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CP-157910

(E79-10021) DETERMINATION AND ERROR
ANALYSIS OF EMITTANCE AND SPECTRAL EMITTANCE
MEASUREMENTS BY REMOTE SENSING (Instituto de
Pesquisas Espaciais, Sao Jose) 23 p
HC A02/"F A01

N79-12532

Unclas
00021

CSCL 20N G3/43



CONSELHO NACIONAL DE DESENVOLVIMENTO CIENTÍFICO E TECNOLÓGICO

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DETERMINATION AND ERROR ANALYSIS OF EMITTANCE AND SPECTRAL
EMITTANCE MEASUREMENTS BY REMOTE SENSING

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Abstract

A review of the emittance and spectral emittance of the leaves, soils and plants is done. From the theory of "remote sensing of surface temperatures", an equation of the upper bound of the absolute error ($|\delta\epsilon|$) of emittance determination is done. It shows that $|\delta\epsilon|$ decreases with an increase in contact temperature whereas it increases with an increase in environmental integrated radiant flux density respectively. Change in emittance has a little influence on $|\delta\epsilon|$. A plot of the difference between temperature and band radiance temperature vs. emittance is given for the following wavelength intervals: 4.5 to 5.5 μm , 8 to 13.5 μm and 10.2 to 12.5 μm . Techniques for determining least upper bound and highest lower bound of the spectral emittance from calibrated spectroradiometric data without knowing the contact temperature are given.

A part of this work was done at the Laboratory for Applications of Remote Sensing (LARS), Purdue University. W. Lafayette, Indiana and sponsored by the National Aeronautics and Space Administration under Grant No. 15-005-112.

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EMITTANCE AND SPECTRAL EMITTANCE

Introduction

All objects above absolute zero radiate energy by virtue of their temperature and emittance. At temperatures normally exhibited by natural objects at or near the earth's surface, this radiation is almost entirely in the infrared wavelength region from approximately 4 μm to 100 μm .

Planck's radiation law states that at any given temperature, T , and wavelength, λ , the maximum possible spectral radiance of emitted radiation is the blackbody spectral radiance at that temperature, T , and wavelength, λ . No natural surface emits like a perfect blackbody due to reflection of rays by the surface due to discontinuity in the index of refraction. Therefore the spectral emittance or spectral emissivity of a target is defined as the ratio of the radiation emitted by the target to the radiation emitted by the blackbody at the same temperature and wavelength. The band emittance and emittance of a target are defined similarly except that the radiation is integrated over a certain wavelength interval λ_1 to λ_2 and the entire wavelength region respectively. Thus, no instruments can yield a correct estimate of surface temperature by remote sensing if the emittance of the surface is not taken into account. Gates and Tantraporn¹ (1952) have pointed out that accurate knowledge concerning the infrared reflectance, absorptance, and emittance of leaves in the 1.0 to 15.0 μm region is essential for a detailed understanding of the energy exchange in the biosphere. Accurate knowledge of the infrared emittance of plants is required in many diverse ecological applications. Most researchers recognized this problem but neglected to apply the needed corrections, arguing that all plant surfaces have a longwave emittance of 0.95 or greater, most leaf emittances being 0.97 to 0.98.

Monteith and Szeicz² (1962) and Gates³ (1963) estimate that assuming the emittance of the plant surfaces equal to one may cause errors of at most 0.2°C in the measurement of their temperature. Fuchs and Tanner⁴ (1966) show, from a simple calculation, that if the incident thermal radiation from the sky and surroundings were 300 watts per square meter, corresponding to an apparent sky temperature of -4°C, and if the surface temperature were 25°C, a change of emittance from 0.95 to 0.98 would cause a measurement error of 2.2°C. For many detailed investigations, such discrepancies are intolerable. Kumar⁵ (1972) has done a thorough review of the general area of "reflection and emission from plants".

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Emittance of Leaves

The emittance of a surface depends on its roughness as well as its temperature, in general. Emittance of leaves given by Falckenberg⁶ (1928), Gates⁷ (1964) and Gates et. al.⁸ (1965) range from 0.95 to 0.98. Gubareff et. al.⁹ (1960), p. 293, indicated the emittance of the leaves to be more than 0.90. Turrell and Austin¹⁰ (1965) reported the emittance of citrus leaves to be about 0.87, using the data of Gates and Tantraporn¹ (1952). Gates and Tantraporn¹ measured the reflectance of upper and lower surfaces of leaves of deciduous trees and herbaceous plants at 3.5, 7.5, 15 and 25 μm , at an angle of incidence of 20° and 65° . The infrared radiant source was the Globar whose radiation was reflected off the leaf surface at the desired angle by means of spherical front-surface mirrors and then focussed upon the entrance slit of the infrared spectrometer. It can be seen from their data the reflectance of most leaves in the infrared wavelength region beyond 2 μm lies between 0 and 10% and its value varies from leaves of one plant to another.

