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# A device for measuring fast temperature fluctuations

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Contents

# 1. INTRODUCTION

This report describes a temperature sensing unit that is capable of measuring temperature fluctuations with frequencies up to a few hundred Hz. Such a device is useful in experimental micrometeorological research because it enables the detection of small eddies with sizes down to the so-called dissipation range. Thus, the device is particularly suitable for eddy correlation flux and temperature spectra measurements close to the earth's surface.

# 2. THE PLATINUM TEMPERATURE SENSOR

## 2.1 Why platinum

The temperature measurement is based on the dependency of the electrical resistance of a fine platinum wire on temperature. Platinum has a very stable specific resistance due to its chemical inertia, and it can be produced in very thin wires by the so-called Wolleston process. These properties make platinum uniquely suitable for the construction of fine temperature sensors.

## 2.2 Construction of the sensor

Almost two centuries ago Wolleston invented a process of making very thin wires. To begin with, a relatively thick platinum wire is inserted in a close-fitting tube of silver. The composite wired is drawn through dies, until a wire is obtained with the desired diameter of the platinum core. The silver jacket is then removed by dissolving it in nitric acid.
The platinum temperature sensor is constructed as follows:
about one cm of Wolleston wire with a diameter of 120 μm is soldered between two prongs. Next, about the mid 3 mm of the silver jacket is removed by dipping the wire in nitric acid. Now the bare platinum wire that has a diameter of 2.5 μm is exposed and the sensor is ready. Although this procedure sounds very simple, skill and experience is needed to bring it to a good end. The electrical resistance of the sensor is approximately 50 Ω. Figure 1 shows the sensor.

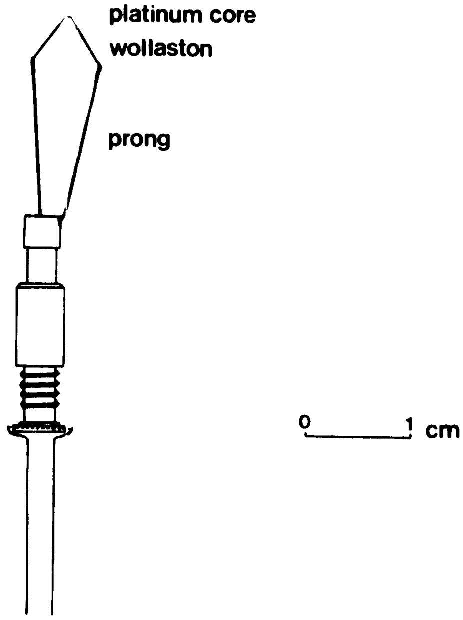



Figure 1. The platinum temperature sensor

## 2.3 Calibration of the sensor

The basic quantity is the temperature coefficient α of the wire:

$$R_t = R_o(1+\alpha t), \quad (1)$$

where $R_t$ is the resistance at t °C and $R_o$ the resistance at 0 °C. In Eq. (1) a quadratic term has been omitted; this term bears no relevance to our application. Following the $IPTS_{48}$ standard, $\alpha = 0.00390\ K^{-1}$. Because α may depend on the crystal structure of the wire, we checked this coefficient for a number of sensors made from the same batch of Wolleston wire. To this purpose a sensor was put in a small protective bottle and immersed in a temperature controlled alcohol bath, and its resistance was observed as a function of temperature. We found values of α ranging from $0.0037\ K^{-1}$ to $0.0039\ K^{-1}$ with a mean value of $0.00374\ K^{-1}$. The electronical calibration procedure (section 3.2) assumes a value of $0.00386\ K^{-1}$ instead. This value stems from alike platinum temperature sensors used by ERL/WPL at Boulder, Co, U.S.A. Consequently, the observed temperature fluctuations are to be upgraded by 0-4%, depending on the particular sensor. For convenience, a fixed correction of 3% is recommended.

