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A METROLOGICAL TEMPERATURE SENSOR NETWORK FOR OPTIMIZING LONG DISTANCE MEASUREMENTS

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Abstract – As part of the digital transformation the usage of sensor networks is rapidly increasing. Metrological applications at the NMI level can benefit from this new technology as well. In this manuscript we report on a sensor network that was installed in VSL's length laboratory to measure in more detail the ambient temperature profile as required for measuring long distances by an interferometric application. The measurement results of the sensor network were compared with the results from the 5 sensors that have been used until now. An offset in the mean temperature of about 0.2 °C was found, which was just about the maximum allowed bias in view of the claimed uncertainty for the distance measurement. At a more general level, it was concluded that such sensor networks provide a useful new tool to increase the understanding of other measurements, to validate assumptions and possibly optimize existing measurements.

Keywords: sensor network, metrology, digital transformation, uncertainty, interferometry, temperature

1. INTRODUCTION

The digital transformation has many aspects. One such aspect is that sensor networks come at an affordable cost, are relatively easy to set-up, and can measure with good accuracy once properly calibrated. In this contribution we report on the installation and usage of a sensor network for measuring the air temperature distribution in VSL's length laboratory. In a 50 meter long climatized corridor in which highly accurate long distance measurements are performed using interferometry a sensor network consisting of 51 temperature sensors was installed, as the knowledge of the air temperature is essential for this application. Traditionally, the temperature has been measured using 5 sensors spread along the corridor, and it was assumed that these measurements were sufficiently representative for the overall mean temperature in the corridor. The installation of the sensor network allowed us to measure the temperature profile in much more detail and to verify the assumption mentioned above. This work was performed in the EMPIR project "Metrology for the Factory of the Future" in a task dedicated to redundant measurements of ambient conditions.

In section 2 the problem will be formulated with more mathematical detail, accompanied by a more detailed presentation of the sensor network. In section 3 the results will be presented, followed by some overall conclusions.

2. PROBLEM FORMULATION AND METHOD DESCRIPTION

2.1. Measurement problem and approximations

The distance measurement takes place in a climatized laboratory in which the temperature is kept between 19.5 °C and 20.5 °C. In the set up distances up to 50 m are measured by a Michelson interferometer with a laser light source with a vacuum wavelength $\lambda_{\text{vac}} = 633$ nm. A measurement is performed by moving an optical target (retroreflector) from the initial position to the final position. The optical target is mounted on a cart which moves smoothly in a straight line on a rail such that the electronics can count the number of fringes m (not necessarily an integer). To convert this number to a measured distance D, it needs to be divided by two and multiplied by the actual wavelength in air λ. This wavelength is derived from the vacuum wavelength by multiplication with the refractive index n, which is evaluated using Edlen's formula at the laser wavelength λ_{vac}, the measured mean air pressure, the measured mean relative humidity and the measured mean air temperature T_0. Finally, using these mean values the resulting estimate D_0 of the distance is calculated by

$$D_0 = m/2\, \lambda_{\text{vac}}\, n(T_0). \tag{1}$$

The claimed expanded uncertainty for D_0, combining a variety of individual uncertainty sources, is essentially 1 ppm relative (with coverage factor $k = 2$), which amounts to $50\,\mu\text{m}$ at a measured distance of $50\,\text{m}$. Equation (1) is based on following assumptions:

1. It is assumed that the non-linearity of the function $n(T)$ is weak and that it is sufficient to evaluate $n(T)$ at the mean temperature value only.

2. Due to local temperature variations, the light might be refracted and not travel in a perfect straight line, but on some curved path, leading to an overestimate of the distance. It's assumed that this effect is small.

3. It is assumed that the mean temperature can be estimated sufficiently well by measuring spot temperatures at only 5 positions.

The validity of assumptions 1 and 2 have been analyzed in a theoretical way and the results are presented in section 3.1 and 3.2. The validity of assumption 3 was assessed by means of installing a dedicated temperature sensor network.

This network will be presented in more detail in the next section.

Using Edlen's formula, it can be calculated that an expanded uncertainty (or bias) of 1 °C in temperature induces an expanded uncertainty (or bias) in distance of $48\,\mu\mathrm{m}$ at a total measured distance of 50 m. The (additional) uncertainty of the mean temperature measurement is not considered significant if it contributes less than about 1/5 of the total uncertainty, as $\sqrt{1^2 + 0.2^2} \approx 1.0$. In this case this means that the expanded uncertainty of the temperature should not be more than $10\,\mu\mathrm{m}$, as the expanded uncertainty is $50\,\mu\mathrm{m}$ at a distance of 50 m. This corresponds to a maximum expanded uncertainty of $\frac{10}{48}$ 1 °C = 0.2 °C for the mean temperature. For a potential systematic bias in the measurement temperature we are using the same threshold of 0.2 °C. The goal of the sensor network is to assess if the measurement bias when determining the mean temperature using only 5 temperature sensors compared to the improved estimate when using 51 sensors lies below this threshold. If this is indeed the case, the usual procedure using only 5 temperature sensors can be retained without a need for increasing the claimed uncertainty to account for a larger than expected uncertainty in the measured mean temperature.

