Group and Phase Delay Measurements with Vector Network Analyzer ZVR

Application Note 1EZ35_1E

Subject to change

10 July 1997, Olaf Ostwald

Products:

ZVR

ZVRE

ZVRL

ROHDE&SCHWARZ

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1 BASICS

The frequency-dependent complex transfer function $H(f)$ of an arbitrary device under test (DUT) can be expressed as follows

$$H(f) = A(f) \cdot e^{j\varphi(f)} \qquad (1)$$

where $A(f)$ denominates the magnitude and $\varphi(f)$ the phase response of the DUT. Vector network analyzers are able to measure both magnitude and phase response.

Group delay measurements are based on phase measurements. The measurement procedure corresponds to the definition of group delay τ_{gr} as the negative derivative of the phase φ (in degrees) with respect to frequency f:

$$\tau_{\mathrm{gr}} = -\frac{1}{360^\circ} \cdot \frac{d\varphi}{df} \qquad (2)$$

For practical reasons, Vector Network Analyzers ZVR measure a **difference quotient** rather than a differential quotient of (2), which yields a good approximation to the wanted group delay τ_{gr} provided that the variation of phase φ is not too nonlinear in the observed frequency range Δf, which is called the aperture.

$$\tau_{\mathrm{gr}} \approx -\frac{1}{360^\circ} \cdot \frac{\Delta\varphi}{\Delta f} \qquad (3)$$

Fig. 1 shows an illustration of the terms $\Delta\varphi = \varphi_2 - \varphi_1$ and $\Delta f = f_2 - f_1$ for linearly decreasing phase response, e.g. of a delay line.

The **aperture** $\boldsymbol{\Delta f}$ should be chosen in accordance with

- the desired measurement accuracy and
- the variation of the group delay of the DUT versus frequency.

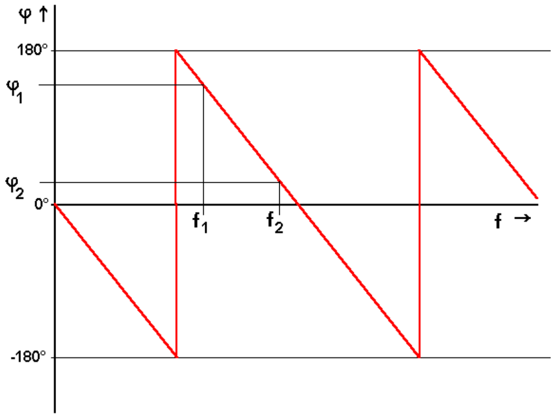

Fig. 1 Definition of phase shift $\Delta\varphi = \varphi_2 - \varphi_1$ and aperture $\Delta f = f_2 - f_1$.

Measurement accuracy can be increased by making the aperture broader. On the other hand, the resolution of group delay measurements with respect to frequency suffers from a wide aperture and fine details of group delay variations versus frequency can no longer be observed. (This is a similar effect as with the well-known **SMOOTHING** function, which takes the average of measurement values at adjacent frequency points. If the smoothing aperture is too broad, it will cause a flat measurement trace without any details left.)

The appropriate choice for the aperture Δf always depends on the group delay characteristics of the DUT.

2 PHASE DELAY MEASUREMENTS

For a **non-dispersive DUT**, e.g. a coaxial cable, group delay is not a function of frequency at all but constant. Consequently, phase $\varphi(f)$ is a linear function of frequency:

$$\varphi(f) = -360^\circ \cdot f \cdot \tau \qquad (4)$$

where τ is the delay time of the cable which is directly related to its mechanical length L_{mech} via the permittivity ε of the dielectric material within the cable and the velocity of light c.

$$\tau = \frac{L_{\mathrm{mech}} \cdot \sqrt{\varepsilon}}{c} \qquad (5)$$

(The velocity of light is: $c \approx 2.9979 \cdot 10^8$ m/s $\approx$ 30 cm/ns $\approx$ 1 ft/ns and can be easily remembered as "one light foot", which is approximately the distance which light travels within 1 ns.)

