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IMPROVED FIELD USE OF A SIMPLE INFRARED THERMOMETER

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SUMMARY

Theory and practice of a sensitive infrared surface thermometer are dealt with. Several problems arising in the field use of this simple instrument are discussed and explained in detail. It is concluded that with the indicated precautions the instrument is operating at optimum reliability and accuracy. However, further increase in sensitivity will not yield higher accuracy.

1. INTRODUCTION

Measuring the temperature of natural and other surfaces still poses a lot of practical problems. Infrared thermometers (also called radiation thermometers) have the great advantage of measuring temperature at a distance, thereby avoiding influencing the measured surface through direct contact (e.g. FUCHS & TANNER 1966, 1968, PIETERS 1972, PIETERS & SCHURER 1973). The importance of infrared thermometry with hand held sensing equipment has very much increased over the past twenty years (JACKSON, PINTER et al. 1980). Following earlier suggestions, for instance by TANNER (1963), recently such equipment has been introduced for routine observations on crop water status in irrigation scheduling (JACKSON, IDSO et al. 1980, 1981). In multi-purpose equipment, which can also be used to measure apparent sky temperature, no signal filtering is applied (e.g. STOUTJESDIJK 1974a, 1974b). Such an instrument can be relatively cheap (e.g. MC GINNIES & ARONSON 1971) but suffers from low sensitivity. Moreover, commercially available equipment of this type often suffers from a lack of testing under actual field conditions (MC GINNIES & ARONSON 1971, STIGTER et al. 1982).

To increase the sensitivity of the instrument described by STOUTJESDIJK (1974b), SCHURER (1977) introduced a few alterations for our measurements (see *fig. 1*) which included the installation of a new sensor. Trials with this equipment by JIWAJI & STIGTER (1982) revealed that employing the new sensor necessitated the use of screened lead wires and another pre-amplification system for undisturbed accurate recording. For this reason the Knick amplifier mentioned by STOUTJESDIJK (1974b) was replaced by an Analogic MP 221 chopper amplifier (TFDL, priv. comm.). We also obtained the new black body used by TFDL and locally recalibrated three instruments using our thermostate controlled baths systems. We were able to confirm the calibration data provided

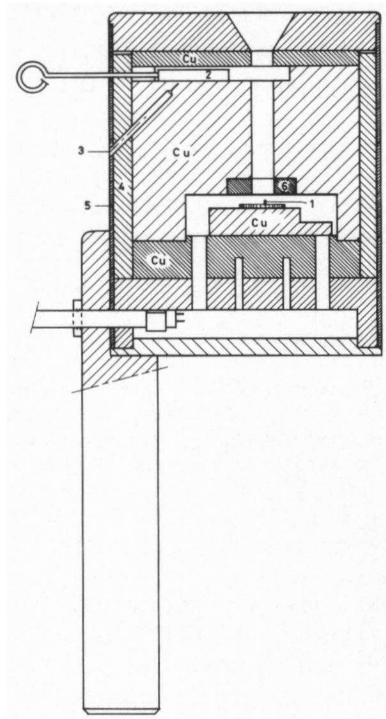

Fig. 1. Most recent T.F.D.L.-infrared thermometer;
1 = thermopile sensor;
2 = glass window for closing the tube during reference measurements;
3 = hole for thermocouple determining reference (= glass window) temperature;
4 = insulation material;
5 = aluminium cover (to be improved);
6 = polyethylene sheet;
Cu = Copper.
The other materials are hard plastics.

by the manufacturer for the range –30 to +60°C (MAKONDA 1981). New field tests by STIGTER et al. (1982) indicated that further increases in sensitivity would not lead to improvement in accuracy of the instrument.

In the present paper we deal in detail with our findings for the modified TFDL-infrared thermometer, in particular with precautions to be taken when using it. We also mention problems arising from the imprecise knowledge of (apparent) emissivities of target surfaces and background surroundings.

2. THEORY OF THE INSTRUMENT

The infrared thermometer used is shown in *fig. 1*. Measuring a temperature in a dark room, the sensing side of its thermopile generates an output from the difference of its own emitted long wave radiation and the radiation received from the tube walls (and polyethylene window sheet) and the target surface. The surface area measured depends on the distance between target and thermometer. We will show in Sect. 3 that this distance should not be too large if corrections for absorption and emission of the air between target and thermometer are to be avoided, unless the air/target temperature difference is small. On the other hand the distance should not be too small to avoid corrections for the presence of the front surface of the instrument, unless the room walls do not differ much from air temperature.

