Measurement Uncertainties
for
Vector Network Analysis

Application Note 1EZ29_1E

Subject to change

21 October 1996, Thilo Bednorz

Products:

ZVR
ZVRE
ZVRL

ROHDE&SCHWARZ

Deviation from ideal behaviour of a network analyzer can be classified into two groups, namely stochastic errors and systematic errors:

1 Stochastic errors

The following stochastic errors are distinguished:

Et	thermal drift of the NWA system
Er	repeatability of connections
En	noise of NWA receiver

Stochastic errors are principally drift of generator and receiver versus temperature, repeatability of connections, and noise of the receiver. Noise affects mainly the measurement accuracy at low power levels at the receiver input (high attenuation of the DUT).

2 Systematic errors

Systematic errors can be distinguished between

Ec	non-linear systematic errors and
Es	linear systematic errors.

Systematic errors are per definitionem reproducible and can therefore be numerically corrected if a suitable model for the NWA and its errors is used. There are linear and non-linear systematic errors. Linear errors are finite directivity (for reflection measurements), source and load port mismatch (for reflection and transmission measurements) and (internal and external) crosstalk between the two ports (for transmission measurements). Non-linear errors result from the non-linear behaviour (compression) of the receiver especially for high signal levels (low attenuation or amplification of DUT).

3 How to reduce the errors

Thermal drift Et

Et depends on the thermal stability of the instrument. It is recommended to use an instrument of high thermal stability as ZVR or ZVRE and to perform calibration and measurement in thermal equilibrium for NWA, DUT and calibration kit as indicated in the data sheet.

Repeatability Er

Er depends on the quality of the connector and the characteristics of the connector type. Therefore high-quality connectors suitable for the chosen frequency range are strictly recommended.

Noise En

En is reduced by increasing the signal-to-noise ratio of the receiver. A narrow IF bandwidth and high output power of the NWA is usefull.

Nonlinearity (e.g. compression) Ec

Ec is dependent of the input power level. To reduce Ec the input power should be in the linear range of the NWA. It is important that a suitable low input level (to avoid compression effects) is used for calibration **and** measurement.

Linear systematic errors Es

Es depends upon system data, source and load port match. Because the raw values of a system with common adapters and cables are often very poor, full two-port calibration of the NWA is absolutely necessary to achieve low Es. This improves the so-called **effective** (describing the residual error after calibration) system data dramatically. Remember: A measurement can only be as good as the calibration. Any further adapter between DUT and the calibrated reference planes of the NWA should be avoided.

4 Determination of measurement uncertainty

To quantify uncertainties for NWA measurements, the influence of the entire system (NWA plus test setup and DUT) has to be taken into account. Usually, the overall uncertainty of the complete measurement setup is determined with the aid of a verification kit, containing highly accurate verification standards. Of course, the verification standards need to have the same connector type as the DUT. If such verification standards are not available, the overall error has to be estimated.

5 Quantitative error estimation of |S21| for 0 dB and 100 dB

5.1 Passband (attenuation ≈ 0 dB)

En
Can be ignored if a suitable narrow IF bandwidth e.g. 300 Hz is chosen, producing a negligible trace noise (which can be controlled with a direct through-connection and normalization).

Er
Depends upon type and quality of connectors. The error Er is determined via performing a repeatability test by comparing the results of several connections of the same DUT.

Typical assumption for precision N-connectors: ±0.01dB.

Et
The error is **less than 0.01 dB** after a 1h warm-up time (see Table on thermal stability in the appendix), and even smaller (≈0.002 dB) especially if measurements are done directly after calibration and can mostly be neglected for this application.

Ec
Depends upon the input level. If -10 dBm power level is used for calibration and measurement, this error is 0.2 dB. Using -20 dBm instead, the receiver is highly linear and this error is smaller than 0.05 dB (or ±0.5%). For further information see „Dynamic uncertainty of the ZVR“ in the appendix. For a low attenuation DUT, power levels for calibration (thru-connection) and measurement are nearly identical. In this case no compression effects have to be considered.

