551.508.2

RADIOMETER CALIBRATION

B.G. Collins and H.A.H. Rabich

CSIRO Division of Atmospheric Physics (formerly Meteorological Physics)
Aspendale, Victoria

(Revised manuscript received September 1971)

ABSTRACT

The equipment currently in use at CSIRO Division of Atmospheric Physics, Aspendale, Victoria, for maintaining radiation standards and calibrating radiation instruments is described. Calibration methods and some tests for determining the quality of radiometers are given.

INTRODUCTION

The calibration equipment to be described has been developed from earlier versions over the past six years, and currently some 400 instruments are calibrated annually. The system will be considered under three headings, namely the standard used and its derivation, the working substandards and auxiliary equipment, and the calibration method. In addition to calibration certain tests which are made to determine radiometer quality are discussed.

RADIATION STANDARDS

Since 1966 the Division of Atmospheric Physics has been designated by the World Meteorological Organization as the Regional Radiation Centre for the South West Pacific (WMO Region V) as well as the National Radiation Centre for Australia. For calibration of instruments to measure thermal radiant flux, the Division is the sole Registered Laboratory of the National Association of Testing Authorities, Australia. A representation of the International Pyrheliometric Scale (1956) (IPS, 1956) must be maintained to meet WMO requirements, and a long wave radiation source is also necessary to comply with the conditions for NATA registration.

The IPS (1956) was derived from comparisons between the original Ångström Radiation Scale and the Smithsonian Scale 1913 (Annals of the IGY), and is maintained by a group of three Ångström compensation pyrheliometers belonging to the Swedish Meteorological and Hydrological Institute at Stockholm. Other standard instruments in the various WMO Regions are compared with one or more of these at inter-regional comparisons held at intervals of five years. Only Ångström compensation pyrheliometers and Abbott Silver Disc pyrheliometers are acceptable at these comparisons. Both instruments measure the intensity of the radiation flux in the sun's direct beam under cloudless skies.

At Aspendale the Regional and National Standard comprises two Ångström short tube instruments (No 502 and 578) made by the Swedish Meteorological and Hydrological Institute, and two Abbott Silver Discs made by the Smithsonian Institute, USA. Local comparisons are held annually and countries in Region V which have either of these types of instrument are welcome to participate in them.

The long wave radiation standard which has been described fully by Collins (1968) is an electrically heated cylindrical cavity of cast aluminium approximately 1 m in height and 30 cm in diameter. It can be maintained at a constant temperature of up to 140°C, and its large thermal capacity minimises short term fluctuations in radiation output. Both the temperature of the cavity and that of the radiometer surroundings can be determined with considerable accuracy to calculate the flux incident on the radiometer. Hitherto there has been some uncertainty as to the value of the Stefan-Boltzmann constant needed for the calculation, a mean difference of 1.6 % existing between the theoretical and experimental determinations. However, a recent experiment by Belvin and Brown (1971) has yielded a result in very close agreement with the theoretical value of 5.67×10^{-9} mW cm^{-2} °K^{-} which is used to calculate the flux from the long wave black body source.

WORKING SUBSTANDARDS AND ANCILLARY EQUIPMENT

For short wave calibration Linke-Feussner pyrheliometers are used as working substandards. These instruments use Moll thermopiles as radiation detectors. Two thermopiles are connected in opposition, one of which is exposed to the radiation and the other shielded. This minimizes the effects of changes in ambient conditions. The output is directly proportional to the radiation flux intensity of the solar beam and is in the range 0-15 mV. This voltage output can be measured directly with a potentiometer or digital voltmeter and hence readings can be taken much more quickly and conveniently than with the standard pyrheliometers.

The two Linke-Feussner pyrheliometers in current use for radiometer calibration are themselves checked once or twice a year against the primary group of standards.

Short wave calibration of radiation instruments in the normal manner using the sun as source is frequently hindered by the presence of cloud. Where a number of instruments is to be calibrated on a routine basis undue delay cannot be tolerated and an alternate source is necessary.

The use of an artificial light source for laboratory short wave calibration is recommended in the IGY Manual, but it is evident, although not stated, that for accurate results any such source should reproduce solar radiation as closely as possible in both intensity and spectral distribution. Except when calibrating narrow angle devices (pyrheliometers), a collimated beam is not essential. Tungsten filament lamps have frequently been employed either directly or in integrating spheres as, for example, by Macdowall (1954) and Hill *et al* (1966). Generally no correction of the spectral energy distributions of these lamps has been applied. Without any correction the method assumes uniform or, alternatively identical, spectral response of the radiometer being calibrated and the standard instrument. Drummond (1956) made an unspecified correction to account for the discrepancy. It is possible to correct the spectral energy distribution of the tungsten lamp by interposing suitable liquid filters to reduce the excess infrared radiation but these absorb much light energy, and a source of correspondingly greater power is needed to compensate for the loss.