The product $L_{mech} \cdot \sqrt{\varepsilon}$ is called the **electrical length** L_{el} of the cable, as it denotes the effective length of the cable as "seen" by the electrical signal to travel. In practice, the **electrical length is always longer than the mechanical length**, because of the permittivity being >1 for all practical dielectrics. (For a pure vacuum the permittivity ε is equal to one, which results in an electrical length identical with the mechanical length. Within a finite frequency range even $\varepsilon<1$ is possible for a plasma, which causes a shorter electrical length.)

As an **example**, a cable with a length of 10.34 m filled with a typical dielectric, e.g. teflon ($\varepsilon = 2.1$), causes a delay time τ of 50 ns. The electrical length is approximately $L_{el} \approx 15$ m. The velocity of propagation for an electrical signal within the cable is $c/\sqrt{\varepsilon} \approx 0.69 \cdot c$ in this example.

As for all **non-dispersive DUTs** and also for the cable of this example, there is no difference between the delay time τ and the group delay τ_{gr} as the phase φ is a linear function of frequency (4). This can be shown analytically and by measurement.

With $\varphi(f) = -360° \cdot f \cdot \tau$ it follows from (2) that $\tau_{gr} = \tau$.

For a measurement example, a coaxial cable as described can be used. A cable with 50 ns delay time produces a phase shift of 360° for a frequency shift of 1 / 50 ns = 20 MHz. For an accurate tracking of the phase shift versus frequency, the frequency span and the number of points for the network analyzer must be chosen so that the **phase shift between each two adjacent frequency points does not exceed 180°**. If this is **not** the case, it is impossible to distinguish between a phase shift of φ_o or $\varphi_o + n \cdot 360°$ (n is an arbitrary integer), because of phase ambiguity.

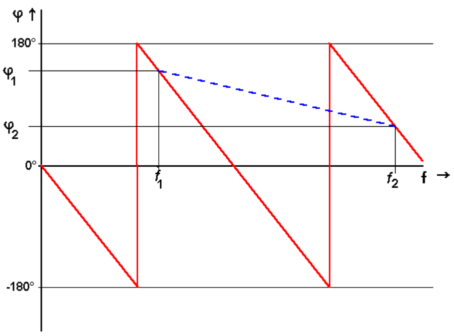

Fig. 2 Incorrect phase tracking caused by too large step width

The described phenomenon is illustrated in Fig. 2, where calculation of the phase difference $\varphi_2 - \varphi_1$ yields an incorrect result for the phase shift $\Delta\varphi$ of approximately -90°, because the phase jump of 360° is simply overlooked. The correct value for $\Delta\varphi$ is approximately -450°, i.e. -90°-360°.

The wrong value is caused by too large step width between adjacent frequency points. (This phenomenon is similar to sampling of an audio signal with too small sampling frequency, thus causing undersampling errors.) To take account of this problem, either the number of frequency points should be increased or the frequency span reduced.

Note: Be aware of the phase-tracking phenomenon when performing phase or delay measurements. Make sure that the phase shift between each two adjacent frequency points is always smaller than 180° to obtain proper phase tracking. Please be especially careful when using **nonlinear** sweep.

In the described example of a 50 ns cable the frequency difference between two adjacent frequency points has to be smaller than 10 MHz. For linear sweep and a START frequency of e.g. 1 MHz and a STOP frequency of e.g. 4 GHz this means that the number of points must be greater than 400. For example, 500 points would be a good choice.

[SWEEP] *NUMBER OF POINTS: 500.*

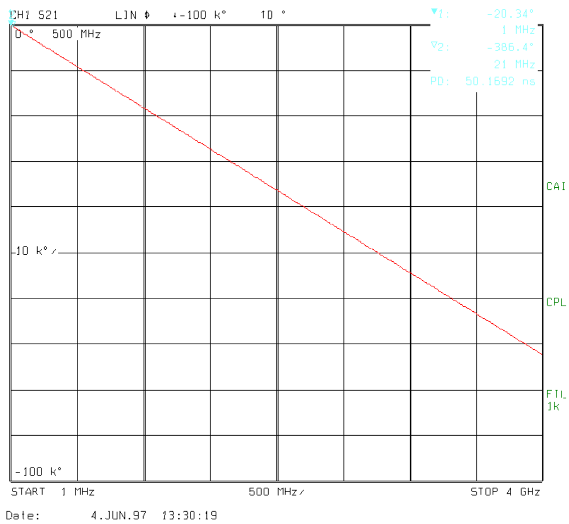

Fig. 3 Phase response of a 50 ns cable

Fig. 3 shows measurement results for the phase of a coaxial cable with approximately 50 ns delay time. The measured phase starts with -20° at 1 MHz and linearly decreases down to -72246° at 4 GHz.

