An Improved Calibration Method for a Chopped Pyrgeometer

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ABSTRACT

An improved calibration method for a chopped pyrgeometer is presented. The chopped pyrgeometer is a system of two radiometers (target radiometer and reference radiometer) modulated by a common chopper. One radiometer measures the temperature of the chopper by modulating an internal blackbody source.

A previously used calibration method needs two steps. The first step is the measurement of the ratio of the responsivities for the two radiometers; the second step is the calibration of the target radiometer against a blackbody source. The first step is based on the assumption of a thermal steady state during the measurement of (typically) a few minutes. Further investigations have shown that this assumption is too idealistic. The errors introduced to airborne measurements by neglecting thermal unstabilities during ratio measurement are calculated using a numerical model of the instrument.

To overcome these problems a new calibration method is presented, which also performs the calibration in two steps. The first step is the calibration of the target radiometer using an isothermal instrument; that is, the temperature of the chopper is known and, most importantly, the whole measurement takes only a few seconds, which provides sufficient thermal stability. In a second step, the calibration of the reference radiometer is done with the help of the previously known responsivity of the target radiometer. The experimental data of a calibration due to the new scheme are discussed.

1. Introduction

In the article of Lorenz et al. (1996) a chopped pyrgeometer has been presented, which consists of two radiometers using the same chopper. One radiometer, called a target radiometer, measures the radiation coming from the atmosphere by comparing it with the radiation of the black chopper. The other radiometer, called a reference radiometer, measures the radiation of the chopper by comparing it to an internal reference blackbody of known temperature.

The principle of the instrument is described by a pair of linear equations for the two radiometer outputs U_1 and U_2 as given in Lorenz et al. (1996):

$$U_1 = R_1 c_1(T_1)\left(\frac{E_{1,\mathrm{TAR}}}{\eta_{1,\mathrm{TAR}}} - \frac{\Omega_1^p B_{\mathrm{CHO}}}{\eta_{1,B,\mathrm{CHO}}}\right) \quad \text{and} \tag{1}$$

$$U_2 = R_1 c_2(T_2)\left(\frac{\Omega_2^p B_{\mathrm{REF}}}{\eta_{2,B,\mathrm{REF}}} - \frac{\Omega_2^p B_{\mathrm{CHO}}}{\eta_{2,B,\mathrm{CHO}}}\right), \tag{2}$$

where U_1, U_2 are the output voltages of target radiometer 1 and reference radiometer 2; B_{REF}, B_{CHO} are the blackbody radiances of reference source/chopper in W m^{-2} sr^{-1}; $E_{1,\mathrm{TAR}}$ is the measured irradiance of target in W m^{-2}; R_1, R_2 are the instrumental constants of target radiometer 1 and reference radiometer 2, for example in V (W m^{-2})$^{-1}$; Ω_1^p is the solid angle of target radiometer ($\Omega_1^p = \pi$); Ω_2^p is the solid angle of reference radiometer; $c_1(T_1)$, $c_2(T_2)$ are the temperature correction factors due to temperature-dependent pyroelectric responsivities (T_1, T_2 are the corresponding detector temperatures); $\eta_{i,B,\mathrm{REF}}$, $\eta_{i,B,\mathrm{CHO}}$ are the spectral correction factors for the target radiometer ($i = 1$) and the reference radiometer ($i = 2$) at temperature T_{REF} and T_{CHO}; and index B refers to blackbody radiation; and $\eta_{1,\mathrm{TAR}}$ is the spectral correction factor for target irradiance.

Due to the modulation scheme, the output of the radiometers is proportional to the difference of two independent radiation terms. Each radiation term contains a spectral correction factor that reflects a nonideal spectral characteristic of the receiver (filter and detector). One of the radiation terms, the chopper radiation, is common to both equations.

The calibration of the instrument has to establish two responsivities, which are not straightforward, since the

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temperature of the chopper is not generally known when an uncalibrated instrument is used. Thus, procedures are needed to establish a special thermal situation of the instrument, which allows one to find out the desired responsivities.