Es
Linear systematic errors are mostly due to multiple reflections between NWA and DUT. Internal and external crosstalk as well as a finite directivity can be neglected if a ZVR (crosstalk <120dB) and a full two-port calibration (e.g. TOM) as well as good cables and connectors are used.

The error contribution due to multiple reflections is calculated by the following formulae:

S'_{21} measured (erroneous) S-param. of DUT
S_{xx} true S-parameters of DUT
$\Gamma_{1/2}$ effective load and source match of NWA

$$\left|\underline{S}'_{21}\right| = \left|\frac{1-\underline{\Gamma}_1\underline{\Gamma}_2}{(1-\underline{\Gamma}_1\underline{S}_{11})(1-\underline{\Gamma}_2\underline{S}_{22})-\underline{S}_{12}\underline{S}_{21}\underline{\Gamma}_1\underline{\Gamma}_2}\right| \left|\underline{S}_{21}\right|$$

$$\mathrm{Es} := \mathrm{Max}\left\{\left|\left|\underline{S}_{21}'\right| - \left|\underline{S}_{21}\right|\right|\right\}$$

$$\mathrm{Es} = \left|\underline{S}_{21}\right| \cdot \left(1 - \left|\frac{1+\left|\underline{\Gamma}_1\underline{\Gamma}_2\right|}{(1-\left|\underline{\Gamma}_1\underline{S}_{11}\right|)(1-\left|\underline{\Gamma}_2\underline{S}_{22}\right|)-\left|\underline{S}_{12}\underline{S}_{21}\underline{\Gamma}_1\underline{\Gamma}_2\right|}\right|\right)$$

Reduction of Es is achieved by improving the test port match (Γ) of the NWA. After calibration the error is described by the effective load and source port match. For ZVR the guaranteed values (after full two-port calibration) are better than 30 dB. The typical values for 1 GHz are 46 dB. The effective load port match can demonstrated after full two port calibration by directly connecting port 1 to port 2 and measuring S22.

Total error

Worst case calculations are most conveniently done with linear values (%) and not dB values:
(dB value) = 20 · log (linear value[%]*100)

For example a true value t of 1 or 100% represents a 0-dB attenuation.

The measured value is a (vectorial) superposition of the true value and error contributions (see appendix). For worst case estimation of maximum total error a scalar addition of the true signal and all errors is performed. The maximum possible measurement value is the sum of the true value t and all error terms, the minimum value is the difference of t and the sum of errors:

Max.= t+En+Er+Et+Ec+Es (linear values)

Min. = t-(En+Er+Et+Ec+Es) (linear values)

En = 0.01 dB	lin. val. 0.001 (300 Hz IFBW)
Er = 0.01dB	lin. val. 0.001 (high qual. con.)
Et = 0.01dB	lin. value 0.001 (1h warm-up)
Ec = 0.01 dB	lin. value 0.001 (0 dB DUT)
Es = 0.05 dB	lin. value 0.006 (40-dB test port match and 10-dB DUT match is assumed)

Max. lin. value = 1.010 ⇒ +0.086 dB
Min. lin. value = 0.990 ⇒ -0.087 dB

The worst case total error for low attenuation (0 dB) is less than 0.1 dB.

5.2 Stopband (attenuation 100dB)

En
Depends upon NWA output power and IF bandwidth. High output power and narrow IF bandwidth are recommended, e.g. 10 Hz. Best results are achieved if calibration is done at -20 dBm and measurement with 0 dBm source power. This error signal can be evaluated by terminating both test ports with an open or short circuit. Thus the behaviour of a total reflective DUT, e.g. passive filter in the stop-band, is considered and the sum of noise and (internal and external) crosstalk is taken into account. A typical value is -120 dB (linear error value = 10 e-6).

Er
Depends on the kind of connector type. This error can be neglected here because of the high attenuating DUT (see total error).

Et
Can be neglected as well (see Er).