## 2.4 Electrical heating error

Through the wire flows an electrical current of 230 μA. The power dissipated by the 50 Ω wire is then $2.6 \times 10^{-6}$ W. Assuming the power being dissipated as a heat flow to the ambient air, the temperature difference between the wire and the air can be calculated if the diameter of the wire and the Nusselt number are known. Adopting expressions for the Nusselt number published by Monteith (1973), and assuming a wind speed of 4 m $s^{-1}$ and a wire diameter of 50 μm, a temperature difference of 0.02 K is found. This value is small enough to be of no concern.

## 2.5 Radiative heating error

Two radiative heating processes are to be discerned: exchange of longwave radiation, and exchange of shortwave radiation. These processes may induce temperature fluctuations in two different ways: first, because of fluctuations of the radiation balance, and second because of a combination of a constant radiation unbalance and a fluctuating wind speed. Longwave radiation primarily acts along the second mechanism, while shortwave radiation may act in either way.

The effect of longwave radiation is considered by the following example: suppose we have a net longwave radiation flux of 100 W $m^{-2}$, a wind speed of 4 m $s^{-1}$ and a wire diameter of 50 μm. From the Nusselt number (see foregoing section) follows a temperature raise of $4 \times 10^{-3}$ K. Consequently, we can discard of longwave radiation as a source of unwanted temperature fluctuations of the sensor.

Turning to the effect of shortwave radiation, we assume a shortwave irradiance of 1000 W $m^{-2}$ and a reflection factor of 0.5. In that case, the temperature raise of the sensor will be 0.02 K (again, a wind speed of 4 m $s^{-1}$ is assumed). This value is of little concern. However, another effect plays a role that may make shortwave heating to an effect of some significance: the Wolleston jackets and the prongs also are raised in temperature by absorption of (shortwave) radiation. Because of the larger diameters, the temperature increase of jackets and prongs exceeds that of the platinum wire. In turn, the temperature of the platinum wire will be affected by the warmer jackets and prongs due to heat conduction. The magnitude of this indirect heating effect was found experimentally by an analysis of the sensor temperature on a day with a strongly fluctuating shortwave irradiance. An effect of $6 \times 10^{-4}$ K per W $m^{-2}$ was found. On a partly cloudy day, irradiance changes of several hundreds of W $m^{-2}$ on a time scale of 10-30 minutes may occur, and the corresponding temperature fluctuations will be in the order of some tenths of K. These fluctuations may definitely increase the observed value of the temperature variance. Fortunately, the real temperature variance will be high under these circumstances, so the relative error may still be small. Little effect is expected on the observed value of <w'T'> because of the poor correlation between the vertical wind speed and the shortwave irradiance.

## 2.6 Effects of jackets and prongs

The platinum wire not only exchanges heat with the atmosphere, but also with the silver jackets and the prongs. Jackets and prongs exchange heat with the atmosphere with time constants larger than that of the wire because of their larger diameters. As a result, the average temperature of the wire depends in a complex way on the frequency of ambient air temperature fluctuations. An analysis of the problem is given by Petit et al. (1981). Fig. 2 is from their paper; it depicts the frequency transfer function H(n) as a function of frequency n for a sensor that is comparable to ours. The governing parameters are the response times of platinum wire, Wolleston jacket and prongs, denoted by M1, M2 and M3, respectively. For frequencies $\omega M_3 = 2\pi n M_3 << 1$, the sensor has unit response (it has been assumed tacidly that the prongs are infinitely long, so no effect of their mounting is considered). At $\omega M_3 \approx 1$ the response drops off because of the thermal inertia of the prongs. For $M_3^{-1} << \omega << M_2^{-1}$, H(n) exhibits a plateau. Here, the prongs cannot follow the temperature fluctuations anymore, while the thermal inertia of the Wolleston jackets is still negligible. At $\omega M_2 \approx 1$ another drop off occurs due to the jackets. The pattern is repeated for $\omega > M_2^{-1}$; Fig. 2 shows the on-set only. In order to make quantitative estimates, we assume the following properties of the wire, jackets and prongs:

diameter: $D_1 = 2.5$ µm $\quad D_2 = 120$ µm $\quad D_3 = 400$ µm (2)

length : $L_1 = 3$ mm $\quad L_2 = 5$ mm (3)

