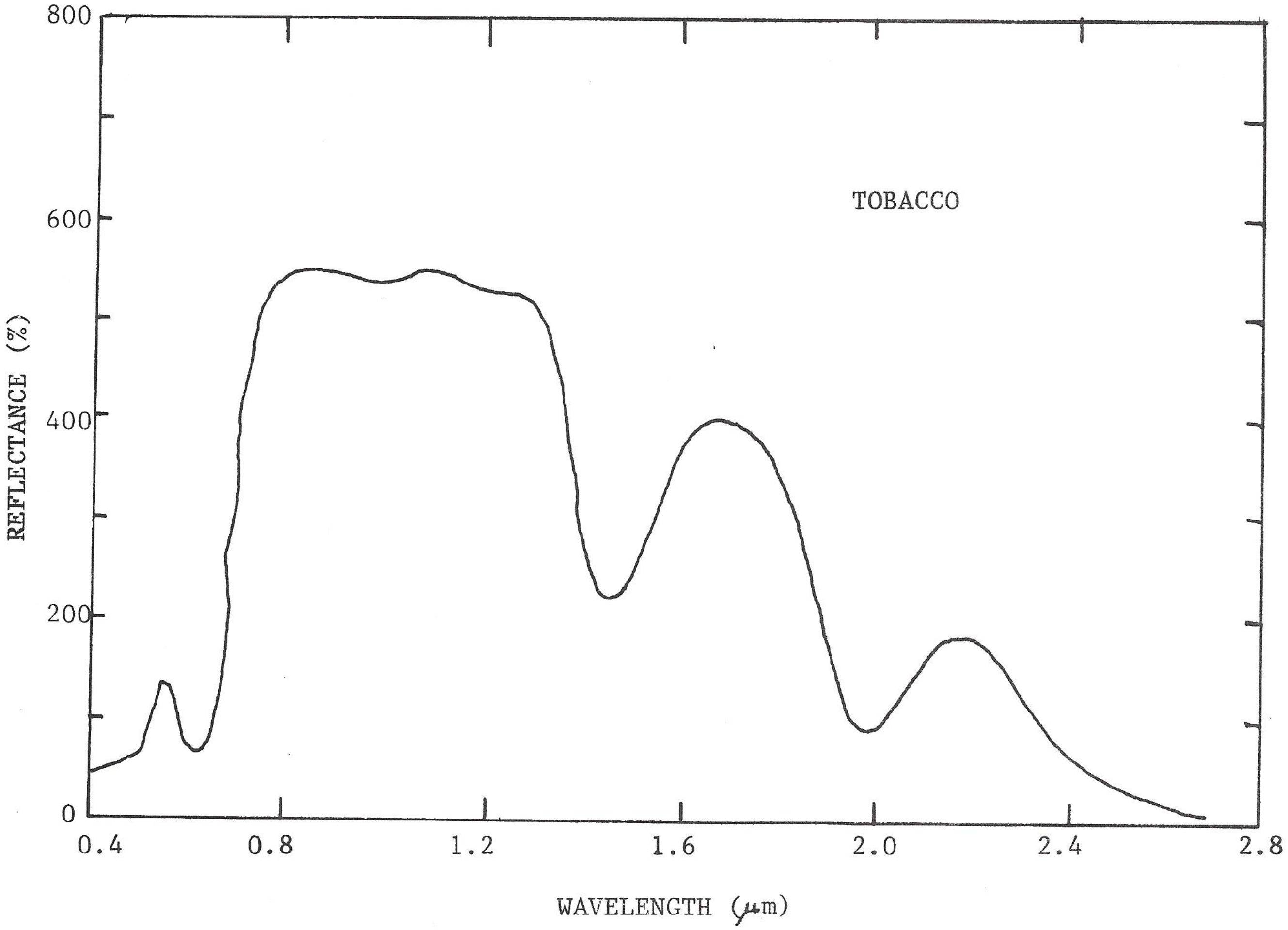

Figure 1. REFLECTANCE SPECTRUM OF A TOBACCO LEAF. (From Knipling, 1970)

Gausman et. al. 1970; Gausman, et. al. 1972 Thomas, et. al. 1966) reflection falls off (with two notable exceptions) to a low value near 2.7μm (Figure 1).

The study reported by Gates et. al (1965) presents a good physiologic overview of the reflectance/absorption properties of plant leaves, and explains why the spectral behavior of plants is of significance. The solar distribution curves presented by Gates (1966) demonstrate that the amount of solar energy reaching the earth's surface is relatively low in the visible region of the spectrum (0.4-0.7μm). Plants can be efficient absorbers of energy at these wavelengths, since the amount of energy absorbed does not dramatically affect the thermal balance of the leaf and its surroundings. This is demonstrated quite well by Knipling's (1970) curve. The situation is quite different in the mid IR region. Since the bulk of incident solar radiation is found in the 0.7 to 3.0μm region, efficient absorption in this region would result in increased plant temperatures, which might lead to the denatering of proteins essential to plant life. Even so, Gates (1963a) demonstrated that sunlit leaf temperatures may frequently reach values $10^{\circ}C$ to $20^{\circ}C$ above ambient air temperature, with absolute leaf temperatures reaching $50^{\circ}C$. Plant proteins begin to be destroyed at slightly higher temperatures.

An additional factor associated with mid IR energy balances is that plant reflectance in this region has been shown to change measureably with the presence of disease. For example, Colwell (1956) presents measurements of fungal infestations of cereal grains that show a decreased reflectance in the mid IR region, presumably due to the replacement of the intercellular air spaces by fungal hyphae, thus eliminating the refractive index component thought to be the major contributing factor in mid IR reflectance by plant leaves.

It has been demonstrated by numerous researchers that the potential exists to extract valuable information from data collected in the mid IR region for other plant/environment interactions, many of which are summarized by Knipling (1967), including research dealing the reflectance changes due to leaf maturation and senescence, leaf type (gymnosperm versus angiosperm), plant nutrition, site salinity, and water stress. The visible as well as near IR regions are covered, and a thorough bibliography is also included. In summary, the major influence on mid IR reflectance by plant leaves is tied to the leaf water status, and any organism or condition which alters this status will have an effect on the reflectance as measured by a mid IR sensitive device.

PAST RESEARCH: THERMAL IR

The second line of interest which developed is in the thermal IR region (3.0-14.0μm) of the electromagnatic spectrum, and is founded in part on the relationship that a target's temperature has with its physical or physiological state, and how well the temperature can be used as an indicator of that state. Here again, plants will be used to illustrate the point.