To show the linear regression of the displayed phase response of distinctly more than ±180°, a special feature of ZVR is utilized, called **PHASE UNWRAP**.

[FORMAT] *PHASE: PHASE UNWRAP*

[SCALE] *MAX VALUE = 0: MIN VALUE = -100 k*

This function forces the phase to be displayed linearly without the usual sawtooth character which could otherwise be seen. As explained above, phase unwrap needs a phase shift of less than 180° between adjacent frequency points to work properly.

The phase unwrap feature is illustrated in Fig. 4 for the example of a 2.5 ns coaxial cable.

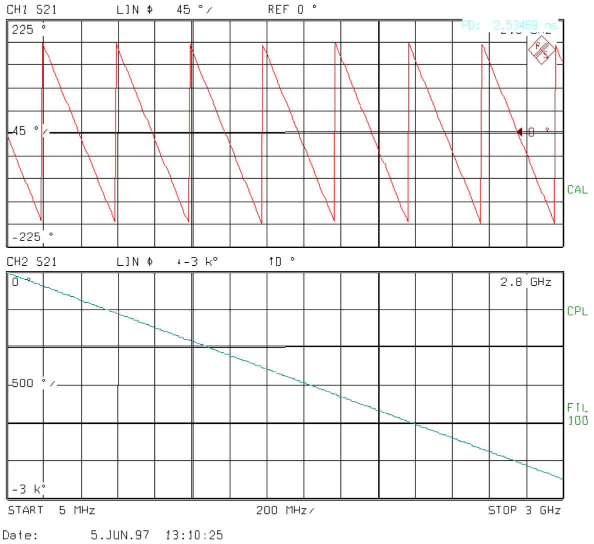

Fig. 4 Phase response of 2.5 ns cable
upper: without phase unwrap
lower: with phase unwrap activated

The delay time of the DUT can simply be calculated from the measured phase shift:

$$\tau = -\frac{1}{360°} \cdot \frac{\varphi_1 - \varphi_2}{f_1 - f_2} \qquad (6)$$

where φ_1 = measured phase at the start frequency f_1 and φ_2 = measured phase at the stop frequency f_2. With actually measured values for the 50 ns cable, the result for τ in (6) is

$$\tau = 50.169 \text{ ns.}$$

It is very convenient that Vector Network Analyzers ZVR offer this type of measurement as a special formatting called **PHASE DELAY.**

[FORMAT] *PHASE DELAY*

For this purpose the phase is measured at the START frequency, then automatically tracked and unwrapped during the sweep and finally measured at the STOP frequency. The PHASE DELAY is eventually calculated from (6). A particular advantage of phase delay measurements is the extraordinary accuracy of this technique, which can simply be demonstrated for the example shown:

The phase measurement uncertainty $\delta\varphi$ stated in the data sheet is <0.4° (and is typically in the range of a few hundreds of a degree). Neglecting the tiny frequency deviation of the ZVR, a **maximum uncertainty** can be calculated from (6) for the measured delay time τ of

$$\delta\tau \approx (0.4° / 72226°) \cdot 50 \text{ ns} \approx \mathbf{0.28\ ps} \qquad (7)$$

Converting the delay time into a length yields

$$\delta L = \delta\tau \cdot c \approx 84\ \mu\text{m}, \qquad (8)$$

which actually is a dramatically tiny inaccuracy for an electrical length measurement.

It is worthwhile keeping in mind that the determined accuracy is an absolute value and does not depend on the length of the cable (if the phase can still be properly tracked). For a 100 ns cable, for instance, the uncertainty is still approximately 0.28 ps. (To achieve proper phase tracking, the number of points in that case should be doubled to 1000.)

The data conversion from **PHASE DELAY** to either **ELECTRICAL LENGTH** or **MECHANICAL LENGTH** can be performed automatically by the ZVR itself if the appropriate softkey in the **FORMAT** menu is activated by the user.