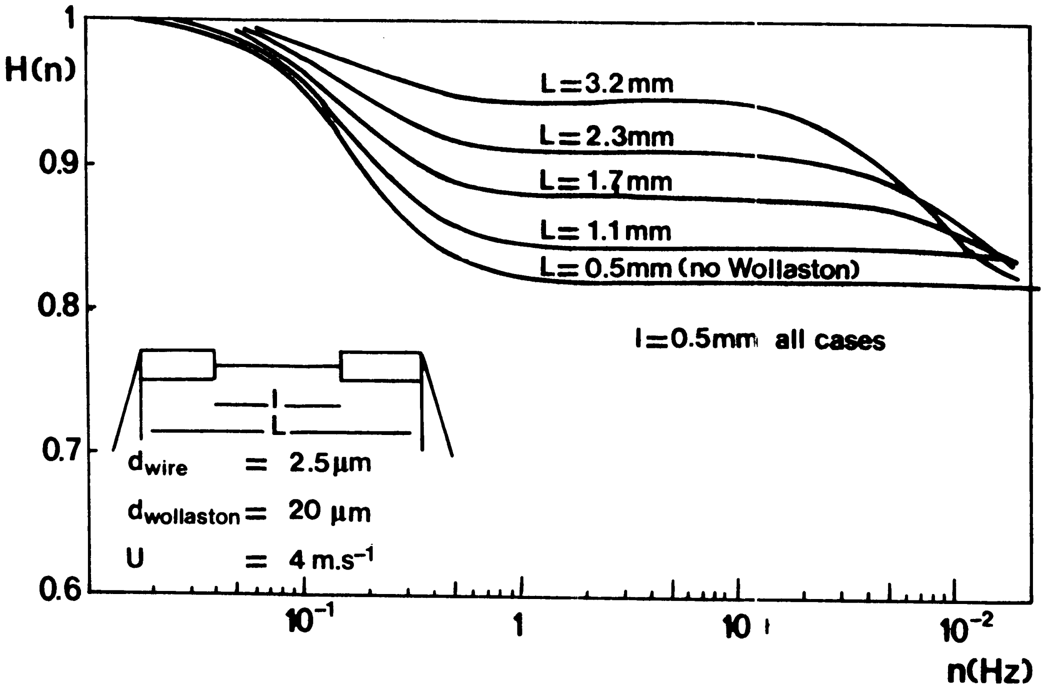



Figure 2. Theoretical transfer function (from Petit et al., 1981).

We also need the heat capacity per unit of volume of the materials, denoted by c, and the heat conductivities, denoted by $\lambda$. The materials are supposed to be: platinum (wire), silver (jackets) and nickel (prongs); then:

$$c_1 = 2.8\times10^6 \text{ J m}^{-3}\text{K}^{-1} \quad c_2 = 2.4\times10^6 \text{ J m}^{-3}\text{K}^{-1} \quad c_3 = 4.0\times10^6 \text{ J m}^{-3}\text{K}^{-1} \qquad (4)$$

$$\lambda_1 = 70 \text{ J m}^{-1}\text{s}^{-1}\text{K}^{-1} \quad \lambda_2 = 420 \text{ J m}^{-1}\text{s}^{-1}\text{K}^{-1} \quad \lambda_3 = 66 \text{ J m}^{-1}\text{s}^{-1}\text{K}^{-1} \qquad (5)$$

We also specify the wind speed in order to calculate response times; assuming it to be 4 m $s^{-1}$ we arrive at:

$$M_1 = 250\ \mu\text{s} \quad M_2 = 0.11 \text{ s} \quad M_3 = 1.0 \text{ s} \qquad (6)$$

H(n) has the following values:

$$H(n) = \begin{cases} 1 & \text{for} \quad n \ll 0.16 \text{ Hz} \\ 0.965 & \text{for} \quad 0.16 \text{ Hz} \ll n \ll 1.4 \text{ Hz} \\ 0.95 & \text{for} \quad 1.4 \text{ Hz} \ll n \ll 640 \text{ Hz} \\ 0.95\, e^{-0.0016\, n} & \quad n \gg 640 \text{ Hz} \end{cases} \tag{7}$$

We now discuss the consequences of these values of H(n). Observations of the inertial subrange of the temperature spectrum usually fall in the second and third frequency regime of Eq. (7). Because measurements of spectral density are directly proportional to $H(n)^2$, an underestimation of 7-10% is expected. Observations of the temperature flux <w'T'> are proportional to H(n); these measurements are weighted towards low frequencies, and thus an underestimation of a few per cent at most is expected. Measurements of the temperature variance lie in between these two cases.