2.2. Temperature sensor network

2.2.1. Construction of Network

Fifty-one temperature sensors were assembled in house in order to get the lowest measurement uncertainty. The sensing part consisted of a 10 kΩ NTC thermistor placed in series with a resistance of 12 kΩ. The communicating part was formed by Texas Instruments CC2531 USB Zigbee modules, communicating wirelessly at a frequency of 2.4 GHz. The voltage over the thermistor was measured by an analogue voltage input of the module. To enhance the stability of the network, 5 additional CC2531 chips with external antennae were used. Whereas the sensor nodes had only meandered antennae on the chip itself, the external antennae more than tripled the link quality. The routers were used to repeat the network signal over the full distance of the measurement. To supply power to the nodes and routers a long wire with USB plugs at 1 meter spacing was used, as this seemed more practical than over 50 individual battery packs. A Texas Instruments CC1352P chip was used as a coordinator in the network. Finally, a Raspberry Pi 3 Model A+ was used to run the Zigbee server to which voltage readings were also logged in real time. In fig. 1 a photo is shown with a temperature sensor mounted below the rail of the measurement set-up, together with a router node with external antenna. The total cost of the hardware was around 1000 EUR.

2.2.2. Calibration

The sensors were calibrated in the following way. The sensors, together with a set of traceable reference sensors, were mounted on an aluminum block which could be brought to a desired temperature by means of a water based heating and cooling device. The block and sensors were well isolated from the environment by means of an insulating box. The digital voltage output which was transmitted wirelessly, was calibrated and a calibration function relating voltage output to temperature was established. Calibration of all sensors took place before and after the measurement campaigns. After calibration, the expanded uncertainty of each of the sensors was 0.04 °C, mainly limited by the resolution of the digital voltage output of the sensors. This uncertainty doesn't include a component for (future) drift of the sensors.

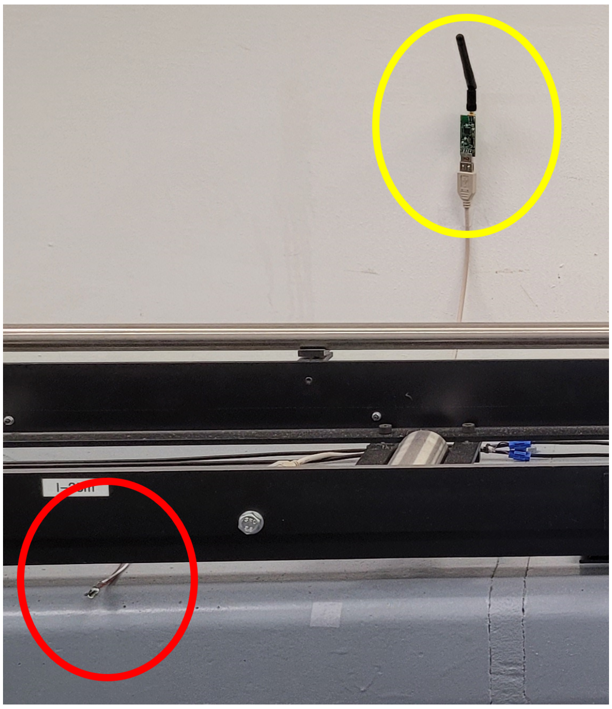

Fig. 1: The horizontal black parts are the rails for the cart used in the interferometer set-up. In the red circle at the lower left corner a the sensing part of a temperature sensor node is visible. In the yellow circle in the top right corner a router node with external antenna is visible, connected to the wire supplying power by means of a USB connector.

2.2.3. Software

To operate the Zigbee network by means of the Raspberry Pi two pieces of software were used. The Zigbee2MQTT software was used to start the Zigbee server. The Zigbee Mosquitto software provides a messaging protocol which was used to interface with the coordinator. These two pieces of software ultimately allow for the text message transmissions containing the voltage readings from the ADCs of each of the sensor nodes to be stored on the Raspberry Pi. Appropriate firmware was installed at the senor nodes and at the coordinator node.

