



Product: ZVR, ZVRE, ZVRL, ZVC, ZVCE, ZVM, ZVK

Reading and Modifying the Correction Data for System Errors and Power of a ZVR Vector Network Analyzer

Application Note

This application note covers system error and power correction data for vector network analyzers of the ZVR family. The error models that underlie the three most important system error correction algorithms are shown as well as the relation of their correction terms to those known from other VNA manufacturers. As further issues, file structure and storage location of the correction data files are treated. Utilities for the conversion of system error correction data to ASCII and back to binary format are presented. Examples show the effects of changing system error correction terms. Finally, power correction data and their file format are dealt with.



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Important note: *This application note is valid for firmware version 1.30 or greater. Within future firmware versions, the data formats mentioned in this application note may be changed without notice. This may also affect the applicability of the utility programs readcal.exe and readasc.exe.*

1 Introduction

A large variety of system error calibration methods is offered for the Vector Network Analyzers (VNAs) of the ZVR family, covering typical measurement setups and calibration standards. This application note does not deal with calibrations methods and their underlying error models in detail. It is assumed that the reader has a fundamental knowledge of these issues. The objective of this application note is to show how system error and power correction data can be read and modified. For most applications, this is not required. There may, however, be users working on special measurement setups who want to apply calibration methods of their own, but still use the correction algorithms implemented in the instrument firmware.

2 System Error Correction Data

The most frequently used system error calibration methods of the ZVR family VNAs can be divided into three groups. The common feature of each group is a specific correction algorithm for the raw measurement data. This application note only covers methods from these groups. They are listed below, along with their corresponding correction algorithms and applications:

Calibration Methods	Correction Algorithm	Application
TOM TRM TRL TNA	7-Term	Full correction of two-port measurements with 4-channel VNA
OSM (PORT 1) OSM (PORT 2)	3-Term	Full correction of reflection measurements
TOSM	12-Term	Full correction of two-port measurements with 3- and 4-channel VNA

For each correction algorithm, the underlying error model and the meaning of the correction coefficients are explained.

7-Term Error Correction

Fig. 1 shows the system error model that applies for 7-term correction.

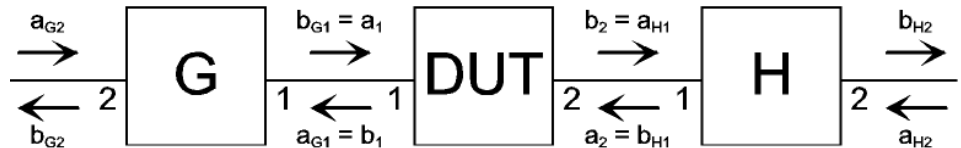


Fig. 1 Error model for 7-term correction

Note that port 1 of both error two-ports G and H is oriented towards the DUT. The port 2 wave quantities of G and H may usually be interpreted as raw measurement values.

The matrices G and H are defined as follows:

$$\begin{pmatrix} a_{G1} \\ b_{G1} \end{pmatrix} = \begin{pmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{pmatrix} \begin{pmatrix} a_{G2} \\ b_{G2} \end{pmatrix} \quad \begin{pmatrix} b_{H1} \\ a_{H1} \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ 1 & H_{22} \end{pmatrix} \begin{pmatrix} b_{H2} \\ a_{H2} \end{pmatrix}$$

The error terms may be normalized to an arbitrary transmission factor of G or H. Here, $H_{21} = 1$ has been chosen.

All VNAs of the ZVR family store the 7-term correction terms in the form of G and H matrices. In some cases, however, a scattering (S-)parameter representation is preferred. In the first step, the matrices G and H are converted to the chain transfer form. This means that the rows of G and the columns of H must be swapped, resulting in:

$$\begin{pmatrix} b_{G1} \\ a_{G1} \end{pmatrix} = \begin{pmatrix} G_{21} & G_{22} \\ G_{11} & G_{12} \end{pmatrix} \begin{pmatrix} a_{G2} \\ b_{G2} \end{pmatrix} \quad \begin{pmatrix} b_{H1} \\ a_{H1} \end{pmatrix} = \begin{pmatrix} H_{12} & H_{11} \\ H_{22} & 1 \end{pmatrix} \begin{pmatrix} a_{H2} \\ b_{H2} \end{pmatrix}$$

