Basic RF Amplifier Measurements using the R&S® ZNB Vector Network Analyzer and “SMARTerCal”.

Application Note

Products:

- ZNBx vector network analyzer

The family of ZNB vector network analyzers (VNA) from Rohde & Schwarz are the perfect instruments for analyzing RF amplifier small signal linear and non-linear performance. This application note presents information on how to configure and use the R&S® ZNB vector network analyzer to successfully make accurate and quick measurement of basic RF amplifier parameters.

The “SMARTerCal” calibration tool is presented, combining systematic error correction with calibrated receiver power, offering enhanced measurement accuracy with minimum effort.

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Basic RF Amplifier Measurements using a R&S® ZNB Analyzer and “SMARTerCal”

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1 Introduction

The R&S® ZNB vector network analyzer provides RF and Microwave designers with a single instrument that is well suited for characterizing RF amplifiers. This document informs the user about configuring and using the instrument to make measurements of small signal operation and parameters associated with the initial effects of compression.

After reviewing key measurement considerations, information is provided on how to use the R&S® ZNB analyzer effectively to characterize basic linear amplifier parameters, e.g. S-parameters, return loss, gain, isolation, impedance and stability. Non-linear measurements are also addressed, including compression point; harmonics; intermodulation products and intercept points; and Amplitude Modulation to Phase Modulation (AM-PM) conversion.

The R&S® ZNB network analyzer, is a versatile self-contained instrument able to measure RF amplifier parameters accurately and effortlessly, and has many benefits including:

- Generous linear source output power.
- Excellent receiver linearity (Absolute max input, +27 dBm).
- Large power sweep range (>100dB).
- Full system error correction and receiver power calibration (**SMARTerCal**), and source power flatness.
- 'Wizard' tools for efficient configuration of measurements (S-parameters and intermodulation products).
- Embedding / de-embedding using lumped element networks.

This application note is complimented by the information given in the *R&S® ZNB, Vector Network Analyzers, User Manual* [1], and the on-instrument "**HELP**" function.

Text marked in "**bold**" indicates an instrument function, accessed either through buttons on the front panel; the soft-key panels on the touchscreen; or the software menu structure. Text marked in "***bold italics***" refers to R&S® ZNB analyzer options or supporting R&S® products.

This application note has been prepared using R&S® ZNB Firmware version: 01.63.

2 Linear Amplifier Measurements

Basic characterization and optimization of RF amplifier devices is simple using the R&S® ZNB analyzer. A typical measurement arrangement is shown in Figure 1 with an RF amplifier, or device under test (DUT), connected to two instrument ports:

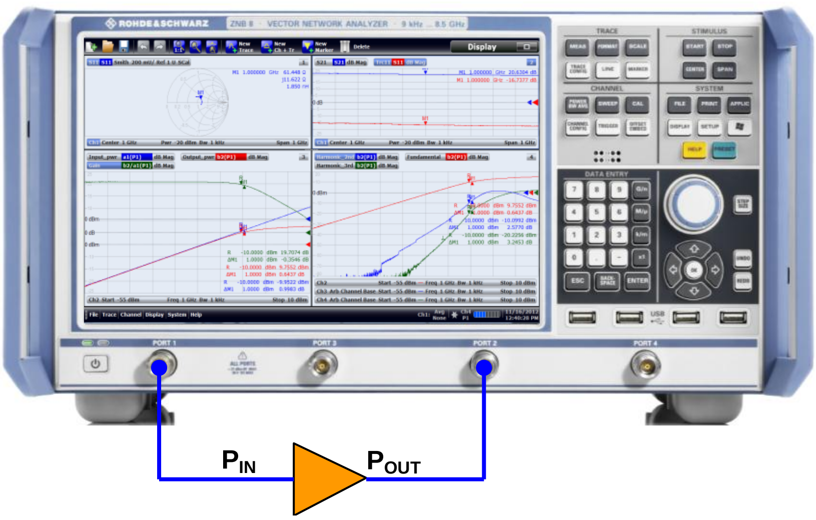

Figure 1– RF amplifier measurements using the R&S® ZNB network analyzer

Before proceeding with the measurements, the R&S® ZNB vector network analyzer must be configured for the amplifier under test. The following parameters must be considered:

Start frequency	
Stop frequency	
Number of points	*Measurement time increases with more points.*
DUT input power	*Set the R&S ZNB source power to a level that does not drive the amplifier under test into compression.*
DUT output power	R&S® ZNB maximum nominal input, +13dBm. *Option **ZNBx-B3x** provides 30dB of additional attenuation for selected receiver ports in 10dB steps.* **Warning: Input damage level +27dBm.**
Measurement bandwidth	*Measurement time increases with smaller bandwidth.*

2.1 S-parameter Measurement

The R&S® ZNB analyzer accurately measures the reflected and transmitted RF power at the amplifier ports. For example, at the amplifier input, the incident power or reference power (**a1**) is measured by the R&S® ZNB *reference receiver*. Reflected power from the device input port or measured power (**b1**) is captured by the ZNB *measurement receiver*.

Transmitted power from the amplifier output (**b2**) is detected by the *measurement receiver* at Port 2.

Absolute measurements of **a1**, **b1** and **b2** are called “wave quantities”.

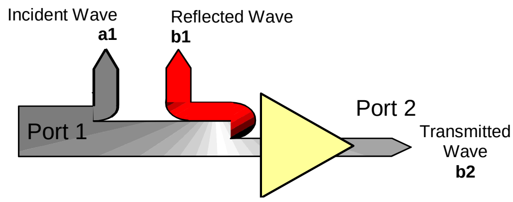

Figure 2 – Incident, reflected and transmitted power referenced to Port1

The R&S® ZNB analyzer has a characteristic impedance of 50 Ω and therefore shows the ratios of the wave quantities as complex S-parameters:

Input reflection coefficient (Γ_{IN} or Γ_1): $$s_{11} = \frac{b_1}{a_1}\bigg|_{a_2=0}$$

Forward transmission coefficient: $$s_{21} = \frac{b_2}{a_1}\bigg|_{a_2=0}$$

Port 2 can be stimulated to provide a reverse sweep measurement, giving the following wave quantities and S-parameters, where **a2** is the incident wave from Port 2.