Ec
Can be neglected if calibration is performed at -20 dBm source power. Then noise effects at 100 dB attenuation are significantly higher than effects due to any nonlinearity of the ZVR. To achieve a high dynamic range however, it is recommended to use the highest available source power of 0 dBm during measurements, and to use -20 dBm source power for calibration to reduce nonlinearity effects.

Es
Systematic errors due to multiple reflections.

The contribution due to multiple reflection is calculated by the same formulae as for the passband:

$$\left|\underline{S}'_{21}\right| = \left|\frac{1-\underline{\Gamma}_1\underline{\Gamma}_2}{(1-\underline{\Gamma}_1\underline{S}_{11})(1-\underline{\Gamma}_2\underline{S}_{22})-\underline{S}_{12}\underline{S}_{21}\underline{\Gamma}_1\underline{\Gamma}_2}\right| \left|\underline{S}_{21}\right|$$

$$\mathrm{Es} := \mathrm{Max}\left\{\left|\left|\underline{S}_{21}'\right|-\left|\underline{S}_{21}\right|\right|\right\}$$

$$\mathrm{Es} = \left|\underline{S}_{21}\right| \cdot \left(1-\left|\frac{1+\left|\underline{\Gamma}_1\underline{\Gamma}_2\right|}{(1-\left|\underline{\Gamma}_1\underline{S}_{11}\right|)(1-\left|\underline{\Gamma}_2\underline{S}_{22}\right|)-\left|\underline{S}_{12}\underline{S}_{21}\underline{\Gamma}_1\underline{\Gamma}_2\right|}\right|\right)$$

Assumptions:

$\Gamma_{1/2}$ = -40dB ≅ 0.01(lin)
$S_{11/22}$ = 0dB ≅ 1 (lin)
$S_{21/12}$ = -100dB ≅ 1 e-5 (lin)

Total error

Worst case calculation is again done with linear values:

True val. t= 100dB ≅ 1e-5 (lin)

Max. val. = t +En+Er+Et+Ec+Es (lin. values)

Min. val. = t -(En+Er+Et+Ec+Es) (lin. values)

En = -120 dB	lin. value 1e-6
Er	lin. value 0 (neglected)
Et	lin. value 0 (neglected)
Ec	lin. value 0 (neglected)
Es = -154 dB	lin. value 2e-8 (neglected)

Max. lin. value = 1.1e-5 ⇒ -99 dB
Min. lin. value = 0.9e-5 ⇒ -101 dB

The worst case total error for high attenuation (100 dB) is approx. 1 dB.

(This additionaly shows that other errors, e.g. linearity, repeatability etc. can be neglected.)

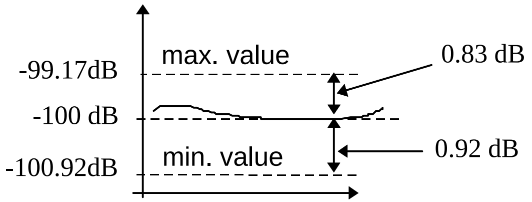
6 How to measure passband and stopband in one sweep with high accuracy?

In the calculations above two different source power levels of the NWA were recommended during measurements. The first level was -20 dBm for the passband, and the second 0 dBm for the stopband. Such a measurement with two different source power levels can be very easily done with the ZVR in one sweep by using the so called SEGMENT SWEEP. Different frequency segments can be edited to have individual source power levels and bandwidths. So high power (0 dBm) and narrow IF bandwidth (10 Hz) for the stopband and low power (-20 dBm) and a moderate IF bandwidth (300 Hz) for the passband, as recommended, can be combined in a very comfortable way for each sweep. For (full two-port) calibration however the power for the whole frequency band should be set to -20 dBm to avoid compression during calibration, as explained above.

7 Appendix

7.1 Fast estimation of uncertainty with the help of a table

If there is only one main error source as in the case of a S21 measurement in the stopband, error estimation can be made without calculation of linear values using Table 7.2.



