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Effect of ambient conditions on calibration of hand-held infrared radiothermometers

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Summary — Hand-held infrared radiothermometers are frequently used in water stress studies and in the management of irrigation water to measure soil and plant canopy temperatures. Different models of these instruments are available but manufacturers' calibration methods are not the same. Five models of radiothermometers were compared during field experiments on water stress studies on grain sorghum and soybeans at Montpellier, France. The *in situ* recalibration method advocated by Verbrugghe and Guyot (1992) was used in the field. It was confirmed that field and laboratory calibration equations were not the same. The effects of the main climatic parameters influencing the performance of radiothermometers were examined. Consequences of calibration methods on the calculation of certain stress indices, especially the stress degree day (SDD), were also examined.

radiothermometer / calibration / stress degree day / ambient conditions / canopy temperature

Résumé — Effet des conditions de milieu sur l'étalonnage de radiothermomètres portatifs. *Les radiothermomètres portatifs sont fréquemment utilisés pour étudier le stress hydrique et gérer l'irrigation en suivant les températures d'émission des sols et des plantes. Différents modèles de radiothermomètres sont disponibles mais les méthodes d'étalonnage des fabricants diffèrent entre elles. Cinq modèles de radiothermomètres ont été comparés entre eux dans des études au champ concernant des cultures de sorgho et de soja à Montpellier, France. La méthode d'étalonnage* in situ *préconisée par Verbrugghe et Guyot (1992) a été utilisée. Il a ainsi pu être confirmé que les équations des étalonnages réalisés au laboratoire et au champ sont différentes. Les effets des principaux facteurs du climat qui influencent la réponse des radiothermomètres sur le terrain sont examinés. Leurs conséquences pour l'application des coefficients de correction à plusieurs indices de stress, et particulièrement au* stress degree day *(SDD) sont examinées aussi.*

radiothermomètre / étalonnage /* stress degree day *(SDD) / condition du milieu / température du couvert

INTRODUCTION

Soil and plant canopy temperatures are easily and rapidly measured using the infrared thermometry method. High precision is frequently required of these measurements in agriculture but is difficult to obtain in the field (Graham *et al*, 1989). Although many models of infrared thermometers exist, most of them were originally designed for use in enclosed buildings or controlled environments. In consequence, changing ambient conditions in the field affect their performance as confirmed by many authors (Fuchs and Tanner, 1966; Jackson and Idso, 1969; Graham *et al*, 1989; Wright, 1990; Wanjura and Upchurch, 1991; Verbrugghe and Guyot, 1992). Verbrugghe and Guyot (1992) showed that the calibration of hand-held infrared thermometers carried out inside and outside a laboratory were significantly different and therefore proposed a simple *in situ* method of recalibration in the field. Wanjura and Up-

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church (1991) also investigated the effects of calibration method on 18 portable radiothermometers and found that there were significant differences in relative temperatures (that is, target minus infrared thermometer detector temperature) obtained with field and manufacturers' calibrations. They therefore concluded that individual and periodic recalibrations of these instruments were necessary for better accuracy. The instruments were calibrated in the laboratory by submerging each radiothermometer in a temperature-controlled water bath. In the field the calibration procedure involved holding a blackbody calibration standard, Everest Interscience Inc Model 1000 so that it filled the field of view of the instrument. In both cases the output voltages for temperatures over a certain range were measured. Fuchs and Tanner (1966) showed that the effects of radiation emitted by the surroundings and reflected from the target to the sensor can be accounted for if the emissivity is a constant over all wavelengths within the waveband interval of the measuring instrument. If this effect is accounted for, the error in the determinations of vegetal surface temperatures does not exceed ± 0.1°C, if the calibration of the instrument is checked for zero offsets at the time of measurement, and ± 0.3°C otherwise (Fuchs and Tanner, 1966).

During 3 yr of field studies of water stress in sorghum and soybean, accurate determination of soil and plant canopy temperatures has been our concern. Therefore, systematic recalibrations of radiothermometers were carried out during periods of experiments, at the beginning as well as at the end of growing season. This paper is an attempt to examine the propositions suggested by Verbrugghe and Guyot (1992) in the light of our data and to analyse the main climatic parameters which might influence performance of these instruments in the field. It also aims at examining the consequences of calibration methods on the calculation of certain indices, especially the stress degree day (SDD), which are used for predicting crop yields and in management of irrigation water.