Fuchs and Tanner⁴ (1966) found the emittance of single leaves of snap beans and tobacco to be 0.96 and 0.97, respectively. They covered the temperature-controlled anodized surface by the base of a "skewed" aluminum cone with a highly polished reflecting surface. The leaf was placed at the base of the cone, and the apex of the cone was cut to fit the entrance pupil of the infrared thermometer, so that the leaf behaves like a blackbody. Idso et. al.¹¹ (1969) described a method for determining the infrared emittance of individual plant leaves which is relatively simpler than Fuchs and Tanner (F - T) method. Measurements on a wide variety of plant surfaces by this method indicated that significant differences of emittance exist among the various species. The emittance values ranged from about 0.94 to 0.995. They pointed out that the values of emittance, determined by infrared thermometers of different spectral sensitivity, are not uniquely related, thereby emphasizing the importance of emittance measurements.

The emittance of a single leaf is not representative of the emittance of a plant canopy because of the multiple internal reflections resulting from the plant geometry; therefore, the emittance of a plant canopy has to be determined separately⁴. For determining the emittance of a plant canopy, one has to define a meaningful temperature of a plant. For example, the temperature of a plant canopy can be defined as the average of the temperature of its leaves. It is extremely difficult to measure the temperature of the plant surfaces in

the field conditions because the surface temperature varies quite rapidly, especially when the wind is blowing. Fuchs and Tanner⁴ determined the radiation emitted by the vegetal surface. Then, they covered the vegetal surface with a bottomless, hemispherical "pop tent" covered on the inside with aluminum foil so that vegetal surface behaves approximately like a blackbody¹². They determined the emittance as the ratio of radiant flux density emitted by a vegetal surface to the radiant flux density emitted by it, when it is covered with the pop tent. Covering the vegetal surface by the tent changes its energy balance and thus its surface temperature. During daytime, the tent cuts off the solar radiation and sky radiation. It affects the convective heat exchange and may also modify the transpiration pattern. They found the emittance of dense canopies of alfalfa and sudangrass to be between 0.97 and 0.98 on clear, calm nights when surface temperatures are more steady. The author believes that the emittance of a wide variety of leaves has not been measured carefully, in the natural environment in which the plants grow. The effect of orientation, temperature, moisture content, plant diseases, nutrient deficiency, etc., on the emittance of the leaves should be studied.

Emittance of Soils

With the advent of radiation data now available from the infrared measurements made by the satellite, there is an increasing need to know accurately the values of terrestrial surface emittance in order to interpret the data¹³. Most of the investigators (for example, Wark et. al.¹⁴) have assumed black earth in interpreting data of the satellite. Buettner et. al.¹³ (1964) have pointed out that the other data and literature are quite conflicting and confusing. For example, Falckenberg⁶ (1928) shows that sand of the Baltic has an emittance of 0.89 at 300° K. While Kruse et. al.¹⁵ (1962) give a value for "terrain" of 0.35 (it is not clear here whether this is the emittance of the whole spectrum or just a portion of it, but presumably the entire spectrum). Barnes¹⁶ (1963) lists values of emittance of 0.28 to 0.44 for gravel, plowed field, and granite. Falckenberg⁶ (1928) also lists the value for snow emittance as 0.995, while Miller¹⁷ (1963) lists the window value (water vapor window) as 0.35.

Buettner et. al.¹³ also reported that infrared signals received in the 8 to 12 μ m water vapor window by weather satellites and aircraft are dependent on surface temperature, surface emittance and atmospheric interference. Nowhere can variations of surface emittance be neglected in order to

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evaluate the correct surface temperatures. They presented three methods of determining surface emittance: (1) reflection data from polished samples ran on a spectrophotometer, (2) a device constructed by Buettner and Kern¹³ called an emissivity box, and (3) emittance as inferred from the TIROS satellite data. They gave geological interpretations of the TIROS satellite data along with the values of emittance determined by the above three methods. Emittance of quartz, granite, feldspar, obsidian, basalt, dunite, dolomite, sand, water, etc., ranged from about 0.7 to 0.97.

In the emissivity box (Buettner and Kern (B - K) Method¹³), the radiosity of the soil is first measured when it is exposed to a highly reflecting enclosed surface. The soil is then exposed to a highly emitting surface. The emittance of the soils is determined as the ratio of the two measurements. Because of the large size of the B - K apparatus, this method is used almost exclusively for determining infrared emittance of bare soils and rocks. On the other hand, the method presented by Fuchs and Tanner⁴ (F - T Method) is well adapted to this use and, in addition, is suitable for measuring the infrared emittance of plant leaves, but it requires that the base of the cone needed to create the black-body cavity should be larger than the individual leaves of most plants. Fuchs and Tanner¹⁸ (1968) recommended that aluminum cones with apex angles of 120° or larger, or shallow cylindrical cavities which have smaller apparent emissivities, be used to improve accuracy of the measurements. Idso et. al.¹¹ (1969) proposed a method for determining emittance of plants and soils which overcomes the dimensional limitations of the methods of Fuchs and Tanner as well as Buettner and Kern and it gives results in good agreement to both of them.

