Application Note

R&S®NTS RF POWER TRANSFER STANDARDS

Functionality and calibration procedures

Products:

- R&S®NTS18T
- R&S®NTS33T
- R&S®NTS40T
- R&S®NTS50T
- R&S®NTS67T
- R&S®NTS170TWG

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Contents

Symbols

Quantity	Symbol	Description	Unit of measurement[1)]
Frequency	f	Measurement frequency	Hz (GHz)
Reflection coefficient	Γ	(Equivalent) reflection coefficient of DUT or source	1
Line impedance	Z_0	Characteristic impedance of transmission line	Ω
RF power	$P_{\mathrm{RF,sens}}$	RF power dissipated in the 1st heater, sensed by the thermopile of the thermoelectric transfer standard	W (mW)
RF power	$P_{\mathrm{RF,abs}}$	Net RF input power absorbed by the transfer standard	W (mW)
Thermopile output voltage	U_{Th}	Thermopile output voltage of thermoelectric transfer standards	V (µV)
Sensitivity of 1st heater, RF sensitivity	s_{RF}	Effect of the absorbed RF power in the 1st heater on the thermopile output voltage U_{Th}	V/W (µV/mW, mV/W)
Heating coefficient of 1st heater	$k_{\mathrm{RF}} = \frac{1}{s_{\mathrm{RF}}}$	Inverse of RF sensitivity	W/V
Sensitivity of 2nd heater, DC sensitivity	s_{DC}	Effect of the DC power applied to the 2nd heater on the thermopile output voltage U_{Th}	V/W (µV/mW, mV/W)
Heating coefficient of 2nd heater	$k_{\mathrm{DC}} = \frac{1}{s_{\mathrm{DC}}}$	Inverse of DC sensitivity	W/V
Calorimeter response	e	Thermopile output voltage of microcalorimeter	V (µV)
Calorimeter heating coefficient	m	Inverse of the effect of the absorbed power in the microcalorimeter on the calorimeter response e	W/V
Resistance of 2nd heater	R_{DC}	Resistance of 2nd heater	Ω
Voltage at 2nd heater	U_{DC}	DC voltage at 2nd heater	V
Power at 2nd heater	P_{DC}	DC power applied to 2nd heater	W (mW)
Substituted DC power	P_{sub}	Substituted DC power at constant thermopile voltage	W (mW)
Parasitic series resistance	R_{S}	Parasitic series resistance in DC heater feed lines	Ω (mΩ)
Calibration factor	CF	Calibration factor of RF power sensors	1
Generalized efficiency	η_{gen}	For thermoelectric transfer standards, the generalized efficiency is defined as the ratio of substituted DC power in the second heater to the absorbed RF power in the transfer standard at constant sensor thermopile output voltage.	1
Transmission coefficient	a_{RF}	Transmission coefficient between the RF port and the absorbing element (1st heater)	1
Effective efficiency	η_{eff}	For thermistor-mount transfer standards, the effective efficiency is defined as the ratio of substituted DC power to the absorbed RF power in the mount.	1
Detector temperature	T_{det}	Absolute detector temperature in kelvin	K
Detector temperature	ϑ_{det}	Detector temperature in degree Celsius	°C

[1)] Base unit (unit with typically used unit prefix)

Acronyms

Acronym	
SMU	Source measure unit
DMM	Digital multimeter
NVM	Nanovoltmeter
NMI	National metrology institute
PTB	The Physikalisch-Technische Bundesanstalt, the National Metrology Institute of Germany, is a scientific and technical higher federal authority falling within the competence of the Federal Ministry for Economic Affairs and Energy.
TC	Temperature coefficient
TEC	Thermoelectric cooler with peltier elements
VNA	Vector network analyzer
TDR	Time domain reflectometry
DUT	Device under test

Revision history

Revision	Date	Changes
1.0	2025-09	Initial release

1 Overview

Figure 1 R&S®NTS product family of RF power transfer standards

This application note outlines the functionality, measurement and calibration procedures for the R&S®NTS RF power transfer standards. It covers advanced topics such as sensitivity to power levels (operating points) and ambient temperature variations.

Intended for developers and technicians at national metrology institutes (NMIs) and calibration laboratories, this application note provides metrology experts with a concise and comprehensive introduction to utilizing R&S®NTS transfer standards.

It facilitates a seamless transition from thermistor mount-based traceable RF power calibration to R&S®NTS thermoelectric transfer standards.

2 Introduction

With the introduction of R&S®NTS, a new era of traceable RF power measurement has commenced. The R&S®NTS RF power transfer standards do not only replace the outdated thermistor mounts used in traceable RF power calibration but also surpass them in multiple aspects. Thermoelectric transfer standards excel over thermistor mounts in:

- Frequency range:
  - Extending down to DC (coaxial models)
  - Reaching up to 170 GHz (waveguide models)
- Robustness and reliability
- Ease of use, eliminating the need for an external measurement bridge

The R&S®NTS RF power transfer standards are thermoelectric RF power sensors specifically designed for metrological applications.

RF power transfer standards facilitate the transfer of calibration for the physical unit of RF power (expressed in mW or dBm) across the upper levels of the calibration hierarchy, as illustrated in Figure 2.

At the highest level, RF power is traced back to SI units through complex physical experiments conducted at National Metrology Institutes (NMIs).

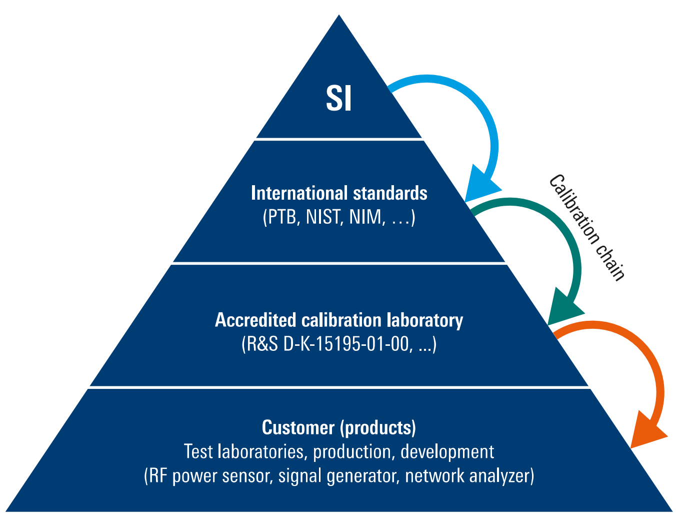

Figure 2 Calibration hierarchy

Generally, the RF power is traced back via the DC substitution method using a microcalorimeter and suitable RF power sensors.
A critical requirement for these RF power sensors is passivity, which is why R&S®NTS devices do not contain any electronics active during measurements.

In the microcalorimeter, the effective efficiency η_{eff} of thermistor-mount transfer standards or the generalized efficiency η_{gen} of thermoelectric transfer standards is determined. For further information on calibrating transfer standards in a microcalorimeter, refer to [1].

The subsequent level of traceable RF power calibration is achieved by transferring the microcalorimeter calibration of an R&S®NTS to another device under test (DUT), a process known as the direct comparison method. Depending on the application, the DUT being calibrated can be another R&S®NTS, an R&S®NRPC power standard, an NRP sensor, or similar power sensors.

Accredited calibration laboratories disseminate further calibrations to customers using custom calibration systems or RF power calibration kits, such as the R&S®NRPC.

3 General information

3.1 Thermoelectric transfer standards

Thermoelectric RF power transfer standards are thermocouple-based RF power sensors that utilize the Seebeck effect. Absorbed RF or DC power heats a resistor ("heater"), creating a temperature gradient detected by a series of thermocouples (thermopile). This thermopile generates a DC voltage proportional to the absorbed power.

R&S®NTS devices feature separate heaters for RF and DC, affecting the same thermopile with optimized symmetry.

The thermoelectric effect has been employed in commercial RF power sensors such as R&S®NRV and NRP for decades [2]. The suitability of thermoelectric RF power sensors for the traceability of the physical quantity RF power was demonstrated early on [3].

Despite this, the traceable RF power calibration in microcalorimeters has predominantly relied on established thermistor-mount transfer standards.
The obsolescence of these thermistor-mount transfer standards, particularly waveguide models (with production ceasing in the 1990s), and the demand for traceable calibration above 110 GHz, prompted the development of thermoelectric R&S®NTS RF power transfer standards.

3.1.1 R&S®NTS transfer standards

Figure 3 Photograph of R&S®NTS170TWG

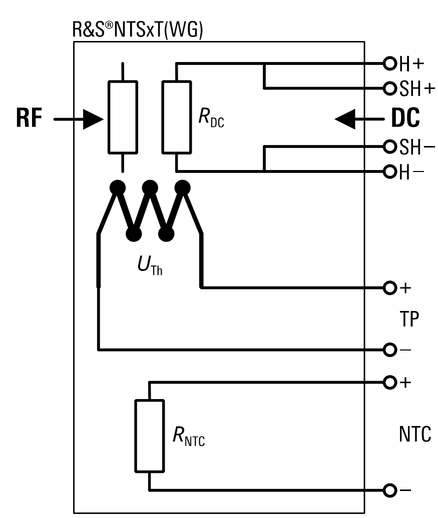

Figure 4 Functional diagram of the R&S®NTS family

From an electrical perspective, the transfer standards comprise a thermoelectric transducer, an NTC resistor for temperature measurement, and their connections to the RF input port on the front side and the DC connector on the rear side.

The 1st heater of the thermoelectric transducer is connected to the RF port via a low-reflective transition, while the 2nd heater is connected to the DC connector via a 4-wire connection for precise DC power measurement.