Where a number of radiometers is to be calibrated at the one time, a further requirement is the uniform irradiation of an area sufficiently large to accommodate the instruments and the working standard radiometer. This requirement is difficult to satisfy. For instance the system designed by Liebmann (1968), although not strictly comparable with that described here, provided collimated radiation of intensity approaching that of extra-terrestrial sunlight uniform to within ± 5% over an area 1.5 m^2 employed nine 6.5 kW sources with a complex optical system.

The system in use at Aspendale irradiates a smaller area, sufficient for the calibration of five net pyrradiometers at an intensity of 60% of maximum direct solar radiation with a uniformity of better than ±1.0% and a spectral energy distribution approximating closely to that of sunlight. The system, which uses a high pressure Xenon arc, is described in detail by Collins (1970).

CALIBRATION METHODS AND ADDITIONAL TESTS

The majority of the instruments calibrated at Aspendale are new net pyrradiometers manufactured locally under licence from a CSIRO patent. The original design is described by Funk (1959). It is necessary not only that they should be calibrated but that their performance should be assessed so that each instrument for which a calibration certificate is provided is known to be satisfactory in every respect for the purpose for which it has been built. To this end, besides the calibration, a number of tests have been devised which help to evaluate the quality of a radiometer.

Short wave calibration To calibrate the response of a radiometer to short wave radiation (wavelength 0.3 to 3.0 μm) the occulting technique is used, with either the sun or Xenon arc lamp as radiation source. The output voltage of the instrument, V, is measured when it is alternately exposed to, and shielded from the incident beam. The sensitivity is then the difference between these two readings divided by the intensity of the flux in the beam as measured by a working substandard pyrheliometer or pyranometer.

In the case of a radiation balance meter the sensitivities of the front and back surfaces are determined separately. It is more important that they should be equal than that they should be large or have any definite value.

The "unbalance value" A may be defined by

$$A = \frac{2(S_f - S_b)}{S_f + S_b}$$

where S_f is the front sensitivity

and S_b is the back sensitivity.

Long wave calibration Long wave calibration is carried out using the black body radiation source already mentioned. The instrument is located inside a calibrating box placed under the aperture of the source, so that it is exposed to radiation when the shutter of the box is open. The temperature of the calibrating box is in the range 20°C to 30°C and is kept constant within ±0.1°C during the calibration by water circulation. The instrument's output is then measured with the radiometer successively exposed to and shielded from the long wave radiation. The radiation intensity can be calculated from the measured temperatures of the source and calibrating box. The net flux is R_L where

$$R_L = \sigma \psi (T_1^4 - T_2^4) . \qquad \ldots 2$$

The effective aperture ψ, which is calculated by the method of Bossy and Pastiels (1948), represents the ratio between the radiation the sensor would receive from a solid angle 2π, and the radiation actually received through the aperture, σ is the Stefan-Boltzmann constant and T_1 and T_2 respectively the absolute temperatures of source and calibration box. The emissivity of the source is here taken to be 100%, and in fact is known to be better than 99.9%. Then if E is the long wave sensitivity of the pyrradiometer and e_1 and e_2 are the output e.m.f.'s in the exposed and shielded positions respectively,

$$E = \frac{e_1 - e_2}{R_L} \qquad \ldots 3$$

e_2 is normally zero, or very close to it.

The sensitivity of a net pyrradiometer is determined separately for each side and the two values do not differ by more than 3% in an acceptable instrument.

The calculations are done by computer. The program takes into account the known accuracies of the input values and in addition checks the consistency of three measurement runs. Inconsistent values are identified.

Time response The output of a radiometer subject to a step function change in incident radiation reaches its final value asymptotically. The time response curve is obtained experimentally by displaying the electrical output on an autographic recorder whilst an occulting disc is used to interrupt the incident beam. The time to reach a steady value (*ie* the time after which the output varies only within the limits of the precision of the measurement) differs from one instrument to another, and also the shape of the curve varies. Funk (1960) described overshooting which is not uncommon, and Q the degree of overshoot may be defined by

$$Q = (M - F)/F \qquad \ldots 4$$

where M and F are the maximum and final values respectively.

The shape of the curves generated by irradiation of the top and bottom sensor plates of net pyrradiometers should be similar. The importance of this may be illustrated by reference to a particular instrument No K83. The top and bottom sensor plates are irradiated successively to give the time response of each. In neither case did the reading reach a constant value after ten minutes which in itself indicates a defect in the instrument. The response curve for the front showed an overshoot of about 6% with a maximum after 1.7 min, but the back overshot by only a tenth of this with a maximum after 4.5 min (Fig 1).