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The second step is the conversion of the chain transfer matrices to S-matrices:

$$\begin{pmatrix} b_{G1} \\ b_{G2} \end{pmatrix} = S_G \begin{pmatrix} a_{G1} \\ a_{G2} \end{pmatrix} = \frac{1}{G_{12}} \begin{pmatrix} G_{22} & G_{12}G_{21} - G_{11}G_{22} \\ 1 & -G_{11} \end{pmatrix} \begin{pmatrix} a_{G1} \\ a_{G2} \end{pmatrix} \quad (1)$$

$$\begin{pmatrix} b_{H1} \\ b_{H2} \end{pmatrix} = S_H \begin{pmatrix} a_{H1} \\ a_{H2} \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} - H_{11}H_{22} \\ 1 & -H_{22} \end{pmatrix} \begin{pmatrix} a_{H1} \\ a_{H2} \end{pmatrix} \quad (2)$$

Frequently, the error terms in S-parameter representation are defined by:

$$S_G = \begin{pmatrix} e_{11} & e_{10} \\ e_{01} & e_{00} \end{pmatrix} \quad (3) \quad S_H = \begin{pmatrix} e_{22} & e_{23} \\ e_{32} & e_{33} \end{pmatrix} \quad (4)$$

As will be shown later, $H_{21} = 1$ implies $e_{32} = 1$. Comparing (3) to (1) and (4) to (2) yields the error terms in a frequently used nomenclature:

e_{00}	forward directivity	$-\frac{G_{11}}{G_{12}}$
e_{11}	forward source match, reverse load match	$\frac{G_{22}}{G_{12}}$
$e_{01}e_{10}$	forward reflection tracking	$\frac{G_{12}G_{21} - G_{11}G_{22}}{G_{12}^2}$
e_{10}	forward transmission tracking	$G_{21} - \frac{G_{11}G_{22}}{G_{12}}$
e_{33}	reverse directivity	$-H_{22}$
e_{22}	reverse source match, forward load match	H_{11}
e_{23}	reverse reflection tracking	$H_{12} - H_{11}H_{22}$
$e_{01}e_{23}$	reverse transmission tracking	$\frac{H_{12} - H_{11}H_{22}}{G_{12}}$

Note that the load match and transmission tracking terms resulting from a 7-term calibration are different from those obtained by a 12-term calibration, since the error models of these calibrations represent different physical subsystems of the VNA. A 7-term calibration does not provide the "true" load match and transmission tracking terms that can be physically measured.

The inverse transformations start with the S-parameters given by equations. (3) and (4), leading to:

$$G = \frac{1}{e_{01}} \begin{pmatrix} -e_{00} & 1 \\ e_{01}e_{10} - e_{00}e_{11} & e_{11} \end{pmatrix} \quad (5)$$

$$H = \frac{1}{e_{32}} \begin{pmatrix} e_{22} & e_{23}e_{32} - e_{22}e_{33} \\ 1 & -e_{33} \end{pmatrix} \quad (6)$$

From (6), it can be seen that normalizing G and H to H_{21} implies $e_{32} = 1$.

If the tracking terms are given instead of the individual e_{ij} , e_{01} can be calculated from the reflection and transmission tracking terms of either measurement direction.

3-Term Error Correction

Fig. 2a shows the system error model for reflection measurements at VNA test port 1, Fig. 2b the model for test port 2.

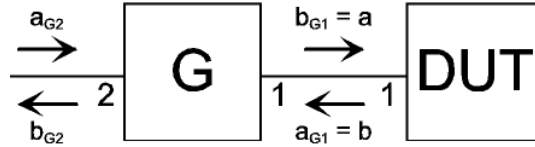


Fig. 2a Error model for 3-term correction at test port 1

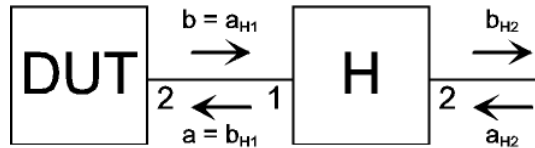


Fig. 2b Error model for 3-term correction at test port 2

Comparing these models to Fig. 1, it becomes clear that Fig. 2a is the left half and Fig. 2b the right half of Fig. 1. The matrices G and H are defined in the the same way as before. For the correction of reflection measurements at test port 1, the two transmission terms of two-port G appear always in product form. Therefore, one of the terms, here G_{12} , may be set equal to unity. The relations between G and H and the e_{ij} terms are the same as for 7-term correction. (5) and (6) show that $G_{12} = H_{21} = 1$ results in $e_{01} = e_{32} = 1$. Then the correspondences simplify to:

e_{00}	forward directivity	$-G_{11}$
e_{11}	forward source match, reverse load match	G_{22}
e_{10}	forward reflection tracking	$G_{21} - G_{11}G_{22}$
e_{33}	reverse directivity	$-H_{22}$
e_{22}	reverse source match, forward load match	H_{11}
e_{23}	reverse reflection tracking	$H_{12} - H_{11}H_{22}$

