Infrared calibration of net radiometers and infrared thermometers

M.J. Savage\textsuperscript{a} and J.L. Heilman\textsuperscript{b}

\textsuperscript{a}Soil-Plant-Atmosphere Continuum Research Unit, Agrometeorology Discipline, School of Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, Republic of South Africa

\textsuperscript{b}Department of Soil and Crop Sciences, Texas A & M University, College Station, Texas, USA

Address for paper correspondence:
M.J. Savage, Agrometeorology Discipline, School of Environmental Sciences, University of KwaZulu-Natal, P Bag X01, Scottsville, 3209 South Africa

FAX 27 33 2605514 or 27 33 2605426
Tele 27 33 2605510
E-mail savage@ukzn.ac.za
ABSTRACT

A standard and accurate method for calibrating net radiometers would assist in unravelling reasons for the perplexing lack of surface energy balance closure as well as improve on the accuracy of evaporation estimations using the energy balance residual method. A relatively inexpensive, accurate and quick laboratory method using a large water-heated or water-cooled radiator containing circulated water, with surface-embedded thermocouples, was used to obtain reproducible net radiometer calibration factors for the infrared waveband for a wide range in net irradiance. A method was also used for the shortwave calibration of net radiometers by placement of a net radiometer adjacent a standard shortwave radiometer, both instruments placed above the radiator. Measurements from heated-needle anemometers demonstrated that thermally-induced wind speed was not a significant factor in the infrared calibrations. Furthermore, the temperature gradient across the radiator was fairly uniform at any time. Infrared calibration factors for two-component, four-component, miniature polyethylene, polyethylene-domed (with and without ventilation) and domeless net radiometers were obtained. The two- and four-component net radiometers yielded average root mean square errors of 0.88 and 0.97 W m\(^{-2}\) respectively compared to 1.00 W m\(^{-2}\) for the polyethylene-domed net radiometers, 2.56 W m\(^{-2}\) for three domeless units and 2.27 W m\(^{-2}\) for a polyethylene-domed miniature net radiometer. Theory presented and collected measurements allowed the net radiometer infrared calibration factor to be determined for cases when the infrared irradiance from the environment was not constant. For the broadband domeless net radiometers used, the shortwave and infrared calibration factors were within 6.6 % of each other and yet roughly 25 % different for some of the polyethylene-domed instruments. Ventilation of polyethylene-domed net radiometers resulted in more variable data and larger-than-expected infrared calibration factors. The radiator method also provides a convenient method for calibrating a number of infrared thermometers (IRT) simultaneously.
for a wide temperature range. A regression procedure was applied to obtain estimates of the
radiator surface temperature for IRTs without a body temperature sensor. A modified
procedure was applied for IRTs with a body temperature sensor. The calibration method and
the data analysis procedure resulted in residuals, between the average radiator surface
temperature and the corresponding IRT target temperature measurements, of within 0.15 °C
for all IRT types except for a handheld IRT unit which was within 0.2 °C. The radiator
method used allows net radiometers to be calibrated for both infrared and shortwave
wavebands under near-identical conditions, as well as IRTs to be calibrated and is relatively
simple to set up and operate.

**Keywords:**
- Net radiometer calibration
- Infrared thermometer
- Energy balance closure
- Net radiation

1. Introduction

Net irradiance measurements are an essential part of surface energy balance investigations
and especially so when estimating latent heat flux, as a residual of the energy balance using
measurements of net irradiance $R_{net}$ (W m$^{-2}$) and sensible and soil heat flux, or when
investigating closure of the energy balance. Often, the weakest point of energy balance
investigations is the lack of or unknown accuracy of the $R_{net}$ measurements caused by absent
or non-reliable infrared calibration and in some cases unreliable or incorrect shortwave
calibration measurements. From personal communications we know that other workers
arrived at similar conclusions for their $R_{net}$ measurements. Invariably, the calibration factor
specified by the manufacturer is used (for example, Brotzge and Duchon, 2000; Sridhar and
Elliott, 2002; Cobos and Baker, 2003), for many years or until a recalibration, together with
the measured net radiometer voltage(s) to obtain $R_{\text{net}}$.

Shuttleworth (1991) and Brotzge and Duchon (2000) describe $R_{\text{net}}$ as one of the most
difficult micrometeorological variables to measure accurately and Cobos and Baker (2003)
state that despite efforts to develop accurate and cost-effective instrumentation for $R_{\text{net}}$
measurement, there is still no widely accepted best field-measurement method. Calibration of
a net radiometer, domed or domeless (Brotzge and Duchon, 2000; Cobos and Baker, 2003),
may involve use of a standard radiometer for a shortwave calibration or involves a net
radiometer intercomparison. Laboratory/field instrument comparisons of net radiometers or
pyrgeometers are rare – some examples of such include the work by Halldin and Lindroth
(1992), Philipona et al. (1998) and Reda et al. (2002).

A common field method for calibrating net radiometers for shortwave is the “occulting"
or “shading” (Idso, 1974) or partial shading (Fritschen and Fritschen, 2007) method. Fritschen
and Fritschen (2007) however advocate the use of a translucent shade procedure to avoid
negative $R_{\text{net}}$ values during shading, indicative of the magnitude of the net infrared irradiance
exceeding the net shortwave irradiance. The change in the net radiometer voltage between
unshaded and (partially) shaded conditions is a measure of the known change in shortwave
irradiance recorded by the pyranometer or pyrheliometer standard, measurements from the
latter adjusted for the solar elevation, allowing a calibration factor for the net radiometer to be
determined.

Ohmura et al. (1998) note that due to the lack of a well-accepted standard [and method]
for infrared irradiance, none of the pyrgeometers or net radiometers can be regarded as correct
or incorrect. To date, there is no international agreement for the calibration procedure and
choice of a radiation standard for pyrgeometers (Kohsiek et al., 2007) and treatment of the
data. The World Meteorological Organisation has a classification system for pyranometers, e.g. primary standard, secondary standard, etc., but not for net radiometers. Most net radiometer “calibrations” are therefore performed in the field by comparing one net radiometer against another (for example, Brotzge and Duchon, 2000); in one case, a round-robin pyrgeometer calibration experiment was undertaken (Philipona et al., 1998). In the round-robin experiment, differences of up to 20 % from the median instrument responsivity were obtained by the various participating specialist laboratories. In another case, an unexpected shift in the time series of infrared data, following a change in the calibration procedures for field instruments, was noted (Stoffel, 2005).

In the FIFE micrometeorological investigation (Kanemasu et al., 1987; Field et al., 1992; Nie et al., 1992), five participating groups measured a midday \( R_{net} \) of between 300 and 530 W m\(^{-2}\) – more than a 75 % variation. Field et al. (1992) noted 5 to 7 % relative differences in \( R_{net} \) for side-by-side sun/shade shortwave calibrations for instruments of the same manufacture and 10 to 15 % differences between instruments of different manufacture. Fritschen and Fritschen (2007) commented that these field comparisons used outdated net radiometers with old calibration factors. Brotzge and Duchon (2000) found \( R_{net} \) differences that parallel those found by Field et al. (1992) and Halldin and Lindroth (1992).

Duchon and Wilk (1994) also demonstrated significant day-time and night-time \( R_{net} \) differences for instruments of different manufacture. Kustas et al. (1998) found inconsistent differences in \( R_{net} \) measured using different instrument models, indicating that there was no possibility of removing bias between the instruments for all conditions. For the almost cloudless conditions of the EBEX-2000 experiment, the error in \( R_{net} \) was estimated at within 25 W m\(^{-2}\) during the day (typically within 5 %) and within 10 W m\(^{-2}\) at night (typically within 20 %) (Kohsiek et al., 2007). Halldin and Lindroth (1992), using a four-component net radiometer, found for reference and individual instruments relative differences in \( R_{net} \) between
and 20% and commented: “(data) support a general scepticism toward the calibration factors given by the manufacturers” and cautioned that it seems mandatory to have a standard established for the infrared calibration of net radiometers and pyrgeometers.

Polyethylene-domed net radiometers should be recalibrated every six months when the domes are replaced – Brotzge and Duchon (2000) noted domes degrading after a few months of exposure and Cobos and Baker (2003) found dome degradation over three months. This again justifies the need for a convenient and inexpensive method for regular net radiometer calibration.

In the case of two- or four-component net radiometers, the shortwave calibration may be performed using standard pyranometers or sub-standard pyranometers calibrated against a standard without resorting to the shading or partial shading method. In such cases, the shortwave calibration may result in accurate estimation of the net shortwave irradiance but the net infrared irradiance is then measured without calibration. For domed net radiometers, Fritschen and Fritschen (2007) advocate laboratory methods, as opposed to outdoor calibrations, using ventilated net radiometers for shortwave and infrared calibrations. Ventilation is not often used – for example, most of the participating laboratories in the round-robin pyrgeometer calibration experiment (Philipona et al., 1998) did not use instrument ventilation.

Cook and Holdridge (2006) found that the source of $R_{net}$ differences between two instrument models was mostly in the infrared, not the shortwave, for their side-by-side field comparisons. They note that the transmittance of polyethylene is weak for wavelengths of strongest infrared transmission by water vapour and speculate that there may be a systematic water vapour dependent error for the infrared for polyethylene-domed net radiometers.

A common calibration method for pyrgeometers, as judged by the protocols of the participating groups in the round-robin pyrgeometer calibration experiment, involves the use
of blackbody cones or cylinder cavities (Philipona et al., 1998). Idso (1971) and Campbell and Diak (2005) used a large-area blackbody radiator of known temperature to calibrate domed net radiometers for the infrared.

Huband and Monteith (1986) and Campbell and Norman (1990) discuss limitations on precision and accuracy for surface temperature measurements using radiometric thermometers, suggesting values of 0.4 K for precision and 1.0 K for accuracy. Barber and Brown (1978) used a blackbody surface for the calibration of infrared thermometers (IRTs). Their unit could display the blackbody surface temperature but no temperature control was possible. Sadler and van Bavel (1982) devised a method, modified by Ham (1990), for the calibration of IRTs using a blackbody calibration chamber. Amiro et al. (1983) and Kalma and Alksnis (1988) describe the use and calibration of IRTs. Baker et al. (2001) used a continuously-calibrated infrared system using a blackbody cavity, the temperature of which was controlled by a Peltier block and measured using thermocouples. Pinnock and Bugbee (undated) used a copper plate sprayed with flat black paint to calibrate their IRTs. Most published methods only allow for single-unit IRT calibrations and are also not suitable for the infrared calibration of net radiometers. Water-cone IRT calibrators are convenient (Bugbee et al., undated) and inexpensive but may result in water condensation on the IRT window area and the maintenance of the water-cone during the entire heating and/or cooling calibration period is often not possible.

The aim of this work is to describe an accurate, relatively quick, relatively inexpensive and repeatable laboratory method, based on established physical theory, for infrared calibration of various types of net radiometers and calibration of IRTs placed above a radiator, for a wide range in infrared irradiance and surface temperature respectively. A laboratory method using a standard pyranometer and the same radiator for the shortwave calibration of net radiometers is also presented and used. This shortwave calibration method avoids the
problems in the field associated with the sun/shade calibration technique previously described and also allows comparisons for the same instrument of the calibration factors for both shortwave and infrared wavelengths under near-identical laboratory conditions. In the case of the IRT calibrations, the method avoids the problems of the water-cone calibration method.