The DC connector also facilitates the measurement of the thermopile voltage U_{Th} and the NTC resistance.

For detailed pin allocations of the connector, refer to the R&S®NTS manual [4].

3.1.2 Thermoelectric transducer

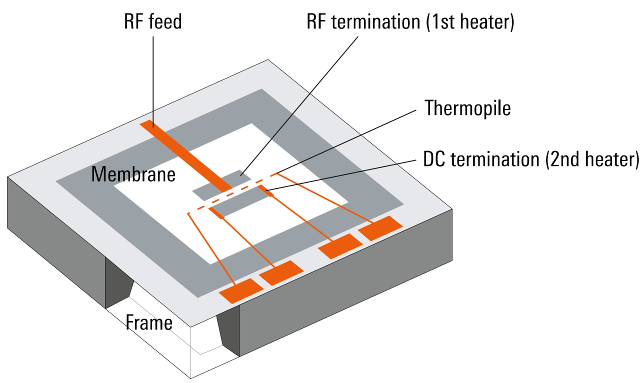

Figure 5 Thermoelectric transducer schematic view.
Hot junction of thermocouples in thermopile indicated as dashed line in the symmetry axis of the two heaters.

The core component of the R&S®NTS transfer standards is a thermoelectric transducer (see Figure 5). This transducer comprises an RF termination (1st heater) and a second heater element (2nd heater) intended to be powered by a DC source. Both heaters are placed on a membrane. The 1st heater is connected to the RF connector via a coplanar RF feed line. A low-reflective transition is positioned in front of the coplanar connection, leading to either the coaxial RF port or the waveguide RF port.

When power is dissipated in one or both heaters, the resulting temperature increase of the membrane is measured using a thermopile, which is a series of thermocouples connected in sequence. For the R&S®NTS, a specialized chip layout of the thermoelectric transducer was developed comprising two symmetric heaters with improved equivalence of RF-DC substitution.

3.2 Comparison to thermistor-mount standards

In thermistor-mount transfer standards, two semiconductor resistors with a high negative temperature coefficient (thermistors) integrate the functions of termination and temperature sensing into a single component. These thermistors simultaneously absorb the RF power to be measured and a DC power (see Figure 6).

Thermistor power meter

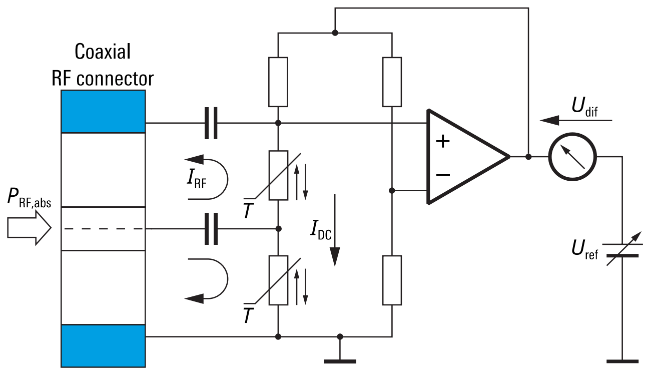

Figure 6 Principle of thermistor power meter. The absorbed RF power can be calculated from the measured voltage difference U_{dif}. With the RF power switched off, U_{ref} is adjusted to give zero voltage difference (zero adjustment). Adapted from [5].

Within a bridge circuit, the DC resistance of the thermistors is kept constant by adjusting the DC power. Any increase in RF power is compensated (substituted) by a corresponding decrease in DC power, and vice versa. The substituted DC power can be easily measured.

For thermistor-mount transfer standards, the effective efficiency η_{eff} is essentially determined by the RF attenuation from the RF port to the absorber (thermistor bead).

R&S®NTS thermoelectric transfer standards

In contrast to thermistor-mount transfer standards, the R&S®NTS thermoelectric transfer standards contain two separate terminations (heaters) for RF and DC power featuring optimized symmetry. The resistances of the heaters have a very low temperature coefficient (see Section 5.9.2).

For thermoelectric transfer standards, the generalized efficiency η_{gen} is essentially determined by the RF attenuation from the RF port to the absorber (1st heater), multiplied by the ratio of the sensitivities of the two heaters.

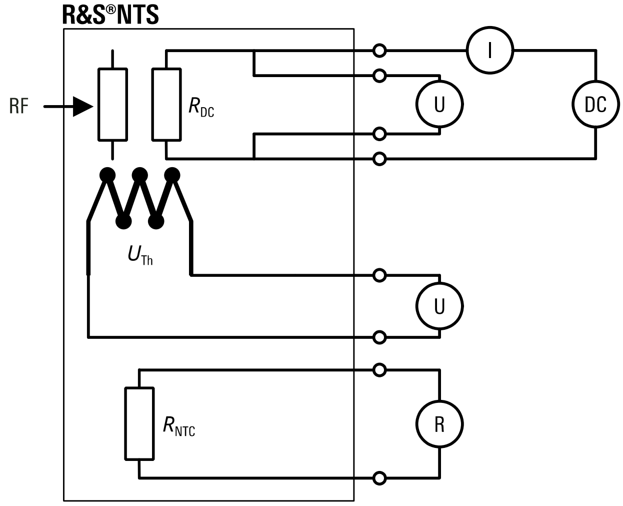

Figure 7 Functional and connection diagram of the R&S®NTS family of thermoelectric RF power transfer standards

A DC-RF power substitution principle similar to thermistor-mount transfer standards can be applied to R&S®NTS thermoelectric transfer standards, offering greater flexibility, as explained in the following sections.

R&S®NTS provide several practical advantages over thermistor-mount transfer standards:

- No proprietary external bridge required
- Reflection coefficient is independent of any bias power
- Calibration requires only standard DC instruments (see Figure 7)
  - DC source (e.g., SMU)
  - Digital multimeters (DMM)
  - Nanovoltmeter (NVM)
- Enhanced robustness
- Operational capability down to DC (coaxial models)

3.3 Measurement principles of R&S®NTS transfer standards

A first terminating resistor, known as the 1st heater, absorbs RF power, while a second resistor, the 2nd heater, absorbs DC power.

The increase in heater temperature is measured using a thermopile, which generates the output voltage U_{Th}.

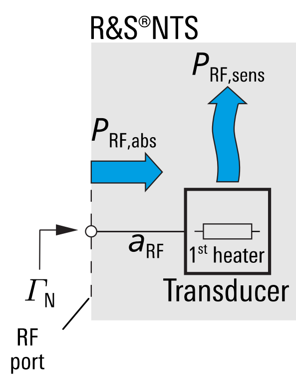

Figure 8 RF Power absorption in R&S®NTS

Generally, the thermopile output voltage is a nonlinear and temperature-dependent function of the RF power dissipated in the 1st heater and the DC power dissipated in the 2nd heater. Using a linear approximation, we derive:

$$U_{\mathrm{Th}} = f\left(P_{\mathrm{DC}}, P_{\mathrm{RF,sens}}\right) = s_{\mathrm{DC}} \cdot P_{\mathrm{DC}} + s_{\mathrm{RF}} \cdot P_{\mathrm{RF,sens}}$$

$$P_{\mathrm{RF,sens}} = P_{\mathrm{RF,abs}} \cdot a_{\mathrm{RF}}$$

With $P_{\mathrm{RF,sens}}$ as the power dissipated in the 1st heater and $P_{\mathrm{RF,abs}}$ as the RF power absorbed by the transfer standard.

a_{RF} is the frequency-dependent transmission coefficient of RF power between the RF port of the R&S®NTS transfer standard and the RF absorbing resistor (1st heater) accounting for the internal transmission line losses.

We obtain the equation for the thermopile output voltage:

$$U_{\mathrm{Th}} = s_{\mathrm{DC}} \cdot P_{\mathrm{DC}} + s_{\mathrm{RF}} \cdot a_{\mathrm{RF}} \cdot P_{\mathrm{RF,abs}} = s_{\mathrm{DC}} \left(P_{\mathrm{DC}} + \frac{s_{\mathrm{RF}}}{s_{\mathrm{DC}}} a_{\mathrm{RF}} \cdot P_{\mathrm{RF,abs}}\right) = s_{\mathrm{DC}}\left(P_{\mathrm{DC}} + \eta_{\mathrm{gen}} P_{\mathrm{RF,abs}}\right)$$

Introducing the definition of the generalized efficiency η_{gen}:

$$\eta_{\text{gen}} = a_{\text{RF}} \cdot \frac{s_{\text{RF}}}{s_{\text{DC}}}$$

η_{gen} depends on a_{RF} and the ratio of heater sensitivities s_{RF} to s_{DC}, which is close to 1 for R&S®NTS [6].

It can be assumed that η_{gen} is, to a first order, independent of the ambient temperature and absorbed power. However, s_{DC} and s_{RF} alone depend on the ambient temperature and absorbed power, which must be considered.

The R&S®NTS transfer standards are optimized such that the 1st and 2nd heaters produce nearly identical effects on the thermopile output voltage. Nonlinearities of both heaters cancel each other out at constant thermopile voltage and temperature. This heater symmetry allows for the substitution of absorbed RF power by DC power with high equivalence — a fundamental requirement for traceable RF power calibration in microcalorimeters.

In Section 5, these temperature-dependent and power-dependent effects are presented in more detail.