Processing of the data was done using some scripts written in the Python language.

2.2.4. *Test procedure*

The main aim of the measurement campaign was to gain insight into the overall temperature profile along the corridor, and specifically, to assess if the mean value of the 5 climate system sensors was sufficiently close to the mean temperature of the 40 sensor network sensors. In order to get some further insights, a test plan with the following five test cases was defined:

1. Undisturbed profile
2. Person sitting at a fixed spot
3. Person walking around all the time
4. Person walking around and then leaving
5. Profile during a simulated measurement with the moving cart

All sensors were calibrated in week 1. Then the test plan was executed in week 2 and repeated in week 3. In week 4 all sensors were recalibrated in order to assess their drift.

3. RESULTS

3.1. *Non-linearity of refractive index formula*

The effect of the neglected non-linearity of the refractive index as function of temperature in equation (1) was analyzed using a worst-case approach. If the mean temperature is 20 °C, then the worst case is that half of the path length is at 19.5 °C and the other half at 20.5 °C. It was calculated that the induced measurement error by using the approximation of equation (1) amounts to $-0.03\,\mu\mathrm{m}$ at a distance of $50\,\mathrm{m}$, which is very minor. This finding was confirmed by more detailed numerical simulations.

3.2. *Curved light path*

If a light beams travels from one medium into another medium with a different refractive index (e.g., air with a different temperature), it may change its direction of propagation following Snell's law. This depends on the difference of the refractive indices and on the angle the light beam makes with the normal vector to the interface between the two mediums. Two dimensional curves were simulated by assuming a one-dimensional Gaussian process along the main travel direction for the temperature profile and a random normal vector for the interface between neighboring path sections, see Fig. 2. In this simulation only the geometric path length was assessed, thus the effect of different actual wavelengths in different path sections is not included in the results in this section. It was found that the maximum path increase significantly depended on the used parameter values. As a reasonable choice for the kernel of the Gaussian process a squared exponential kernel was selected with correlation parameter of 1 m and a standard deviation of 0.25 °C. For this choice the simulated increase in path length remained below $1\,\mu\mathrm{m}$, thus being negligible. Nevertheless note that one can mathematically construct worst-case temperature profiles with worst-case normal vectors in which the light travels an almost arbitrary path of arbitrary large distance, e.g. the light can change direction by 180°.

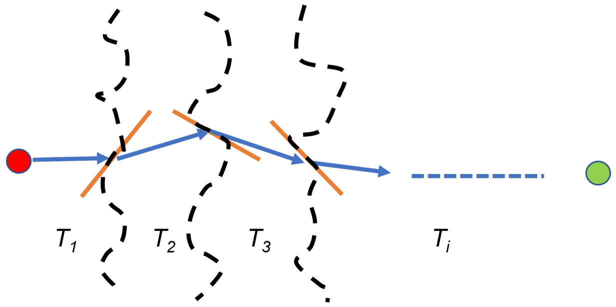

Fig. 2: Two dimensional simulation of curved light paths due to refraction effects. The vertical curvy black dashed lines delimit zones with different temperatures. The slanted orange lines indicate the assumed direction of the local interface between these zones. The light is assumed to travel from the red spot on the left to the green spot on the right and back.

3.3. *Sensor network measurements*

The test procedure as specified in section 2.2.4 was executed twice in two consecutive weeks. The data were subsequently analyzed using some Python scripts. The main points of attention were the changes of the measurement values of the individual sensors over time, the spatial temperature profile of the mean sensor values in the corridor, the comparison of the measured values by the 5 sensors of the fixed installed climate system and the 5 sensors of the sensor network that were in the closest proximity, and any other interesting observations that were made. After the first test campaign it turned out that some of the 51 sensors reported readings only sporadically, or not a all. Therefore fewer sensors were used during the second campaign. In the first campaign data from 40 sensors were available, whereas in the second campaign data from 30 sensors were used.

The temperature traces over time were generally very stable, although incidentally some higher and/or lower values were measured. In Fig. 3 a typical temperature profile in space is shown, in this case for test case 5 simulating a real measurement. As some measurement instruments and computers are present near the start of the corridor the temperature is slightly higher in that region.