2. Theory

Suppose that a net radiometer to be calibrated is placed directly above the centre of a circular radiator of radius $r$ and area $A$. From radiation geometry, the net radiometer view factor $F$ for the circular radiator positioned at a vertical distance $d$ away from the nearest net radiometer sensing element is given by:

$$F = \sin^2 \beta = \frac{r^2}{(r^2 + d^2)} = \frac{A}{A + \pi d^2}$$  \hspace{1cm} (1)

where $\beta$ is the angle between the vertical and the line from the sensor to the edge of the circular radiator. If a sufficiently large rectangular radiator with area $A$ is used, the radiator radius $r$ may be estimated with sufficient accuracy as $\sqrt{A/\pi}$.

The upward infrared irradiance $L_{u\, rad}$ (W m$^{-2}$) from the radiator, at uniform surface temperature $T_{rad}$ (K), is therefore:

$$L_{u\, rad} = -F e_{rad} \sigma T_{rad}^4$$  \hspace{1cm} (2)

where $e_{rad}$ is the radiator infrared emissivity, $\sigma = 5.6704 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$ is the Stefan-Boltzmann constant and where the negative sign denotes an upward irradiance (loss) from the upper radiator surface to the atmosphere. If the radiator infrared reflectivity is $\rho_{l\, rad}$, then using Kirchhoff’s Law, $\rho_{l\, rad} = 1 - e_{rad}$ and:
where $L_{d \text{ surr}}$ is the downward infrared irradiance from the surrounds. The net infrared irradiance $L_{\text{net}}$ measured by a net radiometer suspended above the centre of the radiator a distance $d$ away would however also include from the surrounds the downward and the upward infrared irradiances $L_{d \text{ surr}}$ and $(1 - F)L_{u \text{ surr}}$ respectively and hence:

$$L_{\text{net}} = -F \varepsilon_{\text{rad}} \sigma T_{\text{rad}}^4 - F (1 - \varepsilon_{\text{rad}}) L_{d \text{ surr}} + L_{d \text{ surr}} - (1 - F) L_{u \text{ surr}}. \tag{4}$$

Equation (4) may be simplified for a radiator for which $\varepsilon_{\text{rad}} = 1$ and therefore the second term on the right hand side could be neglected. The net infrared irradiance may be varied by altering $T_{\text{rad}}$ and maintaining constant or measuring the other infrared components of Eq. (4).

The net irradiance $R_{\text{net}}$ above the radiator surface at the net radiometer position is therefore:

$$R_{\text{net}} = -F \varepsilon_{\text{rad}} \sigma T_{\text{rad}}^4 - F (1 - \varepsilon_{\text{rad}}) L_{d \text{ surr}} + L_{d \text{ surr}} - (1 - F) L_{u \text{ surr}} + I_s (1 - \rho_{s \text{ rad}}) \tag{5}$$

where $I_s$ is the shortwave irradiance and $\rho_{s \text{ rad}}$ the shortwave reflection coefficient of the radiator surface. The measured $R_{\text{net}}$ is calculated from the measured net radiometer voltage $V_{\text{net}}$ and the net radiometer calibration factor $k$ (W m\(^{-2}\) mV\(^{-1}\)) by using:

$$R_{\text{net}} = k V_{\text{net}}. \tag{6}$$

For some net radiometers and two-component net radiometers, two calibration factors for
the same sensor are specified, one for positive $R_{net}$ and one for negative $R_{net}$ for the former and
for two-component instruments, $k_s$ and $k_l$ for the calibration factors for net shortwave and
net infrared irradiances respectively. Using these factors for two-component net radiometers,
the net irradiance $\hat{R}_{net\,2-\text{comp}}$ is estimated using the shortwave and infrared voltages $V_{net\,s}$ and
$V_{net\,l}$ respectively as:

$$\hat{R}_{net\,2-\text{comp}} \approx k_s V_{net\,s} + k_l V_{net\,l}. \quad (7)$$

Campbell and Diak (2005) show that unless the product of dome transmittance and plate
absorptance is equal for shortwave and for infrared irradiances, the calibration factors for the
two wavebands will be different.

Assuming that $L_{d\,surr}$ and $L_{u\,surr}$ are constant during the calibration period and that $I_s$ and
$\rho_{s\,rad} I_s$ are also constant or negligible and that $1 - \varepsilon_{rad} \approx 0$, using Eqs. (5) and (6),

$$\partial (F \sigma T_{rad}^4) / \partial V_{net} = -k_i. \quad (8)$$

Varying $T_{rad}$ and measuring the corresponding net radiometer voltage $V_{net}$ will calibrate the
net radiometer for the infrared assuming $F$ is known or almost 1 (Eq. (1)).

If it is necessary to account for the infrared irradiance from the surrounds due to changing
surrounding temperature $T_{surr}$ during the calibration period, and assuming that in magnitude
$L_{u\,surr} \approx L_{d\,surr} \approx \sigma T_{surr}^4$, then using Eqs. (5) and (6),

$$\partial (F \sigma T_{rad}^4 - F L_{d\,surr}) / \partial V_{net} = -k_i. \quad (9)$$

If the upward radiator infrared irradiance $F \sigma T_{rad}^4$ is calculated from independent $T_{rad}$ surface
temperature measurements and the known view factor $F$ (Eq. (1)), measurement of the corresponding net radiometer voltage will calibrate the net radiometer for infrared irradiance using Eq. (9). It is assumed here that $\varepsilon_{\text{rad}} \approx 1$ and that, as previously mentioned, the infrared irradiance from the surrounds - $L_{u,\text{surr}}$ and $L_{d,\text{surr}}$ - are of approximately equal magnitude and $I_s$ and $\varrho_{s,\text{rad}} I_s$ are constant or negligibly small (Eq. (5)).

Using the method described, it is also possible to calibrate two- and four-component net radiometers for the infrared using the radiator method (Eq. (5)) by applying Eq. (8) and ensuring that the associated underlying assumptions are met and if not, then by applying Eq. (9) to account for small changes in temperature of the surrounds.

If a shortwave irradiance source is suspended above a near-perfect radiator with a net radiometer placed close to the latter, the changes in net radiometer voltage will correspond only to the changes in the incident shortwave irradiance with the reflected amount from the radiator constant or negligible (Eq. (5)). For broadband net radiometers, it may be necessary to correct for any temperature changes of the surrounds during the shortwave calibration since the shortwave source may alter the temperature of the radiator surface and hence alter $L_{u,\text{rad}}$. However, corrections for such changes in the infrared conditions may be applied using $F$ and measurements of $T_{\text{rad}}$ and $T_{\text{surr}}$.

If the radiator has a surface temperature $T_{\text{rad}}$ and an infrared emissivity $\varepsilon_{\text{rad}}$ and an infrared thermometer (IRT) registers a temperature of $T_{\text{IRT}}$ (K) for the radiator, then:

\[ \sigma T_{\text{IRT}}^4 = \varepsilon_{\text{rad}} \sigma T_{\text{rad}}^4 + (1 - \varepsilon_{\text{rad}}) \sigma T_{\text{surr}}^4. \]  

(10)

Hence, by rearrangement of Eq. (10):

\[ \varepsilon_{\text{rad}} = (T_{\text{IRT}}^4 - T_{\text{surr}}^4) / (T_{\text{rad}}^4 - T_{\text{surr}}^4). \]  

(11)
If the surrounds are imperfect radiators with unknown temperature, then $\varepsilon_{\text{rad}}$ can only be estimated and then with least error if $T_{\text{rad}} \gg T_{\text{surr}}$ and in that case, $\varepsilon_{\text{rad}} = T_{\text{IRT}}^4 / T_{\text{rad}}^4$. If $T_{\text{IRT}} = T_{\text{rad}}$, then $\varepsilon_{\text{rad}} = 1$ (Eq. (11)).

From an analysis of data for the laboratory calibration of IRTs using the radiator with surface-embedded thermocouples, an approach which is similar but not identical to that of Kalma and Alksnis (1988) was used: the relationship between the corrected target temperature of an IRT, $T_{\text{CTT}}$ (K), $T_{\text{IRT}}$ and the body temperature of the sensor $T_{\text{SB}}$ (K) is expressed empirically by:

$$\sigma T_{\text{CTT}}^4 = c_1 \sigma T_{\text{IRT}}^4 - c_2 \sigma T_{\text{SB}}^4 + c_3 T_{\text{IRT}}^4 - c_4 T_{\text{SB}} + c_5.$$  (12)

The second to last term on the right hand side of Eq. (12) involving $T_{\text{SB}}$, not included by Kalma and Alksnis (1988), improves the regression analysis. Furthermore, their method did not include the first term to fourth order involving $T_{\text{IRT}}$ and the empirical constants $c_1$, $c_2$, $c_3$, $c_4$ and $c_5$. Corresponding measurements of the radiator surface temperature from the embedded thermocouples, taken as $T_{\text{CTT}} = T_{\text{rad}}$, and IRT estimates of the radiator surface $T_{\text{IRT}}$ and its body temperature $T_{\text{SB}}$ allow the empirical constants to be determined by linear regression, thereby calibrating the IRT.

3. Materials and methods

3.1. Calibration equipment and materials

Infrared calibration of net radiometers

A large-size truck radiator (0.710 m by 0.481 m – for which $F = 0.9869$ for $d = 65$ mm – and 50 mm thick) was manufactured for the initial experiments. A larger radiator (0.800 m by
0.675 m – for which $F = 0.9916$ for $d = 65$ mm – and 34 mm thick) was later used at another location for subsequent calibrations (Fig. 1, top). In both cases, the radiators were electrically grounded. The radiator was placed on a thick (37 mm) polystyrene base covered with aluminium foil that had been painted matt black. Matt black paint (Sprayon, Bedford Heights, Ohio, USA – industrial acrylic enamel flat black number 03725, emissivity listed as 0.95 at 25 °C) was applied to the surface of the radiator although as mentioned by Campbell and Diak (2005), the colour of the radiator surface is not important for (infrared) calibrations. Furthermore, the multiple cavity reflections would result in a radiator emissivity greater than 0.95. The cavities of both radiators were triangular-shaped when viewed from above (Fig. 1, bottom left) with a depth to aperture ratio of 5 in the one direction and a ratio of 20 in the perpendicular direction for the smaller radiator and respective ratios of 4 and 11 for the larger radiator.

A number of 24-gauge copper-constantan thermocouples (model PR-T-24, Omega Engineering Inc., Stamford, Connecticut, USA) were used to measure the surface temperature of the radiator (Fig. 1, bottom right) as well as the temperature of the water pumped into and out of the radiator.