Hovis, Jr.¹⁹ (1966) has given spectral reflectance of some common minerals like carbonates, sulfates, nitrates, salt, silica, etc. from 0.5 to 6 μ m. He pointed out that the infrared reflectance spectra of these minerals exhibit spectral absorption band patterns that can be detected in reflection from surface minerals.

Hovis, Jr.²⁰ (1966) made the spectral reflectance measurements in the 0.5 to 22 μ m, from a number of soils including some beach sands and some common surface minerals - calcium carbonate, calcium sulfate or gypsum, sodium chloride, sodium carbonate, and sodium nitrate. He reported that if the measurements are restricted to the windows in the atmosphere of earth, the 10 μ m to 12 μ m interval seems to be the best choice for radiometry since, in this interval, minerals are most uniformly black. Lorenz²¹ (1966) found the gray

reflectances of some natural surfaces -- sand, concrete, coarse gravel, brick roof tile, fine basaltic gravel, asphalt and lawn to be in the range 0.027 to 0.062. Gray emittance can be found from gray reflectance using Kirchhoff's law.

Emittance Changes

Gates²² (1965) has pointed out that plants, like animals, must regulate their temperature in order to function at optimum physiological efficiency. This is accomplished through three mechanisms: radiation, transpiration and convection. The question arises: does a leaf adjust its emittance in order to regulate its temperature? The emittance of a leaf can be changed by changing its surface geometry and/or its orientation. A change in environmental conditions can change the leaf moisture content, which in turn changes its surface geometry. The author believes, yet to be confirmed by experiments, that it is unlikely that a leaf adjusts its surface geometry in order to regulate its emittance and hence temperature, because it is much easier for a leaf to change its orientation in order to adjust its heat load and hence temperature. For example, on a hot sunny day, it can change its orientation with respect to direct sunlight to reduce solar radiation absorbed by it.

Conaway and Van Bavel²³ (1966) reported that their radiometrically determined temperatures of the plant canopy could be explained by postulating a widely varying emittance of the plant canopy. They said that the possibility of widely varying emittance of the plant canopy exists since many changes occur in a plant canopy, as factors such as wind speed, solar radiation and water availability vary, but no attempt was made to study these.

Error Analysis of Emittance and Spectral Emittance Measurements

Fuchs and Tanner⁴ (1966) have discussed the theory of remote sensing of surface temperatures using infrared radiometer, a part of which is summarized here. They made the following assumptions for remote sensing of plants.

- 1.) Gray emittance in the wavelength range sensed by the radiometer (i.e., 8 μm to 20 μm) or

$$\epsilon(\lambda) = \epsilon \quad (8 \mu\text{m} \leq \lambda \leq 20 \mu\text{m}) \quad (1)$$

- 2.) $\epsilon(\lambda)$ is independent of temperature

3.) Kirchhoff's Law is valid.

$$\epsilon(\lambda) = \alpha(\lambda) = 1 - \rho(\lambda) \quad (2)$$

(transmission = 0 in $8 \mu\text{m} \leq \lambda \leq 20 \mu\text{m}$)

where

$\rho(\lambda)$ = the reflectance at wavelength λ

Under these assumptions, the total apparent outward radiant flux density measured by the radiometer is given by F_o .

$$F_o = \epsilon f(T) \sigma T^4 + (1 - \epsilon) f(T_s) F_s \quad (3)$$

radiant flux density emitted by the plant	radiant flux density reflected from the plant
---	---

T = contact temperature of the plant. For example, temperature of a plant can be defined as the average temperature of its constituents.

$$f(T) = \frac{\int_0^\infty f(\lambda) F_{\lambda,b}(T) d\lambda}{\int_0^\infty F_{\lambda,b}(T) d\lambda} \quad (4)$$

where

$F_{\lambda,b}(T)$ = the blackbody radiant flux density at temperature T and wavelength λ

F_s = environment integrated radiant flux density at temperature T_s

$f(\lambda)$ = filter characteristics for the infrared radiometer (for example, for Barnes infrared radiometer: $f(\lambda) \neq 0, 8 \mu\text{m} \leq \lambda \leq 20 \mu\text{m}$, $f(\lambda) = 0$, otherwise).

Equation (3) is the fundamental equation describing the quantity of radiation received at the detector of the radiometer. Since the absolute value of $f(T)$ is not important, but only its form, an assumption is now made that $f(T)$ is constant for the range of biological temperatures encountered. The radiometer is calibrated according to the quantity.

$$F_d \equiv F_o / f(T) \quad (5)$$

where

\equiv denotes that the quantity is defined.