Browne & Escombe (1905) established that such plant physiologic processes as CO_2 uptake, respiration, and transpiration are all quantatively tied to the plant leaf temperature. Fuchs and Tanner (1956) also mention this, and state: "the physiological reactions and the physical transport phenomena at the interface of the plant and the atmosphere depend upon the temperature of the plant leaf."

In a study conducted by Bartholic, et. al. (1972), the effect of temperature is related to the state of agronomic crops by referencing the work done by Weigand, et. al., (1968-soil surface tempertures reaching 50°C - 60°C can kill emerging plants), Bartholic, et. al. (1970-soil surface temperature collected in the winter and early spring months may indicate the need for freeze protection practices), Linacre (1967-plant temperature increases with decreasing soil moisture availability), and studies by David (1969), Horton et. al. (1970), Myers, et. al. (1970) and Wiegand, et. al. (1966), which show that canopy temperatures could be used as an indicator of the relative need for irrigation.

Temperature is also a useful quantity to know in other fields, such as thermal discharge studies (Scarpace, et. al. 1975, Schott, 1979) soil related investigations (Byne, et. al. 1979; Price, 1980), geology (Kahle, 1977; Pohn, et. al. 1974; Schieldge, et. al, 1980; Watson, 1975), oceanagraphy (Colacino, et. al., 1970; Rao, 1972, Vinogradov, et. al. 1972), geomorpology (Schneider, et. al. 1979; Stewart, et. al. 1978), atmospherics (Ismail, 1977; Koffler, et. al. 1973; Peckham, 1974), snow field studies (Outcalt, et. al. 1975), and urban studies (Price 1979, 1979a).

In the past, temperatures were obtained by making direct measurements of the target of interest, using thermometers, thermistors, or thermocouples. However, use of these devices may in fact alter the thermal nature of the surface, resulting in questionable temperature measurements (McAlister, 1964). An alternative to direct measurement of target temperature is the use of a radiometer designed to measure electromagnetic energy in the thermal IR region. Then, based on certain known or determinable properties of the target, measured energy can be converted to temperature through the use of established equations.

Unlike radiation in the mid IR region, (which has been shown to be primarily reflective in nature, depending to a large degree, on the refractive index change between hydrated plant cell walls and the intercellular air spaces), energy in the thermal IR region arises from a much more complex source. Since an understanding of the relationship between thermal IR radiation associated with a target and its temperature is fundamental to knowledgeable use of such data, the relationship will now be discussed.

THERMAL IR THEORY

Consider, if you will, a "perfect target" situated in outer space, well removed from the earth's atmosphere at a temperature above absolute zero, and in continuously clear view of the sun. Such a perfect target, which shall be called a black body, will behave in a predictable manner as defined by the Stephan-Boltzman law:

$$W = \sigma T^4 \qquad (1)$$

where W = radiant emittance $(\mathrm{w\ cm^{-2}})$

σ = 5.6687 X 10^{-12} $(\mathrm{w\ cm^{-2}\ {}^{o}K^{-4}})$ (known as the Stephen-Boltzman constant)

T = absolute temperature $({}^{o}\mathrm{K})$

Thus, over the entire electromagnetic spectrum, the radiant emittance of a black body is directely related to the fourth power of the absolute temperature.

If we were to examine selected wavelengths (such as those defining the thermal IR region), we would find that, for any particular wavelength λ, the spectral radiant emittance of a black body is defined by Planck's equation:

$$W_\lambda = \frac{C_1}{\lambda^5\left(e^{\frac{C_2}{\lambda T}} - 1\right)} \tag{2}$$

where W_λ = the spectral radiant emittance at wavelength λ ($w\ cm^{-2}\ \mu m^{-1}$)

$C_1 = 3.7413 \times 10^{-16}\ wm^{-2}$

$C_2 = 0.014388\ m\ ^oK$

Most targets of interest, unfortunately, do not behave like a black body and thus the two preceeding equations do not completely define the situation.

Consider then a non-black body target (NBBT), whose spectral radiant emittance ($W_{\lambda T}$) for a particular wavelength and temperature are measured without error (the subscript "T" denotes non-black body target). Planck's equation furnishes, for the same wavelength and temperature, black body spectral radiant emittance (W_λ). A relationship exists between W_λ and $W_{\lambda T}$ that is referred to as target spectral emissivity, and is defined by:

$$\varepsilon_\lambda = \frac{W_{\lambda T}}{W_\lambda} \tag{3}$$

which is a unitless ratio comparing the spectral radiant emittance of the target to that of a black body. As is indicated by the subscript, ε_λ does in fact change with wavelength and is related to various physical, chemical, and biological attributes of the target. The maximum spectral radiant emittance at any wavelength and temperature is achieved only by black bodies (the denominator of the ratio). Hence, it can be seen that ε_λ will have bounds $o \leq \varepsilon_\lambda \leq 1$ for all λ.

The Stephan-Boltzman equation can be derived by integrating spectral radiant emittance, W_λ, over all wavelengths. Thus, we can rewrite blackbody radiant emittance as:

$$W = \int_0^\infty W_\lambda \, d\lambda. \tag{4}$$

Having previously defined ε_λ, this equation could be generalized to the case of any target as:

$$W_T = \int_0^\infty \varepsilon_\lambda W_\lambda \, d\lambda \tag{5}$$

where W_T is the radiant emittance for the target. Should the target exhibit black body characteristics, $\varepsilon_\lambda = 1$ for all λ, this would reduce equation (5) to the form given in equation (4).

From the preceeding discussion of emissivity, it can be seen that, knowning ε_λ, Planks equation could be solved for T at any λ. Thus, based on equation (5), if we know the type of target we are observing, and know all ε_λ values (for $0 \leq \lambda \leq \infty$) we could calculate the targets temperature based on error free measurements of W_T. It should be obvious that this would be a cumbersome task at best, given the myriad of targets of interest and all of the variability in a "type" of target (e.g. "oak leaf").

Recall that most targets do not behave as black bodies. A black body, according to Kirchoff's Law, absorbs all energy incident on it ($\alpha = 1$), emits all energy absorbed ($\varepsilon = 1$), and is opaque (transmits no energy; $\tau = 0$) regardless of wavelength. Kirchoff's law also states that for opaque targets

$$\frac{W_T}{\alpha} = W \tag{6}$$

so that for black bodies (where α is equal to 1) $W = W_T$.

Solving equation (6) for α,

$$\alpha = \frac{W_T}{W} = \varepsilon \tag{7}$$

It is also known that, given $\tau = 0$,

$$\alpha = 1 - \rho \tag{8}$$

where ρ is the ratio of radiant energy reflected by a target to that incident on it; $o \leq \rho \leq 1$.