To obtain an equivalent definition of η_{gen} to [7], the substitution of RF to DC power in the transfer standard must be considered with:

$U_{\text{Th}_2} = s_{\text{DC}}\left(P_{\text{DC}_2} + \eta_{\text{gen}} P_{\text{RF,abs}}\right)$ (RF and DC power absorbed)

$U_{\text{Th}_1} = s_{\text{DC}} P_{\text{DC}_1}$ (only DC power absorbed, RF turned off)

and the condition:

$U_{\text{Th}_1} = U_{\text{Th}_2}$, respectively $U_{\text{Th}} = \text{const}$

The relation of absorbed powers can be written as:

$$P_{\text{DC}_2} + \eta_{\text{gen}} P_{\text{RF,abs}} = P_{\text{DC}_1}$$

Introducing the substituted DC Power P_{sub} as:

$$P_{\text{sub}} = P_{\text{DC}_1} - P_{\text{DC}_2}$$

results in:

$$\eta_{\text{gen}} P_{\text{RF,abs}} = P_{\text{sub}}$$

which gives the definition:

$$\eta_{\text{gen}} = \left.\frac{P_{\text{sub}}}{P_{\text{RF,abs}}}\right|_{U_{\text{Th}} = \text{const}}$$

The generalized efficiency η_{gen} is defined as the ratio of the substituted DC power in the 2nd heater P_{sub} and the absorbed RF power $P_{\text{RF,abs}}$ for constant thermopile output voltage U_{Th}.

4 Performing measurements

In this section, the measurement methods for R&S®NTS thermoelectric transfer standards are discussed in detail. The fundamentals of calibrating thermoelectric transfer standards in a microcalorimeter are presented. This section also introduces the relationship between the calibration factor and the measured generalized efficiency, describing the further dissemination of RF power calibration.

4.1 Measurement modes

The descriptive equation of the transfer standards is:

$$U_{\mathrm{Th}} = s_{\mathrm{DC}}\left(P_{\mathrm{DC}} + \eta_{\mathrm{gen}} P_{\mathrm{RF,abs}}\right)$$

We assume that the generalized efficiency η_{gen} is known from the calibration within the microcalorimeter. The procedure for performing this calibration is detailed in Section 4.2.

Based on the equation, the two primary modes of operation are most practical: an alternating substitution mode and a continuous substitution mode.

A constant thermopile voltage U_{Th} can either be reached by only applying RF power or DC power at a time (alternating substitution mode) or by applying both at the same time (continuous substitution mode).

Also the so-called sensor mode is another variant that operates without the condition $U_{\mathrm{Th}} = \mathrm{const}$.

4.1.1 Sensor mode

After determination of η_{gen} for the R&S®NTS thermoelectric transfer standard, this calibration can be applied to operate the R&S®NTS using only the RF heater, expressed in a linearized form as:

$$U_{\mathrm{Th}} = s_{\mathrm{DC}} \cdot \eta_{\mathrm{gen}} \cdot P_{\mathrm{RF,abs}}$$

Since nonlinearities and temperature dependencies (refer to Section 5) are not compensated by keeping $U_{\mathrm{Th}} = \mathrm{const}$ by DC substitution, the thermopile response must be corrected for linearity and temperature effects. This correction is performed using a look-up table approach based on prior characterization of the thermopile response.

4.1.2 Alternating substitution mode

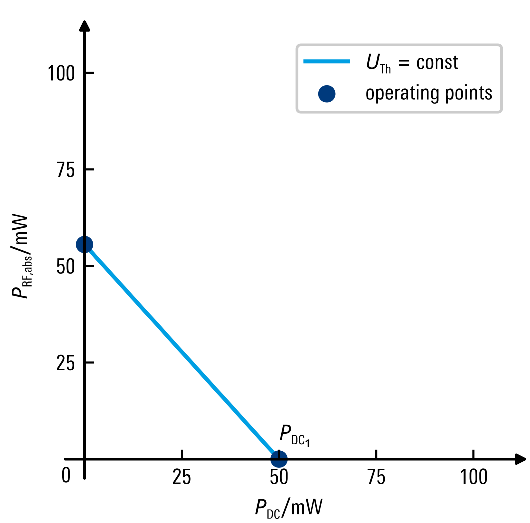

Figure 9 Operating points in alternating substitution mode, η=0.9

In the alternating substitution mode, either the DC power or RF power is exclusively applied to the transfer standard. Figuratively, the operation points of the R&S®NTS are located solely on either the x- or y-axis in Figure 9, keeping the thermopile voltage U_{Th} constant.

The basic setup for alternating substitution in Figure 10 consists of the following instruments:

- RF signal generator

- RF power monitor “PM”, comprising a power sensor and a directional coupler or RF power splitter (e.g. an R&S®NRPC)
- DC power supply (e.g. a source measure unit) for applying DC power to the 2nd heater
  - Two digital multimeters for monitoring voltage and current of 2nd heater (optional, if a source measure unit is used as a DC source)
- Nanovoltmeter for measuring the thermopile voltage
- Digital multimeter for monitoring the NTC temperature

Refer to the R&S®NTS manual [4] for suggested instruments based on the calibration frequency range.

A measurement in alternating substitution mode is performed using the following procedure for one frequency point:

1. Apply RF power (nominal calibration level) and measure U_{Th}, without DC power.
2. Apply DC power to 2nd heater and determine P_{DC_1} at the same value of U_{Th}, without RF power.
3. Calculate $P_{\mathrm{RF,abs}}$:

$$P_{\mathrm{RF,abs}} = \frac{P_{\mathrm{DC}_1}}{\eta_{\mathrm{gen}}}$$

Ambient temperature drift must be minimized during the measurement. We recommend monitoring the detector temperature of the R&S®NTS with a DMM (see section 5.2).

The manufacturer's accuracy specifications for the SMU can significantly contribute to the overall uncertainty. Therefore, we recommend comparing the SMU readings to a reference DMM beforehand [8].

Alternatively, two additional DMMs (Figure 10) can be used alongside the DC source to measure voltage and current of the 2nd heater with improved accuracy.

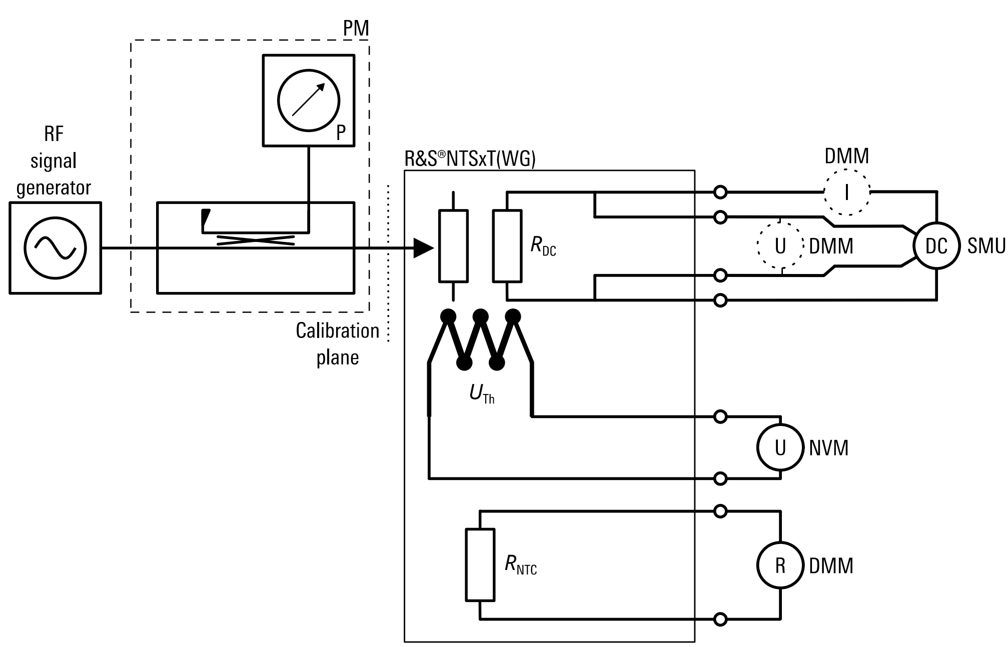

Figure 10 Test setup for alternating substitution mode, remote control interfaces and controlling computer are omitted for clarity

4.1.3 Continuous substitution mode

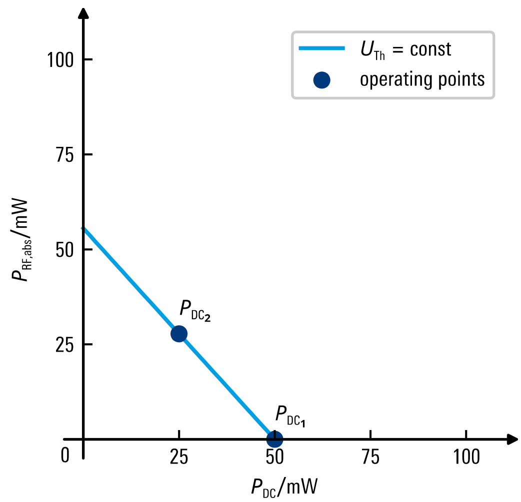

Figure 11 Operating points in continuous substitution mode, η=0.9

In the continuous substitution mode, a control loop keeps the thermopile output voltage U_{Th} constant. Figuratively, the operation points of the R&S®NTS are located on a secant of the constant thermopile voltage U_{Th}, intersecting the x- and y-axis at the corresponding P_{DC} and $P_{\mathrm{RF,abs}}$ power levels in Figure 11.

The control loop (operating point regulator) in the measurement setup (Figure 12) can be implemented either as an analog circuit [9] or as a digital control loop using a similar instrument setup as in Figure 10, with a PC program executing the control loop.

