IMPROVING SOIL MEASUREMENTS FOR BOUNDARY LAYER RESEARCH

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Abstract

The temperature profile in the soil is an important parameter to determine the surface heat exchange. It is measured by a set of 9 temperature needles down to a depth of 50 cm. A new, high accuracy setup has been developed.
In this setup, specially designed Pt needles have been selected which have a horizontal sensitivity of 30 cm. All needles are individually calibrated and KNMI's accurate sensor interface SIAM is used to collect the data. The sensors are installed sideways into the soil using specific techniques to keep soil disturbance to a minimum. The cables coming from the needles are routed horizontally to prevent water and heat transport along the cables. A double configuration is used to prevent disturbing the soil in case of a sensor malfunction. In order to monitor long-term drift, two additional sensors are also installed which are calibrated on a yearly basis.
An error analysis shows that with all the above mentioned measures, the resulting relative accuracy between the sensors is about 5 mK.
In addition to the temperature profile, new self-calibrating heat flux sensors are also being installed.

Introduction

In boundary layer research, the interaction between the lower atmosphere and the earth surface is studied. At the KNMI research site Cabauw, measurements to determine the surface energy balance have been performed for many years. The exchange of heat and moisture between the soil and the atmosphere has been measured using various techniques. Some of these measurements are now in need of an upgrade.

The soil temperature profile measurements are perfomed to gain insight into the vertical temperature distribution of the ground. If the measurements are within a certain accuracy, they can also be used to extract and/or verify the soil heat flux. Therefore, these measurements are being upgraded. The specifications for the new temperature measurements are:

sample frequency:	60 s
absolute accuracy:	0.1 °C
relative accuracy (between sensors):	0.01 °C
measuring length:	≥ 30 cm
life time:	> 10 years
measuring depth:	0 – 50 cm, using 9 sensors

In addition to the upgrade of the soil temperature profile measurements, the soil heat flux measurements will also be upgraded. New, self-calibration heat flux plates will be installed. These measurements will be compared with the other methods. However, these sensors are currently being installed and so there are no data available yet. Therefore, this paper will focus on the soil temperature profile measurements.

Soil temperature sensors

Because the sensors need to be able to measure along a 30 cm horizontal line, a single Pt element does not suffice. Therefore, five Pt-100 elements are placed in series in a 35 cm long, 3 mm thick stainless steel needle. The distance between the Pt-100 elements is 75 mm, and the needle is filled with a powder which is a reasonable thermal conductor and a very good electrical insulator (Corund powder). This results effectively in a Pt-500 temperature needle which is sensitive over 30 cm.

The Pt elements are specified with an accuracy of 0.1 DIN (IEC 751 norm). This assumes a relation between resistance and temperature following the Callendar – Van Dusen equation:

$$R_t = R_o * (1 + \alpha t + \beta t^2), \qquad (1)$$

with R_t the resistance at temperature t, R_o the resistance at 0 °C and t the temperature (in °C). α and β are standard Callendar – Van Dusen coefficients. Because using the standard coefficients results in an absolute accuracy of only 0.1 K, the coefficients and R_o are determined individually for each needle (*i.e.* five Pt-100 elements in series).

This is done by calibrating the needles in an ethanol calibration bath (Fluke 7341, Hart Scientific, see Figure 1). The resistance of the sensors is measured at temperatures between – 15 °C and + 35 °C at 5 °C intervals. An additional measurement is taken at 50 °C. A second degree polynomial through these data results in the Callendar – Van Dusen coefficients for each sensor. The difference between the measurements and the curve using these coefficients indicates the deviation from the ideal quadratic relationship between resistance and temperature (Eq. (1)). This difference is, on average, about 2.2 mK.

Figure 1. The calibration bath containing the sensors and the reference thermometer.