[FORMAT] *ELECTRICAL LENGTH* or

[FORMAT] *MECHANICAL LENGTH*

For the conversion to **MECHANICAL LENGTH** an arbitrary permittivity may be chosen from the **SET DIELECTRIC TABLE** of the **FORMAT** menu, e.g. one of the predefined materials, as for instance teflon with a predefined permittivity ε = 2.1, or a newly edited user-defined dielectric.

The measured value is indicated on the display in the upper righthand corner beneath the marker readout values, with a prefix PD, EL or ML for **PHASE DELAY**, **ELECTRICAL LENGTH** or **MECHANICAL LENGTH.**

3 Group Delay

As already mentioned, in contrast to a Phase Delay measurement, Group Delay measurements are also possible for **dispersive DUTs**, i.e. devices with a nonlinear phase response versus frequency.

Two different possibilities of entering the **aperture** for the Network Analyzers ZVR are available. One is called **Step Aperture**, the other is called **Frequency Aperture.** The two modes use different group delay measurement methods and offer different features.

3.1 Step Aperture Technique

Usually the **Step aperture** technique is employed, which can be entered as follows:

[Format] *Group Delay: Step Aperture: N*

where N is an arbitrary integer with

$1 < N <$ (**Number of Points** - 1), e.g. $N = 10$.

For **Step Aperture** the aperture Δf is defined via the set frequency **Span** and the chosen **Number of Points** as:

$\Delta f = N \cdot$ (**Span**) / (**Number of Points** - 1)

The quotient (**Span**) / (**Number of Points** - 1) can be interpreted as the **step width s** between two measurement points as illustrated in Fig. 5.

$$\Delta f = N \cdot s \qquad (9)$$

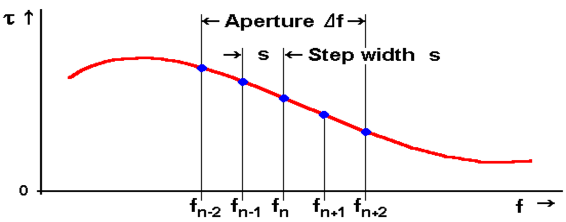

Fig. 5 Step aperture Δf for $N = 4$

With linear frequency sweep this group delay measurement method is usually employed. It has the advantage that, in order to determine group delay, phase measurements have only to be performed at exactly those frequency points which are already part of the frequency grid.

The phase shift $\Delta\varphi$ of (3) is determined from the difference of the measured phases at frequency f_{n+2} and frequency f_{n-2} respectively (Fig. 5). Generally, the phase difference between these two frequencies should not exceed 180° in order to ensure proper phase tracking. However, for Vector Network Analyzers ZVR a special feature is additionally implemented, called **implicit phase tracking** between each two adjacent frequency points. This allows a maximum phase shift of $N \cdot 180°$ within the aperture and increases the measurement accuracy. In the example of Fig. 5 with $N = 4$ this means that a maximum phase shift of 720° between f_{n-2} and $\mathbf{f}_{n+2}$ is allowed, thus enhancing the measurement accuracy by the factor of N as compared to a group delay measurement without implicit phase tracking.

Please note the reduced measurement accuracy near the Start and the Stop frequencies. This effect is due to a natural reduction of the aperture at both edges of the frequency span.

3.2 Frequency Aperture Technique

For some applications it may be a disadvantage that the aperture Δf cannot be chosen arbitrarily and independently of the frequency grid. Especially when using **nonlinear sweep, Step Aperture** results in a **non-constant aperture** $\boldsymbol{\Delta f}$ versus frequency, which might cause problems.

Therefore, Vector Network Analyzers ZVR offer an alternative technique for defining the aperture Δf for group delay measurements, called **frequency aperture technique**. It can be selected with the **Frequency Aperture** softkey:

[Format] *Group Delay: Frequency Aperture:* e.g. 100 kHz

Now the aperture Δf can be directly entered as an absolute frequency value of e.g. 100 kHz. The desired aperture however does not always fit to the step width s between adjacent measurement points of the frequency grid as it did with the step aperture technique (Fig. 5).

This means that it is necessary to determine a separate frequency grid with matching frequency points for the group delay measurement. This grid is automatically calculated by the ZVR. It yields a proper and well-defined group delay measurement with a **fixed-frequency aperture** $\boldsymbol{\Delta f}$ irrespective of the chosen number of points and regardless of linear or nonlinear frequency sweep being selected.