The working principle of infrared thermometry

The general principle of infrared thermometry has been well described by many authors (Jackson *et al*, 1981; Wanjura and Upchurch, 1991; Verbrugghe and Guyot, 1992). Infrared thermometers are equipped with an optical assembly which collects the infrared radiation from the object being measured (target) and focuses it on a small detector (fig 1). They also contain spectral filters generally allowing measurements between 8–14 μm. The detector transforms the infrared flux into an electric signal which is then converted into a temperature reading. Two types of instruments are available: static (DC) and chopped (AC) radiometers. AC radiometers are more stable than DC radiometers because the chopper blades are used as a temperature reference. The signal delivered by the sensors of such radiometers is proportional to the difference between the radiance of the viewed target and that of the chopper. It does not depend on the sensor temperature. On the contrary, DC radiometers use only an internal compensation based on the measurement of the sensor temperature. Most field radiothermometers are DC radiometers with complementary capabilities such as digital output (RS 232 port), data storage, laser beam pointer, etc.

The measurement of the radiative temperature of a given target comprises 2 successive steps involving the detector (thermopile or thermistor bolometer) and the temperature sensor (thermistor) (Wanjura and Upchurch, 1991):

– the radiative flux exchange between the viewed target and the detector (fig 1) induces a change in the detector temperature which is translated into an electrical signal. In most cases the manufacturers assume a fifth-order polynomial equation relating this electric signal to the radiative temperature difference δT existing between the target and the body of the detector T_d for DC radiometers;

– the temperature T_d of the detector (or of the case of the detector) is determined with the help of a thermistor.

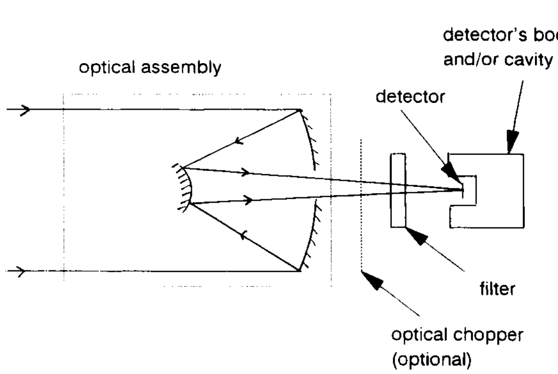

Fig 1. Optical system of a radiothermometer.

Therefore the radiative temperature of the surface (T_s) becomes:

$$T_s = T_d + \delta T \qquad \text{(in °C)} \qquad [1]$$

where δT is the difference in temperature between the target and the detector.

Equation [1] shows that the error on T_s depends on the measurement errors on T_d and δT. The error on T_d is due to the internal temperature gradients existing between the detector, its cavity and its temperature sensor (Kalma *et al,* 1988). This error is strongly reduced when a chopper is used. As indicated by Verbrugghe and Guyot (1992) this error depends on the design of the radiothermometer, which can be more or less protected against external heating.

The error in δT is due to the heating of the optical system (lenses and bandpass filter) which has to cut the incident solar short-wave radiation flux. If the temperature of the optical system components varies as a function of ambient short-wave radiation, a parasitic thermal radiation flux is superimposed to that coming from the target (Verbrugghe and Guyot, 1992). This can cause a variation in the calibration equation as a function of the experimental conditions.

The calibration equations of the radiothermometers available are expected to be linear. However slopes and intercepts depend on prevailing conditions at the time of measurement. What then are the main climatic variables that influence these coefficients and how?