An attempt was made to give support to these corrections by comparing temperature variance and temperature flux measurements using the Pt wire with measurements of these quantities using a sonic anemometer. The scatter going with the comparisons turned out to be of the same magnitude as the theoretical corrections, however, so no conclusion could be drawn. Also optically observed temperature structure parameters were compared with in situ observations using Pt wires. A correction of 0 to 5% instead of 7-10% followed from these experiments.

Concluding, at present there is no firm experimental evidence available that supports the above mentioned theoretical corrections, and we prefer to apply no such corrections.

## 3. ELECTRONICS

### 3.1 Outlines

The electronical equipment was built after a design of G.R. Ochs of ERL/WPL Boulder, Co, U.S.A. Fig. 3 illustrates the operation principle. A constant current of 230 μA is fed through the sensor by connecting it in series with a large resistor to a constant voltage. The voltage generated across the sensor

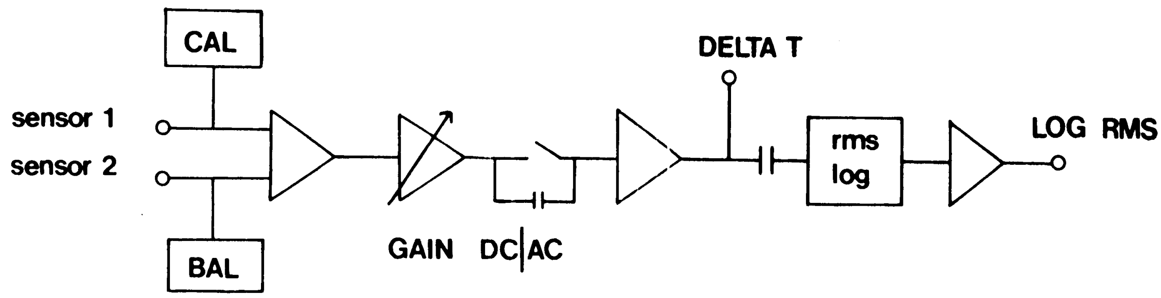



Figure 3. Block scheme of the electronics.

is led to one of the two inputs of a high quality operational amplifier. The other input may be connected to a second sensor, or to a fixed resistor. In the first case, a temperature difference measurement is made (which is relevant to e.g. temperature structure parameter measurements), and in the second case temperature fluctuations at one location are sensed (relevant to e.g. heat flux measurements). The output signal of the first amplifier is amplified by two following stages. The overall gain can be controlled by the panel potmeter labelled "GAIN". By means of a switch "DC/AC", the third amplifier can be either dc or ac coupled to the second one. If AC coupling is chosen, a high frequency cut off at 0.16, 0.016 of 0.0016 Hz can be selected (switch "HIGH PASS"). AC coupling is often preferred if large time scale temperature changes may drive the electronics to saturation. If DC coupling is selected, the off-set can be controlled by means of potmeter "BALANCE".
A calibration circuit has been added to one of the signal inputs. Calibration is achieved by a step change of the electrical current through the sensor. The step has a relative magnitude of 0.00358, which is equal to the relative change of a platinum resistor if the temperature changes by 1 °C at 20 °C. The step change is produced by means of the push button "CAL 1 C". Also for calibration purpose, a block wave of which the amplitude is controlled by potmeter "ADJ" can be superimposed on one of the signal inputs (switch "CAL UIT AAN"). If a tungsten sensor is used instead of a platinum one, a current step change of 0.00396 can be selected instead of 0.00358 (switch "W/PT"). In section 3.2 the calibration procedure will be discussed in more detail. The amplified signal finally is available at jacket "DELTA T".