Example:

True value = -100dB
Error = -120 dB

⇒ Difference = 20 dB

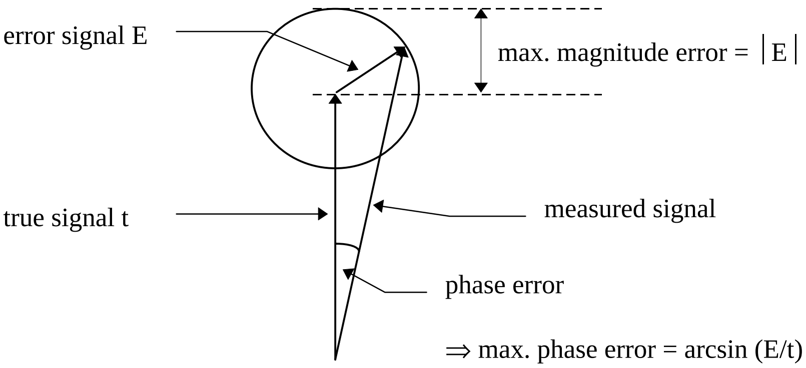
- Now look up row X = 20 dB
- Read deviation to higher values (more positive) in column (1+X) ⇒ +0.83 dB
- Read deviation to lower values (more negative) in column (1-X) ⇒ -0.92 dB

- Read the total error margin in column 1±X ⇒ 1.74 dB

With the help of this table the phase error can also be evaluated in the same manner:

- Again look up row X = 20 dB
- and read deviation of the phase error in degrees in column Δφ, eg 5,74°.

It is interesting to note that the maximum error in magnitude coincides with a zero phase error, and for the maximum error in phase the magnitude error is nearly zero.