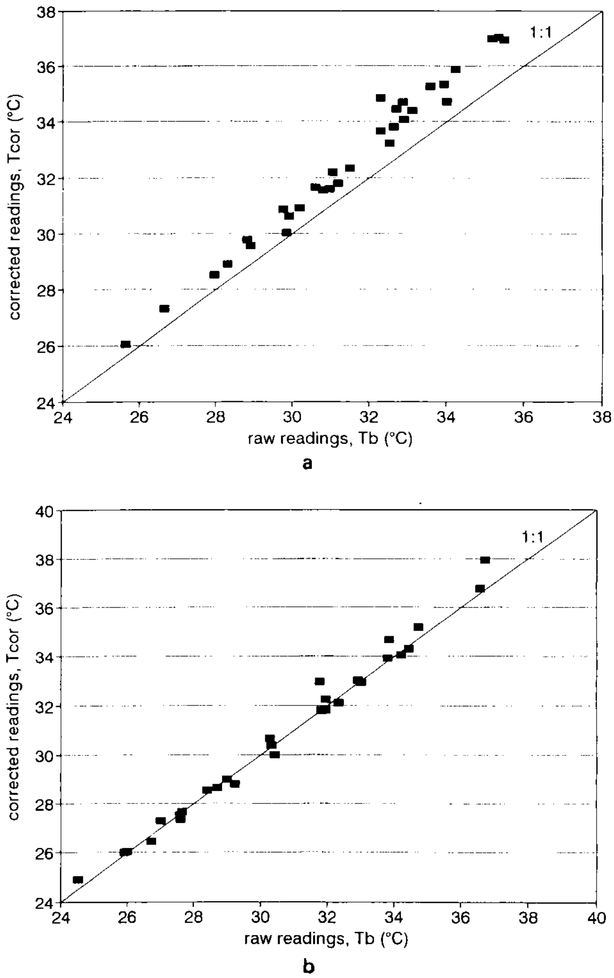

Fig 2. (a) Relationship between raw and corrected readings of Tasco THI300; (b) Relationship between raw and corrected readings of Everest 510.

MATERIALS AND METHODS

At the beginning of each growing season a number of radiothermometers are compared at the Laboratoire de Bioclimatologie, INRA, Avignon, France in order to check their thermal stability with time. The black body considered consists of 2 cones soldered at the base and lined with a special black paint (3M velvet coating 101–C10 black). In the field, the *in situ* calibration method suggested by Verbrugghe and Guyot (1992) and similar to that described by Berliner *et al* (1984) was used. Two well-stirred water baths at temperatures of 20°C and 40°C (which is the range of expected crop canopy temperature in the field, see fig 2a,b) were viewed vertically by the radiothermometer. The calibration procedure consisted of taking surface water temperature readings of water baths before and after the usual field measurements of crop canopy temperature at solar noon. The readings of the radiothermometers were then compared with that of a reference thermometer. The emissivity of water was assumed to be 0.98 (Robinson and Davies, 1972; Berliner *et al,* 1984; Verbrugghe and Guyot, 1992).

Three of these radiothermometers, namely, Everest 510B, Tasco THI 300 and Raytek PM3, were used in the field during water stress studies of sorghum and soybean at the Centre d'Étude de Machinisme Agricole du Génie Rural des Eaux et des Forêts (CEMAGREF) experimental station Lavalette, Montpellier. The data discussed in this paper concern a series of radiothermometer calibrations carried out in the laboratory in April 1991 and April 1992, and in the field during the monitoring of canopy temperature of grain sorghum and soybeans in Montpellier in 1991 (using Tasco THI300 and Everest 510). The monitoring started in the field when sorghum (or soybean) had a leaf area index (LAI) of 2 (soil was well covered) up to a LAI of about 5. These readings were taken at solar noon during clear days and in a number of differentially irrigated plots. Canopy temperature was computed as the average of 10 readings (Olufayo *et al,* 1993).

RESULTS AND DISCUSSION

Since the relationship between radiothermometer readings and true "black-body" temperature is expected to be linear, calibration equations are expressed as linear models:

$$T_{ref} = a\, T_b + b \qquad \text{(in °C)} \qquad [2]$$

where: T_{ref}: reference temperature of black body; T_b: radiothermometer readings; and a, b: slope and intercept.

For example, figure 3 is a calibration curve for Tasco THI300 using the black body in the laboratory at Avignon (whose emissivity is assumed to be 1.00). The radiothermometer body was maintained at laboratory room temperature (that is, about 20°C). The temperature at the point of intersection with the diagonal is about 25°C. In other words, the radiothermometer underestimates the black body's temperature below this point and *vice versa*. Similar points of intersection were observed when all field calibration data were regrouped. Table I contains a summary of calibration equations of 8 radiothermometers obtained 10 April, 1991 and 20 April, 1992. A high degree of correlation was observed in all cases (coefficient of correlation $r^2 > 0.989$).

