Bode 100 - Application Note

Evaluation of Broadcast and Ham Radio Antennas

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Visit www.omicron-lab.com for more information.
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Table of Contents

Note: Basic procedures such as setting-up, adjusting and calibrating the Bode 100 are described in the Bode 100 user manual. You can download the Bode 100 user manual at www.omicron-lab.com/bode-100/downloads#3

Note: All measurements in this application note have been performed with the Bode Analyzer Suite V3.0. Use this version or a higher version to perform the measurements shown in this document. You can download the latest version at www.omicron-lab.com/bode-100/downloads

1 Abstract

This application note explains how to measure the impedance, reflection factor and VSWR of broadcast antennas as well as Ham Radio Antennas. These antenna parameters are measured with the following two measurement methods supported by the Bode 100:

- Direct Impedance / Reflection / VSWR measurement in the frequency sweep mode
- Impedance / Reflection / VSWR Measurement with increased output power using an external power amplifier and an external directional coupler.

In the appendix of this document you will find a summary on things to consider when you use external directional couplers and amplifiers in combination with the Bode 100.

2 Measurement Tasks

To avoid reflections and to ensure that the maximum broadcast power is achieved, the impedance of a broadcast or Ham Radio antenna needs to match the impedance of the connected signal source. The **V**oltage **S**tanding **W**ave **R**atio (VSWR) and the reflection factor ($\underline{r}$) are two internationally used parameters to qualify how well an antenna matches its nominal impedance.

By analyzing a medium wave broadcast antenna as well as a two different Ham radio antennas the following topics are covered:

- Some theory about the relationship between impedance, VSWR and $\underline{r}$
- Direct Impedance / VSWR / $\underline{r}$ measurement with the Bode 100
- What problems can arise when antennas are measured?
- The advantages of Impedance / VSWR / $\underline{r}$ measurements using the external coupler mode of the Bode 100
- Appendix: Using amplifiers with the Bode 100

3 Theory, Measurement Setup & Results

3.1 VSWR, Impedance and $\underline{r}$

The Bode 100 directly measures the complex impedance $\underline{Z}$ by analyzing the forward and reflected wave. The reflection coefficient $\underline{r}$ and the resulting VSWR are than calculated from the measured $\underline{Z}$ and the nominal impedance Z_0 using the following relations:

$$\underline{Z} = \frac{\underline{V}}{\underline{I}} \qquad \underline{r} = \frac{\underline{Z} - Z_0}{\underline{Z} + Z_0} \qquad VSWR = \frac{1 + |\underline{r}|}{1 - |\underline{r}|}$$

$\underline{V}$	…voltage at the reference plane	$\underline{r}$	…reflection coefficient
$\underline{I}$	…current at the reference plane	VSWR	…**V**oltage **S**tanding **W**ave **R**atio
$\underline{Z}$	…Impedance	Z_0	…nominal impedance

Note: The nominal impedance Z_0 can be set in the Measurement area if *Reflection* is set in at least one of the Traces.

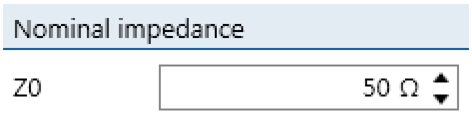

Figure 1: set nominal impedance

The nominal impedance is used for the calculation of the reflection coefficient and therefore influences the VSWR result as well. The Bode Analyzer Suite enables you to change the nominal impedance in the range from 1 Ω...1 kΩ. This allows calculating the VSWR and $\underline{r}$ also for systems with a $Z_0 \neq 50$ Ω.

Example:
The center of the Smith chart indicates the point with ideal matching ($\underline{r}$=0).

Reflection: Z_0= 50 Ω

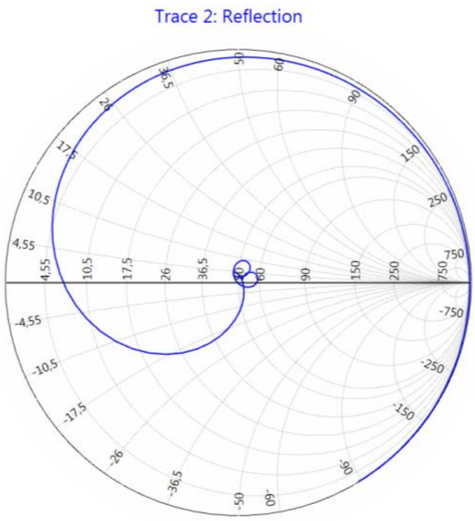

Figure 2: smith chart with Z0 = 50Ω

Reflection: Z_0= 75 Ω

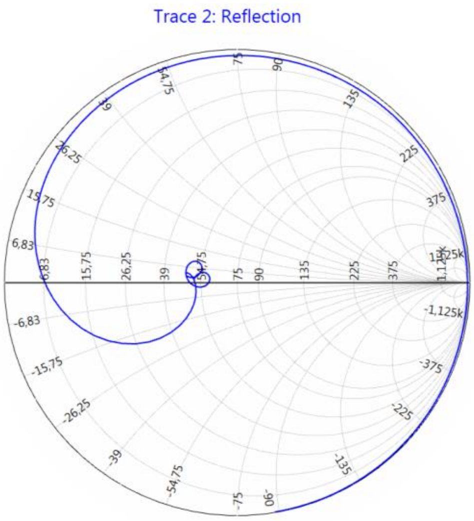

Figure 3: smith chart with Z0 = 75 Ω

The charts above show a measurement of the same filter terminated with 50 Ω. The left chart was calculated for $Z_0 = 50\ \Omega$ while the right one shows the results for $Z_0 = 75\ \Omega$.
It is important to minimize reflected signals to maximize the power radiated by the antenna. The optimum efficiency of a broadcast antenna is reached when the impedance of the antenna exactly matches the source resistance (= nominal impedance Z_0). The reflection coefficient $\underline{r}$ is defined in the range from 1 to -1 and the VSWR parameter in the range from 1 (for ideal matching with $\underline{r} = 0$) to infinite.

3.2 Direct Measurement of a Broadcast Antenna

3.2.1 Description of the Measured Antenna

All measurements described in this chapter where performed on a medium wave transmission site which was not in use at the time this document was written. The measured broadcast antenna has the following characteristics:

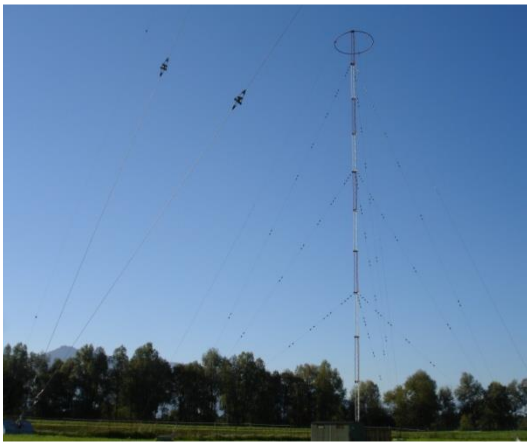

Figure 4: device under test

- The antenna aerial has a triangular cross section and an omni directional, vertically polarized antenna pattern
- The antenna height (length) is 50 meters
- The electrical length of the antenna is defined by its roof capacitance and a coil which is connected in series to the antenna.
- The electrical antenna length was optimized for an AM medium wave signal with a carrier frequency of 1.026 MHz.

3.2.2 Reflection Loss & Impedance Measurement

Before we started our measurements we used a spectrum analyzer to check the signal received by the antenna to exclude possible problems for the input channels of the Bode 100.

