ABSTRACT

Infrared thermometers with a bandpass filter from 8μ to 13μ can be used to measure the real temperature of vegetal surfaces with errors in the range of 0.1C to 0.3C. To do this the emissivity must be either known or determined and a correction accounting for the reflected radiation from the surroundings must be made. Values of emissivities found for dense canopies of alfalfa and of sudangrass were between 0.97 and 0.98. Emissivities of single leaves of snap bean and tobacco were 0.96 and 0.97, respectively. Depending upon the radiation of the surroundings corrections of +0.6C to +1.4C had to be added to the apparent radiative temperature of these surfaces in order to yield real surface temperature.

THE PHYSIOLOGICAL REACTIONS and the physical transport phenomena at the interface of the plant and the atmosphere depend upon the temperature of the plant surface. Brown and Escombe (3) pointed out the close quantitative relation between the energy balance of the leaf, its surface temperature, its uptake of CO₂, its respiration and its transpiration.

Early attempts to measure surface temperatures of leaves or other objects were systematically biased by radiation, conduction, and exposure errors (6, 15, 16). In recent years, the miniaturization of the thermometers and radiation compensating methods (18, 19) have reduced these errors, but sampling problems remain when canopies are to be studied.

Many of these difficulties can be eluded with remote sensing of surface temperatures through thermal radiation measurements. The energy flux, R, of the electromagnetic radiation from any surface of emissivity ε, is related to the surface temperature, T in degrees K, by

\[ R = e \sigma \varepsilon T^4 \]  

where \( \sigma \) is the Stephan–Boltzmann constant. In theory, radiation sensing does not interfere with the surface and yields a measurement that is integrated over the field-of-view of the sensor.

Radiative measurements of surface temperature in biology were initiated by Aldrich (1) who devised a bolometer for skin temperature measurements. Stoll and Hardy (20) developed a method for measuring environmental radiative temperature. Using the Stoll–Hardy radiometer Gates (10, 11), and Gates et al. (13) range from 0.95 to 0.98. Monteith and Szeicz (17) and Gates (11) estimate that assuming ε = 1 may cause errors of at most 0.2C. A simple computation shows that if the incident thermal radiation from the sky and surroundings were 300 w m⁻² corresponding to an apparent temperature of -4C, and if the real surface temperature were 25.0C, a change of emissivity from 0.95 to 0.98 would cause a measurement error of 2.2C. We propose a method for correcting surface temperature measurements for emissivity within the limits of sensitivity of the IR thermometer used.

PRINCIPLE

For a perfectly diffuse and opaque surface the outward flux of thermal energy \( W(\lambda) d\lambda \) in the small wavelength interval between \( \lambda \) and \( \lambda + d\lambda \) is

\[ W(\lambda) d\lambda = \varepsilon_\lambda E(\lambda, T) d\lambda + (1 - \varepsilon_\lambda) B(\lambda, T_\ast) d\lambda \]  

where \( \varepsilon_\lambda \) is the emissivity of the surface at wavelength \( \lambda \); \( E(\lambda, T) \) is the apparent radiative temperature. This causes errors that only can be minimized by short exposure and frequent reference to a calibration source. The strong absorption (emission) bands of water vapor in the infrared cause measurement errors that depend upon the humidity and viewing path-length. These limitations considerably restrict the usefulness of the above instruments for extensive field work.

In order to avoid these shortcomings, an instrument should have a regulated reference temperature, a radiation sensor mounted behind a filter with a sharply defined bandpass in a water vapor window, and a reflective chopper outside the optics. We have used two infrared (IR) thermometers, with 8–13μ bandpass filters which meet these requirements. One has a 30° field-of-view and is used mainly where a spatially integrated surface temperature is desirable. The other thermometer has a fixed focus and views a target area 3 mm in diameter at a distance 7 cm in front of the lens; beyond the focal plane the field-of-view is about 7°. The focused instrument is used for localized surface temperature measurements on individual leaves or small areas. The instruments are provided with a calibrated meter and a millivolt output that will drive recorders. Measurements, including calibration, preferably are recorded rather than read visually.