All openings into the radiator were sealed with silicon sealant to prevent water leaks apart from an inlet and an outlet opening (Fig. 1, top). The radiator was placed horizontally on a trolley, for ease of transport, and positioned in the centre of the laboratory. The inlet opening of the radiator was connected using plastic hoses to the outlet of the water-well with the radiator outlet connected to the inlet of a heater stirrer. Short and thermally-insulated water hoses were used to ensure rapid water circulation between the water-well and the radiator, to minimise temperature gradients across the radiator surface and to reduce the rate of heating (or cooling) of the radiator surface. A 30-W water pump (Fig. 1, top) with a rated and maximum capacity of 16 and 30 l min$^{-1}$ respectively was used to circulate the water into the
radiator from the water bath (Haake Gebruder, Berlin, Germany, type FE number 67236
distributed by PolyScience Corp., Evanston, Illinois, USA) and back to the water bath.

For the smaller radiator, a Campbell Scientific 21X datalogger (Logan, Utah, USA) was
used to perform slow differential radiator temperature measurements, and in subsequent
calibrations using the larger radiator, a Campbell CR3000 datalogger was used. The
dataloggers were always electrically grounded to the radiator and in turn firmly connected to
earth.

The radiator surface temperature measurements were cross-checked, showing excellent
agreement, against that measured using two Fenwal thermistors (model UUA32J4 with a
0.2 °C interchangeability and equivalent to 192-222LET A01, Honeywell, Golden Valley,
Minnesota, USA) embedded so as to be flush with the surface of the radiator: slope = 1.0025
± 0.0002, adjusted coefficient of determination $r^2 = 0.9999$, root mean square error (RMSE)
= 0.12 °C for surface temperatures between 1.2 and 51.7 °C. A prior calibration of the
thermocouple temperature measurements against a mercury-in-glass thermometer registering
the temperature of stirred water in the water bath was also used as an independent check of
the accuracy of the thermocouple temperatures.

Shortwave calibration of net radiometers

Laboratory shortwave calibrations were performed using six 50-W AC halogen lamps
directed at the centre of the radiator, more than 600 mm away, with a lamp attached to a matt-
black wooden dowel rod at each corner of the radiator and a lamp at the middle positions of
the radiator widths. The intensity of all lamps was altered using a 0 to 10-V noise-suppressed
DC-controlled dimmer (model K8064, Velleman Components NV, Gavere, Belgium) that
was electronically modified so as to be controlled by a 0 to 5-V signal from a datalogger.
Field shortwave calibrations of six polyethylene-domed net radiometers were performed
following the shading method of Idso (1971) for which measurements from a standard pyranometer and each net radiometer before and after shading were obtained.

For the infrared calibrations using the smaller radiator, the surface temperature of the radiator was measured at five locations. The thermocouples were pushed through from the bottom of the radiator, with the radiator in the horizontal position, to the top. The 5-mm tip end of the thermocouple was bent to form an “L” shape. The thermocouple was then soldered on to the radiator surface so as to be flush with the radiator surface (Fig. 1, bottom left). Electrical checks confirmed that there were no electrical ground loops – the paint of the radiator prevented electrical contact between the radiator metal and the thermocouples. Each thermocouple was about 50 mm away from the nearest other thermocouple with the complete array in the shape of a large plus sign centred on the centre position of the radiator. For the larger radiator there were nine thermocouples also arranged in the shape of a large plus sign (Fig. 1, bottom right). Each thermocouple was also sprayed with matt black paint. These important procedures minimized temperature differences between the cavities of the radiator and the thermocouples. A single electrically-insulated thermocouple was also used to measure the temperature of the circulated water in the well of the heater stirrer and water bath. A pair of insulated thermocouples was used to measure the inlet and outlet water temperatures to check for temperature gradients across opposite corners of the radiator (Fig. 1, top). The polystyrene base ensured that radiative cooling from the radiator surface was uniform across the radiator and mostly from the topside. For non-controlled cooling-cycle infrared calibrations, these procedures also lessened the rate of temperature reduction after the heater circuit was switched off. For the larger radiator, a water pump and a water-well stirrer was used to ensure rapid water flow and to minimise radiator surface temperature gradients. It was important to ensure that the radiator contained as little air as possible – air instead of water increased the variability of the radiator surface temperatures slightly.
The change in radiator infrared irradiance was by design fairly similar for heating and cooling cycles but more importantly slow – less than 1.6 W m\(^{-2}\) min\(^{-1}\) and averaging 1 W m\(^{-2}\) min\(^{-1}\) for both radiators used for radiator surface temperatures less than 55 °C. These slow rates ensured that the time response of the net radiometer did not result in a significant non-correspondence between net radiometer voltage and radiator surface temperature. For surface temperatures greater than 55 °C, the rate of change for non-controlled cooling exceeded 5 and 2 W m\(^{-2}\) min\(^{-1}\) for the smaller and larger radiators respectively. These rates were considered too large for accurate calibrations and therefore routinely the datalogger-controlled heating was limited to 55 °C. Other checks were performed to ensure that the influence of instrument time response was small. Fritschen and Gay (1979, p41) present an analysis for dealing with instrument time response, for which in this case the net radiometer voltage asymptotically approaches the voltage corresponding to the actual \(R_{net}\). A ramp change in the net infrared irradiance was assumed and the net radiometer voltages were corrected for their instrument time response – around 30 s for domed instruments and less than 20 s for domeless instruments. The polyethylene-domed net radiometer time response was investigated further by collecting data for the same net radiometer infrared calibration run in two ways.

### 3.2. Net Radiometer calibration procedures

For a heating cycle calibration, the datalogger was programmed to cause water-heating every 5 min by 1 °C and collect 1-s net radiometer voltage and radiator and laboratory roof temperatures averaged every 15 s and 1, 2, 3 and 4 min after the heating was applied. Normal regressions were applied using Eq. (9) to obtain the infrared calibration constant.

A typical cycle of infrared calibration measurements was as follows: ice was added to the stirred water in the water–well and after melting a single net radiometer was placed at the centre of the radiator at a typical distance of 65 mm from the surface of the radiator.
Measurements commenced and the temperature of the heater stirrer slowly increased under
datalogger control at a rate of 0.5 °C every 2 min from close to 0 to about 55 °C taking 2 h for
the smaller radiator and 3.5 h for the larger radiator. Placement of the radiometer closer than
45 mm from the radiator caused too great a heating of the radiometer dome, or cooling when
ice was used, and slightly more variable voltage measurements. Since the temperature of the
net radiometer housing may affect the infrared values, particularly for the large four-
component instruments, care needs to be exercised to ensure that housing temperature
changes do not effect the calibrations. Before reaching 55 °C, the water circulation was
continued and the heater circuit of the heater stirrer controlled to allow pulsed heating so as to
maintain cooling at the same rate of 0.5 °C every 2 min. This rate was maintained unless the
natural cooling rate was less than 0.5 °C every 2 min in which case the pulsed heating was not
applied. A datalogger was programmed to perform slow (16.67-ms integration time)
differential temperature measurements of the radiator thermocouples and differential net
radiometer voltage measurements. Measurements were performed every 1 s with the average
and the standard deviation of these measurements over a one-minute period being recorded
for the early calibrations and every 15 s for later calibrations. Measurements were continued
after the end of the heating cycle for an additional period of about two hours for the smaller
radiator and an additional four hours for the larger radiator at which time the water
temperature had decreased to close to the ambient temperature of the laboratory.

The surface temperature of the radiator \( T_{rad} \) was calculated as the average of the
temperatures measured using the embedded thermocouples. No correction was applied to
these temperature measurements. For each net radiometer, a plot of \( L_{rad} \) on the y-axis vs the
measured net radiometer voltage on the x-axis, the former calculated from \( F\sigma T_{rad}^4 \) (Eq. (8)),
was performed and the slope magnitude calculated to yield the instrument calibration constant
for the infrared (assuming that \( \varepsilon_{rad} \approx 1 \) due to the cavity-like structure of the radiator). In
cases where the downward infrared irradiance was estimated using temperature measurements from a set of averaging thermocouples affixed to the roof of the laboratory (at four positions) or from $L_{d,\text{surr}}$ measurements using the CNR 1 four-component net radiometer, the slope magnitude of a plot $F \sigma T_{\text{rad}}^4 - F L_{d,\text{surr}}$ vs $V_{\text{net}}$ (see Eq. (9)) yielded the infrared calibration factor for the net radiometer.

In some cases, for test purposes, the infrared calibration procedure was repeated for the same net radiometer some days later or repeated with the net radiometer inverted, another net radiometer chosen or another laboratory used for the infrared calibration. For some of the calibrations, laboratory lights were left on or half on and in other calibrations, the lights were switched off. In some cases, windows were darkened to reduce the possible influence of outside shortwave irradiance on measurements. In all cases, the air-conditioning setting in the laboratories was not altered but any possible influence was monitored using roof-attached thermocouples. For selected net radiometers, the calibration was repeated many times but most radiometers were calibrated at least twice.

For some of the net radiometer infrared calibrations, a number of additional experiments were conducted: (a) fine-wire type-T thermocouples were attached to the inside of the domes of the polyethylene-domed net radiometers during calibration runs. Measurements included the radiator surface temperature, laboratory roof temperature, upper and lower dome temperatures and air temperature as well as the net radiometer voltage; (b) three heated-needle anemometers (model SNA22 originally from SoilTronics, Burlington, Washington State, USA: 40-mm length and 0.7 mm diameter positioned horizontally and in some cases vertically) were used to measure the vertical (or horizontal) wind speed above the radiator for heating- and cooling-cycle calibration runs. The needle anemometers were individually field-calibrated against the vertical wind speed measured using a three-dimensional sonic anemometer (model SWS-211/3V, Applied Technologies, Boulder, Colorado, USA) – typical
regression statistics: slope = 1.030 ± 0.070, \( r^2 = 0.974 \), \( RMSE = 0.107 \text{ m s}^{-1} \), \( n = 727 \) for wind speed varying between 0.08 and 3.2 m s\(^{-1}\); (c) the sensor-radiator distance \( d \) for selected net radiometer infrared calibrations was varied from 45 to 110 mm, particularly for a four-component net radiometer; (d) for selected polyethylene-domed net radiometers, small fans were used to pass air across both the upper and lower domes with minimal disturbance to the surface temperatures of the radiator. The ventilation system was similar to that used by Fritschen and Fritschen (2006).

For the laboratory shortwave calibrations, domeless, polyethylene-domed, miniature and two-component net radiometers were used. A datalogger-controlled light dimmer was used to alter the shortwave irradiance every 7 min. The 15-s voltage measurements from the standard pyranometer and an adjacent net radiometer were made in the last 2 min of the 7-min period. The instruments were placed at the centre of the radiator. The sensors were always maintained at a height of 70 mm above the radiator for the shortwave calibrations. During these calibrations, the radiator temperature was maintained at room temperature using circulating water and the laboratory roof, air and radiator temperatures measured. The near isothermal conditions ensured a net infrared irradiance of near 0 W m\(^{-2}\). Near isothermality was easily achieved by performing measurements within an hour. Measurements made using a pair of pyranometers, one inverted, demonstrated that the shortwave reflection coefficient of the radiator was less than 0.5 % and this radiation balance component was therefore neglected and not measured during the shortwave calibrations.

