

Article

Interlaboratory Comparison of Power Measurements at Millimetre- and Sub-Millimetre-Wave Frequencies

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Abstract: The aim of this paper is to compare the power measurement capabilities in millimetre- and sub-millimetre-wave frequency bands of several national metrology institutes and one research institute. The first comparison, in WR-6.5 waveguide (110 GHz to 170 GHz), involved NPL, TUBITAK UME and PTB. The second comparison, in WR-1.5 waveguide (500 GHz to 750 GHz), involved NPL, METAS, TUBITAK UME, LNE, WAT, GUM and VDI. Two types of travelling standards were used for these comparisons: a thermoelectric power sensor in the WR-6.5 band and a calorimetric power sensor in the WR-6.5 and WR-1.5 bands. The thermoelectric power sensor was characterised by the participants against their own standards and a generalised effective efficiency was calculated. The calorimetric power sensor operating in the WR-6.5 band was measured to observe its behaviour during the comparison and was also measured in the WR-1.5 band after being fitted with a suitable waveguide taper and used in conjunction with a frequency multiplier. The participants measured the output of the calorimetric power sensor and their own power sensor standard. A normalised power ratio method was used as a comparison parameter for the WR-1.5 band measurements. In addition, a pyroelectric power standard was used by METAS to measure absolute power, and a frequency of 650 GHz was used as a link between the absolute power and the power ratios. Finally, all but two of the measurement points compared between the participants achieved agreement in terms of $|E_n|$ scores less than 1. For the first time, an interlaboratory comparison of power measurements at sub-millimetre frequencies has been performed and, overall, good agreement was achieved between the different laboratories.

Keywords: power; comparison; measurement; microwave; sub-millimetre; traceability; waveguide

1. Introduction

Power is a critical parameter for microwave applications, such as 5G, 6G, autonomous vehicles, etc., which have been accessing higher and higher frequency ranges over the last

few decades. Accurate measurements of power levels at high frequencies are essential for certain applications, as well as for the environment. Insufficient power transfer can affect the performance of a system, causing ineffective operation. Over-consumption of power can be detrimental to the environment and cause a drain on natural and financial resources. Therefore, to achieve a reliable application result and help conserve resources, the accuracy or uncertainty of any generated power should be known.

Nowadays, SI power traceability is widely available from a few kHz to 110 GHz [1], but power measurement devices operating up to 325 GHz and, in some cases, even up to 3 THz, are already available on the market [2,3].

In order to achieve traceability of electrical quantities at sub-millimetre frequencies, the European project “Traceability for Electrical Measurements at Millimetre-wave and Terahertz frequencies for communications and electronics technologies” (TEMMT) has been formed under the EMPIR umbrella [4,5]. As part of this effort, the National Physical Laboratory (NPL-UK), the Physikalisch-Technische Bundesanstalt (PTB-Germany) and the Laboratoire National de Metrologie et d’Essais (LNE-France) recently developed primary measurement systems to improve the SI traceable power measurement capability from 110 GHz to 170 GHz and compared their results [6].

International comparisons are a very useful tool for demonstrating the capability of a laboratory and for establishing measurement confidence [7–14]. Two power measurement comparisons were performed by the TEMMT project partners, i.e., NPL (Teddington-UK), TUBITAK UME (Kocaeli-Türkiye), LNE (Trappes-France), WAT and GUM (Warszawa-Poland), METAS (Bern-Switzerland), VDI (VA-USA) and PTB (Braunschweig-Germany), using different travelling standards covering the frequency bands from 110 to 170 GHz (D-band, WG 29 or WR-6.5) and from 500 to 750 GHz (WR-1.5 or WM-380). These travelling standards were designed to facilitate comparison of the results of the different measurement systems and methodologies used by each laboratory. To our knowledge, this is the first time that this type of international comparison exercise has been carried out for power measurements in the WR-6.5 and WR-1.5 bands.

This paper describes these interlaboratory power comparisons from 110 GHz to 170 GHz and from 500 GHz to 750 GHz. Section 2 provides a brief overview of the comparison activities and a description of the travelling standards. Section 3 describes the measurement systems and methodologies used by the participants. Section 4 presents the measurement results, and, finally, Section 5 summarises the results of the comparison.

2. Travelling Standards for Power Comparisons at Millimeter and Sub-Millimetre Frequencies

The two interlaboratory power comparisons performed were as follows: i. the characterisation of a thermoelectric power sensor (TPS) by defining a generalised effective efficiency at frequencies from 110 GHz to 170 GHz; ii. the measurement of the power ratio of a calorimetric power sensor (CPS) with a WR-1.5-to-WR-10 taper attached across the 500 to 750 GHz band. The generalised effective efficiency is a parameter which defines the relation between a power sensor’s output power and the incident power that is dissipated in the sensor. In addition, to monitor the behaviour of the travelling CPS during circulation between the participants, the power ratio for the travelling CPS was measured from 110 GHz to 170 GHz.

In total, a travelling TPS, a CPS, a WR-10 to WR-1.5 taper, a WR-1.5 frequency multiplier and other necessary accessories were circulated between the participants for use in the measurement comparisons.

2.1. WR-6.5 Thermoelectric Power Sensor Heading

The participating laboratories in the WR-6.5 TPS comparison were NPL, TUBITAK UME, LNE and PTB. The travelling standard, a Rohde & Schwarz (R&S) NTS170TWG (s/n 900014) designed to operate between 110 GHz and 170 GHz, is shown in Figure 1. It was provided by R&S and calibrated by PTB. The TPS consists of an RF resistor, a

DC resistor, a thermistor-type resistor with negative temperature coefficient (NTC) and a thermopile. The RF resistor is used to terminate the applied microwave power to the TPS input. The DC resistor is used to obtain SI traceability for microwave power by DC power substitution. The NTC is used to measure the internal temperature of the TPS, and a thermopile is used to measure the effect of any dissipated power in the RF or DC resistors. There is a linear behaviour between dissipated power and thermopile output. Therefore, the correction factor of the TPS, which is called generalised effective efficiency, is defined as the ratio of the thermopile output voltage to the dissipated microwave power (V/W). This type of power sensor is suitable for primary- and secondary-level SI traceable power measurements.



Figure 1. The thermoelectric power sensor manufactured by Rohde & Schwarz, designed to operate from 110 GHz to 170 GHz.

As part of the comparison, participants were asked to measure the microwave parameters of thermoelectric power sensor, specifically, the generalised effective efficiency and the voltage reflection coefficient (VRC), at frequencies from 110 GHz to 170 GHz in 5 GHz steps, using their own measurement setups and procedures.