2. The calibration as presented by Lorenz et al. (1996)

The calibration presented in the article of Lorenz et al. (1996) is performed in two steps: measurement of the ratio $q = (R_1\pi)/(R_2\Omega_2^g)$, called a q measurement, and the calibration of the target radiometer using a blackbody at different temperatures.

The q measurement is based on Eq. (10b) of Lorenz et al. (1996):

$$\frac{c_2}{c_1}U_1 = \frac{c_2}{c_1}A + qlU_2, \qquad (3)$$

where c_1, c_2 are the temperature correction factors, as explained in Eqs. (1) and (2), A is a constant, and $l = (\eta_{2,B,\mathrm{CHO}})/(\eta_{1,B,\mathrm{CHO}})$.

The q measurement is performed by measuring U_1 and U_2 with the radiometer head on a blackbody source at a constant temperature and the chopper drifting in temperature after having been cooled, as described in the paper.

As shown by Lorenz et al. (1996), Eq. (3) is valid if the following quantities are constant during the q measurement: the target irradiance $E_{1,\mathrm{TAR}}$; the temperatures T_1, T_2 of the two detectors; the temperature T_{REF} of the internal reference blackbody, and the spectral correction factors η. The validity of these assumptions will be discussed below.

As an alternative to the derivation given in Lorenz et al. (1996), Eq. (3) can be obtained from Eqs. (1) and (2) by substituting R_2 by q and eliminating B_{CHO} without the restriction of assuming any physical parameter to be constant during the measurement; this approach more clearly shows the influence of all physical quantities and leads to

$$\frac{c_2}{c_1}U_1 = \frac{c_2R_1}{\eta_{1,\mathrm{TAR}}}E_{1,\mathrm{TAR}} - \frac{c_2\pi lR_1}{\eta_{2,B,\mathrm{REF}}}B_{\mathrm{REF}} + qlU_2. \qquad (4)$$

The first and second terms on the right-hand side of Eq. (4) represent the factor (c_1/c_2) A of Eq. (3), which has been assumed to be constant as a necessary condition to derive q from a linear regression.

a. *Discussion of required constancy of physical parameters*

In a first step we now discuss the constancy of physical parameters within the first two terms of the right-hand side of Eq. (4) during a q measurement. In a second step, an error analysis is presented on the basis of a numerical model.

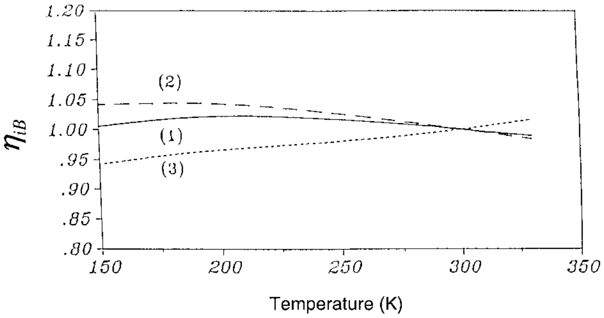

FIG. 1. Spectral correction factors for three types of domes, according to Fig. 5 of Lorenz et al. (1996). 1) Silicone dome, 2) Reading-type dome, and 3) 01B K7–type dome for a blackbody source. The index i of the spectral correction factor η (ordinate) refers to either target 1 or the reference 2 detector.

The spectral correction factors η for the two radiometers (indexes 1 and 2) and valid for blackbody radiation are shown in Fig. 1. Assuming a temperature change of 10 K at the chopper during the q measurement $l = (\eta_{2,B,\mathrm{CHO}})/(\eta_{1,B,\mathrm{CHO}})$ will change by about 1% since the correction factor of the target radiometer (index 1) increases by 0.5% (curve 3 of Fig. 1), whereas the correction factor of the reference radiometer (index 2) decreases by 0.5% (curve 1 of Fig. 1), going from 300 to 290 K. If the target radiometer is equipped with another type of dome (curve 2, Fig. 1) the change in l becomes negligible since both correction factors change approximately in the same way. This means that depending on the optical materials used in the two radiometers one may have to consider the changes in l. Since the temperature of the chopper is not measured and not accessible from the formalism (B_{CHO} has been eliminated), assumptions have to be made for the time profile of the chopper temperature to perform a first-order correction.