3.3. Calibration procedures for infrared thermometer calibrations

The procedures for the laboratory calibration of the eleven IRTs were similar to the net radiometer infrared calibrations. The IRTs were placed directly above the centre of the radiator at a distance of 0.97 m from the radiator for the 4° field-of-view units and 0.4 m for
the others. These distances accommodated for the wider field of view than that specified by the manufacturers, as mentioned by Bugbee et al. (undated). Once the temperature of the radiator had decreased from a high value (65 to 80 °C) to room temperature, water at near 0 °C was used to decrease the radiator surface temperature to below 15 °C. Measurements were collected as the system slowly equilibrated back to room temperature. Unlike the net radiometer calibrations for which only one sensor at a time was calibrated, many IRTs were calibrated simultaneously since for these calibrations, the radiation balance components were not required.

Measurements of $R_{\text{net}}$ and $T_{\text{rad}}$, the latter using the IRTs, were slightly more variable when $T_{\text{rad}}$ was at or below the laboratory dewpoint temperature. The resultant condensation of water on the radiator surface could not easily be avoided for laboratories without air-conditioning. However, judging from the calibration data, the condensation event did not significantly affect the calibration calculations.

### 3.4. Calibration instruments

Twelve Radiation and Energy Balance Systems (Seattle, Washington, USA) (six Q*6 and six Q*7) polyethylene-domed net radiometers, two thin polyethylene-domed Middleton Instruments (Carter-Scott Design, Brunswick, Victoria, Australia) net radiometers, a Middleton miniature polyethylene-domed net radiometer, three Kipp and Zonen (Delft, The Netherlands) NR LITE domeless net radiometers, a two-component CNR 2 and a four-component CNR 1 net radiometer (Kipp and Zonen) were used for the net radiometer calibration tests. All net radiometers were in a new condition at the time of calibration apart from the Middleton instruments. For the laboratory shortwave calibrations of the net radiometers, a Kipp and Zonen CM 11 pyranometer was used as the standard and measurements confirmed using a CMP 3 pyranometer. An Eppley model 60 standard
radiometer (The Eppley Laboratory Inc., Newport, Rhode Island, USA) was used for the field shortwave calibrations of the six domed REBS Q*6 net radiometers. The Q*6 net radiometer instruments were designed to have equal infrared and shortwave responsivity by the addition of white paint on the sensor surface (Vogt et al., 1996). The Q*7 net radiometers are supplied with one factor for positive net irradiance and one for negative.

For the two- and four-component net radiometers, two and four voltages were measured respectively. For the former instrument, the two calibration factors $k_s$ and $k_l$ supplied with the instrument were used for net shortwave and net infrared irradiance respectively to calculate $\hat{R}_{net2-comp}$ (Eq. (7)). In the case of the four-component net radiometer, the internal temperature of the instrument was measured (YSI thermistor 44032, Yellow Springs, Ohio, USA) and also used in estimating $R_{net}$ according to normal recommendations.

For the calibrations of the eleven IRTs, with emissivity set to 1.0 if applicable, the following IRTs were used: Apogee models IRTS-P and IRR-P (Apogee Instruments, Logan, Utah, USA), Everest Interscience Inc. (Tucson, Arizona, USA) IRT models (4000ALCS, 40004-A, 4004AL and hand-held 110) and Omega model OS36SM-K-80F. All calibrations were performed at least twice. The Everest and Omega units had no body temperature sensor. For the Omega units, the sensors were inserted into an aluminium housing and a type-K thermocouple added to measure the sensor body temperature inside the housing.

A possible source of error in the calibration method used for both net radiometers and IRTs is the assumption that the cavity emissivity is equal to 1. Heinisch (1972) showed that a matt-black painted right-regular cylindrical cavity with a depth to aperture ratio greater than 2.0 has an emissivity greater than 0.9915. Bedford (1972) showed that the ratio was 10.0 for spherical cavities. Based on this, the assumption of an emissivity of near unity for the two radiators used is a good one. Using a pair of IRTs, one directed at the radiator and another directed at the laboratory roof, using a calibrated IRT, it was possible to estimate $\varepsilon_{rad}$ for the
radiator (Eq. (11)). The upward facing IRT was used to measure $T_{\text{surr}}$ and this estimate was compared with the temperature estimate of $[L_{d,\text{surr}}/(F \sigma)]^{1/4}$ calculated from the y-intercept using Eq. (8) from polyethylene-domed net radiometer data.

4. Results and discussion

4.1. Thermal conditions, instrument time response and convective radiator conditions

The infrared calibration method is based on the premise that temperature gradients across the radiator are small but at the same time gradual increments in $T_{\text{rad}}$ with time are imposed and that convective influences on net irradiance measurements are small. A measure of the thermal gradients across the radiator was obtained from the standard deviation of all measured radiator surface temperatures. Another measure of the gradients was the temperature difference between the outlet and inlet water temperatures over a distance of about 0.95 m. Typically, the standard deviation of all radiator temperatures for each time period for an infrared calibration was less than 0.08 °C and the outlet and inlet temperature differences were less than 0.06 °C in magnitude at any time with the largest magnitude difference occurring at the greatest radiator temperatures (Fig. 2). These standard deviations and temperature differences are small, justifying the assumption of constant temperature across the radiator at a given time.

The influence of net radiometer time response was investigated using the correction method of Fritschen and Gay (1979). The correction applied to polyethylene-domed net radiometer voltages due to the instrument 30-s time response, resulted in calibration slopes that were within 0.7 % of the uncorrected slopes when using 15-s output data. For 60-s output data, the difference in slopes was even smaller. To further determine if the instrument time response affected the results, net radiometer calibrations for a heating cycle at a temperature increase rate of 1 °C every 5 min were performed for a Q*7 polyethylene-domed net
radiometer (instrument 2 in Table 1 with a manufacturer’s negative $R_{net}$ calibration factor of 10.75) averaged voltages every 15 s and every 1 min from 0 min to 4 min after a 1 °C heating. The calculated infrared calibration constants ($k_I$, W m$^{-2}$ mV$^{-1}$) based on Eq. (8) were 11.35 for 15-s data, 11.36 for data 0 min after heating increment, 11.35 for 1 min after heating, 11.35 for 2 min after heating, 11.36 for 3 min after heating and 11.38 for 4 min after heating. Therefore, for the rate of heating used, the 15-s measurements were not impaired by instrument time response.

The issue of the possible influence of thermally-driven vertical convection, causing unstable net radiometer voltages and therefore unreliable infrared calibrations, was investigated. Heated-needle anemometer wind speeds, measured near the centre of the radiator showed that vertical and horizontal wind speeds were less than 0.62 m s$^{-1}$ at all times. Vertical wind speeds gradually increased from around 0.3 to 0.62 m s$^{-1}$ with increase in $T_{rad}$ from 0 to 55 °C followed by a slow decrease to around 0.3 m s$^{-1}$ as the radiator was allowed to cool (Fig. 2). The wind speed correction for the maximum wind speed of 0.62 m s$^{-1}$ using the correction function recommended by the manufacturer of the polyethylene-domed units is 0.9986 and 1.007 for the domeless units and therefore based on these corrections the influence of thermally-generated wind speed does not affect the infrared calibration results significantly.

During an infrared calibration of a polyethylene-domed net radiometer (Fig. 3a), the increase in the lower dome temperature with time mirrored the increase in vertical wind speed, with the lower dome increasing in temperature by about 18 °C with an increase in air temperature of about 10 °C (Fig. 3b). Also shown in Fig. 3a and b by the vertical arrow for the net radiometer voltage $V_{net} = 0$ mV, are the nearly equal radiator surface, laboratory roof, air, lower and upper dome temperatures at 15 °C although there is a slight time lag in the dome temperatures. This equality is good affirmation of the correct functioning of the infrared
4.2. Infrared calibration of net radiometers

For a cooling-cycle infrared calibration, the change in $T_{rad}$ and also $L_u = F \sigma T_{rad}^4$ and the corresponding standard deviation in temperature for all surface-embedded thermocouple temperatures, as a function of net radiometer voltage for a polyethylene-domed net radiometer, is shown (Fig. 4). The largest radiator temperature standard deviations generally occurred at low and at high radiator temperatures.

Only data points for which $T_{rad}$ was less than 55 °C were included in the regression analysis for the $F \sigma T_{rad}^4$ vs $V_{net}$ plots. Strictly, these calibration plots should have $F \sigma T_{rad}^4$ as the independent variable on the x-axis. However, given the high $r^2$, it is immaterial except that as shown in Fig. 4, the RMSE of the irradiance is conveniently shown, the slope is the calibration multiplier (W m$^{-2}$ mV$^{-1}$) and the equation intercept corresponds to $L_{d \text{surr}}$.

Care needs to be exercised to ensure that the downward infrared irradiance $L_{d \text{surr}}$ is not influenced significantly by the elevated temperature of the radiator or the lowered temperatures when ice or cold water is used, particularly in small laboratories. If the temperature of the surrounds $T_{surr}$ is elevated and then decreases as the radiator cools, there may be a non-linear relationship between $F \sigma T_{rad}^4$ and net radiometer voltage $V_{net}$. In such cases Eq. (9), which requires measurement of $T_{surr}$, could be applied as opposed to Eq. (8). Care also needs to be exercised to ensure that changes in shortwave irradiance do not significantly influence the infrared calibrations. Most of the calibrations were in darkened laboratories or performed overnight.

The infrared calibration data for two domeless net radiometers are shown (Fig. 5), the calibrations performed on different days. The confidence belts of Fig. 5 represent those for a single-predicted value at the 99 % level of confidence. The dotted lines have slope
magnitudes equal to those supplied with the instrument (shown in square brackets after the
calibration regression equations). There is a 7.0 % difference in the slopes of these two net
radiometers. The difference in the intercepts would be due to the different laboratory wall and
ceiling temperatures for the two days. The one calibration was performed in a laboratory in
which the lights were switched off. Extraneous light from outside the building was visible. In
the other calibration, the laboratory lights were switched off and the room completely
darkened. The shortwave irradiance measured using a pyranometer was less than 1 W m\(^{-2}\). For
these two net radiometers, the slopes for these infrared calibrations agreed quite well with the
manufacturers’ shortwave calibration performed some two to three months previously under
windless and clear-sky outdoor conditions (Table 1). The intercepts were different (Fig. 5 and
Table 1, 7\(^{th}\) column marked intercept), and consistent with \(L_{d,surr}\) calculated from the
laboratory roof temperatures. For a net radiometer placed above a radiator for which \(L_u,rad\) is
calculated using Eq. (3), it is therefore possible to separate the upward and downward infrared
irradiance components of \(R_{net}\) by equating the y-intercept of Fig. 5 to \(L_{d,surr}\).