Equations (5) and (6) become

$$G = \begin{pmatrix} -e_{00} & 1 \\ e_{10} - e_{00}e_{11} & e_{11} \end{pmatrix} \quad (7)$$

$$H = \begin{pmatrix} e_{22} & e_{23} - e_{22}e_{33} \\ 1 & -e_{33} \end{pmatrix} \quad (8)$$

12-Term Error Correction

The error model that is assumed for 12-term correction is shown in Figs. 3a and b. For each stimulus direction of a two-port measurement there is a separate model.

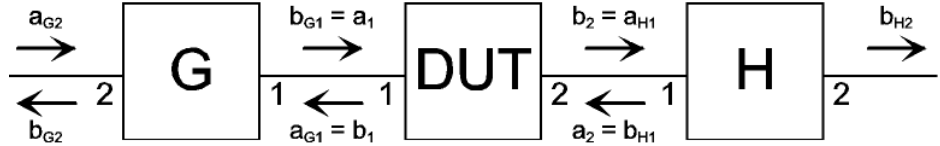


Fig. 3a Error model for 12-term correction (forward direction)

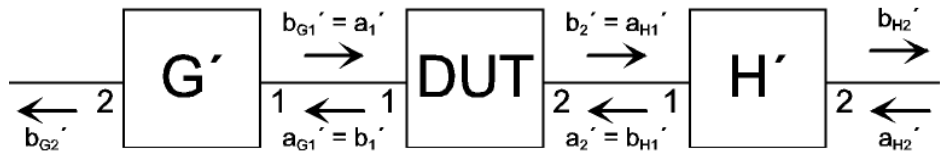


Fig. 3b Error model for 12-term correction (reverse direction)

The ZVR VNAs do not store the 12-term error terms as G and H matrices, but in the S-parameter form e_{ij} (see above). The error terms for the reverse stimulus direction are marked with an apostrophe:

e_{00}	forward directivity
e_{11}	forward source match
e_{01}	forward reflection tracking
e_{22}	forward load match
e_{32}	forward transmission tracking
e_{30}	forward isolation
e_{33}'	reverse directivity
e_{22}'	reverse source match
e_{32}'	reverse reflection tracking
e_{11}'	reverse load match
e_{01}'	reverse transmission tracking
e_{03}'	reverse isolation

Note that normalization of the reflection and transmission tracking terms is different to 7- and 3-term correction.

3 System Error Correction Data Files

The VNAs of the ZVR family store system error correction data in files. After performing a new system error calibration, correction data is stored in the file *user.caX*. Here *X* stands for the letter *c*, if the display channels were coupled at calibration time. If they were decoupled, *X* is a number between 1 and 4, expressing the active display channel. For example, if channel 2 was active and the channels were decoupled at calibration time, the file name is *user.ca2*. If they were coupled, it is *user.cac*.

The path of new correction data (after calibration) depends on whether the VNA runs under Windows NT (these instruments have a blue bezel around the screen, e.g. all ZVMs and ZVKs) or is an older one (red bezel around the screen). In the latter case the path is *d:\runtime\cal*, for NT instruments it is *c:\r_s\instr\cal*.

Please note that the preceding holds only for the case that no *SAVE* operation has been performed. A *SAVE* that includes calibration data (this is the default setting, which may be changed via *SEL ITEMS TO SAVE*) moves the correction data file to the specified name and path. For example, performing a calibration with coupled channels and saving the default setup items under the name *set_1* in the default path, results in the correction data file being stored under *c:\user\config\set_1.cac*.

The error correction data files are organized in two blocks: header and body. The header contains statistical information as well as the most important hardware settings of the VNA at calibration time. This is needed for several reasons, e.g. when a calibration is activated and the original sweep settings are to be restored.

Do not change the header data. Otherwise, data consistency problems may lead to a system crash.

Due to the complexity of the subject and mutual dependencies that are not obvious, the structure of the header will not be described here in detail. However, some information that is not included in the file body may be interesting for users who intend to modify correction data. One such information is frequency. Knowing about the overall frequency grid of a correction data file as well as the consecutive number of a certain frequency point in the file, the individual frequency of this point can be calculated. Frequency grid information can be interrogated from the VNA via the IEC bus.