At the present, two electronical amplifiers are available that differ from one another by two features. In order to distinguish the two amplifiers, one has been provided with black labels and the other with red ones.
The differences are:

1. For the black amplifier the sensors are connected (via large series resistors) to a stabilized voltage of 2.5 V, whereas for the red device are they connected to the negative outlet of the power supply (usually -15 V). Consequently, the black amplifier's calibration is not sensitive to changes of the power supply, whereas the red amplifier certainly is. The built-in power supplies of the amplifiers are well stabilized, but there are situations when it is preferred to operate from batteries. Then, it is advised to use the black amplifier
2. With the black amplifier a direct measurement of $\overline{\Delta T^2}$ can be made by means of a built-in root-mean-square voltmeter. The signal is available at jacket "LOG RMS". For details, see section 3.2.4. The red device lacks this provision.

The electronical design allows for a linear relationship between temperature changes and voltage changes over a broad dynamical range, limited only by saturation of the electronics and the inherent sensor qualities. Furthermore, accurate temperature measurements can be made with unmatched sensors (i.e., unequal resistances). Resistance differences are simply compensated for by matched current differences through the sensors, so that at zero temperature difference between the sensors the output voltage is zero also. Some quantitative information on these aspects is given in section 3.5.

## 3.2 <u>Calibration procedures</u>

### 3.2.1 Two platinum sensors

Calibration is performed by the following steps:

1. Put the sensors in their respective protection bottles in order to minimize temperature fluctuations. The environmental temperature should be around 20 °C (see also NOTE 1).
2. Set "DC/AC" switch at DC.
3. Adjust "DC BAL" for zero voltage at "DELTA T".
4. Push button "CAL 1 C" and adjust "GAIN" for the desired voltage step. A

temperature change of 1 °C will now give this change of voltage, too.

5. If the dc voltage drifts, use of the block wave may be of ease. Turn switch "CAL" to "AAN". Observe the block wave at "DELTA T" on an oscilloscope. Adjust "ADJ" for a voltage sweep equal to the voltage change produced by the "CAL 1 C" button. Pushing the "CAL 1 C" at high frequency is the best way of doing. Adjust "GAIN" for the desired voltage sweep of the block wave, which now corresponds to a 1 °C temperature change.
6. After these steps the "DC/AC" switch may be set on AC. But do not change "DC BAL".

NOTE 1. In the above procedure it was supposed that both sensors are at a temperature of about 20 °C. The reason is that the relative resistance change for a 1 °C temperature change depends on temperature:

$$\frac{dR_t}{R_t} = \frac{\alpha}{1+\alpha t}\,dt\ , \tag{8}$$

where $R_t$ is the sensor's resistance at temperature t ( °C). With $\alpha = 0.00386\ K^{-1}$, $\Delta t = 1\,°C$ and t = 20 °C one finds: $\Delta R_t/R_t = 0.00358$, which is equal to the relative change of the current through one of the sensors if the "CAL 1 C" button is pushed. If the calibration is done at a temperature different from 20 °C, the readings have to be increased by a factor (1 + 0.00386 t)/1.077.

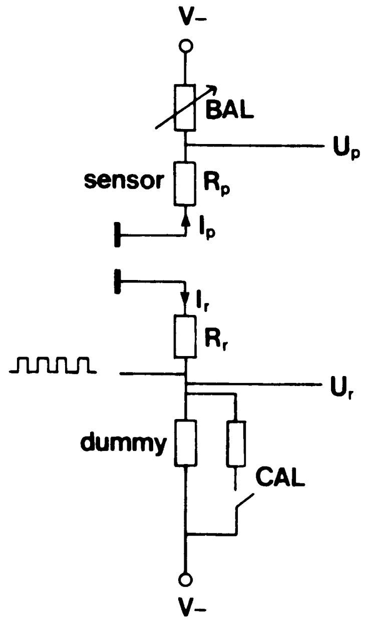
NOTE 2. There still remains the difference between the above value of α, and the one valid for our sensors, viz. $\alpha = 0.00374\ K^{-1}$. Thus all temperature fluctuation measurements are to be increased by 3%.