In early calibration tests using Q*6 polyethylene-domed instruments in which \(T_{rad}\) was
allowed to exceed 80 °C, a plot of \(F \sigma T_{rad}^4\) vs \(V_{net}\) for the first 10 °C yielded a greater \(L_{d,surr}\)
intercept than the intercept value for the next 10 °C. These differing intercept values were due
to increased temperatures of the environs due to the heated radiator causing increased \(L_{d,surr}\)
values, possibly due to the temperature difference between the upper and lower domes
particularly during a heating calibration cycle and possibly also due to net radiometer time
constant limitations. However, the measured vertical convection currents were shown to be
less than 0.62 m s\(^{-1}\) for \(T_{rad}\) less than 55 °C, and therefore of minor influence and the time
constant limitations have been shown to be minor. The data of Fig. 3b show the upper and
lower dome temperatures. The upper dome temperatures were measured using a fine-wire
thermocouple attached to the underside (side nearest the sensor) and for the lower dome the
sensor was also attached to the side nearest the sensor. From these data, the infrared irradiance from dome to sensor may be calculated. For the heating cycle calibrations, assuming a dome emissivity of 0.06 (Fritschen and Fritschen, 2007), the net flux difference from dome to sensor ranged from -1.8 to 3.5 W m$^{-2}$ for radiator temperatures increasing from 0 to 55 °C – the upper dome increasing from 18 to 26 °C and the lower dome increasing from 12 to 35 °C. For cooling cycle calibrations, the difference between the dome to sensor fluxes for upper and lower domes decreased from 3.5 W m$^{-2}$ at 55 °C to 1.8 W m$^{-2}$ at room temperature – upper dome decreasing from 26 to 19 °C and the lower dome decreasing from 35 to 23 °C. For most of the time, the flux difference was almost constant at 1.8 W m$^{-2}$ since both upper and lower domes tended to cool at similar rates. To also check that their influence was small, we repeated some of the domed calibrations with and without ventilation. For the ventilated calibrations, small fans were used to pass air across both the upper and lower domes with minimal disturbance to the surface temperatures of the radiator. The calibration slopes using dome ventilation (Table 1, net radiometer 2, runs 8, 9, 12, 13) were significantly greater in magnitude than the negative $R_{net}$ calibration factor supplied by the manufacturer and greater than those for no ventilation but with the ventilator in place (runs 10, 11, 14 to 17) and greater than those for when the ventilator was not used (runs 1 to 7 in laboratory 3 and runs 18, 19 in laboratory 4). It would appear that the placement of a ventilator alongside the net radiometer significantly affects the calibration slope and was therefore not used routinely.

The infrared calibrations and recalibrations of the polyethylene-domed net radiometers were repeatable (e.g. net radiometer 2 of Table 1, Fig. 4) and reasonably consistent. Side-by-side calibration for a pair of net radiometers at a time gave slightly more variable calibration data (data not shown) and is therefore not recommended.

The domeless (instruments 4, 5 and 6) and miniature polyethylene-domed (instrument 3) net radiometer infrared calibration data (Figs. 6a, b), for heating and heating/cooling cycles
respectively, were more variable compared to their polyethylene-domed counterparts (average \( RMSE = 2.35 \text{ W m}^{-2} \) and \( 2.38 \text{ W m}^{-2} \) respectively for all calibration runs) compared to 0.50 \text{ W m}^{-2} \) (Table 1) for the polyethylene-domed net radiometer 2 of Fig. 4 (and an average of 0.98 \text{ W m}^{-2} \) for calibration runs shown in Table 1 but excluding the ventilation runs). Presumably the polyethylene-domed net radiometers are less sensitive to convective exchanges between the surface of the net radiometer and the surrounding atmosphere, due to greater time constants and the protection provided by the domes, than the domeless and miniature polyethylene-domed net radiometers. In the case of Fig. 6b, for the miniature polyethylene-domed net radiometer, Eq. (9) which accounts for the influence of any changes in the surrounding temperature on the measurements, was applied. As expected, compared to the application of Eq. (8), the slope value was similar – within 0.9 % of that obtained by applying Eq. (9). This confirms the assumption that the surrounding infrared irradiance contribution to the radiation balance is reasonably constant during the calibration. The calibration for a domeless net radiometer inverted yielded a very similar calibration slope magnitude (Table 1, instrument 4) with slopes within 0.7 % of the manufacturer’s calibration factor obtained six months previously using a shortwave calibration for the upper surface. Domeless instruments 5 and 6 were purchased at the same time but some 30 months after instrument 4, the latter with a very different measured and manufacturer calibration factor compared to the former pair.

The two-component net radiometer infrared calibrations were very consistent apart from runs 1, 2 and 3 (Table 1, instrument 7) with an average \( RMSE = 0.88 \text{ W m}^{-2} \), similar to the average of 1.00 \text{ W m}^{-2} \) for the polyethylene-domed net radiometers even when inverted. For the two-component calibrations, the instrument net irradiance was regressed against \( L_{u \text{ rad}} - F L_{d \text{ surr}} \) \text{ Eq. (9)}. \)

A four-component net radiometer (instrument 8) was used to check the assumptions of
Eq. (9) and the sensitivity of the calculated sensor infrared calibration factor to the sensor-radiator distance $d$ (Eq. (1)). As was the case with the two-component net radiometer, the instrument net irradiance was regressed against $L_{u\text{rad}} - F L_{d\text{surr}}$. Varying the sensor-radiator distance from 45 mm to 110 mm resulted in a very small change in calibration slope with no obvious relationship between $d$ and the calibration slope if the calibration for $d = 110$ mm is excluded. However, the manufacturer estimate of $R_{\text{net}}$ underestimates the measured $R_{\text{net}}$ (average slope of 0.96). For a distance of 110 mm, the slope of the regression relationship is 0.993 with a RMSE lower than the average for the other distances. Possibly therefore, for larger instruments, the distance away from the radiator should be increased. For these calibrations, the $L_{d\text{surr}}$ values were within 0.2% between the beginning and end of the measurements (data not shown). The measured downward infrared irradiance was within 0.7% of that estimated using the roof-affixed thermocouples. The $\rho_{s\text{rad}} I_s$ values were negative at times, typical of thermopile sensors exposed to low shortwave irradiance (Reda et al., 2005) but this did not affect the calibration results since both the $\rho_{s\text{rad}} I_s$ and $I_s$ values were reasonably constant for the calibration period.

The repeatability of the infrared calibration measurements was also demonstrated by the twelve repeat calibrations of the four-component net radiometer, once in the inverted position, showing a relative variation in the slopes from the mean between -2.2 and 3.3% (Table 1). The two-component and four-component net radiometers generally exhibited the smallest RMSE values (Table 1). Generally, calibration data collected by cooling as opposed to radiator heating exhibited smaller RMSE values particularly calibration under datalogger control with a slow incremental change in infrared irradiance of about 1 W m$^{-2}$ min$^{-1}$.

4.3. Shortwave calibration of net radiometers

Calibrations for domeless net radiometers demonstrated differences between shortwave and
infrared calibration factors $k_s$ and $k_l$ with an average ratio of $k_s/k_l = 0.95$ for domeless instruments 5 and 6 (Table 1). For instrument 5, the $k_s$ values were consistently less than that of the manufacturer’s value by about 6 % compared to an underestimate of 1 % for instrument 6.

For the Q*6 net radiometers, for which the manufacturer matched the positive $R_{net}$ and negative $R_{net}$ calibration factors (Vogt et al., 1996), the infrared calibration slopes agreed remarkably well with the manufacturer’s calibration performed some two to three months previously in a chamber using a quartz iodine lamp and shortwave irradiance measurements using a standard shortwave pyranometer (Table 1, instrument 1). There is a greater inequality between $k_s$ and $k_l$ for the Q*7 polyethylene-domed instrument (Table 1, domed-radiometer 2 calibration runs 20 (S) to 27 (S) with and without correction for infrared irradiance from the surrounds) with $k_s/k_l = 0.76$ (compared to 0.83 for the positive and negative net irradiance calibration factors supplied). Similarly, there is inequality between $k_s$ and $k_l$ for the miniature polyethylene-domed net radiometer (instrument 3) for which $k_s/k_l = 0.87$. A ratio of $k_s/k_l < 1$ for polyethylene-domed net radiometers is consistent with the findings of Cook and Holdridge (2006) that transmittance of polyethylene is weaker for wavelengths of strongest infrared transmission by water vapour.

For the two-component net radiometer, the value of $k_s$ was consistent with a percentage difference of 2.3 % from the manufacturer’s value (Table 1, instrument 7) obtained two to three months previously under a metal-halide lamp, 1.1 m vertically above the sensor, for which the shortwave irradiance was about 500 W m$^{-2}$. For the shortwave calibration data of Table 1, a range of shortwave irradiance values was used in obtaining the calibration factor.

4.4. Calibration of infrared thermometers

A typical calibration relationship for an IRT using a cooling cycle is shown (Fig. 7). The
calibration relationship for the various IRTs showed marked variation between different sensors (Table 2). In the case of IRT 1 (Table 2), the deviation between the actual radiator surface temperature measured using the embedded thermocouples ($T_{rad}$, °C in this case) of the radiator and the IRT estimate of the same ($T_{IRT}$, °C) decreased to -1.5 °C at $T_{rad} = 60$ °C compared to about -0.2 °C for IRT 2 (run 2). All but two of the IRTs exhibited a plateau as shown in the $T_{rad} - T_{IRT}$ vs $T_{rad}$ curves (Fig. 7). In one case, for IRT 2, second calibration, the shape of $T_{rad} - T_{IRT}$ vs $T_{rad}$ was parabolic with a maximum of 0.6 °C at 30 to 40 °C and a minimum of -0.4 °C at 70 °C. The hand-held IRT model 110 had an almost linear $T_{rad} - T_{IRT}$ vs $T_{rad}$ relationship. For this IRT, $T_{rad} - T_{IRT}$ was 0 °C at 20 °C increasing almost linearly to 6 °C at 70 °C. The Everest IRTs tended to underestimate $T_{rad}$ for temperatures less than 40 °C, by differing amounts.

The hand-held IRT (model 110) was calibrated twice for temperatures ranging between 15 and 70 °C: once with ten calibration points (Table 2, run 1) and once with nearly 1000 data points (run 2). There was no significant difference in slope or intercept of the calibration relationship for the two calibrations (Table 2). This hand-held model 110 IRT had the greatest temperature bias for all units tested, underestimating radiator temperature at 50 °C by 3 °C and overestimating by 1 °C at 15 °C (Fig. 8).

For the IRTs without a body temperature sensor, fitting a cubic polynomial to the residual $T_{rad} - T_{IRT}$ as a function of $T_{IRT}$ (instead of $T_{rad}$ as shown in Figs. 7 and 8) allows an estimate of the radiator temperature $\hat{T}_{rad}$, to be calculated:

$$\hat{T}_{rad} = T_{IRT} + (a_0 + a_1T_{IRT} + a_2T_{IRT}^2 + a_3T_{IRT}^3).$$ (13)

The residual plot after this procedure is shown in Fig. 9. The Everest sensors (a, b) had no body temperature sensor (Eq. (13) applied) and for the other sensors (c, d, e), a body
temperature correction was applied (Eq. (12)). Using this procedure, for the hand-held IRT, the estimate of radiator temperature for this procedure applied three times to further minimise the residuals is within 0.2 °C of actual for temperatures between 5 and 55 °C without the need for any correction for IRT body temperature (Table 3).