Another issue of interest is the correction method, which determines how many error terms are stored per frequency point and what they mean. The correction method is stored as a 2-byte unsigned integer entry, which starts at byte position 2546 (decimal, referring to the first byte in the file at position 0). In the context of this application note, the following decimal values of this entry are relevant:

Entry Value	Correction Algorithm
26704	7-term
26708	3-term
26705	12-term

The file body starts at byte position 2564. In the body, blocks of error terms, where each block belongs to an individual frequency point, are stored in the

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order of increasing frequency. This holds also for the case of overlapping segments, where the frequency points interleave.

In the following tables, the sequence of error terms within such a block is listed for each correction algorithm:

Table 1 7-term correction: Sequence of error terms within a block

Byte Offset Relative to First Byte	Error Term
0	G_{11}
8	G_{12}
16	G_{21}
24	G_{22}
32	H_{11}
40	H_{12}
48	H_{22}

Table 2 3-term correction: Sequence of error terms within a block

FULL ONE PORT PORT 1		FULL ONE PORT PORT 2	
Byte Offset Relative to First Byte	Error Term	Byte Offset Relative to First Byte	Error Term
0	G_{11}	0	H_{11}
8	$G_{12} (=1)$	8	H_{12}
16	G_{21}	16	$H_{21} (=1)$
24	G_{22}	24	H_{22}
32	not used	32	not used

Table 3 12-term correction: Sequence of error terms within a block

Byte Offset Relative to First Byte	Error Term
0	e_{00}
8	e_{01}
16	e_{11}
24	e_{22}
32	e_{32}
40	e_{01}'
48	e_{11}'
56	e_{22}'
64	e_{32}'
72	e_{33}'
80	e_{30}
88	e_{03}'

For unused error terms, byte positions are reserved in the same way as for used ones.

The error terms are stored as complex values (C type *COMPLEX 32*). Real and imaginary parts are float values with 4 bytes each, resulting in 8 bytes for one error term.

4 Conversion of System Error Correction Data to ASCII Format

The utility *readcal.exe* converts a system error correction data file (caX format, X: see above) into ASCII text. Only 7-term, 3-term single port, and 12-term calibration files will be correctly processed. The correction data file can be selected on the left side of the window (Fig. 4). Only files with the extension .ca? will be displayed in the list. The directory from where *readcal* is started serves as default path for input and output files. Name and path of the ASCII output file may be arbitrarily chosen. Finally, conversion is started via the keypad *Read and Write*. *Cancel* terminates the program.

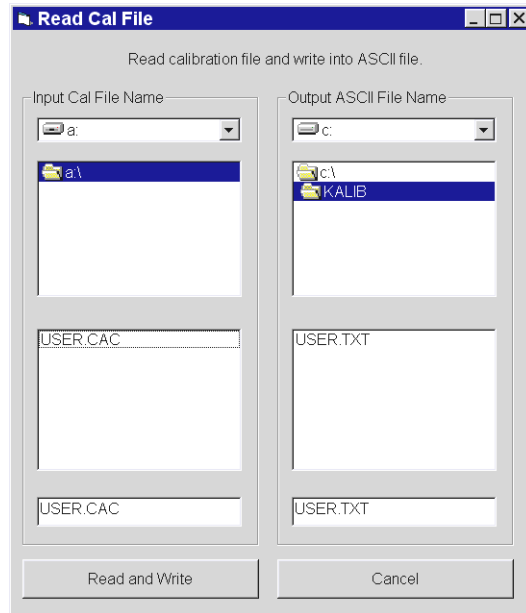


Fig. 4 User interface of *readcal.exe*

readasc.exe is complementary to *readcal.exe*. It converts an ASCII file, which has been created by *readcal* and has possibly been modified, back into the ZVR binary format. The ASCII file can be selected on the left side of the window (Fig. 5). The file type filter on the lower left can be changed. The directory from where *readasc* is started serves as default path for input and output files. Name and path of the binary cal data output file may be arbitrarily chosen. As with *readcal*, conversion is started via the keypad *Read and Write*. *Cancel* terminates the program.

In order to enable the modified correction data, it is not sufficient to simply write the .caX file back to its original location since correction data files are only read during instrument startup or after a recall. Therefore, the best solution is to store the modified file in an arbitrary directory and then to perform a recall from that location. The name of the “setup” to be recalled is just the name of the correction data file without extension. Before starting the recall operation, all setup items except *CAL DATA* should be disabled (softkey *SEL ITEMS TO RECALL*). After the recall, be sure that the enhancement label *CAL* on the right of the screen is lit. Otherwise, switch the softkey *UNCAL* in the *CAL* menu off. Of course, these operations may be also performed via IEC bus.