The radiation received from the target surface depends on the emissivity, ε_s, of the surface. In the case of grey-body radiation we have $\varepsilon_s < 1$ and constant for all emitted wavelengths. The sensor output, E_1, in a dark-room, assuming no temperature gradients anywhere within the infrared thermometer, is given by:

$$E_1 = C(T_{it})\,[\varepsilon_s T_s^4 + (1-\varepsilon_s)T_{eff}^4 - T_{it}^4] \quad (1)$$

where T_s is the target surface temperature, T_{it} is the instrument temperature and $T_{eff}^4 = \varepsilon_w T_w^4$, T_{eff} being the effective or apparent temperature of the background of the infrared thermometer when taken to be a black-body background.

The term $\varepsilon_s T_s^4$ yields the target emission. The following term yields the long wave radiation reflected by the target, in this case originating from room walls with emissivity ε_w at temperature T_w. In general it originates from the background at temperature T_{eff}. The third term is the radiation emitted towards the target from the surface of the sensor, at temperature T_{it}, at the bottom of the tube *(fig. 1)*, appearing as a black-body to the target surface ($\varepsilon_{it} = 1$). The parameter $C(T_{it})$ contains Boltzmann's constant, instrument and sensor geometrical factors and sensor sensitivity factors. The latter give rise to a slight temperature dependence of the sensor, whose temperature is assumed to be independent of target temperature.

If the target surface is replaced by a glass window stored within the instrument before being placed over the opening and consequently at instrument temperature T_{it}, the sensor output, E_2, is given by:

$$E_2 = C(T_{it})\,[\varepsilon_{gl} T_{it}^4 - T_{it}^4] \quad (2)$$

If we assume the glass surface to be a black body from the sensor's point of view, we have $\varepsilon_{gl} = 1$ and $E_2 = 0$. This makes the output, E_2, suitable as a detector of any existing temperature gradients between the location at which T_{it} is actually measured (near the glass window) and the place where the sensor is mounted, between the sensor and the tube walls and between the sensing and reference sides of the thermopile. Theoretically we can now obtain T_s by replacing E_1 in Eq. (1) by $E = E_1 - E_2$.

The calibration of the infrared thermometer indoors is carried out with a real black-body cavity ($\varepsilon_s = 1$) of known temperature T_s, whose opening is coincident with the infrared thermometer front. Eq. (1) then becomes:

$$E_1 = C(T_{it})\,(T_s^4 - T_{it}^4) \quad (3)$$

from which we can easily derive (e.g. Schurer, 1977):

$$E' = E_1 - E_2 = A(T_{it}, \Delta T)\,(T_s - T_{it}) \quad (4)$$

where $\Delta T = (T_s - T_{it})$. $A(T_{it}, \Delta T)$ is the calibration parameter of the instrument.

3. PRACTICAL PROBLEMS WITH THE INSTRUMENT: DISCUSSION AND CONCLUSIONS

It follows from Sect. 2 that in determining actual surface temperatures one has to correct the experimental result (E) for $\varepsilon_s \neq 1$ and the presence of radiating surroundings at T_{eff} to obtain E′. Only then can the iteration procedure be started to obtain T_s from Eq. (4) (comp. SCHURER 1977). In correcting for $\varepsilon_s \neq 1$ one should be aware of the fact that most surfaces, natural ones included, are non-grey, which means that their emissivity is a function of wavelength (SCHURER 1976). In that case, for high accuracies a weighted average of $\varepsilon_s(\lambda)$ should in fact be used. In practice such data are rarely available and ε_s has to be estimated, which somewhat limits the accuracy of the measurements concerned.

So far we have discussed procedures for undertaking measurements in a dark isothermal room, in which the surface and wall temperatures constitute the only variables. The use of the infrared thermometer in the field introduces further problems. Solutions to six such problem areas are discussed below. For our own measurements outdoors we developed a calibration plate of known ε_s, which approximated very closely a grey body, whose uniform surface temperature could be accurately determined with thermocouples (STIGTER et al. 1982).