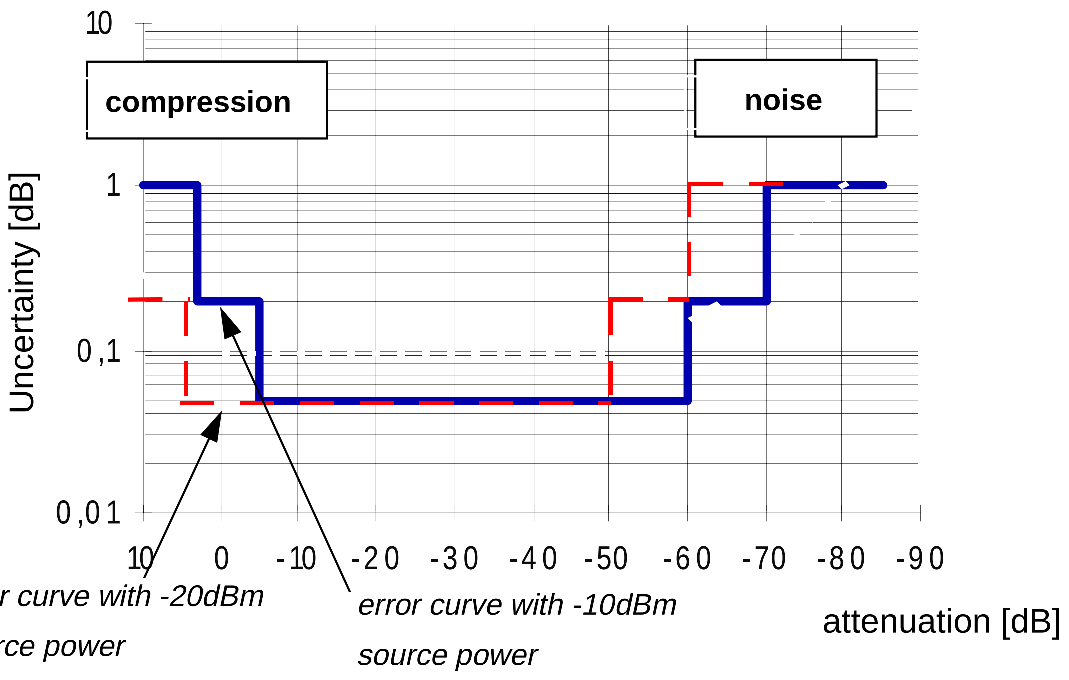


7.2 Table for error estimation

X	1+X	1-X	1±X	Δφ
0 dB	+6,02 dB	-∝ dB	∝ dB	90,00°
1 dB	+5,53 dB	-19,27 dB	24,81 dB	63,03°
2 dB	+5,08 dB	-13,74 dB	18,81 dB	52,59°
3 dB	+4,65 dB	-10,69 dB	15,34 dB	45,07°
4 dB	+4,25 dB	-8,66 dB	12,91 dB	39,12°
5 dB	+3,88 dB	-7,18 dB	11,05 dB	34,22°
6 dB	+3,53 dB	-6,04 dB	9,57 dB	30,08°
7 dB	+3,21 dB	-5,14 dB	8,35 dB	26,53°
8 dB	+2,91 dB	-4,41 dB	7,32 dB	23,46°
9 dB	+2,64 dB	-3,81 dB	6,44 dB	20,78°
10 dB	+2,39 dB	-3,30 dB	5,69 dB	18,43°
11 dB	+2,16 dB	-2,88 dB	5,03 dB	16,37°
12 dB	+1,95 dB	-2,51 dB	4,46 dB	14,55°
13 dB	+1,75 dB	-2,20 dB	3,96 dB	12,94°
14 dB	+1,58 dB	-1,93 dB	3,51 dB	11,51°
15 dB	+1,42 dB	-1,70 dB	3,12 dB	10,24°
16 dB	+1,28 dB	-1,50 dB	2,78 dB	9,12°
17 dB	+1,15 dB	-1,32 dB	2,47 dB	8,12°
18 dB	+1,03 dB	-1,17 dB	2,20 dB	7,23°
19 dB	+0,92 dB	-1,03 dB	1,96 dB	6,44°
20 dB	+0,83 dB	-0,92 dB	1,74 dB	5,74°
21 dB	+0,74 dB	-0,81 dB	1,55 dB	5,11°
22 dB	+0,66 dB	-0,72 dB	1,38 dB	4,56°
23 dB	+0,59 dB	-0,64 dB	1,23 dB	4,06°
24 dB	+0,53 dB	-0,57 dB	1,10 dB	3,62°
25 dB	+0,48 dB	-0,50 dB	0,98 dB	3,22°
26 dB	+0,42 dB	-0,45 dB	0,87 dB	2,87°
27 dB	+0,38 dB	-0,40 dB	0,78 dB	2,56°
28 dB	+0,34 dB	-0,35 dB	0,69 dB	2,28°
29 dB	+0,30 dB	-0,31 dB	0,62 dB	2,03°
30 dB	+0,27 dB	-0,28 dB	0,55 dB	1,81°
31 dB	+0,24 dB	-0,25 dB	0,49 dB	1,62°
32 dB	+0,22 dB	-0,22 dB	0,44 dB	1,44°
33 dB	+0,19 dB	-0,20 dB	0,39 dB	1,28°
34 dB	+0,17 dB	-0,18 dB	0,35 dB	1,14°
35 dB	+0,15 dB	-0,16 dB	0,31 dB	1,02°
36 dB	+0,14 dB	-0,14 dB	0,28 dB	0,91°
37 dB	+0,12 dB	-0,12 dB	0,25 dB	0,81°
38 dB	+0,11 dB	-0,11 dB	0,22 dB	0,72°
39 dB	+0,10 dB	-0,10 dB	0,19 dB	0,64°
40 dB	+0,09 dB	-0,09 dB	0,17 dB	0,57°
41 dB	+0,08 dB	-0,08 dB	0,15 dB	0,51°
42 dB	+0,07 dB	-0,07 dB	0,14 dB	0,46°
43 dB	+0,06 dB	-0,06 dB	0,12 dB	0,41°
44 dB	+0,05 dB	-0,05 dB	0,11 dB	0,36°
45 dB	+0,05 dB	-0,05 dB	0,10 dB	0,32°
46 dB	+0,04 dB	-0,04 dB	0,09 dB	0,29°
47 dB	+0,04 dB	-0,04 dB	0,08 dB	0,26°
48 dB	+0,03 dB	-0,03 dB	0,07 dB	0,23°
49 dB	+0,03 dB	-0,03 dB	0,06 dB	0,20°
50 dB	+0,03 dB	-0,03 dB	0,05 dB	0,18°
51 dB	+0,02 dB	-0,02 dB	0,05 dB	0,16°
52 dB	+0,02 dB	-0,02 dB	0,04 dB	0,14°
53 dB	+0,02 dB	-0,02 dB	0,04 dB	0,13°
54 dB	+0,02 dB	-0,02 dB	0,03 dB	0,11°
55 dB	+0,02 dB	-0,02 dB	0,03 dB	0,10°
56 dB	+0,01 dB	-0,01 dB	0,03 dB	0,09°
57 dB	+0,01 dB	-0,01 dB	0,02 dB	0,08°
58 dB	+0,01 dB	-0,01 dB	0,02 dB	0,07°
59 dB	+0,01 dB	-0,01 dB	0,02 dB	0,06°
60 dB	+0,01 dB	-0,01 dB	0,02 dB	0,06°