The instruments can provide an absolute temperature reading for a blackbody surface (ε = 1) within 0.3C and detect differences of 0.1C provided the output is either filtered by a large capacitor or integrated for a few seconds. This is necessary because of output fluctuation caused principally by the reference temperature regulation and amplifier design. Both instruments have an effective working range of 50°C which includes the plant's growth range.

Equation [1] shows that no instruments can yield a correct estimate of the surface temperature if the emissivity of the surface is not taken into account. All the previously cited authors have recognized this problem but have neglected to apply the needed corrections, arguing that the emissivity of plant material is very close to unity. Emissivities given by Falkenberg (7), Gates and Tantravarn (12), and Gates et al. (13) range from 0.95 to 0.98. Monteith and Szeicz (17) and Gates (11) estimate that assuming ε = 1 may cause errors of at most 0.2C. A simple computation shows that if the incident thermal radiation from the sky and surroundings were 300 w m⁻² corresponding to an apparent temperature of -4C, and if the real surface temperature were 25.0C, a change of emissivity from 0.95 to 0.98 would cause a measurement error of 2.2C. We propose a method for correcting surface temperature measurements for emissivity within the limits of sensitivity of the IR thermometer used.

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2 Research Assistant, and Professor of Soils.

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Infrared Thermometry of Vegetation

M. Fuchs and C. B. Tanner
is the value of Planck’s energy distribution law for the wavelength, $\lambda$, and the surface temperature, $T$; and $B(\lambda, T_s)$ is the radiant energy flux of wavelength, $\lambda$, incident to the surface from the surrounding which has an integrated radiative temperature $T_s$. The outward flux, $R_o(\lambda)\,d\lambda$, as sensed by an instrument having a response $0 \leq f(\lambda) \leq 1$ is given by

$$R_o(\lambda)\,d\lambda = f(\lambda)W(\lambda)\,d\lambda = \varepsilon(\lambda)f(\lambda)E(\lambda, T)\,d\lambda + (1 - \varepsilon(\lambda))f(\lambda)B(\lambda, T_s)\,d\lambda \tag{3}$$

The integration of [3] yields the total measured outward flux of thermal energy, $R_o$.

$$R_o = \int_0^\infty \varepsilon(\lambda)f(\lambda)E(\lambda, T)\,d\lambda + \int_0^\infty (1 - \varepsilon(\lambda))f(\lambda)B(\lambda, T_s)\,d\lambda \tag{4}$$

The emissivity of the surface, $\varepsilon$, weighted for the instrument response, is defined by

$$\varepsilon = \int_0^\infty \varepsilon(\lambda)f(\lambda)E(\lambda, T)\,d\lambda / \int_0^\infty f(\lambda)E(\lambda, T)\,d\lambda \tag{5}$$

In the biological range of temperatures, $\varepsilon$ is very nearly independent of temperature.

It is also useful to define a lumped filter function, $f(T)$, as

$$f(T) = \int_0^\infty f(\lambda)E(\lambda, T)\,d\lambda / \int_0^\infty f(\lambda)E(\lambda, T)\,d\lambda \tag{6}$$

Since $\int_0^\infty E(\lambda, T)\,d\lambda = \sigma T^4$ where $\sigma$ is the Stephan–Boltzmann constant, we may write [6] as

$$\int_0^\infty f(\lambda)E(\lambda, T)\,d\lambda = f(T)\sigma T^4 \tag{7}$$

The characteristics of the filter of the Barnes IR thermometer (5, 9) are approximated very well by

$$f(\lambda) = \begin{cases} 0, & \lambda \leq 8\mu \\ \varepsilon, & 8\mu < \lambda \leq 13\mu \\ 0, & \lambda > 13\mu \end{cases} \tag{8}$$

Applying condition [8] and the identity established by [7], [5] becomes

$$\int_0^\infty f(\lambda)\,d\lambda = \int_0^\varepsilon f(\lambda)\,d\lambda + \int_\varepsilon^1 f(\lambda)\,d\lambda = f(T)\sigma T^4 \tag{9}$$

Equation [9] solves the first integral in [4] with no other assumption than that of condition [8] on the filter response. In order to complete the integration of the second term, we can use condition [8] and write by analogy with [6] that

$$\int_\varepsilon^1 B(\lambda, T_s)\,d\lambda = \int_\varepsilon^1 f(\lambda)B(\lambda, T_s)\,d\lambda = f(T_s)B_s \tag{10}$$

where $B_s = \int_\varepsilon^1 B(\lambda, T_s)\,d\lambda$.