Output reflection coefficient (Γ_{OUT} or Γ_2): $$s_{22} = \frac{b_2}{a_2}\bigg|_{a_1=0}$$

Reverse transmission coefficient: $$s_{12} = \frac{b_1}{a_2}\bigg|_{a_1=0}$$

2.1.1 S-parameter Wizard

The "**S-parameter Wizard**" is an in-built tool that efficiently configures the R&S® ZNB analyzer ready for S-parameter measurements. Access to start the wizard is through the "**Meas**" button on the front panel keypad, or through the soft-key or software menu structure, "**Trace → Meas → S- Params → S-Param Wizard…**". Six intuitive steps are progressed using the "**Next**" or "**Back**" soft buttons:

1. **Test Setup** – *define the measurement type, e.g. balanced or single ended. Simple amplifier measurements are 'Single-ended 2-port'*.
2. **Port Reference Impedance** – *Default impedance is 50 Ω. Leave unchanged for simple amplifier measurements*.
3. **Display** – *select the format of displayed results from one of three options*.
4. **Frequency Sweep** – *Define the frequency band and the number of measurement points*.
5. **Bandwidth and Power** – *Select the measurement bandwidth. For low gain amplifiers, select an input power of -20dBm, although the power level may need to be adjusted to avoid saturation of the amplifier, or to avoid high output power from the amplifier which could damage the* analyzer *input.*
6. **Calibration** – *If no calibration is required, press "***Finish***", else proceed to the manual calibration. "***Automatic calibration***" is available when a* ***R&S® NRP-Zxx*** *power meter and* ***R&S® ZV-Z5x*** *automatic calibration unit are connected to the R&S® ZNB analyzer USB interfaces.*

Once the wizard and calibration are completed, the display will show the selected results. Figure 3 shows the S-parameters for a typical RF amplifier.

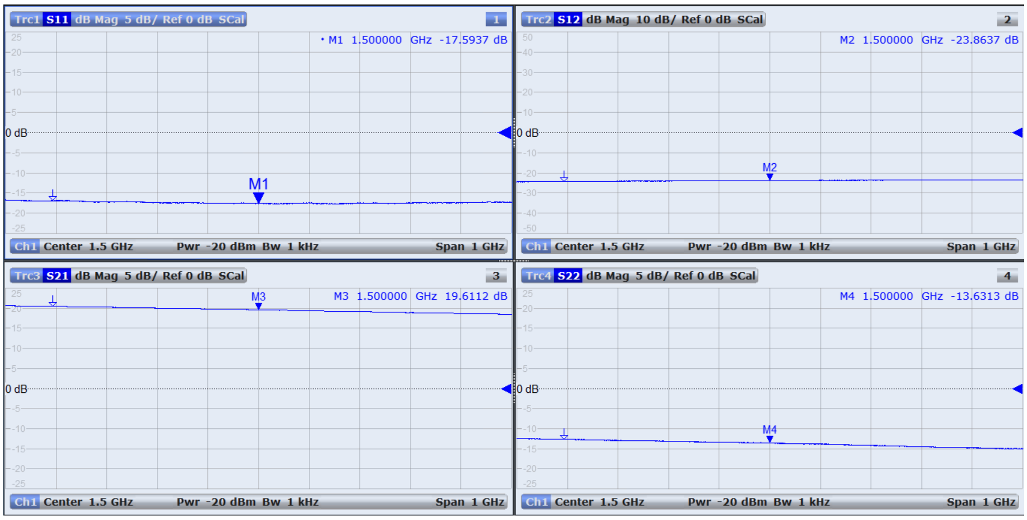

Figure 3 – RF amplifier S-parameters

Additionally, Y and Z-parameters can be measured and displayed. These are manually configured by selecting the required trace and following "**Meas → Y- Z- Params**".

2.2 Return Loss, Gain, VSWR and Impedance

Figure 3 shows the magnitude components of the complex S-parameters. For input and output reflection coefficients, a measure of the magnitude is called *Return Loss*:

$$\textit{Return Loss} \quad = -20\log_{10}\left(|\Gamma|\right)$$

The magnitude component of the forward transmission coefficients is called *Gain*:

$$\textit{Gain} \quad = 20\log_{10}\left(|S_{21}|\right)$$

The equivalent term for the reverse transmission coefficient is called *Isolation*:

$$\textit{Isolation} \quad = -20\log_{10}\left(|S_{12}|\right)$$

The charts in Figure 3 can be easily changed by the user. To fill the display with a single chart, double tap the chart on the touch sensitive display. Double tapping again, restores the four charts. The "**Scale**" button on the front panel keypad allows changes to the Y-axis information. Additionally, trace related information may be changed using the trace label above the chart. For example, double tapping on the scale information will auto-scale the Y-axis. Or pressing the parameter in the trace label for more than 2 seconds will bring up an option menu. Else, use the software menu or soft-key panels.

The Voltage Standing Wave Ratio (VSWR) or **SWR** is derived from the reflection coefficients. This is the ratio of the voltage maxima to minima of a standing wave on a transmission line and is caused by impedance mismatch:

$$VSWR = \frac{V_{max}}{V_{min}} = \frac{1+|\Gamma|}{1-|\Gamma|}$$

To view **SWR**, add or select a trace and change the format, "**Format → SWR**" (Figure 4).

The amplifiers input and output complex reflection coefficients can be displayed on a Smith chart providing complex impedance measurements as shown in Figure 5 ("**Format → Smith**").

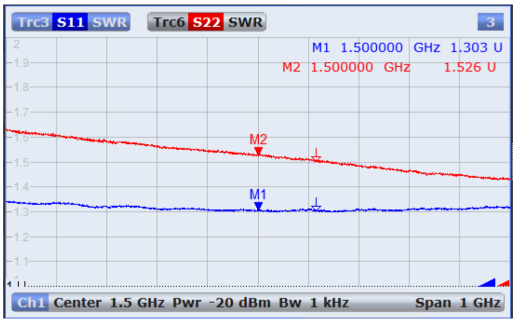

Figure 4 - Input and output SWR

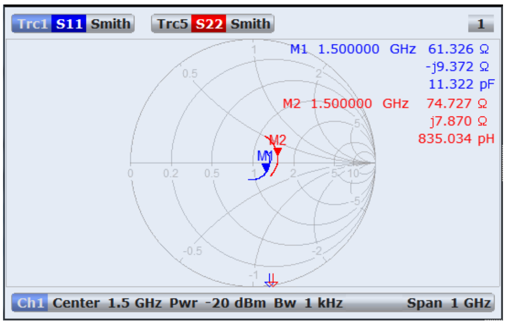

Figure 5 - Input and output impedances

2.2.1 Embedding / De-embedding using Ideal Lumped Elements

The R&S® ZNB analyzer has software functionality for simulating the response of ideal lumped element impedance networks applied to the amplifier input and/or output. The user can use these impedance networks to embed or de-embed the DUT. For single ended measurements, each port has eight different impedance structures, each comprising of a shunt and series reactive element and associated resistive element. Figure 6 shows examples of the **Offset Embed** function, accessed either directly from the front keypad or through the software menu structure. The different impedance structures are selected by touching the screen to highlight the circuit window, and then swiping left or right on the circuit window to select the desired network. Applying the impedance networks shown in Figure 6 to the amplifier characteristic in Figure 3, results in the narrow band response given in Figure 7.

