

Determining Emittances for Use in Infrared Thermometry: A Simple Technique for Expanding the Utility of Existing Methods¹

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ABSTRACT

A simple laboratory technique is described for making rapid emittance measurements with an infrared thermometer. It is shown that when the infrared thermometer head is held flush against a surface, its output is a linear function of surface emittance. Thus, viewing two or more surfaces of known emittance in this manner "calibrates" the infrared thermometer, so that viewing an unknown surface at the same temperature in this manner will yield its emittance. Emittance values of the standard surfaces employed may be obtained via any of a variety of emittance measurement methods previously developed. A nomograph is presented that shows the possible errors that can occur as a result of temperature differences that may exist between the test and standard surfaces.

1. Introduction

In order to obtain accurate temperature measurements of terrestrial surfaces such as soil, rock, vegetation, etc., by means of infrared thermometry, it is necessary to know the emittances of the surfaces viewed—particularly as weighted for the spectral sensitivity of the radiometer employed (Idso *et al.*, 1969). Uncertainties in emittance values of only 0.01 unit can introduce errors in derived surface temperatures on the order of 0.7°C (Fuchs and Tanner, 1966). Since plant emittance values have been measured to range from 0.938 to 0.995 (Idso *et al.*, 1969) and since soil emittances have been measured to range from 0.88 or less for sands to close to 0.98 for clayey and loamy soils (Falckenberg, 1928; Buettner and Kern, 1965; Lyon, 1965; Hovis, 1966; Idso and Jackson, 1969), a knowledge of surface emittance is seen to be an absolute prerequisite for the accurate remote assessment of surface temperatures via infrared thermometry.

To cope with this problem, a variety of techniques has been developed over the years to measure infrared emittances of terrestrial surfaces with infrared thermometers. Some of the more commonly used methods were devised by Combs *et al.* (1965) [with variations by Lorenz (1966) and Fuchs and Tanner (1966, 1968)], by Buettner and Kern (1965) [with variations by Conaway and Van Bavel (1966) and Dana (1969)], by Idso *et al.* (1969), and by Dana (1969). Although there has been some discussion as to the relative accuracies of these different techniques (Fuchs and Tanner, 1966, 1968), it has been shown by Idso and Jackson (1969), Idso

et al. (1969), and Buettner and Dana (1969) that they all yield very similar emittance values when applied to identical surfaces. Thus, there appears to be no need to improve upon these methods in terms of accuracy. In terms of ease and rapidity of multiple measurements, however, all of the methods could stand improvement. We thus describe herein a simple laboratory technique that can be used in conjunction with all of the previously developed emittance measurement methods to greatly expand their utility.

2. Theory

Consider an infrared thermometer perpendicularly viewing a test surface. The radiant energy it senses may be expressed as

$$B(T, T_s) = \pi^{-1} \int_0^{\infty} f(\lambda) \epsilon(\lambda, T) e_b(\lambda, T) d\lambda + \pi^{-1} \int_0^{\infty} f(\lambda) \rho(\lambda, T) H(\lambda, T_s) d\lambda, \quad (1)$$

where T is the absolute temperature of the test surface, T_s the absolute effective radiative temperature of the surroundings, λ wavelength, ϵ the emittance of the test surface, ρ the reflectance of the test surface, f the radiometer sensitivity, e_b the blackbody emissive power, and H the incident radiative energy flux from the surroundings.

Absolving (1) of its explicit wavelength dependence by integration, we may write

$$B(T, T_s) = \pi^{-1} f(T) \epsilon(T) e_b(T) + \pi^{-1} f(T_s) \rho(T, T_s) H(T_s). \quad (2)$$

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Written in this form, the radiometer sensitivity functions and the radiative properties of the test surface are defined as

$$f(T) = \frac{\int_0^\infty f(\lambda)e_b(\lambda,T)d\lambda}{\int_0^\infty e_b(\lambda,T)d\lambda} = \frac{\int_0^\infty f(\lambda)e_b(\lambda,T)d\lambda}{e_b(T)} \quad (3a,b)$$

$$f(T_s) = \frac{\int_0^\infty f(\lambda)H(\lambda,T_s)d\lambda}{\int_0^\infty H(\lambda,T_s)d\lambda} = \frac{\int_0^\infty f(\lambda)H(\lambda,T_s)d\lambda}{H(T_s)} \quad (4a,b)$$

$$\epsilon(T) = \frac{\int_0^\infty f(\lambda)\epsilon(\lambda,T)e_b(\lambda,T)d\lambda}{\int_0^\infty f(\lambda)e_b(\lambda,T)d\lambda} \quad (5)$$

$$\rho(T,T_s) = \frac{\int_0^\infty f(\lambda)\rho(\lambda,T)H(\lambda,T_s)d\lambda}{\int_0^\infty f(\lambda)H(\lambda,T_s)d\lambda} \quad (6)$$