Hence,

$$F_d = \epsilon \sigma T^4 + (1 - \epsilon) \frac{f(T_s)}{f(T)} F_s = \sigma T_s^4 \quad (6)$$

where

T_s = full radiator surface temperature as sensed by the radiometer.

The radiometer interprets the contact surface temperature, T , to be full radiator surface temperature T_s . If $\epsilon = 1$, then $T_s = T$. Also, if the integrated full radiator temperature of the surroundings (T_s) is equal to the contact surface temperature (T), then $T_s = T$. If the surface has an emittance substantially less than unity, and if the surface images sun or cold sky, the full radiator surface temperature as measured with the IR radiometer may be quite different from the contact temperature. Hence, there is a need for determining emittance and environment integrated full radiator temperature, T_s , accurately. Equation (6) can be written as

$$F_d = \epsilon \sigma T^4 + (1 - \epsilon) F_s^* \quad (7)$$

where

$$F_s^* = \frac{f(T_s)}{f(T)} F_s$$

Fuchs and Tanner assumed that F_s^* is a constant (i.e., independent of temperature T), which in turn assumes that $f(T)$ is constant. $f(T) = \text{constant}$ is a good approximation for small variations of T . Equation (7) can be rearranged to give

$$\epsilon = \frac{F_d - F_s^*}{\sigma T^4 - F_s^*} \quad (8)$$

F_d and T are experimentally measured values and contain measurement error. Let δF_d and δT be the measurement errors in F_d and T respectively. Then Eq. (8) can be rewritten as

$$\epsilon + \delta\epsilon = \frac{F_d + \delta F_d - F_s^*}{\sigma (T + \delta T)^4 - F_s^*} \quad (9)$$

where

$\delta\epsilon$ = error in the determination of emittance

From Eqs. (8) and (9), assuming $\left|\frac{\delta T}{T}\right| < 1$, $\left|\frac{4\delta T}{T} \frac{\sigma T^4}{\sigma T^4 - F_S^*}\right| < 1$

and neglecting second order and higher orders of $\frac{\delta T}{T}$ (i.e., $\left(\frac{\delta T}{T}\right)^2$, $\left(\frac{\delta T}{T}\right)^3$, etc.), we get

$$\delta \epsilon = \delta F_d - \frac{4\delta T}{T} \frac{\sigma T^4 (F_d - F_S^*)}{\sigma T^4 - F_S^*} \quad (10)$$

It should be pointed out that Eq. (7) is not an exact equation because of a number of assumptions made in deriving the equation. A complete error analysis should also include another term in δF_d representing the error due to the assumptions made. Equation (10) can be rewritten as

$$|\delta \epsilon| = \frac{1}{|\sigma T^4 - F_S^*|} \left| \delta F_d - \frac{4\delta T}{T} \frac{\sigma T^4}{(\sigma T^4 - F_S^*)} (F_d - F_S^*) \right| \quad (11)$$

where

$| |$ = denotes the absolute value

or

$$|\delta \epsilon| \leq \frac{1}{|\sigma T^4 - F_S^*|} \left[|\delta F_d| + \frac{\left| \frac{4\delta T}{T} \right|}{|\sigma T^4 - F_S^*|} \right] \quad \begin{array}{l} \text{(using the} \\ \text{triangle} \\ \text{inequality)} \end{array} \quad (12)$$

It should be pointed out that when the environment integrated radiant flux density, $F_S^* = \sigma T^4$, the radiant flux density coming from the target is equal to σT^4 (blackbody radiant flux density) irrespective of the emittance of the target. Thus, the radiometer cannot be used to measure the emittance of the target in this particular case.

Using Eq. (12), $|\delta \epsilon|$ is plotted against F_S^* with the parameters ϵ , t , $|\delta T|$ and $|\delta F_d|$ in Figs. 1 to 4. It is clear from Figs. 1 to 4 that the upper bound of $|\delta \epsilon|$ (absolute error in the determination of emittance) increases with the increase in F_S^* . Thus, for accurate determination of emittance of the plant surfaces in the field, the experiment should be conducted when the sky is relatively clear to have a small value of F_S^* and hence small $|\delta \epsilon|$. Fig. 1 shows that the emittance of

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the target, say a leaf, has a very little influence on $|\delta\epsilon|$. Fig. 2 shows that $|\delta\epsilon|$ decreases with an increase in temper-

Temperature = 25°C
 δT = Max. Error in Temp.
Meas. = 0.1°C
 ϵ = Emittance

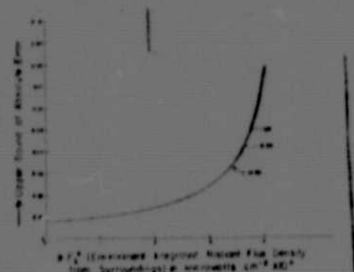


Fig. 1 $|\delta\epsilon|$ as a function of F_s^* with ϵ as a Parameter

$\delta R_b = \sigma(T + 0.5)^4 - T^4$
Emittance $\epsilon = 0.95$
 $\delta T = 0.1^\circ\text{C}$

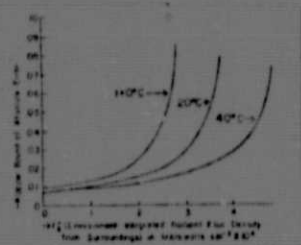


Fig. 2 $|\delta\epsilon|$ as a function of F_s^* with t as a Parameter

ature. Figs. 3 and 4 show, as expected, that increasing the error in temperature measurements and radiometric measurements, respectively, results in an increase in error in emittance determination.