Setup / installation

The specifications require very accurate measurements. Therefore, a number of measures are taken to assure that these specifications can be met. In the setup and installation, the following measures are taken:

- The location is chosen such, that no shade from nearby objects can reach the setup.
- The soil should not be disturbed during the life time of the setup. This means that if a sensor fails, it cannot be replaced. Therefore, two identical setups have been installed. These are at 20 cm distance from each other.

- In order to keep track of the long-term behaviour of the sensors, two additional sensors are placed in the soil. These are not part of the setup, and data are not collected. They are dug up and calibrated in the laboratory once a year.
- For both the identical setups, the 9 sensors are placed at 0, 2, 3, 6 ,8, 12, 20, 30 and 50 cm depth. The sensors at 0, 3, 8, 20 and 50 cm are placed above one another. The sensors at 2, 6, 12 and 30 cm depth are also placed above one another, all at 5 cm distance from the first series. This is to prevent the sensors influencing each other.
- For the installation, a manhole is dug. Next, a template and stainless steel rods are used to pre-drill the holes for the needles. Subsequently, the rods are removed and the sensors are inserted horizontally into the undisturbed soil. See Figure 2.
- For each needle, the cable coming from the needle is placed at the same depth as the needle itself. This means that the cable is at the same temperature as the needle, and no heat transport can take place along the cable. Also, this prevents water transport along the cable.
- The earth from the manhole is replaced in the same order it was dug up, so that the soil types are placed back at the original depths.
- Once every three months, the top sensors are inspected. If they are visible, a small amount of soil is added.
- The grass is kept at a length between 8 and 12 cm.

Figure 2. The setup and installation. On the left, the manhole and the template can be seen. On the right, the upper needles and cables are visible above the partially re-filled manhole.

Measuring data

The data from the sensors are measured using a KNMI sensor interface (SIAM). The resistance of the needles is determined by sending a current through them and measuring the voltage. Again, certain measures were taken to ensure a high accuracy:

- To prevent heating of the element due to the excitation current, the current is limited at 1.5 mA.
- The constants determined in the calibration are used for each individual needle instead of the standard Callendar – Van Dusen coefficients (see Equation (1)).
- Reference resistors of 500 and 600 Ω are used. These have very high accuracy and very low temperature drift. They are individually calibrated, using the same digital multimeter that is used for the calibration of the temperature needles. These resistors are calibrated on a yearly basis.
- Also to prevent heating of the element by the excitation current, the duration of the excitation current is kept as short as possible.
- Out of 5 subsequent measurements (taken in 2.5 s), the highest and lowest values are discarded and the remaining three are averaged to give the final value.

Uncertainty analysis

The sensors are calibrated in the KNMI calibration laboratory, using the calibration bath, a reference thermometer and a digital multimeter. All these measurements were done using calibrated instruments with traceable references. An overview of the various error sources is shown below.

- Accuracy of the reference thermometer
- Inhomogeneity of the calibration bath
- Accuracy of the resistance measurement of the needles by the digital multimeter
- Accuracy of the resistance measurement of the reference resistors by the same digital multimeter
- Ageing of the sensors
- Non-linearity of the sensors
- Thermal drift of the reference resistors and the sensor interface SIAM
- Self-heating of the sensors due to the excitation current
- Heat transfer though the connections
- Instability of the excitation current (supplied by the SIAM)

Other aspects influencing the accuracy are:

- Inaccuracy in the exact depths of the sensors
- Variation in the soil conditions (drying out, cracks, water transport along the cables and/or needles)

These latter two aspects are hard to quantify. The other error sources are investigated using the guidelines of the European cooperation for Accreditation (see [1]).

Reference thermometer
This is a ASA F250 mk.II. The complete calibration setup, including this thermometer, has been calibrated by the National Metrology Institute of the Netherlands. A deviation of −6 mK below 0 °C and −5 mK above 0 °C has been determined, with a 6 mK measurement uncertainty. A correction for the deviation has been implemented, and the 6 mK measurement uncertainty remains.