The changes in $\eta_{1,\mathrm{TAR}}$ and $\eta_{2,B,\mathrm{REF}}$ are negligible (<0.05%) since the temperature drifts of the corresponding sources are much smaller ($\Delta T < 1$ K) as compared to the chopper.

The changes in the two temperature correction factors c_1 and c_2 are negligible (<0.05%) since the temperature drift of the detectors is small (<0.2 K) and the correction factors are in the order of 0.2% K^{-1}.

The change of the target radiance $E_{1,\mathrm{TAR}}$ during the measurement of q can be held negligible (<0.1%) by setting the radiometer head on a blackbody source at constant temperature.

The temperature of the reference blackbody T_{REF}, however, will show a drift since there is some thermal interaction between the cold/hot chopper and the reference blackbody. Measurements show that this temperature drifts up to 1 K during a q measurement, which corresponds to a change of B_{REF} of 1.3% at 300 K. Therefore, the assumption of thermal steady state during q measurement in Lorenz et al. (1996) is too idealistic and may result in considerable errors of the calibration parameters q and R_1.

In principle a temperature stabilization of the reference blackbody could solve this problem. The additional system increases the costs and is not useful for the purpose of atmospheric flux measurement. These problems can be avoided using the new calibration scheme.

b. Model calculations

To demonstrate the errors mentioned above, a simplified model of the calibration procedure (q measurement and calibration of R_1) has been programmed including the errors introduced to a typical airborne measurement of the downward flux.

The simplifications in the model are as follows. 1) All spectral correction factors are constant ($=1$), and 2) the temperature correction factors c_1 and c_2 are constant ($=1$).

As mentioned in section 2a, only the spectral correction factors forming $l = (\eta_{2,B,\mathrm{CHO}})/(\eta_{1,B,\mathrm{CHO}})$ can show the changes that have to be considered. On the basis of reasonable assumptions (time profile of chopper temperature), these changes can be established with sufficient accuracy if needed, so they are not considered in the model. The changes to the temperature correction factors c_1 and c_2 are negligible, as pointed out above.

Thus the model reflects errors introduced by neglecting temperature drifts of the reference blackbody during q measurement.

The logical structure of the model calculation is demonstrated in the following steps:

1) Model the q measurement
   - Assume a model value of q and R_1;
   - define a series of temperature values for T_{REF} and T_{CHO} describing the temperature drifts of the reference source and the chopper as observed during a typical q measurement;
   - calculate the corresponding model radiometer outputs U_1 and U_2 using the model values of q and R_1 and Eq. (1) above and Eq. (5c) of Lorenz et al. (1996),

$$U_2 = c_2\pi\frac{R_1}{q}\left(\frac{B_{\mathrm{REF}}}{\eta_{2,B,\mathrm{REF}}} - \frac{B_{\mathrm{CHO}}}{\eta_{2,B,\mathrm{CHO}}}\right); \quad \text{and} \qquad (5)$$

   - determine the measured value of q, q_m from the linear regression of Eq. (3).

2) Model the R_1 calibration according to Eq. (11) of Lorenz et al. (1996):

$$\frac{U_1}{c_1} - l\frac{U_2}{c_2}q = R_1\left(\frac{E_{1,\mathrm{TAR}}}{\eta_{1,\mathrm{TAR}}} - l\frac{\pi B_{\mathrm{REF}}}{\eta_{2,B,\mathrm{REF}}}\right) \qquad (6)$$

   - Perform the model calibration of R_1 assuming three calibration irradiances $E_{1,\mathrm{TAR}}$, as used in a typical calibration, and take the corresponding temperatures T_{CHO} and T_{REF}, as can be found from experimental data;

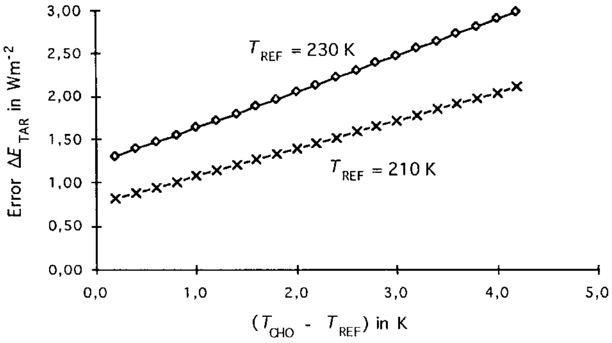

FIG. 2. Absolute error of an airborne downward flux measurement of 30 W m^{-2} as a function of the difference between temperatures of the reference source and the chopper; model results for two temperatures (210 and 230 K) of the reference source are shown.