NOTE 3. The resistances of the cables connecting the sensors to the amplifier may introduce an error. Although the effect can be corrected for, it is advised to avoid such a correction by keeping the cable resistances much lower (1%, or less) than the sensor resistance.

$U_p = I_p R_p = I_p R_o (1 + \alpha t)$

$\Delta t = 1\ °C \rightarrow \Delta U_p = I_p R_o \alpha = I_p R_p \frac{\alpha}{1+\alpha t}$

BALANCE $\rightarrow I_p R_p = I_r R_r \rightarrow \Delta U_p = I_r R_r \frac{\alpha}{1+\alpha t}$ (A)

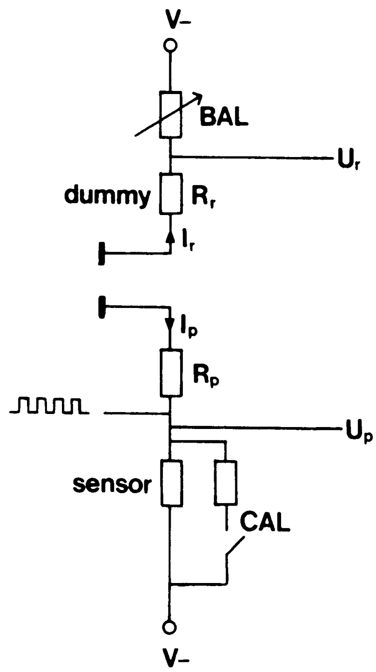



$U_r = I_r R_r$

CAL $\rightarrow \Delta U_r = \Delta I_r R_r = \alpha' I_r R_r$ , (B)

with $\alpha' = \frac{0.00386}{1 + 0.00386 \times 20} = 0.00358$

(A) = (B) if BALANCE done at t = 20 °C




$\Delta t = 1\ °C \rightarrow \Delta U_p = I_p R_p \frac{\alpha}{1+\alpha t}$ (C)

CAL $\rightarrow \Delta U_p = \alpha' I_p R_p$ (D)

(C) = (D) if CAL done at t = 20 °C

BALANCE is not critical

Figure 4. Calibration set-ups. Top: sensor connected to the upper input jacket, fixed resistor to the lower jacket. Bottom: sensor at lower jacket, fixed resistor at upper jacket.

### 3.2.2 One platinum sensor

In place of the second sensor, a fixed resistor is connected to the input. A metal film resistor of about the same value as the sensor should be used. The temperature coefficient of a metal film resistor is typically $50 \times 10^{-6}$ $K^{-1}$. Note that there are two options: temperature sensor connected to the upper input jacket and the resistor to the lower one, and vise versa. The calibration procedure is not indifferent to the choice, because of the asymmetrical balance and calibration connections. First, consider the case that the sensor is connected to the upper jacket (Fig. 4):

1. Put the sensor in its protection bottle.
2. Set "DC/AC" switch at DC.
3. Adjust "DC BAL" for zero voltage at "DELTA T". This should be done at 20 °C. See also NOTE 1 of section 3.2.1.

4-5. are the same as in 3.2.1. These steps may be done at any temperature, however.

6. The "DC/AC" switch may be set on AC after this.
   But do not change "DC BAL".

Next, consider the situation that the sensor is connected to the lower jacket (Fig. 4):

1. Put the sensor in its protection bottle.
2. Set "DC/AC" switch at DC.
3. Adjust "DC BAL" for about zero voltage at "DELTA T". Balancing is not critical in this case and may be done at any temperature.

4-5. are the same as in 3.2.1. These procedures must be done at 20 °C, otherwise a correction as discussed in NOTE 1 of 3.2.1 is necessary.

6. The "DC/AC" switch may be set on AC now.

In either case, NOTE 2 and NOTE 3 of section 3.2.1 apply.