The form of $B(\lambda, T_s)$ is generally unknown. When $B(\lambda, T_s)$ is unknown, [10] can be used to integrate the last term in [4] only with the assumption of constant emissivity

$$f(T) = \varepsilon \tag{11}$$

Equation [4] then becomes:

$$R_o = \varepsilon \sigma T^4 + (1 - \varepsilon) f(T_s)B_s \tag{12}$$

Data given by Gates and Tantraporn (12) and Gates et al. (13) indicate that in the case of leaf surfaces, assumption [11] is good. On the other hand, measurements made by Beutner and Kern (4) show that approximation [11] is not valid for quartz, and leads to important errors in the determination of $\varepsilon$. We wish to emphasize that the magnitude of the error resulting from [11] depends only on the second term of the right-hand side of equation [12], and therefore $B_a$ should be as small as possible during measurements of $\varepsilon$. Equation [12] is also a valid integration of [4] for any surface having an emissivity close to unity throughout the range where $f(\lambda) \neq 0$.

Equation [12] can be solved for $T$ but the solution is long and cumbersome because $f(T)$ has to be evaluated by iteration. However, computations show that for a square bandpass filter between 8$\mu$ and 13$\mu$ at $T = 273$K, $f(T) = 0.30$; at $T = 298$K, $f(T) = 0.52$; at $T = 323$K, $f(T) = 0.34$. Therefore in the range of biological temperatures, $f(T)$ may be considered as constant. We define

$$R_o = f(T)\sigma T^4 \tag{13}$$

where $T_s$ is the apparent surface temperature, and

$$B_a = f(T_a)\sigma(T_a)B_a \tag{14}$$

and simplify [12] to

$$R_o = \varepsilon \sigma T^4 + (1 - \varepsilon) B_a \tag{15}$$

Equation [15] can be solved easily for $T$ provided $R_o$ is related by a calibration curve to the output of the IR thermometer and $\varepsilon$ and $B_a$ are known. The term $B_a$ has little physical meaning; it is related by [14] to the total surrounding radiation, $B_s$, that impinges on the surface. Equations [13] and [15] express how the temperature obtained directly from the IR thermometer is related to the real temperature of the surface and the reflected radiation from surroundings. An emissivity less than unity decreases the apparent temperature, whereas the reflection of radiation impinging on the surface increases it. When the radiative temperature of the surroundings is equal to the real surface temperature, no corrections are needed.

In field work, the radiation from the surroundings includes that from the sky, the instrument and its operator, and any object that intercepts part of the hemisphere that is viewed by the surface.

Under clear sky conditions, $B_s$ and $B_a$ are expected to be very small because of the low temperatures and low emissivity of the cloudless sky in the 8–13$\mu$ band. The sky under these conditions typically emits 200 W m$^{-2}$. If a 25% portion of the sky is intercepted by the instrument, its operator, etc., which have an average 300K blackbody temperature, the value of $B_s$ is approximately 275 W m$^{-2}$. Changes in the surroundings that affect the solid angle of exposure of the surface to the sky may modify [15] substantially—the instrument alone at 0.20 m, from the surface has a 12% interception.