7.3 Dynamic uncertainty of ZVR receiver

The graph below shows the uncertainty due to receiver nonlinearity (compression) and receiver noise. Uncertainties for an attenuation value of 0 dB are indicated for a nominal power level of -10 dBm during calibration and measurement and a source power level of -20 dBm.



Guaranteed dynamic uncertainty (solid line) of the receiver (200kHz-4GHz).
Nominal source power for calibration and measurement -10 dBm, IFBW 10Hz.
Decreasing the source power by 10 dB to -20 dBm shifts the curve 10 dB to the left

7.4 Thermal stability of ZVR

ZVR: Reproducibility test with cold device (the warm unit was normalized the day before)

Time	Magnitude	Phase
Directly after switching on (cold)	0.05 dB	2°
After 20 minutes	0.02 dB	0.5°
After one hour	0.01 dB	0.2°
After two hours	0.005 dB	0.1°
After 8 hours	0.01 dB	0.1°

Typical results of investigation of stability

(The stabiltity of effective directivity was about 60dB directly after switching on and increased after one hour up to 80dB)

Thilo Bednorz, 1ESP
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21 October 1996

8 Further Application Notes

[1] O. Ostwald: 3-Port Measurements with Vector Network Analyzer ZVR, Appl. Note 1EZ26_1E.

[2] H.-G. Krekels: Automatic Calibration of Vector Network Analyzer ZVR, Appl. Note 1EZ30_1E.

[3] O. Ostwald: 4-Port Measurements with Vector Network Analyzer ZVR, Appl. Note 1EZ25_1E.

[4] T. Bednorz: Measurement Uncertainties for Vector Network Analysis, Appl. Note 1EZ29_1E.

[5] P. Kraus: Measurements on Frequency-Converting DUTs using Vector Network Analyzer ZVR, Appl. Note 1EZ32_1E.

[6] J. Ganzert: Accessing Measurement Data and Controlling the Vector Network Analyzer via DDE, Appl. Note 1EZ33_1E.

[7] J. Ganzert: File Transfer between Analyzers FSE or ZVR and PC using MS-DOS Interlink, Appl. Note 1EZ34_1E.

[8] O. Ostwald: Group and Phase Delay Measurements with Vector Network Analyzer ZVR, Appl. Note 1EZ35_1E.

[9] O. Ostwald: Multiport Measurements using Vector Network Analyzer, Appl. Note 1EZ37_1E.

[10] O. Ostwald: Frequently Asked Questions about Vector Network Analyzer ZVR, Appl. Note 1EZ38_3E.

[11] A. Gleißner: Internal Data Transfer between Windows 3.1 / Excel and Vector Network Analyzer ZVR, Appl. Note 1EZ39_1E.