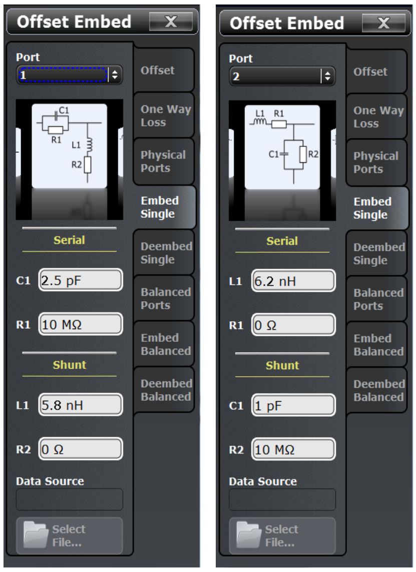

Figure 6 – Using Offset Embed to place lumped element matching networks at the device input and output

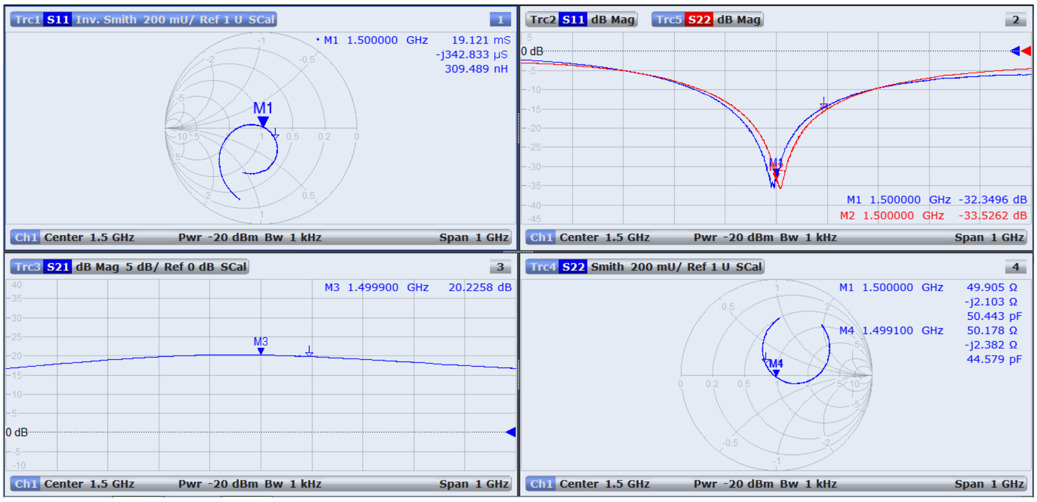

Figure 7 – Example of Offset Embed, using embeded lumped elements.

Alternatively, 2-port data files (*.s2p) can be loaded. For example, measured results from an impedance matching circuit can be applied.

2.3 Stability Factors

For some linear devices, specific source and load complex impedances can cause the generation of unwanted spurious frequencies, or oscillations. Mathematical analysis of the S-parameters gives an indication of whether a device is:

- Unconditionally stable – *Does not oscillate regardless of source and load impedances.*
- Conditionally stable – *Oscillation is likely for certain combinations of source and load impedance.*

The R&S® ZNB network analyzer can compute and plot three stability factors. They are derived from S-parameters and are accessed through the "**Meas → Stability**" menu. An example is shown in Figure 8.

$$K = \frac{1 + \left|S_{11}S_{22} - S_{21}S_{12}\right|^2 - \left|S_{11}\right|^2 - \left|S_{22}\right|^2}{2.\left|S_{21}S_{12}\right|}$$ *Rollett stability factor*

$$\mu_1 = \mu_{source} = \frac{1 - \left|S_{11}\right|^2}{\left|S_{22} - S_{11}^*.(S_{11}.S_{22} - S_{12}.S_{21})\right| + \left|S_{12}.S_{21}\right|}$$

$$\mu_2 = \mu_{load} = \frac{1 - \left|S_{22}\right|^2}{\left|S_{11} - S_{22}^*.(S_{11}.S_{22} - S_{12}.S_{21})\right| + \left|S_{12}.S_{21}\right|}$$

S_{xx}^* *is the complex conjugate of* S_{xx}

For $K < 1$, the device is conditionally stable. The device is only unconditionally stable when both $K \geq 1$ and the stability factors $\mu_1 > 1$ or $\mu_2 > 1$.

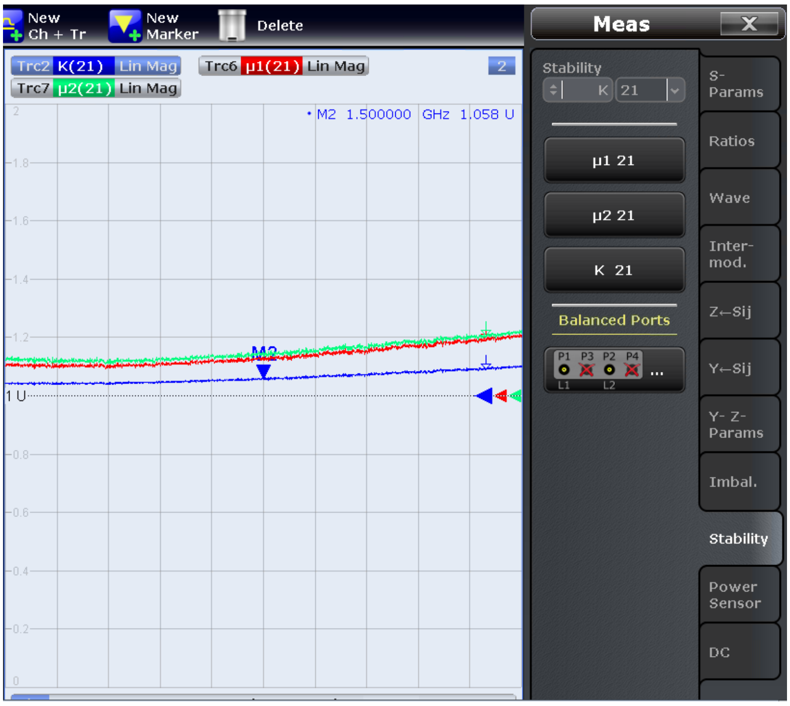

Figure 8 - Plotting stability factors

Note that the analysis of stability is confined to the measured frequency band.

2.4 User Defined Analysis

The R&S® ZNB network analyzer supports an equation editor that displays the mathematical trace defined in the "**User Def Math**" dialog. Select the wanted trace and then access "**Trace Config → Mem Math → Define Math**".