It follows then that

$$\alpha = \varepsilon = 1 - \rho. \tag{9}$$

In equations (8) and (9), the magnitude of ρ is determined by such things as target surface characteristics, internal structure, chemical composition, and a host of other factors. Examination of the literature will clearly demonstrate that ρ, α, and ε vary with λ, such that equation (9) may be written as:

$$\alpha_\lambda = \varepsilon_\lambda = 1-\rho_\lambda \quad (\text{given} \quad \tau_\lambda = 0). \tag{10}$$

The fact that there is reflection of some of the radiant energy which is incident on a NBBT leads to the realization that measurements of "radiant energy" associated with NBBTs include this "reflected" component. Thus when attempting to solve equation (5) for temperature, ignoring the reflected component is the same as assuming $\varepsilon_\lambda = 1$, which is not the case. In order to examine this problem further, define $H_{\lambda T}$ as the spectral irradiance incident on a target at wavelength λ (w $cm^{-2}\mu m^{-1}$), and $H_{\lambda D}$ as the irradiance incident on our measurement device at wavelength λ (w $cm^{-2}\mu m^{-1}$). Then the quantity ρ_λ $H_{\lambda T}$ represents the amount of reflection occurring at λ for a NBBT. This quantity could also be written (according to Kirchoff's Law) as $(1 - \varepsilon_\lambda)$ $H_{\lambda T}$. The total specular irradiance resulting from reflection would then be:

$$\int_0^\infty (1-\varepsilon_\lambda)\, H_{\lambda T}\, d\lambda.$$

Since our measurement device makes no distinction between radiant emittance and reflected specular irradiance, the total irradiance at the measurement device can be defined as:

$$\int_0^\infty H_{\lambda D} d\lambda = W_T + \int_0^\infty (1 - \varepsilon_\lambda)\, H_{\lambda T} d\lambda \qquad (11)$$

which is equivalent to:

$$\int_0^\infty H_{\lambda D} d\lambda = \int_0^\infty \varepsilon_\lambda W_\lambda\, d\lambda + \int_0^\infty (1 - \varepsilon_\lambda)\, H_{\lambda T} d\lambda \qquad (12)$$

where the term on the left hand side represents the total irradiance measureable by our device. In a more specific sense, the limits of the integrals in equation (12) could be replaced by λ_1 and λ_2 to define any particular wavelength region of interest.

Equation (12) depends on the pre-established condition that the transmissivity τ_λ is equal to zero. As was earlier pointed out by Gates and Tantraporn (1952), this is in fact the case for wavelengths greater than 1.0μm when dealing with plant leaves. At wavelengths shorter than this (i.e. closer to the ultraviolet) and perhaps for other targets of interest, τ_λ takes on non zero positive values. Thus, when examining leaves in the 0.29-1.0μm region (including the visible and some of the near IR), transmissivity must be accounted for.

The above discussion has centered on the properties of the target that influence the manner in which electromagnetic energy interacts with the target, and it was shown, at least for the thermal IR, that a target's temperature and emissivity are the primary contributors to measured energy levels. The development of equation (12) was also based on the assumption of a target in space (no atmosphere). However, for most targets of interest this is not the case. Therefore, in order to be able to relate measurements taken by devices located at some distance from a target to the actual state of the attribute measured, the effects of the intervening atmosphere must also be removed, since it is a well documented fact that electromagnetic energy interacts with the earth's atmosphere, (Davis and Vizee 1964, Fraser, et. al. 1977, Goodell, 1981, Gordon and Clark 1981, LaRocca, 1975, and others), and that this interaction has an influence on measurements made by remote sensing devices (Dana, 1976; Dave, 1980; Jurica and Parsons, 1974; Otterman et. al., 1980; Shaw and Irbe, 1972; Sinha, et. al., 1980, Stowe and Flemming, 1980; Turner, 1973, 1974; Watson and Hummer-Miller, 1981). It is therefore imperative that the atmospheric effects be accounted for during data analysis, so that measurements made by remote sensors (e.g. aircraft or spacecraft bourne devices) can be related to measurements collected in the field. Thus, the next step in the development of the target/energy relationship involves the consideration of atmospheric effects.

ATMOSPHERIC EFFECTS

As an example of the general nature of the atmospheric correction required, let us again consider the NBBT examined earlier. If the NBBT is located on the earth's surface, and our measurement device is at some considerable distance away, measurements made with the remote device will not agree with similar measurements made in close proximity to the target, all other things being equal. This is a very good example of the results of "atmospheric effect." Dutton (1962), and Bauer and Dutton (1962) realized that there would be an atmospheric effect, and greatly reduced the problem by operating the aircraft data collection platforms at very low altitudes. Even so, some effect was still included in the data that they analyzed.

The situation was not so easily dealt with when earth orbiting satellite devices were used. In these situations, corrections for the effects of the earth's atmosphere had to be developed. As an example Wark, et. al. (1962) state "if a knowledge of the (atmosphere) is lacking, errors in the (predicted) infrared surface temperature can range from near zero to 10 degrees (C) or more."

Returning to the NBBT, the difference in measurements (all other things being equal) is a direct result of the fact that the energy produced by the sun has passed through the earth's atmosphere and, in the process, has undergone a considerable metamorphasis. While traversing the atmosphere, ozone, water vapor, carbon dioxide, dust, and a host of other components of "air" have caused reflection (Raliegh and Mie scattering), absorption, and reradiation at altered wavelength to occur, completely distorting the solar spectral distribution curve as it existed in space. In certain regions of the spectrum the effect is minimal (e.g. 0.48μm), whereas in other regions (e.g. < .29μm known as the Herzberg and Schumann-Runge bands), the result is a total extinction of solar radiation incident on the earth's atmosphere. Thus, it would be imprudent to look for radiant emitance over all λ, since on the earth's surface (where our targets are located) energy at certain λ's does not even exist. Figure 2 (taken from Valley, 1965) presents a graphic picture of the extent to which various components of the atmosphere modify the solar spectrum (by