Calibration of the IR Thermometer

A point on the instrument calibration curve can be obtained if the output, $E_o$, of the IR thermometer is measured while it is reading a blackbody surface of known temperature. With $\varepsilon = 1$, [15] yields

$$E_o \sim R_o = \sigma T^4 \tag{16}$$

where the correspondence between $E_o$ and $R_o$ is unique. The complete curve for the working range of the instrument is obtained by repeating the procedure for various surface temperatures. This curve is then used to define the relationship between the output of the instrument and $R_o$ in [16]. According to [13] the curve also yields $T_s$, the apparent surface temperature. In order to achieve a blackbody surface, a standard reference surface with $\varepsilon < 1$ is viewed in an arrangement that makes it appear black.

We used as a standard surface, a 10 $\times$ 10 $\times$ 1 cm block of anodized aluminum. The temperature was monitored by 4 copper-constantan 0.25 mm wire thermocouples in series, mounted inside the block less than 0.5 mm from the surface. The block was kept at constant temperature by a thermostatic heater of considerable thermal mass. The temperature control was within 0.05°C. The anodized aluminum was chosen as the standard reference surface because its emissivity between 8$\mu$ and 13$\mu$ is of the order of the emissivity of leaves and is very nearly constant. It is also a very stable surface and can be made easily in the laboratory. Lastly, the anodic layer is thin and is coupled well thermally with the aluminum substrate so that the temperature of the surface is represented well by the temperature measured in the aluminum substrate.
Table 1. Experimental values for emissivity, $\varepsilon$, and determination of the surrounding correction, $B_s^\star$.

<table>
<thead>
<tr>
<th>Surface</th>
<th>$\varepsilon$ at $T = 20^\circ C$</th>
<th>$B_s^\star$ at $T = 20^\circ C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anodized aluminum</td>
<td>0.956 ± 0.003</td>
<td>315 ± 22</td>
</tr>
<tr>
<td>Black paint</td>
<td>0.995 ± 0.002</td>
<td>393 ± 11</td>
</tr>
<tr>
<td>Graphite</td>
<td>0.831 ± 0.005</td>
<td>339 ± 8</td>
</tr>
</tbody>
</table>

† Standard deviation.

Measurements

Emissivity of reference surfaces. The emissivity, $\varepsilon_A$, of the anodized aluminum for $8/\mu < \lambda < 13/\mu$ was determined as accurately as the sensitivity of the IR thermometers permitted using equation [15] for several surface temperatures with $B_s$ constant. Buettner and Kern [4] have proposed another procedure which keeps the surface temperature constant and varies $B_s$; the accuracy of their method, however, relies heavily upon assumption [11]. In order to have $B_s$ small, as imposed by [12], the measurements were made with the surface exposed to a large portion of the clear sky. The surface temperature of the anodized target was monitored and regulated following the same procedure as used in the calibration. For each surface temperature, $\sigma T^4$ was computed and $R_b$ was measured with the calibrated IR thermometer. From the linear relationship [15] between $R_b$ and $\sigma T^4$, $\varepsilon_A$ and $B_s^\star$ were obtained respectively as the slope and from the ordinate intercept at $T = 0$. This assumed that $B_s^\star$ does not vary with the temperature of the surface, and [14] indicates that this is true only if $f(T)$ is constant, which has been shown to be a good approximation only for small variations of $T$. Therefore measurements were restricted to a 30°C temperature range. The emissivities of a black paint (3M velvet coating 101–C10) and of a graphite slab were determined using the same procedure as for the anodized aluminum. Results are reported in Table 1.

The differences between the values obtained for $B_s^\star$ with the three surfaces are larger than expected from the standard deviation. This is due to the high emissivities of the surfaces used which amplify any error in the value of the intercept. A more accurate estimate of $B_s^\star$ could be obtained if a reference surface, such as aluminum, of relatively low but constant emissivity between $8/\mu$ and $13/\mu$ ($14)$ were used. Because $B_s^\star$ is generally small, this procedure involves the use of a second IR thermometer with a working range below the usual biological temperatures. This additional effort is not justified because the inaccuracy in $B_s^\star$ is of little importance if the value of $B_s^\star$ is used to solve [15] for vegetal surface temperature. When $\varepsilon > 0.95$, $\varepsilon \sigma T^4$ is at least one order of magnitude larger than $(1 - \varepsilon)B_s^\star$.