2.2. WR-6.5 Calorimetric Power Sensor

A commercially available calorimetric power sensor with meter, a VDI Erickson PM5 [3] provided by TUBITAK UME, was selected as the travelling standard for the second power measurement comparison. In order to monitor the behaviour of the travelling CPS during circulation between the participants with their suitable standard, each partner was asked to measure the power sensor/meter combination's power performance over the WR-6.5 band. The native waveguide interface of this sensor was WR-10, so each participant was expected to attach their own WR-10 to WR-6.5 taper to the sensor for measurement purposes.

2.3. WR-1.5 Calorimetric Power Sensor

The same CPS standard used in the WR-6.5 band was used as the reference standard for WR-1.5 band power measurement, with a suitable taper from the WR-1.5 band to WR-10. In addition to the CPS, a WR-1.5 band frequency multiplier provided by VDI (SGX) was used to multiply up the signal generated by the RF source in order to supply power at 500 GHz to 750 GHz. The frequency multiplier had two frequency inputs and it was suggested to use the high-input (lower multiplication factor) option to minimize potential harmonic effects.

The participants for this comparison exercise were NPL, TUBITAK UME, METAS, LNE, WAT, GUM and VDI. Each participant was asked to measure the microwave performance of the travelling CPS and the output power of the travelling frequency multiplier using their own measurement method. The frequencies for this comparison were 500 GHz to 750 GHz in 10 GHz steps, with the addition of the 693 GHz frequency point, which was also included in the data analysis as agreed between the participants.

3. Participants' Measurement Systems

Each participant used their own measurement setups and methods to perform measurements for each of the activities. These are explained below.

3.1. NPL Measurement Setups

3.1.1. Thermoelectric Power Sensor Measurement

The travelling TPS was characterized using two different systems at NPL. First, the generalised effective efficiency of the travelling standard was measured using the measurement system described in [6] at 110 GHz, 115 GHz and 120 GHz. As the travelling standard includes a microwave termination, a DC heater and a thermopile (used to measure the thermoelectric effect of the dissipated microwave power), the DC heater and the thermopile should be used for SI traceable DC substitution, allowing for the measurement of absolute power. After the measurements of the travelling standard at these first three frequencies, the DC heater was observed to be out of specification. Therefore, it was not possible to measure the remaining comparison frequencies using this DC-substituted power method.

To overcome this problem, the generalised raw effective efficiency from 110 GHz to 170 GHz was measured using the power measurement system shown in Figure 2. The signal generator in use includes both a microwave signal generator and a WR-6.5 multiplier to produce the required frequency output and power to be applied to the input port (1) of a directional coupler. A portion of this signal was coupled to port 2 and measured with a standard power sensor/meter (STD) combination. This STD was characterised using NPL's primary power measurement facility. The travelling TPS was connected to the output port (port 3) of the directional coupler. A nanovoltmeter was used to measure the output voltage of the travelling TPS. Microwave power was applied to port 1 from 110 GHz to 170 GHz in 5 GHz steps and was measured simultaneously with the STD and TPS.

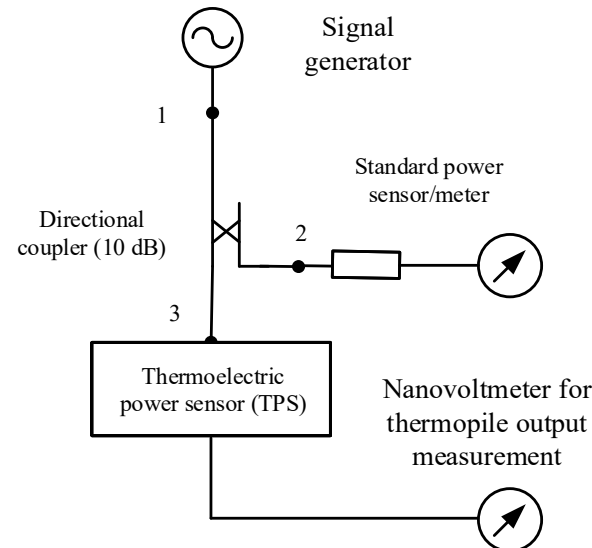


Figure 2. Block diagram of the NPL power measurement system for the WR-6.5 band.

The generalised effective efficiency of the TPS, $\eta_{DUT,v}$, was calculated using the measurement system parameters, as follows:

$$\eta_{DUT,v} = \eta_{STD} \frac{V_{DUT}}{P_{STD}} \frac{|S_{21}|^2}{|S_{31}|^2} \frac{1 - |\Gamma_{STD}|^2}{1 - |\Gamma_{DUT}|^2} \frac{|1 - \Gamma_3 \Gamma_{DUT}|^2}{|1 - \Gamma_2 \Gamma_{STD}|^2} \quad (1)$$

where η_{STD} is the effective efficiency of the STD, P_{STD} is the microwave power measured by the STD, and S_{31} and S_{21} are the voltage transmission coefficients (VTCs) from port 1 to port 3 and port 1 to port 2, respectively, for the waveguide coupler. Γ_{DUT} is the VRC of the travelling TPS, Γ_{STD} is the VRC of the STD, Γ_2 and Γ_3 are VRCs for port 2 and port 3 of the

directional coupler, respectively, and V_{DUT} is the output thermoelectric voltage reflects to dissipated power of the TPS.

The generalised effective efficiency calculated using (1) lacks traceability, as the thermocouple is not characterized. Therefore, the generalised effective efficiencies from 110 GHz to 170 GHz were referenced to the result at 110 GHz using the following ratio:

$$\eta_{DUT,vf} = \frac{\eta_{DUT,v}}{\eta_{DUT,vr}} \quad (2)$$

where $\eta_{DUT,vr}$ is the generalised effective efficiency at 110 GHz, measured using the system shown in Figure 2.

Finally, the generalised effective efficiencies for all frequencies for the travelling TPS were calculated using the referenced generalised effective efficiencies and the measured traceable generalised effective efficiency at 110 GHz ($\eta_{DUT,r}$), using the system provided in [6] and described earlier, as follows:

$$\eta_{DUT,f} = \eta_{DUT,vf} \eta_{DUT,r} \quad (3)$$

3.1.2. Calorimetric Power Sensor Measurement

The travelling CPS was measured in the WR-6.5 and WR-1.5 frequency bands. The WR-6.5 measurements were performed using the measurement setup shown in Figure 3a. NPL's WR-6.5-to-WR-10 taper, which is part of the STD, was used for the STD, and travelling CPS measurements and the STD and CPS were both connected to and measured when the system was turned on. Two voltmeters were used to measure the recorder output voltage of the two power meters. A WR-6.5 frequency multiplier with a multiplication factor of $\times 6$ was used, in conjunction with a signal generator, to achieve a bandwidth of 110 GHz to 170 GHz. The power over the frequency band varied between 7 mW and 18 mW, and the power meters were set to the 20 mW range. The measured powers from both the STD and the CPS were used to calculate the corresponding power ratio.

