

Submillimetre thermistors for balloon-borne applications up to lower stratosphere: preliminary characterization with 0.02 K uncertainty

F. Sparasci,^{a,*} D. Jouin,^a T. Deuzé,^a J. Bordereau,^b G. Coeur-Joly,^b D. Sourgen^b and A. Hertzog^b

^a *Laboratoire Commun de Métrologie LNE-CNAM, La Plaine Saint-Denis, France*

^b *Laboratoire de Météorologie Dynamique, École Polytechnique, Palaiseau, France*

ABSTRACT: The French metrological laboratory LNE-CNAM, in the framework of a study commissioned by the Laboratory of Dynamic Meteorology LMD, has carried out a preliminary metrological characterization of a device based on submillimetre thermistors, to be used for atmospheric temperature and humidity measurements from the ground up to the lower stratosphere. The device is a measuring system intended to perform temperature measurements between 173 K (around -100°C) and 233 K (around -40°C). It is composed of a self-manufactured electronic device, in which submillimetre thermistors measure both air temperature and the temperature of a hygrometer sensor, in order to determine accurately water vapour concentration. Since the needed final measurement uncertainty is below 0.05 K, a comprehensive metrological characterization must be performed. One instrument prototype was supplied to the LNE-CNAM, to be characterized between 173 K and 273 K (around 0°C). Measurements were carried out in the quasi-adiabatic calorimeter used by the LNE-CNAM to realize the national temperature standard below 84 K. The calorimeter was adapted to work at temperatures up to 273 K. At any setpoint between 173 K and 273 K, the stability of the temperature was within 5 mK for several hours. The thermistors were calibrated by comparison to a calibrated reference thermometer. Preliminary results showed that calibrations with an uncertainty of around 0.02 K are possible. Tests are going to be performed *in situ* by the LMD, and further characterizations will be carried out to assess the obtained uncertainties and check long-term reproducibility.

KEY WORDS calibration; thermistors; uncertainty; stratosphere; metrological characterization

Received 2 October 2014; Revised 26 December 2014; Accepted 8 February 2015

1. Introduction

Traceability to the International System of Units (SI) of climate-related measurements is a key element to the establishment of reliable monitoring of the global climate. Since the beginning of the 21st Century, the scientific community involved in climatological research has formally recognized the need of improved metrological traceability in Essential Climate Variable (ECV) measurements. Fifty ECVs are identified by the Global Climate Observing System (GCOS): they are variables for which international exchange is required for both current and historical observations. In the last few years there has been a progressive approach between the meteorological and metrological communities, in order to satisfy such an increasing need of accuracy in climate-related measurements. A notable example in the field of atmospheric measurements is the GCOS Reference Upper-Air Network (GRUAN), which is a reference network for upper-air climate observations, expected to provide long-term, highly accurate measurements of the atmospheric profile.

It is in this general framework that the French Laboratory of Dynamic Meteorology (LMD) has commissioned a study to the French national measurement institute LNE-CNAM, to perform

an accurate metrological characterization of a device based on submillimetre thermistors, designed to measure air-temperature and humidity in the atmosphere, from the ground level up to the lower stratosphere.

LNE-CNAM is one of the French national measurement institutes, in charge of the realization and the continuous improvement of some national measurement standards in France: temperature, length, mass and luminous intensity. The LMD is a laboratory involved in designing, realizing and calibrating meteorological instruments that are deployed in long-duration (3-month long) stratospheric balloon campaigns, directed at studying the atmospheric processes involved in climate change.

The LMD in particular works on balloon-borne temperature and humidity measurements up to the lower stratosphere and has currently developed a new frost-point hygrometer. The system is intended to work at temperatures ranging between 173 K (around -100°C) and 233 K (around -40°C). It is composed of a self-manufactured electronic device, in which submillimetre thermistors measure the temperature of the hygrometer sensor and that of the surrounding air space. The goal is to determine water vapour concentration in the atmosphere, with 10% accuracy in terms of mixing ratio. To reach such an objective, the required expanded uncertainty (at 95% confidence level) on temperature measurement is around 50 mK. To assess such an uncertainty level, a comprehensive metrological characterization of the temperature measurement system must be performed. [According to the “Guide to the expression of uncertainty in measurement” (JCGM 100:2008), the term ‘expanded

*Correspondence: F. Sparasci, Laboratoire Commun de Métrologie LNE-CNAM, La Plaine Saint-Denis, France. E-mail: fer-nando.sparasci@cnam.fr

Table 1. Uncertainty budget for the calibration of the full LMD measurement device, composed of a printed circuit board connected to two thermistors.