### 3.2.3 Tungsten sensors

There is no difference in calibration procedure between platinum and tungsten sensors except that the switch "W/PT" has to be set in the proper position. Note that the temperature coefficient of tungsten is subject to more uncertainty than that of platinum. A value of 0.0043 $K^{-1}$ has been assumed. The temperature correction discussed in NOTE 1 (section 3.2.1) has to be adjusted accordingly.

### 3.2.4 The rms meter

The black labelled amplifier offers a true root-mean-square voltage measurement of the signal at "DELTA T". Calibration is done as follows:

1. Apply a dc voltage of 0.100 V at pin 1 of the AD536. Adjust the print potmeter labelled "ZERO" for 0.00 V at output jacket "LOG RMS".
2. With 1.000 V at pin 1, adjust the print potmeter "LOG CAL" for 2.00 V at "LOG RMS".

The calibration is fixed and only occasional check-ups are necessary. At output jacket "LOG RMS" the logarithm of the rms value of the voltage on jacket "DELTA T" is presented; their interrelation is:

$$U_{log} = 2 \log \overline{U}_{\Delta T} + 2 \,, \qquad (9)$$

where $U_{log}$ is the voltage at jacket "LOG RMS" and $U_{\Delta T}$ the voltage at "DELTA T". The rms circuit incorporates a high pass filter with a time constant of 0.3 s, and the settling time of the output signal is 4 s. The dynamical range of the logarithmic output is 60 dB, or $-2 \lesssim U_{log} \lesssim 4$ V.

## 3.3 Frequency response

High frequency response characteristics are dominated by the first amplification stage of the electronics. With the OPA27 the 3 dB cut off frequency is about 2 kHz. The low frequency limit can be set by means of the "DC/AC" switch; in the AC position, high pass filters with 3 dB points at 0.16, 0.016 and 0.0016 Hz can be chosen.

## 3.4 Noise

With 50 Ω sensors, broadband noise is equivalent to 0.05 °C peak-peak or 0.015 °C rms. The device may pick up 50 Hz (line frequency) radiation from external sources like power supplies. Although care has been taken to shield off the internal power supply, an effect of 0.02 °C peak-peak has been left. The internal power supply can be bypassed by connecting the amplifier to an external power supply (dual supply, ±15 V) through three banana plugs on the control panel. Noice produced by the sensor itself is negligible as compared to electronical noise.

### 3.5 Symmetry, linearity, common mode rejection, unmatched sensors

A symmetry and linearity test was performed by connecting one input to a 50 Ω resistor, and the other to a decade resistor bank. The decade bank was varied between 50 and 51 Ω. Next, the procedure was repeated with reversed input connection. The output voltage varied linearly with the decade resistance, and was also symmetrical with respect to reversion of the inputs, within the limit of accuracy of this test, which is about 1%. Common mode rejection was investigated by connecting each input to a resistor bank. The resistances were equal and varied between 30 and 100 Ω. At the output jacket "DELTA T" a response of one per 500 was observed, in the sense that a temperature change of 1 °C of both sensors would give a change in the output reading of 1/500 °C.

The same procedure was done with decade resistors that had a constant difference of 20%, thus reflecting unmatched sensors. Again, a common mode response of one per 500 was observed, thus proving that matching of the sensors is not essential.

## 4. SPECIFICATIONS

### 4.1 Platinum sensor

| | |
|---|---|
| Resistance | 50 Ω |
| Diameter | 2.5 μm |
| High frequency cut off (3 dB) at 4 m $s^{-1}$ wind speed | 700 Hz |
| Accuracy | 5% (see also NOTE 2 page 11) |

### 4.2 Electronics

| | |
|---|---|
| High frequency cut-off (3 dB) | 2000 Hz |
| Noise equivalent (peak-to-peak) | 0.05 °C |
| (rms) | 0.015 °C |
| Symmetry and linearity error | <1% |
| Common mode rejection equivalent | 0.002 °C per °C |
| Temperature drift equivalent | 0.005 °C per °C |
| Power consumption | 0.6 W |

Acknowledgement

Mr. F. Bosveld provided data on the comparison of temperature fluctuations measured with a sonic anemometer and with the platinum sensor.