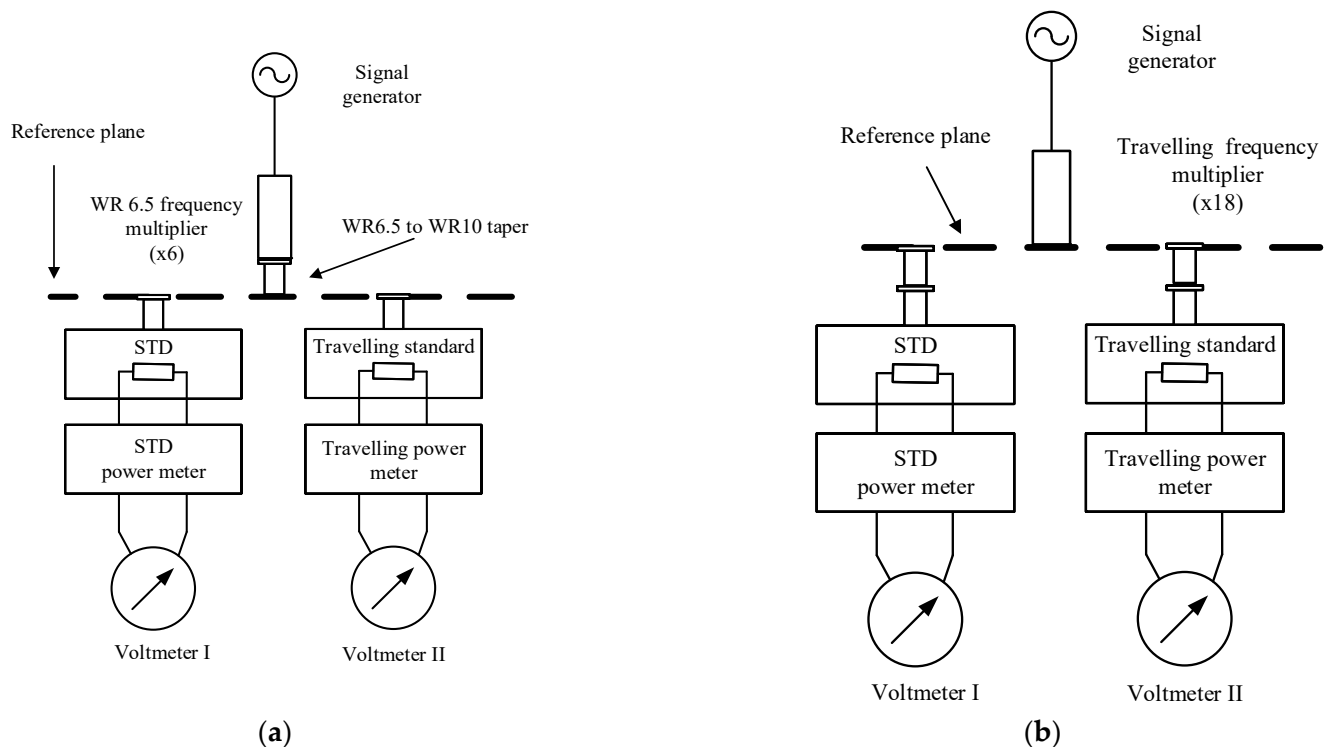


Figure 3. Block diagram of the NPL power measurement systems (a) from 110 GHz to 170 GHz and (b) from 500 GHz to 750 GHz.

The measurement system for the WR-1.5 band is shown in Figure 3b. A signal generator output was connected to the high input of the travelling frequency multiplier ($\times 18$) to reduce any potential harmonic effects. The output of the frequency multiplier was measured with the travelling CPS attached to the travelling WR-1.5-to-WR-10 taper. After this measurement, the travelling CPS/taper combination was removed and the NPL's CPS and WR-1.5-to-WR-10 taper combination was connected to the multiplier output for power measurement. Two voltmeters were used to measure the recorder output voltage with the power meter ranges set to 2 mW. The results of the power measurements for the defined frequencies were used to calculate the appropriate power ratio.

3.2. METAS Measurement Setup and Calibration Process

METAS performed power measurements in the WR-1.5 band using a pyroelectric type of sensor as an STD. The main challenge was to adapt a microwave waveguide source to the sensitive open surface of the optical/THz power detector. Horn antennas, in general (classic pyramid, conical, corrugated, etc.), or modified open-waveguide apertures could be suitable solutions to launch the microwave power from the waveguide source and direct it to the detector. In this case, the calibration process incorporates the evaluation of the entire scattering (S-) parameters of the antenna and the air gap (Figure 4).

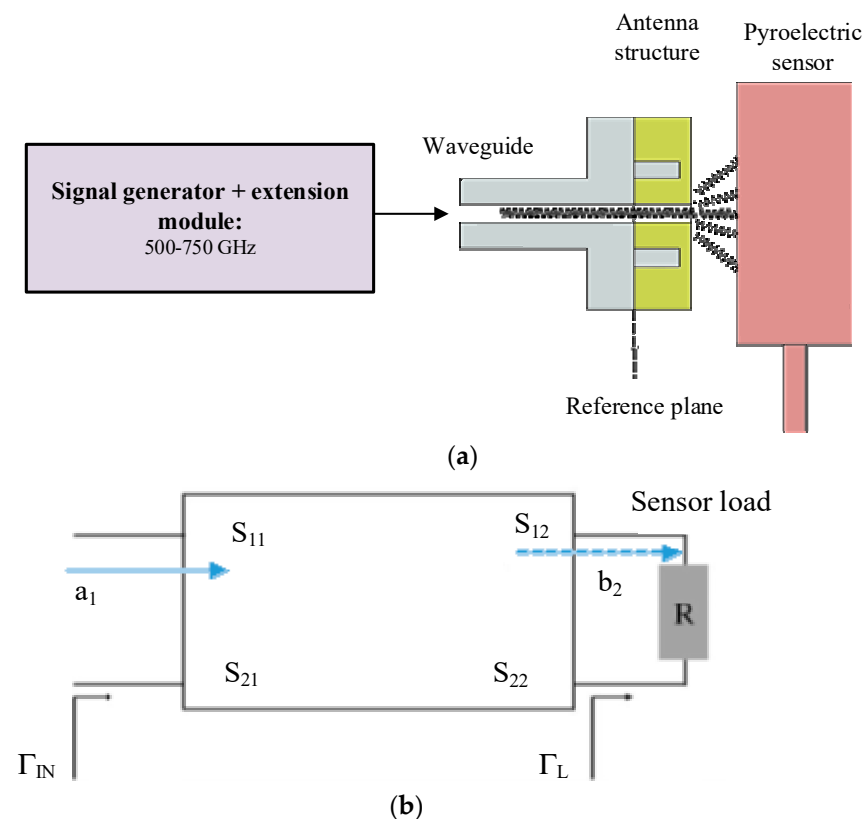


Figure 4. (a) Schematic of power transfer from the “waveguide-source” to the detector as incorporated in the METAS measurement setup and (b) the model for the scattering parameters [15].

