# International Comparison of Thermal Noise-Temperature Measurements at 2, 4, and 12 GHz

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***Abstract*—We discuss an international comparison of thermal noise-power measurements (GTRF-92-2), which has recently been completed under the auspices of the Consultative Committee for Electricity and Magnetism (CCEM). The noise temperatures of two solid-state sources with GPC-7 connectors were measured at 2, 4, and 12 GHz at the national laboratories in France, Germany, the United Kingdom, and the United States. Good agreement was found among the results from the different laboratories, with all results agreeing within the expanded uncertainties, which ranged from approximately 0.5% to 2.9%. The comparison was performed in accordance with the guidelines recently adopted by the Bureau International des Poids et Mesures (BIPM).**

***Index Terms*—International comparison, noise, noise measurement, noise temperature, thermal noise.**

## I. Introduction

An INTERNATIONAL thermal noise comparison has been performed, comparing noise-temperature measurements made at 2, 4, and 12 GHz. The participating laboratories were the Laboratoire Central des Industries Electriques (LCIE) in France, Physikalisch-Technische Bundesanstalt (PTB) in Germany, the National Physical Laboratory (NPL) in the United Kingdom, and the National Institute of Standards and Technology (NIST) in the United States, which served as the pilot laboratory. The comparison was initially approved by the CCEM in 1992 and was assigned the number GTRF-92-2. It became dormant shortly thereafter and remained so until August 1995, which was shortly after the BIPM had adopted a set of guidelines for conducting such international comparisons. We decided to make every effort to follow the guidelines, and a schedule was adopted which did so (approximately). Thus, in addition to comparing noise measurements, this comparison also serves as a test case for the new guidelines.

The schedule adopted for the comparison called for an initial period of organization and protocol development, lasting through the end of 1995. The measurement phase commenced in January 1996, with initial measurements at NIST. The artifacts were then circulated to LCIE, NPL, PTB, and finally back to NIST for repeat measurements to verify that the noise temperatures of the artifacts had not changed during the course of the comparison. The timetable for the circulation and measurement of the standards at the participating laboratories (including twice at the pilot laboratory) allowed a total of 60 weeks for the five sets of measurements, somewhat longer than the ten weeks per laboratory suggested by the guidelines. The scheduling was complicated by the facts that one of the participants performed the relevant measurements at only one time during the year, and that another participant's laboratory facilities were shut down for a period of time due to an internal move.

The artifacts used as traveling standards were two commercial broadband noise sources with GPC-7 connectors. In the interlaboratory transfers, the two sources were shipped on different days so that a single mishap could not damage or lose both at once. Special travel cases were provided by NIST and were used throughout the circulation of the sources. Each laboratory measured the noise temperature of each source at 2, 4, and 12 GHz. The participating laboratories used their own power supplies, operating the sources according to the manufacturer's specifications. The laboratory temperature was to be kept at $(296 \pm 1)$ K. In past experience with the same type of noise source, the noise temperature of the source had varied with the physical temperature of the output connector, and the temperature had risen during use of the source. To avoid this problem, participating laboratories were advised to hold the output connector at room temperature if feasible. The BIPM guidelines specify that the measurements should be performed using the state of the art in the laboratory at the time of the comparison, without additional research or development. Accordingly, the measurements performed for the comparison should be representative of calibrations performed by each laboratory for their usual clients.

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## II. Standards and Radiometers

The standards and radiometers used in the measurements vary among the participating laboratories, and we briefly review the methods and equipment used at each. Summaries of the NIST and PTB standards and systems were given in the report of an earlier, bilateral comparison [1], and so we confine ourselves to brief descriptions here.

The radiometer used at LCIE is of the switching (Dicke) type and uses a 30 MHz receiver. For the 2 GHz measurements the test port to which the device under test (DUT) was connected has a coaxial connector. For 4 and 12 GHz the test port is a waveguide, and adapters are used. At all three frequencies, transfer or working standards are used with the radiometer. Solid-state transfer standards, calibrated at NPL, are used at 2 and 4 GHz. At 12 GHz the transfer standard is a gas discharge tube with R-100 waveguide output, calibrated against LCIE's primary standard, which uses an oven at 1023 K.

At PTB the traveling standards were measured against a coaxial working standard at 2 and 4 GHz. The working standard was calibrated against the PTB primary coaxial standard [2], [3]. At 12 GHz, an R-100 waveguide working standard and a calibrated precision adapter (R-100/GPC-7) were used. The R-100 working standard was calibrated against the PTB R-100 primary standard [4]. Both primary standards consist of a heated termination connected by a (waveguide or coaxial) transmission section to the output section, which is maintained at ambient temperature by circulating water. The operating temperature of the termination is in the range 650–700 K, with output noise temperatures from about 600 to about 650 K. The PTB radiometers are of the switching (or Dicke) type. For the 2 and 4 GHz measurements a coaxial radiometer [1], [5] is used, and for 12 GHz an R-100 waveguide radiometer [6] is used.