As pointed out earlier, the previous investigators have assumed the emittance of the natural targets = 1 for the interpretation of multispectral scanner data in the thermal channel. Neglecting the radiant flux density reflected from a target, Fig. 5 shows the difference between temperature of the target and the band radiance temperature (i.e., temperature

Translation of the Target to a BB
Assuming $\epsilon = 0.95$ and $\delta T = 0.1^\circ\text{C}$
The Band Radiance Temperature is T_b
 $\epsilon_b = 1$ with a λ of $10.5 \mu\text{m}$

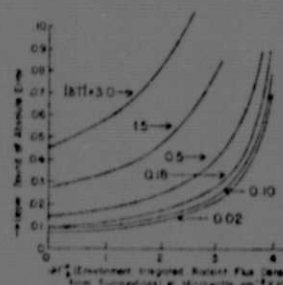


Fig. 3 $|\delta\epsilon|$ as a function of F_s^* with $|\delta T|$ as a Parameter

found by assuming the target to be a blackbody) versus emittance for the thermal channels which have been used in multispectral scanners of Environmental Research Institute of Michigan, formerly called Willow Run Laboratory, University of Michigan (4.5 to 5.5 μm , 8 to 13.5 μm and 9.3 to 11.7 μm), and Skylab (10.2 to 12.5 μm). Fig. 5 shows that for a given value of the emittance, the difference between temperature and band radiance temperature is least in the 4.5

Temperature $t = 25^{\circ}\text{C}$

Emittance $\epsilon = 0.95$

δT = Maximum Error in Temperature Measurement $= 0.1^{\circ}\text{C}$

$T = 273.16 + 25$ in $^{\circ}\text{K}$

δR_o = Maximum Measurement Error of Radiometer

$$\delta R_{b1} = \sigma((T + 0.1)^4 - T^4)$$

$$\delta R_{b2} = \sigma((T + 0.5)^4 - T^4)$$

$$\delta R_{b3} = \sigma((T + 1.0)^4 - T^4)$$

$$\delta R_{b4} = \sigma((T + 2.0)^4 - T^4)$$

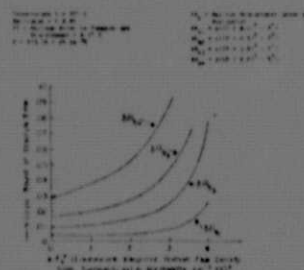


Fig. 4 $|\delta\epsilon|$ as a Function of R_S^* with $|\delta R_b|$ as a Parameter

in the 4.5 to 5.5 μm thermal channel as compared to their emittance in other thermal channels shown in Fig. 5.

- (ii) Atmosphere is less transparent in the 4.5 to 5.5 μm in thermal channel as compared to in other thermal channels shown in Fig. 5.
- (iii) The radiance of a natural target in the temperature range 0°C to 50°C (temperature range generally encountered in the natural targets) is considerably smaller in the 4.5 to 5.5 μm thermal channel as compared to its radiance in other thermal channels shown in Fig. 5. Thus, signal to noise ratio in the thermal channel 4.5 to 5.5 μm is expected to be lower than in other thermal channels shown in Fig. 5.

to 5.5 μm thermal channel, as compared to the band radiance temperature in the other thermal channels mentioned above. However, certain disadvantages of using 4.5 to 5.5 μm thermal channel are given as follows:

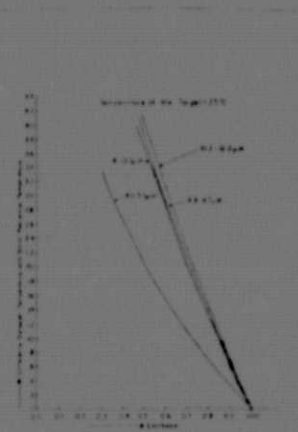


Fig. 5 Difference between Temperature and Band Radiance Temperature vs. Emittance

- (i) Most natural targets have lower emittance

EMITTANCE AND SPECTRAL EMITTANCE

Determination of Temperature and Spectral Emittance

It is quite important to know the temperature of the natural target -- say plants -- to detect the subtle changes in their temperature due to stresses by insects, plant diseases, physiological disorders, nutrient deficiency and adverse environment effects. Optimum temperature exists for certain biological activity in the organisms. It is also necessary to know the temperature of a target for energy balance calculations.

