New PTB Calibration Service for dc SQUID-based Noise Thermometers to Disseminate PLTS-2000

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***Abstract* - The Physikalisch-Technische Bundesanstalt has started a new calibration service for dc SQUID based noise thermometers according to the PLTS-2000. The thermometers are easy-to use, compact, robust and allow temperature measurements with less than 1% uncertainty in short times in the temperature range from 1 K down to the millikelvin region. New developments in low-temperature thermometry are briefly discussed.**

***Keywords* –Noise thermometry, temperature scales, dc SQUID, magnetic gradiometer, calibration service**

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Reliable low-temperature thermometry is still a demanding task. If traceability to the international system of units SI is required, users need to refer to the International Temperature Scale of 1990 (ITS-90) or the Provisional Low Temperature Scale 2000 (PLTS-2000), *i.e.*, a direct realization of the mentioned temperature scales or a traceably calibrated thermometer has to be used. For practical thermometry the second option is preferable in view of costs and effort.

To provide for users of cryogenic equipment an easy-to-use thermometer for the temperature range from helium temperatures down to the millikelvin region, PTB has developed the magnetic field fluctuation thermometer (MFFT) in cooperation with Heidelberg University and the company Magnicon [1, 2]. This variant of a noise thermometer measures the magnetic field fluctuations originating from thermally induced electrical noise currents in an unbiased conductor. Despite the primary nature of its working principle, the MFFT can be applied as a secondary thermometer requiring calibration for practical thermometry. PTB now has established a new customer service and set up a facility for calibrating MFFTs according to the PLTS-2000.

The MFFT comprises a niobium shielded temperature sensing unit with a dc SQUID gradiometer directly placed on a metallic noise sensor made of high purity copper, a SQUID electronics, a DAC data acquisition and an analysis software. The design of the temperature sensor is compact, mostly insensitive to external influences and provides good thermal contact to the object which temperature is to be measured. This is an advantage especially at very low temperatures compared to other thermometers.

The measured thermal magnetic flux noise signals exhibit a low-pass-like power spectral density (PSD) of the following form:

$$S(f,T,\theta) = \frac{aT}{\left(1+\left(\frac{2f}{\pi f_c}\right)^{2p_1}\right)^{p_2}},$$

where $\theta = (a, f_c, p_1, p_2)^{\mathrm{T}}$ is the vector of model parameters, T is temperature, f is frequency, and f_c represents the roll-off frequency of the power spectral density. At low temperatures, where the electrical conductivity of the high-purity metallic noise sensor is independent of temperature, the model parameters f_c, p_1, and p_2 are constant and the spectral shape doesn't change with temperature. For calibration θ is determined at a very precisely known calibration temperature T_{cal} traceable to the PLTS-2000. Then, an unknown temperature T can be determined from the measurement of the PSD of the thermal magnetic flux noise $S(f,T,\theta)$ using the simple relation: $T = T_{cal} S(f,T,\theta) / S(f,T_{cal},\theta)$.

The MFFT systems are optimised with respect to the useful frequency range, number of frequency bins, number of averages of the noise signals and possible non-thermal noise sources. The parameters are chosen such to ensure MFFT temperature measurements with an overall relative uncertainty less than 1% in less than 1 min over the whole working range of dilution refrigerators.

Figure 1 (see page 2) shows the PSD for calibration at about 0.85 K where the parameter vector θ is determined (red line). When reducing the temperature, the values of the PSD of thermal magnetic flux noise also scale down linearly with temperature, as shown by the orange line for T ~ 0.015 K. Further lowering the temperature leads to an increase in the signal to noise ratio, *i.e.*, non-thermal noise contributions as such of the SQUID itself (green line) become noticeable in the frequency range considered. For a selected MFFT, the optimization of calibration consists in the determination of a useful frequency range (shown in Figure 1 by a light blue area) and a minimal temperature T_{min} (blue line) for which a relative uncertainty of 1% in the measured temperature can be guaranteed. For calculating this 1% uncertainty level all statistical and systematic uncertainty contributions for the temperature measurement are taken into account.

