Traceability of RF measurement q

This article by Germany´s National Metrology Institute (Physikalisch-Technische Bundesanstalt, PTB) describes how RF power, an important measurand for Rohde & Schwarz, is traced back to the national primary standard of the Federal Republic of Germany.* The article illustrates the enormous test effort required to produce precision T&M instruments with competitive features.

* Using RF power as an example, the article starting on page 34 describes the efforts Rohde & Schwarz undertakes to ensure that the relevant measurands of its RF T&M instruments are fully traceable to recognized national standards with minimal loss of accuracy.

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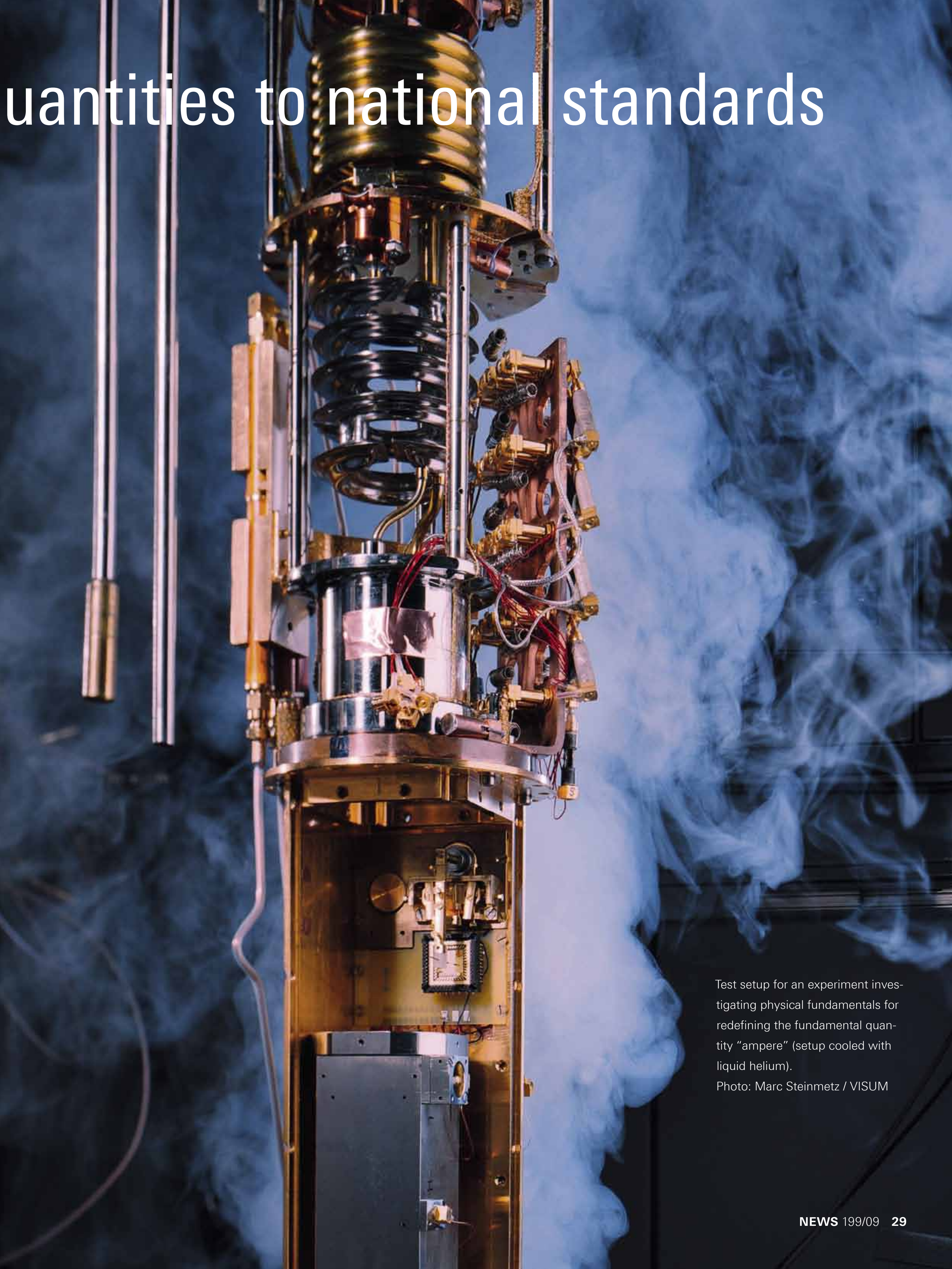