At this point, all of the several emittance measurement methods that have been developed to date essentially substitute $[1 - \epsilon(T)]$ for $\rho(T,T_s)$ in (2), whereby it is possible to express $\epsilon(T)$ as

$$\epsilon(T) = \frac{\pi B(T,T_s) - f(T_s)H(T_s)}{f(T)e_b(T) - f(T_s)H(T_s)} \quad (7)$$

They then, by various techniques, obtain the three radiation terms of Eq. (7) and solve for $\epsilon(T)$. If, however, Eq. (7) is rewritten in the form

$$B(T,T_s) = \epsilon(T)\pi^{-1}[f(T)e_b(T) - f(T_s)H(T_s)] + \pi^{-1}f(T_s)H(T_s), \quad (8)$$

it is observed that if the radiation terms $f(T)e_b(T)$ and $f(T_s)H(T_s)$ are held constant but different, so that the bracketed term of (8) does not vanish, $B(T,T_s)$ becomes a linear function of $\epsilon(T)$. Thus, viewing at least two surfaces of known emittance and common T under these conditions will calibrate the voltage output of the infrared thermometer in terms of the infrared emittance of the surface viewed. In our technique we use

the internal cavity of the infrared thermometer head as the source of the $f(T_s)H(T_s)$ term, since it is a standard feature of the instrument and is controlled at a constant temperature. For surfaces of standard emittance values we use metal plates painted with various proportions of black and aluminum paint that have had their emittances previously determined by one of the other emittance measurement methods. For the work described herein we used the standard heating and cooling technique that has been described by Conaway and Van Bavel (1966), Dana (1969) and Idso (1971).

Before proceeding to the experimental verification of our postulated emittance measurement method, some comments are in order regarding the substitution of $[1 - \epsilon(T)]$ for $\rho(T,T_s)$ in (2) that led to the development of Eqs. (7) and (8). Up to that point, everything in the theory had been exact. It is obvious, however, and all of the originators of the various emittance measurement methods have been careful to point out, that this step is not strictly proper, and that $[1 - \epsilon(\lambda,T)]$ should instead be substituted for $\rho(\lambda,T)$ in Eq. (1). Only under certain conditions will these two procedures be equivalent. Specifically, all of the investigators cited in Section 1 have noted the valid case obtaining when spectral emittance is constant with wavelength, i.e., $\epsilon(\lambda,T) = \epsilon(T)$. Since this requirement is never precisely met in the real world (and is often grossly lacking), they all realize that an error is being committed.

With respect to this error, Fuchs and Tanner (1966) have noted that its magnitude depends only on the size of the second term of the right-hand side of (2). Thus, they, Combs *et al.* (1965), Lorenz (1966) and Idso *et al.* (1969) have all attempted to minimize this error by using the clear sky as a minimal source for $H(T_s)$. Similarly, Dana (1969) attempted to minimize it by means of a refrigerated dome kept at -70°C . Prior to the present study, only Buettner and Kern (1965) had failed to attempt this type of amelioration, along with Conaway and Van Bavel (1966). These investigators even used a heated source for $H(T_s)$, as we have in this paper. Because of this, Fuchs and Tanner (1966, 1968) have twice criticized the Buettner and Kern (1965) technique as being inferior to the other procedures, although Idso and Jackson (1969) demonstrated that they are operationally equivalent.