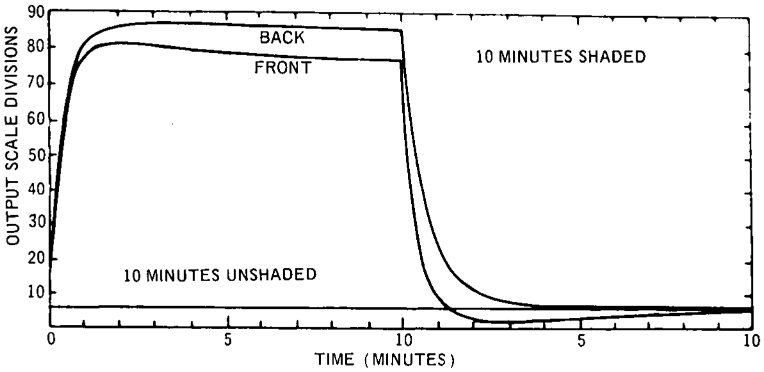

Fig 1 Time response of Net Pyrradiometer K 83.

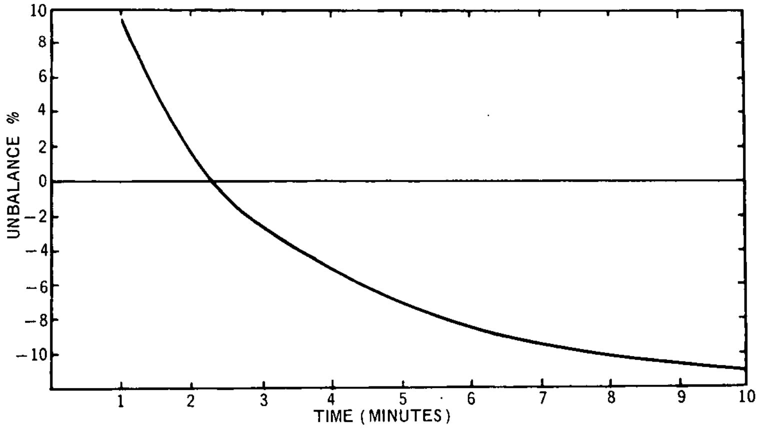

Fig 2 Calculated unbalance curve of Net Pyrradiometer K 83

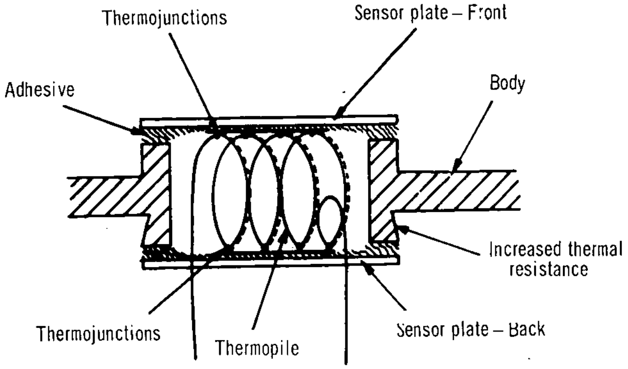

Fig 3 Net Pyrradiometer K 83. Cross section (schematic).

From eq 1 the unbalance A is given by

$$A = \frac{2(V_{u,f} - V_{s,f} - V_{u,b} + V_{s,b})}{V_{u,f} - V_{s,f} + V_{u,b} - V_{s,b}} \qquad \ldots 5$$

where the suffices f, b have the same meanings as before, and u and s refer to unshaded and shaded readings respectively.

It is now evident that the value of A is a function of the time elapsed between the step function radiation change and the readings of the radiometer output. Fig 2 shows the variation of A with time elapsed for instrument K83. It can be seen that any value between +10% and -10% can be obtained by taking the readings at appropriate times. Values taken 2.2 min after the step function changes would suggest that the instrument is balanced (A = 0).

The reason for the difference in response of the two sensor plates must be sought in the physical construction of the radiometer, of which Fig 3 is a schematic cross section. The sensor plates are attached to the body of the instrument by an adhesive and the proportion of the plates in direct contact with the body is about 30%.

Normally the whole arrangement is symmetrical about the horizontal plane through the axis of the body. In this particular case an attempt had been made to compensate for an initial unbalance by increasing the thermal resistance between the bottom sensor plate and the body by about 40%. This is an acceptable technique for adjusting only small degrees of unbalance. It appears that the initial unbalance of the instrument was caused by inequalities of heat paths other than between the sensor plates and the body, and it was impossible to adjust the unbalance.