3.1. Reflected solar radiation

Our calibration plate had a maximum diffuse reflection of 2% for solar radiation, which posed no measuring problems, as its effects on E_1 and E_2 are of the same small order. For most natural and a lot of other surfaces this parameter is much higher. STOUTJESDIJK (1974b) indicated how to correct for the short wave radiation error. The same values and procedure are applicable in our case. Under Dar-es-Salaam conditions a diffuse reflection of 80% of maximum solar radiation load would yield a supplementary radiation (with window open) identical to about 100 °C apparent rise of target surface temperature. With the absorption of solar radiation by the glass window and the highly reflective sensor surface of 10% each, the necessary correction of E′ would amount to the equivalent of nearly 2 °C apparent target surface temperature rise in this extreme case. This correction will normally be much smaller.

3.2. Casting of shades

As has been shown by REIFSNYDER (1967) for short wave radiation and by IDSO & COOLEY (1972) for net radiation, shades cast by the measuring instrument may influence the radiation received by the sensors. It can be derived from their work that provided the shade concerned does not change the temperature of the sunlit target area sensed, no errors are introduced in the case of a long wave radiation sensor. Problems are therefore less with a smaller angle of view (only 12° for our instrument). In our location the small zenith angles of the sun allowed the prevention of shades in the wrong places by slight inclinations of the calibration plate.

3.3 Distance between target and instrument

As shown theoretically and experimentally by IDSO & COOLEY (1971), vertical long wave radiation divergence due to temperature differences between surface and air is a source of appreciable errors in net radiation measurements if the distance between surface and instrument is too large. Because the downward flux is hardly influenced by the height of measurement of net radiation, their results are applicable to our long wave radiation sensing instrument. They conclude that measurements at a distance greater than 50 cm will introduce appreciable errors if the surface is much warmer than the air at the position of the instrument. This is in line with a rough calculation by STOUTJESDIJK (1974b). However, his conclusion that a much shorter distance between the target surface and the instrument would hence usually be recommendable is not always justified.

In the case of horizontal net radiometers IDSO & COOLEY (1972) argue that regarding interference of the instrument with thermal radiation exchange between atmosphere (T_{eff}!) and surface, the radiometer can *only* influence the net radiation if it alters the surface temperature and changes its rate of emission of thermal radiation. This is true for Idso's & Cooley's experiment with horizontal sensors with 180° angles of view, not less than 20 cm above the ground to avoid shade effects. With our instrument the area sensed at a distance of 5 cm has a diameter of less than 2 cm. In this case the radiating surroundings of the surface measured are largely occupied by the front of the measuring instrument. Failing to take this into account may again lead to appreciable errors in cases where T_{eff} changes appreciably when placing the infrared thermometer in front of the surface area to be measured. In our investigations with a horizontal black plate with only 2% reflection of long wave radiation, a 20 °C difference in T_{eff}, resulting when replacing the effective sky temperature for clear skies with the instrument front, would lead to an error of 0.4 °C in measured temperature for $T_s \simeq T_{it} \simeq T_{fr}$ (instrument front temperature). For 10% reflection ($\varepsilon_s = 0.9$) this would become 2 °C. These values are calculated from differences in reflected long wave radiation only. This effect is added to any temperature effect on the measured surface due to changes in its long wave balance.

A view factor approach (REIFSNYDER 1967) from the surface point of view shows that at more than 15 cm distance less than 5% of the radiating surroundings is occupied by our instrument front surface. It is therefore recommended that if the target area to be sensed is not smaller than 4 cm, the target/instrument distance should be 15 cm if T_{eff} is very different from T_{fr}. This also reduces possible perturbation of the original target temperature. Measurements performed by us employing distances between 15 and 45 cm and surface temperatures of up to 58 °C completely confirmed these conclusions (STIGTER et al. 1982; compare also *table 3*).

Arguments regarding any influence of multiple long wave reflections between surface and instrument (LOWRY & GAY 1970, 1971) can be disregarded as long as long wave reflectivities of measured surface and instrument front surface are low (comp. IDSO et al. 1971). In the intrinsically difficult case of surfaces with low ε_s, short distances may give rise to additional problems in this respect.

3.4. Variability of T_{eff}

It follows from Eq. (1) and the arguments made above that the lower ε_s, the higher the required accuracy of T_{eff}. Approximations of T_{eff} in the case of sky radiation are dealt with by MONTEITH (1973) and IDSO (1981). In cases where T_{eff} is very different from T_s and T_{it} best results are obtained by measuring T_{eff} with the same or an identical infrared thermometer. In case of high cloud variability, sampling and averaging would be necessary if high accuracies are needed (DALRYMPLE & UNSWORTH 1978).