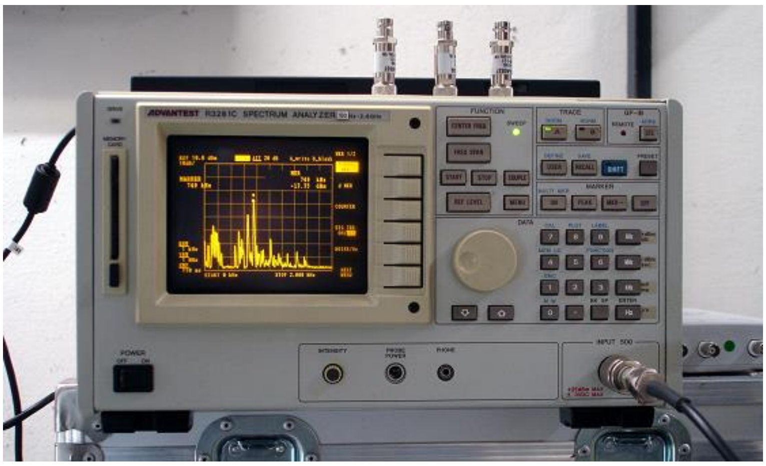

Figure 5: measurement with spectrum analyzer

To measure the impedance of the antenna, the measurement type *One-Port* is selected and the measurement settings as well as the Trace settings are as follows:

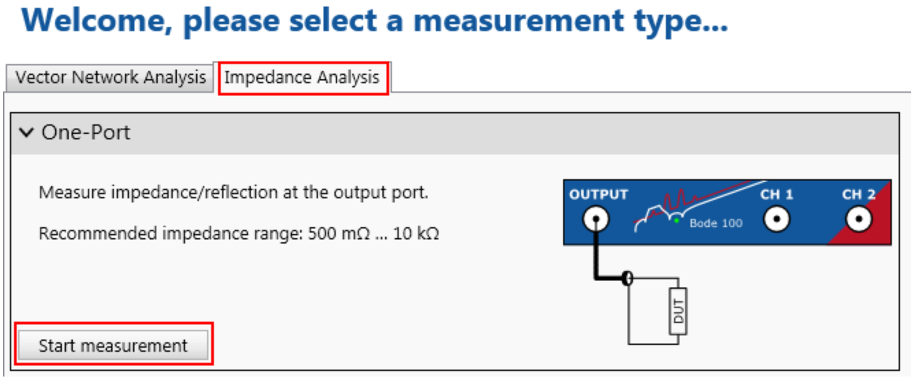

Figure 6: select measurement type

Measurement settings:

- Start Frequency: 500 kHz
- Stop Frequency: 1.5 MHz
- Sweep mode: linear
- Number of points: 401 or more
- Source level: +13 dBm
- Attenuators Receiver 1 & 2: 10 dB
- Receiver Bandwidth: 300 Hz

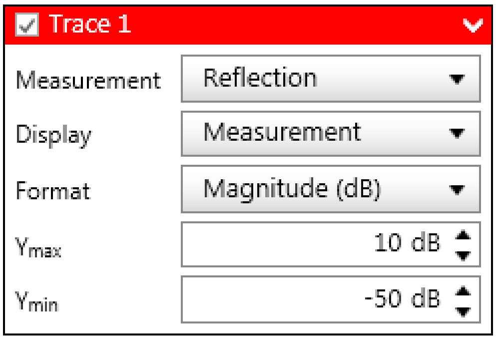

Figure 7: Trace 1 settings

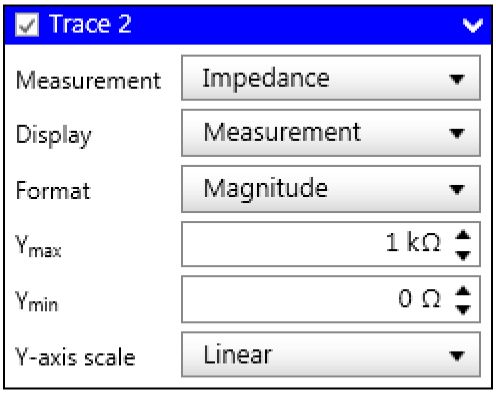

Figure 8: Trace 2 settings

OPEN, SHORT and LOAD calibration was performed to remove the influence of the connection cable.

The antenna was connected to the Bode 100 as shown in the pictures below:

Figure 9: adapters for the connection

Figure 10: connection setup

Starting a frequency sweep leads to reflection and impedance of the antenna:

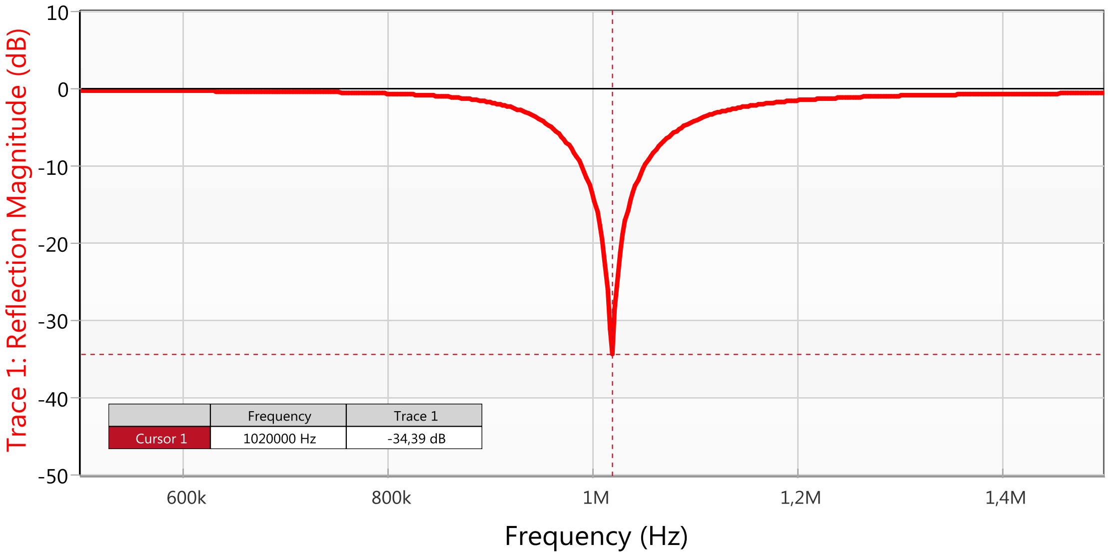

Figure 11: reflection measurement

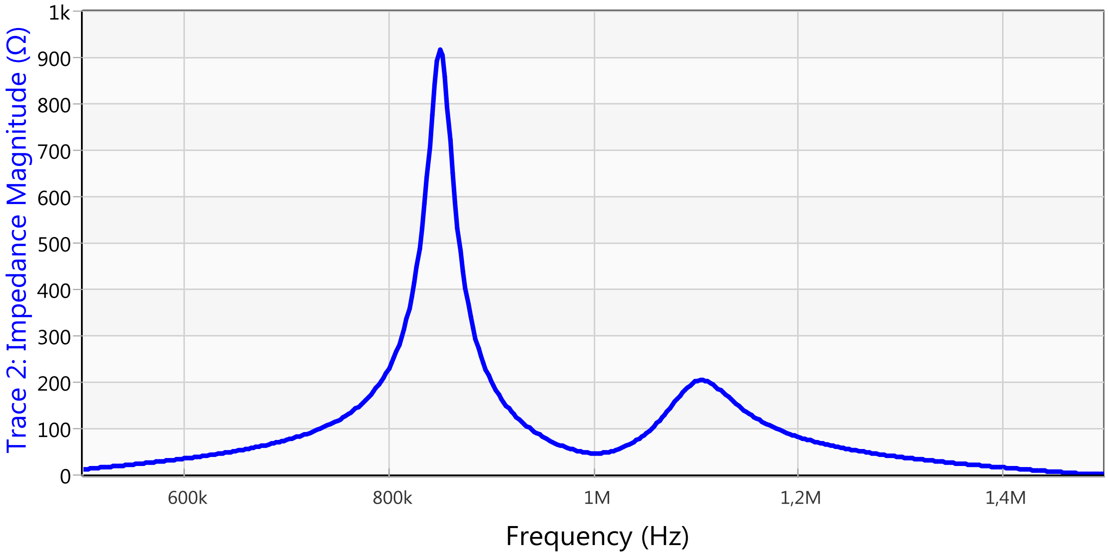

Figure 12: impedance measurement

Result: We measured a minimum reflection of -34.4 dB at 1.020 MHz which equals an impedance of 51.87 Ω. This shows that the antenna is not perfectly matched at the carrier frequency of 1.026 MHz.