Component	Uncertainty Low-sensitivity chain (mK)	Uncertainty High-sensitivity chain(mK)
Reference thermometer repeatability	0.3	0.3
Thermistor repeatability	3.2	4.2
Reference thermometer calibration	2.5	2.5
Reference thermometer self-heating	3.5	3.5
Noise on thermistor resistance measurement	3.5	4.9
Thermistor measurement reproducibility	17.0	7.0
Correction of the two-wire resistance	3.8	3.8
Temperature of the electronic PCB	— ^a	— ^a
Power input variations on the PCB	— ^a	— ^a
Temperature uniformity of the calibration system	— ^a	— ^a
Humidity in air	— ^a	— ^a
Airflow	— ^a	— ^a
Total	19.0	12.5
Total expanded (coverage factor $k = 2$)	38.0	23.0

Each thermistor is connected to a distinct acquisition chain. Chain sensitivities are set differently, to determine their influence on the overall uncertainty budget.

^aAdditional environmental terms not quantifiable with the laboratory calibration facility described in this work. Slight modifications to the calibration system will allow, in future works, quantification of PCB effects and temperature uniformity of the calibration system. Air humidity and airflow effects should be quantified in other facilities.

uncertainty' in this study refers to the uncertainty of the result of a measurement expressed as a standard deviation (standard uncertainty), multiplied by a coverage factor $k=2$ based on a normal distribution, to define an interval estimated to have a level of confidence of 95%. This is the usual way in which uncertainty is expressed in calibration certificates of temperature sensors.]

This study shows that the temperature measurement device realized by the LMD is suitable to perform measurements with an overall uncertainty below 50 mK. Table 1 shows that the lowest attainable expanded uncertainty in laboratory calibration is 23 mK, leaving room for the additional uncertainties appearing in *in situ* measurements. The following sections describe the working principle of the temperature measurement system, the facility used to perform accurate temperature calibrations, the analysis realized on measurements and the final uncertainty budget associated to the calibration.

2. Thermistor-based device for temperature measurements

The device for balloon-borne temperature measurements is developed by the LMD. It makes use of small-size thermistors, with a diameter of few hundred micrometres. In the preliminary characterization performed in this study, GE Sensing model BB05JA202N thermistors have been used. They are bare bead, 150 μm diameter thermistors, with 2 k Ω nominal resistance at

298 K (25 °C), growing up to around 1.5 M Ω at 173 K. The thermistors are connected *via* a two-wire connection to the self-manufactured measurement device.

The measurement chain implemented in the device consists of a series of electronic elements. The thermistor is directly connected to a potentiometric input circuitry that converts the thermistor resistance into voltage. This voltage is then low-pass filtered, amplified and analogue-to-digital converted. A micro-controller implements the temperature calculations from the measured voltage and offers an RS-232 serial communication interface. The device is powered by a 9 V battery. The voltage supplied to the thermistors is automatically varied by the device, typically between 0.02 and 1 V, in order to keep the power dissipated by the thermistors below 50 μW .

All the electronic components, except the thermistors and the battery, are mounted on a printed circuit board (PCB) accommodating two independent measurement chains.

3. Calibration needs

The LMD needs a full metrological characterization of the temperature measurement device in the range between 173 and 273 K, to assess its suitability to perform balloon-borne measurements with an overall uncertainty of 50 mK. Such global uncertainty includes both the calibration uncertainty and other components related to the use of the device in the real measurement environment. If calibration uncertainties are too close to the target value, the device may not be suitable for balloon-borne measurements, as there would be no room for the additional components coming from the *in situ* deployment. Therefore, the calibration system has to be designed to provide reference calibration temperatures with the lowest possible uncertainty, in order to minimize the overall calibration uncertainty of the device. Other uncertainty components such as resolution, noise, reproducibility [In JCGM 100:2008, reproducibility (of results of measurements) is the 'closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement'] and stability are intrinsic to the device: they cannot be reduced by merely improving the quality of the calibration system. Finally, where feasible, laboratory calibration conditions must be as close as possible to real-use conditions. This is even more important since long-duration balloon flights, on which the sensors are deployed, generally do not allow recovering the instruments to re-calibrate the sensors after the flights.