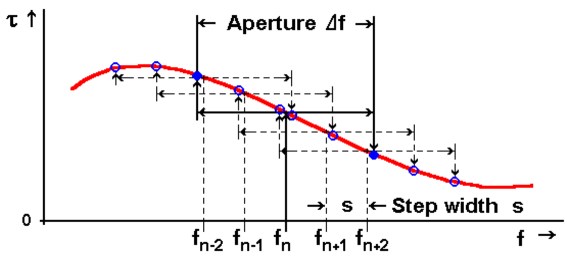

Fig. 6 Frequency aperture Δf

Fig. 6 shows the determination of the frequency aperture Δf for an arbitrary frequency point f_n in solid lines and for some other frequency points f_{n-2} to f_{n+2} in dotted lines. For determining the group delay at frequency f_n, the phase is measured at the two frequencies, each of them spaced half the aperture apart from f_n, i.e. $f_n - \Delta f/2$ and $f_n + \Delta f/2$. In contrast to the step aperture technique, no phase measurement is performed at f_n, as the frequency aperture Δf is in general no integer multiple of the step width s.

This is why the number of phase measurements is doubled as compared to the step aperture technique and consequently the sweep rate is halved. This might be a small disadvantage compared to a group delay measurement with STEP APERTURE.

The separate frequency grid for group delay measurements with frequency aperture is independently determined from the displayed frequencies. This results in a further advantage. In contrast to step aperture technique, absolutely no edge effects occur for FREQUENCY APERTURE.

Fig. 7 shows results of a group delay measurement using this technique. Again a 50 ns coaxial cable served as the DUT. The frequency sweep was logarithmic and a fixed frequency aperture of 5 MHz was used.

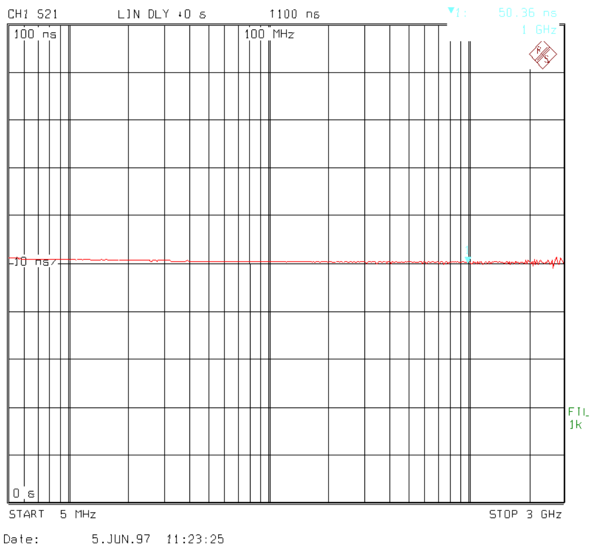

Fig. 7 Measured group delay of 50 ns cable

3.3 MEASUREMENT ACCURACY

Generally, the **accuracy for group delay measurements** is directly proportional to the chosen aperture Δf. (In the case of STEP APERTURE the accuracy is additionally increased by the implicit phase unwrap of ZVR.)

The expected uncertainty $\delta\tau_{gr}$ for the measured group delay thus is inversely proportional to Δf. According to (7)

$$\delta\tau_{gr} \approx \frac{\delta\varphi}{\Delta\varphi} \cdot \tau_{gr} \qquad (10)$$

is obtained. Again the tiny frequency uncertainty of the ZVR is negligible. Assuming a phase uncertainty $\delta\varphi \approx 0.4°$ and an **appropriately chosen aperture** $\boldsymbol{\Delta f}$, so that the measured phase shift $\Delta\varphi$ is less than 180° but sufficiently large to ensure high accuracy, e.g. $\Delta\varphi \approx 100°$, the expected group delay uncertainty is

$$\delta\tau_{gr} \approx 0.004 \cdot \tau_{gr}\,. \qquad (11)$$

In contrast to the phase delay uncertainty, which was determined under (7) above, the uncertainty in this case is a relative value and depends on the group delay to be measured. For instance, a group delay of 50 ns can be determined with a deviation of 0.2 ns, while for a group delay of 100 ns the deviation increases to 0.4 ns.