The analysis of the calibration data for IRTs with a body temperature sensor was different (Figs. 9c, d, e). From collected data of the actual target temperature, obtained using the average of all thermocouples embedded in the surface of the radiator \( T_{CTT} = T_{rad} \), \( T_{IRT} \) (K), and the infrared sensor body temperature \( T_{SB} \) (K), the coefficients \( c_1 \) to \( c_5 \) of Eq. (12) were determined using linear regression. From this regression, the residual \( T_{rad} - T_{IRT} \) was plotted as a function of \( T_{IRT} \) (°C) (Fig. 9c, d, e). For most of the IRTs used, the residuals were within 0.15 °C for temperatures between 4 and 60 °C. The approach used can be applied to different makes of IRTs, allows for the inclusion of the sensor body temperature \( T_{SB} \) and improves on the method used by Kalma and Alksnis (1988).

The evaporation of condensed water, caused by the radiator temperatures being less than the atmospheric dewpoint, resulted in a temporary decrease in \( T_{rad} - T_{IRT} \) (Fig. 9c, d, e) – data were excluded for this event.

In view of the differences between different model IRTs and differences between IRTs of the same model, it is important to calibrate such units prior to and after use and especially so for surface temperatures exceeding 35 °C.

4.5. Emissivity

Although near unity, there is a non-linear variation in the estimated \( \varepsilon_{rad} \) vs \( T_{rad} \) (Fig. 7) and the estimate is affected by the event corresponding to the addition of cold water. This calculation for \( \varepsilon_{rad} \) assumes no error in the IRT estimate of the temperature of the surroundings at all temperatures. The non-linear shape would imply that the shape of the upward infrared
irradiance vs net radiometer voltage calibration relationships (Eqs. (8) and (9)) would also be
non-linear. No such gradual curvature in the net radiometer calibration relationship was
observed for the temperature range 55 to near 0 °C (Figs. 4 to 6).

5. Summary and conclusions

Energy balance closure investigations or estimates of evaporation as a residual term of the
energy balance are critically dependent on $R_{\text{net}}$. In spite of the importance of $R_{\text{net}}$, there is still
no widely accepted best field-measurement method, associated calibration method and data
treatment. Some workers have suggested that the extent of energy balance closure between
FLUXNET sites is probably the result in bias errors in $R_{\text{net}}$ with biases of up to 15 % noted.

Procedures for the infrared calibration of net radiometers using a water-heated or cooled
radiator using circulated water and calibrated surface-embedded thermocouples and a method
for shortwave calibration of net radiometers are presented and tested. Calibration for various
types of net radiometers included polyethylene-domed, miniature polyethylene-domed,
domeless, two-component and four-component net radiometers. Calibration factors for the
polyethylene-domed net radiometers were repeatable and reasonably consistent with the
manufacturers’ calibration factor. Calibration tests included measurements of upper and lower
domes, air, radiator surface and laboratory roof temperatures, net radiometer voltage(s) as
well as the thermally-driven vertical and horizontal wind speed. Routine calibrations included
measurement of radiator and laboratory roof temperatures and net radiometer voltage(s). The
calibration method is reasonably quick, datalogger-controlled and relatively inexpensive in
that apart from a datalogger, a heater stirrer and an inexpensive radiator, no additional
equipment is required. The shortwave calibrations showed consistent calibration factors for
the different runs that were in reasonable agreement with the manufacturer values.

The same radiator may also be used for the calibration of IRTs. A statistical procedure,
for minimising for a wide range in temperature, the temperature residual between the radiator
surface temperature and the IRT estimate of the radiator surface temperature, was applied
with the result that the residuals were within 0.15 °C for all makes and models of IRT sensors
used apart from a hand-held IRT which was within 0.2 °C.

The radiator method for calibrating net radiometers, for infrared and shortwave, and IRTs
is relatively simple to set up and operate and requires no specialised equipment apart from the
data collection equipment. Accurate and reproducible calibrations are achievable.

Acknowledgements

Funding from the Water Research Commission (South Africa), University of KwaZulu-Natal,
the South African National Research Foundation and the United States Council for the
International Exchange of Scholars for a Fulbright grant is gratefully acknowledged. Dr
Gaylon S. Campbell (Decagon, Pullman, Washington, USA) contributed to some of the early
impetus of this work. Mr Guy M. Dewar of the Electronics Centre of the University of
KwaZulu-Natal ably assisted with the electronics for heater stirrer and lighting control of the
large radiator and Mr Roelie Hendriks of the Mechanical Instruments Workshops assisted
with the water bath and pump. The manuscript benefitted from comments from the reviewers
and the Associate Editor.

References

Amiro, B.D., Thurtell, G.W., Gillespie, T.J., 1983. A small infra red thermometer for


during FIFE. J. Geophys. Res. 97 (D17), 18681–18695.


Reda, I., Hickey, J.R., Sto1el, T., Myers, D., 2002. Pyrgeometer calibration at the National


Figure captions

Fig. 1 - The large radiator system: (a) top: the radiator, a net radiometer, insulated hoses, grounding wires, water pump, water bath and outlet and inlet TCs and some of the halogen lamps, the latter for shortwave calibrations; (b) bottom left: close-up of radiator cavities and a single TC; (c) bottom right: the array of surface-mounted thermocouples and the radiator cavities. Not shown are the two TCs for measuring outlet and inlet water temperatures.

Fig. 2 - Conditions during a polyethylene-domed infrared net radiometer calibration: temporal variation in the standard deviation of the radiator surface temperatures $SD_{rad}$, temperature difference between water out of and into the radiator ($T_{out} - T_{in}$) and temporal variation in vertical wind speed $w$.

Fig. 3 - Conditions during a polyethylene-domed net radiometer infrared calibration for a heating cycle followed by a cooling cycle: (a) temporal variation in net radiometer voltage plotted as $-V_{net}$ and $L_{u rad}$; (b) temporal variation in upper and lower dome temperatures, radiator surface, air and laboratory roof temperatures.

Fig. 4 - A plot of the upward infrared irradiance $L_{u rad}$ (left hand y-axis, W m$^{-2}$) estimated from $F \sigma T_{rad}^4$ for a heating cycle, the radiator surface temperature $T_{rad}$ (bottom right-hand axis, °C) and the standard deviation of the radiator surface temperature (top right hand y-axis, °C) as a function of the net radiometer voltage (mV) for net radiometer number 2 (run 4). The dotted line has a slope magnitude equal to that supplied with the instrument (shown in square brackets after the calibration regression equations).
Fig. 5 - A plot of the upward infrared irradiance $L_{u, rad}$ (W m$^{-2}$) as a function of the net radiometer voltage (mV) for net radiometer numbers 4 and 5 (domeless instruments) for a heating cycle.

Fig. 6 - (a) A plot of the upward infrared irradiance (W m$^{-2}$) as a function of the net radiometer voltage (mV) for net radiometer number 4 (domeless, run 3, heating cycle) – dotted line corresponds to a slope magnitude equal to that supplied with the instrument (shown in square brackets after the calibration regression equations); (b) a plot of the upward infrared irradiance minus $F L_{d, surr}$ (W m$^{-2}$) as a function of the net radiometer voltage (mV) for net radiometer number 3 (miniature polyethylene-domed, run 5, heating and cooling cycles).

Fig. 7 - A plot of the IRT (number 2, run 2) temperature (left hand y-axis, °C), the temperature difference between radiator surface and IRT temperatures (bottom right hand y-axis, °C), and calculated emissivity of the radiator (top right hand y-axis, unitless).

Fig. 8 - A plot of the IRT (hand-held model 110) temperature (left hand y-axis, °C) and the temperature difference between radiator surface and IRT temperatures (right hand y-axis, °C).

Fig. 9 - A plot of the radiator surface and IRT temperature residuals for selected IRT sensors. The five horizontal lines correspond to a residual of 0 °C.
Table captions

Table 1 - Details and statistical results for selected net radiometer infrared (I) and shortwave (S) calibrations. The outdoor calibrations for the domed net radiometers, last column, were performed using the field short-wave sun/shade technique.

Table 2 - Details and statistical results of the IRT laboratory calibrations.

Table 3 - The statistical results of the hand-held IRT laboratory calibration with and without application of the statistical method used to reduce the residuals ($n = 970$ and $r^2 > 0.9997$ for all data sets).
Figure 4

$y = -11.78x + 466.6$ [10.75]

RMSE = 0.50 W m$^{-2}$
Figure 5

Radiometer 4
run 2

$y = -69.06x + 456.5$ [69.44]
RMSE = 0.70 W m$^{-2}$

Radiometer 5
run 1

$y = -74.23x + 425.3$ [74.07]
RMSE = 2.90 W m$^{-2}$

Upward infrared irradiance (W m$^{-2}$)

Domeless net radiometer voltage (mV)
Figure 6a

The graph shows a linear relationship between upward infrared irradiance (W m$^{-2}$) and domeless net radiometer voltage (mV). The equation of the line is $y = -69.00x + 418.2$ [69.44], with an RMSE of 3.87 W m$^{-2}$.

Key points:
- $L_{u, rad}$
- $SD(T_{rad})$
- $T_{rad}$
- The graph includes various data points and trends.
Figure 6b

The graph shows the relationship between the miniature net radiometer voltage (mV) and the difference in energy fluxes ($L_{\text{rad}} - F L_{\text{surr}}$). The linear regression equation is given as $y = -174.27x + 0.161$ with an RMSE of 2.31 W m$^{-2}$. The standard deviation ($SD(T_{\text{rad}})$) is also plotted.
Figure 7

Emissivity

Addition of cold water

IRT temperature (°C)