Test setup for an experiment investigating physical fundamentals for redefining the fundamental quantity "ampere" (setup cooled with liquid helium).
Photo: Marc Steinmetz / VISUM

Traceability of industrial calibrations – a prerequisite for high quality and improved competitiveness

Precision measurements represent an important part of industrial quality assurance and are a prerequisite for top-quality industrial production. In accordance with international standards for quality management systems (DIN EN ISO 9000) as well as requirements from the areas of product liability and environmental protection, measuring instruments must be calibrated and be traceable to national standards. Moreover, test results are reliable only if they are obtained through the use of calibrated measuring instruments.

The National Metrology Institute PTB is the primary metrology laboratory in Germany, representing the top of the calibration hierarchy (FIG 1). The PTB performs fundamental research and development work in the field of metrology as a basis for all the tasks it has to accomplish with regard to the determination of fundamental and natural constants, the realization, maintenance and dissemination of the legal units of the SI. For this purpose, the PTB operates physical setups that allow the most important measurement quantities to be realized with maximum accuracy (primary standard). The German Calibration Service (DKD), which is jointly operated by government and industry, represents the next level in the calibration hierarchy. With more than 300 accredited calibration labs, it is responsible for calibrating industrial T&M equipment and particularly for the calibration of working standards used by industry for internal quality assurance. The reference standards used in the DKD labs are calibrated by the PTB with reference to the primary standards. The PTB and DKD thus promote test and measurement infrastructure, improve industry's ability to compete, and make an essential contribution to technology transfer.

The DKD labs operated by Rohde&Schwarz in Munich, Memmingen, and Cologne provide traceability to national standards of all measurands (FIG 2) that are important for test instruments from Rohde&Schwarz. These labs make a critical contribution to the company's quality assurance efforts.

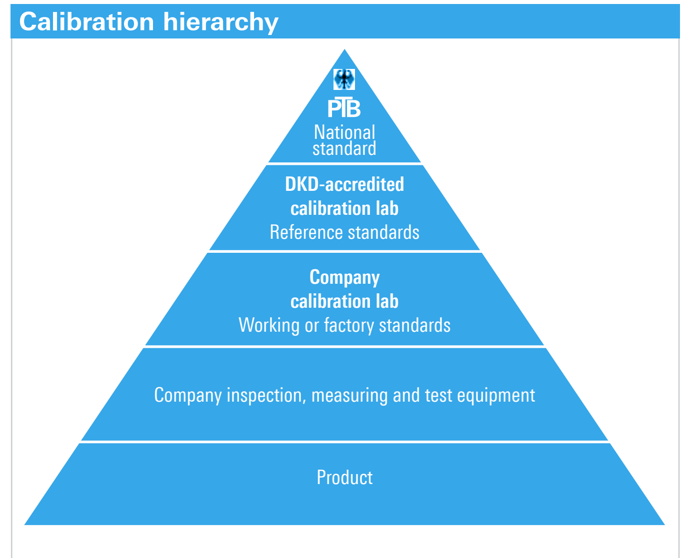


FIG 1 The calibration hierarchy in Germany.

DC quantities	Direct voltage, direct current, DC resistance
	Capacitance
LF quantities	Alternating voltage, alternating current
	AC-DC voltage transfer difference
	AC-DC current transfer difference
RF quantities	RF power, RF attenuation, RF impedance
Time	Time interval, frequency

FIG 2 Accredited measurands of the DKD labs at Rohde&Schwarz.