The setup consists of a corrugated horn antenna operating in the 500 GHz to 750 GHz range and a modulated RF signal source with a 23 Hz rectangular pulse shape. This is necessary for the pyro-detection process. The horn antenna can be modelled as a Gaussian source with a calculable beam size on its aperture and in the near-field region. The S-parameters of the setup, modelled as denoted in Figure 4, were evaluated in detail in order to fully characterise the setup. Full details can be found in [15].

The output power of the WR-1.5 frequency multiplier at the reference plane was measured with the pyroelectric detector and calculated using the evaluated S-parameters of

the setup. The same output power at the reference plane was measured with the travelling CPS connected, and the power ratio was subsequently calculated.

3.3. TUBITAK UME Measurement Setup

3.3.1. Thermoelectric Power Sensor Measurement

Measurement of waveguide power sensors at millimetre-wave frequencies using the direct comparison transfer method was established at TUBITAK UME using the measurement setup shown in Figure 5. To perform the calibration, software was developed in the C# platform, and measurements were performed in the WR-6.5 band.

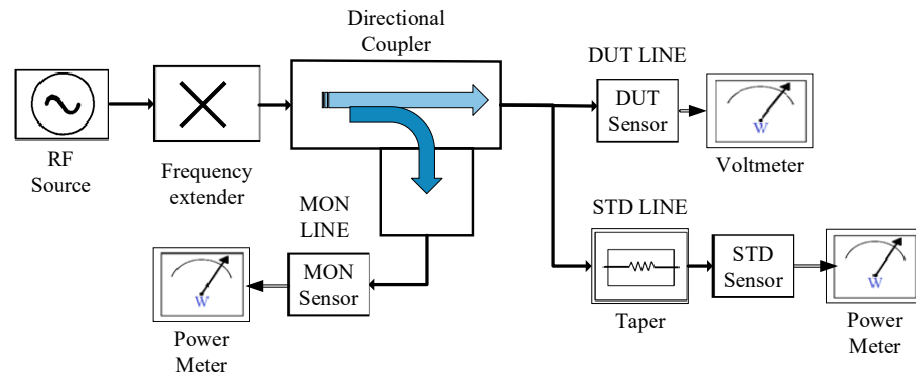


Figure 5. TUBITAK UME power measurement setup for the WR-6.5 band.

The travelling TPS was measured as a DUT sensor using the developed software. To determine the calibration factor of the TPS, an Agilent E8257D was used as the RF signal source, a VDI SGX372 as the frequency extender, a VDI PM5 waveguide power sensor with corresponding power meter as an STD power sensor, another VDI PM5 power sensor and meter as the monitor (MON), and a VDI WR-6.5 directional coupler (10 dB) for sampling the power. Measurements were performed at $8 \text{ dBm} \pm 2 \text{ dB}$.

When the travelling TPS power sensor was connected to the directional coupler, a voltmeter was used to measure the thermopile output of the TPS at each individual frequency. The generalised effective efficiency of the TPS (η_{DUT}) was calculated as follows:

$$\eta_{DUT} = \frac{CF_{STD}}{1 - |\Gamma_{DUT}|^2} \frac{P_D P_{mS}}{P_S P_{mD}} \frac{(1 + |\Gamma_D|^2 |\Gamma_{DC}|^2 - 2|\Gamma_D| |\Gamma_{DC}| \cos(\theta_D + \theta_{DC}))}{(1 + |\Gamma_S|^2 |\Gamma_{DC}|^2 - 2|\Gamma_S| |\Gamma_{DC}| \cos(\theta_S + \theta_{DC}))} \quad (4)$$

where CF_{STD} is the calibration factor of the STD, P_D and P_S are the measured output signals from the TPS and STD, respectively, P_{mS} is the measured microwave power from the MON power sensor when the STD power sensor is connected, P_{mD} is the measured microwave power from the MON power sensor when the TPS connected, $|\Gamma_D|$ and $|\Gamma_S|$ are the VRC values of the TPS and STD, respectively, $|\Gamma_{DC}|$ is the equivalent source reflection coefficient of the directional coupler output port, and θ_D , θ_S and θ_{DC} are the corresponding phases of the TPS, STD and directional coupler output port, respectively. The generalised effective efficiency of the travelling TPS was calculated using the calibration factor and VRC parameters. The uncertainty calculation of the calibration factor was evaluated according to international guidelines on the expression of uncertainty in measurement [16].

3.3.2. Calorimetric Power Sensor Measurement

A comparative power measurement method (setup shown in Figure 6) was used by TUBITAK UME to measure the travelling CPS in both WR-6.5 and WR-1.5 frequency bands.

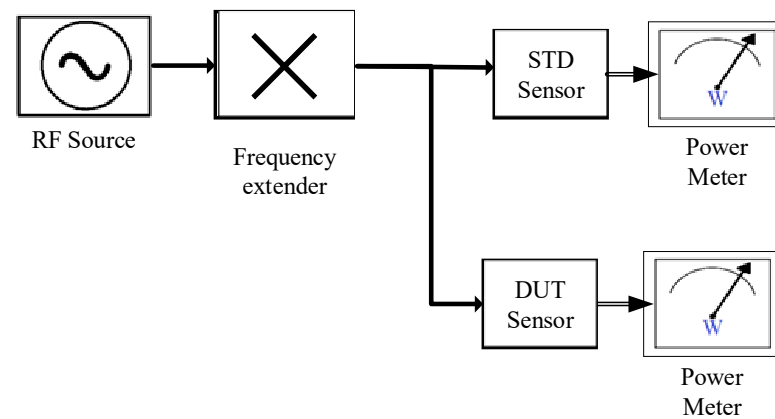


Figure 6. Measurement setup at TUBITAK UME for calorimetric power sensor measurements in the WR-6.5 and WR-1.5 bands.

The travelling CPS as a DUT and STD power sensors fitted with WR-6.5-to-WR-10 tapers were connected, in turn, to the output of the frequency extender, as shown in Figure 6, and power measurements were performed. The powers were measured directly with their appropriate power meters from 110 GHz to 170 GHz in 5 GHz steps using the software, and the power ratios were then calculated.

Power measurements of the same CPS and STD power sensor were performed from 500 GHz to 750 GHz in 10 GHz steps. The travelling CPS was attached to the travelling WR-1.5-to-WR-10 taper, while the laboratory CPS was attached to a laboratory WR-1.5-to-WR-10 taper during the measurements. The CPSs, now fitted with tapers, were connected to the output of the travelling frequency extender, and power measurements were recorded using the software. The power ratio was calculated using the average power for the travelling and laboratory CPSs.

3.4. WAT and GUM Measurement Setup

WAT, in cooperation with GUM, performed power measurements of the travelling CPS in the WR-1.5 band. The measurement setup used is shown in Figure 7.