One of the reasons for this equivalence and the reason why it is equally valid to use a heated dome in place of a very cold one, or the clear sky as a source for the $H(T_s)$ term, arises from the fact that there is one other case when $[1 - \epsilon(T)]$ may validly be substituted for $\rho(T,T_s)$ in (2) in addition to that prevailing when $\epsilon(\lambda,T) = \epsilon(T)$. This case occurs when $H(\lambda,T_s)$ is of identical (or nearly so) spectral shape as $e_b(\lambda,T)$, as is readily seen by making the substitutions of $[1 - \epsilon(\lambda,T)]$ for $\rho(\lambda,T)$ in the right-hand side of (6) and $[1 - \epsilon(T)]$ for $\rho(T,T_s)$ in the left-hand side. Then, the $\epsilon(T)$ defined

by (6) becomes

$$\epsilon(T) = \frac{\int_0^\infty f(\lambda)\epsilon(\lambda, T)H(\lambda, T_s)d\lambda}{\int_0^\infty f(\lambda)H(\lambda, T_s)d\lambda} \quad (9)$$

By comparison of (9) with (5), it is observed that if the radiation from the surroundings approaches blackbody characteristics at a temperature T_s , not too far distant from T , so that $H(\lambda, T_s)$ is not too different from $e_b(\lambda, T)$ with respect to spectral shape, then the $\epsilon(T)$ defined by (9) will be essentially identical to the $\epsilon(T)$ defined by (5), and all of the equations will be compatible.

3. Experimental verification

The only criterion that must be met by an infrared thermometer in order to utilize it for emittance measurements as we have described them, is that its output be a linear function of radiant energy sensed. Fig. 1 shows how the infrared thermometer we used satisfies this requirement. The calibration line was obtained by viewing a metallic plate painted with Parson's Optical

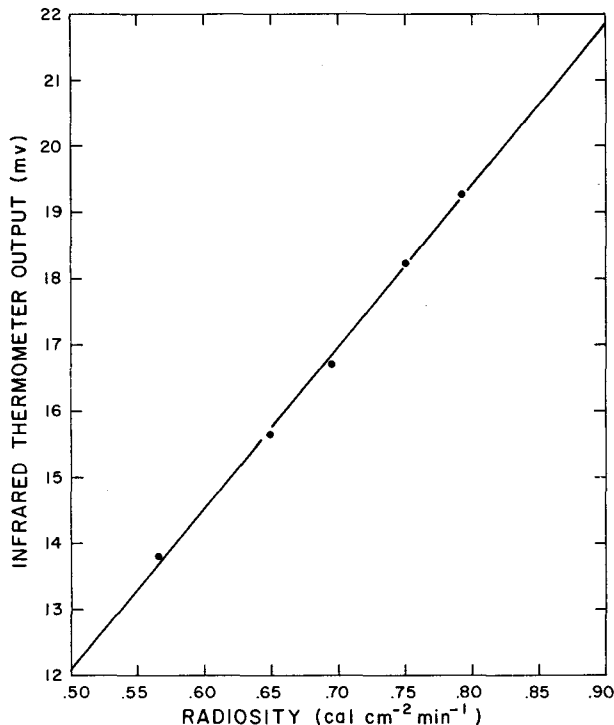


FIG. 1. The output of a Barnes PRT-5 infrared thermometer plotted as a function of the radiosity of a metallic plate painted with Parson's Optical Black Lacquer and equilibrated at five different constant room temperatures. In this situation the radiosity is equivalent to the emissive power of a blackbody.

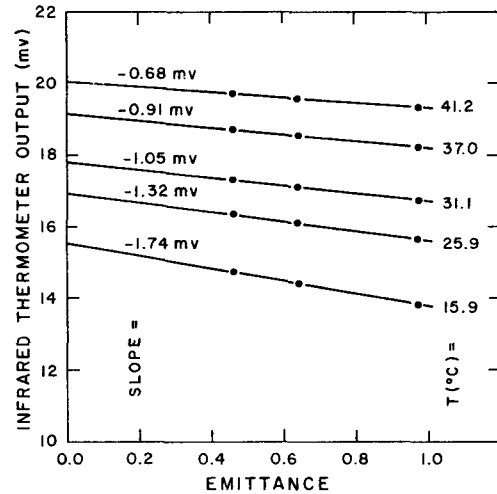


FIG. 2. The output of a Barnes PRT-5 infrared thermometer plotted as a function of plate surface emittance when the plates are viewed with the head of the infrared thermometer flush against them. Results are presented for plates at five different sets of common plate-room temperatures.