It was observed that the coefficients of the calibration equations obtained in the laboratory and in the field were different irrespective of the model of the instrument. Hence there is need to carry out a periodic recalibration of each instrument used, in similar conditions to the time of measurement. This confirms the observations made by Verbrugghe and Guyot (1992). Higher values

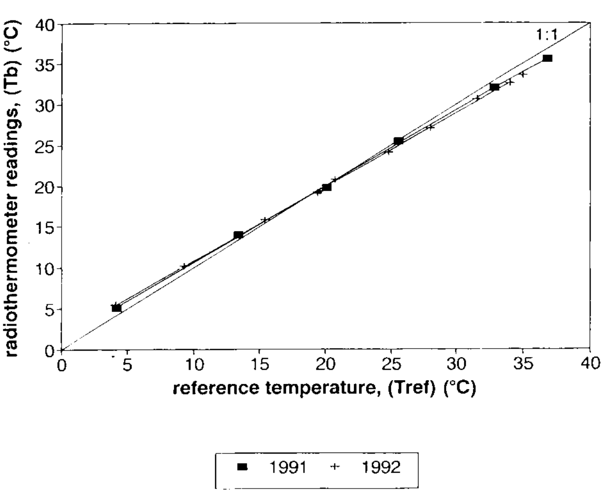

Fig 3. Calibration curves of Tasco THI300 in April 1991 and April 1992.

of the standard error of the estimates were observed in the field. This could be explained by changing conditions in the field as opposed to stable conditions inside a laboratory.

Consequences on the calculation of stress indices

Field radiothermometer readings were corrected using calibration equations (eq [2]) obtained in the field (see above). Measurement error, E_{rr}, can be defined as the difference between corrected radiothermometer readings T_{cor} (from daily field calibrations) and uncorrected radiothermometer readings T_b (that is, $E_{rr} = T_{cor} - T_b$). In this experiment the range of T_b was between 25°C and 38°C (table II) and E_{rr} varied between 0°C and 4°C (Wright 1990 recorded a range of –5°C to +8°C for an unchopped model of radiothermometer over a wide range of its body temperature). The effect of this discrepancy can be very significant in the estimation of certain indices based on canopy temperature. An example is the stress degree day defined by Idso *et al* (1977) as:

$$SDD_i = (T_c - T_a)_i \qquad \text{(in °C)} \qquad [3]$$

where T_c is the canopy temperature and T_a the air temperature measured around solar noon on day *i*. (A more detailed description of the experimental procedure for measurements of air and canopy temperature is given by Olufayo *et al* 1993.) The summation of stress degree day (ΣSDD) over a given period is therefore expressed as:

$$\Sigma SDD_i = \Sigma(T_c - T_a)_i \qquad \text{(in °C•day)} \qquad [4]$$

During this experiment ΣSDD was calculated using only positive values of SDD (Jackson *et al*, 1977). It was initialised after a rainfall event greater than 10 mm. The error in the calculation of ΣSDD is cumulative and can therefore have a significant effect when used for timing of irrigation. In order to illustrate this point, the ΣSDD of grain sorghum was estimated using corrected and uncorrected values of canopy temperature (monitored with Tasco THI300). As shown in figure 4, a difference of 40°C•day was observed in the 2 values of ΣSDD in the stressed plot 75 days after emergence. Under Montpellier conditions a threshold value of 35°C•day for irrigation appeared appropriate for optimum yield. Hence if

Table I. Calibration coefficients of different radiothermometers determined in the laboratory with a temperature-controlled black body.

Type of portable radiothermometer	*Date*	a *	b *	r^2 *	n *
Everest 510 B	April 1991	0.993	0.428	0.9998	6
	April 1992	1.029	–0.486	0.9997	9
Everest 110 (No 1)	April 1991	1.008	–0.025	0.9997	6
Everest 110 (No 2)	April 1991	1.001	0.368	0.9998	6
Tasco (No 080)	April 1991	1.072	–1.325	0.9999	6
	April 1992	1.103	–1.882	0.9997	13
Tasco (No 012)	April 1991	1.060	–1.267	0.9999	6
	April 1992	0.075	–1.269	0.9995	13
	April 1991	0.947	2.266	0.9950	8
Agema Raytek (No 439)	April 1992	1.005	0.464	0.9997	13
Raytek (No 440)	April 1992	1.020	–0.080	0.9996	13

* *a*, *b*: slope and intercept; r^2: correlation coefficient; *n*: number of data points.

Table II. Variables tested in the stepwise multiple regression procedure.