Once the emissivity of the standard surface has been determined, $B_s^\star$ can be obtained with sufficient accuracy for any surrounding's condition at any time, by a single measurement of $T$ and $R_b$.

Emissivity of vegetal surfaces. The emissivity of a single leaf is not representative of the emissivity of a vegetal cover because of the multiple internal reflections resulting from the cover geometry; therefore the emissivity of a vegetal cover has to be determined in situ. The method used to find the emissivity of the anodized aluminum cannot be used for a canopy because the surface temperature of vegetation cannot be controlled over the necessary temperature range; furthermore, surface temperatures of canopies cannot be measured with contact thermometers. If $B_s^\star$ is determined with the help of the anodized aluminum sur-
face, a measurement of $\sigma T^4$ and $R_\theta$ over the vegetal surface is sufficient to compute $\varepsilon$ from [15]. It should be remembered that $B_\theta^*$ includes the thermal radiation emitted by the IR thermometer; therefore, the IR thermometer should subtend approximately the same solid angle with respect to the surface when it is aimed alternately at the anodized aluminum and the vegetal surface.

In order to obtain $\sigma T^4$, the vegetal surface was covered with a bottomless, hemispherical “pop-tent”* covered on the inside with aluminum foil. A hole near the tent apex fitted the entrance pupil of the IR thermometer. This arrangement reproduces at a larger scale the geometry of the cone in Fig. 1 and creates a “blackbody cavity” of temperature close to that of the surface. Consequently, the IR thermometer reads $\sigma T^4$. When the tent is removed, the thermometer reads $R_\theta$.

When the vegetal surface is covered by the tent, its energy balance is changed and so is its surface temperature. During daytime, the tent cuts off the solar radiation and the sky radiation. It affects the convective heat exchange and may also modify the transpiration pattern. At night, especially if the weather is calm, only the sky radiation is affected markedly by the tent. As may be expected during the day, the surface temperature changes drastically and rapidly when the tent is set over the surface. At night there is a period of 5 to 15 seconds during which the temperature remains practically unchanged, following which, for about one minute, the temperature increases gradually to reach a new equilibrium, usually 1.0 to 1.5°C higher than the initial temperature.

The emissivity of two vegetal surfaces was determined on clear, calm nights when surface temperatures are most steady. Three measurements of tall sudangrass (*Sorghum sudanense*) taken at small time intervals with the focussed thermometer yielded emissivity values of 0.978, 0.976, and 0.969. Three measurements with the 30° field-of-view instrument all gave 0.976 as a unique result. An emissivity of 0.977 was found on alfalfa (*Medicago sativa*) using the 30° field-of-view instrument.

Measurements of surface temperatures. Once the emissivity of the vegetal surface is known, its surface temperature can be determined by pointing the IR thermometer successively at the anodized aluminum surface, whose temperature is monitored, and at the vegetal surface. Equation [15] is then applied for both measurements to yield first $B_\theta^*$ which in turn is used to solve for $T_s$, the surface temperature of the canopy. The computations are expedited by the available tabulation of $\sigma T^4$ (21).

Measurements were made on a clear day (Arlington, Wisconsin, August 14, 1965) over tall sudangrass (*Sorghum sudanense*) in a rectangular field of 4.3 m by 3.4 m. A surface temperature of 33.4°C was recorded whereas the corrected surface temperature was 25.1°C. At 1900 hour CST, a light haze covered the sky, and $B_\theta^*$ was then 295 w m⁻²; an apparent radiative temperature of the surface was 34.8°C. At 1400 hour CST, $B_\theta^*$ was 132 w m⁻². The leaf temperatures measured with the IR thermometer and the cone agreed within 0.2°C or better with the thermocouple measurements. This is within the combined accuracy of the two sensors.

Both the IR thermometer and the thermocouples showed that when the leaf is covered with the thermometer cone the leaf temperature remains constant for less than 10 seconds and then increases to a new equilibrium 0.6 to 1.0°C above the initial temperature in about one minute. This heating is due to the strong reduction of the heat exchange with the surroundings and not to heat injection from the heated cavity of the IR thermometer since covering the leaf by the cone alone caused the same temperature rise.