T_{IRT}

T_{rad} - T_{IRT}

y = 1.019x - 1.15

RMSE = 0.13 °C

Radiator temperature (°C)
Addition of cold water

\[ y = 0.881x + 2.78 \]
RMSE = 0.11 °C
Figure 9

(a) △ Everest handheld  RMSE = 0.039 °C

(b) □ Everest  RMSE = 0.077 °C

(c) ○ Omega  RMSE = 0.039 °C

(d) + Apogee IRR-P  RMSE = 0.035 °C

(e) × Apogee IRTP  RMSE = 0.035 °C

Evaporation of condensed water

IRT temperature (°C)
Table 1 - Details and statistical results for selected net radiometer infrared (I) and shortwave (S) calibrations. The outdoor calibrations for the domed net radiometers, last column, were performed using the field short-wave sun/shade technique.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Radiometer number</th>
<th>Calib momentum (cooling phase, C; heating, H), d (mm)†</th>
<th>Equation used</th>
<th>n</th>
<th>Intercept (W m⁻²)</th>
<th>$SE_{\text{intercept}}$ (W m⁻²) ††</th>
<th>Slope magnitude (W m⁻² mV⁻¹)</th>
<th>$SE_{\text{slope}}$ (W m⁻² mV⁻¹)</th>
<th>$r^2$</th>
<th>RMSE (W m⁻²)</th>
<th>Manufacturers’ shortwave (S) or infrared (I) calibration factor (W m⁻² mV⁻¹)</th>
<th>Short-wave calibration factor (W m⁻² mV⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>REBS</td>
<td>1 Polyethylene-domed Q*6</td>
<td>1 (I)</td>
<td>2 (C)</td>
<td>8</td>
<td>77</td>
<td>435.2</td>
<td>0.16</td>
<td>13.86</td>
<td>0.035</td>
<td>0.9995</td>
<td>0.84</td>
<td>13.7 (S and I)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 (I)</td>
<td>2 (C)</td>
<td>246</td>
<td>432.9</td>
<td>0.09</td>
<td>13.82</td>
<td>0.019</td>
<td>0.9995</td>
<td>1.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 Polyethylene-domed Q*7</td>
<td>1 (I)</td>
<td>3 (H, 55)</td>
<td>8</td>
<td>907</td>
<td>459.5</td>
<td>0.04</td>
<td>11.61</td>
<td>0.004</td>
<td>0.9999</td>
<td>1.17</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 (I)</td>
<td>3 (C, 55)</td>
<td>940</td>
<td>459.7</td>
<td>0.06</td>
<td>11.61</td>
<td>0.009</td>
<td>0.9994</td>
<td>1.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 (I)</td>
<td>3 (H, 50)</td>
<td>857</td>
<td>457.6</td>
<td>0.03</td>
<td>11.52</td>
<td>0.004</td>
<td>0.9999</td>
<td>0.91</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 (Fig. 4) (I)</td>
<td>3 (H, 50)</td>
<td>446</td>
<td>466.6</td>
<td>0.05</td>
<td>11.78</td>
<td>0.005</td>
<td>0.9999</td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 (I)</td>
<td>3 (C, 57)</td>
<td>1008</td>
<td>475.9</td>
<td>0.02</td>
<td>11.58</td>
<td>0.004</td>
<td>0.9999</td>
<td>0.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 (I)</td>
<td>3 (C, 57)</td>
<td>959</td>
<td>472.4</td>
<td>0.05</td>
<td>11.71</td>
<td>0.008</td>
<td>0.9996</td>
<td>0.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7 (I)</td>
<td>3 (C, 57)</td>
<td>959</td>
<td>468.2</td>
<td>0.03</td>
<td>11.54</td>
<td>0.005</td>
<td>0.9998</td>
<td>0.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 (I)</td>
<td>4 (H, V)††††, 61</td>
<td>1038</td>
<td>430.9</td>
<td>0.05</td>
<td>13.15</td>
<td>0.009</td>
<td>0.9996</td>
<td>1.43</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>9 (I)</td>
<td>4 (C, V), 61</td>
<td>900</td>
<td>427.5</td>
<td>0.08</td>
<td>13.74</td>
<td>0.010</td>
<td>0.9995</td>
<td>1.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 (I)</td>
<td>4 (H, U) †††††, 61</td>
<td>227</td>
<td>432.4</td>
<td>0.17</td>
<td>11.25</td>
<td>0.031</td>
<td>0.9983</td>
<td>2.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>11 (I)</td>
<td>4 (C, U)</td>
<td>61</td>
<td>189</td>
<td>427.3</td>
<td>0.20</td>
<td>11.98</td>
<td>0.035</td>
<td>0.9984</td>
<td>1.13</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>12 (I)</td>
<td>4 (H, Y)</td>
<td>62</td>
<td>840</td>
<td>418.0</td>
<td>0.06</td>
<td>13.33</td>
<td>0.008</td>
<td>0.9997</td>
<td>1.55</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>13 (I)</td>
<td>4 (C, Y)</td>
<td>62</td>
<td>958</td>
<td>416.5</td>
<td>0.01</td>
<td>13.66</td>
<td>0.011</td>
<td>0.9994</td>
<td>1.37</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>14 (I)</td>
<td>4 (H, U)</td>
<td>61</td>
<td>198</td>
<td>436.8</td>
<td>0.22</td>
<td>11.73</td>
<td>0.024</td>
<td>0.9992</td>
<td>2.86</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15 (I)</td>
<td>4 (C, U)</td>
<td>61</td>
<td>223</td>
<td>429.1</td>
<td>0.21</td>
<td>12.45</td>
<td>0.028</td>
<td>0.9989</td>
<td>1.69</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>16 (I)</td>
<td>4 (H, U), 60</td>
<td>856</td>
<td>418.2</td>
<td>0.10</td>
<td>11.69</td>
<td>0.010</td>
<td>0.9994</td>
<td>2.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>17 (I)</td>
<td>4 (C, U), 60</td>
<td>901</td>
<td>416.6</td>
<td>0.04</td>
<td>12.11</td>
<td>0.006</td>
<td>0.9987</td>
<td>0.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>18 (I)</td>
<td>4 (H)</td>
<td>63</td>
<td>842</td>
<td>409.3</td>
<td>0.08</td>
<td>11.75</td>
<td>0.008</td>
<td>0.9996</td>
<td>2.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>19 (I)</td>
<td>4 (C)</td>
<td>63</td>
<td>958</td>
<td>409.0</td>
<td>0.07</td>
<td>11.99</td>
<td>0.008</td>
<td>0.9996</td>
<td>1.13</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>20 (S)</td>
<td>4, 57</td>
<td>7</td>
<td>72</td>
<td>19.2</td>
<td>0.29</td>
<td>8.66</td>
<td>0.014</td>
<td>0.9998</td>
<td>1.18</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>21 (S)</td>
<td>-0.4</td>
<td>0.24</td>
<td>8.97</td>
<td>0.012</td>
<td>0.9999</td>
<td>0.99</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>22 (S)</td>
<td>4, 75</td>
<td>45</td>
<td>10.0</td>
<td>0.35</td>
<td>8.75</td>
<td>0.012</td>
<td>0.9999</td>
<td>1.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>23 (S)</td>
<td>-2.0</td>
<td>0.82</td>
<td>8.99</td>
<td>0.027</td>
<td>0.9996</td>
<td>2.70</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>24 (S)</td>
<td>4, 70</td>
<td>69</td>
<td>23.5</td>
<td>0.17</td>
<td>8.91</td>
<td>0.011</td>
<td>0.9999</td>
<td>1.20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

IR correction

IR correction
<table>
<thead>
<tr>
<th>IR correction</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Middleton</td>
<td>25 (S)</td>
<td>4, 60</td>
<td>18</td>
<td>4.1</td>
<td>0.33</td>
<td>8.86</td>
<td>0.017</td>
<td>0.9999</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>26 (S)</td>
<td>18</td>
<td>12.7</td>
<td>0.20</td>
<td>8.70</td>
<td>0.010</td>
<td>1.0000</td>
<td>0.59</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unknown</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kipp and Zonen</td>
<td>1 (I)</td>
<td>3 (H), 46</td>
<td>9</td>
<td>1795</td>
<td>0.226</td>
<td>0.063</td>
<td>175.46</td>
<td>0.123</td>
<td>0.9991</td>
</tr>
<tr>
<td></td>
<td>2 (I)</td>
<td>3 (H), 46</td>
<td>1823</td>
<td>0.952</td>
<td>0.067</td>
<td>175.14</td>
<td>0.131</td>
<td>0.9990</td>
<td>2.53</td>
</tr>
<tr>
<td></td>
<td>3 (I)</td>
<td>3 (H), 46</td>
<td>1835</td>
<td>-1.138</td>
<td>0.058</td>
<td>176.29</td>
<td>0.115</td>
<td>0.9992</td>
<td>2.22</td>
</tr>
<tr>
<td></td>
<td>4 (I)</td>
<td>3 (H), 46</td>
<td>1813</td>
<td>1.154</td>
<td>0.053</td>
<td>175.70</td>
<td>0.104</td>
<td>0.9994</td>
<td>1.97</td>
</tr>
<tr>
<td></td>
<td>5 (Fig. 6b) (I)</td>
<td>3 (H), 46</td>
<td>1821</td>
<td>0.161</td>
<td>0.061</td>
<td>174.27</td>
<td>0.121</td>
<td>0.9991</td>
<td>2.31</td>
</tr>
<tr>
<td></td>
<td>6 (S)</td>
<td>4, 68</td>
<td>7</td>
<td>18</td>
<td>16.03</td>
<td>0.926</td>
<td>153.06</td>
<td>0.745</td>
<td>0.9996</td>
</tr>
<tr>
<td></td>
<td>Unknown</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>66.62 (S), 79.30 (I)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR correction</td>
<td>29th May 2008 vintage</td>
<td>1 (I)</td>
<td>3 (H), 53.5</td>
<td>8</td>
<td>273</td>
<td>417.6</td>
<td>0.22</td>
<td>69.18</td>
<td>0.121</td>
</tr>
<tr>
<td></td>
<td>2 (I)</td>
<td>3 (H), 50</td>
<td>1473</td>
<td>456.5</td>
<td>0.03</td>
<td>69.06</td>
<td>0.039</td>
<td>0.9995</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>3 (I)</td>
<td>3 (H), 50, sensor inverted</td>
<td>212</td>
<td>418.2</td>
<td>0.31</td>
<td>69.00</td>
<td>0.187</td>
<td>0.9985</td>
<td>3.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR correction</td>
<td>29th May 2008 vintage</td>
<td>1 (I)</td>
<td>4 (H), 59</td>
<td>8</td>
<td>809</td>
<td>425.3</td>
<td>0.12</td>
<td>74.23</td>
<td>0.082</td>
</tr>
<tr>
<td></td>
<td>2 (I)</td>
<td>4 (C), 59</td>
<td>959</td>
<td>426.5</td>
<td>0.17</td>
<td>74.29</td>
<td>0.131</td>
<td>0.9970</td>
<td>2.80</td>
</tr>
<tr>
<td></td>
<td>3 (I)</td>
<td>4, 60</td>
<td>15</td>
<td>20.4</td>
<td>1.03</td>
<td>69.85</td>
<td>0.370</td>
<td>0.9996</td>
<td>2.93</td>
</tr>
<tr>
<td></td>
<td>4 (I)</td>
<td>4, 60</td>
<td>18</td>
<td>24.3</td>
<td>0.65</td>
<td>69.66</td>
<td>0.248</td>
<td>0.9998</td>
<td>1.97</td>
</tr>
<tr>
<td></td>
<td>5 (I)</td>
<td>4, 60</td>
<td>24</td>
<td>19.88</td>
<td>0.71</td>
<td>69.97</td>
<td>0.291</td>
<td>0.9998</td>
<td>1.97</td>
</tr>
<tr>
<td></td>
<td>6 (I)</td>
<td>4, 60</td>
<td>18</td>
<td>24.29</td>
<td>0.65</td>
<td>69.66</td>
<td>0.248</td>
<td>0.9998</td>
<td>1.97</td>
</tr>
<tr>
<td></td>
<td>7 (I)</td>
<td>5, 53.5</td>
<td>32</td>
<td>12.55</td>
<td>0.64</td>
<td>69.18</td>
<td>0.228</td>
<td>0.9997</td>
<td>2.94</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR correction</td>
<td>29th May 2008 vintage</td>
<td>1 (I)</td>
<td>4 (H), 57</td>
<td>8</td>
<td>824</td>
<td>419.7</td>
<td>0.08</td>
<td>77.72</td>
<td>0.055</td>
</tr>
<tr>
<td></td>
<td>2 (I)</td>
<td>4 (C), 57</td>
<td>423</td>
<td>421.8</td>
<td>0.37</td>
<td>79.11</td>
<td>0.215</td>
<td>0.9968</td>
<td>2.55</td>
</tr>
<tr>
<td></td>
<td>3 (I)</td>
<td>4, 60</td>
<td>15</td>
<td>-8.46</td>
<td>1.03</td>
<td>72.52</td>
<td>0.308</td>
<td>0.9997</td>
<td>2.32</td>
</tr>
<tr>
<td></td>
<td>4 (I)</td>
<td>4, 60</td>
<td>114</td>
<td>16.3</td>
<td>0.42</td>
<td>74.51</td>
<td>0.159</td>
<td>0.9995</td>
<td>2.92</td>
</tr>
<tr>
<td></td>
<td>5 (I)</td>
<td>4, 60</td>
<td>114</td>
<td>-24.1</td>
<td>0.19</td>
<td>74.43</td>
<td>0.067</td>
<td>0.9999</td>
<td>1.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR correction</td>
<td>Two-component CNR 2</td>
<td>1 (I)</td>
<td>3 (C), 48</td>
<td>9</td>
<td>959</td>
<td>-3.50</td>
<td>0.022</td>
<td>1.035</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>2 (I)</td>
<td>3 (H), 83</td>
<td>1044</td>
<td>-0.50</td>
<td>0.027</td>
<td>1.039</td>
<td>0.000</td>
<td>0.9999</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>3 (I)</td>
<td>3 (C), 83</td>
<td>949</td>
<td>0.52</td>
<td>0.013</td>
<td>1.032</td>
<td>0.000</td>
<td>0.9999</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>4 (I)</td>
<td>3 (H), 50</td>
<td>2180</td>
<td>1.97</td>
<td>0.035</td>
<td>1.006</td>
<td>0.001</td>
<td>0.9984</td>
<td>1.39</td>
</tr>
<tr>
<td></td>
<td>5 (I)</td>
<td>3 (H), 50</td>
<td>1037</td>
<td>0.53</td>
<td>0.087</td>
<td>1.014</td>
<td>0.001</td>
<td>0.9981</td>
<td>1.74</td>
</tr>
<tr>
<td></td>
<td>6 (I)</td>
<td>4 (H), 63.5</td>
<td>846</td>
<td>-4.46</td>
<td>0.034</td>
<td>1.000</td>
<td>0.000</td>
<td>0.9999</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>7 (I)</td>
<td>4 (C), 63.5</td>
<td>958</td>
<td>-2.70</td>
<td>0.027</td>
<td>0.992</td>
<td>0.000</td>
<td>0.9999</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>8 (I)</td>
<td>4 (H), 67.5</td>
<td>849</td>
<td>0.34</td>
<td>0.049</td>
<td>1.003</td>
<td>0.000</td>
<td>0.9998</td>
<td>1.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor inverted</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 (I)</td>
<td>4, sensor inverted</td>
<td>32</td>
<td>-3.43</td>
<td>0.434</td>
<td>65.27</td>
<td>0.14</td>
<td>0.9999</td>
<td>1.89</td>
<td></td>
</tr>
<tr>
<td>12 (S)</td>
<td>4, sensor inverted</td>
<td>32</td>
<td>-0.63</td>
<td>0.375</td>
<td>64.46</td>
<td>0.12</td>
<td>0.9999</td>
<td>1.66</td>
<td></td>
</tr>
</tbody>
</table>
Infrared calibration data were obtained for cooling (C) and heating (H) phase. In some cases, the data for both radiator heating and radiator cooling (indicated by H, C) were combined.