3.5. Variable temperature gradients in the instrument body

Taking the above into account we retested our thermometers in the laboratory on a melting ice surface ($\varepsilon_s = 0.965$) and out of doors on our calibration plate (JIWAJI 1981, MAKONDA 1981, STIGTER et al. 1981, 1982). We obtained excellent results in the laboratory. Out of doors measurements yielded consistently low values in full sunshine and generally results fluctuated. The difference between calibration plate temperature and the temperature recorded by the infrared thermometer appeared to depend on rate and direction of change of solar radiation flux density.

The fact that the thermocouples attached to the surface of the calibration plate have a much smaller time constant than the infrared thermometer and are thus able to respond much more quickly to sudden changes explains part of the thermocouple/infrared thermometer discrepancies in such cases. These discrepancies decreased after a sudden disappearance of the sun (sometimes even changing sign) and rose to values much in excess of the mean error after the reappearance of the sun. This effect could only be explained in part through infrared thermometer sensor inertia. Although decreasing, these discrepancies remained higher than average for long periods after big changes, only slowly reaching average. An example is given in *table 1*. At the end of the day or after prolonged cooling due to heavy clouds, errors gradually became smaller and eventually again even changed sign. The infrared thermometer was found to read too high permanently under the latter conditions.

In a new series of experiments we first shaded the infrared thermometer, without casting shades on the plate. The errors decreased appreciably but results were found to remain variable. An example is given in *table 2*. Finally we covered all of the instrument, with the exception of its front surface, with 2 cm of tempex insulation and an outer layer of aluminized Mylar (polyester tape). This solved the discrepancy problem entirely and greatly reduced fluctuations. The remaining fluctuations were caused by the discussed differences in response times during fluctuating radiation and wind speed and by variation in T_{eff} during sky radiation variability. *Table 3* shows such a result for high solar radiation load.

Our outdoors data suggested that the outer surface temperature of the infrared thermometer as it was manufactured was at least one of the causes of our

Table 1. Comparison of temperatures measured outdoors at the calibration plate surface by thermocouples and by an unshaded infrared thermometer. Values are averages for consecutive periods of 6 minutes. Average reference body temperature shows the warming up of the instrument.

Plate ±0.1 °C	Infrared ±0.5 °C	Diff.	Body temp. ±0.1 °C
41.3	38.2	3.1	29.1
41.3	36.9	4.4	29.2
51.6	41.4	10.2	29.6
49.3	41.9	7.4	30.2
45.2	43.6	1.6	30.7
38.1	39.7	−1.6	30.8
45.4	40.4	5.0	30.3
45.3	42.4	2.9	31.0
52.7	46.9	5.8	31.2
54.8	48.7	6.1	31.5
54.4	50.7	3.7	32.0
55.2	50.9	4.3	32.1
54.8	51.4	3.4	32.3
55.2	50.8	4.4	32.7
55.3	52.0	3.3	33.1
55.7	53.8	1.9	33.6
55.3	53.4	1.9	34.0
52.8	52.8	0.0	34.1
55.7	54.1	1.6	34.2
55.4	55.1	0.3	32.4
52.3	52.7	−0.4	34.2

problems. As mentioned in Sect. 2, E_2 of Eq. (2) is an indicator of temperature gradients within the instrument. We therefore monitored E_2 within the laboratory at constant ambient temperature. When it had reached a constant value we warmed the outer surface leading to an almost immediate decrease in E_2 which in turn should be interpreted as an apparent decrease of the glass window temperature. The body reference temperature reacted only slowly after a considerable delay. When we cooled the outer surface below ambient, the opposite effect was observed. The apparent temperature of the glass window and after opening of the window also the apparent temperature of the black body calibration cavity increased heavily although both were kept at constant temperature. The initial change was particularly large.

The only possible explanation of this effect is that changes in the outer surface temperature of the infrared thermometer create heat flows at the reference side of the extremely sensitive thermopile. Under the prevailing conditions out of doors this causes the instrument to read low on warming, and increased rate of warming increasing the error and vice versa. This means that the changes of temperature at the sensor are non-linear. Alternating measurements with the window opened and closed, as is the normal procedure, could therefore not correct for the effects, which are bound to increase with the sensitivity of the sensor.