We'll now present some observations that were based on the measurement results. A person sitting between two sensors does not seem to cause any significant perturbation in the temperature measurements of the sensors. A person

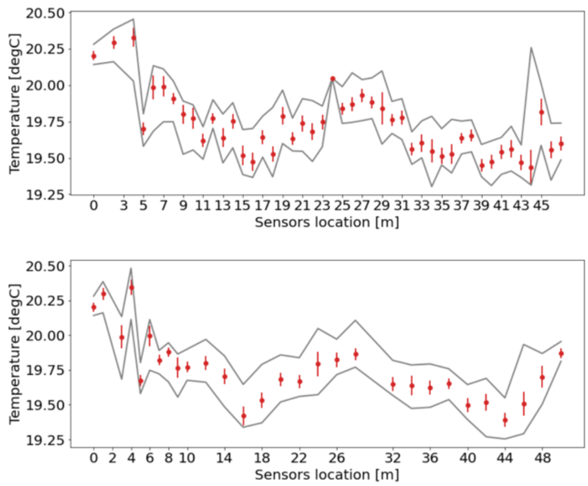

Fig. 3: Temperature profile in space for test case 5 simulating a real measurement for the two repetitions A (top) and B (bottom). The circular marker is at the mean value and the error bars are at plus minus one standard deviation. The lines above and below connect the maximum and minimum measured values during the entire time span.

walking around the lab caused significant perturbations in the sensors reading during the first execution but not during the second. During test case 5 a battery powered temperature sensor was mounted on the moving cart and its values were compared with the values of the non-moving sensors mounted closest by when the cart passed. The differences varied from 0.05 °C to a few 0.1 °C with a maximum of even 0.6 °C, which is higher than expected. The reason for this is not clear. The values of the 5 fixed installed climate system sensors were compared with the values of the nearest sensors of the sensor network, both placed on the 50 meter long granite support for the interferometric measurement set-up. Two climate sensors agreed with the closest sensor network sensors within the mutual uncertainties, whereas a third sensor agreed part of the time. Two sensors didn't agree and differences of 0.15 to 0.20 °C were present between the mean values of the climate system sensors and the sensor network sensors. The differences could be due to the sensor hanging in free air or not, or to locally warmer air flows (one such a flow was detected close to an electrical device mounted half way the corridor). This indicates that the location of the sensors can be an important factor when measuring the temperature of the lab.

In Tab. 1 the main result of the measurement campaigns is shown, i.e., the mean temperature measured by both the climate system and the sensor network and their difference. It turned out that this difference was at most 0.25 °C with an expanded uncertainty of 0.06 °C. When taking the expanded measurement uncertainty into account as a tolerance, the threshold of 0.20 °C was not exceeded. It was therefore decided that it is not needed to improve the temperature measurement in the corridor for this application in a permanent way, nor to increase the claimed uncertainty.

Table 1: Mean temperature and expanded uncertainty in parentheses ($k = 2$) as measured by the climate system (CS) and by the sensor network (SN), and their differences (Diff.), as measured in the 5 test cases and the two test campaigns A and B.

Case nr.	CS [°C]	SN [°C]	Diff. [°C]
1-A	19.91 (0.06)	19.67 (0.03)	0.24 (0.06)
1-B	19.89 (0.06)	19.73 (0.03)	0.16 (0.06)
2-A	19.92 (0.06)	19.69 (0.03)	0.24 (0.06)
2-B	19.93 (0.06)	19.75 (0.03)	0.18 (0.06)
3-A	19.94 (0.06)	19.70 (0.03)	0.25 (0.06)
3-B	19.91 (0.06)	19.76 (0.03)	0.15 (0.06)
4-A	19.91 (0.06)	19.68 (0.03)	0.23 (0.06)
4-B	19.90 (0.06)	19.75 (0.03)	0.15 (0.06)
5-A	19.93 (0.06)	19.73 (0.02)	0.20 (0.06)
5-B	19.92 (0.06)	19.76 (0.03)	0.16 (0.06)

4. CONCLUSIONS

The digital transformation makes it economically and practically possible to perform a larger number of measurements in a much finer spatial grid by means of sensor networks. This can help to better monitor the ambient measurement conditions of a measurement set-up and as a consequence potentially reduce its measurement uncertainty. In this contribution a sensor network with 51 sensors for measuring the ambient temperature in a corridor used for interferometric long distance measurements was presented. This network enabled the analysis of the temperature profile in much more detail than what was possible until recently, together with a more accurate measurement of the mean temperature. Simulation results showed that it is sufficient to focus on the mean temperature only, as well as that the effect of a non-straight optical path due to refraction effects is negligible. The measurement results using the network showed that the mean temperature measured by the 5 climate system sensors was on average about 0.2 °C higher than the more accurate measurement by the sensor network. Based on this result it was decided that the current practice with only five temperature measurements and a claimed relative measurement uncertainty of 1 ppm is valid. In future work the network might be used in other applications where temperature measurement is of critical importance. Furthermore, employment and recalibration at longer time scales will give more information about the metrological stability of such sensor networks.

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