   - calculate the corresponding model radiometer outputs U_1 and U_2 using Eqs. (1) and (5) and the model values R_1 and q; and
   - determine the measured value of R_1, R_{1m} from Eq. (6) using q_m.

3) Model an atmospheric measurement, Eq. (6) of Lorenz et al. (1996):

$$E_{1,\mathrm{TAR}} = \eta_{1,\mathrm{TAR}}\left(\frac{U_1}{c_1R_1} - \frac{lqU_2}{c_2R_1} + l\frac{\pi B_{\mathrm{REF}}}{\eta_{2,B,\mathrm{REF}}}\right) \qquad (7)$$

   - Assume a model target irradiance $E_{1,\mathrm{TAR}}$ that is typical for airborne measurements;
   - assume a value for T_{REF} and a temperature difference between T_{REF} and T_{CHO} as a model variable—studying various flight situations, one can find plausible sets for these quantities;
   - calculate the true radiometer outputs U_1 and U_2 for the measurement in the atmosphere using Eqs. (1) and (5) and the model values R_1 and q;
   - determine the measured value of $E_{1,\mathrm{TAR}}$, $E_{1,\mathrm{TAR},m}$ with Eq. (7) using R_{1m} and q_m; and
   - note the difference $E_{1,\mathrm{TAR},m} - E_{1,\mathrm{TAR}}$ leads to the absolute error shown in the graphs below.

Figures 2 and 3 show the absolute error for atmospheric downward fluxes of 30 and 90 W m^{-2} caused by neglecting the changes of T_{REF} during q measurement as part of the calibration. The two curves in each graph correspond to the two temperatures of the reference source, which have been chosen as being representative for measurements of radiation fluxes at upper-tropospheric levels. The simulations show for this case a positive error of the atmospheric measurement, on the order of 1 to 4 W m^{-2}, depending on the thermal situation of the instrument. Since the thermal situation of the instrument can rapidly change during the various flight conditions, this error will produce changes on the calculated fluxes that look like an instability of the instrument. Thus, one of the most important advantages of the chopped pyrgeometer, its radiometric stability in-

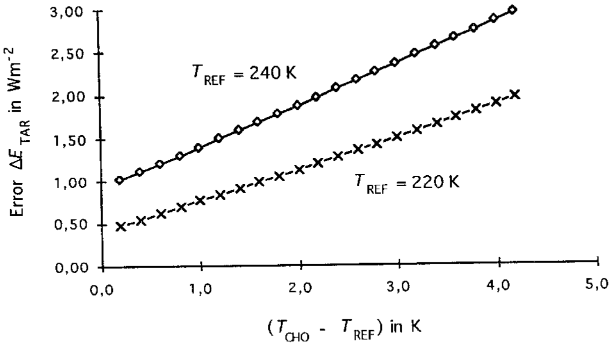

FIG. 3. Absolute error of an airborne downward flux measurement of 90 W m^{-2} as a function of the difference between temperatures of the reference source and the chopper; model results for two temperatures (220 and 240 K) of the reference source are shown.

herent to the modulation process, is lost to a certain extent.

It must be clearly pointed out that the errors presented here are introduced only by assuming a steady-state condition during q measurement, thus neglecting the drift of the reference temperature that occurs during actual measurement.

