

Infrared Thermometry of Vegetation¹

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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 CO_2 , 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

$$R = \epsilon\sigma T^4 \quad [1]$$

where σ 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) measured temperatures of vegetal surfaces. Similar measurements were carried out over grass by Monteith and Szeicz (17) with a Linke-Feussner radiometer and independently by Fimpel (8) using a modified Ardonox pyrometer. The output of all these radiation sensors depends upon ambient temperature and must be adjusted accordingly. They also require absorbing filters for separating the reflected solar radiation from the emitted infrared radiation. The temperature of these filters depends upon the amount of radiation absorbed and consequently may differ in temperature from the reference cavity of the instrument. 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 $8\text{--}13\mu$ bandpass filters which meet these requirements³. 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 focussed 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 ($\epsilon = 1$) 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 50C 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 Falckenberg (7), Gates and Tantraporn (12), and Gates et al. (13) range from 0.95 to 0.98. Monteith and Szeicz (17) and Gates (11) estimate that assuming $\epsilon = 1$ 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 λ and $(\lambda + d\lambda)$ is

$$W(\lambda)d\lambda = \epsilon_\lambda E(\lambda, T)d\lambda + (1 - \epsilon_\lambda)B(\lambda, T_s)d\lambda \quad [2]$$

where ϵ_λ is the emissivity of the surface at wavelength λ ; $E(\lambda, T)$

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³Opti-therm infrared thermometers, Model IT-2 and IT-3, Barnes Engineering Company, 30 Commerce Road, Stamford, Conn. 06902.

is the value of Planck's energy distribution law for the wavelength, λ , and the surface temperature, T ; and $B(\lambda, T_s)$ is the radiant energy flux of wavelength, λ , 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

$$R_o(\lambda)d\lambda = f(\lambda)W(\lambda)d\lambda = \epsilon_\lambda f(\lambda)E(\lambda, T)d\lambda + (1 - \epsilon_\lambda)f(\lambda)B(\lambda, T_s)d\lambda \quad [3]$$

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

$$R_o = \int_0^\infty \epsilon_\lambda f(\lambda)E(\lambda, T)d\lambda + \int_0^\infty (1 - \epsilon_\lambda)f(\lambda)B(\lambda, T_s)d\lambda \quad [4]$$

The emissivity of the surface, ϵ , weighted for the instrument response, is defined by

$$\epsilon = \left[\int_0^\infty \epsilon_\lambda f(\lambda)E(\lambda, T)d\lambda \right] / \left[\int_0^\infty f(\lambda)E(\lambda, T)d\lambda \right] \quad [5]$$

In the biological range of temperatures, ϵ is very nearly independent of temperature.

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

$$f(T) = \left[\int_0^\infty f(\lambda)E(\lambda, T)d\lambda \right] / \left[\int_0^\infty E(\lambda, T)d\lambda \right] \quad [6]$$

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

$$\int_0^\infty f(\lambda)E(\lambda, T)d\lambda = f(T)\sigma T^4 \quad [7]$$

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

$$\begin{aligned} f(\lambda) &= 0 & \lambda < 8\mu \\ f(\lambda) &\neq 0 & 8\mu \leq \lambda \leq 13\mu \\ f(\lambda) &= 0 & \lambda > 13\mu \end{aligned} \quad [8]$$

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

$$\int_0^\infty \epsilon_\lambda f(\lambda)E(\lambda, T)d\lambda = \int_8^{13} \epsilon_\lambda f(\lambda)E(\lambda, T)d\lambda = \epsilon f(T)\sigma T^4 \quad [9]$$

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

$$\int_0^\infty f(\lambda)B(\lambda, T_s)d\lambda = \int_8^{13} f(\lambda)B(\lambda, T_s)d\lambda = f(T_s)B_s \quad [10]$$

where $B_s = \int_0^\infty B(\lambda, T_s)d\lambda$.

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

$$\epsilon_\lambda = \epsilon \quad [11]$$

Equation [4] then becomes:

$$R_o = \epsilon f(T)\sigma T^4 + (1 - \epsilon)f(T_s)B_s \quad [12]$$

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 Buettner and Kern (4) show that approximation [11] is not valid for quartz, and leads to important errors in the determination of ϵ . 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_s should be as small as possible during measurements of ϵ . 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