Since the time response curve gives a good insight into the thermal quality of a radiometer it is routinely examined before calibration of an instrument.

Linearity, spectral response According to Collins and Kyle (1966) the short wave sensitivity of a net pyrradiometer is a few percent higher than the long wave sensitivity. If this is so, they can be equalized by painting narrow white strips on the black surface of the sensor plate, using a paint which has a high short wave reflectivity but is a good absorber on the long wave. Occasionally, however, the long wave sensitivity is found to exceed the short wave. This may be due to any of a number of causes, one of which is non-linearity of response with irradiation intensity, since the long wave sensitivity is measured at an irradiation intensity of only 10 or 12% of that at which the short wave sensitivity is determined. Using the laboratory artificial light source the linearity of a radiometer can be measured by interposing in the beam rotating sector discs of known obscuration ratio, and observing its sensitivity with irradiation reduced in this way to a level similar to that at which the long wave sensitivity is determined. Any instrument which is found to be markedly non-linear (more than 3%) is not regarded as suitable for general use.

The calibration methods so far described are of application to net pyrradiometers with polythene windshields or other allwavelength instruments without windshields, assuming that the black surfaces of their sensor plates have uniform spectral sensitivity. This is because the polythene used for the windshields has an almost uniform spectral transmissivity, apart from some relatively narrow absorption bands. Pyranometers, however, have glass shields of which the spectral transmissivity is usually unknown, and is liable to vary from one instrument to the next. It is found that this variation is sufficient to cause discrepancies between results obtained with solar radiation and those using the laboratory light source, since the Xenon arc does not have precisely the same spectral energy distribution as sunlight.

Some comparative tests carried out with five different pairs of glass hemispheres of unspecified spectral transmissivities showed differences of the order of 1% in pyranometer sensitivity between solar and Xenon arc calibrations. Accordingly, for the most accurate work solar radiation only is used for calibrating pyranometers.

Certain other types of radiometers are also not suitable for calibration under the laboratory radiation source, because their physical dimensions are greater than those of the uniform radiation area. For example, strip radiometers up to three metres in length have been submitted, but these can only be calibrated in sunlight.

CONCLUDING REMARKS

The equipment described has been used to calibrate the 400 or so instruments currently being received each year. However, as demands on the calibration service may continue to increase substantially, reduction of the manual labour content of the process has been planned, and some development work commenced on a system whereby all measurements in both the long and short wave calibrations will be made by a semi-automatic method using a digital voltmeter coupled directly to a paper tape punch. In the computer the readings would be examined for inconsistencies and then the sensitivity, linearity and time response calculated for each radiometer. Such an arrangement would enlarge the capacity of the system.

REFERENCES

Annals of the IGY, Vol. 5, Pt. VI. *Radiation instruments and measurements*. Pergamon Press, London.

Blevin, W.R. and Brown W.J., 1971. A precise measurement of the Stefan-Boltzmann constant. *Metrologia*, *7*, 15-29.

Bossy, L. and Pastiels, R. 1948. Etude des propriétés fondamentales des actinomètres. *Brussels Inst. Roy. Met. de Belgique Memoires*, *29*, 116 pp.

Collins, B.G. and Kyle, T.G. 1966. The spectral variation of the sensitivity of a polythene shielded net radiometer. *Pure and Appl. Geophys.*, *63*, 231-236.

Collins, B.G. 1968. A long wave radiation source for net pyrradiometer calibration. *J. Sci. Inst.*, *Ser 2*, *1*, 62 - 64.

Collins, B.G. 1970. A laboratory system for short wave calibration of net pyrradiometers. *Pure and Appl. Geophys.*, *80*, 371-377.

Drummond, A.J. 1956. On the measurement of sky radiation. *Archiv für Met. Geoph. u Bioklim.*, *Serie B*, *Band 7*, 413.

Funk, J.P. 1959. Improved polythene shielded net radiometer. *J. Sci. Inst.*, *36*, 267-270.

Funk, J.P. 1960. Transient response of net radiometers. *Archiv für Met. Geoph. u. Bioklim.*, *Serie B*, *Band 10*, 228.

Hill, A. N., Latimer, J. R., Drummond, A. J. and Greer, H. W., 1966. Standardized procedures in the North American continent for calibration of solar radiation pyranometers. *Solar Energy*, *10*, No 4, 1-11.

Liebmann, R. 1968. Solar simulator for a 3 m space environment chamber. *Appl. Opt.*, *7*, 315.

Macdowall, J. 1954. A paper of the Meteorological Research Committee (London), *MRP 858*. (A copy is available in the Library of the Meteorological Office).