Thermistor power sensors as reference standards for RF power

Traceability of RF power, a measurand that is very important to Rohde&Schwarz, is ensured by the PTB through calibration of special power sensors that the DKD labs at Rohde&Schwarz send in at defined intervals. There are five different types that cover the frequency range from 100 kHz to 50 GHz. Above 18 GHz, only power sensors with waveguide connectors are used, which – except in one case – are thermistor power sensors. This type of power sensor disappeared from industrial testing decades ago, but due to its outstanding long-term stability it is still ideal for calibration applications.

This capability results from the functional principle underlying a thermistor power meter: Instead of a termination with a fixed resistance value as its power-absorbing element, it uses a highly temperature-dependent resistor (negative temperature coefficient, NTC), commonly known as a thermistor. This thermistor is heated up using a DC voltage generated in the power meter so that its resistance value adjusts to that of an ideal termination (i.e. 50 Ω in the case of coaxial connectors). If RF power is fed to the power sensor, a control loop reduces the DC voltage so that the thermistor retains its resistance value and its temperature. Thus, the power converted into heat in the thermistor remains constant. Based on the difference between the two DC voltages, the power meter can

Physikalisch-Technische Bundesanstalt (PTB) – Germany's National Metrology Institute

The PTB provides scientific / technical services to Germany and simultaneously serves as the country's top authority in the area of metrology. It was originally founded in Berlin in 1887 as the Physikalisch-Technische Reichsanstalt (PTR) based on the initiatives and ideas of Werner von Siemens and Hermann von Helmholtz. The PTB belongs to the area of competence of the Federal Ministry of Economics and Technology. Through its activities, the PTB ensures and promotes the development and use of advanced, reliable test and measurement equipment, which is important in all areas of society, industry, and science (FIG 3).

Correct measurement results and reliable T&M equipment

The public's interest in correct dimensions and reliable test equipment extends to numerous areas of everyday life. For example, this includes all official measurements made for collection of customs duties or for monitoring traffic on roadways, measurements required in the commercial domain where consumers expect correct measurement results, and measurements used in medicine as well as in environmental protection, radiation protection and occupational safety. This is why these areas are regulated under national and European law. Measuring instruments that are placed on the market must receive a relevant pattern approval. In Germany, pattern approval is required for scales, fuel dispensers, gas and electric meters, taximeters, and traffic radar equipment, for example. The PTB performs a number of statutory tasks in this area by performing pattern approval tests of measuring instruments.

Fundamentals of metrology and technological innovations

Fundamental research into the physical aspects of metrology plays an important role in the PTB's work and is the basis for all of its activities. Focus areas include development of national standards, determination of fundamental constants, exploitation of quantum effects for representing units, creation of reference materials and determination of the properties of materials.

Fundamental constants are quantities that do not change with respect to time and space. Their immutability makes them suitable for realizing and reproducing the legal SI units (FIG 4).

Examples of the traceability of SI units to natural constants are the realization of the volt voltage unit by means of the Josephson effect and of the ohm resistance unit by means of the quantum Hall effect. Realization of fundamental units at the highest level is the basis of metrology and is one of the PTB's core activities. Through its long-term research activities, the PTB secures the fundamentals of metrology, gains extended scientific insights in the area of physics, and contributes to technical innovation.

FIG 3 Statutory activities of the PTB (selection).