Variable	*Symbol*	*Units*	*Range*	*Mean*	*sd*
Dependent:					
Measurement error	E_{rr}	°C	0.03 – 3.40	1.07	0.69
Independent:					
Raw radiothermometer reading	T_b	°C	25.6 – 37.9	30.88	2.93
Air temperature	T_a	°C	25.8 – 35.6	30.67	2.90
Vapour pressure deficit	*VPD*	KPa	0.9 – 4.3	2.71	0.91
Solar radiation	*Rg*	W/m2	406 – 972	821	133
Wind speed	*W*	m/s	1.1 – 3.6	1.94	0.56

this recommendation had been followed using the raw data from the radiothermometer, it would had been done 6 d later than the data obtained from corrected values. If this period fell at a critical stage for sorghum, it would lead to a decrease in grain yield of up to 30–40% (Langlet, 1973).

This example shows the relativity of the stress degree day concept. The threshold value for irrigation can vary as a function of the radiothermometer used. Field calibration appears to be a better way of obtaining reliable data. It is also necessary to emphasize that the accuracy of other indices like the crop water stress index (CWSI) (Jackson *et al*, 1981) based on the difference between canopy temperature (T_c) and air temperature (T_a) would seriously be affected if uncorrected values were used (Campbell and Norman, 1990). The CWSI can be defined as (Jackson *et al*, 1988):

$$\text{CWSI} = \frac{(T_c - T_a) - (T_c - T_a)_{ll}}{(T_c - T_a)_{ul} - (T_c - T_a)_{ll}} \quad [5]$$

where $(T_c - T_a)$ is the measured temperature difference. The upper limit of $T_c - T_a$, $(T_c - T_a)_{ul}$

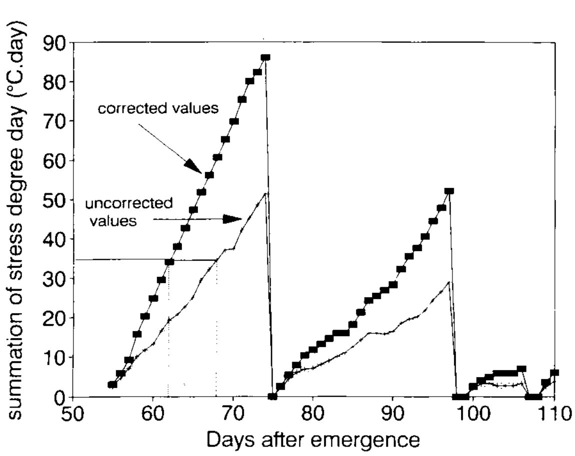

Fig 4. Summation of stress degree day of a stressed sorghum canopy.

represents a completely stressed, non-transpiring canopy. The lower limit, $(T_c - T_a)_{ll}$, represents a non-stressed canopy transpiring at potential rate.

The maximum amplitude of $(T_c - T_a)$ for sorghum in the Mediterranean climate is only a few degrees Celsius (about 10°C). An error of about 2–3°C on the estimation of canopy temperature has a direct consequence on the calculation of CWSI using either empirical (Idso *et al,* 1981) or theoretical methods (Jackson *et al,* 1981).

Effects of ambient conditions

Figure 5 illustrates the influence of some ambient conditions (air temperature (T_a), solar radiation *(Rg)*, and wind speed (*W*)) measurement errors on stressed sorghum canopy temperature. The climatic data used were obtained from an automatic meteorological station (CIMEL Co) located 120 m from the experimental site and correspond to average values during the time of usual field measurement at solar noon (that is, 11.00 h – 12.00 h). Measurement errors (obtained using Tasco THI300) were estimated by correcting the indicated temperatures using the daily *in situ* calibration equations. As shown in figure 5, there appeared to be definite trends in the relationship between ambient air temperature (T_a), wind speed and measurement error. During hot weather the radiothermometer body temperature rises and hence heats up the detector which results in a measurement error as discussed earlier. In the case of wind speed, there appears to be an inverse relationship: strong