Comparison measurements carried out on a MFFT with a high-accuracy realization of the PLTS-2000 have proved the consistency of the calibration procedure within the stated uncertainty bounds. The MFFT noise thermometer systems are calibrated as complete systems with all their hardware components. A change of any hardware component would alter the system parameters and noise signals. Therefore, the stated calibration uncertainty and parameters can be guaranteed only for a complete MFFT system of selected components.

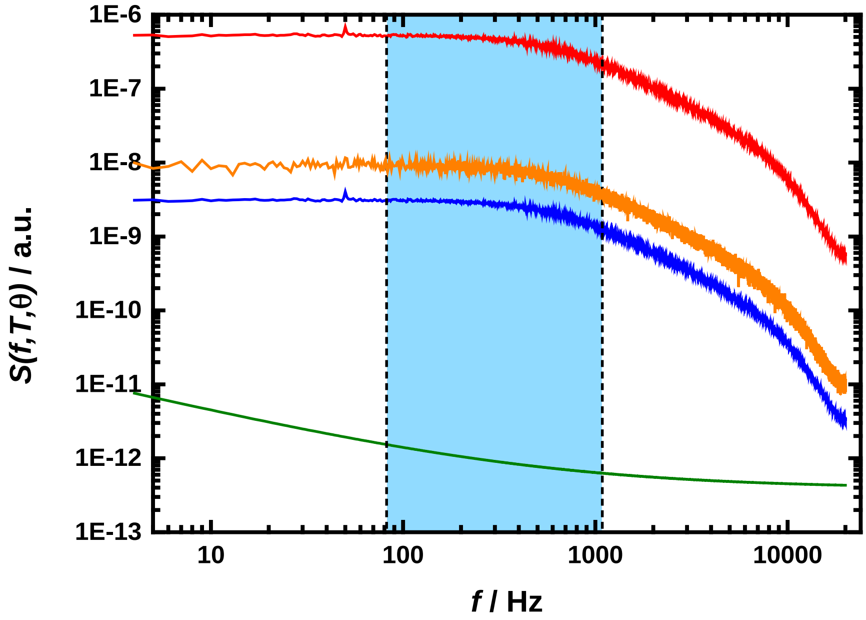

Fig. 1. Power spectral densities of magnetic flux noise for a MFFT noise thermometer system. Red line – PSD at calibration temperature T_{cal} ~ 0.85 K, orange line – PSD at 0.015 K, blue line – PSD scaled to T_{min}, green line - PSD of non-thermal noise contributions from the SQUID itself. The light-blue area marks the frequency range useful for temperature measurements down to T_{min} with 1% relative uncertainty.

In this way, calibrated MFFTs are a new, efficient and cost–saving route for dissemination of the PLTS-2000. MFFT noise thermometer systems are commercially available from Magnicon. When ordered with calibration, the system is calibrated at PTB according to the PLTS-2000 and provided with an official PTB calibration certificate. In dependence on customer needs and requests, this calibration service could be extended to other types of noise thermometers to complement the existing PTB calibration services for low-temperature thermometry.

Recent progress made in temperature metrology in general has led to adoption of the "*mise en pratique*" for the definition of the kelvin [3] by the Comité Consultatif de Thermométrie of the BIPM. In the future it will be also accepted to realize and disseminate the kelvin in accord with the SI directly by primary methods. In this context the project "Implementing the new kelvin" (InK) [4] is underway within the European Metrology Research Programme (EMRP). One part of the project is devoted to the development of primary thermometers for the low temperature range. Partners from Royal Holloway University of London (UK), MIKES (Finland), Aalto University (Finland), LNE-CNAM (France), and PTB (Germany) are working on thermometers such as current sensing noise thermometers, Coulomb blockade thermometers, acoustic gas thermometers and magnetic field fluctuation thermometers. The expected results of InK will provide the means to facilitate the dissemination of the PLTS-2000 as well as thermodynamic temperatures and resolve still existing problems of temperature scale inconsistencies in the low temperature region.

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