Thus, the calibration process has to fulfil the following minimum requirements:

- provide reference temperatures with the lowest possible uncertainty, through a very well temperature-controlled environment, minimizing thermal gradients and temperature drifts;
- closely reproduce the balloon deployment configuration, by performing a full chain calibration; a given thermistor must be connected to the same measurement chain, both at the time of calibration and in balloon-borne use;
- define the components of the calibration uncertainty budget;
- identify the possible additional uncertainty terms, to be included in the uncertainty budget of *in situ* measurements.

4. Calibration device

The 'Thermal Metrology' department of the LNE-CNAM is in charge of the realization of national temperature standards in

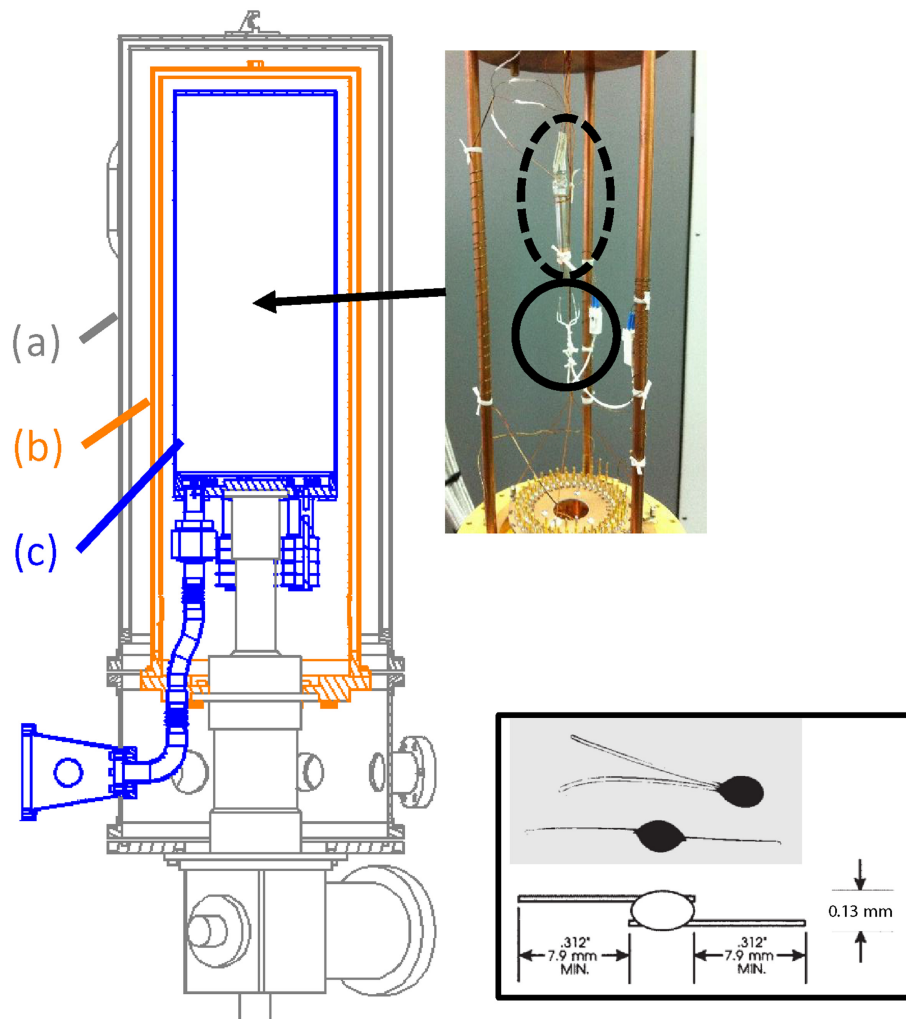


Figure 1. Scheme of the cryostat, with (a) the vacuum enclosure, (b) the first-stage shield, (c) the second-stage shield. The picture on top-right shows the emplacement of the reference calibrated thermometer (dashed circle) and that of the thermistors (solid circle). The picture on bottom-right shows the shape and the size of the thermistors under calibration (from 'GE NTC THERMISTORS: TYPE BB05/07/11' datasheet).