In the paper of Lorenz et al. (1996) some results have been presented of the pre-EUCREX Intercomparison Campaign of 1992 where five pyrgeometers (two Eppley pyrgeometers, two Foot pyrgeometers, one chopped pyrgeometer) have been flown simultaneously on three airplanes. Results of a boxlike pattern flown at an altitude of 6.1 km MSL have been analyzed. The results of all five instruments for measurements along the legs and the changes between the legs of the flight box show that the chopped pyrgeometer provides a radiometric stability that is at least as good as that of the Foot pyrgeometers. Another significant finding was the fact that the chopped pyrgeometer yields the smallest flux values of all five instruments throughout the four legs of the box. The difference was about 10 W m^{-2} as compared to the average value (~90 W m^{-2}) of the other four instruments. The model calculation presented above would predict a decrease of the measured flux values in the order of 1 W m^{-2} [Fig. 3: ($T_{\mathrm{CHO}} - T_{\mathrm{REF}} \sim 0$), $T_{\mathrm{REF}} \sim 230$ K] for the chopped pyrgeometer if the new calibration method would have been applied, thus creating a somewhat greater difference to the findings of the other instruments. Since calibration sensitive components (detector, dome, etc.) of the chopped pyrgeometer used for the pre-EUCREX measurements have been changed in the meantime, it is not possible to apply the new calibration to the original instrument.

3. The new calibration method

To demonstrate the new calibration method, Eqs. (1) and (2) are rewritten as follows:

$$\frac{U_1}{c_1(T_1)} = R_1\left(\frac{E_{1,\mathrm{TAR}}}{\eta_{1,\mathrm{TAR}}} - \frac{\pi B_{\mathrm{CHO}}}{\eta_{1,B,\mathrm{CHO}}}\right) = R_1\Delta B_T \quad \text{and} \tag{8}$$

$$\frac{U_2}{c_2(T_2)} = R_2\Omega_2^p\left(\frac{B_{\mathrm{REF}}}{\eta_{2,B,\mathrm{REF}}} - \frac{B_{\mathrm{CHO}}}{\eta_{2,B,\mathrm{CHO}}}\right) = \tilde{R}_2\Delta B_R. \tag{9}$$

Since Ω_2^p is a constant system parameter we rewrite R_2

$$\tilde{R}_2 = R_2\Omega_2^p.$$

The basic idea of the new calibration is to calibrate the target radiometer in the first step by performing the measurement of each calibration point (blackbody temperature) within a short time span (typically a few seconds) in order to maintain the desired isothermal conditions of the instrument during that process. If the responsivity of the target radiometer is known, the calibration of the reference radiometer is straightforward, as shown below.

a. Calibration of the target radiometer

As is obvious from Eq. (8) the target radiometer can be calibrated with a blackbody source if the temperature of the chopper is known during calibration. This can be achieved if the radiometer head is in an isothermal condition during the measurement of a calibration point; then the chopper temperature equals the reference temperature, which is measured by PT100 (accuracy: ±0.15 K, $-50°\mathrm{C} < T < 50°\mathrm{C}$). In this case ΔB_T can be calculated since B_{CHO} and $E_{1,\mathrm{TAR}}$ are known blackbody radiations and $\eta_{1,\mathrm{TAR}}$ and $\eta_{1,B,\mathrm{CHO}}$ are spectral correction factors derived for the known temperatures of the radiators.

The procedure to achieve an isothermal radiometer head during target radiometer calibration is as following. In a thermally quiet laboratory the radiometer head (switched off) is put under a protection box for some hours to reach isothermal conditions. After that, the box is removed and the head is switched on and positioned on a blackbody source. These activities can be performed in less than 10 s; thus isothermal conditions are maintained during that time with sufficient accuracy. Immediately after correct position on the blackbody, a signal of the target radiometer can be registered (time constant of the radiometer signals is on the order of 0.1 s) for a few seconds. During that time the signal of the reference radiometer begins to drift away from zero since the temperature of the chopper slowly drifts toward the temperature of the calibration blackbody source, thus creating a radiometric difference ΔB_R [Eq. (9)] between chopper and reference source. Therefore, the signal of the reference radiometer can be used to indicate proper isothermal conditions during the measurement and to establish an error value; this signal can be maintained at less than 10 mV throughout the measurement, corresponding to a ΔT of 0.1 K (300 K blackbody). The whole procedure is repeated for each calibration point.