Hint: You can export your measurement data for further calculations in other software using the csv export function of the Bode 100.

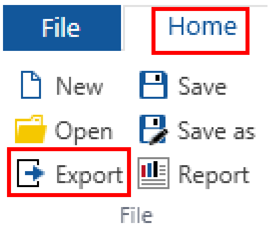

Figure 13: export trace data

3.2.3 Measurement of VSWR and *r*

To display the VSWR and *r* you can keep your impedance measurement and apply the following new settings for Trace 1 & 2:

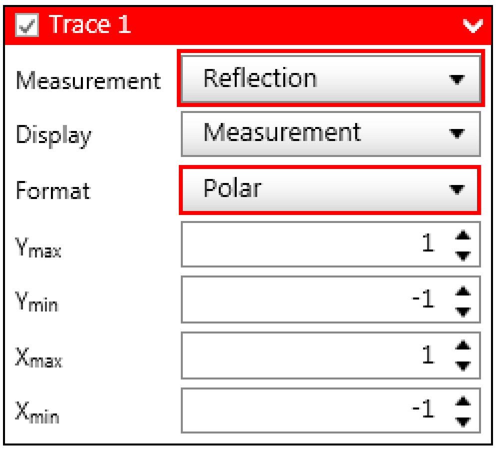

Figure 14: new Trace 1 settings

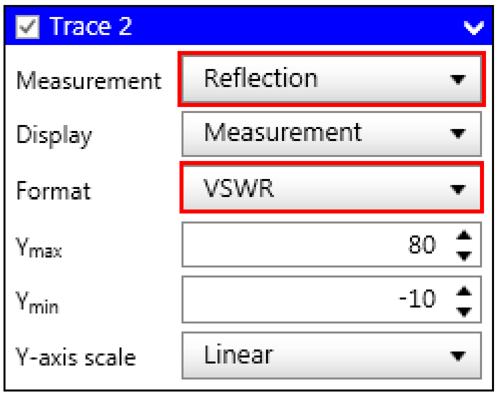

Figure 15: new Trace 2 settings

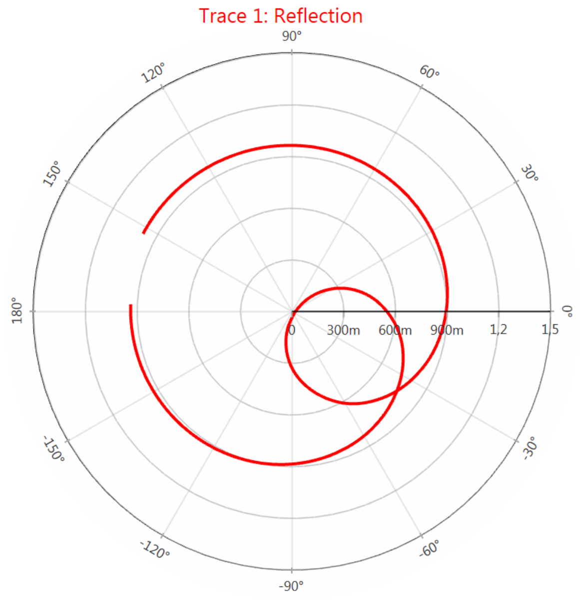

Figure 16: measurement result polar chart

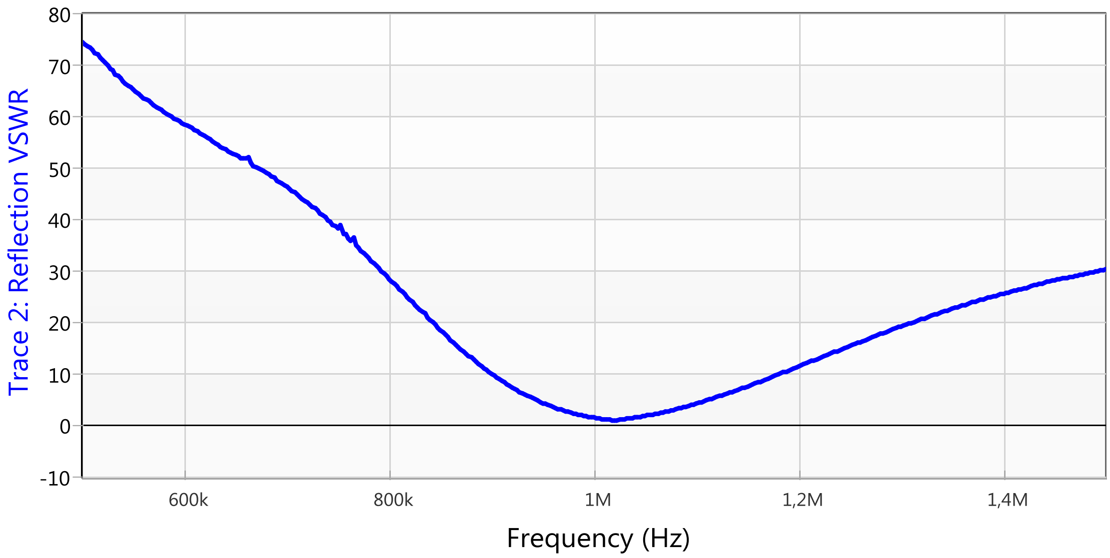

Figure 17: measurement result VSWR

3.2.4 Potential Problems with Direct Measurements

For some measurements the Bode 100 maximum output level of 20 mW (13 dBm) may not be sufficient – this could result in noisy curves as shown in the graph below.

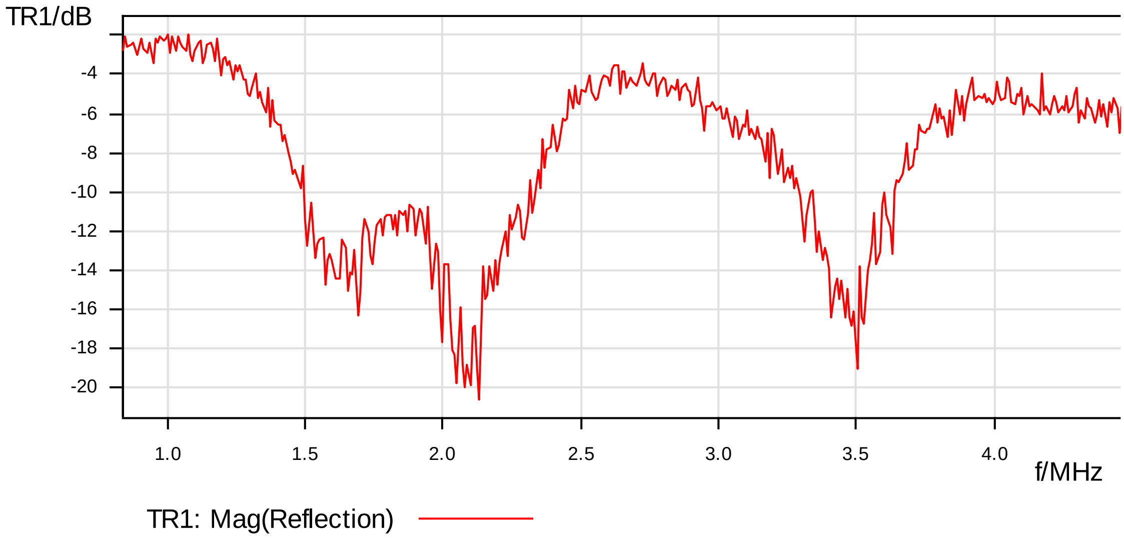

Figure 18: one-port measurement with distortions

To increase the output level of the Bode 100, OMICRON Lab's B-AMP 12 amplifier can be used. Please find more information about it on our webpage (https://www.omicron-lab.com/bode-100/accessories.html).