France, in a wide temperature range going from 13 K to above 1800 K. The laboratory develops a wide variety of top-accuracy calibration facilities and, below 173 K, is specialized in the development of quasi-adiabatic calorimeters for the calibration of resistance thermometers (Sparasci *et al.*, 2011). It has also recently carried out a determination of the Boltzmann constant with a relative uncertainty of 1.2×10^{-6} , in view of the redefinition of the kelvin (Pitre *et al.*, 2011).

4.1. Calorimeter

For the calibration of LMD devices, the most suitable equipment is an adiabatic calorimeter based on a cryocooler, slightly modified to calibrate thermistors between 173 and 273 K. The calorimeter is composed of an external vacuum chamber, containing the cold head of a two-stage cryocooler and several cylindrical thermal shields made of copper. The first shield is connected to the first stage of the cryocooler: its temperature can be controlled between 40 and 273 K, with a stability of around 5 mK. Inside, another copper shield is connected to the second stage of the cryocooler and its temperature can be controlled between 6 and 273 K, ensuring stability and uniformity within 1 mK over several weeks. The second-stage shield is gas-tight

and can be either vacuum-pumped, or filled with gas, independently from the external insulation vacuum. The second-stage shield holds the adiabatic region of the calorimeter. This area has been slightly modified in this experiment, to accommodate both the thermistors under calibration and one reference calibrated thermometer. Since the thermistors are too small to be properly fixed on a metallic comparison block, it has been decided to suspend them nearby the reference thermometer and to fill the surrounding volume with dry air. Air acts as an exchange medium among the thermometers and the shield, and uniformizes the temperature inside the adiabatic area. It is representative of the real conditions in which thermistors operate on a balloon, provided that air pressure can be controlled and varied, to reproduce atmospheric pressure variations. Figure 1 shows the calibration system.

4.2. Electrical measurements

Thermistors under calibration are connected to the LMD measurement device through the wires of the cryostat, by two-wire connections. Wire resistance affects measurements and must be subtracted from the overall thermistor resistance. To evaluate the correction and its associated uncertainty, the resistance of two

nearly identical wires in the cryostat is continuously measured. Corrections are applied when data are processed.

During the calibration process, the temperature of the external environment surrounding the electronic PCB should be varied, to simulate the conditions of the real balloon-borne use. In fact, PCB components could drift with temperature, introducing offsets and additional uncertainties in measurements. The uncertainty budget in Table 1 takes account of this possibility, but the current calibration system does not allow evaluating such effect. The PCB does not fit inside the calorimeter and it is kept all the time at room temperature. In future calibrations, the PCB could be introduced in a separate thermostat, running simultaneously with the calibration calorimeter and reproducing the same temperatures. In this way, it should be possible to evaluate the uncertainties related to PCB temperature changes reliably.

4.3. Calibrated reference thermometer

The reference thermometer is a Capsule-type Standard Platinum Resistance Thermometer (CSPRT), calibrated by the LNE-CNAM according to the International Temperature Scale of 1990 (ITS-90), at the highest degree of accuracy (Hill *et al.*, 2012). It is connected with four electrical wires to a thermometry resistance bridge (Automatic Systems Laboratories, model F18), to be compared with a calibrated standard resistor (Tinsley, model 5685A). It allows measuring temperature with the lowest possible uncertainty, as described in (Sparasci *et al.*, 2011).

4.4. Air-pressure control

The system for air-pressure control inside the adiabatic calorimeter is composed of an absolute pressure sensor (Paroscientific Digiquartz®, model 745-100A) and a mass-flow controller (Vögtlin Instruments AG, model red-y). Dry air from a gas bottle is introduced in the calorimeter *via* the vacuum-pumping tube. Air injection perturbs slightly the thermal equilibrium of the calorimeter, but temperature equilibrium is quickly restored in few tens of minutes. At the present time, there is no way to admit humid air, although it would represent more closely real-use conditions.