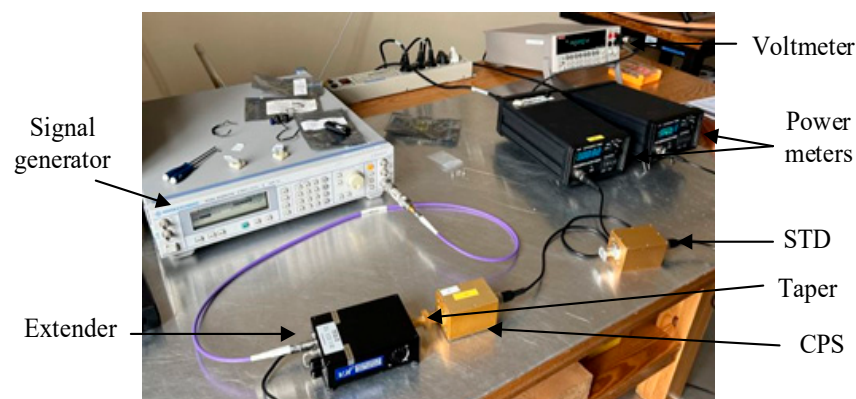


Figure 7. The power measurement setup for the WR-1.5 band used by WAT and GUM.

A VDI SGX 736 extender (500 to 750 GHz) with a taper (WR-1.5–WR-10) was used as the radiation source, and an R&S SMR 20 signal generator with a 3 dB attenuator was used as the RF source. The generated power was set to +13 dBm. The travelling frequency extender was set to operate with a multiplication factor of a $\times 54$ (RF input (L)). The extender output was connected via a taper to a standard and a travelling CPS head of an Erickson power meter. To readout the analogue signal from the power meters, a Keithley 2010 voltmeter was used.

WAT provided a VDI PM4 as a laboratory CPS to be used as an STD which was compared with the travelling CPS. The power meters were used sequentially and separately. As shown in Figure 7, only one CPS head was connected to the travelling frequency extender during the frequency sweep. After data collection in the 500 GHz to 750 GHz band, measurements with a second power meter were performed. The power meter range was set to 2 mW.

3.5. LNE Measurement Setup

LNE measured the power ratio (W/W) between the travelling CPS/taper combination and their own calorimetric power standard, a VDI PM5B, in the 500 to 750 GHz band, as well as the power ratio between the travelling CPS and an R&S TPS (R&S NTS170 TWG, SN: 900003) in the 110 GHz to 170 GHz band. The standard TPS was calibrated in advance using LNE's primary setup as described in [6]. As the reference plane for the power measurement for the comparison was defined at the frequency multiplier output, the losses of the sensor head (including the 1" WR10SWG section) and the waveguide taper used in the case of the travelling CPS (PM5) were taken into account, and corrections were applied to the calorimetric measurement data.

3.6. VDI Measurement Setup

VDI supplied the frequency multiplier (a VDI SGX 736) for the 500 GHz to 750 GHz band and measured the output power before and after the comparison to ensure its stability. VDI used its own Erickson calorimetric power sensor/taper combination for the measurements.

4. Measurement Results

The travelling standards were measured in the corresponding frequency bands by the participants as described above, and the measurement results were sent to NPL for processing and evaluation. The results were evaluated with the help of the participants and are discussed below.

4.1. Travelling TPS Measurement Results

The travelling TPS provided and characterised by PTB was measured by TUBITAK UME, NPL and LNE, respectively. The DC heater of the travelling standard malfunctioned during the NPL measurements; therefore, LNE could not provide generalised effective efficiency results.

The generalised effective efficiencies measured by PTB, NPL and TUBITAK UME are illustrated in Figure 8. The PTB and NPL measurements are traceable to their own microcalorimeters [6], and TUBITAK UME used a commercial power sensor as a standard. Each participant used the law of propagation method described in the BIPM-GUM [16] to calculate their uncertainties. The uncertainties included Type A and Type B contributions from the measurement device and the mismatch effect. The uncertainties of NPL, PTB and TUBITAK vary between 0.046 and 0.104 V/W, 0.080 and 0.201 V/W and 0.041 and 0.189 V/W, respectively, while the measurement result varies between 0.630 and 0.840 V/W, 0.622 and 0.845 V/W and 0.578 and 0.830 V/W, respectively. Therefore, the average of the NPL and PTB measurements was used to evaluate the results. The uncertainty in the average result was calculated using the NPL and PTB uncertainties and the standard deviation of the average. The average as a reference and its expanded uncertainty with coverage factor $k = 2$ to obtain a ~95% confidence level [16] are also depicted in Figure 8.

The generalised effective efficiency results vary from 0.6292 V/W at 120 GHz to 0.8442 V/W at 145 GHz, with an average of 0.7650 V/W. The expanded uncertainty ($k = 2$) varies from 0.0401 V/W at 110 GHz to 0.1077 V/W at 165 GHz.

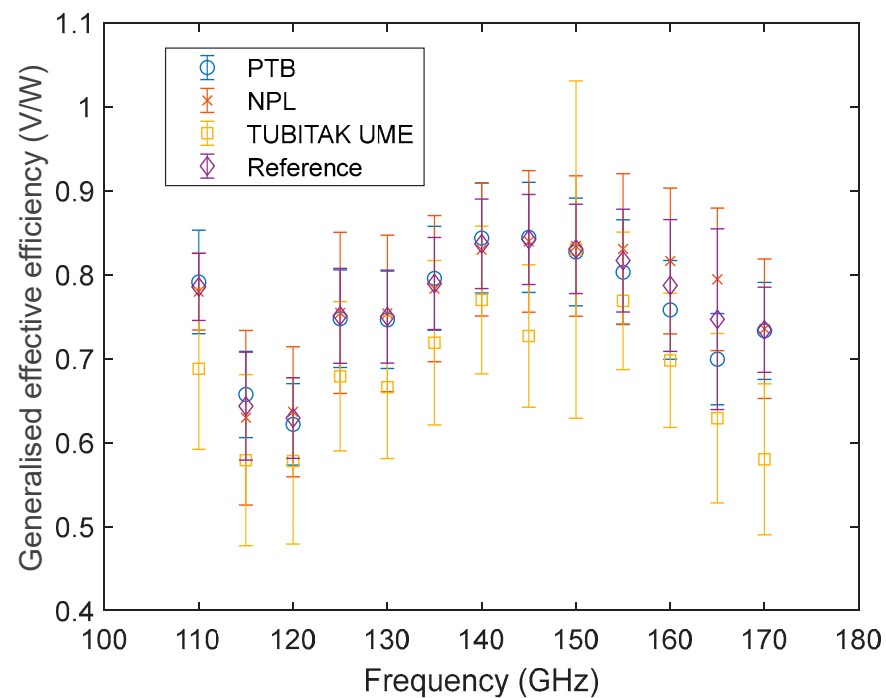


Figure 8. Generalised effective efficiency measurement results for the travelling thermoelectric power standard in the WR-6.5 band from the three participating laboratories, with measurement uncertainties.