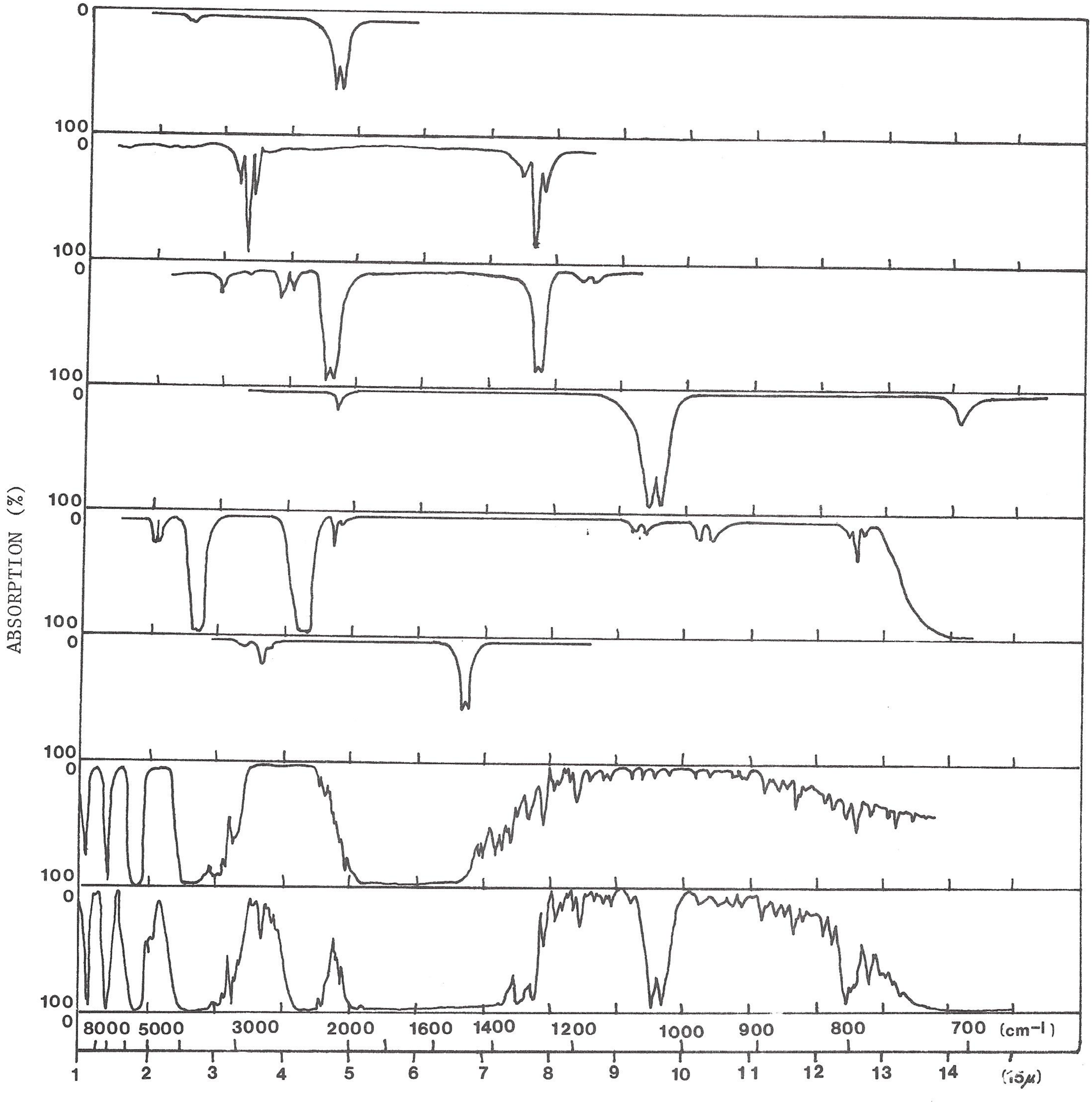

Figure 2. COMPARISON OF THE NEAR-INFRARED SOLAR SPECTRUM WITH LABORATORY SPECTRA OF VARIOUS ATMOSPHERIC GASES. (From Valley, 1965)

molecular absorption/scattering). Within the mid IR region, the definition of λ_1 and λ_2 is directed, to a large degree, by strong water absorption near 1.5μm and 1.8μm, and by a combination of absorption by water and carbon dioxide from near 2.5μm to near 3.0μm. Knowledge of this phenomena helps researchers to better understand the recommendation made by researchers such as Siegrist and Schnetzler (1980) and Tucker (1978).

Let us therefore redefine

$$W_T = \int_{\lambda_1}^{\lambda_2} \varepsilon_\lambda \ W_\lambda \ d\lambda \qquad (13)$$

to be the radiant emittance of our target over a wavelength region bounded by λ_1 and λ_2. In so doing, we can select values of λ_1 and λ_2 which will minimize atmospheric effects. (Should $\lambda_1 = 0$ and $\lambda_2 = \infty$, equation (13) becomes indentical to equation (5)).

The selection of the wavelength region in which measurements are made has for the most part been limited to the visible and near (reflected) IR regions of the spectrum (0.5-1.1μm), partially due to state-of-the-art hardware limitations, and partially due to the behavior of targets in the thermal IR region. However, advances in technology as previously mentioned, and a realization that over 50 percent of the radiation reaching the earth's surface lies in the IR region, has caused increasing interest in this region.

When dealing with thermal IR, atmospheric considerations require the selection of $\lambda_1 \approx 8\mu m$; $\lambda_2 \approx 12\text{-}13\mu m$, due to severe CO_2 absorption (4-5μm) and water absorption, (5-8μm), on the short wavelength side, and CO_2 absorption, (12.5-20μm), and water aborption (>20μm) on the long wavelength side. Ozone presents yet another absorption problem near 9.6μm. Overall atmospheric absorption is at a minimum in the 10μm-12μm region, known as an atmospheric "window". Atmospheric effects accounts for the fact that most early thermal IR research was dominated by measurements taken in the 8-14μm region, and why recent reasearch contains more restrictive wavelength boundaries (e.g. 10-12μm; 12-13μm, etc.) on the measurements being collected.

If the atmosphere exhibits variable "transmissivity" (with wavelength) for incomming solar radiation as previously mentioned, the same must hold true for outgoing reflected/emitted radiation. Thus, as more and more atmosphere is placed between a target and the measurement device, the greater the difference will be between actual target condition and our measured condition. In order to take this into account, define τ_λ to be the atmospheric transmittance of energy at wavelength λ with bounds $0 \leq \tau_\lambda \leq 1$. This is simply an expression of the fraction of energy incident at some point in the atmosphere which passes unaltered through some unit distance of atmosphere. Thus, equation (12) can be rewritten as:

$$\int_{\lambda_1}^{\lambda_2} H_{\lambda D} d\lambda = \int_{\lambda_1}^{\lambda_2} \tau_\lambda \varepsilon_\lambda W_\lambda d\lambda + \int_{\lambda_1}^{\lambda_2} \tau_\lambda (1 - \varepsilon_\lambda) H_{\lambda T} d\lambda \qquad (14)$$

There is an additional atmosphere-related component which also must be taken into account. This involves absorption and re-emission of energy by the atmosphere which is independent of target, but nonetheless is detected by our measurement device.