4.5. Software for measurement and control

The full calibration process and the acquisition of data are entirely computer-controlled. Software programmes derive from those developed and employed at the LNE-CNAM for routine calibrations. They are compliant with the laboratory quality system based on the standard ISO 17025.

Software allows programming the required number of temperature setpoints, which are executed in increasing temperature order. After a setpoint change, the system waits until the temperature of the calorimeter is stable and then starts calibration measurements. Inner air pressure is continuously monitored by the pressure gauge and is controlled only during temperature transients. When temperature is stable and calibration is running, no air is admitted nor withdrawn, to avoid perturbing the thermal equilibrium. Raw data are stored in a text file, at the rate of the resistance bridge measuring the reference thermometer (generally, one sample each 50 s). Faster measurements coming from the LMD device (one sample each second) are additionally stored in a separate file.

5. Measurements and uncertainty budget

Measurements were performed by the LNE-CNAM on one LMD device with two acquisition chains, equipped with two thermistors. Sensitivities of the chains were set differently. One, identified as the high-sensitivity chain, was three times more sensitive than the other at around 173 K, and its sensitivity peak was 30% higher. Nevertheless, it showed saturation below 169 K (−104 °C). The low-sensitivity chain was capable to measure temperatures properly even below 153 K (−120 °C).

After a series of few test measurements, to adjust the parameters of the full calibration system, eight full measurement runs were carried out. In each run, 14 temperature setpoints were realized between 153 K and 273 K. On each setpoint, temperature was maintained stable for 2 h to perform the calibration, with a linear temperature drift not exceeding 2.5 mK h^{−1}. Data from the reference thermometer were acquired at the rate of one sample every 50 s, while thermistors were measured at the rate of one sample *per* second.

Pressure should be progressively increased with temperature, in order to reproduce the change of altitude in balloon-borne measurements. However, because of a gas leak in the pressure system, such emulation of the atmospheric pressure gradient was hardly realizable in the calorimeter. So, it was preferred to fix the pressure in each run at the values of 1 mPa (vacuum), 2, 10 and 101 kPa. Under vacuum, the poor thermal contact between the reference sensor and the thermistors induced large reproducibility discrepancies. At 101 kPa, the leak affected the measurements, as the pressure was not stable enough. Therefore, only data at 2 and 10 kPa were taken into account, as they were reproducible within few millikelvins (see Figure 2). Measurements at 2 kPa showed slightly better reproducibility than data at 10 kPa. A plausible explanation is that the pressure was less stable at 10 kPa than at 2 kPa, with an effect on the temperature stability of the calorimeter. In fact, pressure was stable within 100 Pa at 2 kPa and within 500 Pa at 10 kPa. No further improvement was possible, because of the gas leak in the calorimeter.

Thermistor calibrations were determined by calculating the co-efficients of a third-order Steinhart–Hart polynomial (Steinhart and Hart, 1968). This is the standard calibration equation for thermistors, linking resistance values to temperatures.

The uncertainty budget associated to the calibration was determined by defining a list of uncertainty components and providing a value when possible. ‘Type A’ and ‘Type B’ uncertainty evaluation techniques were used, [In JCGM:2008, Type A evaluation (of uncertainty) is a ‘method of evaluation of uncertainty by the statistical analysis of series of observations’. Type B evaluation (of uncertainty) is a ‘method of evaluation of uncertainty by means other than the statistical analysis of series of observations’.] Table 1 shows the list of the uncertainty components identified in the uncertainty budget.

The following sections describe how measurements were processed and how calibration and uncertainties were evaluated by the LNE-CNAM.