Furthermore the measured antenna could receive distortions and signals from other transmitters. The picture below shows a spectrum analyzer record of the signals we received over the measured broadcast antenna.

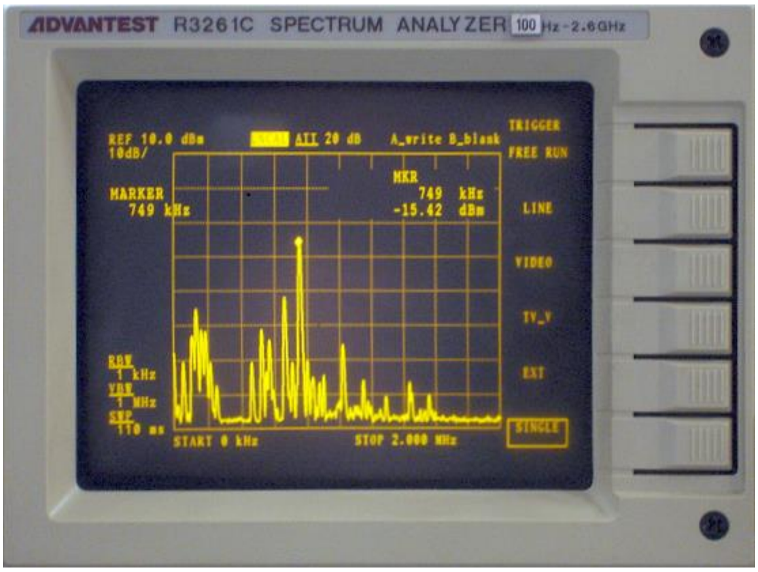

Figure 19: spectrum analyzer measurement of antenna

If the signal received by the antenna is large enough it could damage the Bode 100.

3.3 Broadcast Antenna Measurements with External Coupler

3.3.1 Measurement setup

To avoid potential problems that come with direct antenna measurements, the Bode 100 offers a measurement mode which allows the use of an external directional coupler in combination with an external amplifier.

The measurement setup for this mode is shown below:

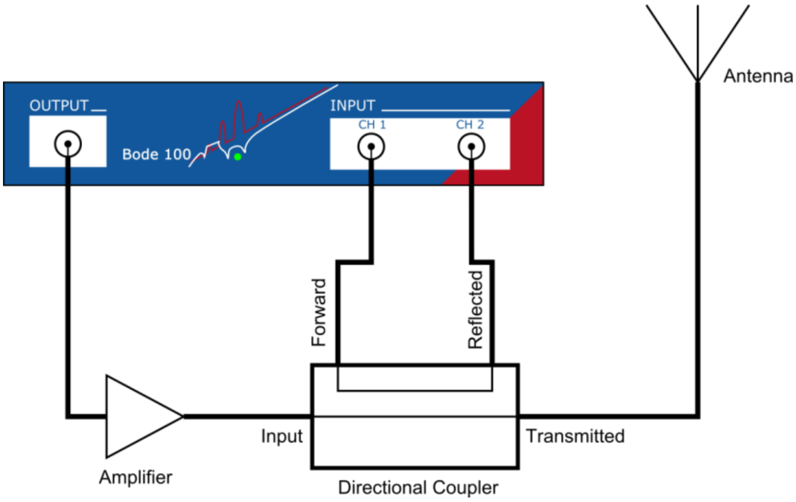

Figure 20: measurement setup external coupler

The Bode 100 output is connected to the amplifier input, the amplifier's output to the input port of the direction coupler, the forward port to CH1 as reference signal, the reflected port to CH2 and the antenna to the transmitted port.

ATTENTION: **To avoid damaging the Bode 100 please read the Appendix of this document before using an external amplifier.**

The following measurements were performed in the *Reflection with external coupler* measurement type:

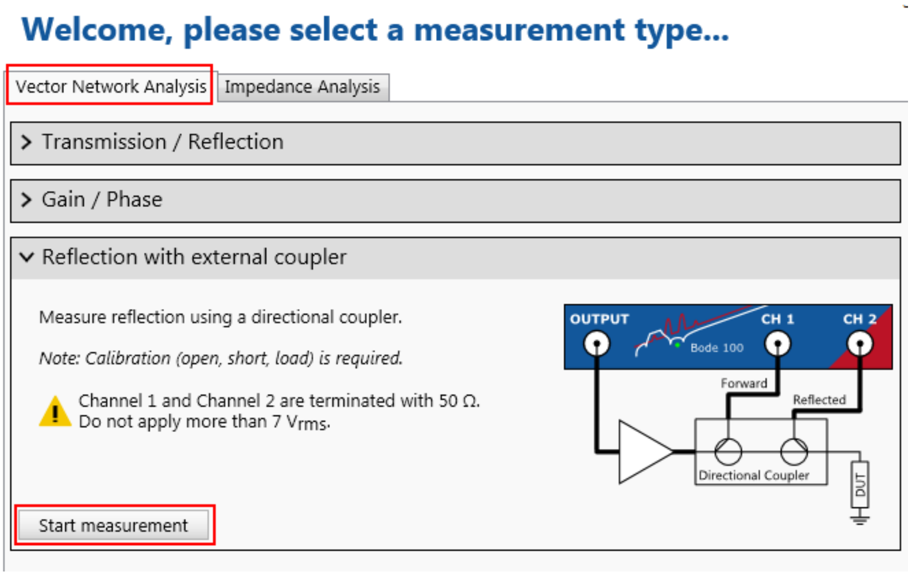

Figure 21: measurement type reflection with external coupler

3.3.2 Impedance / VSWR and $\underline{r}$ Measurement in the Reflection with external coupler Mode

Calculation of the attenuator settings using the measurement results gathered from the first measurements:
The gain of the amplifier we used is 38 dB. Our coupler has a 25 dB loss for its coupled port and a 25 dB loss for the reflected port. Therefore the signal at the inputs CH1 & CH2 is 13 dB higher than the output level of the Bode 100.

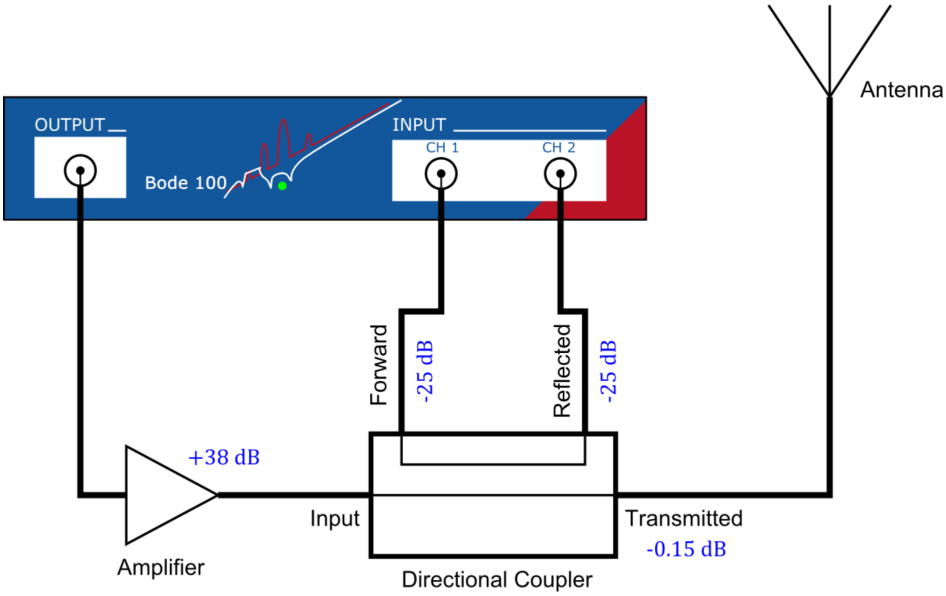

Figure 22: measurement setup

To achieve an optimum noise rejection we use the highest possible output level for our measurement. To choose this level we have to consider the maximum allowed input power for CH1 & CH2 (P_{max} @ 50 Ω input impedance = 30 dBm) and the overload condition for these channels (see Appendix).

$$P_{CH} = P_{out} + Gain_{ampl+coupler} = 13\ \text{dBm} + 13\ \text{dBm} = 26\ \text{dBm}$$

This calculation shows that we are within the maximum input power range. The attenuators for CH1 & CH2 need to be set to 40 dB to avoid overloading the channels (see attenuator table in the Appendix).