A measurement in continuous substitution mode is performed using the following procedure:

1. Apply DC power (without RF power) and determine P_{DC_1} while the thermopile output voltage U_{Th} is defined depending on the measurement requirements.
2. Apply RF power, while DC power is reduced by the control loop, and measure P_{DC_2} after U_{Th} stabilizes to the same value again.
3. Calculate $P_{\mathrm{RF,abs}}$:

$$P_{\mathrm{RF,abs}} = \frac{P_{\mathrm{DC}_1} - P_{\mathrm{DC}_2}}{\eta_{\mathrm{gen}}}$$

Ambient temperature drift must be minimized during the measurement. We recommend monitoring the detector temperature of R&S®NTS with a DMM (see Section 5.2).

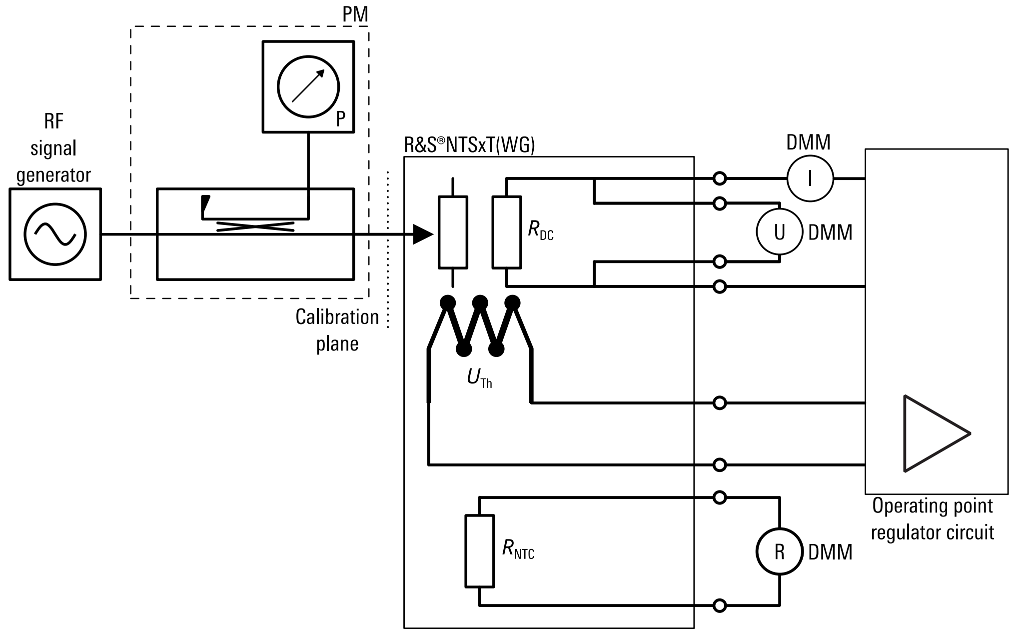

Figure 12 Measurement setup for continuous substitution mode. Remote control interfaces and controlling computer omitted for clarity.

4.2 Calibration within a microcalorimeter

RF power is traced back using a microcalorimeter at a national metrology institute, such as the Physikalisch-Technische Bundesanstalt (PTB) in Germany. The traceability of RF power is ensured through the calibration of RF power transfer standards within a microcalorimeter (see Figure 13 and Figure 14).

The procedure performed at PTB is detailed in [1]. For further reading on microcalorimeters, refer to [10] and [11].

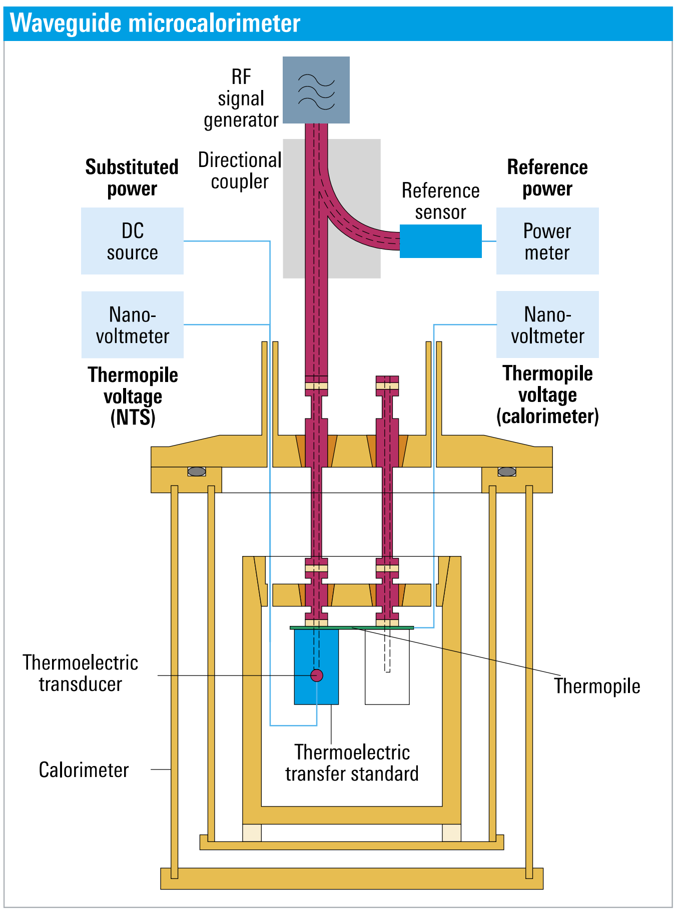

Figure 13 Thermoelectric transfer standard in a microcalorimeter Adapted from [1]

Figure 14 R&S®NTS170TWG mounted in a microcalorimeter at PTB laboratories [12] © Physikalisch-Technische Bundesanstalt

Compared to the calibration of thermistor-mount transfer standards in a microcalorimeter, the calibration of thermoelectric transfer standards features a simplified instrumental setup.
No proprietary external measurement bridge is required; instead, a second nanovoltmeter and a DC source are mandatory (see Figure 13).

4.2.1 General derivation

The calibration of thermoelectric transfer standards in a microcalorimeter consists of two steps.

In a first step, the heating coefficients of the microcalorimeter and the thermoelectric transfer standard are determined with a known DC power.

Using these heating coefficients, the generalized efficiency η_{gen} can be calculated by applying an RF power to the thermoelectric transfer standard in a second step.

1) Apply only DC power without RF power to the 2nd heater of the thermoelectric transfer standard. The following coefficients are measured:

   a) The calorimeter response e_1:
   A known DC power P_{DC_1} absorbed in the transfer standard causes a temperature difference T_1 in the thermopile of the microcalorimeter. The output voltage of this thermopile can be measured as calorimeter response e_1.

   b) The calorimeter heating coefficient m:
   $$m = \frac{P_{\text{DC}_1}}{e_1}$$
   It is the ratio of the applied DC power to the calorimeter response.

   c) The sensor response to the applied DC power P_{DC_1} is measured as thermopile voltage U_{Th_1}.

   d) The heating coefficient of the 2nd heater of the transfer standard, k_{DC}:
   It is defined as $k_{\text{DC}} = \frac{P_{\text{DC}_1}}{U_{\text{Th}_1}}$, the inverse of s_{DC}.

2) Apply RF power and a DC power P_{DC_2} to the 2nd heater of the thermoelectric transfer standard.

   a) The calorimeter response e_2:
   RF and DC power absorbed in the transfer standard cause a temperature difference T_2 in the thermopile of the microcalorimeter. The output voltage of this thermopile can be measured as calorimeter response e_2.

   b) The same calorimeter heating coefficient m is now given as:
   $$m = \frac{P_{\text{RF,abs}} + P_{\text{DC}_2}}{e_2}$$

   c) The sensor response of the transfer standard is measured as thermopile voltage U_{Th_2}:
   $$U_{\text{Th}_2} = \frac{1}{k_{\text{DC}}} \cdot \left(P_{\text{DC}_2} + \eta_{\text{gen}} \cdot P_{\text{RF,abs}}\right)$$

These equations lead to:

$$P_{\text{RF,abs}} = \frac{e_2}{e_1} P_{\text{DC}_1} - P_{\text{DC}_2}$$

and

$$\eta_{\text{gen}} = \left(U_{\text{Th}_2} k_{\text{DC}} - P_{\text{DC}_2}\right) \cdot \frac{1}{P_{\text{RF,abs}}}$$

Thus, the generalized efficiency η_{gen} can be calculated as:

$$\eta_{\text{gen}} = \frac{\frac{U_{\text{Th}_2}}{U_{\text{Th}_1}} P_{\text{DC}_1} - P_{\text{DC}_2}}{\frac{e_2}{e_1} \cdot P_{\text{DC}_1} - P_{\text{DC}_2}} = \frac{\frac{U_{\text{Th}_2}}{U_{\text{Th}_1}} - \frac{P_{\text{DC}_2}}{P_{\text{DC}_1}}}{\frac{e_2}{e_1} - \frac{P_{\text{DC}_2}}{P_{\text{DC}_1}}}$$

4.2.2 Alternating substitution mode

With alternating substitution, either DC power or RF power is exclusively applied to the transfer standard, meaning that $P_{\text{DC}_2} = 0$. The calculation of generalized efficiency reduces to:

$$\eta_{\text{gen}} = \frac{e_1}{e_2} \frac{U_{\text{Th}_2}}{U_{\text{Th}_1}}$$

To eliminate the effect of nonlinearities, U_{Th_1} must be as close as possible to U_{Th_2}.