[12] A. Gleißner: Power Calibration of Vector Network Analyzer ZVR, Appl. Note 1EZ41_2E

[13] O. Ostwald: Pulsed Measurements on GSM Amplifier SMD ICs with Vector Analyzer ZVR, Appl. Note 1EZ42_1E.

[14] O. Ostwald: Zeitbereichsmessungen mit dem Netzwerkanalysator ZVR, Appl. Note 1EZ44_1D.

9 Ordering Information

Order designation	Type	Frequency range	Order No.
Vector Network Analyzers (test sets included) *			
3-channel, unidirectional, 50 Ω, passive	ZVRL	9 kHz to 4 GHz	1043.0009.41
3-channel, bidirectional, 50 Ω, passive	ZVRE	9 kHz to 4 GHz	1043.0009.51
3-channel, bidirectional, 50 Ω, active	ZVRE	300 kHz to 4 GHz	1043.0009.52
4-channel, bidirectional, 50 Ω, passive	ZVR	9 kHz to 4 GHz	1043.0009.61
4-channel, bidirectional, 50 Ω, active	ZVR	300 kHz to 4 GHz	1043.0009.62
3-channel, bidirectional, 50 Ω, active	ZVCE	20 kHz to 8 GHz	1106.9020.50
4-channel, bidirectional, 50 Ω, active	ZVC	20 kHz to 8 GHz	1106.9020.60
Alternative Test Sets *			
75 Ω SWR Bridge for ZVRL (instead of 50 Ω) 1)			
75 Ω, passive	ZVR-A71	9 kHz to 4 GHz	1043.7690.18
75 Ω SWR Bridge Pairs for ZVRE and ZVR (instead of 50 Ω) 1)			
75 Ω, passive	ZVR-A75	9 kHz to 4 GHz	1043.7755.28
75 Ω, active	ZVR-A76	300 kHz to 4 GHz	1043.7755.29
Options			
AutoKal	ZVR-B1	0 to 8 GHz	1044.0625.02
Time Domain	ZVR-B2	same as analyzer	1044.1009.02
Mixer Measurements 2)	ZVR-B4	same as analyzer	1044.1215.02
Reference Channel Ports	ZVR-B6	same as analyzer	1044.1415.02
Power Calibration 3)	ZVR-B7	same as analyzer	1044.1544.02
3-Port Adapter	ZVR-B8	0 to 4 GHz	1086.0000.02
Virtual Embedding Networks 4)	ZVR-K9	same as analyzer	1106.8830.02
4-Port Adapter (2xSPDT)	ZVR-B14	0 to 4 GHz	1106.7510.02
4-Port Adapter (SP3T)	ZVR-B14	0 to 4 GHz	1106.7510.03
Controller (German) 5)	ZVR-B15	-	1044.0290.02
Controller (English) 5)	ZVR-B15	-	1044.0290.03
Ethernet BNC for ZVR-B15	FSE-B16	-	1073.5973.02
Ethernet AUI for ZVR-B15	FSE-B16	-	1073.5973.03
IEC/IEEE-Bus Interface for ZVR-B15	FSE-B17	-	1066.4017.02
Generator Step Attenuator PORT 1	ZVR-B21	same as analyzer	1044.0025.11
Generator Step Attenuator PORT 2 6)	ZVR-B22	same as analyzer	1044.0025.21
Receiver Step Attenuator PORT 1	ZVR-B23	same as analyzer	1044.0025.12
Receiver Step Attenuator PORT 2	ZVR-B24	same as analyzer	1044.0025.22
External Measurements, 50 Ω 7)	ZVR-B25	10 Hz to 4 GHz (ZVR/E/L) 20 kHz to 8 GHz (ZVC/E)	1044.0460.02

1) To be ordered together with the analyzer.
2) Harmonics measurements included.
3) Power meter and sensor required.
4) Only for ZVR or ZVC with ZVR-B15.
5) DOS, Windows 3.11, keyboard and mouse included.
6) For ZVR or ZVC only.
7) Step attenuators required.

*** Note:**

Active test sets, in contrast to passive test sets, comprise internal bias networks, eg to supply DUTs.