For the impedance & reflection loss measurement we applied the following settings in the *Reflection with external coupler* measurement type:

- Start Frequency: 500 kHz
- Stop Frequency: 2 MHz
- Sweep mode: linear
- Number of points: 201 or more
- Level: +13 dBm
- Attenuator Receiver 1 & 2: 40 dB
- Receiver Bandwidth: 300 Hz

Trace 1 & Trace 2 are set like in Figure 7 & Figure 8.

Connect your directional coupler and the required cables to the Bode 100 and perform a User Calibration for OPEN, SHORT and LOAD at the port where you connect the antenna.

Attention: The maximum input power for the delivered 50 Ω load resistor is 1 W. To avoid damaging the 50 Ω calibration load use a lower output level during calibration.

Start a frequency sweep to measure reflection coefficient and impedance of the antenna.

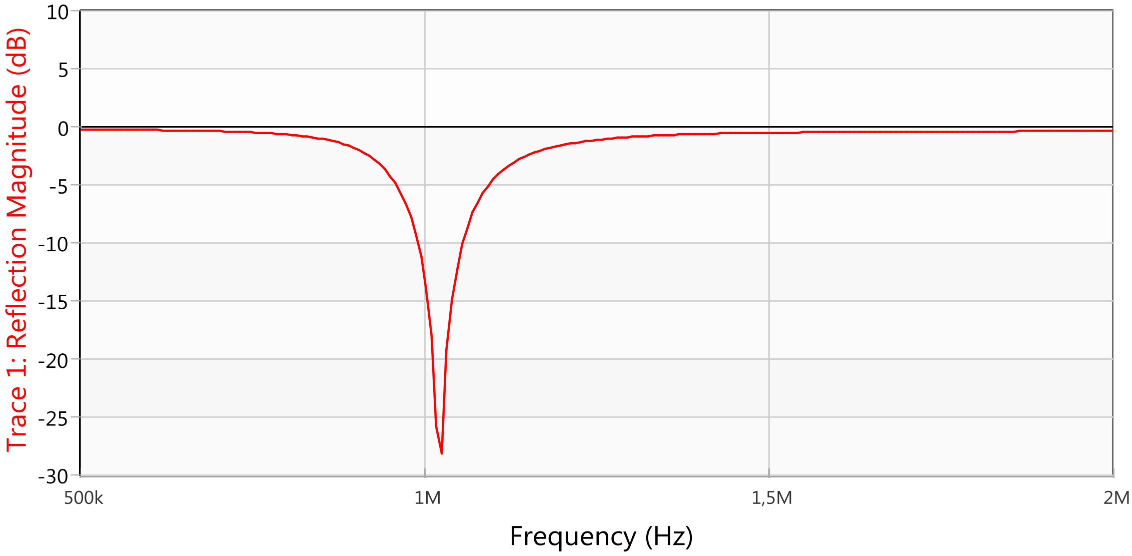

Figure 23: reflection magnitude (dB) measurement with external coupler

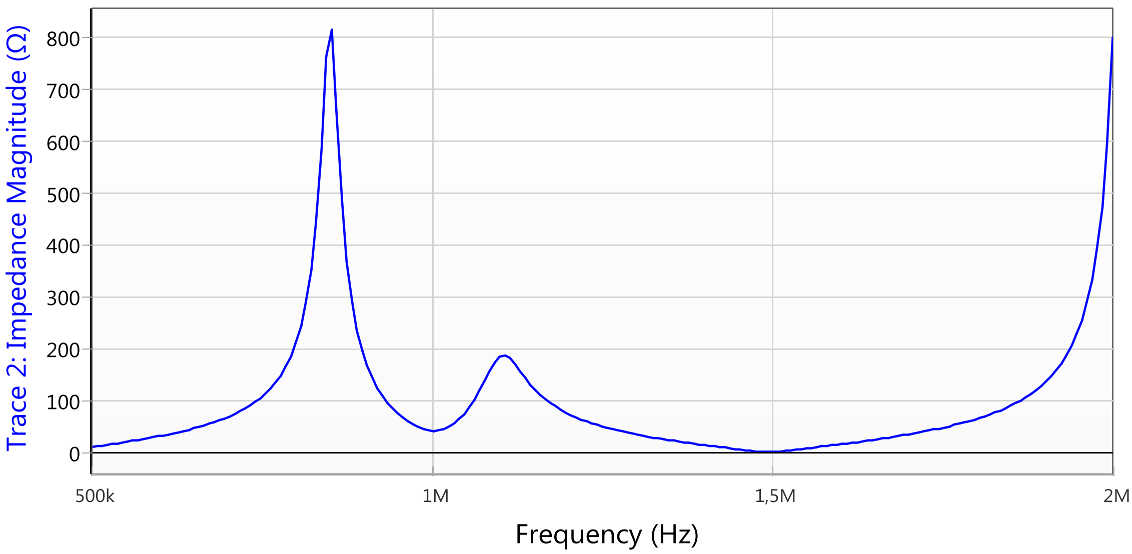

Figure 24: impedance measurement with external coupler

Set the Traces 1 & 2 like in the Figure 14 & Figure 15 for the following diagrams.