4.2.3 Continuous substitution mode

In the continuous substitution mode, a control loop keeps the thermopile output voltage at a constant value, which means that $U_{\mathrm{Th}_1} = U_{\mathrm{Th}_2}$. With this, the calculation of the generalized efficiency reduces to:

$$\eta_{\mathrm{gen}} = \frac{P_{\mathrm{DC}_1} - P_{\mathrm{DC}_2}}{\frac{e_2}{e_1} \cdot P_{\mathrm{DC}_1} - P_{\mathrm{DC}_2}}$$

4.2.4 Measurement conditions

To eliminate nonlinearities of thermoelectrical sensors, perform calibration and measurement at constant thermopile voltages.

Especially for international comparisons, it must be ensured that all participants conduct their measurements at the same operating conditions (temperature and thermopile voltage).

4.3 Definition and relation of calibration factor and generalized efficiency

The traceable calibration of thermoelectric transfer standards relies on determining the generalized efficiency η_{gen} of the transfer standard in a microcalorimeter [7].

Subsequent calibrations utilize the calibration factor CF, with both quantities interconnected through the reflection coefficient of the transfer standard Γ_N, which must be measured separately using a vector network analyzer (VNA).

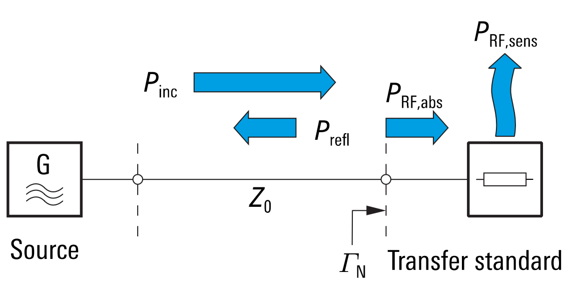

Figure 15 Absorbed and reflected power. Adapted from [5].

The incident RF power to the transfer standard P_{inc} and the reflected RF power P_{refl} are connected through the reflection coefficient of the transfer standard Γ_N:

$$P_{\mathrm{refl}} = |\Gamma_{\mathrm{N}}|^2 P_{\mathrm{inc}}$$

The RF power absorbed in the transfer standard $P_{\mathrm{RF,abs}}$ is the difference of incident and reflected power:

$$P_{\mathrm{RF,abs}} = P_{\mathrm{inc}} - P_{\mathrm{refl}} = P_{\mathrm{inc}} \cdot (1 - |\Gamma_{\mathrm{N}}|^2)$$

Figure 15 gives an overview of these quantities and their relationship.

Introducing the definition of the calibration factor CF as:

$$CF = \frac{P_{\text{sub}}}{P_{\text{inc}}}\bigg|_{U_{\text{Th}} = \text{const}}$$

The following relationship of calibration factor CF to the generalized efficiency η_{gen} is obtained:

$$CF = \eta_{\text{gen}} \cdot (1 - |\Gamma_{\text{N}}|^2)$$

and therefore

$$CF = \eta_{\text{gen}} \cdot \frac{P_{\text{RF,abs}}}{P_{\text{inc}}}$$

4.4 Further dissemination of the calibration

For calibrations at subsequent levels of the calibration hierarchy (see Figure 2), the calibration data obtained for the transfer standard at an NMI is utilized in a direct comparison setup to calibrate additional transfer standards or power sensors.

In a calibration test system (see Figure 16), it is essential to know the reflection coefficient (or equivalent reflection coefficient) of the source to achieve complete mismatch correction during the calibration process.

The R&S®NTS direct comparison application automates the required measurement procedures, as described in Section 4.4.1.

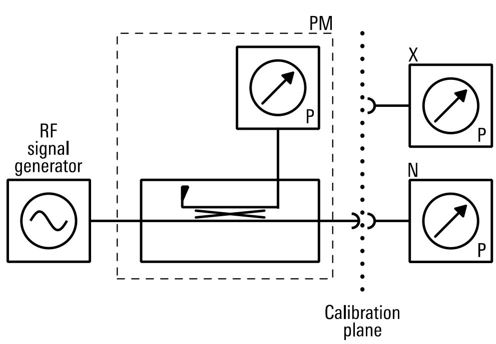

Figure 16 Direct comparison setup

The typical direct comparison setup (see Figure 16 and Figure 17) includes:

- RF signal generator
- RF power monitor “PM”, comprising a power sensor and a directional coupler or RF power splitter (e.g. an R&S®NRPC)
- Transfer standard “N”
- DUT to be calibrated “X”

The calibration factor of the DUT X can be calculated as:

$$CF_{\text{X}} = CF_{\text{N}} \cdot \frac{\frac{P_{\text{X}}}{P_{\text{X,Ref}}}}{\frac{P_{\text{N}}}{P_{\text{N,Ref}}}} \cdot \frac{|1 - \Gamma_{\text{G}} \cdot \Gamma_{\text{X}}|^2}{|1 - \Gamma_{\text{G}} \cdot \Gamma_{\text{N}}|^2}$$

Quantity	Symbol	Description
Calibration factor	CF_{X}	Calibration factor of DUT X
Calibration factor	CF_{N}	Calibration factor of transfer standard N
RF power	P_{X}	Power measured by DUT X
RF power	$P_{\mathrm{X,Ref}}$	Power measured by the power monitor when DUT X connected
RF power	P_{N}	Power measured by the transfer standard N
RF power	$P_{\mathrm{N,Ref}}$	Power measured by the reference power meter when transfer standard N connected
Reflection coefficient	Γ_{G}	Equivalent reflection coefficient of RF power monitor at the calibration plane
Reflection coefficient	Γ_{N}	Reflection coefficient of transfer standard N
Reflection coefficient	Γ_{X}	Reflection coefficient of DUT X

4.4.1 R&S®NTS direct comparison application

The R&S®NTS direct comparison application (see Figure 17) automates the alternating substitution method, simplifying the calibration process with R&S®NTS transfer standards. For more detailed information, refer to the R&S®NTS direct comparison help [13].

The R&S®NTS direct comparison application is available free of charge from the R&S®NTS product website [13], [14].

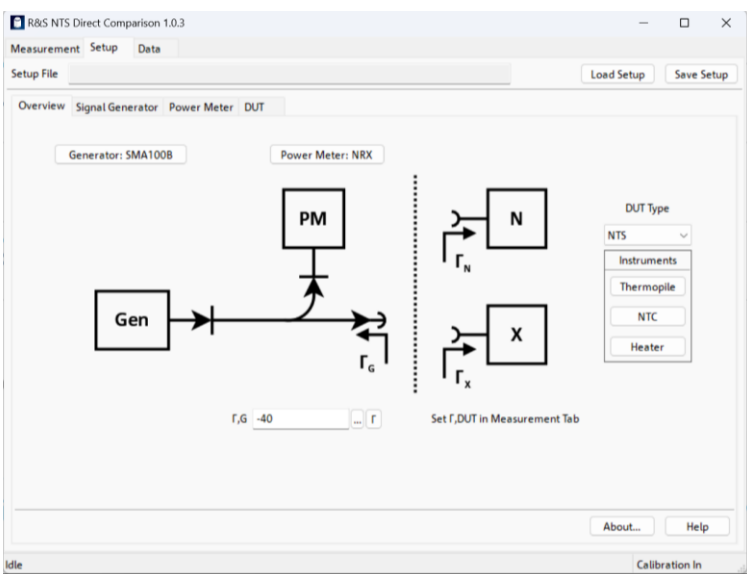

Figure 17 Screenshot of R&S®NTS direct comparison application

5 R&S®NTS characteristics

5.1 Specifications

Refer to the specifications document [6] for specifications of R&S®NTS models.

Refer to the R&S®NTS manual [4], specifically the Section titled “Checking the DC connector”, for typical values of the thermopile resistance, NTC resistance, DC heater resistance and DC feed line resistance.

For details on calculating the NTC resistor temperature from a resistance measurement, see Section 5.2.

5.2 Detector temperature measurement

The detector temperature and temperature drift of the R&S®NTS transfer standards can be monitored by measuring the resistance of an integrated NTC temperature sensor.

The nominal NTC resistance is 30 kΩ at 25°C. For details on calculating the detector temperature from the measured NTC resistance R_{NTC}, refer to Section 7.2.

The test current I_{test} from the DMM through the NTC resistor causes dissipated power in the NTC resistor, calculated as:

$$P_{\mathrm{NTC}} = I_{\mathrm{test}}^2 \cdot R_{\mathrm{NTC}}.$$

This dissipated power in the NTC resistor can be a significant fraction of the nominal calibration level of the R&S®NTS. Therefore, during calibration in a microcalorimeter, we recommend either including P_{NTC} in the system correction or avoiding to monitor the NTC resistance during the acquisition time.

For the direct comparison calibration, it is advisable to keep the resistance measurement continuously active during warm-up and the calibration procedure to minimize thermal settling effects.

Table 1 summarizes power dissipation values for typical test currents of DMMs.

Table 1 Power dissipation in NTC resistor

Test current of DMM $\boldsymbol{I_{test}}$ in 100kΩ range	Power dissipation in NTC resistor $\boldsymbol{P_{NTC}}$ @$\boldsymbol{R_{NTC}}$ = 30 kΩ	Fraction of calibration level of 1mW (0dBm) in %
10 µA	3 µW	0.3 %
5 µA	0.75 µW	0.075 %

5.3 Warm-up and thermal equilibrium

R&S®NTS transfer standards must be operated in a temperature-controlled environment, such as a calibration laboratory. Unnecessary airflow around the test setup must be prevented.

RF power sensors used in the test setup, such as the NRP and R&S®NRPC families, require a warm-up time of at least one hour after startup.

When connecting the R&S®NTS to RF ports with elevated temperatures, such as those near a waveguide power amplifier, it is crucial to monitor thoroughly the thermal settling.