For example, Maximum Available Gain (MAG) is related to S-parameters:

$$MAG = \frac{S_{21}}{S_{12}}\left(K - \sqrt{K^2 - 1}\right) \quad (K > 1)$$

Figure 9 shows the equation editor, where each parameter in the equation is a trace and each trace has been renamed using the "**Trace Manager**" to help understanding.

Figure 9 - Maximum Available Gain defined using "User Def Math"

3 Measurement of Non-Linear Effects

3.1 Compression Point

The R&S® ZNB network analyzer is the perfect choice for making power sweep measurements, achieving typically more than 100dB of range when fitted with option ***R&S® ZNBx-B2x*** (*Extended Power Range*). Use of electronic step attenuators provides fast measurements without the limitations of mechanical attenuators.

Figure 10 – Power sweep characteristic of R&S® ZNB analyzer

The small signal compression point of an amplifier is an important parameter and defines a boundary between linear and non-linear behavior. For a given input power, this is the point where an amplifier starts to enter saturation, resulting in a 'clipped' output or reduced gain. Classically, this is defined as the 1dB compression point and references either the input or output power at which the device gain is reduced by 1dB.

The flexibility of the R&S ZNB analyzer allows extra channels to be added that can be independently configured for separate measurements, e.g. power sweeps. To add an extra channel, follow menu, "**Channel Config → Channels → Add Ch + Tr + Diag**".

The power sweep function on the R&S® ZNB analyzer, "**Sweep → Sweep Type → Power**", coupled with the large dynamic ranges of the source generator and receiver inputs allow measurement of the compression point of small signal amplifiers to be made easily. An example is shown in Figure 11

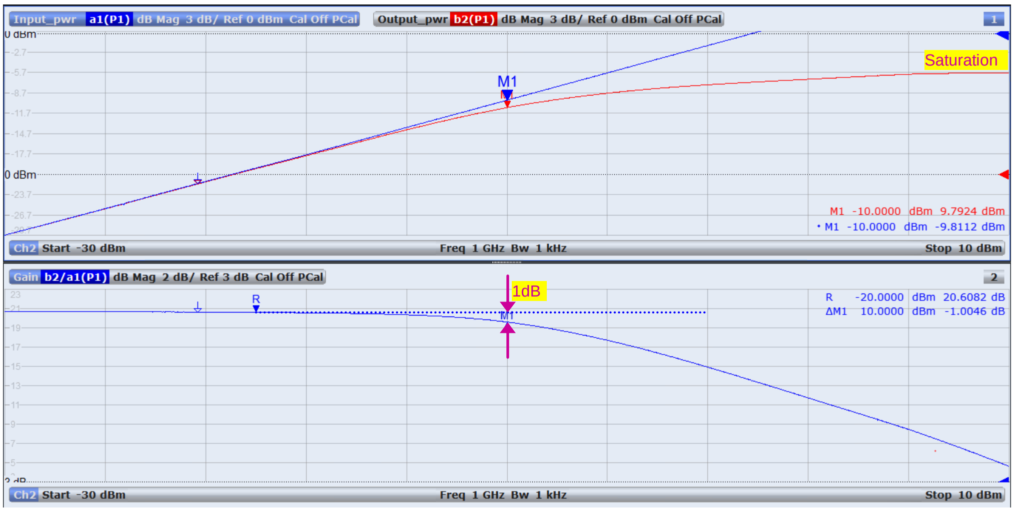

Figure 11 – Using a power sweep to measure 1 dB compression point

For this type of measurement, it is important to know the absolute level of the power source. The R&S® ZNB analyzer is able to deliver an accurately calibrated power source, as described in sections 5.1.2 and 5.1.3.

3.2 Harmonics

As an amplifier approaches compressed operation, non-linear behaviors become more apparent, including increased harmonic content (Figure 12). With the ***R&S® ZNB-K4*** (*Frequency Converting Measurements*) option, the R&S® ZNB analyzer hardware architecture allows a stimulus to be applied at one frequency and measurements to be made at a different frequency.

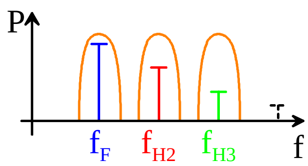

Figure 12 - Example of fundamental signal and harmonics

Figure 13 shows a typical measurement, with a power sweep at the fundamental frequency overlaid with the contributions of the 2nd and 3rd harmonics. This is achieved through adding and configuring extra "**Channels**" for each harmonic.

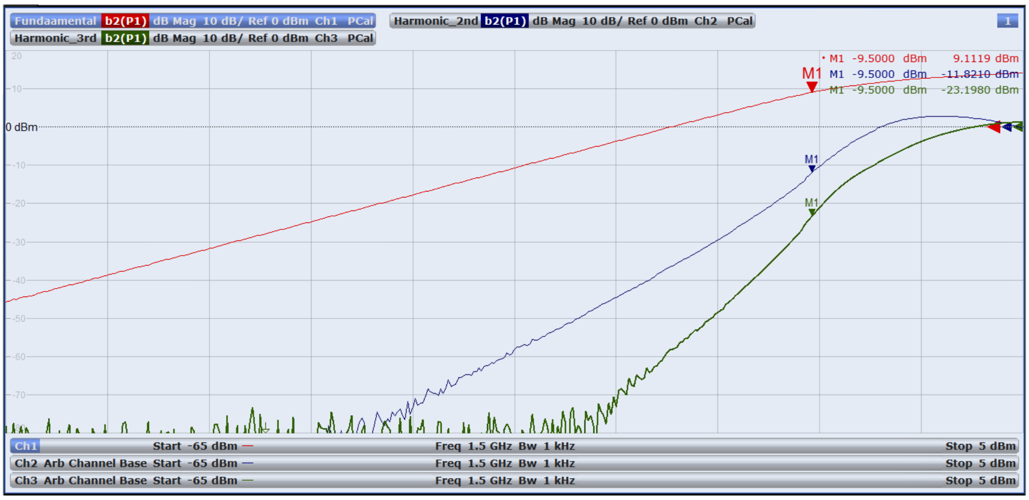

Figure 13 – Power sweep characteristic of fundamental, 2nd and 3rd harmonics.

Figure 13 shows the result of using "**Trace Manager**" ("**Trace → Trace Config → Traces → Trace Manager…**") to assemble traces from different channels on to a single display.

To measure a harmonic, the receiver port frequency is offset using the following menu, "**Channel Config → Port Config → Port Settings**". A multiplication factor is applied to the base frequency, $\mathbf{f_b}$, at the receiver port (Figure 14), e.g. x2 for the 2nd harmonic. For improved accuracy, a power flatness calibration should be performed for each channel (see sections 5.1.2 and 5.1.3).