The normalised error (E_n) was used to evaluate the participant results, as follows:

$$E_n = \frac{X_{lab} - X_{ref}}{\sqrt{U_{lab}^2 + U_{ref}^2}} \quad (5)$$

where X_{lab} and U_{lab} are the participating laboratory's generalised effective efficiency results and their expanded uncertainty, respectively, and X_{ref} and U_{ref} are the calculated reference generalised effective efficiency result and its expanded uncertainty, respectively. The calculated E_n values for each participant are provided in Table 1.

Table 1. E_n values for the participants.

Frequency (GHz)	PTB	NPL	TUBITAK UME
110	0.08	−0.10	−0.94
115	0.17	−0.11	−0.53
120	−0.11	0.08	−0.47
125	−0.04	0.03	−0.68
130	−0.05	0.03	−0.83
135	0.07	−0.06	−0.63
140	0.08	−0.07	−0.65
145	0.03	−0.02	−1.15
150	−0.04	0.04	0.00
155	−0.16	0.13	−0.47
160	−0.30	0.25	−0.80
165	−0.39	0.35	−0.80
170	−0.02	0.01	−1.50

The $|E_n|$ values lower than 1 indicate that the result from the participating laboratory shows good agreement. The maximum, minimum and average E_n values for NPL are 0.35, −0.11 and 0.04, respectively; for PTB, they are 0.17, −0.39 and −0.05, respectively; for TUBITAK UME, they are 0.00, −1.50 and −0.73, respectively. Two TUBITAK UME E_n

values, -1.15 at 145 GHz and -1.50 at 170 GHz, are higher than $|1|$, with all other results lower than $|1|$.

The VRCs of the travelling TPS were also measured as an additional parameter. Figure 9 shows the VRCs measured by each participant. The magnitude of the VRC varies between a minimum of around 0.04 at 160 GHz and a maximum of around 0.2 at 115 GHz. Overall, the results of the participants are in good agreement with each other.

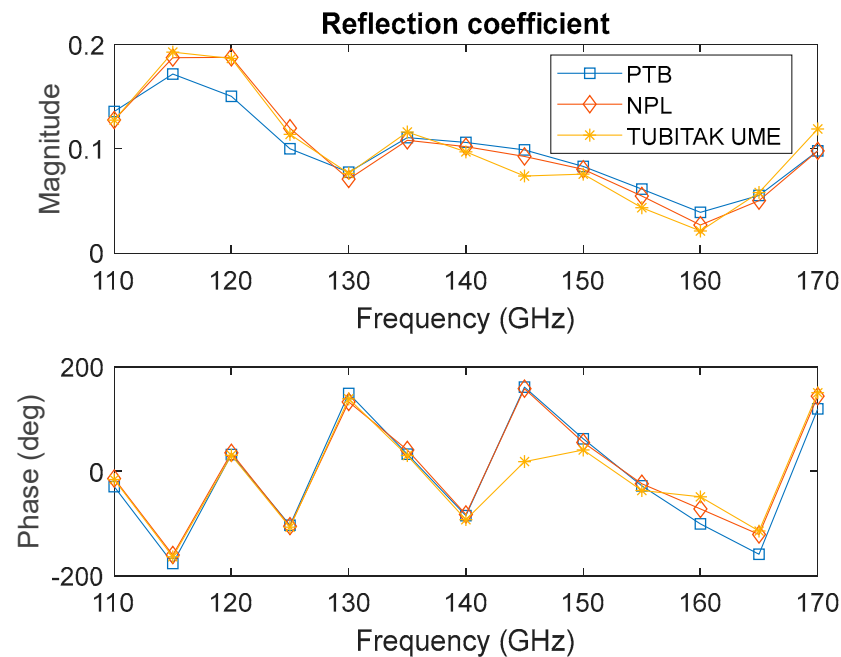


Figure 9. Voltage reflection coefficient measurements of the TPS travelling standard shown in magnitude (**top**) and phase (**bottom**) format.

4.2. Travelling CPS Measurement Results in the WR-6.5 Band

The WR-6.5 band measurements of the CPS were evaluated using power ratios calculated from the reported measurements of the local standards and the travelling CPS. The participants (NPL, LNE and TUBITAK UME) used their own waveguide tapers to interface their measurement systems with their local standard and the travelling CPS. The reported power ratios have been corrected for the taper effects, allowing an evaluation of the sensor performance and helping to assess the sensor stability. NPL and TUBITAK UME performed measurements in 10 GHz steps and LNE in 20 GHz steps.

The measured power varies between 7 mW and 18 mW, 6 mW and 15 mW and 2 mW and 9 mW for NPL, LNE and TUBITAK UME, respectively. The power ratios for NPL, LNE and TUBITAK UME are shown in Figure 10.

The average result at each step, including standard deviations with a coverage factor $k = 2$, were calculated from the NPL, LNE and TUBITAK UME measurements and are represented in Figure 10 by the circles with error bars. The results were used to assess the travelling CPS's behaviour during the comparison period. The average, maximum and minimum values shown in Figure 10 are 1.0026, 1.0112 and 0.9911, respectively. The average, maximum and minimum of the standard deviations are 1.6%, 3.8% and 0.1%, respectively. These results are sufficiently low to show that the travelling CPS was stable during the comparison, and the NPL, LNE and TUBITAK UME measurement methodologies and setups demonstrated good agreement with each other.

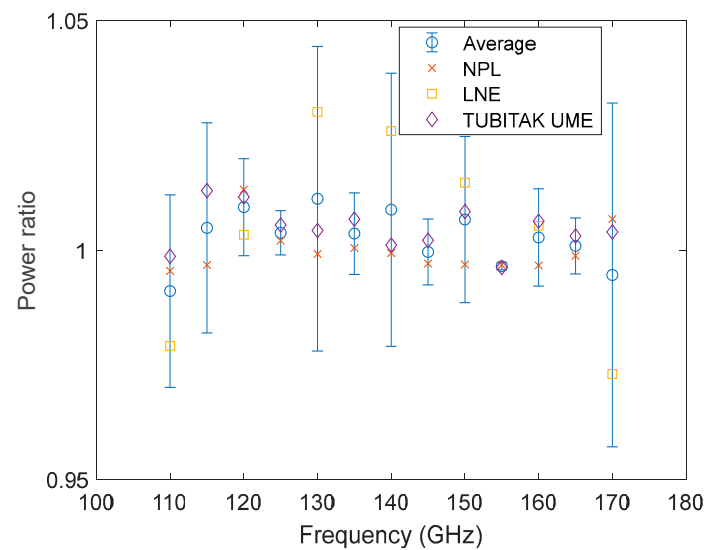


Figure 10. Power ratio measurement results for the travelling CPS in the WR-6.5 band.