Black Lacquer² from a position about 50 cm above the plate in a constant temperature room. Under such conditions the radiosity of any surface within the room is equivalent to the emissive power of a blackbody at the common room-plate temperature. Thus, the voltage output of the infrared thermometer may be equated directly with the emissive power of blackbody radiation at the measured plate temperature (obtained via thermocouples drilled in from the back of the plate and imbedded just beneath the upper surface). If it is known that the calibration curve is linear, it is not even necessary to know the precise equation to determine emittances via our technique, although it is naturally required if subsequent temperature measurements are to be made.

At the same time that we obtained the calibration curve of Fig. 1, we also obtained emittance "calibrations" of our infrared thermometer by viewing the black plate and two other plates with the infrared thermometer head flush against them. These plates had emittance values of 0.974, 0.641 and 0.461, determined as previously described. In making these measurements care had to be exercised to obtain the output readings immediately when the infrared thermometer head just touched the plates, since the plate temperatures would begin to change somewhat after contact with the head had been made. The results thus obtained at a variety of common room-plate temperatures are shown in Fig. 2. Linear regressions run on the individual lines all yielded correlation coefficients greater than 0.9990, or they were discarded and new data obtained. More often than not, the first try yielded satisfactory cor-

² Trade names and company names are included for the benefit of the reader and imply no endorsement or preferential treatment of the product listed by the U. S. Department of Agriculture.

relations. If the emittance of an unknown surface is to be determined, a single reading of the infrared thermometer output in concert with the three standard plate readings is all the effort required. Many surfaces can thus be rapidly checked and their emittances determined in an efficient, straightforward manner.

4. Discussion

Emittance measurements made by our technique will obviously be no better than those of the particular technique used to determine the emittances of the standard surfaces employed. The question arises, however, will they be any worse?

The greatest possibility for error in our technique arises from the possibility that the temperature of the unknown test surface may be different from that of the standard surfaces. To evaluate potential errors arising from this situation, it is necessary to consider the slope of the particular infrared thermometer output vs emittance curve used in the measurement. Inspection of Eq. (8), for instance, indicates that the value of this slope should be a linear function of $f(T)e_b(T)$; and in Fig. 3 we have verified that this indeed is so (this gives another check on the internal consistency of the results).

Using information contained in Figs. 1-3, we have calculated emittance uncertainties arising from various uncertainties in the equivalence of test and standard surface temperatures. Results are plotted in Fig. 4 over the range of surface temperatures 0 to 50°C for our particular infrared thermometer. As is implied by Eq. (8), possible errors tend toward infinity as plate temperatures approach the internal reference temperature

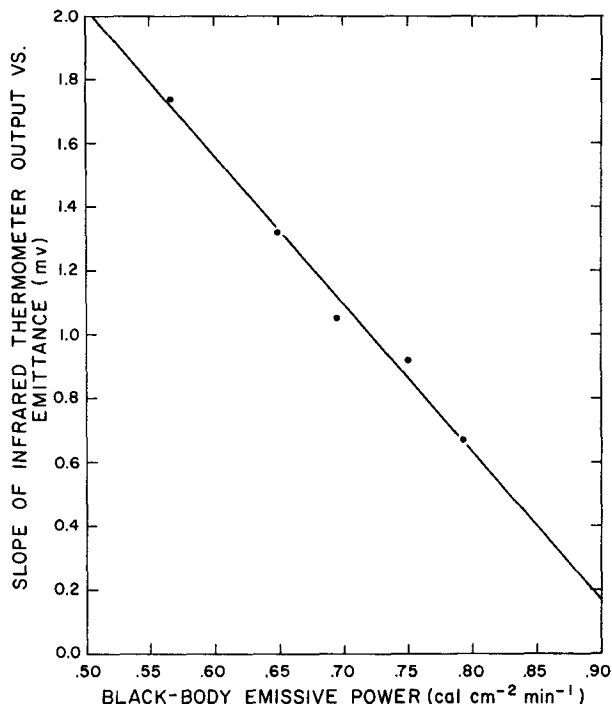


FIG. 3. The slopes of the five relations plotted in Fig. 2 as a functions of the blackbody emissive power at the common plate-room temperatures at which the five relations were obtained.

of the infrared thermometer head. As surface temperatures drop below this value, however, the emittance uncertainties decrease rapidly. For emittance uncertainties of less than ± 0.01 , one must work with surface