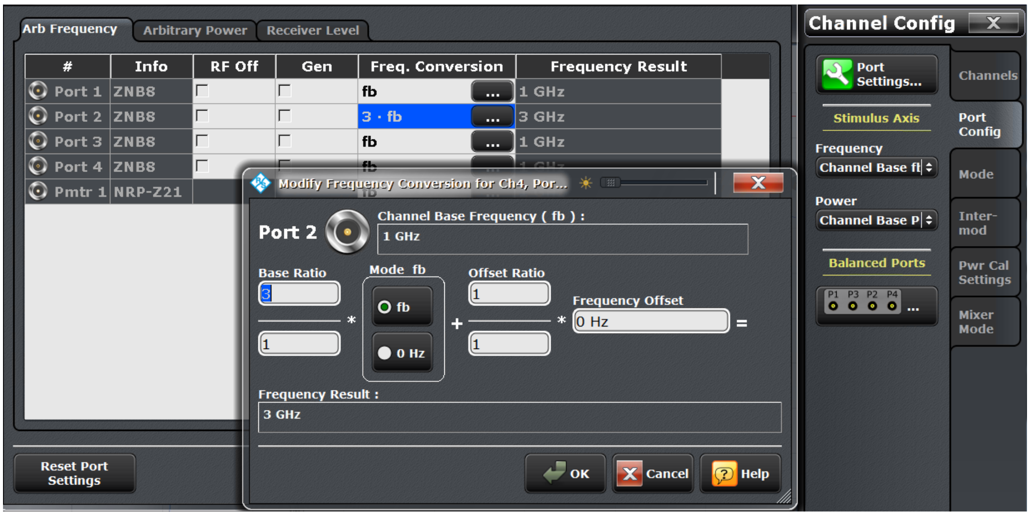

Figure 14 – Configuring the receive port frequency response.

3.3 Intermodulation Products and Intercept Points

Another measure of amplifier non-linearity is analysis of intermodulation products. With options ***R&S® ZNB-K14*** (*Intermodulation Measurements*) and ***R&S® ZNB-K4*** (*Frequency Converting Measurements*), the R&S® ZNB analyzer has an "**Intermodulation Wizard**", which configures the instrument and the displayed results. With a 2-port R&S ZNB analyzer, an external R&S signal generator is remotely controlled by the analyzer and provides the second continuous wave (CW) signal required for this test. However, if measurement speed is important, this can be provided with a 4-port R&S ZNB supporting option ***R&S® ZNB-B2*** (*Internal Second Source*). The "**Intermodulation Wizard**" is intuitive and is supported by a separate R&S Application Note [2].

3.4 AM to PM Conversion

AM to PM conversion is a non-linear amplifier effect, leading to distortion of phase when the signal amplitude is changed. This effect can be easily measured with the R&S® ZNB analyzer using the power sweep mode, as described in section 3.1.

Using the contents of the "**Marker**" menu, a 1dB delta marker can be placed on the trace to show phase change at the required input power (Figure 15).

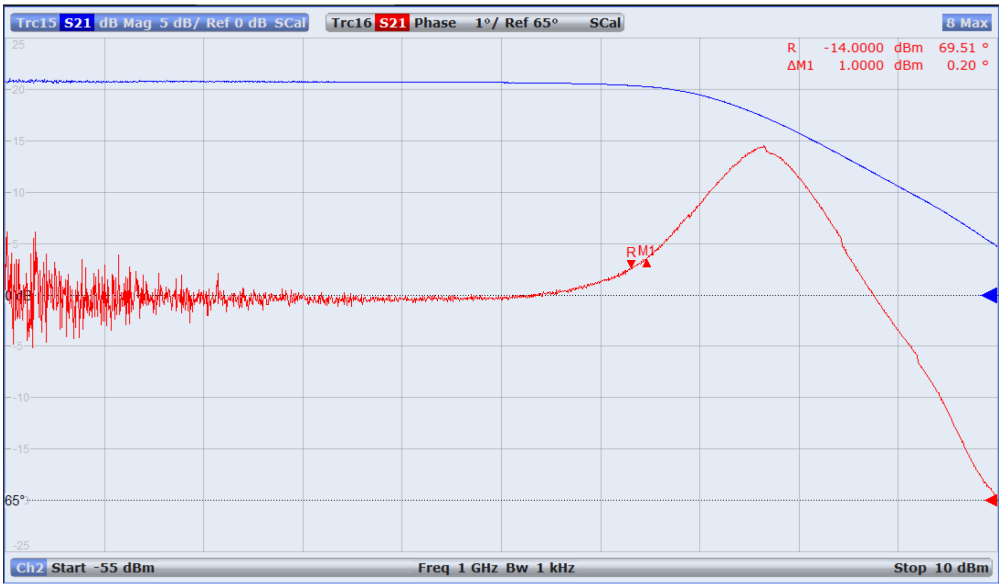

Figure 15 – AM to PM conversion using a power sweep

4 Power Added Efficiency

The Power Added Efficiency (PAE) of an amplifier is the ratio of the added RF power generated by an RF amplifier, to the DC power, P_{DC}, consumed by the amplifier:

$$PAE = \frac{(P_{OUT} - P_{IN})}{P_{DC}}$$

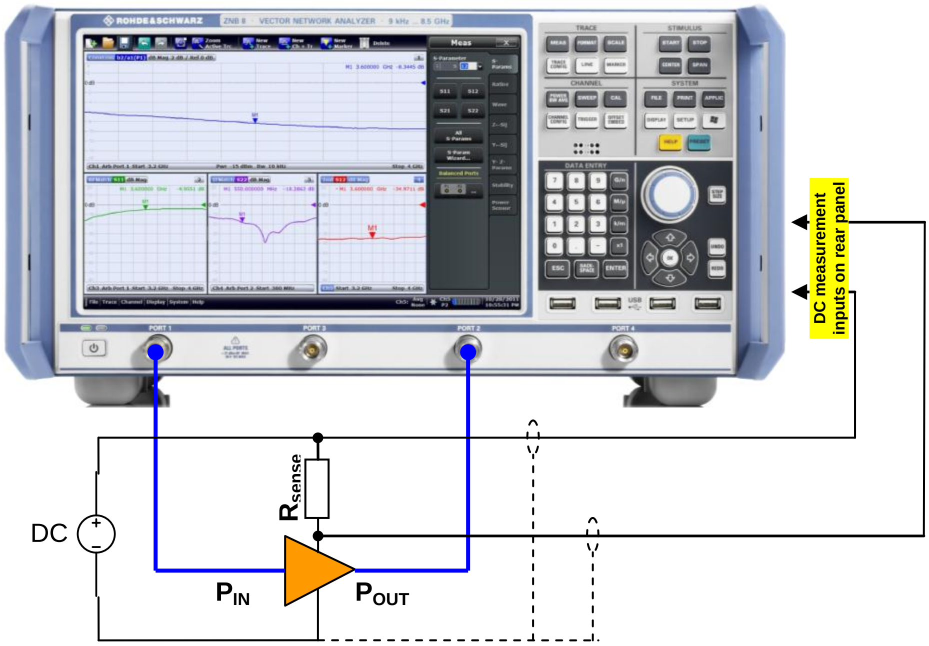

Figure 16 – Measurement of RF amplifier Power Added Efficiency

The R&S® ZNB analyzer with option ***R&S® ZVB-B81*** (*DC Inputs)* allows power added efficiency to be measured with ease. Four BNC sockets on the rear of the instrument provide the connection for DC measurement inputs. By default, the DC input voltage range is ±20V and can be reduced for each input to increase measurement accuracy, "**Menu → DC → Ranges** – **DC x**" (±3V and ±300mV). Real time measurement of the DC inputs can be displayed. This is best achieved by adding a new channel, "**Channel Config → Channels → Add Ch + Tr + Diag**" and then configuring the trace "**Menu → DC → DC x**". The soft-key, "**PAE…**" opens up a window to select and set up one of three different power supply measurements. Once complete, press "**OK**" to update the highlighted trace to show the amplifier PAE.

More information on using the R&S® ZNB for amplifier PAE is available in a separate Rohde & Schwarz Application Note [3].

5 Calibration (including “SMARTerCal”)

To achieve accurate measurements, calibration procedures are performed to remove the effects of system errors, and for power based measurements, correction of the power at the source and *measurement receivers*. More information on the available calibration methods is available in the R&S® ZNB, Vector Network Analyzers, User Manual [1], and the on-instrument “**HELP**” function.

Accurate measurement of a linear device’s small signal S-parameters and related quantities requires a full n-port system error correction, using either a manual calibration kit (e.g. ***R&S® ZV-Z235***) or the ***R&S® ZV-Z5x*** automatic calibration unit. For linear devices, these measurements are ratios of the incident and reflected/ transmitted waves, and do not depend on the absolute power level.

If knowledge of absolute power levels is required, e.g. DUT power sweep, a scalar power calibration is necessary. The ZNB analyzer source power and *measurement receivers* can be calibrated using a ***R&S® NRP-Zxx*** power sensor and a ***R&S® NRP-Z4*** USB interface cable.

5.1.1 SMARTerCal

“**SMARTerCal**” is an advanced calibration tool that couples a ***R&S® NRP-Zxx*** power sensor (and a ***R&S® NRP-Z4*** USB interface cable) with a manual or automatic calibration kit to provide the following:

- Full n-port system error correction with scalar correction of power at each receiver.
- Calibrated measurement of non-linear or frequency conversion device wave quantities and ratios. *For calibrated measurement of linear DUT S-parameters, SMARTerCal can replace a system error correction.*
- Simultaneously calibrate all channels even if each channel is configured for different frequency bands, power levels and sweep functions.
- Intuitive “**SMARTerCal**” tool makes the calibration process simple, quick and accurate.
- Calibration of power at the receivers requires a power meter to be connected to only one port. Power calibration of other port receivers is derived from knowledge of the system error correction and offers significant reduction of calibration time when using multiple ports.
- Accurate measurement of non-linear DUT frequency conversion when “**SMARTerCal**” is combined with a scalar power source calibration.

An example of the versatility of the R&S® ZNB analyzer is demonstrated in Figure 17, showing simultaneous measurement of multiple RF amplifier parameters:

- Input and output impedances (*swept frequency, fixed power*).
- Gain and isolation (*swept frequency, fixed power*).
- Stability factors (*swept frequency, fixed power*).
- Calculated maximum available gain (MAG) (*swept frequency, fixed power*).
- Compressed and saturated output power (*fixed frequency, swept power*).
- 2nd and 3rd harmonics (*offset fixed frequencies, swept power*).

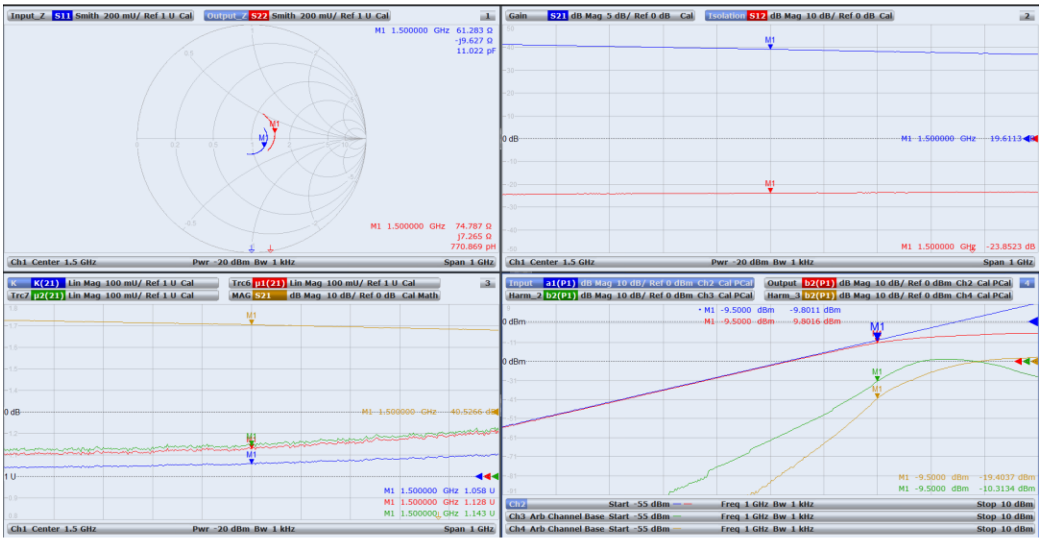

Figure 17 – Basic RF amplifier parameters measured on a R&S® ZNB analyzer. "SMARTerCal" - one calibration procedure for multiple channels and ports.

Using "**SMARTerCal**", this complex multi-channel measurement setup is quickly calibrated, "**Calibration → Start Cal →** (**SMARTerCal) Start…**". Figure 18 shows the calibration menu and the first step of the intuitive "**SMARTerCal**" tool. This progresses through correction of system errors using calibration standards, and is completed with a scalar power calibration using a ***R&S® NRP-Zxx*** power sensor.