Table 2. Comparison of temperatures measured outdoors at the calibration plate surface by thermocouples and by a shaded infrared thermometer. Values are averages for consecutive periods of 6 minutes. Average reference body temperature is now a yardstick for changing air temperature but with a delay and a lower amplitude due to the thermal inertia of the copper body.

Plate ±0.1 °C	Infrared ±0.5 °C	Diff.	Body temp. ±0.1 °C
43.6	42.4	1.2	29.3
44.2	43.4	0.8	29.6
45.3	44.9	0.4	29.7
45.5	45.0	0.5	29.8
45.3	45.0	0.3	29.8
45.3	46.3	-1.0	29.8
50.5	50.0	0.5	31.1
50.5	49.2	1.3	31.4
48.1	47.3	0.8	30.3
46.9	46.2	0.7	30.6
46.0	45.5	0.5	30.0
46.1	46.0	0.1	30.8
45.8	45.4	0.4	30.8
45.1	45.4	-0.3	30.8
44.8	45.4	-0.6	31.0
44.2	45.3	-1.1	31.1
44.5	45.5	-1.0	31.5
44.7	45.9	-1.2	31.5
47.7	49.3	-1.6	31.6
56.2	56.2	0.0	32.4
62.2	61.5	0.7	33.2
61.1	60.4	0.7	32.6
62.2	61.9	0.3	32.7
64.6	63.5	1.1	32.5

3.6. Variable temperature gradients in the sensor body

It was essential to investigate whether exposure time to the surface temperature to be measured could also influence the infrared thermometer output. Apart from the time constant effect described earlier, heat flow or accumulation within the sensor body obtained from target radiation is sometimes found to influence readings of such simple thermometers (McGinnies & Aronson 1971). To investigate this effect, we experimented in the laboratory at constant ambient temperature by exposing the infrared thermometer to a number of greatly varying surface temperatures. We varied the exposure time of the instrument to a very low temperature before suddenly exposing it to a much higher one and vice versa.

These experiments resulted in the discovery of a slight 'memory' effect. Long exposures to ice initially caused the instrument to read too high after sudden exposure to a much warmer surface. True readings were obtained after a certain period of time which was roughly proportional to the period for which the instrument had been exposed to ice. After reexposure to ice, initial readings were too

Table 3. Comparison of temperatures measured outdoors at the calibration plate surface by thermocouples and by a completely protected infrared thermometer. Values are averages for consecutive periods of 6 minutes. Measurements were taken at four distances between 15 and 45 cm between plate surface and thermometer front surface. For this whole series under maximum radiation load the average difference is negligible.

Plate ±0.1 °C	Infrared ±0.5 °C	Diff.
34.3	34.2	0.1
35.0	34.6	0.4
35.4	35.2	0.2
35.8	35.8	0.0
36.4	36.0	0.4
36.8	37.0	-0.2
37.0	36.8	0.2
38.1	38.5	-0.4
39.0	38.9	0.1
39.4	39.1	0.3
47.3	47.5	-0.2
47.4	47.6	-0.2
47.8	48.1	-0.3
48.1	47.5	0.6
48.5	48.8	-0.3
49.1	48.8	0.3
49.7	49.5	0.2
50.8	50.9	-0.1
53.7	53.7	0.0
57.9	58.5	-0.6

low. These effects were normally relatively small and only of importance if long exposure times were followed by big changes in the viewed surface temperature.

The only possible explanations for these effects are heat flows taking place in and near the sensor body, due to the (small) amounts of heat absorbed or lost during sensing. We could not detect any temperature changes in the air at the bottom of the tube. Again it is the extremely high sensitivity of the sensor which makes these effects visible. As soon as these heat flows have become constant they do not influence the measurements any more. Only non-linear effects create problems, which increase with increasing sensor sensitivity.

4. FINAL REMARKS

The above results demonstrate that an even higher sensitivity than the present one does not appear to be useful (STIGTER et al. 1981). It follows from our work that the present TFDL-infrared thermometer can be a very reliable surface temperature indicator if the precautions discussed are taken. It is essential to minimize temperature gradients in the body near the new sensor. The temperature to be measured should be relatively steady. Under such conditions and heeding the relevant remarks made in Sect. 3, a sensitive relatively simple and inexpensive hand held surface thermometer is now available. The ultimate accuracy depends on several of the mentioned factors, but its potential for long term averages appears to be ±0.1 °C and for 6 minute-averages appears to be ±0.5 °C in case of small time constant surfaces. The latter value will improve for higher time constant surfaces.

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