From daytime IR thermometer measurements of $R_\theta$, the outward radiant flux from the bean leaf exposed to the surrounding’s radiation, and simultaneous determination of $B_\theta^*$, the surface temperature of the leaf was computed from [15] using 0.957 for $\varepsilon$. The calculated temperatures agreed within 0.3°C with the thermocouple readings.

Temperature differences. When temperature differences between vegetal surfaces are to be measured, emissivity and reflected surrounding’s radiation corrections may be neglected without causing serious errors, provided surfaces have the same high emissivity and are surrounded by similar radiation backgrounds, as is often the case in experimental plots. This is easily shown by writing [15] as

$$\sigma T^4_\alpha = \epsilon \sigma T^4 + (1 - \epsilon) B_\theta^*$$

where $T^4_\alpha$ can be written in the form of finite differences as

$$\Delta T^4_\alpha = \epsilon \sigma T^4 + (1 - \epsilon) B_\theta^*$$

**The thermocouple measurements of leaf temperatures were made by Mr. Edward T. Kanemasu, Research Assistant in Soil Science.
surroundings's condition is always between these two limits, therefore the relative error in $\Delta T$ will be between $(1 - e^{1/4})$ and $(1 - e)$. Apparent surface temperature differences of 5.8°C were measured between wilting and irrigated snap beans in adjacent plots. The correct $\Delta T$ computed with $e = 0.957$ and $B_{s*} = 200$ w m$^{-2}$ would be 6.0°C. In glasshouses or growth chambers however the surrounding's temperature including hot lights, may be much higher than the plant temperature and lead to larger errors than found in the field.

**CONCLUSIONS**

Accurate temperature determinations of vegetal surfaces can be made with infrared thermometers provided the emissivity of the surface is known and the reflected background thermal radiation is accounted for. The errors will not exceed $\pm 0.1°C$ if the calibration of the instrument is checked for zero offsets at the time of the measurements, and $\pm 0.3°C$ otherwise. The apparent radiative temperature may differ as much as 2°C from the real temperature. For a given emissivity this difference will depend upon the surrounding's thermal radiation.

Radiation from the surroundings can be estimated with the help of a reference surface of known temperature and known emissivity. Anodized aluminum is very convenient for this purpose. The emissivity of the vegetal surface is obtained by measuring its thermal radiation successively when it is enclosed in an approximate blackbody cavity and when it is exposed to the radiation of the surroundings. An adequate blackbody is obtained by covering the vegetal surface with an aluminum cone polished inside, or a "pop tent" internally coated with aluminum foil. However, this operation changes the energy balance at the surface and causes the surface temperature to drift. This effect is minimized by taking measurements of emissivity during the night and by covering the surface for less than 10 seconds. Emissivities of $0.957 \pm 0.005$ and $0.971 \pm 0.002$ were determined for single leaves of snap bean and tobacco respectively. The emissivities of dense canopies, which should be higher than of an individual leaf, were determined for tall sudangrass as 0.97$e$ and for alfalfa as 0.97$e$.

Several assumptions have been introduced to solve the equations. They must be kept in mind when IR thermometers are used. In the determination of the emissivity of the reference surface, its temperature is varied; however, the range over which the surface temperature can be changed is limited by the assumption of a constant instrument filter weighting function $f(T)$. Moreover, when the temperature of vegetal surfaces is measured, the anodized aluminum, which is used to determine the weighted radiation $B_{s*}$ from the surroundings, has to be at a temperature close to the temperature of the plant surface. In order to have $B_{s*}$ constant, the geometry of the background must remain the same when the IR thermometer is pointed toward the measured surface and the reference surface. The emissivity of the surfaces measured has to be constant in the transmission window of the instrument. Errors due to departure from this condition are minimized if the overall emissivity is high and if $B_{s*}$ is small. These conditions are well approximated for vegetal surface in the 8–13μ wavelength band, and enable accurate temperature determinations.

**LITERATURE CITED**