Let $H_{\lambda S}$ be the radiant emittance of the "sky" at wavelength λ. Then over wavelength region $\lambda_1 - \lambda_2$, the total "sky radiation" is given by $\int_{\lambda_1}^{\lambda_2} H_{\lambda S} d\lambda$. Since this value is also detected by the measurement device, it is added to the right hand side of (14) to give:

$$\int_{\lambda_1}^{\lambda_2} H_{\lambda D} d\lambda = \int_{\lambda_1}^{\lambda_2} \tau_\lambda \varepsilon_\lambda W_\lambda d\lambda + \int_{\lambda_1}^{\lambda_2} \tau_\lambda (1 - \varepsilon_\lambda) H_{\lambda T} d\lambda + \int_{\lambda_1}^{\lambda_2} H_{\lambda S} d\lambda \qquad (15)$$

The last term on the right of equation (15) does not contain the atmospheric transmissivity, τ_λ, since it is a measurement of atmospheric radiation as measured at the sensor, and thus already has τ_λ incorporated. The remaining terms on the right of equation (15) contain variables which represent measurements of quantities at the target ($H_{\lambda T}$) or target specific quantities ($\varepsilon_\lambda W_\lambda$). Thus, the energy represented by these variables must travel across the atmosphere to reach the measurement device and are, in the process, affected (indicated by the multiplier τ_λ).

Equation (15) assumes that the <u>total</u> amount of radiation emitted by the target, reflected from the target, and resulting from atmospherics can be measured. We know that radiometers cannot measure the "total" energy emanating from a source into a hemisphere, but only that amount which is incident on the detector through a very narrow solid angle, defined by the "viewing optics". Therefore, the solid angle (measured in steradians) of the scanner, ω, as well as the area of the optics, A, must also be taken into account. To do this, we assume that the target exhibits diffuse emission, reflection, and scattering and relate all energy to a unit solid angle:

$$\int_{\lambda_1}^{\lambda_2} H_{\lambda D} d\lambda = A\omega\pi^{-1} \int_{\lambda_1}^{\lambda_2} \tau_\lambda \varepsilon_\lambda W_\lambda d\lambda + A\omega\pi^{-1} \int_{\lambda_1}^{\lambda_2} \tau_\lambda (1 - \varepsilon_\lambda) H_{\lambda T} d\lambda + \frac{A\omega\pi}{2}^{-1} \int_{\lambda_1}^{\lambda_2} H_{\lambda S} d\lambda \qquad (16)$$

where the factor $A\omega\pi^{-1}$ defines the amount of radiation actually irradiating the measurement device (Holley, at. al, 1962). It has been assumed, to this point in the discussion, that measurement is black body in nature (was made without error) i.e., that all energy falling on the device will be "reported". This is not the case, however, since every measurement device has a characteristic response curve, relating the percent incident radiation detected at each λ for the range of the detector ($\lambda_1 - \lambda_2$) to an output recorded value.

We therefore define ξ_λ to be the detector response function at wavelength λ (output values/w cm$^{-2}\mu$m^{-1}). This variable can be thought of as a compensating factor defining the non-blackbody quality of the measurement device, and includes such considerations as amplifier efficiency, detector chip type and sensitivity, etc.

In order to include ξ_λ in equation (16), its effect should be examined. Since ξ_λ changes with wavelength and can be expressed as a multiplicative factor, equation 16 becomes (with simplifications)

$$\int_{\lambda_1}^{\lambda_2} \xi_\lambda H_{\lambda D} d\lambda = A\omega\pi^{-1} \left(\int_{\lambda_1}^{\lambda_2} \tau_\lambda \varepsilon_\lambda W_\lambda d\lambda + \int_{\lambda_1}^{\lambda_2} \tau_\lambda (1 - \varepsilon_\lambda) H_{\lambda T} d\lambda + 1/2 \int_{\lambda_1}^{\lambda_2} H_{\lambda S} d\lambda \right) \tag{17}$$

This converts the values on the left hand side to the output values which are subsequently recorded and analyzed.

For each wavelength region ($\lambda_1 - \lambda_2$) considered, ξ_λ can be calculated if calibration sources are available. Based on the use of such sources and assuming a linear detector response function between calibration points, the average value (ξ) can be computed and used in place of ξ_λ (which brings ξ outside of the integral). Then, after multiplying both sides of (17) by ($\pi A^{-1} \omega^{-1}$), we obtain:

$$\pi A^{-1} \omega^{-1} \xi \int_{\lambda_1}^{\lambda_2} H_{\lambda D} d\lambda = \int_{\lambda_1}^{\lambda_2} \tau_\lambda \varepsilon_\lambda W_\lambda d\lambda + \int_{\lambda_1}^{\lambda_2} \tau_\lambda (1 - \varepsilon_\lambda) H_{\lambda T} d\lambda + 1/2 \int_{\lambda_1}^{\lambda_2} H_{\lambda S} d\lambda \tag{18}$$

Thus it can be seen that the value recorded by a remote sensing device, (left hand side of equation (18)) is a function not only of the target but of the transmissivity of the atmosphere (τ_λ) and an additive component ($H_{\lambda s}$), which are both independent of the target, as well as peculiarities associated with the specific measurement device being employed (ξ).

Data Sources

As previously mentioned, it is the intent of this research to investigate two areas of interest. The first has to do with the relationship between leaf water content and the quantity (as measured by remote sensing devices) of reflected mid IR energy. The rationale for such an experiment has already been established elsewhere in this report.

Data used to support this portion of the research will be collected by the Landsat-4 Thematic Mapper (TM) system. The TM is an earth orbiting seven channel multispectral scanner, measuring irradiance in the wavelength regions indicated in Table 1. Additional details of Landsat-4 and in particular the TM can be found in a publication prepared by the U.S.G.S. (1982).

TM CHANNEL	WAVELENGTH REGION (μm)	GROUND RESOLUTION (m)
1	0.45-0.52	30
2	0.53-0.60	30
3	0.63-0.69	30
4	0.76-0.90	30
5	1.55-1.75	30
6	10.40-12.50	120
7	2.08-2.35	30

Table 1. Spectral and Spatial Characteristics of the Landsat-4 Thematic Mapper.