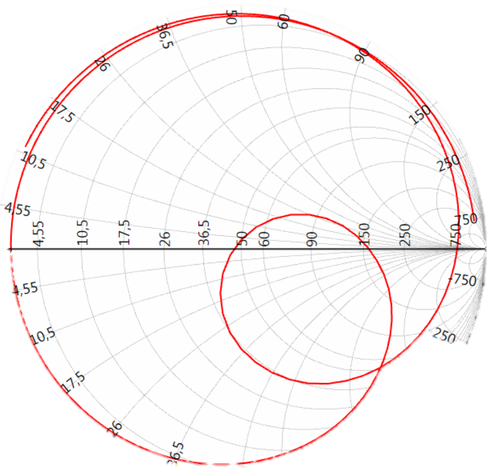

Figure 25: smith chart with external coupler

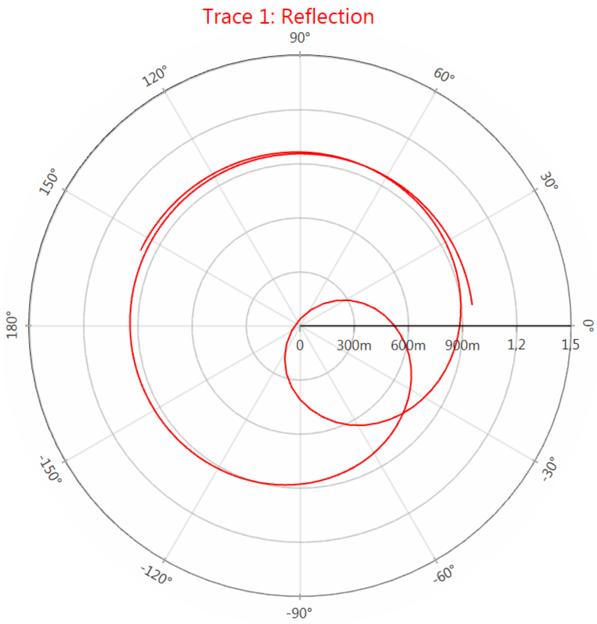

Figure 26: polar chart with external coupler

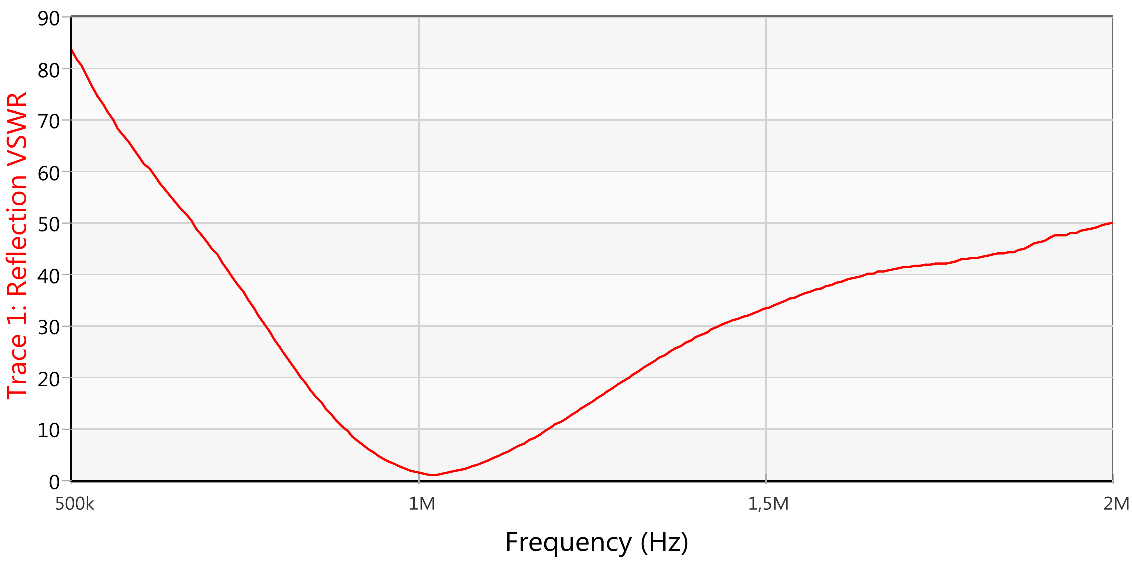

Figure 27: VSWR measurement with external coupler

3.4 Measurement of a Ham Radio Antenna

Special thanks go to the members of the amateur radio station "Klosterkeller Mehrerau" in Bregenz, Austria where we performed the measurements of two of their ham radio antennas. If you want to get more information about this amateur radio station you can visit their homepage at www.oe9.oevsv.at/adl901/.

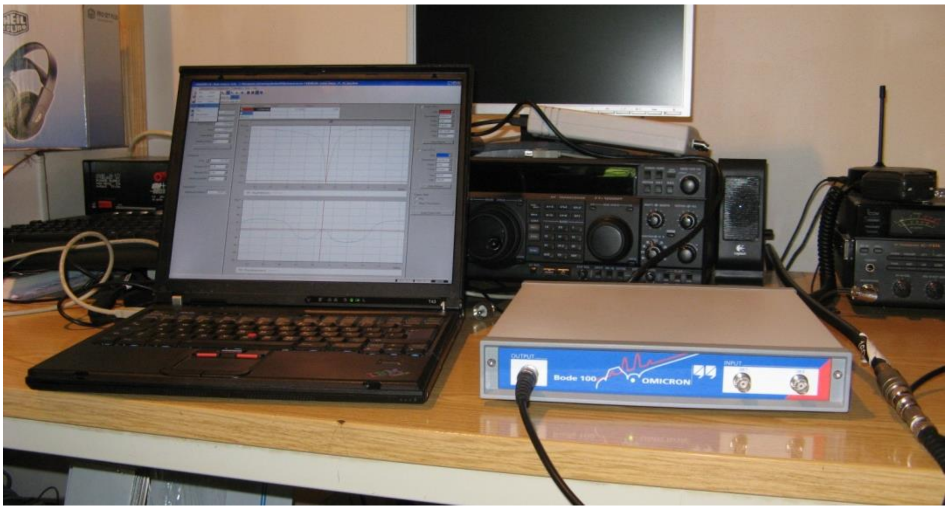

Figure 28: measurement setup

3.4.1 Description of the Measured Antennas

Windom FD 8
160 – 10 meter

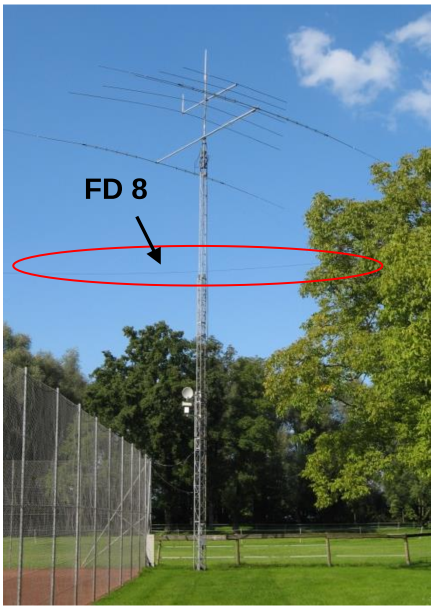

Figure 29: DUT FD 8

This is a wire antenna and therefore hardly visible on the picture.

Cushcraft R7
vertical 40 -10 meter

Figure 30: DUT R7

3.4.2 Impedance / VSWR and r Measurement

Windom FD8 antenna:

The first measurement, using the *one-port* measurement type, was performed to find the carrier frequencies of the antenna with the following result:

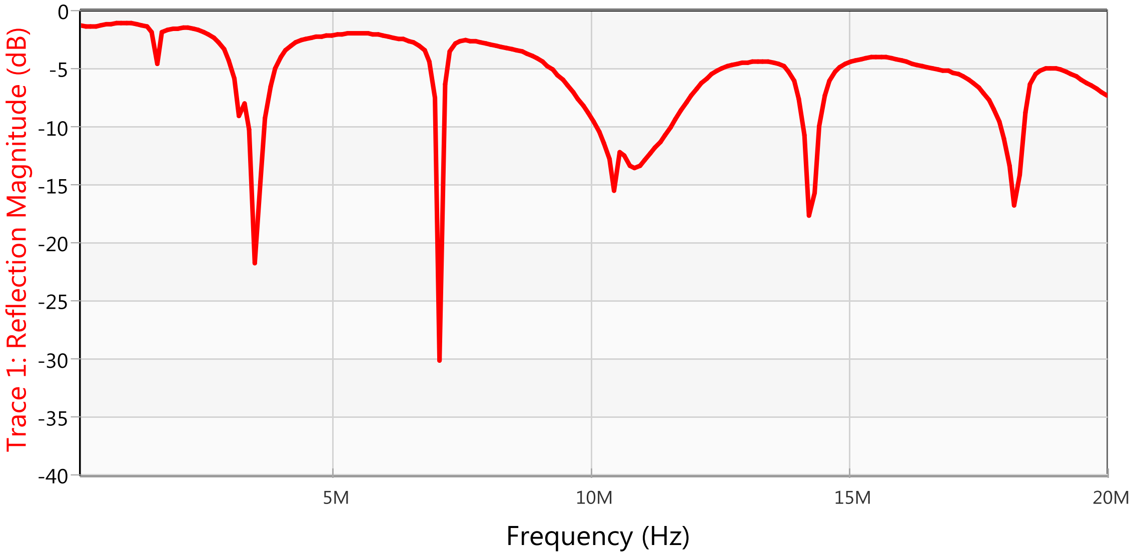

Figure 31: measurement finding carrier frequency

The carrier frequency around 7 MHz was chosen for further measurements using the *Reflection with external coupler* measurement type.