Inhomogeneity of the calibration bath
The inhomogeneity of the calibration bath has been measured by placing a reference thermometer (relative accuracy < 1 mK)) at various locations in the bath. This results in a homogeneity smaller than 2 mK. During the calibration of the sensors, they are placed close to each other, resulting in less inhomogeneity during the calibration. Therefore, the error due to the inhomogeneity of the calibration bath is estimated to be less than 1 mK.

Digital multimeter
The resistance of the sensors is measured with an Agilent 34970A digital multimeter. The accuracy is specified at 100 ppm/reading + 10 ppm/range. Using the 1000 Ω range, this results in an accuracy of 67 Ω. This corresponds to an absolute temperature accuracy of 33 mK.
The reference resistors are also calibrated using the same multimeter. This is why the absolute accuracy is not important, but only the relative one. This relative accuracy is determined by the difference in calibration between the sensors and the reference resistors. This difference is caused by noise, temperature drift and ageing of the Agilent in between the calibrations of the sensors and the reference resistors. Short-term drift and long-term drift (yearly) can be estimated from measurements (monitoring a stable reference resistor for 24 hours) and results from consecutive yearly calibrations, respectively. This amounts to an accuracy of 2.5 mK.

Ageing of the sensors
This ageing cannot yet be determined, as the sensors have only recently been installed. In time, the calibration results from the two reference sensors will provide this information. For now, an estimate

can be made based on the experience with standard Pt500 sensors. This is less than 1 mK over a period of 10 years.

Non-linearity of the sensors
As mentioned earlier, the 2nd order polynomial that is used in the equation between the resistance and the temperature of the sensors (Eq. (1)) is an approximation. In the calibration of the sensors, the difference between the polynomial (using the calibration constants) and the measured data is a measure for this non-linearity. This was determined to be 2.2 mK.

Thermal drift of the reference resistors and the sensor interface SIAM
The reference resistors are Vishay S102KT resistors. These are specified at an increase in resistance of 10 ppm at – 15 °C and 5 ppm at + 50°C. 10 ppm corresponds to about 5 mΩ. This can be corrected for, but is so small that this is unnecessary. Since both resistors drift in the same direction, this will result in an error in the absolute measurement only, amounting to 2.5 mK at most. The relative error is unaffected.

Self-heating of the sensors due to the excitation current
In order to take a measurement, a current is sent through the sensor which dissipates power in form of heat. The temperature increase of the sensor depends on its heat capacity, the duration of the measurement and the heat transfer to the environment. Laboratory measurements have been performed to determine this. The sensors were placed in a box with dry sand (worst-case scenario) and a current was passed through. The change in resistance (and thus temperature) was measured as a function of time. From this, the self-heating coefficient was determined as well as the heating time constant. In the measurement, the sensor is heated for 0.3 s and then cools down for 12 s. Using the determined thermal properties, it can be calculated that this will result in an error of less than 1 mK in absolute value. Because the sensors are heated simultaneously, the relative error is negligible.

Heat transfer through the connections
During the measurements, heat transfer can take place between the sensitive parts of the sensor and the cable connections. In the soil, the sensor and the connection cable are placed at the same depth and thus at the same temperature. However, during the calibration a large temperature difference can occur. Additional laboratory tests have been performed to quantify this effect. The effect was found to be < less than mK.

Instability of the excitation current (supplied by the SIAM)
Because the SIAM measures the sensors relative to the reference resistors, only very short-term drift and noise of the excitation current will influence the measurements. This effect has previously been measured in the lab and amounts to 1.2 mK.

Uncertainty analysis
The uncertainties are summarized in the table below.

	error source	absolute uncertainty (mK)
1	Reference thermometer	6
2	Inhomogeneity calibration bath	<1
3	Resistance measurement by the digital multimeter	33
4	Digital multimeter drift and noises	2.5
5	Ageing of the sensors	<1
6	Non-linearity of the sensors	2.2
7	Thermal drift of the reference resistors	2.5
8	Self heating	<1
9	Heat transfer through the connections	<1
10	Instability excitation current SIAM	2.4

Table 1. Identified uncertainties.