Of particular interest to this study are TM channels 5 and 7, both of which are located in the mid IR region and, as demonstrated by Tucker

(1980), correspond to those wavelength regions which appear to be "the best suited ... for monitoring plant canopy water status from space platforms."

Studies dealing with the thermal IR region have as their objective the determination of target temperature, which has been shown to have widespread use in numerous earth resources disciplines. Data serving as the basis of research in this area will be obtained by the airborne Thermal Infrared Multispectral Scanner (TIMS) from an altitude of near 12,000m (39,370 ft) above mean terrain elevation. This six channel device measures irradiance in the (1) 8.2-8.6μm, (2) 8.6-9.0μm, (3) 9.0-9.4μm, (4) 9.4-10.2μm, (5) 10.2- 11.2μm, and (6) 11.2-12.2μm wavelength region (in the sequence of TIMS channel number). When flown at the 12,000m altitude, the 2.5m aperture results in a 30m X 30m (98 ft X 98 ft) nadir instantaneous field of view (IFOV). The TIMS scans $\pm 30^0$ on both sides of nadir (total 60^0 angle of look). It is significant to note the rather narrow restrictions (0.4μm) on the bounds for the first three channels of the TIMS, with maximum $\Delta\lambda$ equal to 1μm (channels 5 and 6). Thus, the heretofore broad band approach to the thermal IR will be replaced with a narrow band one.

Experimental Premise

Mid IR

The biophysical process by which leaves reflect/transmit energy in the mid IR has been described in detail by Knipling (1970), Gausman (1974), Mestre (1935), Willstätter and Stoll (1918) and others, and is thought to result from (a) differences between the refractive indicies of air (1.0) in the intercellular spaces and hydrated cell walls (1.425), and (b) variations in the refractive indicies of cellular components. It is generally thought that the differences in refractive indicies is the major contributing factor, since the presence of pigments or a cuticle cover were found to be nonsignificant with respect to IR radiation (Knipling, 1970). Beyond 1.3μ, absorption of IR radiation increases primarily due to water absorption. The higher the amount of water present, the greater the absorption. This point is very dramatically illustrated by Knipling (1970) for bean leaves, which exhibit a very marked rise in IR reflectance with decreasing percent water content. It is of interest to note that there was very little change observed in the reflectance data in the 0.7-1.3μm region, while the percentage of reflectance change in the 1.3-2.5μm region was quite striking. Also noted by Knipling was the observation that the overall change in reflectance (with respect to water content) was greater in wavelengths encompassed by TM channel 7 (2.08-2.35μm) than in the wavelength region defining TM channel 5 (1.55-1.75). This would indicate that TM channel 7 might be more sensitive to changes in leaf water content and hence might prove to be more useful for monitoring purposes.

Evidence is presented by other researchers which serves to strengthen the potential utility of TM channels 5 and 7 for monitoring leaf water content. Gausman, et. al. (1978) present the results of spectral comparison of 6 succulent plants (with an average leaf water content of 92.2 percent) with four nonsucculent plants (with an average leaf water content of 71.2 percent) over the 0.4 to 2.5μm wavelength region (with data acquired in 0.05μm wavelength increments). They concluded that the two major groups could be separated using sensor channels encompassing the 1.6 or 2.2μm wavelength regions.

In an earlier study, Gausman et. al. (1972) conclude that three channels centered around 0.68, 0.85, and 1.65μm would be optimum for purposes of differentiating various crop types, with a fourth channel near 2.2μm a good candidate. Weigand, et. al. (1972) also points to the utility of channels centered near 1.65μm and 2.2μm for vegetation discrimination and stress detection.

It is desirable, therefore, based on the studies conducted in the laboratory to date, to determine whether the leaf water/reflectance relationship can be detected from orbital altitudes, specifically in the data recorded in TM channel 5 or 7. Should functional relationships be discernable from orbital altitudes, the synoptic coverage furnished by the TM would enable resource managers to examine large areas, thus enhancing the utility of the spacecraft obtained data. Ground sampling and subsequent laboratory analysis of the plant tissues collected will enable verification of the relationship to occur for species indigenous to the proposed study area. Then, upon receipt of TM data, with concurrent ground data acquisition, data analysis will be conducted with the specific aim of exaimining the leaf water/reflectance relationship. Atmospheric considerations similar to those previously discussed will be included in the satellite analysis work.

Thermal IR

Equation (18) shows that the output value of a remote sensing device is a function of (1) characteristics of the target, (2) the transmissivity of the atmosphere, and (3) the "sky radiation" along the line of sight of the detector (the last two being independent of target). Since we are interested in obtaining an estimate of target temperature, a method must be devised by which atmospheric and "other target" inputs into the system of equation (18) can be calculated and removed.

The unknowns in equation (18) are:

τ_λ the specular atmospheric transmittance,

ε_λ the emissivity of the target,

T the temperature (included in W_λ),

$H_{\lambda S}$ atmospheric sky irradiance, and

$H_{\lambda T}$ the irradiance of the target.

Values for the three atmospheric parameters (τ_λ, $H_{\lambda S}$, and $H_{\lambda T}$) can be estimated using a sophisticated model developed by the Air Force Geophysics Laboratory called LOWTRAN-5. This model was "designed to estimate atmospheric transmittance and radiance for a given atmospheric path at moderate spectral resolution" (Kneizys, et. al. 1980) over an operational wavelength region of from 0.25 to 28.5μm. When using the model, an investigator has the opportunity to select any one of six standard model atmospheres, mix portions of any of the models, or use radiosonde data to construct a definitive site/data specific atmospheric profile. In addition, LOWTRAN-5 contains numerous aerosol models defining the properties of four vertical subdivisions of the earth's atmosphere. Here again the user may select those models thought to best represent the atmosphere above the study site at the time data were collected.

Output from LOWTRAN-5 consists of estimates for each of the atmospheric parameters previously mentioned. Calculations for τ_λ and $H_{\lambda S}$ are straight forward and can be computed for wavelength region (λ_1-λ_2) of interest. $H_{\lambda T}$ specular irradiance of the target, is output by LOWTRAN-5 for single path only, and hence this value must be integrated over the hemisphere in order to obtain the total hemispherical target irradiance $H_{\lambda T}$.