(A) Spectral Radiance Temperature and Average Temperature

If the temperature of a natural target is not constant over the whole target, its meaningful temperature can be defined as the average temperature of the target over its entire area. It was shown by Kumar and Silva²⁴ that, for a target having a non uniform temperature distribution and emittance = 1, the difference between the spectral radiance temperature of a target, as measured by the spectroradiometer, and its average temperature is rather small and within the accuracy of the spectroradiometer.

(B) Spectral Emittance and Temperature Determination

Let a spectroradiometer whose radiance and wavelength scales have been calibrated, record the spectral radiance coming from the natural target at wavelengths $\lambda_1, \lambda_2 \dots \lambda_N$. Let the target be opaque (i.e., transmission = 0) in the wavelength region λ_1 to λ_N . Throughout this section, i will refer to integers 1, 2, ... N; j and k will refer to integers lying between 1 and N. The basic assumption made in this analysis is that the reflected radiation from the target is negligible as compared to the radiation emitted from it. If the sky is clear, this is true for the most natural targets for wavelength longer than approximately $4.6 \mu\text{m}$ ²⁵. Neglecting interference by atmosphere and using Planck's Law,

$$T_s(\lambda_i) = \frac{hc}{k\lambda_i} \frac{1}{\log_e \left\{ 1 + \frac{2hc^2}{\lambda_i^5 L_{\lambda_i}} \right\}} \quad (13)$$

$i = 1, 2, \dots N$

where

$T_s(\lambda_i)$ = spectral radiance temperature at wavelength λ_i

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L_{λ_i} = spectral radiance of radiation emitted by the target at wavelength λ_i

The temperature of a target, for applications to spectroradiometric measurements, is defined using Planck's Law, as follows.

$$T = \frac{hc}{k\lambda_i} \frac{1}{\log_e \left[1 + \frac{2hc^2 \epsilon(\lambda_i)}{\lambda_i^5 L_{\lambda_i}} \right]} \quad (14)$$

It should be pointed out that in actual practice, the value of temperature T , at the wavelengths $\lambda_1, \lambda_2 \dots \lambda_N$ may not be equal because of the experimental errors involved. Throughout this Section, the word "temperature" of a natural target will be used to mean temperature, T , defined by eq. (14)

There are N equations in eq. (13) and N unknowns, $T_s(\lambda_i)$, which can be determined.

$$L_{\lambda_i, b}(T_s(\lambda_i)) = L_{\lambda_i}(T) = \epsilon(\lambda_i) L_{\lambda_i, b}(T) \quad (15)$$

where

$L_{\lambda_i, b}(T_s(\lambda_i))$ = blackbody spectral radiance at wavelength λ_i and temperature $T_s(\lambda_i)$

$\epsilon(\lambda_i)$ = spectral emittance of the target at wavelength λ_i

From Eqs. (14) and (15), one obtains

$$T_s(\lambda_i) \leq T, T_s(\lambda_i) = T \text{ if and only if } \epsilon(\lambda_i) = 1 \quad (16)$$

There are N equations in eq. (15) and $N + 1$ unknowns -- $\epsilon(\lambda_i), i=1, 2, \dots, N$ and T . Therefore, Eq. (15) cannot be solved, in general, i.e., the temperature, T , of the target cannot be determined without any knowledge about its spectral emittance.

The variables of eq. (15) are plotted vs. wavelength in Figs. 6 to 11. Although the wavelength range in these Figures is taken to be 0.5 to 14 μm for illustrative purposes, we are concerned only with the wavelength range about 4 to 14 μm in this Section. Figures 6 and 7 show that the difference between the temperature, T , and spectral radiance temperature,

Fig. 7 Difference Between
Temperature and Spec-
tral Radiance Temper-
ature vs. Wavelength

Figure 10 consists of two graphs showing the variation of the ratio of the rate of polymerization to the rate of monomer disappearance (R_p/R_m) with monomer concentration (M) for the polymerization of styrene at 50°C.

The left graph shows R_p/R_m on the y-axis (ranging from 0.4 to 1.0) versus M on the x-axis (ranging from 0 to 14). The curves are labeled with ΔT values: 0°C, 5°C, 10°C, 15°C, 20°C, 25°C, 30°C, and 35°C. The curves show that R_p/R_m increases with M and decreases with ΔT .

The right graph shows R_p/R_m on the y-axis (ranging from 0.4 to 1.0) versus M on the x-axis (ranging from 0 to 14). The curves are labeled with ΔT values: 0°C, 5°C, 10°C, 15°C, 20°C, 25°C, 30°C, and 35°C. The curves show that R_p/R_m increases with M and decreases with ΔT .