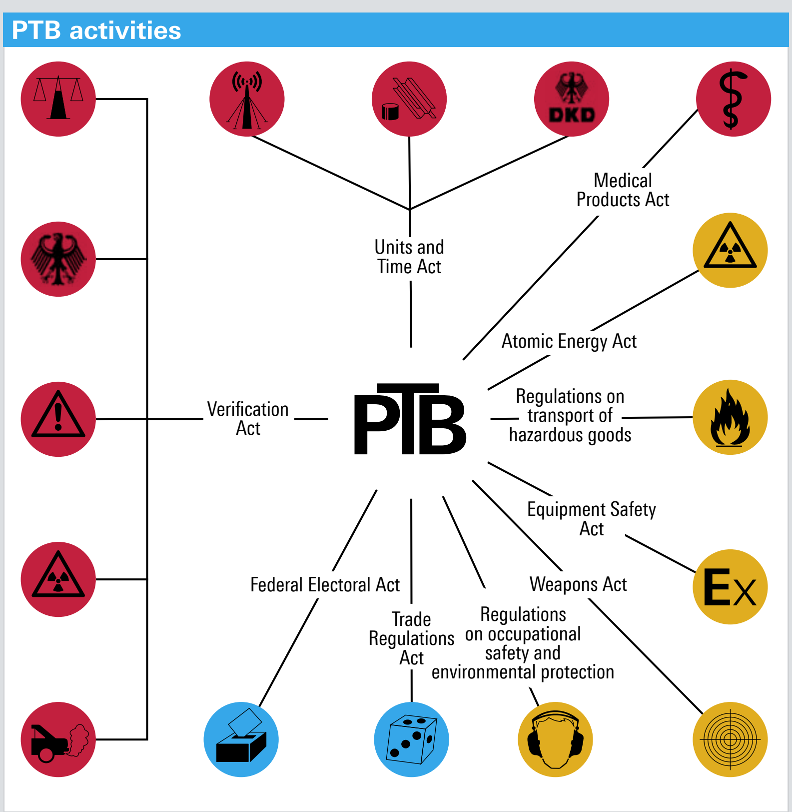
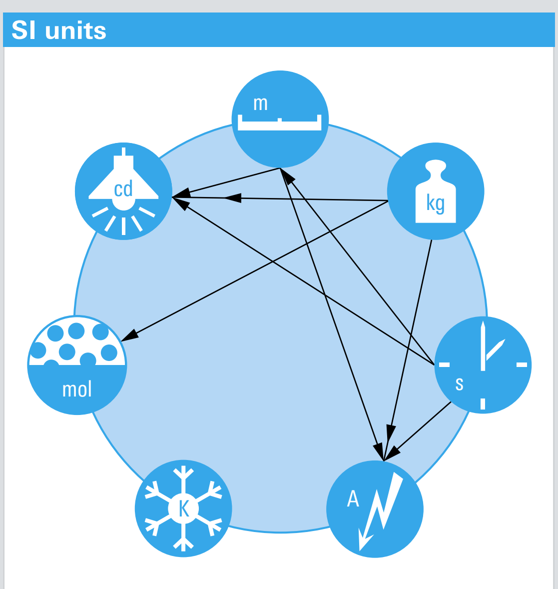


FIG 4 The legal SI units.



measure the DC power substituted with the RF power and thus approximately determine the absorbed RF power. The properties of the thermistor, and particularly the stability of its I/V characteristic, do not play any role.

Since only a fraction of the absorbed RF power reaches the thermistor, RF power can only be measured approximately unless an additional correction is performed. Instead, power is partly converted into heat along the feed line to the thermistor due to the skin effect. The control loop is not capable of compensating for this part so that it remains unknown initially. Without additional correction, the power meter will therefore display a decrease in power level as the frequency increases. To take this effect into account in a measurement, the absorbed RF power losses along the feed line must be determined. The PTB determines these losses by using microcalorimeters to calibrate thermistor power sensors.

Microcalorimeter as a primary standard

Using a microcalorimeter (FIGs 5 and 6) consisting of a thermally well insulated receptacle, it is possible to determine the losses along the feed line and the conversion losses in the thermistor as well as their relationship to the absorbed RF power. The temperature increase generated by the power sensor within the calorimeter is determined, first with the RF power switched off and then switched on. The measurement is performed using an electric thermometer consisting of series-connected thermoelements (thermopile) and is referenced to a second passive thermistor sensor. When the RF power is switched off, the heating is caused exclusively by the DC power that raises the thermistor to the nominal temperature. When the RF power is switched on, additional heating is caused by RF power absorption. The change in temperature and DC voltage that occurs after applying the RF power yields the effective efficiency as follows:

$$\text{Effective efficiency} = \frac{\text{DC substitution power}}{\text{total absorbed RF power}}$$

As soon as this quantity is known, the displayed result of a thermistor power meter can be corrected as a function of frequency. In T&M applications, the effective efficiency as the correction quantity is converted into the calibration factor, which takes into account the reflection of the sensor and is referenced to the power of the incident wave.