## 5. REFERENCES

J.L. Monteith (1973): Principles of Environmental Physics. Publisher Edward Arnold, London.

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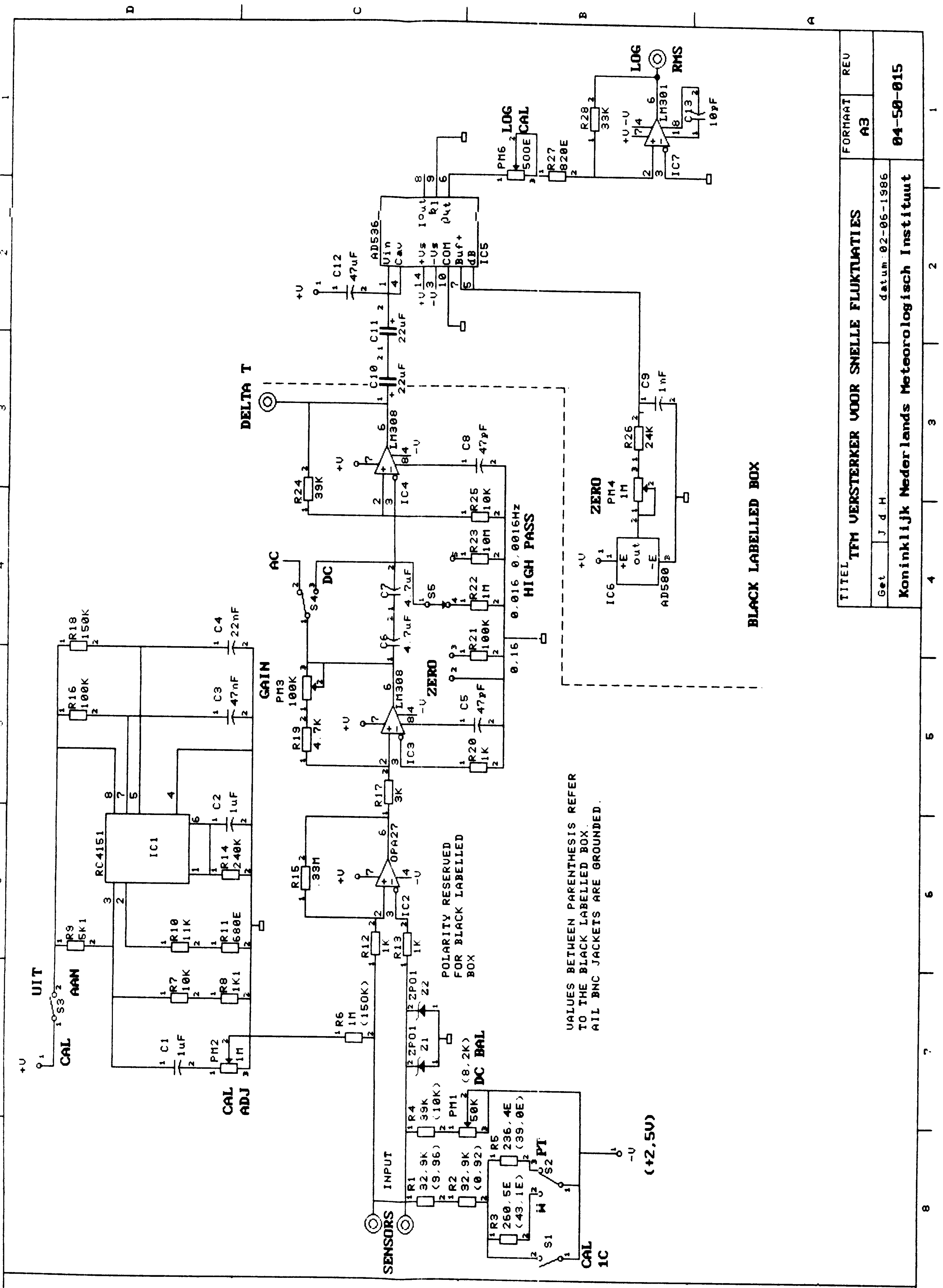


Figure 5. Scheme electronics.