Fig. 9 Spectral Emittance
vs. Wavelength

increasing wavelengths; and the accuracy is weakly dependent upon the temperature of the target. As pointed out earlier, eq. (15) cannot be solved in general. However, the solutions of some of the special cases of eq. (15) are discussed as follows.

- (a) If the target is a blackbody at one or more wavelengths λ_j , $1 \leq j \leq N$, one gets

$$T = T_s(\lambda_j) = \max_{\lambda_i} [T_s(\lambda_i)], i = 1, 2, \dots, N \quad (17)$$

- (b) The spectral emittance at some wavelength λ_j is a known function of the spectral emittance at some other wavelength λ_k , i.e.,

$$\epsilon(\lambda_j) = f[\epsilon(\lambda_k)] \quad (18)$$

Equations (15) and (18) have $(N+1)$ equations and $(N+1)$ unknowns -- $\epsilon(\lambda_i)$, $i = 1, 2, \dots, N$ and T . Thus, the unknowns can be calculated.

It should be pointed out that if $T_s(\lambda) = T = \text{constant}$ (i.e., independent of wavelength), it does not imply that the target is necessarily a blackbody, for its spectral emittance, $\epsilon(\lambda)$, could be given by

$$(e^{hc/\lambda kT} - 1) / (e^{hc/\lambda kT'} - 1) \quad (19)$$

In actual practice, however, it is very unlikely that the spectral emittance of a natural target is given by eq. (19). In actual practice, if $T_s(\lambda) = \text{constant} \pm e$, in the wavelength range about 7 to 14 μm ,

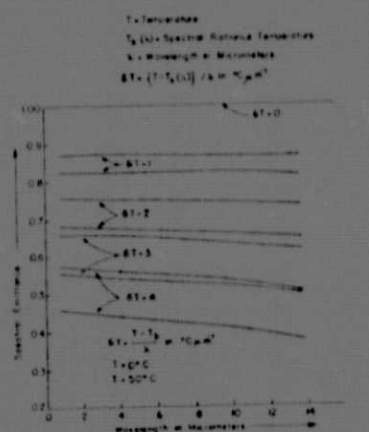


Fig. 10 Spectral Emittance vs. wavelength

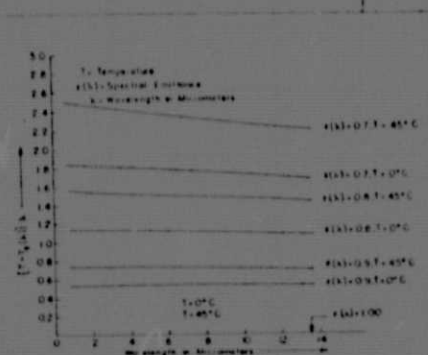


Fig. 11 Plot of $\frac{T - T_s(\lambda)}{\lambda}$ vs. λ

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one could say that the target is probably almost a blackbody with spectral emittance greater than approximately 0.98; where e = average of absolute value of the error involved in determination of $T_s(\lambda)$ (Figure 7). A typical value of e is 0.5°C .

(c) Let the upper and/or lower bounds on the spectral emittance of the target be known in some known wavelength intervals $\lambda_j < \lambda < \lambda_k$. These bounds may be determined from the available data of spectral emittance in the literature and/or researcher's own experience and knowledge.

(i) Upper Bounds

$$\min. e(\lambda_i) \leq m_1, \max. e(\lambda_i) \leq m_2 \quad (20)$$

Let

$$\max. T_s(\lambda_i) = T_1 \text{ (found from spectroradiometric data)} \quad (21)$$

$$\text{or} \quad \max. T_s(\lambda_i) = T_1 \text{ (known value)}$$

$$T \geq T_1 \text{ (eq. (16))} \quad (22)$$

Let $\{ \}$ denote the assumed value. Assume $\{T\}_1 = T_1$. Determine values of $\{e(\lambda_i)\}_1$ using eq. 15 and check if $\min. e(\lambda_i) \leq m_1$. If not, then continue taking $\{T\}_2 = T_1 + \Delta T$, $\{T\}_3 = T_1 + 2\Delta T$, ... until at some $\{T\}_k = T_2$, $\min. e(\lambda_i) = m_1$ within certain prechosen suitable accuracy. Here ΔT is some suitable increment in temperature. For example, one can take ΔT as the average of absolute error involved in the determination of spectral radiance temperature by spectroradiometer. Similarly, one can determine T_3 corresponding to the condition $\max. e(\lambda_i) = m_2$.

Let

$$\max. [T_1, T_2, T_3] = T_{h.l.b.} \quad (23)$$

where

$$T_{h.l.b.} = \text{high lower bound of the temperature } T$$

If any other lower bound on T is known, it should also be included in eq. (23) to determine $T_{h.l.b.}$.

$$e(\lambda_i)_{l.u.b.} = \frac{L_{\lambda_i, b}(\lambda_i, T_s)}{L_{\lambda_i, b}(\lambda_i, T_{h.l.b.})} \quad (24)$$

Where

$$\epsilon(\lambda_i)_{l.u.b.} = \text{low upper bound on the spectral emittance} \\ \epsilon(\lambda_i)$$

(ii) Lower Bounds

The same procedure used in "Upper Bounds" can be followed to determine $T_{l.u.b.}$ and $\epsilon(\lambda_i)_{h.l.b.}$ from the known lower bounds on spectral emittance.