Generally, the expected deviation can be determined from (3)

$$\delta\tau_{gr} \approx \frac{1}{360°} \cdot \frac{\delta\Delta\varphi}{\Delta f} \qquad (12)$$

with $\delta\Delta\varphi < 0.4°$ yielding $\delta\tau_{gr} \approx 0.001 / \Delta f$.

To sum up, for an **optimum measurement accuracy** for group delay measurements the aperture should be chosen so that the phase shift within the aperture is slightly less than 180°. Based on this assumption and with a given group delay for the DUT, the following is obtained according to (3):

$$\Delta f < 0.5 / \tau_{gr}\,. \qquad (13)$$

$\Delta f \approx 0.3 / \tau_{gr}$ is a good choice for the aperture. This yields high accuracy and avoids possible tracking failures, which might occur in case of maximum aperture if the variation of τ_{gr} of the DUT versus frequency is greater than predicted.

Group delay τ_{gr}	Aperture Δf		
	Minimum	Optimum	Maximum
10 ns	100 kHz	30 MHz	50 MHz
100 ns	10 kHz	3 MHz	5 MHz
1 µs	1 kHz	300 kHz	500 kHz
10 µs	100 Hz	30 kHz	50 kHz
100 µs	10 Hz	3 kHz	5 kHz
1 ms	1 Hz	300 Hz	500 Hz

Table 1 Useful apertures versus group delay

As already explained, it is possible to significantly exceed the maximum aperture listed in Table 1 up to N·Maximum if

1. a group delay measurement with step aperture technique is used, and if
2. the number N (i.e. the number of measurement points – 1 within the aperture) is greater than 1, and if
3. the group delay variations are smooth.

This yields a group delay measurement accuracy enhanced by the factor of N provided that the phase shift between each two adjacent frequency points within the aperture is sufficiently high, e.g. 100°.

Aperture Δf	Measurement uncertainty $\delta\tau_{gr}$
1 kHz	1 µs
2 kHz	500 ns
5 kHz	200 ns
10 kHz	100 ns
20 kHz	50 ns
50 kHz	20 ns
100 kHz	10 ns
200 kHz	5 ns
500 kHz	2 ns
1 MHz	1 ns
2 MHz	500 ps
5 MHz	200 ps
10 MHz	100 ps
20 MHz	50 ps
50 MHz	20 ps
100 MHz	10 ps

Table 2 Uncertainty of group delay measurements versus aperture

As already explained above, the accuracy can be further enhanced by using step aperture technique with N » 1 (implicit phase tracking).

By using **small apertures** the resolution of group delay variations versus frequency is increased which allows a better insight into the fine structure of the group delay of the DUT. Small apertures however affect the accuracy, as can be seen from Table 2. Apertures of less than 0.001 / τ_{gr} should never be used, since otherwise the phase shift to be measured is in the same order of magnitude as any phase shift measurement inaccuracies, thus causing a noisy group delay measurement trace.

The accuracy of group delay measurements can be affected by multiple reflections between the DUT and the network analyzer. To reduce this influence, a full two-port calibration of the network analyzer, e.g. TOM, is recommended.

Especially with **group delay measurements on frequency-converting DUTs** (Options ZVR-B4 and ZVR-B6 being required) the measurement accuracy may be further decreased due to spurious signals either originated by the DUT or by the internal source of the network analyzer and then frequency-converted by the DUT.

As an **additional feature** Vector Network Analyzers ZVR offer the possibility of adding an arbitrary **OFFSET** to the measurement results. This can be a MAGNITUDE, PHASE or DELAY TIME OFFSET. The offset may be added at PORT 1 or PORT 2 or at both ports. Alternatively to a DELAY TIME OFFSET an ELECTRICAL LENGTH or a MECHANICAL LENGTH may be added.

Use of the **AUTO LENGTH** function of the OFFSET menu is very convenient since it automatically calculates a linear regression for the measured phase response and subtracts an optimum DELAY TIME OFFSET yielding a **maximally flat phase response**. The automatically chosen DELAY TIME OFFSET can simply be indicated by pressing

[OFFSET] *DELAY TIME*.

Olaf Ostwald, 1ES3
Rohde & Schwarz
10 July 1997

5 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.

6 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.