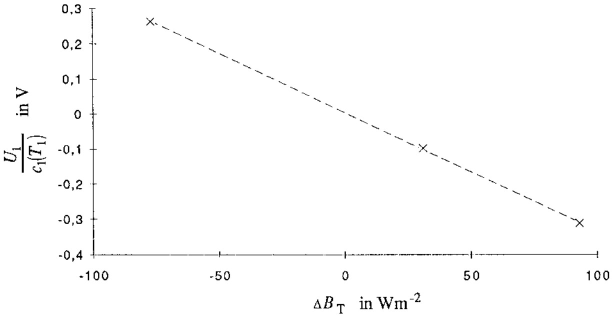

FIG. 4. Example of a calibration of the target radiometer; the hatched line is the linear regression of the measured data points (crosses). Each of the three calibration temperatures contains between 8 and 11 samples.

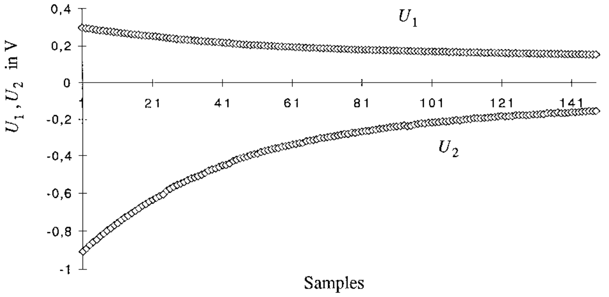

FIG. 6. Output signals of target radiometer U_1 and reference radiometer U_2 during calibration of the reference radiometer.

The graph (Fig. 4) of a target radiometer calibration due to Eq. (8) shows three calibration points that correspond to three temperatures of the calibration blackbody source (280.4, 300.3, and 310.4 K) and the corresponding linear regression. Each of the three calibration points contains n ($n \approx 10$) samples (1-s sampling interval) registered during the first n seconds after positioning the radiometer head on the calibration blackbody source; the points are too close together to be resolved in the plot. The linear regression line shows a zero offset of about 4 mV, corresponding to a ΔT of 0.2 K (300-K blackbody), which is consistent with the accuracy of a PT100. This offset can be explained as follows. The radiometric measurement compares the radiation of the reference source with that of the calibration source (both related to the chopper radiation). On the other hand, the calculation of the radiometric terms in Eqs. (8) and (9) is based on the measurement of two independent temperatures (calibration blackbody and reference source). For the purpose of demonstration we assume that the calibration blackbody, the chopper, and the reference source are at the same temperature, that is, isothermal conditions are valid. In this case both radiometer signals will be zero. The temperature measurements at the two sources, however, will show some difference due to systematic errors of the PT100 sensors. Consequently, the radiometric evaluation will predict a radiometric difference ΔB that is somewhat different from zero. Thus the observed offset is due to a more or less unavoidable difference between the measured temperature and the real radiometric temperature of the two sources. If we assume a constant error in the absolute temperature measurement over the range of interest, the slope of the linear regression provides the correct response; the offset is constant and can be omitted in subsequent data evaluation.

Figure 5 shows the deviation of the individual samples of the three calibration points from the regression line, where 1 mV corresponds to a ΔT of 0.05 K (300-K blackbody). Since the sign changes between the sample groups of highest and lowest calibration temperature to the group of the intermediate temperature, the calibration shows a small nonlinearity on the order of 0.1 K ($\approx$0.15% of the 300-K blackbody); this nonlinearity may be due to small errors in spectral correction factors or errors caused by deviations from a flat spectral emissivity over a wide spectral range (1–100 μm) of the black radiating surfaces (reference source and chopper).

b. Calibration of the reference radiometer

The calibration of the reference radiometer is now straightforward because R_1 is already known. One brings the radiometer head to a nonisothermal condition, for example, by warming the chopper with hot air, and

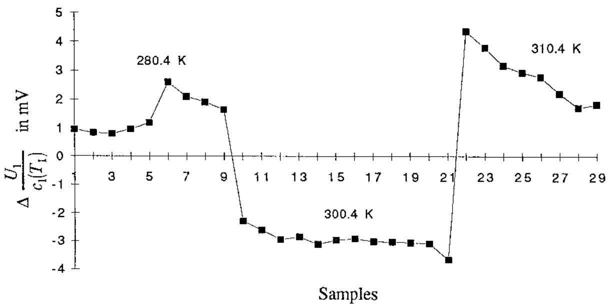

FIG. 5. Offset of the individual samples from the linear regression line shown in Fig. 4. The calibration temperature is shown near the corresponding set of samples.