Let the wavelengths at which $\min. \{\epsilon(\lambda_i)_{l.u.b.}\}$, $\min. \{\epsilon(\lambda_i)_{h.l.b.}\}$, $\max. \{\epsilon(\lambda_i)_{l.u.b.}\}$ and $\max. \{\epsilon(\lambda_i)_{h.l.b.}\}$, minimized/maximized over the wavelength range λ_1 to λ_N occur be λ_a , λ_b , λ_c and λ_d , respectively. Then $\min. \{\epsilon(\lambda_i)\}$ lies between λ_a and λ_b and $\max. \{\epsilon(\lambda_i)\}$ lies between λ_c and λ_d respectively. If $T_s(\lambda_j) \geq T_s(\lambda_k)$ for all $\lambda_j \geq \lambda_k$, where $1 \leq j \leq N$, $1 \leq k \leq N$, it implies that $\min. \epsilon(\lambda_i)$ and $\max. \epsilon(\lambda_i)$ would occur at wavelengths $\lambda_a = \lambda_b$, and $\lambda_c = \lambda_d$, respectively.

The author emphasizes that for most of the plant canopies with good ground cover (say, ground cover > 0.70), one can take $T_{h.l.b.}$ as the approximation to the temperature, T , of the plant defined by Eq. (14) because the spectral emittance of most plant canopies with good ground cover probably lies between about 0.95 and 1.00 in 7 to 14 μm wavelength range. If no more information on the spectral emittance of the target is available other than upper and/or lower bounds of its spectral emittance which have been used to calculate $T_{h.l.b.}$ and $T_{l.u.b.}$ respectively, one can take T (estimated) = $(T_{h.l.b.} + T_{l.u.b.})/2$.

One practical way of determining the temperature of a natural target — say a plant canopy is to take spectroradiometric data on the plant canopy at two different times when the sky is clear (cloud free) so that the reflected radiation from the target is negligible as compared to the radiation emitted by it. These times should be selected close enough so that the geometry (orientation of the leaves, stems, etc. percent ground cover) of the plant canopy can be assumed to be practically the same at both times. Wind should be steady at both of these times so that the wind does not change the geometry of the plant. Also, these two times should

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be such that the temperature of the plant at one time is likely to be significantly (at least 2°C) different from its temperature at the other time. This can be approximately checked by making a few measurements of contact temperature of the leaves directly visible from the spectroradiometer by thermometer. Now, an assumption can be made that the emittance of the plant canopy is equal at both of these times since its geometry is practically the same at both times. This gives one additional equation (eq. (18)) and hence temperature, T , of the plant canopy can be determined. However, if the temperature of the plant canopy at one time is close to its temperature at another time within the experimental accuracy, then the spectral radiance of the plant canopy recorded by spectroradiometer will be equal at two times within experimental accuracy, i.e., two equations of eq. (15) are the same within experimental accuracy. So, there are only N independent equations in (15) and $N+1$ unknowns -- $\epsilon(\lambda_i)$, $i=1, 2, \dots, N$, and T . Temperature, T , cannot be determined without any knowledge of the spectral emittance of the target.

The same procedure can be followed to determine the temperature of a plant canopy by taking spectroradiometric data on two plant canopies of the same crop, maturity, geometry (orientation of leaves, stems, etc.) soil background, percent ground cover etc. These plant canopies can be assumed to have equal spectral emittance in the wavelength range of the spectroradiometer. Thus if their temperatures are different, one can determine their emittance and temperature.

To create an illustration, previously acquired calibrated data of the Exotech Model 20 C spectroradiometer in the wavelength range 2.8 to $5.6\ \mu\text{m}$ on Russell Silt Loam Soil were available²⁴. Maximum value of spectral radiance temperature from this data was found to be 42°C at $3.64\ \mu\text{m}$ (eq. (21)). So, the contact temperature of the soil should be at least 42°C (eq. (22)). Assuming contact temperature of the soil to be 42°C , its spectral emittance was calculated avoiding the wavelength region close to the $4.3\ \mu\text{m}$ CO_2 band and is shown in Table I. Obviously spectral emittance at $3.64\ \mu\text{m} = 1$. Note that Table I gives the upper bound of the spectral emittance.

Table I Upper Bound of Spectral Emittance

Wavelength in μm	3.4	3.6	3.8	4.6	4.8	5.0	5.5
Upper Bound of Spectral Emittance	0.73	0.82	0.81	0.71	0.72	0.74	0.75

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