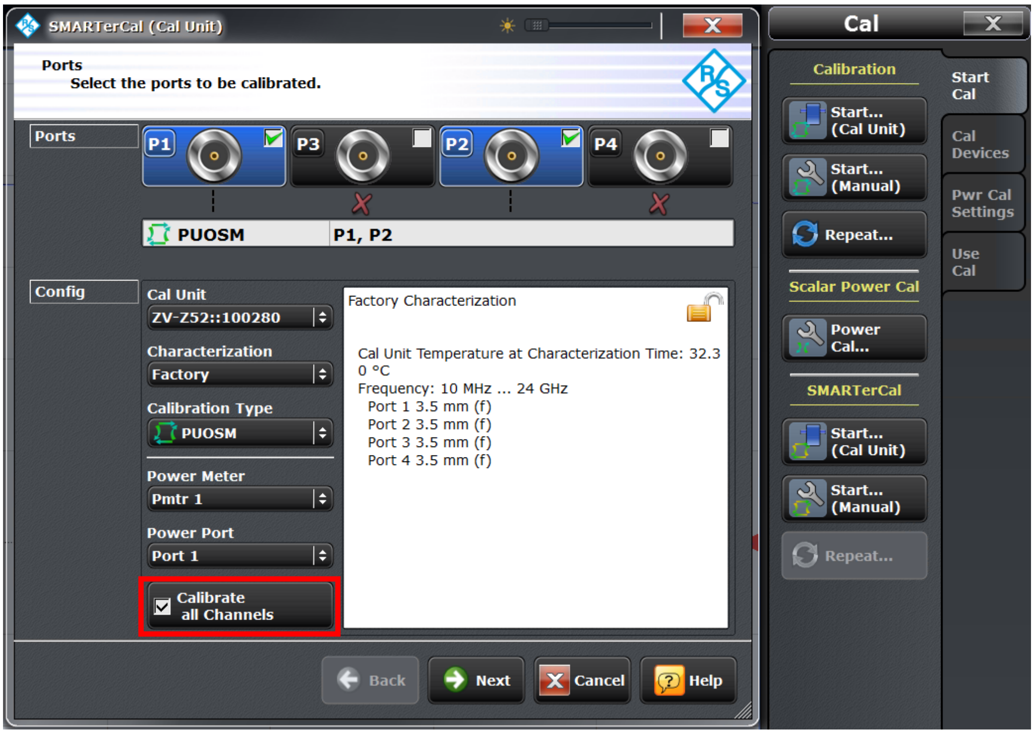

Figure 18 - Calibration menu and SMARTerCal (*Cal Unit*) window.
Note tick box for "Calibrate all Channels" if required.

5.1.2 Source Power Flatness Calibration (SMARTerCal)

In addition to calibrating the power level at the receivers using “**SMARTerCal**”, the R&S® ZNB analyzer sources can be calibrated to support applications that require an absolute measure of the power incident at the DUT. Typically these are non-linear measurements and may need the incident power to be swept, e.g. for measurement of amplifier compression point, harmonics or intermodulation products.

Using a ***R&S® NRP-Zxx*** power sensor coupled to a ***R&S® NRP-Z4*** USB interface cable, calibration of the source progresses using, “**Calibration → Start Cal → Power Cal**” (Figure 18). If multiple channels are in use, a window appears allowing selection of all channels or the present active channel. The display then shows information about the power calibration as shown in Figure 19, including which channels will be calibrated. Clicking on “**Source Flatness**” for the required port brings up the window shown in Figure 20, requesting application of either the DUT or a 50Ω match. Follow the on-screen instructions. When the desired source flatness calibrations are completed, press “**Apply**”.

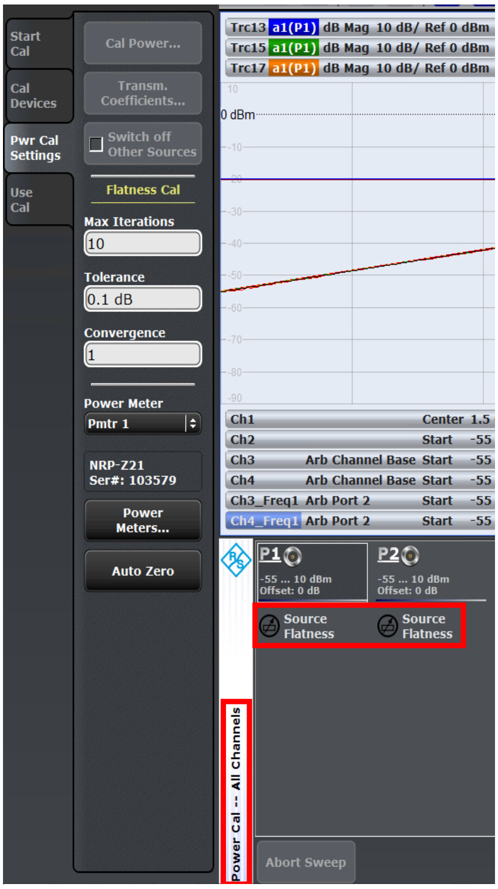

Figure 19 - Source power flatness

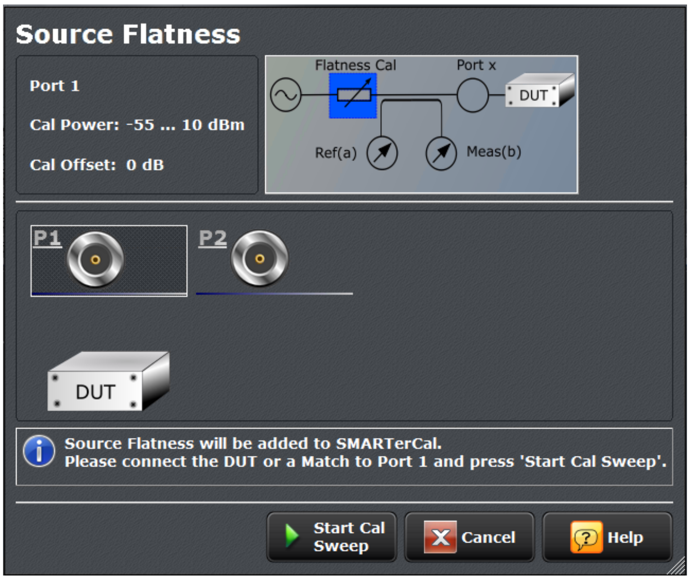

Figure 20 – Source power flatness calibration

5.1.3 Source Power Flatness and Receiver Power Calibrations (non SMARTerCal)

If "**SMARTerCal**" is not used, the R&S® ZNB analyzer still allows the user to calibrate the power levels of the sources and the receivers. Using the menu, "**Calibration → Start Cal → Power Cal**" (Figure 18), the user is given the option to calibrate all channels, before entering the power calibration window.