The measurements at NPL were performed on a total-power, single-sideband, mismatch-correcting radiometer [7], [8]. The measurements were made against the working standard for the frequency in question, a coaxial working standard at 2 GHz, WG-10 at 4 GHz, and WG-16 at 12 GHz. The working standards were calibrated against the NPL primary thermal noise standards. The primary standard at NPL is a high-temperature thermal source operating at about 650 K.

At NIST the traveling standards were measured directly against a cryogenic primary standard. The primary standard [1], [9] consists of a resistive termination immersed in liquid nitrogen at its boiling temperature, connected by a coaxial transmission line to a GPC-7 output connector at ambient temperature. The measurements were made on total-power radiometers [1], [10], with internal six-port reflectometers to measure relevant reflection coefficients. The radiometers were configured to have GPC-7 connectors and were calibrated in that configuration. Three separate radiometers were used, covering the frequency ranges 2–4 GHz, 4–8 GHz, and 8–12.4 GHz. At 4 GHz, the traveling standards were measured on both radiometers covering that frequency.

Although some of the standards are similar or not entirely independent, there is still sufficient diversity among the standards and radiometers at the participating laboratories to provide a meaningful comparison. Two entirely different types of primary standards are used (cryogenic and oven) and there are also two different types of radiometers (switching and total power). The combinations represented by the participating laboratories are oven standards with switching radiometers at two laboratories, oven standards with a total-power radiometer at one laboratory, and a cryogenic standard with total-power radiometers at one laboratory.

TABLE I
MEASURED NOISE TEMPERATURES (IN K) FOR SOURCE (a) 12 136 AND (b) 12 137

| Laboratory | 2.0 GHz | 4.0 GHz | 12.0 GHz |
|---|---|---|---|
| NIST-1 | 9840 ± 81 | 9409 ± 82 | 10 276 ± 97 |
| LCIE | 9993 ± 232 | 9501 ± 216 | 10 477 ± 308 |
| NPL | 9898 ± 125 | 9499 ± 135 | 10 333 ± 140 |
| PTB | 9834 ± 56 | 9427 ± 70 | 10 264 ± 56 |
| NIST-2 | 9855 ± 81 | 9420 ± 81 | 10 291 ± 97 |
| Mean | 9850 ± 42 | 9435 ± 48 | 10 280 ± 45 |

(a)

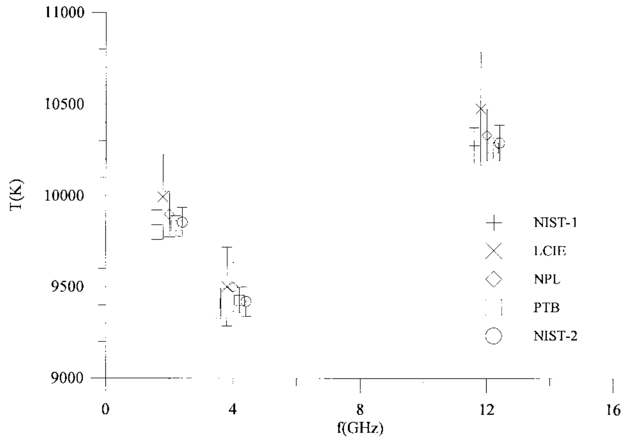
| Laboratory | 2.0 GHz | 4.0 GHz | 12.0 GHz |
|---|---|---|---|
| NIST-1 | 9693 ± 80 | 9347 ± 88 | 10 488 ± 106 |
| LCIE | 9869 ± 228 | 9436 ± 214 | 10 711 ± 314 |
| NPL | 9746 ± 120 | 9430 ± 135 | 10 513 ± 155 |
| PTB | 9673 ± 55 | 9369 ± 69 | 10 474 ± 56 |
| NIST-2 | 9703 ± 80 | 9350 ± 80 | 10 496 ± 99 |
| Mean | 9696 ± 42 | 9373 ± 48 | 10 486 ± 46 |

(b)

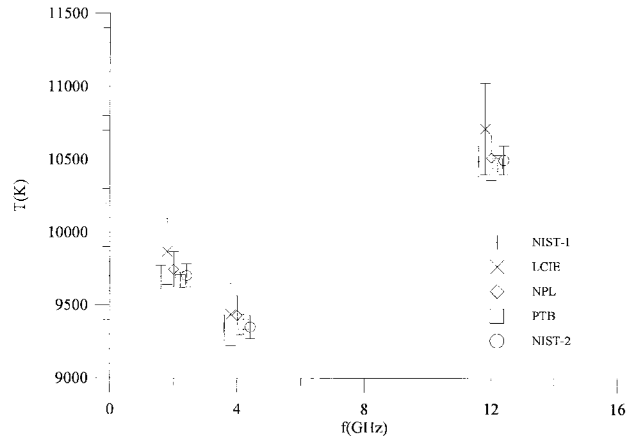
A final point that must be addressed before comparing results is the location of the reference plane at which the noise temperature is measured. LCIE, NPL, and PTB all measure the noise temperature at the plane of the output connector of the source, whereas NIST measures the noise temperature at a plane in the transmission line between the source and the output connector. The difference in noise temperature at the two different planes can be estimated from the connector loss. It is generally less than 0.01 dB for a good GPC-7 connector pair, which for a high noise temperature would lead to a difference of about 0.1% between the temperatures at the two different reference planes. We will not attempt to correct for this difference, but we do note its existence.