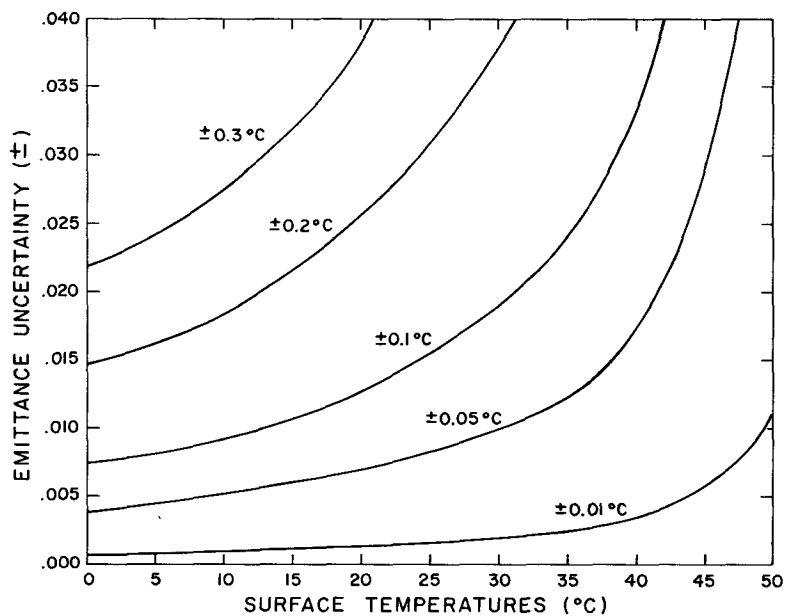


FIG. 4. Emittance uncertainty due to test and standard surface temperatures differing from each other by several stated fractions of 1°C plotted as a function of mean plate surface temperature.

temperatures on the order of 13°C that vary from each other by no more than $\pm 0.1^\circ\text{C}$. Or, these limitations may be somewhat exceeded if the plate temperatures can be measured and Fig. 4 used to apply the appropriate corrections.

REFERENCES

- Buettner, K. J. K., and R. Dana, 1969: Reply (to Idso and Jackson). *J. Appl. Meteor.*, **8**, 169.
- , and C. D. Kern, 1965: The determination of infrared emissivities of terrestrial surfaces. *J. Geophys. Res.*, **70**, 1329–1337.
- Combs, A. C., H. K. Weickmann, C. Mader and A. Tebo, 1965: Application of infrared thermometers to meteorology. *J. Appl. Meteor.*, **4**, 253–262.
- Conaway, J., and C. H. M. Van Bavel, 1966: Remote measurement of surface temperature and its application to energy balance and evaporation studies of bare soil surfaces. Tech. Rept. ECOM 2-67-P-1, Fort Huachuca, Ariz., 136 pp.
- Dana, F. W., 1969: Measurements of 8–14 micron emissivity of igneous rock and mineral surfaces. NASA Sci. Rept. NsG-632, Goddard Space Flight Center, Greenbelt, Md., 78 pp.
- Falckenberg, G., 1928: Die Absorptionskonstanten einiger meteorologist wichtiger Körper für infrarote Wellen. *Meteor. Z.*, **45**, 334–337.
- Fuchs, M., and C. B. Tanner, 1966: Infrared thermometry of vegetation. *Agron. J.*, **58**, 597–601.
- , and —, 1968: Surface temperature measurements of bare soils. *J. Appl. Meteor.*, **7**, 303–305.
- Hovis, W. A., 1966: Optimum wavelength intervals for surface temperature radiometry. *Appl. Opt.*, **5**, 815–818.
- Idso, S. B., 1971: A simple technique for the calibration of long-wave radiation probes. *Agric. Meteor.*, **8**, 235–243.
- , and R. D. Jackson, 1969: Comparison of two methods for determining infrared emittances of bare soils. *J. Appl. Meteor.*, **8**, 168–169.
- , W. L. Ehrler and S. T. Mitchell, 1969: A method for determination of infrared emittance of leaves. *Ecology*, **50**, 899–902.
- Lorenz, D., 1966: The effect of long-wave reflectivity of natural surfaces on surface temperature measurements using radiometers. *J. Appl. Meteor.*, **5**, 421–430.
- Lyon, R. J. P., 1965: Analysis of rocks by spectral infrared emission (8 to 25 microns). *Econ. Geol.*, **60**, 715–736.