8μ and 13μ at $T = 273K$, $f(T) = 0.30$; at $T = 298K$, $f(T) = 0.32$; at $T = 323K$, $f(T) = 0.34$. Therefore in the range of biological temperatures, $f(T)$ may be considered as constant. We define

$$R_b = R_o/f(T) = \sigma T_a^4 \quad [13]$$

where T_a is the apparent surface temperature, and

$$B_s^* = [f(T_s)/f(T)]B_s \quad [14]$$

and simplify [12] to

$$R_b = \epsilon \sigma T^4 + (1 - \epsilon)B_s^* \quad [15]$$

Equation [15] can be solved easily for T provided R_b is related by a calibration curve to the output of the IR thermometer and ϵ and B_s^* are known. The term B_s^* 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_s^* are expected to be very small because of the low temperatures and low emissivity of the cloudless sky in the 8-13 μ band. The sky under these conditions may emit 200 $w m^{-2}$. If a 25% portion of the sky is intercepted by the instrument, its operator, etc., which have an average 300K radiative 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 $\epsilon = 1$, [15] yields

$$E_o \sim R_b = \sigma T^4 \quad [16]$$

where the correspondence between E_o and R_b 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_b in [16]. According to [13] the curve also yields T_a , the apparent surface temperature. In order to achieve a blackbody surface, a standard reference surface with $\epsilon < 1$ 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 0.05C. The anodized aluminum was chosen as the standard reference surface because its emissivity between 8 μ and 13 μ 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.

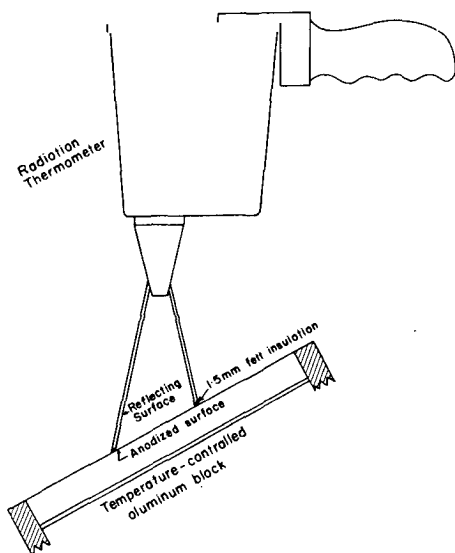


Fig. 1. Schematic diagram of IR thermometer (focussed model) with aluminum cone used for calibration.

In order to have the surface behave as a blackbody it was covered by the base of a "skewed" aluminum cone with a polished inner surface (Fig. 1); the inner surface of the cone must be highly reflective to thermal radiation. The apex of the cone was cut to fit the entrance pupil of the IR thermometer. The "skewed" cone is used to avoid the direct reflection of the beam emitted by the cavity of the instrument back into itself when specular surfaces, such as glass, are viewed. With this arrangement the ratio of the apex aperture area to the base area is small. The effective emissivity, e , resulting from this geometry is given (2) by

$$e = \epsilon_A / [\epsilon_A + r(1 - \epsilon_A)] \quad [17]$$

where ϵ_A is the emissivity of the anodized aluminum and r is the ratio of the apex area over the base of the cone. For the focussed instrument, r was equal to 0.04. Values for ϵ_A quoted in the literature (14) indicate that it is higher than 0.9. Taking 0.9 as a conservative estimate for ϵ_A and $r = 0.04$, [17] yields a value of 0.996 for e . Later determinations indicate that ϵ_A is 0.956 and consequently the value of e is 0.998. To make sure that the departure from unity is beyond the sensitivity of the IR thermometer, the value of r is varied. To induce a shift of 0.1C in the calibration curve, the value of r had to become as large as 0.15, which yields 0.992 for e .

The calibration was repeated using a black-painted surface (3M velvet coating 101-C10 black) and also a stirred water surface in a reflecting cavity. They reproduced exactly the same calibration curve. The surface of a graphite slab was also tried, but yielded a slightly different calibration curve. The emissivity of the graphite we measured is 0.63, and for $r = 0.04$ the value of e is 0.976, which is sufficiently different from unity to be within the sensitivity of the instrument.

We found that the calibration curves are reproducible to 0.3C if the instruments are allowed at least a 1-hour warm-up period. However, after instrument repairs, calibrations had to be repeated.

Table 1. Experimental values for emissivity, ϵ , and determination of the surrounding correction, B_S^* .

	$\epsilon \pm \text{s. d.} \dagger$	$B_S^* \pm \text{s. d.} \dagger$ W m^{-2}
Anodized aluminum	0.956 ± 0.003	315 ± 22
Black paint	0.896 ± 0.003	362 ± 11
Graphite	0.631 ± 0.009	339 ± 8

† Standard deviation.

Measurements

Emissivity of reference surfaces. The emissivity, ϵ_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, σT^4 was computed and R_b was measured with the calibrated IR thermometer. From the linear relationship [15] between R_b and σT^4 , ϵ_A and B_S^* were obtained respectively as the slope and from the ordinate intercept at $T = 0$. This assumed that B_S^* 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 30C 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^* 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^* could be obtained if a reference surface, such as aluminum, of relatively low but constant emissivity between 8μ and 13μ (14) were used. Because B_S^* 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^* is of little importance if the value of B_S^* is used to solve [15] for vegetal surface temperature. When $\epsilon > 0.95$, $\epsilon\sigma T^4$ is at least one order of magnitude larger than $(1 - \epsilon)B_S^*$.