†† SE: standard error; \( r^2 \): coefficient of determination; RMSE: root mean square error

††† V: calibration performed using ventilation of upper and lower domes

†††† U: calibration with the ventilator in place but the fans off
Table 2 - Details and statistical results of the IRT laboratory calibrations.

<table>
<thead>
<tr>
<th>Model and number</th>
<th>Calibration number</th>
<th>Radiator temperatures (°C)</th>
<th>Maximum, minimum</th>
<th>Intercept (°C)</th>
<th>SE_intercept (°C)</th>
<th>Slope</th>
<th>SE_slope</th>
<th>$r^2$</th>
<th>RMSE (°C)</th>
<th>MSE_unsystematic</th>
<th>MSE_systematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Everest Model 4000ALCS</td>
<td>1</td>
<td>10.29, 81.7</td>
<td>233</td>
<td>-1.18</td>
<td>0.03</td>
<td>1.041</td>
<td>0.001</td>
<td>0.997</td>
<td>0.29</td>
<td>0.15</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>20.55, 84.10</td>
<td>144</td>
<td>-1.19</td>
<td>0.06</td>
<td>1.039</td>
<td>0.002</td>
<td>0.996</td>
<td>0.32</td>
<td>0.22</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>24.09, 83.10</td>
<td>189</td>
<td>-1.35</td>
<td>0.05</td>
<td>1.043</td>
<td>0.001</td>
<td>0.998</td>
<td>0.23</td>
<td>0.11</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2.89, 83.10</td>
<td>521</td>
<td>-0.44</td>
<td>0.03</td>
<td>1.022</td>
<td>0.001</td>
<td>0.995</td>
<td>0.31</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Everest Model 110 (hand-held)</td>
<td>2</td>
<td>1</td>
<td>26.78, 74.97</td>
<td>-1.50</td>
<td>0.05</td>
<td>1.020</td>
<td>0.001</td>
<td>0.999</td>
<td>0.14</td>
<td>0.01</td>
<td>0.99</td>
</tr>
<tr>
<td>(Fig. 7)</td>
<td>2</td>
<td>1</td>
<td>26.64, 69.58</td>
<td>-1.15</td>
<td>0.04</td>
<td>1.019</td>
<td>0.001</td>
<td>0.999</td>
<td>0.13</td>
<td>0.07</td>
<td>0.93</td>
</tr>
<tr>
<td>Everest Model 8</td>
<td>1</td>
<td>20.33, 81.7</td>
<td>10</td>
<td>2.89</td>
<td>0.11</td>
<td>0.880</td>
<td>0.002</td>
<td>1.000</td>
<td>0.17</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>(Fig. 9)</td>
<td>2</td>
<td>1</td>
<td>17.00, 75.13</td>
<td>-1.48</td>
<td>0.01</td>
<td>1.061</td>
<td>0.000</td>
<td>0.998</td>
<td>0.11</td>
<td>0.05</td>
<td>0.95</td>
</tr>
<tr>
<td>Apogee IRTP 8</td>
<td>1</td>
<td>1</td>
<td>1.04, 60.11</td>
<td>-0.07</td>
<td>0.05</td>
<td>1.036</td>
<td>0.002</td>
<td>0.998</td>
<td>0.78</td>
<td>0.28</td>
<td>0.72</td>
</tr>
<tr>
<td>2 (Fig. 9)</td>
<td>2</td>
<td>4.35, 60.13</td>
<td>959</td>
<td>-1.33</td>
<td>0.05</td>
<td>1.086</td>
<td>0.002</td>
<td>0.998</td>
<td>0.76</td>
<td>0.13</td>
<td>0.87</td>
</tr>
<tr>
<td>3</td>
<td>0.88, 60.00</td>
<td>952</td>
<td>-0.71</td>
<td>0.06</td>
<td>1.070</td>
<td>0.002</td>
<td>0.9975</td>
<td>0.93</td>
<td>0.19</td>
<td>0.19</td>
<td>0.81</td>
</tr>
<tr>
<td>1</td>
<td>1.04, 60.11</td>
<td>933</td>
<td>-0.76</td>
<td>0.06</td>
<td>1.070</td>
<td>0.002</td>
<td>0.9977</td>
<td>0.88</td>
<td>0.18</td>
<td>0.18</td>
<td>0.82</td>
</tr>
<tr>
<td>IRR-P 10</td>
<td>1 (Fig. 9)</td>
<td>4.57, 60.13</td>
<td>958</td>
<td>-0.99</td>
<td>0.06</td>
<td>1.063</td>
<td>0.002</td>
<td>0.9980</td>
<td>0.77</td>
<td>0.22</td>
<td>0.78</td>
</tr>
<tr>
<td>2</td>
<td>0.88, 60.00</td>
<td>952</td>
<td>-0.27</td>
<td>0.06</td>
<td>1.047</td>
<td>0.002</td>
<td>0.9972</td>
<td>0.96</td>
<td>0.31</td>
<td>0.31</td>
<td>0.69</td>
</tr>
<tr>
<td>3</td>
<td>1.04, 60.11</td>
<td>933</td>
<td>-0.55</td>
<td>0.06</td>
<td>1.053</td>
<td>0.002</td>
<td>0.9976</td>
<td>0.88</td>
<td>0.27</td>
<td>0.27</td>
<td>0.73</td>
</tr>
<tr>
<td>Omega 11</td>
<td>1 (Fig. 9)</td>
<td>4.35, 60.13</td>
<td>959</td>
<td>-0.98</td>
<td>0.06</td>
<td>1.077</td>
<td>0.002</td>
<td>0.9974</td>
<td>0.89</td>
<td>0.17</td>
<td>0.83</td>
</tr>
<tr>
<td>2</td>
<td>0.88, 60.00</td>
<td>952</td>
<td>-0.24</td>
<td>0.07</td>
<td>1.059</td>
<td>0.002</td>
<td>0.9965</td>
<td>1.10</td>
<td>0.25</td>
<td>0.25</td>
<td>0.75</td>
</tr>
<tr>
<td>3</td>
<td>1.04, 60.11</td>
<td>933</td>
<td>-0.45</td>
<td>0.07</td>
<td>1.063</td>
<td>0.002</td>
<td>0.9969</td>
<td>1.01</td>
<td>0.22</td>
<td>0.22</td>
<td>0.78</td>
</tr>
</tbody>
</table>
Table 3 - The statistical results of the hand-held IRT laboratory calibration with and without application of the statistical method used to reduce the residuals ($n = 970$ and $r^2 > 0.9997$ for all data sets).

<table>
<thead>
<tr>
<th>Statistical parameters</th>
<th>Without application of Eq. (13)</th>
<th>Application of Eq. (13)</th>
<th>Reapplication of Eq. (13)</th>
<th>Third application of Eq. (13)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>0.881</td>
<td>0.986</td>
<td>0.998</td>
<td>1.001</td>
</tr>
<tr>
<td>$SE_{slope}$</td>
<td>0.0005</td>
<td>0.0003</td>
<td>0.0003</td>
<td>0.0003</td>
</tr>
<tr>
<td>Intercept (°C)</td>
<td>2.78</td>
<td>0.33</td>
<td>0.04</td>
<td>-0.02</td>
</tr>
<tr>
<td>RMSE (°C)</td>
<td>0.11</td>
<td>0.07</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Mean bias error (°C)</td>
<td>-0.184</td>
<td>-0.093</td>
<td>-0.019</td>
<td>0.005</td>
</tr>
<tr>
<td>Mean absolute error (°C)</td>
<td>0.307</td>
<td>0.096</td>
<td>0.050</td>
<td>0.041</td>
</tr>
<tr>
<td>d–index (Willmott, 1981)</td>
<td>0.9958</td>
<td>0.9999</td>
<td>1.0000</td>
<td>1.0000</td>
</tr>
</tbody>
</table>