5.1. Calibration equation

The Steinhart–Hart co-efficients of the calibration equation were calculated by interpolating reference temperature measurements and the corresponding thermistor resistance values. On a given setpoint, 40 reference temperatures $T_i^{\text{ref}}|_{i=\{1..40\}}$ were measured, one every 50 s. One average thermistor resistance $\bar{R}_i$ was

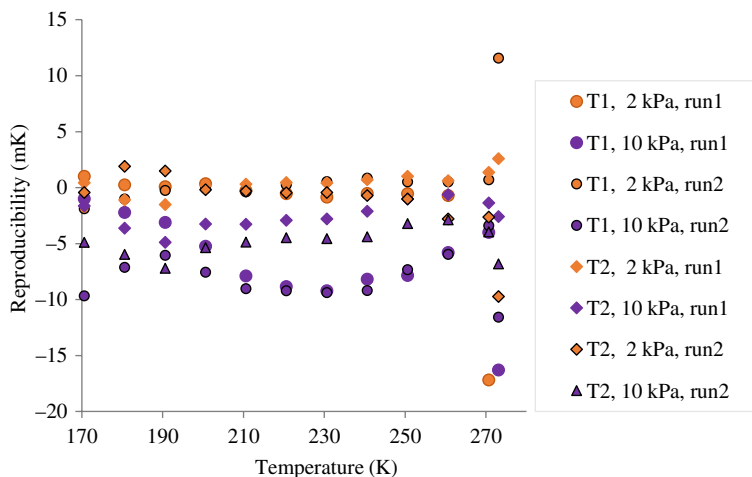


Figure 2. Reproducibility of temperature measurements between -105 and 0°C . T1 and T2 identify, respectively, the thermistor on chain 1 (low sensitivity) and on chain 2 (high sensitivity). Measurements at 2 and 10 kPa are shown. Each run is identified as well.

associated to each T_i^{ref} . It was calculated through the 50 resistance values R_j measured by the LMD device in that time interval, i.e. $\bar{R}_i = \sum_{j=1}^{50} R_j / 50$. The calibration temperature at each setpoint was then calculated as the average of 40 reference temperatures, i.e. $\bar{T}^{\text{ref}} = \sum_{i=1}^{40} T_i^{\text{ref}} / 40$, while the thermistor resistance was evaluated as $\bar{R} = \sum_{i=1}^{40} \bar{R}_i / 40$. Data were corrected from the temperature drift. Calibration co-efficients were determined from $\bar{T}^{\text{ref}}$ and $\bar{R}$ values.

5.2. Uncertainties at the calibration points

Uncertainty components listed in Table 1 were evaluated as follows:

1. Reference thermometer repeatability: evaluated from the standard deviation s^{ref} of 40 reference temperatures T_i^{ref} :

$$s^{\text{ref}} = \sqrt{\frac{1}{39} \times \sum_{i=1}^{40} \left(\bar{T}^{\text{ref}} - T_i^{\text{ref}} \right)^2}$$

[In JCGM 100:2008, repeatability (of results of measurements) is the ‘closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement’.]

2. Thermistor repeatability: evaluated from the standard deviation s^{therm} of 40 temperatures $\bar{T}_i^{\text{therm}} = f_{\text{cal}}(\bar{R}_i)$, where f_{cal} is the Steinhart–Hart calibration function:

$$s^{\text{therm}} = \sqrt{\frac{1}{39} \times \sum_{i=1}^{40} \left(\bar{T}_i^{\text{therm}} - \bar{T}^{\text{therm}} \right)^2},$$

where $\bar{T}^{\text{therm}} = f_{\text{cal}}(\bar{R})$

3. Reference thermometer calibration: evaluated from ITS-90 fixed point uncertainties, applying uncertainty propagation and non-uniqueness equations available in the literature (White *et al.*, 2008);

4. Reference thermometer self-heating: evaluated on self-heating measurements performed on the reference thermometer;
5. Noise on thermistor resistance measurement, evaluated as:

$$\max_{i=1..40} \left(\sqrt{\frac{1}{49} \times \sum_{j=1}^{50} \left(T_j^{\text{therm}} - \bar{T}_i^{\text{therm}} \right)^2} \right),$$

where $T_j^{\text{therm}} = f_{\text{cal}}(R_j)$

[In this experiment, *noise* is determined from the scattering of the 50 thermistor measurements acquired in the 50 s period necessary to get one measurement of the reference thermometer. It differs from *thermistor repeatability*, which is evaluated from the scattering of 40 averages, each one calculated on 50 thermistor measurements. Noise and repeatability are evaluated separately, to help final users in determining an appropriate uncertainty budget for balloon-borne measurements. In fact, repeatability is determined at calibration time and can be included ‘as is’ in the balloon-borne uncertainty budget. Noise instead can be different from laboratory to balloon conditions, and must be evaluated on each measurement.]