From here on, errors smaller than 1 mK are ignored. There are four measurements influenced by these uncertainties: the temperature of the calibration bath t_v, the resistance of the sensor during calibration R_v, the reference resistors R_r and the resistance of the sensors in the field measurement R_s. Because the same digital multimeter is used for the calibration of the sensors and the reference resistors, its absolute error is irrelevant.

parameter	error source	absolute uncertainty (mK)	relative uncertainty (mK)
t_y	1	6	
R_y	4	2.5	2.5
R_r	4	2.5	2.5
R_s	6, 7,10	4.1	3.3*

Table 2. Relevant uncertainties. The error source refers to Table 1. *: only error sources 6 and 10 are relevant.

The resulting absolute uncertainty is 8.1 mK. The resulting relative uncertainty is 4.8 mK.

Field data

An example of the field data is shown in Figure 3.

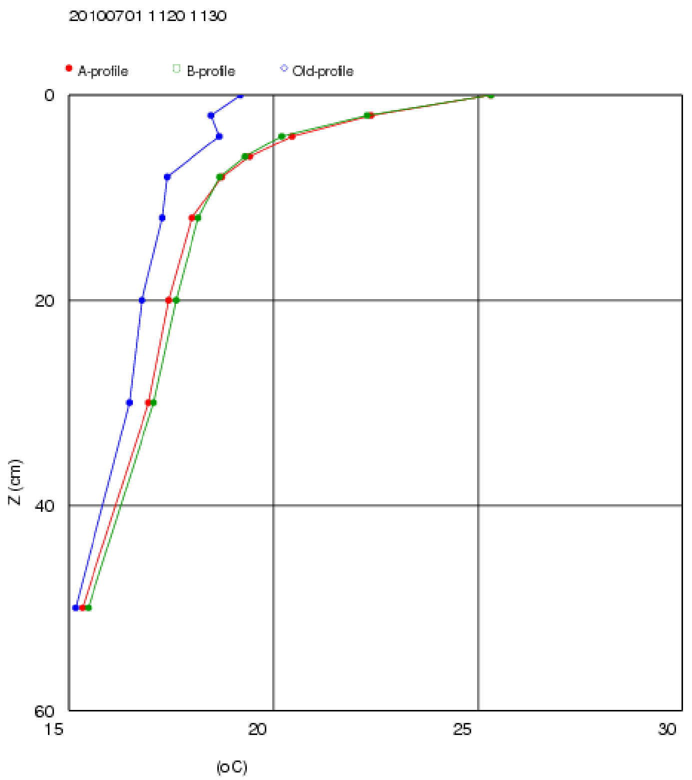

Figure 3. Example of the field data from 1 July 2010, 11:30 UTC. On the x-axis the (10-minute averaged) temperature in °C, on the y axis the depth Z in cm. The red and green curves are the two new temperature profiles, the blue curve is from the old setup.

The two new temperature profiles correspond well with each other and follow an expected shape. The old profile, which is measured using nickel needles, is clearly not as accurate as the new profile. More extensive analysis of the field data will take place at a later stage.

Discussion and conclusions

Soil measurements to determine the surface energy balance at the KNMI research site Cabauw are being upgraded. Firstly, the temperature profile measurements have been improved. Nine purposely-designed Pt-500 temperature needles are used up to a depth of 50 cm. With accurate sensors and extensive measures to reduce all possible error sources, soil temperature measurements have been achieved with very high accuracy. The uncertainty in the absolute measurements has been shown to be 8.1 mK, the uncertainty in the relative measurements 4.8 mK.
Soil heat flux measurements are currently being upgraded as well.

References

1. EAL Taskforce for the revision of WECC doc. 19-1990, 1999: Expression of the Uncertainty of Measurement in Calibration. *Publication Reference EA-4/02*, European cooperation for Accreditation.