We recommend using the integrated NTC temperature sensor to monitor the R&S®NTS detector temperature, see Section 7.2 for temperature calculation.

Ideally, the detector temperature of the R&S®NTS must be constant during a substitution measurement. Practically, it is advised that the temperature drift rate of the detector is below 100 µK/s before initiating calibration.

5.4 Heating losses in heater supply lines

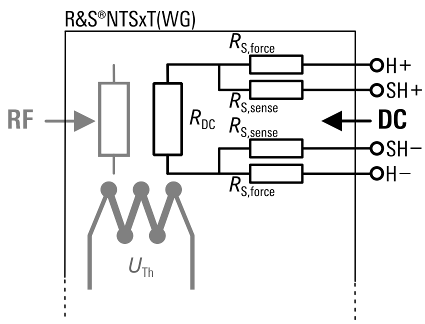

Figure 18 Parasitic series resistances in DC heater supply lines of R&S®NTS

In R&S®NTS transfer standards, the force terminals of the 4-wire heater supply lines to the 2nd heater, labeled H+ and H- in Figure 18, are optimized for low resistance to minimize parasitic heating losses outside the 2nd heater.

Within R&S®NTS transfer standards, the typical internal resistance values of the heater supply lines between the thermoelectric transducer and the DC connector are (see Figure 18):

- $R_{\text{S,force}} \approx$ 50 mΩ
- $R_{\text{S,sense}} =$ 300 mΩ to 600 mΩ

Although the corresponding heater sense and force supply lines are connected in parallel at the thermoelectric transducer, their functions are not interchangeable due to the difference in line resistance.

5.5 Frequency response of coaxial models

A distinctive feature of coaxial R&S®NTS models is their nearly ideal physical behavior regarding frequency-dependent losses in the coaxial waveguide, as illustrated in Figure 19.

These losses and the normalized frequency response can be modeled using the quantity equation:

$$\eta_{\text{gen}}/\eta_{\text{gen}}(\text{DC}) = 1 - \left(k_{\text{coax}} \cdot \sqrt{(f/\text{GHz})} + k_{\delta} \cdot f/\text{GHz}\right)$$

Where:

- k_{coax} is the resistive loss coefficient of a coaxial waveguide.
- k_{δ} is the dielectric loss coefficient.

By applying a fit to this physical frequency response model or using polynomial interpolation, the number of calibration frequencies can be reduced, by that decreasing the measurement time in the microcalorimeter.

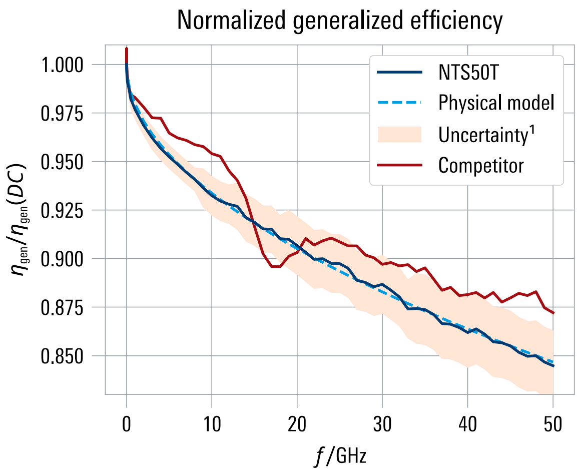

Figure 19 Measured normalized generalized efficiency of an R&S®NTS50T, with fit to a physical model
[1] extended uncertainties of calibration factor at PTB for direct comparison (2.4 mm connector, see Section 7.1)

5.6 Reflection coefficient of special models

Special models of R&S®NTS with modified RF input impedance are utilized to determine correction factors for microcalorimeters, compensating for losses in the RF feeding lines of the microcalorimeter [15].

The 1st heater of the thermoelectric transducer has been modified to create open, short, and mismatch (100 Ω) conditions at precise locations. Refer to Figure 20 for a time domain reflectometry (TDR) plot of the input reflection coefficient of the R&S®NTS50T special models.

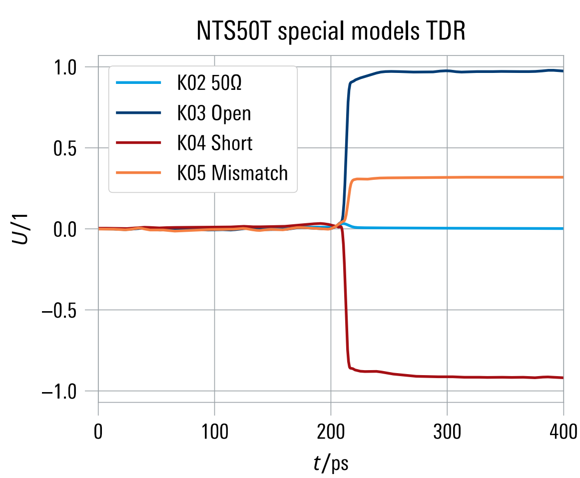

Figure 20 TDR plot of input reflection coefficient of R&S®NTS50T special models

5.7 Linearity of thermopile output voltage

For transfer standard applications, nonlinearity over RF power can be compensated by employing substitution methods at a constant thermopile voltage, as previously described.

The effects of ambient temperature change can be minimized by carefully designing the experimental setup to reduce thermal drift between substitution steps and by monitoring thermal drift using the built-in NTC temperature sensor of R&S®NTS.

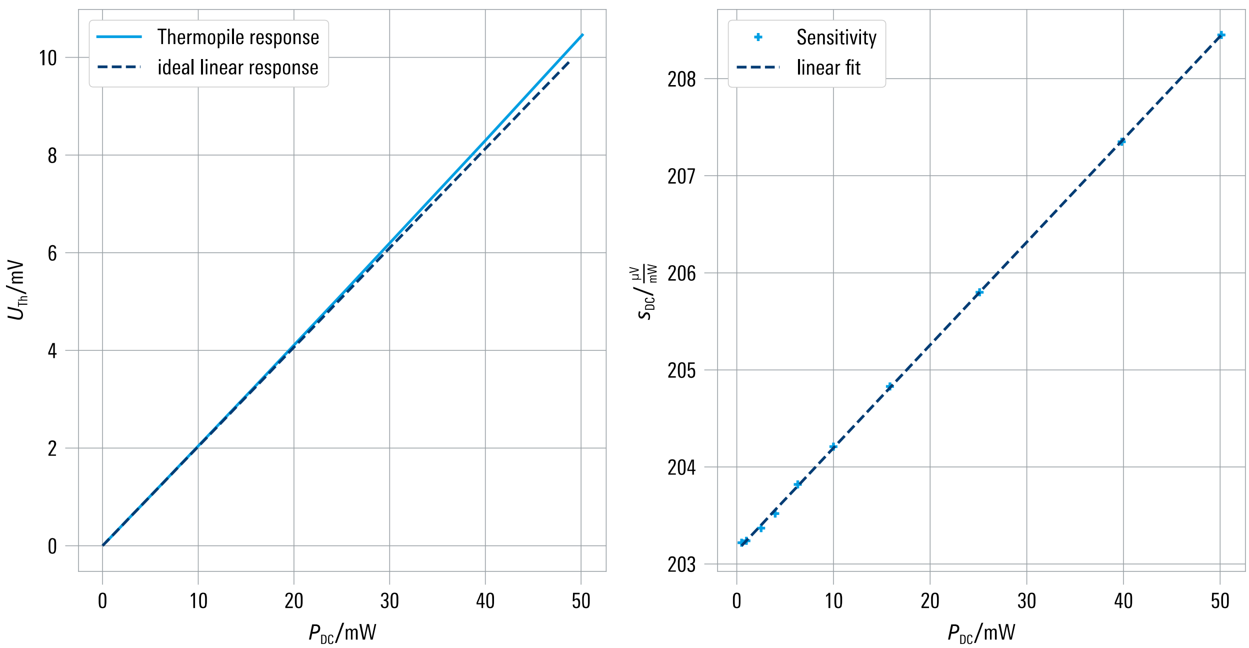

Figure 21 Linearity of thermopile output voltage, measurements conducted with R&S®NTS18T
Left: Raw thermopile output voltage vs input power and deviation from ideal linear response, extrapolated from small signal response (approx. 2.6% at 50 mW)
Right: Sensitivity vs. input power

Figure 21 illustrates the measured linearity of the thermopile thermoelectric transducer over DC power at a constant temperature.

The thermopile output voltage U_{Th} exhibits a slightly quadratic large-signal behavior, resulting in the sensitivity s_{DC} having a linear relationship with the applied power P_{DC}.

5.8 Calibration factor vs. power

The dependency of the calibration factor CF on absorbed power was determined using a DC-DC alternating substitution setup where the RF signal source was replaced by a precision DC source feeding the 1st heater of R&S®NTS18T specimens.

At DC, the calibration factor is a direct representation of the ratio of heater sensitivities, as the input reflection coefficient Γ_{N} becomes 0 and the transmission coefficient a_{RF} equals to 1.

$$CF(\mathrm{DC}) \cong \eta_{\mathrm{gen}}(\mathrm{DC}) \cong \frac{s_{\mathrm{RF}}}{s_{\mathrm{DC}}}$$

The measurements in Figure 22 include an old model of R&S®NTS18T comprising a thermoelectric transducer without optimized heater symmetry ($CF{\sim}1.36$), like the transfer standard referenced in [16].

With the optimized heater symmetry of current R&S®NTS, the ratio of sensitivities is close to 1 and nonlinearities of both heaters are almost perfectly canceled out.