Before incorporating the LOWTRAN-5 estimates, equation (18) can be expanded to give:

$$\pi A^{-1}\omega^{-1}\xi \int_{\lambda_1}^{\lambda_2} H_{\lambda D}d\lambda = \int_{\lambda_1}^{\lambda_2} \tau_\lambda \varepsilon_\lambda W_\lambda d\lambda + \int_{\lambda_1}^{\lambda_2} \tau_\lambda \left(H_{\lambda T} - \varepsilon_\lambda H_{\lambda T}\right) d\lambda + 1/2 \int_{\lambda_1}^{\lambda_2} H_{\lambda S}d\lambda \qquad (19)$$

which is equivalent to:

$$\pi A^{-1}\omega^{-1}\xi \int_{\lambda_1}^{\lambda_2} H_{\lambda d}d\lambda = \int_{\lambda_1}^{\lambda_2} \tau_\lambda \varepsilon_\lambda W_\lambda d\lambda + \int_{\lambda_1}^{\lambda_2} \tau_\lambda H_{\lambda T}\, d\lambda - \int_{\lambda_1}^{\lambda_2} \tau_\lambda \varepsilon_\lambda H_{\lambda T} d\lambda + 1/2 \int_{\lambda_1}^{\lambda_2} H_{\lambda S}\, d\lambda \qquad (20)$$

Rearranging terms leads to

$$\pi A^{-1}\omega^{-1}\xi \int_{\lambda_1}^{\lambda_2} H_{\lambda D}\, d\lambda = \int_{\lambda_1}^{\lambda_2} \tau_\lambda \varepsilon_\lambda W_\lambda d\lambda - \int_{\lambda_1}^{\lambda_2} \tau_\lambda \varepsilon_\lambda H_{\lambda T}\, d\lambda + \int_{\lambda_1}^{\lambda_2} \tau_\lambda H_{\lambda T} d\lambda + 1/2 \int_{\lambda_1}^{\lambda_2} H_{\lambda S}\, d\lambda \qquad (21)$$

The last two terms on the right hand side of equation (21) are composed of variables for which we can obtain estimates using LOWTRAN-5, and thus represent constants for the wavelength region (λ_1-λ_2).

$$\text{Define } \Psi = \int_{\lambda_1}^{\lambda_2} \tau_\lambda H_{\lambda T} d\lambda + 1/2 \int_{\lambda_1}^{\lambda_2} H_{\lambda S} d\lambda \qquad (22)$$

Then, after subtraction,

$$\xi^{-1}\left(\pi A^{-1}\omega^{-1}\xi \int_{\lambda_1}^{\lambda_2} H_{\lambda D} d\lambda\right) - \Psi = \int_{\lambda_1}^{\lambda_2} \tau_\lambda \varepsilon_\lambda W_\lambda d\lambda - \int_{\lambda_1}^{\lambda_2} \tau_\lambda \varepsilon_\lambda H_{\lambda T}\, d\lambda \qquad (23)$$

The term ξ^{-1} on the left hand side of equation (23) converts recorded data value to an energy term, which is then consistent with Ψ.

Equation (23) still contains both ε_λ and temperature, and solving for one requires making assumptions about or measurement on the other. For instance, Kahle, et. al. (1980) used the value of $\varepsilon_\lambda = 0.96$ (for $\lambda_1 = 12\mu m$ $\lambda_2 = 13\mu m$) as developed by Vincent et. al. (1975) for silicate rocks.

Thus, equation (23) involves only observed data values, calculated atmospheric contributions, and temperature. In that particular study, silicate rocks were the only target of interest, and thus the application of $\varepsilon_\lambda = 0.96$ to other land covers was not detrimental to the limited scope of the study.

The assumption of constant ε_λ over some portion of the thermal IR region ("grey body") is equally valid for other land covers as well. Of particular interest to this research are data published by Gates et. al. (1965), which show that absorption (α_λ) for a typical green leaf remains fairly constant in the 8-14μm region (Figure 3). Since transmissivity of plant leaves beyond 1.0μm was shown to be zero (Gates and Tantraporn 1952), Kirchoff's law can be used to equate α_λ to ε_λ (see equation 7). Thus, Figure 3 (beyond 1.0μm) represents ε_λ values for a green leaf. When viewed from this perspective, leaves behave as gray bodies in the 8-14μm region.

The fact that the ε_λ values of plant leaves remain constant over λ_1 to λ_2 can be used to rewrite equation 23 as:

$$\xi^{-1}\left(\pi A^{-1}\omega^{-1}\xi \int_{\lambda_1}^{\lambda_2} H_\lambda d\lambda\right) - \Psi = \varepsilon\left(\int_{\lambda_1}^{\lambda_2} \tau_\lambda W_\lambda d\lambda - \int_{\lambda_1}^{\lambda_2} \tau_\lambda H_{\lambda T} d\lambda\right) \quad (24)$$

For the purposes of the research described in this document, averaged values of τ_λ over λ_1 to λ_2 were used in equation (24), resulting in:

$$\xi^{-1}\left(A^{-1}\pi\, \omega^{-1}\xi \int_{\lambda_1}^{\lambda_2} H_{\lambda D} d\lambda\right) - \Psi = \tau\varepsilon\left(\int_{\lambda_1}^{\lambda_2} W_\lambda d\lambda - \int_{\lambda_1}^{\lambda_2} H_{\lambda T} d\lambda\right) \quad (25)$$

The second term inside the parenthesis on the right hand side of equation (25) can be estimated through implementation of LOWTRAN-5, and thus represents a constant.