4.3. WR-1.5 Frequency Multiplier Measurement

The WR-1.5 frequency multiplier was used for the 500 GHz to 750 GHz measurements. The frequency multiplier was supplied by VDI and measured before (VDI 1) and after (VDI 2) the comparison loop to ensure its performance and stability. It has two frequency inputs, one being $\times 18$ (RF input (H)) and the other $\times 54$ (RF input (L)). It was suggested that the participants use the high-frequency input ($\times 18$) for the comparison. The output power of the frequency multiplier with respect to the high-frequency input was measured with a calorimetric power sensor by VDI.

The output power measurements of all participants are illustrated in Figure 11. With the exception of VDI, which used its own CPS for the power measurements, all participants in this WR-1.5 band measurement comparison used the travelling CPS and taper. WAT-GUM and METAS used the $\times 54$ input of the frequency multiplier. The displayed results are raw measurements. The average and one-sigma experimental standard deviation of the measurements were calculated and are depicted in Figure 11 by the circles with error bar. The average, maximum and minimum standard deviations were calculated to be 14%, 26% and 9%, respectively, while the average power varies between around 0.08 mW and 0.39 mW.

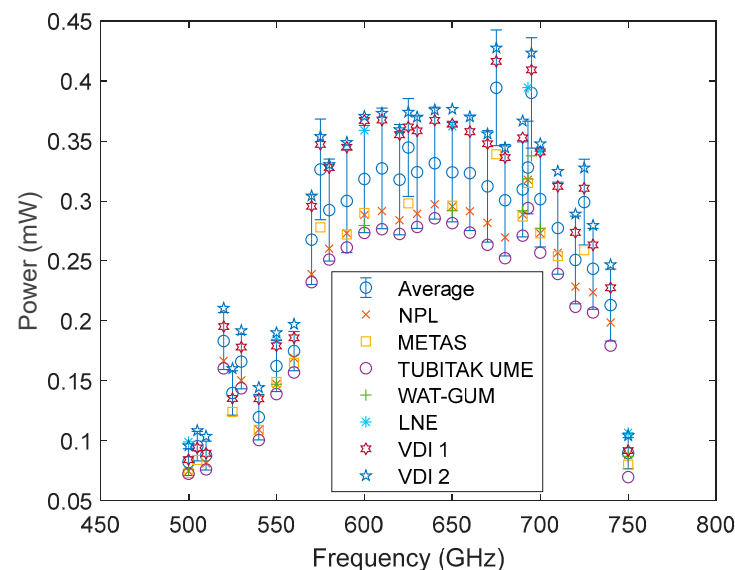


Figure 11. Output power of the WR-1.5 travelling frequency multiplier measured throughout the duration of the comparison.

A total of 156 points were measured by all participants, and 71% of them agree with the average within a one-sigma standard deviation limit. Furthermore, all the measurements obtained are within the limits of the two-sigma standard deviations. We can conclude from the results that the frequency multiplier was stable during the comparison and that use of the different input settings did not significantly affect the output.

4.4. Travelling CPS Measurement Results in the WR-1.5 Band

WR-1.5 band power measurements of the travelling CPS, with WR-10 to WR-1.5 taper attached, were performed by NPL, LNE, TUBITAK UME, METAS and WAT-GUM. NPL, LNE, WAT-GUM and TUBITAK UME measured the travelling CPS/taper combination against their own calorimetric power sensor/taper standard and reported the power measurements of their standard and the travelling CPS. In addition, the power ratio for each laboratory between the laboratory standard and the travelling CPS was calculated to minimise additional effects such as errors due to the laboratory standard, possible sub-harmonics, environmental conditions and different power levels.

METAS used a pyroelectric sensor as a standard for power measurements in the WR-1.5 band. Pyroelectric sensors can be characterised using traceable optical standards [17] and are a good candidate as standards for obtaining traceability of guided power at sub-millimetre-wave frequencies [18]. The modulated signals with a 23 Hz rectangular pulse shape were generated from 500 GHz to 750 GHz using a signal generator and the travelling frequency multiplier with LF input ($\times 54$) and applied to the pyroelectric sensor via an antenna structure.

A correction was applied to the measured power from the pyroelectric sensor using the pyroelectric sensor, antenna structure and air effects as described in [15] to define the output power of the travelling frequency multiplier at the reference point as shown in Figure 4. The S-parameters of the antenna structure and the air gap were evaluated with an estimated expanded uncertainty ($k = 2$) of less than 7%, and, finally, the expanded uncertainty ($k = 2$) for the calculated power was estimated to be 12%.

After the pyroelectric sensor measurement, the travelling CPS/taper combination was connected to the frequency multiplier output port, and the power was measured with the power meter. The calculated power with expanded uncertainty ($k = 2$) at the output port of the travelling frequency multiplier and the power measured by the travelling CPS/taper combination are illustrated in Figure 12.

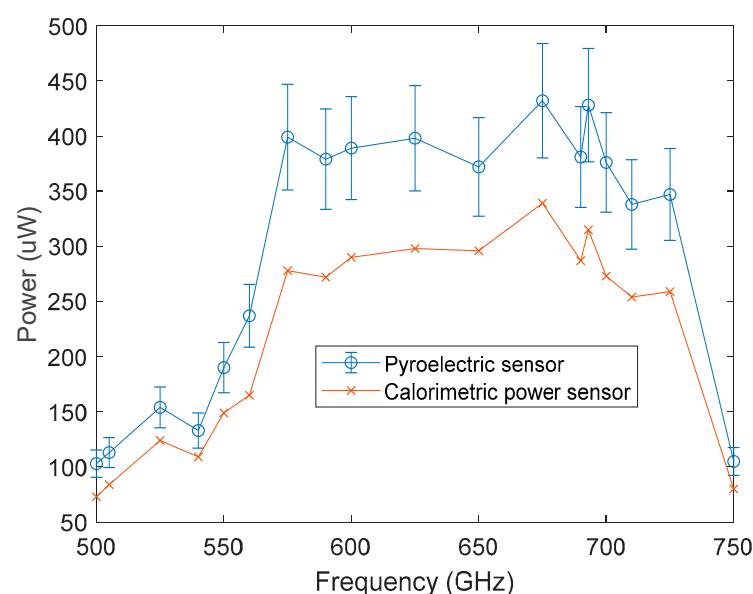


Figure 12. METAS power measurements of the pyroelectric sensor standard and the travelling CPS in the WR-1.5 band.

The CPS results are outside the expanded uncertainty limits of the pyroelectric sensor due to the loss caused by the attached taper. The insertion losses of the taper and the straight waveguide section integrated as part of the travelling CPS are provided by the manufacturer as 0.65 dB and 0.30 dB, respectively [19]. The measured power of the travelling CPS, including the straight section and taper combination, was corrected using the total insertion loss in order to obtain the same reference plane for the measurements of the pyroelectric sensor and the travelling CPS. The corrected results are shown in Figure 13.