Compared to the old R&S®NTS18T models, the influence of absorbed power on the calibration factor was reduced by two orders of magnitude.

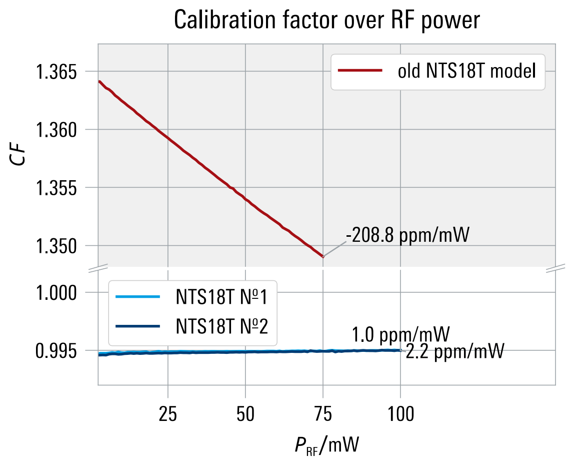

Figure 22 Coefficient of calibration factor over absorbed power, measurements conducted using alternating substitution mode at DC

5.9 Sensitivity to ambient temperature

5.9.1 Temperature coefficient of sensitivity

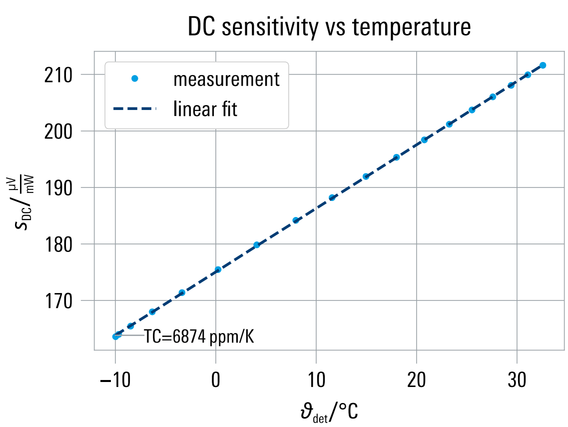

Figure 23 Temperature coefficient of the sensitivity of the thermopile, measurements conducted with R&S®NTS18T

The sensitivity s_{DC} has a strong dependency on temperature with a coefficient of around 0.7 %/K, as shown in Figure 23. Consequently, the sensor mode (described in Section 4.1.1) is not recommended in transfer standard applications.

Instead, the proposed substitution modes are advised, as they are susceptible only to thermal drift between the substitution steps.

5.9.2 Temperature coefficient of heater resistance

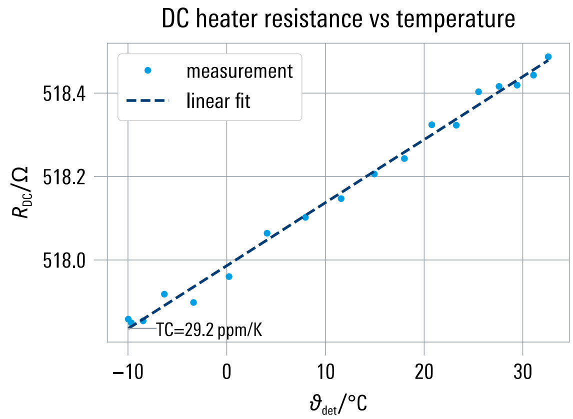

Figure 24 Temperature coefficient of DC heater resistance, measurements conducted with R&S®NTS18T

Figure 24 illustrates the measurement of the temperature coefficient of R_{DC}, which is typically around 30 ppm/K.

This is insignificant in most applications, particularly when current and voltage are monitored separately by DMMs using the 4-wire connection to the DC heater (see Figure 10).

5.9.3 Temperature coefficient of calibration factor

Figure 25 depicts the experimental setup used to determine the temperature coefficient of the calibration factor. An R&S®NRPC was used as a reference and kept at ambient temperature, while the R&S®NTS was directly tempered with attached thermoelectric coolers (TEC). The calibration factor of the R&S®NTS was measured using the alternating substitution mode.

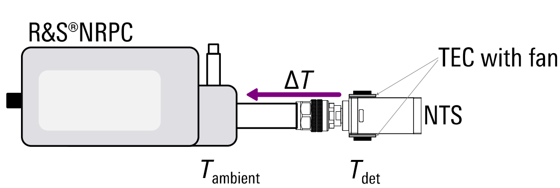

Figure 25 Experimental setup for determination of the temperature coefficient, RF and DC connections omitted for clarity

Coaxial models

Coaxial R&S®NTS models exhibit a temperature coefficient of the calibration factor CF that is proportional to the losses between the RF port and the 1st heater $(1 - a_{\mathrm{RF}})$, see Figure 26.
Refer to Figure 19 for the frequency response of R&S®NTS50T.

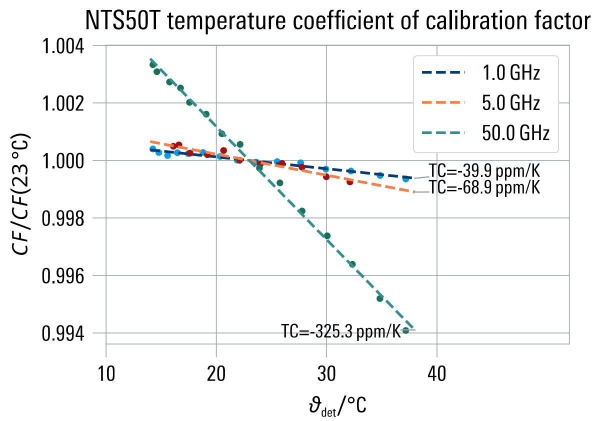

Figure 26 R&S®NTS50T: Temperature coefficient of the calibration factor at different frequencies.

Waveguide models

The data in Figure 27 was determined with a similar experimental setup as depicted in Figure 25 and the R&S®NTS170TWG model for selected frequencies, with a D-band signal source and a directional waveguide coupler instead of the R&S®NRPC.

The temperature coefficient (TC) of the calibration factor CF is almost constant over the operating frequency range of the R&S®NTS170TWG, considering the minimal frequency response of the calibration factor.

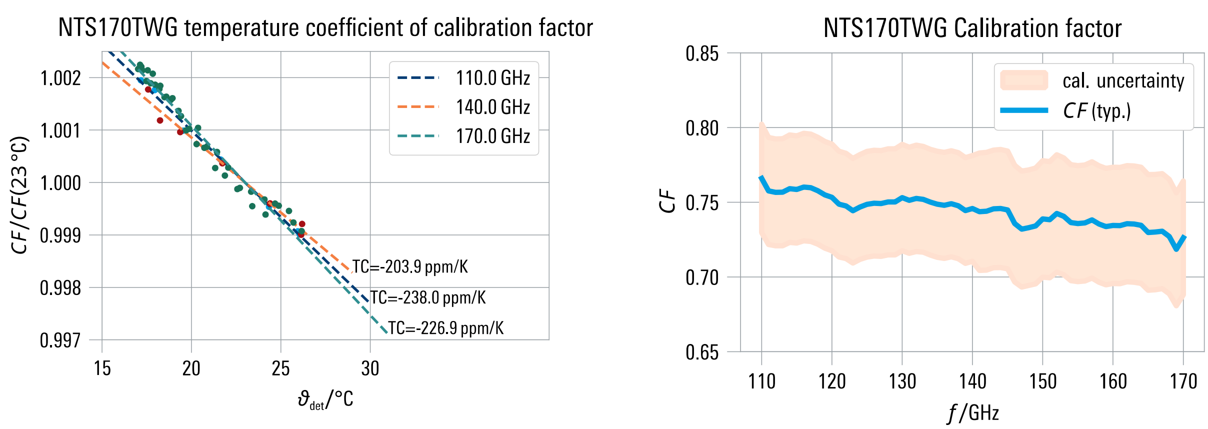

Figure 27 R&S®NTS170TWG: Temperature coefficient of calibration factor and frequency response of calibration factor.

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7 Appendix

7.1 Uncertainties of traceable RF power calibration

To provide a quantitative context to the discussed characteristics of R&S®NTS transfer standards, Figure 28 presents an overview of the uncertainties of calibration factor at the national metrology institute of Germany, PTB.

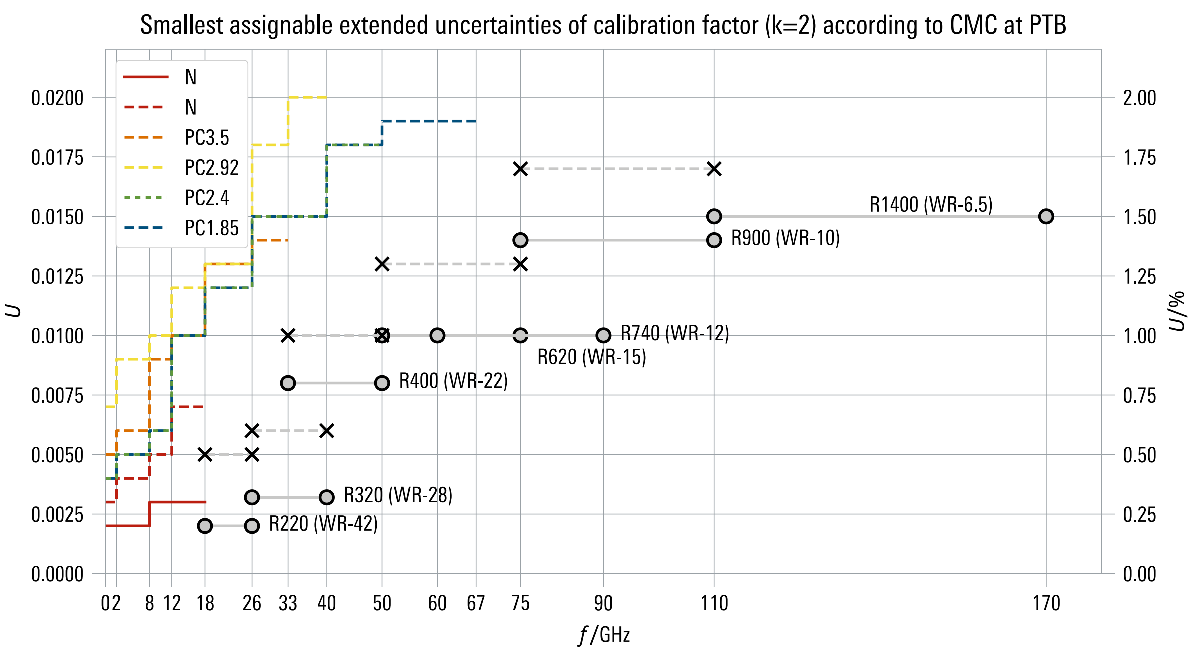

Figure 28 Uncertainties of RF power calibration at PTB, source: BIPM, April 2025.
Solid lines indicate calibration in the microcalorimeter, dashed lines indicate calibration using direct comparison outside the microcalorimeter.