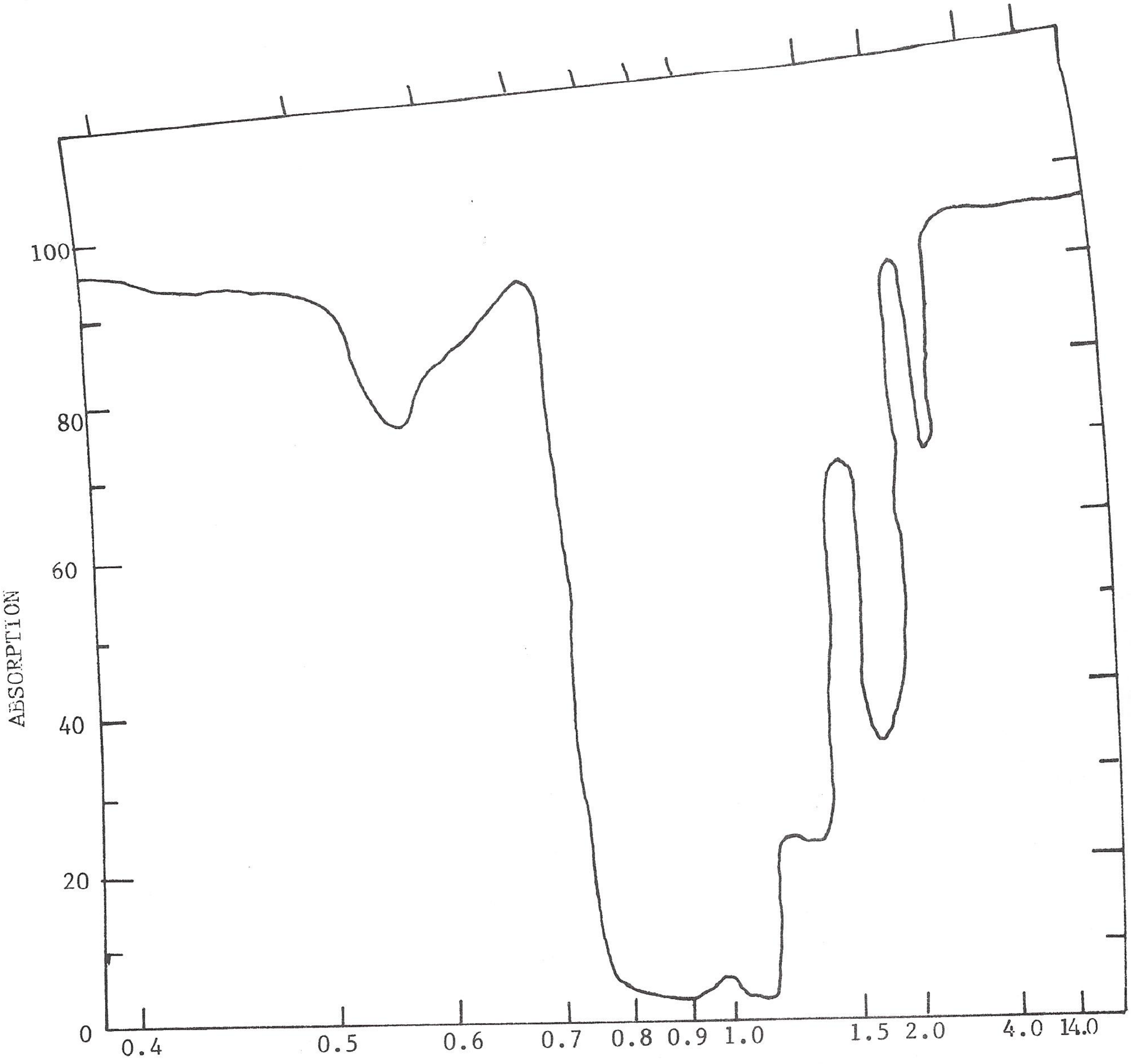

Figure 3. Absorption (1-Reflectance) curve for Populus deltoides (after Gates et. al. 1965).

Recall that the TIMS samples specular irradiance in six wavelength regions in the thermal IR. Thus since equation (25) can be applied to all six channels, and since ε appears as a multiplicative term in equation 25, (and is yet considered to be constant and equal for both λ_1 to λ_2 and λ_3 to λ_4) ratioing any two TIMS channels will eliminate the need to know or estimate ε, resulting (after simplification) in:

$$\frac{\xi^{-1}\left(\xi \int_{\lambda_1}^{\lambda_2} H_\lambda d\lambda\right) - \Psi}{\xi^{*-1}\left(\xi^* \int_{\lambda_3}^{\lambda_4} H_\lambda d\lambda\right) - \Psi^*} = \frac{\tau\left(\int_{\lambda_1}^{\lambda_2} W_\lambda d\lambda - \int_{\lambda_1}^{\lambda_2} H_{\lambda T}\, d\lambda\right)}{\tau^*\left(\int_{\lambda_3}^{\lambda_4} W_\lambda d\lambda - \int_{\lambda_3}^{\lambda_4} H_{\lambda T}\, d\lambda\right)} \qquad (26)$$

where λ_1-λ_2 are the wavelength bounds for one TIMS channel,

λ_3-λ_4 are the wavelength bounds for a second TIMS channel, and

Ψ^* is the correction (identical in form to Ψ) for the second TIMS channel defined by wavelength bounds λ_3-λ_4, and

τ^* is the atmospheric transmissivity for the region sampled by the second TIMS channel

ξ^* is the detector response function for the second TIMS channel.

THERMAL IR SENSITIVITY TO ERROR

It is of interest to note that, given a target with a temperature of 300°K, an error in the estimation of ε of .01 will result in the following temperature errors in each TIMS channel (ignoring atmospherics): channel 1 $\pm$ 0.59°C; channel 2 $\pm$ 0.62°C; channel 3 $\pm$ 0.67°C; channel 4 $\pm$ 0.71°C; channel 5 $\pm$ 0.77°C; and channel 6 $\pm$ 0.83°. Thus the fact that ε values can be eliminated using the ratio technique takes on significance, particularly if scene temperature changes of 1°C or less are of importance. For instance, Buetner and Kern (1965) and Cup and Phinney (1980) demonstrate that the emissivities of most vegetation fall between 0.90 and 0.98. Without prior knowledge of the type of vegetation, assuming an average ε of 0.94 would translate into a $4 \times 0.59^{o}C = \pm 2.36^{o}C$ error for vegetation with $\varepsilon = 0.90$ or 0.98 for TIMS channel 1. The situation would be worse if an assumed ε of 1.0 was used, in which case the maximum error would approach $6^{o}C$ for TIMS channel 1. Errors of this magnitude could easily mask out the thermal phenomena of interest in temperature related studies.

All values in equation (26) are known or can be estimated except $W_{\lambda}d\lambda$, which contains the unknown temperature of interest. However, if an "assumed" value for temperature is inserted into equation (26) and the corresponding ratio is calculated, the equality can be checked based on data obtained by the TIMS. Values of temperature can be iteratively inserted into equation (26) (thereby altering the value of the right hand side) until the equality holds true. This then is the sought after target temperature, which can be output and stored elsewhere for subsequent use. Alternatively, numerous values of temperature can be used to calculate the value of the right hand side of equation 26, each of which is stored in a table with the corresponding temperature. Then, as values of the left hand side of equation (26) are computed, they can be compared in a "table lookup" fashion to values already calculated. The latter approach is computationally faster, and thus will be used in this research.

In order to test the effectiveness of equation (26), TIMS data and concurrent ground truth data will be collected. Measurements will be made of several atmospheric parameters which will permit the generation of more site specific LOWTRAN-5 estimates. Equation (26) will be implemented (using several channel combinations) and the results will be compared with temperature measurements collected at the time of the TIMS mission.

A detailed analysis of the results will be incorporated into a subsequant report.

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