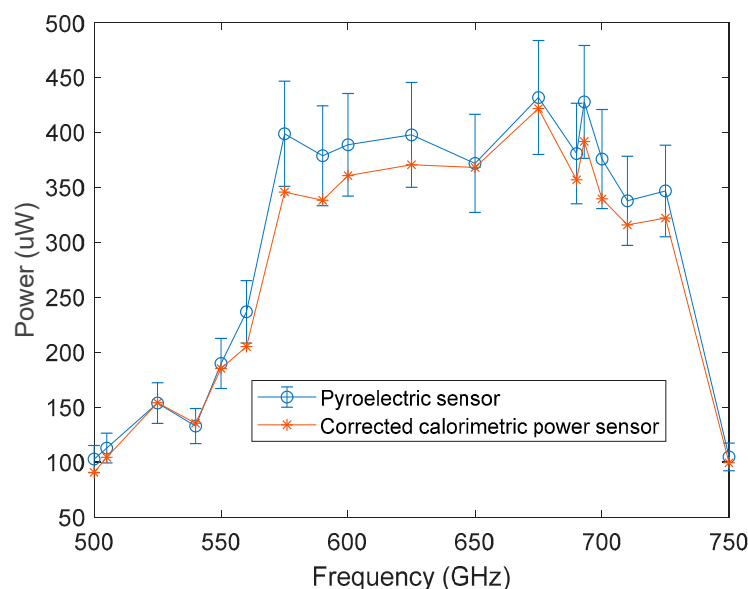


Figure 13. METAS power measurements of the pyroelectric sensor standard and the travelling CPS in the WR-1.5 band with correction for the straight section and taper loss applied.

All the power measurements of the travelling CPS, except at 560 GHz and 575 GHz, are within the expanded uncertainty band of the pyroelectric sensor results. The differences at 560 and 575 GHz are less than 13.5%, while the expanded uncertainty ($k = 2$) is 12%. It is worth noting that the uncertainty contributions due to the straight section, the taper, the travelling CPS and environmental conditions were not studied and considered in this work.

Prior to the comparison, it was agreed that the 693 GHz frequency point would act as a link between the pyroelectric sensor and the travelling CPS measurements. This frequency is one of the calibration frequencies for the pyroelectric standard because of a standard laser. However, it was noticed that the frequency multiplier output power at 693 GHz showed a clear deviation compared to that at other frequencies (see Figure 11). Therefore, it was decided to use one of the measured neighbouring frequencies, being either 650 GHz or 700 GHz. 650 GHz was subsequently agreed upon as the link frequency instead of 693 GHz, as there was no such deviation at this frequency, and a constant responsivity was shown by the pyroelectric sensor at 650 GHz [17].

The power ratios between the travelling CPS and the local standards for the participants were calculated using the reported participants' power measurements, and the power ratios were normalised to the ratio at 650 GHz. The output power of the pyroelectric sensor at 650 GHz measured by METAS was 370 μ W with an uncertainty of 12% ($k = 2$). The CPS-normalised power ratios for the measurements by NPL, LNE, METAS, WAT-GUM and TUBITAK UME are depicted in Figure 14. The average of the normalised power ratios, with uncertainties at each comparison frequency and Type A uncertainties for the participant results, are also shown. All the results are within the expanded uncertainty limits and, therefore, are in good agreement with the average result.

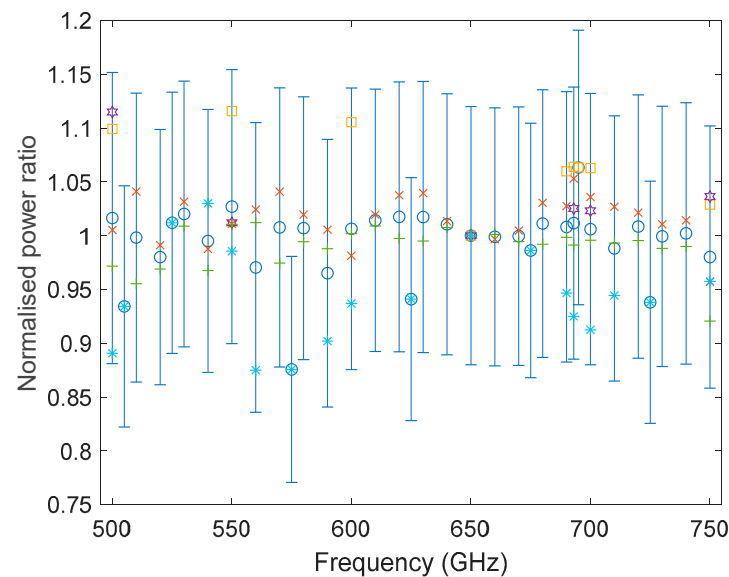


Figure 14. Normalised power ratio results for the travelling CPS in the WR-1.5 band. The normalisation frequency is 650 GHz. Average (Φ), NPL ($\times$), WAT-GUM ($\square$), LNE ($\ast$), TUBITAK UME ($+$) and METAS ($\ast$).

5. Conclusions

International power comparisons in millimetre- and sub-millimetre-wave frequency bands were performed, and, as a result, the power measurement capabilities of several laboratories were compared. A comparison of power measurement in the 110 GHz to 170 GHz band involving TUBITAK UME, NPL and PTB used a thermoelectric power sensor as a travelling standard. Another comparison in the 500 GHz to 750 GHz band, involving NPL, WAT-GUM, TUBITAK UME, LNE, METAS and VDI, used a calorimetric power standard with a taper attached. In addition, a frequency multiplier was provided to the participants to attach to the travelling standard to achieve the required power at sub-millimetre wave frequencies. The calorimetric power sensor was also measured by three of the participating laboratories from 110 GHz to 170 GHz to assess response across the course of the comparison and was shown to be stable.

The generalised effective efficiency of the thermoelectric power sensor was evaluated by the participants in the WR-6.5 band comparison, and E_n values were calculated to evaluate the results from the participants. In total, 95% of the $|E_n|$ results obtained were lower than 1, demonstrating good agreement. The evaluated power ratios of the travelling calorimetric power sensor in the WR-1.5 band were normalised to the 650 GHz result and evaluated. The absolute value power at 650 GHz was measured by METAS with an uncertainty of 12% ($k = 2$), and the participants results were all within the expanded uncertainty ($k = 2$) limits of the average value of the comparison participants' results.

In summary, the two comparisons, of which one is the first of its kind, were successfully performed and have established the equivalence of power measurement capabilities of the participants at millimetre- and sub-millimetre-wave frequencies.

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Conflicts of Interest: Steven Durant and Jeffrey Hesler were employed by Virginia Diodes, Inc. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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