7.2 Calculation of temperature from NTC resistance

NTC resistors of the TE Connectivity 30K5CG3 type are used in all R&S®NTS transfer standards. The temperature of the NTC resistor, and thus the detector temperature of the R&S®NTS, can be calculated by the following equations.

Steinhard-Hart equation:

$$\frac{T}{\mathrm{K}} = \frac{1}{9.331719 \cdot 10^{-4} + \left(2.213984 \cdot 10^{-4} + 1.263797 \cdot 10^{-7} \cdot \ln\frac{R_{\mathrm{NTC}}}{\Omega} \cdot \ln\frac{R_{\mathrm{NTC}}}{\Omega}\right) \cdot \ln\frac{R_{\mathrm{NTC}}}{\Omega}}$$

Quadratic approximation:

$$\frac{T}{\mathrm{K}} = 0.014 \cdot \left(\frac{R_{\mathrm{NTC}}}{\mathrm{k\Omega}}\right)^2 - 1.62464 \cdot \frac{R_{\mathrm{NTC}}}{\mathrm{k\Omega}} + 334.3$$

With $\vartheta = T - 273.15 \qquad \vartheta$ in °C, T in K.

The quadratic approximation has a worst-case deviation of 0.0299 K in the temperature range of 20°C to 30°C.

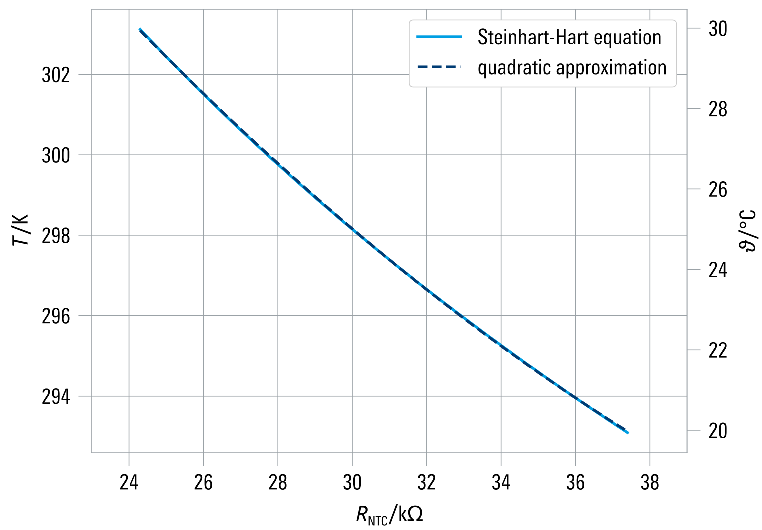

Figure 29 Results of Steinhard-Hart equation vs quadratic approximation over a temperature range of 20°C to 30°C

Example code (Python)

```
import numpy as np

def t_steinhart(R_NTC):
    a, b, c = 9.331719e-4, 2.213984e-4, 1.263797e-7
    T_NTC = (a + b * (np.log(R_NTC)) + c * ((np.log(R_NTC)) ** 3)) ** -1
    return T_NTC
```

7.3 Connectors and cables

Pre-assembled cables, R&S®NTS-ZKL, are available as accessories for R&S®NTS transfer standards.

For custom cable sets, the connectors for R&S®NTS and nanovoltmeter sides are specified in the following sections.

The maximum wire cross section of the wires is limited to 28 AWG by the connectors on R&S®NTS side, shown in Table 2.

The wire pair for the thermopile voltage must be twisted and shielded.

7.3.1 DC connector

For custom cable sets, such as those used in microcalorimeters, straight and angled push-pull plugs (9-pin, size 0, coding 0°) can be sourced from the manufacturer ODU® and other manufacturers offering compatible products.

For the pin allocations, refer to the R&S®NTS manual [4].

Table 2 ODU® plugs compatible with R&S®NTS models

Plug type	ODU® order number
ODU® straight plug	S20L0C-P09MCC0-x20S
ODU® right-angled plug	W20L0C-P09MCC0-x20S

7.3.2 Nanovoltmeter connector

The recommended nanovoltmeters for use with R&S®NTS transfer standards are the Keithley®2182A and Keysight®34420A models. Both nanovoltmeters feature low-thermal EMF connectors.

Use channel 1 to measure the thermopile voltage of R&S®NTS transfer standards.

The accompanying cable set, R&S®NTS -ZKL, connects the thermopile of the R&S®NTS models to channel 1 of the nanovoltmeters. Also, the R&S®NTS direct comparison application requires that the thermopile is connected to channel 1 of the nanovoltmeter.

Matching connectors for use with both nanovoltmeter models can be obtained from LEMO®.

Table 3 Nanovoltmeter Plugs

Plug type	LEMO® order number
Low thermal EMF plug	FVN.1S.304.CLYC37Z

7.4 Using R&S®NRPC power standards as reference source

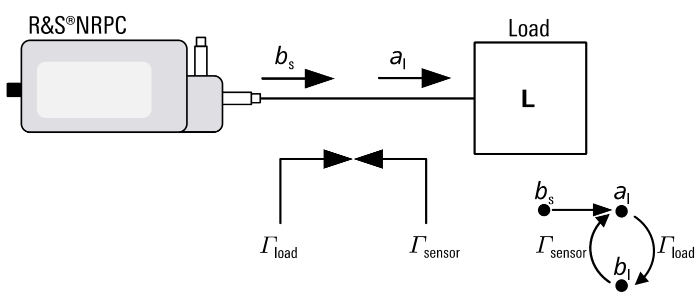

Figure 30 NRPC as reference source

R&S®NRPC power standards are ideal companion instruments for calibration with R&S®NTS models up to 67 GHz. For recommended instruments and setups for specific frequency ranges, refer to the R&S®NTS manual [4]. R&S®NRPC can serve as a precision power calibration source with built-in mismatch correction. The equivalent source match of the R&S®NRPC is stored in its calibration data and can be accessed via SCPI commands. Furthermore, the reflection coefficient of the DUT can be sent to the R&S®NRPC via SCPI commands, allowing the R&S®NRPC to perform mismatch correction.

R&S®NRPC systems are fully supported by the R&S®NTS direct comparison application, which includes internal and external mismatch correction and readout support for equivalent reflection coefficients from R&S®NRPC power standards and NRP power sensors.
Also, R&S®NRPC power standards can handle full S-parameter correction of two-port devices, such as attenuators or coaxial-waveguide adapters.

7.4.1 Theory

If the complex reflection coefficient of the load (e.g. an R&S®NTS or DUT for calibration) is known, the interaction of reflections between the sensor and the load can be corrected through mismatch correction. The relationship between the wave propagating forward from the sensor b_s and the wave incident on the load a_l is expressed as follows:

$$a_l = b_s \cdot \frac{1}{1 - \Gamma_{sensor}\Gamma_{load}}$$

For the expectation value of the power incident on the load $|a_l|^2$, the following applies:

$$|a_l|^2 = \frac{1}{M_1} \cdot |b_s|^2$$

With the mismatch factor M_1:

$$M_1 = |1 - \Gamma_{\text{sensor}}\Gamma_{\text{load}}|^2$$

7.4.2 SCPI commands

Refer to the manuals of the R&S®NRPC, R&S®NRX and NRP families for further details.

Querying the input reflection or equivalent source match

```
[SENSe:]IGAMma[:MAGNitude]?
[SENSe:]IGAMma:PHASe?
```

For the NRP power sensors, these commands query the magnitude and phase of the complex input reflection coefficient.

For the R&S®NRPC power standards, this command queries the equivalent source match of the R&S®NRPC.

Setting the complex reflection coefficient of the source or DUT

```
CALCulate[:CHANnel]:SGAMma[:MAGNitude] <value>
CALCulate[:CHANnel]:SGAMma:PHASe <value>
```

For the NRP power sensors, these commands set the magnitude and phase angle of the complex reflection coefficient of the source.

For the R&S®NRPC power standards, this command sets the complex reflection coefficient of the DUT.

Mismatch correction can be enabled in the R&S®NRPC with:

```
CALCulate[:CHANnel]:SGAMma:CORRection:STATe ON
```

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Application Note | R&S®NTS RF Power Transfer standards
Data without tolerance limits is not binding | Subject to change