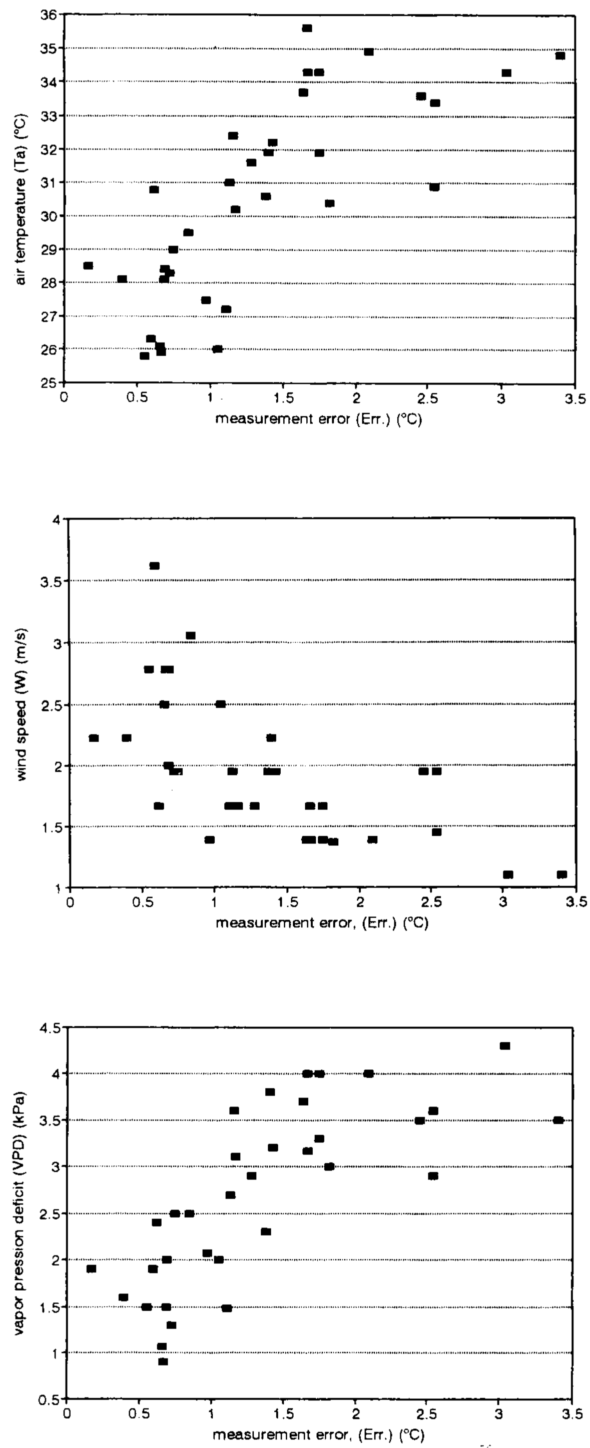

Fig 5. Relationship between measurement error and climatic variables.

wind produces a cooling effect thereby reducing the instrument body's temperature. There is no distinct trend in the case of solar radiation since measurements are usually carried out during bright sunny days. Similar observations were made from data in a well-watered plot.

Correlation between variables

The stepwise multiple linear regression analysis technique was employed in order to determine the most important variables influencing the measurement error (Scherrer, 1984). The variables tested are summarized in table II. The matrix of correlation between variables are presented in table III. The measurement error E_{rr} used is based on daily corrected canopy temperature, T_{cor} and daily raw readings T_b, of both stressed and well-watered sorghum plots (using Tasco THI 300). E_{rr} was highly correlated with radiothermometer raw readings and air temperature and least correlated with solar radiation. Although high correlation was observed between the measurement error and vapour pressure deficit (VPD), the latter would not be a pertinent parameter influencing the infrared thermometer measurement. This factor varies with air temperature as indicated by its high correlation T_a. The measurements are performed within the atmospheric window and it is evident that variation of water content of the optical path between the canopy and the radiometer (few meters) would not have significant effect on the radiation flux measured (Jackson *et al*, 1981). It is important to note that T_b is highly correlated with T_a.

Multiple linear regression

The stepwise regression procedure established that the raw radiothermometer readings and wind speed explained 66% of the measurement error. Other variables were not significant. The resulting relationship is as follows:

$$E_{rr} = -3.558 + 0.165\,T_b - 0.242\,W \quad \text{(in °C)} \quad [6]$$

$r = 0.801$; $n = 73$.

The statistical properties of this regression are shown in table IV. The influence of air temperature has been incorporated in the sorghum canopy temperature (T_b). As indicated earlier, the 2 variables were highly correlated.