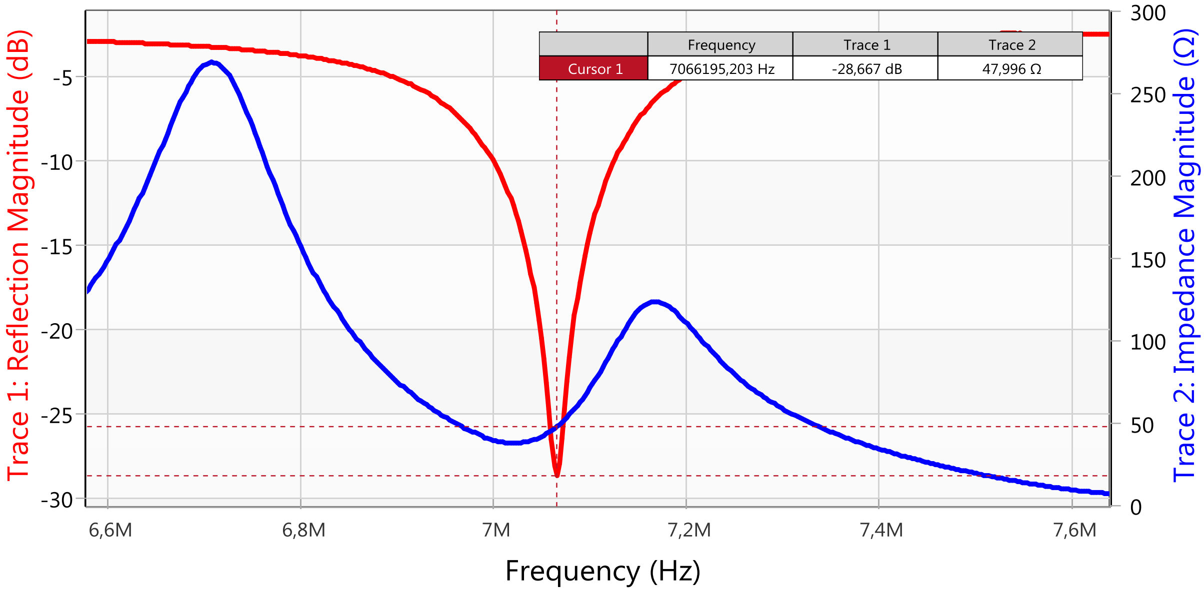

Figure 32: measurement result reflection & impedance

A change of the format settings at Trace 1 or 2 to polar, smith or VSWR chart leads to the following graphs. The cursor marks the frequency with the highest return loss.

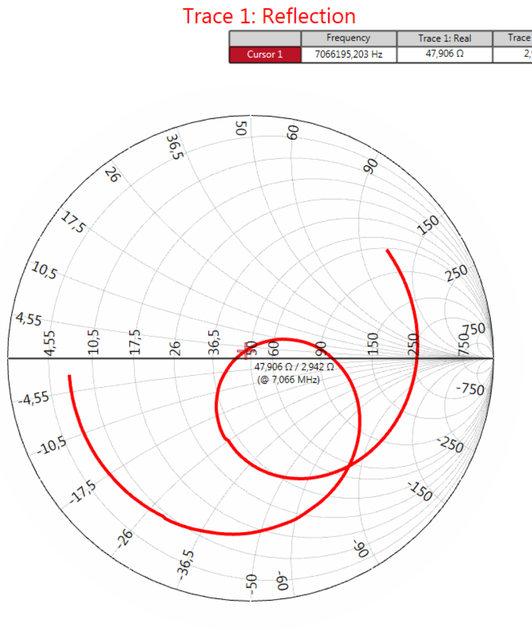

Figure 33: smith chart of FD8

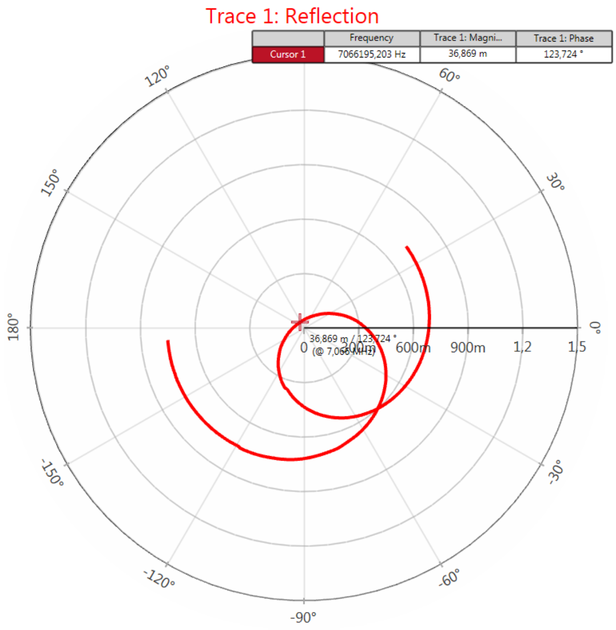

Figure 34: polar chart of FD8

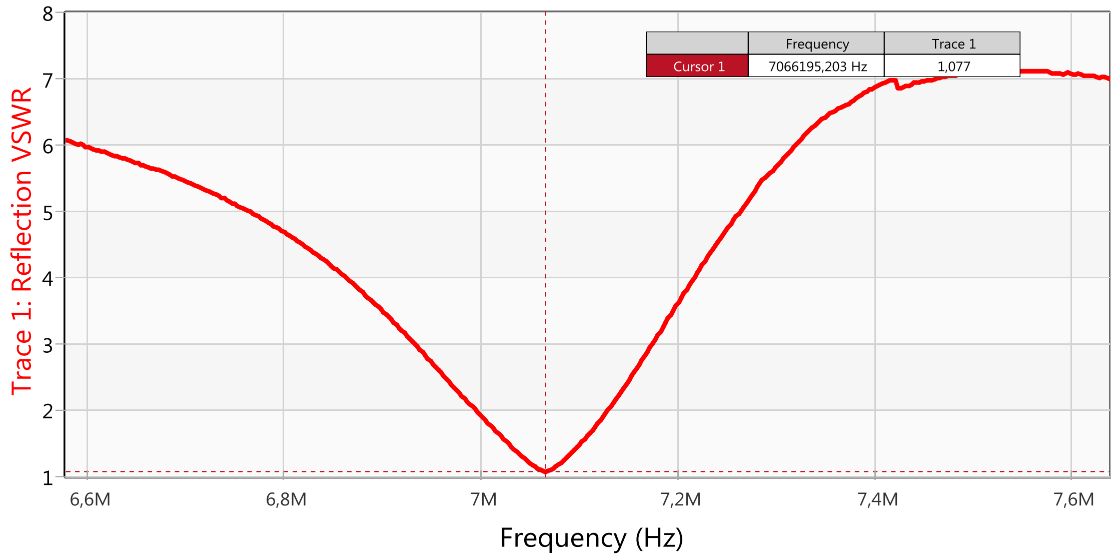

Figure 35: VSWR of FD8

Result: At the chosen frequency of 7.066 MHz the VSWR is 1.077 and the impedance of the antenna is 47.9 Ω.

Cushcraft R7 antenna:

Beside a closer look on single carrier frequencies it can also be measureed the antenna characteristic over a lager frequency range. The chart below shows the reflection respectively VSWR from 25 to 35 MHz of the Cushcraft R7 antenna (*one-port* measurement type). Two low reflection points are marked with cursors.