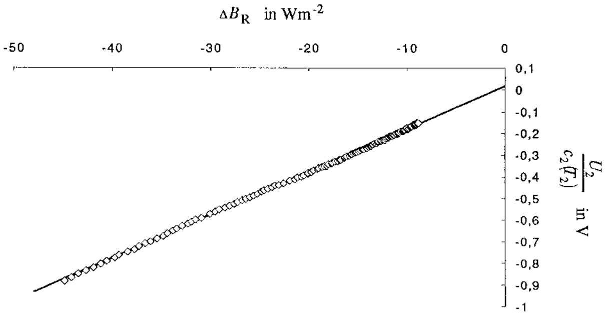

FIG. 7. Example of calibration of the reference radiometer; the solid line is the linear regression on the measured data points. Since the chopper temperature drifts, a continuous series of calibration points exists along the linear regression.

puts the radiometer head on a calibration blackbody, which is conveniently at ambient temperature. The chopper temperature will drift toward ambient and create varying output signals for both radiometers. The evaluation of the measurement is as follows. Using Eq. (8) one can calculate the chopper radiance B_{CHO} for each measurement sample of the target radiometer output U_1 because R_1 and all other quantities are known. The chopper radiation now can be used in Eq. (9) to calculate ΔB_R and perform a linear regression to find $\tilde{R}_2$.

The procedure to calibrate the reference radiometer is somewhat similar to the q measurement discussed above. The important difference, however, is that no assumptions are necessary of a thermal steady state of various radiometer components since all dynamic quantities, including the temperature of the reference source, are known and can be correctly used in the formalism.

Figures 6 and 7 show an example of the reference radiometer calibration. The blackbody calibrator is at ambient temperature in this case. Before starting the measurement, the chopper is warmed to achieve nonzero outputs in both radiometers. During the measurement the signals of the two radiometers are drifting toward zero (Fig. 6) since the chopper slowly drifts to ambient temperature. The plot for calibration (Fig. 7) according to Eq. (9) shows the data points and the linear regression. The measurement starts with a temperature difference between chopper and reference source of about 7 K, which corresponds to the data points at high values of ΔB_R. The data points taken for the calibration cover 140 samples (1-s sampling interval); after that period the further change of the temperature difference (now $\approx$ 1.3 K) gets slower, thus additional information gain is low. The parameters of the linear regression show a nonzero y intercept of the regression line of 17 mV, which corresponds to a ΔT of 0.15 K of a 300-K blackbody. The nature of this offset is the same as discussed above for the target radiometer.

4. Conclusions

The calibration of the chopped pyrgeometer as proposed by Lorenz et al. (1996) has been analyzed. This calibration scheme (q measurement) requires the validity of various assumptions on the thermal condition of the instrument during the calibration procedure. It could be shown that one of the assumptions—that is, the stability of the reference temperature during the q measurement—is too optimistic and leads to systematic errors in the calibration constants and consequently to systematic errors of measured atmospheric fluxes.

The new calibration method is based on the assumption of isothermal conditions over a short period of time (a few seconds) to perform the calibration of the target radiometer. This condition can be established quite simply and can easily be verified using the signal of the reference radiometer. The formalism of the new calibration method is more transparent since it does not need further assumptions of the instruments thermal behavior. The procedures of the calibration are somewhat easier (10-s registration time for one calibration point) and offer additional information (signal of reference radiometer) about the required isothermal conditions during target radiometer calibration. The main effort, however, is to avoid a systematic error, which is part of the previous calibration scheme.

The instruments built so far have been specially designed for airborne use. A development of a cheaper instrument mainly designed for ground-based measurements is currently under way. Therefore, the authors expect wider use of the instrument in the community within the next few years. The new calibration is a step forward to improve the acceptance of the instrument.

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