Due to the large mass of the sensor, the temperature changes are in the order of only one millikelvin (thousandths of a degree) and the time required to reach thermodynamic equilibrium during the measurement ranges from 60 to 90 minutes per frequency point. Accordingly, complete calibration of a power sensor with typically 40 frequency points takes several days if multiple frequency sweeps are performed.

To minimize unwanted heating of the setup due to RF feed line losses outside of the sensor, thermal insulation sections are built into the RF feed lines. The remaining heat flow is modeled using sophisticated computer simulations and is also determined experimentally and corrected through measurements.

Based on this functional principle, the PTB carries out power calibrations in the frequency range from 10 MHz to 50 GHz. Different types of microcalorimeters are available, including one for the 7 mm coaxial system and three for the waveguide bands from 18 GHz to 50 GHz. Additional calorimeters for higher frequencies are currently in preparation.

Waveguide microcalorimeter

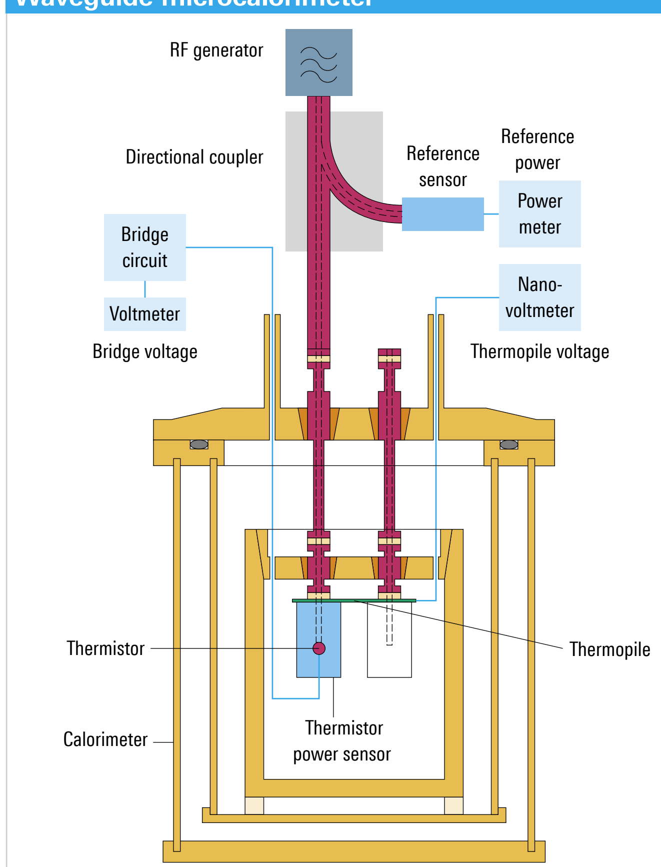


FIG 5 Waveguide microcalorimeter for determining the effective efficiency of thermistor power sensors.

FIG 6 Waveguide microcalorimeter insert with thermistor power sensors.