Once the emissivity of the standard surface has been determined, B_S^* 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^* is determined with the help of the anodized aluminum sur-

face, a measurement of σT^4 and R_b over the vegetal surface is sufficient to compute ϵ from [15]. It should be remembered that B_s^* 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 σT^4 , the vegetal surface was covered with a bottomless, hemispherical "pop-tent"⁴ 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 σT^4 . When the tent is removed, the thermometer reads R_b .

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 1.5C 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 only.

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_s^* which in turn is used to solve for T , the surface temperature of the canopy. The computations are expedited by the available tabulation of σT^4 (21).

Measurements were made on a clear day (Arlington, Wisconsin, August 14, 1965) over tall sudangrass ($\epsilon = 0.97_6$). At 1400 hour CST, B_s^* was 132 w m⁻². The apparent radiative temperature of the surface was 33.4C. Corrections accounting for ϵ and B_s^* gave a surface temperature of 34.8C. At 1900 hour CST, a light haze covered the sky, and B_s^* was then 295 w m⁻²; an apparent surface temperature of 24.5C was recorded whereas the corrected surface temperature was 25.1C.

Similar measurements were carried out on irrigated alfalfa ($\epsilon = 0.97_7$) during a partly cloudy day (Hancock, Wisconsin, September 3, 1965). During the period of measurement the cloud fraction remained more or less the

same. The value of B_s^* was 262 w m⁻², and a correction of approximately 0.6C was required to obtain the surface temperature.

If nighttime surface temperature measurements are required, the use of the anodized plate to determine the surface temperature can be eliminated. The correction to the apparent temperature can be found simply by taking at regular intervals, such as one hour, the temperature reading difference between the normally exposed surface and the same surface covered with the "pop tent" for a period less than 10 seconds.

Another set of measurements was made in a glasshouse on a single leaf of snap bean (*Phaseolus vulgaris*) and of tobacco (*Nicotiana tabacum*). Leaves were threaded with iron-constantan thermocouples 0.08 mm in diameter,⁵ to provide an independent measurement of the leaf temperature. Emissivities of 0.957 ± 0.005 for the bean and 0.971 ± 0.002 for the tobacco were determined at night using the same procedure as for the canopy but with the aluminum cone of Fig. 1, instead of the "pop tent". The leaf temperatures measured with the IR thermometer and the cone agreed within 0.2C 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 1.0C 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_b , the outward radiant flux from the bean leaf exposed to the surrounding's radiation, and simultaneous determination of B_s^* , the surface temperature of the leaf was computed from [15] using 0.957 for ϵ . The calculated temperatures agreed within 0.3C 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

$$\sigma T_a^4 = \epsilon \sigma T^4 + (1 - \epsilon) B_s^* \quad [18]$$

which can be written in the form of finite differences as

$$\Delta T_a / \Delta T \approx \bar{\epsilon} \bar{T}^3 / \bar{T}_a^3 \quad [19]$$

where ΔT_a is the difference between the apparent temperatures of two surfaces, ΔT the difference between their real temperatures, $T_a = (T_{a1} + T_{a2}) / 2$ and $\bar{T} = (T_1 + T_2) / 2$ are the means of the apparent and real temperatures of the two surfaces. When $B_s^* = 0$, $\epsilon \approx \bar{T}_a^4 / \bar{T}^4$ and [19] becomes $\Delta T_a / \Delta T \approx \epsilon^{1/4}$. When the surfaces are close to thermal radiation equilibrium with the surrounding, then $B_s^* = \sigma T^4$ and $\Delta T_a / \Delta T \approx \epsilon$. In field applications the

⁴Thermos Division of King-Seeley Thermos Co., Macomb, Illinois.

⁵The thermocouple measurements of leaf temperatures were made by Mr. Edward T. Kanemasu, Research Assistant in Soil Science.

surrounding's condition is always between these two limits, therefore the relative error in ΔT will be between $(1 - \epsilon^{1/4})$ and $(1 - \epsilon)$. Apparent surface temperature differences of 5.8C were measured between wilting and irrigated snap beans in adjacent plots. The correct ΔT computed with $\epsilon = 0.957$ and $B_s^* = 200 \text{ w m}^{-2}$ would be 6.0C. 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 $\pm 0.1\text{C}$ if the calibration of the instrument is checked for zero offsets at the time of the measurements, and $\pm 0.3\text{C}$ otherwise. The apparent radiative temperature may differ as much as 2C 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 ± 0.005 and 0.971 ± 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 0.97₆ and for alfalfa as 0.97₇.

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 8–13 μ wavelength band, and enable accurate temperature determinations.

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