The full regression analysis between daily measurement error, E_{rr}, and raw readings and climatic variables gives:

$$E_{rr} = 0.17\,T_b - 0.09\,T_a + 0.32\,VPD - 0.001\,Rg - 0.26\,W - 1.23 \quad [7]$$

n = 74; $r = 0.817$.

Although the VPD parameter does not have a direct effect on the measurement of surface temperature, it influences the atmospheric long-wave radiation as shown by the following equation:

$$R_a = 1.24\,(e/T)^{1/7}\,\sigma T^4 \quad \text{(Brutsaert, 1975)} \quad [8]$$

where R_a (W/m^2) is atmospheric long-wave radiation, T (K) is air temperature, e is vapour pressure (Pa) and σ is the Stefan Boltzmann constant (W/m^2K^4).

Fuchs and Tanner (1966) and Jackson (1982) showed that atmospheric long-wave radiation that is partly emitted by the surroundings influences the accuracy of measurements of surface temperature.

Similar analyses were carried out with data obtained using the Everest 510. There was no influence of climatic variables in the calculated measurement errors:

$$E_{rr} = 0.03\,T_b - 0.008\,T_a + 0.043\,VPD + 0.0001\,Rg - 0.023\,W - 0.736 \quad [9]$$

n = 29; $r^2 = 0.10$.

Table III. Matrix of correlation between variables.

	E_{rr}	T_b	T_a	VPD	Rg	W
E_{rr}	1.000	0.780**	0.618**	0.604**	0.142	–0.475**
T_b		1.000	0.721**	0.637**	0.240*	–0.397**
T_a			1.000	0.918**	0.249*	–0.607**
VPD				1.000	0.356**	–0.535**
Rg					1.000	–0.015
W						1.000

* Significant correlation at $0.05 > P > 0.01$; ** significant correlation at $P < 0.01$.

Table IV. Regression of E_{rr} on T_b and W.

Variable	*Coefficient*	*Standard error*	*Student* t-*value*
Constant	−3.558	0.664	−5.357
T_b	0.165	0.018	9.007
W	−0.242	0.096	−2.520

Degrees of freedom: 70; residual mean square: 0.1755; R squared: 0.6415.

This is explained by the greater accuracy observed using Everest 510 as compared to Tasco THI300. (The root-mean-square errors in the measurement of surface temperature using Tasco THI300 and Everest 510 are 1.27 and 0.42, respectively.) Everest 510 is more complex instrument which self-calibrates using a mechanical chopper of known temperature and emissivity. The chopper moves in a regular manner in front of the instrument's viewing aperture. Similar observations were made by Wright (1990) who compared the performance of unchopped and chopped infrared thermometers under conditions of changing ambient temperature. The chopped model gave better accuracy and there was high correlation between measurement error and instrument body temperature in the unchopped model. A correction based on empirical function between measurement error and instrument body temperature was proposed for the unchopped model.

It may also be possible to carry out similar corrections using the empirical function such as equations [6] or [7] above. It is evident that the empirical relationship would only be valid under conditions to which it has been adjusted and for the specific radiothermometer. The establishment of such empirical functions for each instrument (which is not the aim of this paper) should take into account the representativity of climatic data used (*ie* instantaneous or averaged data).

CONCLUSION

We have examined the problem of recalibration of 5 models of radiothermometers in the laboratory and in the field during water stress studies of certain crops at Lavalette, Montpellier. There were significant differences in the calibration equations obtained. These discrepancies were due to differences in each instrument's mode of construction and to the effects of environmental conditions on calibration equations. The magnitude of error observed in AC-type radiothermometers (with choppers) was less than that of DC radiothermometers (without choppers). In the case of the DC-type radiothermometers (Tasco THI300) examined in this paper, certain climatic variables such as air temperature, vapour pressure deficit and wind speed had varied effects on its *in situ* calibration equations.

A direct consequence of this is the relativity of the water stress indices concepts based on canopy temperature (*eg* SDD, CWSI). The importance of reliable data in the calculation of these indices, which are often used in deciding irrigation, cannot be over-emphasized.

Hence there is a need for periodic, and individual recalibration of these instruments in order to improve their precision. The *in situ* method of calibration advocated by Verbrugghe and Guyot (1992) is very simple and practical and would not present any problems to farmers.

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