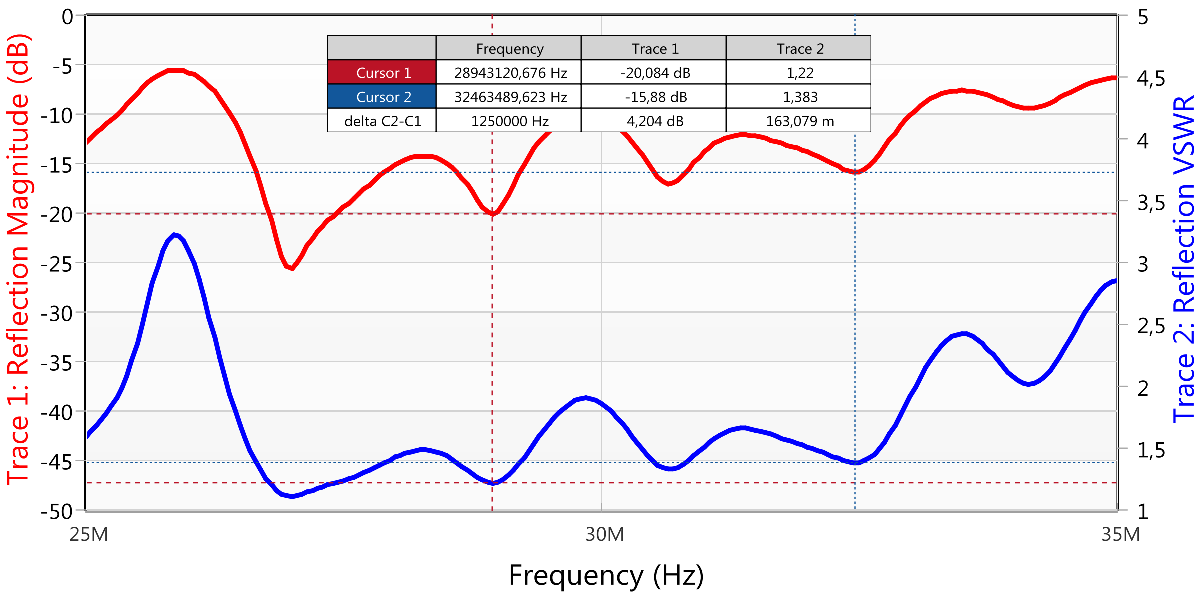

Figure 36: magnitude (dB) and VSWR of R7 antenna

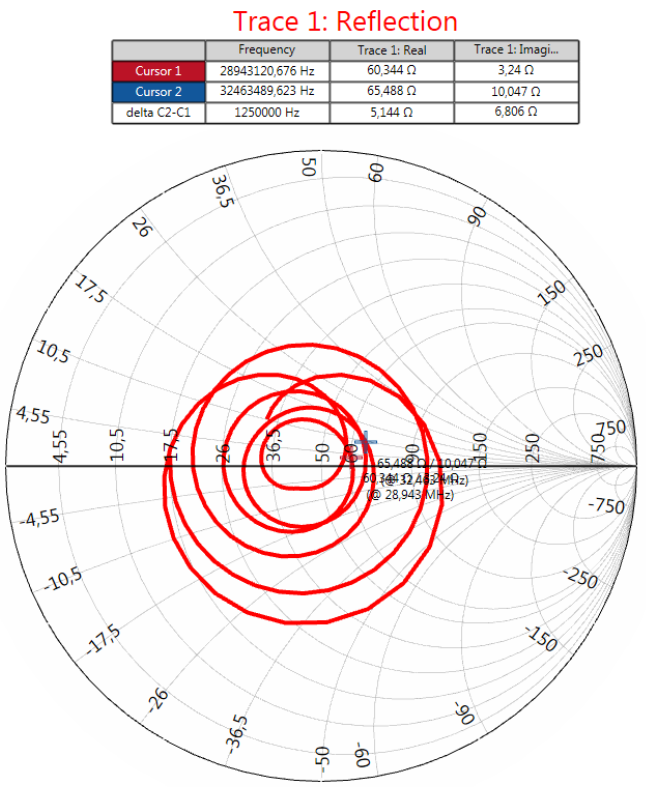

Figure 37: smith chart of R7 antenna

4 Conclusion

The Bode 100 offers all necessary tools to perform measurements on short, medium and long wave antennas. All important parameters as impedance, reflection coefficient or Voltage Standing Wave Ratio (VSWR) can be measured and displayed easily. The Bode Analyzer Suite offers all graphical possibilities to display Smith-Charts, linear and logarithmic axis scaling or polar plots of results.

Appendix

Guideline for the use of External Amplifiers

To avoid damage it is important that the maximum allowed input power applied to the Bode 100 is not exceeded at any point of the measurement.
Before an amplifier can be used, the maximum input ratings for both receivers have to be considered to avoid damaging the Bode 100. It is also important to avoid overload during the measurements.

The input of the Bode 100 is displayed in the following figure:

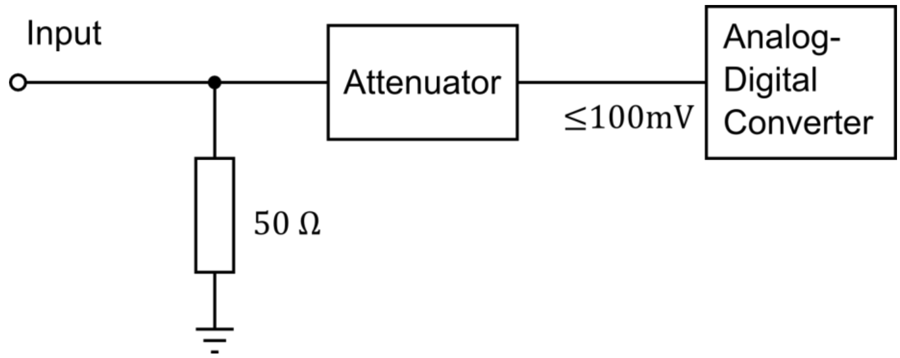

Figure 38: Bode 100 input

The absolute maximum ratings for the Bode 100 Channel 1 and Channel 2 inputs (50Ohm input impedance) are defined as follows:

Maximum input power: 1 W
Maximum input voltage: 7 V_{rms}

The maximum allowed input power in dBm can be calculated as follows:

$$P_{\max(\mathrm{dBm})} = 10 \cdot \log\left(\frac{P_{max(\mathrm{W})}}{1\ \mathrm{mW}}\right) = 10 \cdot \log\left(\frac{1\ \mathrm{W}}{1\ \mathrm{mW}}\right) = 30\ \mathrm{dBm}$$

Example:
If you plan to measure the gain of a 37dB amplifier you will have to keep the Bode 100 source signal (= the input signal of the amplifier) at least below -7dBm to avoid damaging the inputs.

$$P_{sourcemax} = P_{\max(\mathrm{dBm})} - Gain_{Amp(\mathrm{dB})} = 30\ \mathrm{dBm} - 37\ \mathrm{dB} = -7\ \mathrm{dBm}$$

The maximum input voltage to avoid an overload of Ch1 & Ch2 which would result in measurement failures is defined by the maximum input voltage of the internal ADC and the chosen attenuator settings.

Input sensitivity: 100 mV full scale for input attenuator 0 dB

Attenuator	P_{CHmax}	V_{CHmax}
0 dB	- 7 dBm	0.10 V_{rms}
10 dB	3 dBm	0.316 V_{rms}
20 dB	13 dBm	1.0 V_{rms}
30 dB	23 dBm	3.16 V_{rms}
40 dB	33 dBm	10.0 V_{rms}

Example:
Let's say we use the same amplifier as before. We have to keep the Bode 100 source level below -14 dB for an attenuator adjustment of 30 dB to avoid an overload.

$$P_{sourcemax} = P_{CHmax(dBm)} - Gain_{Amp(\mathrm{dB})} = 23\ \mathrm{dBm} - 37\ \mathrm{dBm} = -14\ \mathrm{dBm}$$

The following formulas were used for the calculations:

$$\Delta V_{(\mathrm{dB})} = 20 \cdot \log\left(\frac{V_2}{V_1}\right)\mathrm{dB} \qquad \Delta P_{(\mathrm{dB})} = 10 \cdot \log\left(\frac{P_2}{P_1}\right) \qquad P = \frac{V^2}{R}$$

In the following we did summarize the important points which need to be considered when using the Bode 100 in combination with an external amplifier and an external coupler.

Important points:

- **Overcharge:** The maximum allowed input power for the 50 Ω input impedance is 30 dBm. Using signals with more power will damage the Bode 100.
- **Overload:** To avoid measurement failures the input voltage is limited by the overload range of the ADC and the chosen attenuator settings.
- **Tolerances:** Always consider a possibly higher gain than specified of your amplifier due to its tolerances.

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