6. Thermistor measurement reproducibility: evaluated from the scattering of measurements on several runs, as shown in Figure 2;
7. Correction of the two-wire resistances: evaluated from the resistance variation of the two wires nearly identical to those connecting the thermistors to the PCB.

Other components in the uncertainty budget were not evaluated at the calibration stage. Some of them can be determined by further modifying the calibration system, while others are rather complicated or impossible to be evaluated in laboratory. They were introduced in the uncertainty budget to promote their assessment by the LMD during balloon-borne measurement campaigns.

The numerical values in Table 1 are based on worst-case evaluations. They show that overall expanded calibration uncertainties do not exceed 40 mK, and can be reduced to 23 mK by setting properly the sensitivity of the acquisition chain.

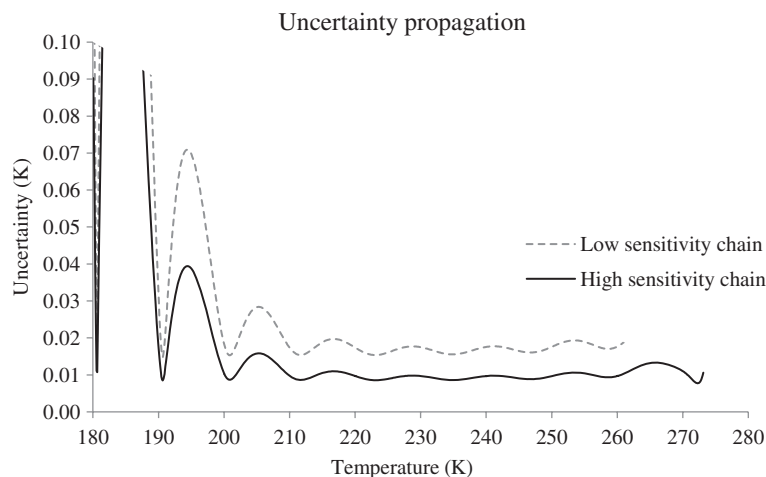


Figure 3. Calibration uncertainty propagated in the temperature range 180–273 K. Both high-sensitivity and low-sensitivity chains are represented.

5.3. Uncertainty in the full calibration range

Uncertainties in Table 1 are calculated at the calibration temperatures. Uncertainty on any other temperature in the calibration range is evaluated by the propagation equation (11) in (White *et al.*, 2014). Between 173 and 180 K, uncertainty may reach several tenths of kelvin and then decreases and falls down below 20 mK between 200 and 273 K. Figure 3 shows the overall uncertainties for both the low-sensitivity and the high-sensitivity chains, calculated according to the values provided in Table 1.

6. Conclusion

A device for balloon-borne air-temperature measurements up to the lower stratosphere was set up by the LNE-CNAM and was metrologically characterized by the LNE-CNAM, between 173 and 273 K. A calibration facility was developed by the LNE-CNAM, by adapting an existing low-temperature calibration system. Extensive measurements were carried out on a prototype of the LMD device, in order to verify its suitability for air-temperature measurements. The requirement was the capability of performing balloon-borne measurements with an overall expanded uncertainty below 50 mK.

A calibration uncertainty budget was defined, and additional components were identified, to take account of the possible supplementary uncertainties appearing in balloon-borne measurement campaigns. The study showed that, if the sensitivity of the device is properly tuned, the attainable expanded calibration uncertainty is 23 mK, leaving room for additional *in situ* uncertainty components. Consequently, the device was considered suitable for balloon-borne air-temperature measurements, with the capability of providing measurement uncertainties below 50 mK.

After this preliminary study, the LMD intends to realize copies of the measurement device, to be characterized and calibrated at the LNE-CNAM, for an application in balloon-borne measurements. The LNE-CNAM plans to improve the calibration system,

by repairing the air-pressure control system and adding a second reference thermometer, to completely assess the absence of any thermal gradient. Some solutions to study the effect of temperature changes on the electronic PCB will be implemented as well.

Acknowledgements

This work is being developed within the frame of the European Metrology Research Program (EMRP) joint research project ‘ENV07 METEOMET’. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

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