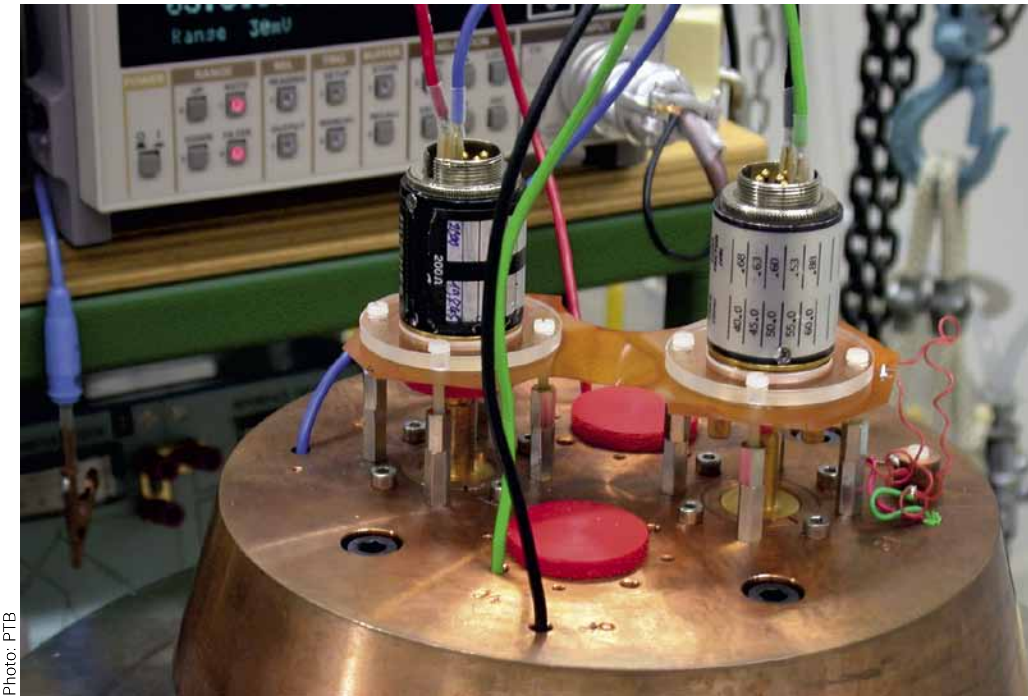


Photo: PTB

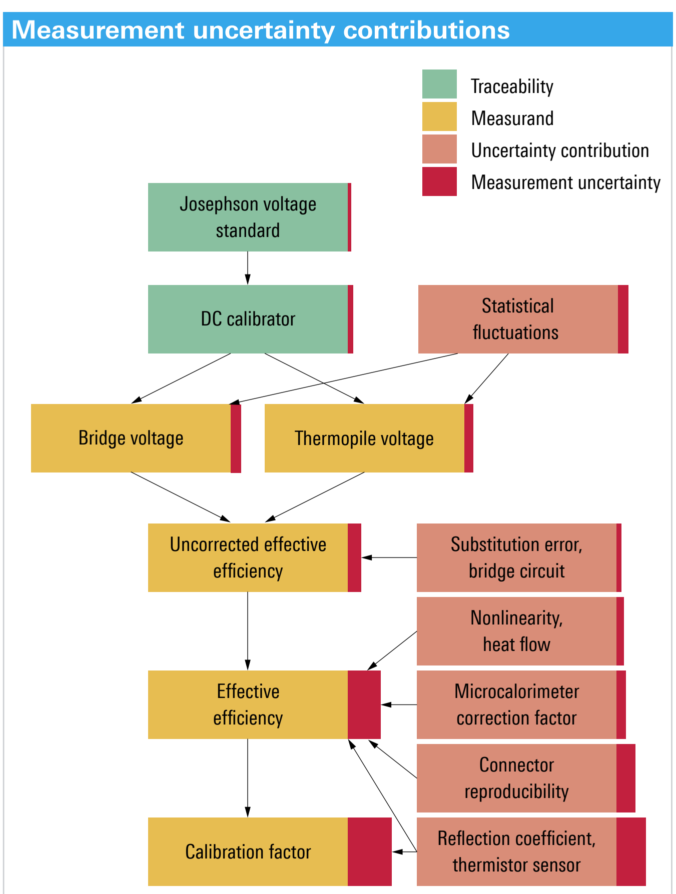


FIG 7 Traceability and measurement uncertainty contributions during calibration of the effective efficiency in the microcalorimeter.

Traceability chain and measurement uncertainty

FIG 7 illustrates how the bridge voltage and the thermopile voltage, i.e. measurands that occur during microcalorimeter calibration, are traced back to voltage as the fundamental quantity, which is realized by means of the Josephson effect. Moreover, the dominant measurement uncertainties and their contribution to the overall measurement uncertainty are also shown in qualitative terms. Note that the ratio between the expanded relative measurement uncertainties of voltage (in the order of 10^{-9}) and the effective efficiency of thermistor sensors (in the order of 5×10^{-3}) is equal to multiple orders of magnitude. This is due to characteristics of RF circuits such as mismatch, power loss, and limited connector reproducibility which cannot be eliminated even by using sophisticated test procedures and equipment.

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