## III. RESULTS

Results of the measurements of the noise temperatures of the two devices at each of the laboratories are given in Table I(a) and (b). The uncertainties are the expanded ($k = 2$) uncertainties, corresponding approximately to a 95% coverage probability. The equivalent results for the available excess noise ratio ($\mathrm{ENR}_{av}$) are given in Table II(a) and (b). The order of the laboratories in the tables corresponds to the chronological order of the measurements, beginning and ending at NIST (NIST-1 and NIST-2, respectively). The agreement between NIST-1 and NIST-2 demonstrates the stability of the two traveling standards over the course of the comparison. The maximum difference between before and



(a)



(b)

Fig. 1. (a) Measured noise temperatures for source 12 136. (b) Measured noise temperatures for source 12 137.

TABLE II
MEASURED ENR$_{av}$ (IN DECIBELS) FOR SOURCE (a) 12 136 AND (b) 12 137

| Laboratory | 2.0 GHz | 4.0 GHz | 12.0 GHz |
|---|---|---|---|
| NIST-1 | 15.176 ± 0.037 | 14.975 ± 0.039 | 15.370 ± 0.042 |
| LCIE | 15.245 ± 0.103 | 15.019 ± 0.101 | 15.457 ± 0.130 |
| NPL | 15.202 ± 0.057 | 15.018 ± 0.064 | 15.395 ± 0.061 |
| PTB | 15.173 ± 0.025 | 14.984 ± 0.033 | 15.365 ± 0.024 |
| NIST-2 | 15.183 ± 0.037 | 14.981 ± 0.039 | 15.376 ± 0.042 |

(a)

| Laboratory | 2.0 GHz | 4.0 GHz | 12.0 GHz |
|---|---|---|---|
| NIST-1 | 15.109 ± 0.037 | 14.946 ± 0.042 | 15.461 ± 0.045 |
| LCIE | 15.189 ± 0.102 | 14.988 ± 0.101 | 15.555 ± 0.129 |
| NPL | 15.133 ± 0.055 | 14.985 ± 0.064 | 15.472 ± 0.066 |
| PTB | 15.099 ± 0.025 | 14.956 ± 0.033 | 15.455 ± 0.024 |
| NIST-2 | 15.113 ± 0.037 | 14.947 ± 0.039 | 15.465 ± 0.042 |

(b)

after measurements is 15 K, or about 0.15%, and the average difference is 10 K, about 0.10%.

The final entry in the noise-temperature tables is the weighted mean of the results from the four laboratories and the associated expanded uncertainty, computed from

$$\overline{T} = U_T^2 \sum_i \frac{T_i}{U_i^2}, \quad U_T^2 = \frac{1}{\sum \frac{1}{U_i^2}} \tag{1}$$

with the sums running over the four laboratories. In computing the mean, only one entry was used for NIST, corresponding to the average of NIST-1 and NIST-2. This was done to avoid unfairly weighting the mean toward the NIST results, although in practice the effect would have been slight.

The salient feature of the results is the good agreement among the participating laboratories. Each laboratory, at each frequency, for each device, agrees with the mean within the expanded uncertainty quoted by that laboratory. Considering that the expanded uncertainties are quite small, ranging from approximately 0.5–2.9%, this represents a significant achievement. The agreement is also evident in graphs of the results, presented in Fig. 1(a) and (b). In the graphs, the results at each frequency (2.0, 4.0, and 12.0 GHz) have been grouped near the actual frequency to visually separate the individual data points.

## IV. CONCLUSION

Two principal conclusions may be drawn from this comparison, one technical and the other procedural. The technical conclusion is that measurements at the participating laboratories, made with differing primary standards and different radiometer designs, all agree within the quoted uncertainties, which range approximately from 0.5% to 2.9%. This agreement suggests that both the measurement techniques and the associated uncertainty analyzes at the participating laboratories are correct—to the extent tested by this comparison.

The procedural issues are related to the BIPM guidelines for conducting international comparisons. After its revival in 1995, this comparison was conducted according to the CCE guidelines. The biggest challenge posed by the guidelines was the timetable. At the start of the comparison a schedule that (essentially) met the BIPM guidelines was adopted, and this original schedule was actually followed for the full course of the comparison. Meeting the schedule was facilitated by the BIPM stipulation that the measurements should be done according to the state of the art at the laboratories at the time of the comparison. Additional research or development was not to be done. Consequently, the measurements were treated as (almost) routine calibrations. Typical complications arose and were overcome during the course of the comparison: personnel turnover, measurements at one laboratory performed at only one time during the year, an intramural relocation of one laboratory, delays in customs, and temporary closure of one laboratory. In summary, we found it possible, though not easy, to follow the BIPM guidelines for international comparisons. It required some effort, the cooperation and support of all participating laboratories, and perhaps a little good fortune.

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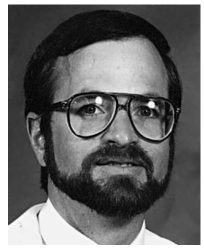

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