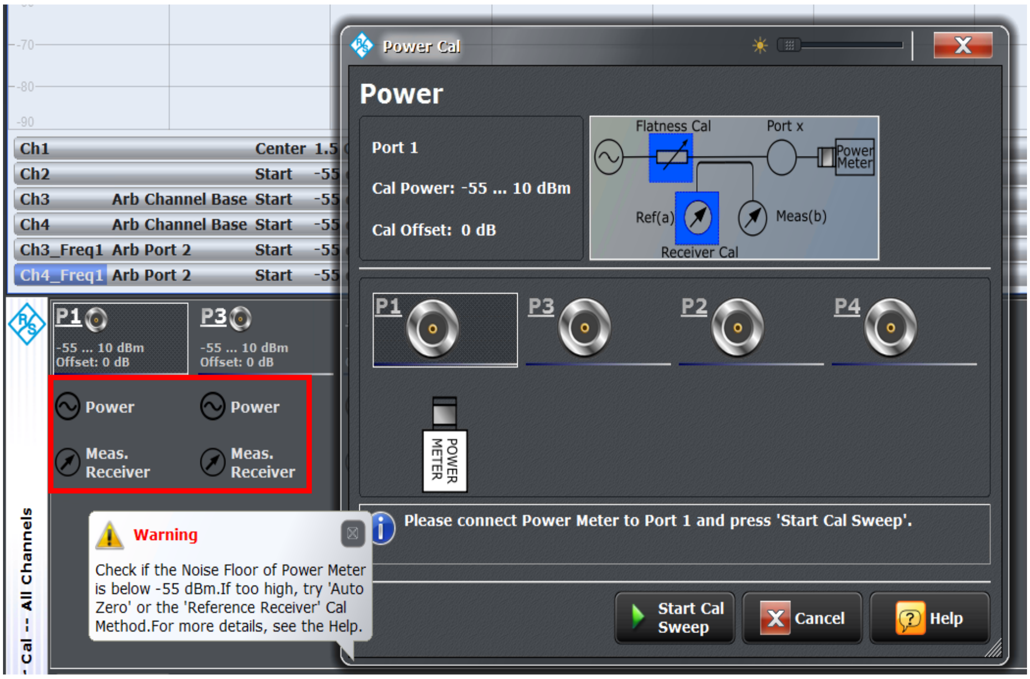

Figure 21 – Active source power calibration window in front of main power calibration window.

Figure 21 shows a 2-port measurement with a window open for calibrating **Port 1** source power and the *reference receiver*. This window opens after clicking "**Power**" (*red box*) in the window behind. Follow the window instructions and connect the power sensor to the calibration reference plane on **Port 1** and press "**Start Cal Sweep**". **Port 1** *reference receiver* and source will be calibrated for power flatness. When complete, select **Port 2** "**Meas. Receiver**". The **Port 1** and **Port 2** calibration planes are connected together and calibration proceeds using the **Port 1** source as the reference. Power calibrations can be performed in this way on any port source and *reference receiver*, and any *measurement receiver*.

For DUT requiring low power levels, the required source power may be too low and outside the power meter input requirements, preventing calibration. The R&S® ZNB analyzer has highly linear receivers and this feature allows the *reference receiver* to be aligned with a power meter at a high source power level (typically 0dBm) and then the calibrated *reference receiver* is used to perform a source power flatness calibration at a lower power level if required. This enhances accuracy and measurement time.

The menu "**Calibration → Pwr Cal Settings → Cal Power…**" opens the window shown in Figure 22, allowing the user to change the power level used for the calibration of the *reference receiver* by unchecking "**Use Port Power Result**" and entering the required power level. It is applicable to "**SMARTerCal**" and standard source power calibrations.

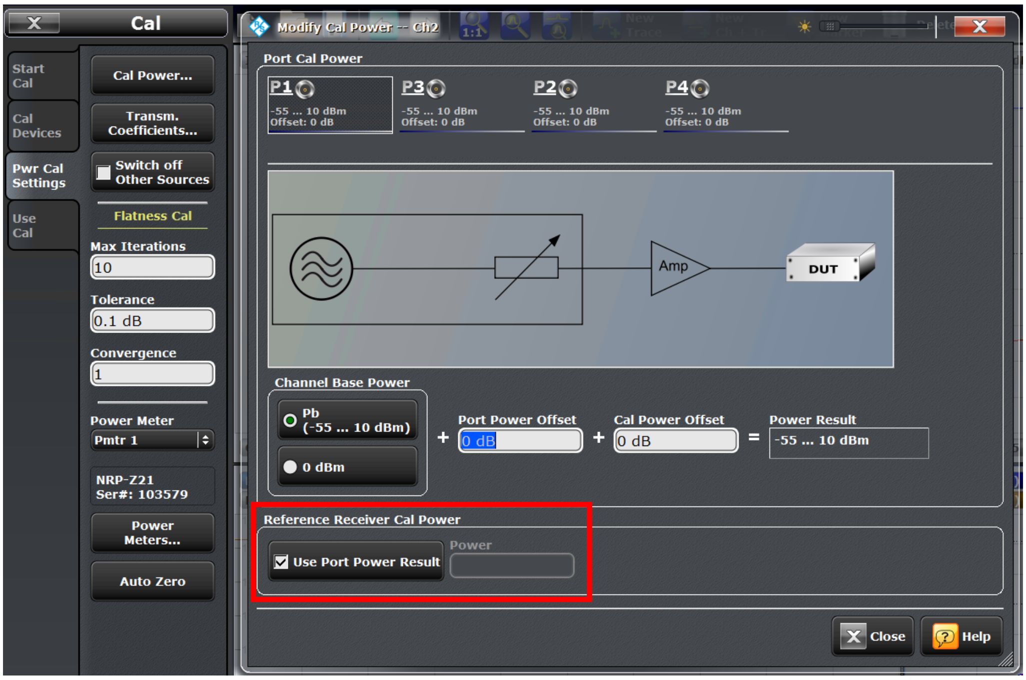

Figure 22 – Good receiver linearity allows calibration of the reference receiver with a power meter at a high power and calibrated operation at low power levels.

6 Bibliography

[1] R&S® ZNB, Vector Network Analyzers, User Manual, (1173.9163.02 — 12).

[2] R&S® Application Note: "*R&S® ZNB Vector Network Analyzer – Intermodulation Measurements Made Simple*".

[3] R&S® Application Note: "*Power Added Efficiency Measurement with R&S®ZNB/R&S®ZVA*", 1EZ64-1E.

7 Additional Information

This Application Note is subject to change without notice. Please visit the website http://www.rohde-schwarz.com to download the latest versions.

Please send any comments or suggestions about this application note to TM-Applications@rohde-schwarz.com.

About Rohde & Schwarz

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