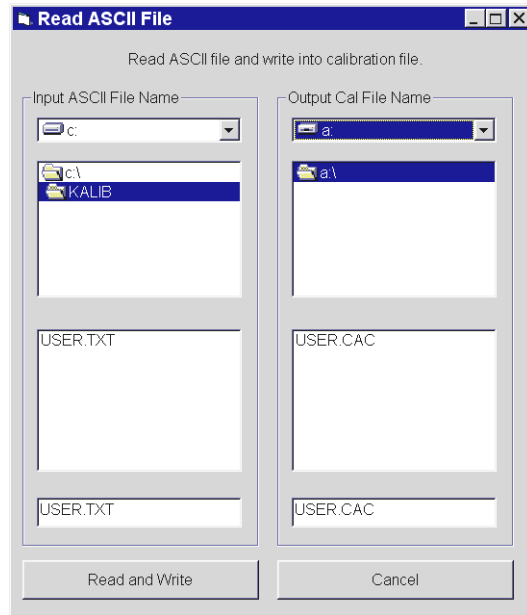


Fig. 5 User interface of *readasc.exe*

5 Modification of System Error Correction Data: Examples

The two following examples show how changing a single error term, here in S-parameter representation, influences a measured result. The consequences of such a change may be different from what one expects at first glance.

For the first example, a TOM 7-term calibration was performed. Then the forward transmission tracking term e_{10} was multiplied by 0.1, which means that the assumed transmission attenuation of two-port G was set 20 dB higher than in reality. From this, one should expect that the measured forward gain of a DUT increases by 20 dB. Fig. 6 shows the four S-parameters of the THROUGH that had been used for calibration.

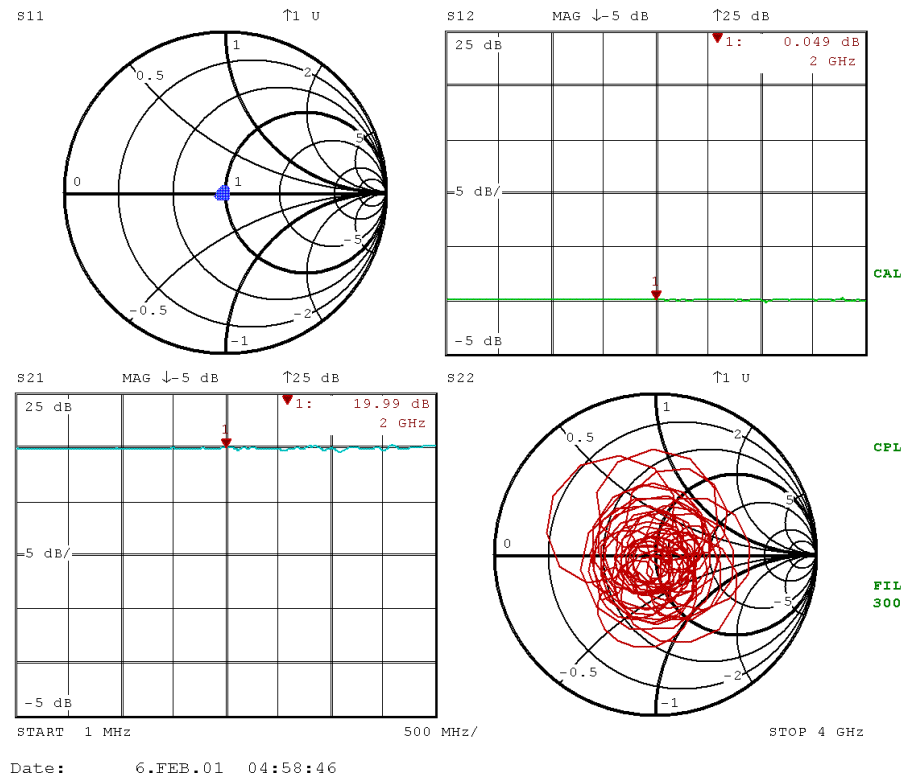


Fig. 6 Measured S-parameters of a THROUGH after modification of forward transmission tracking term

Indeed, the magnitude of S_{21} equals approximately 20 dB, but there is a slight ripple on the trace. S_{12} and S_{11} , which should remain unaffected, show a small nonideality, too. S_{22} , however, deviates far from matched condition. Closer inspection of the 7-term correction formula (Equation 9) reveals that basically each S-parameter is affected by each G_{ij} and H_{ij} :

$$S = \begin{pmatrix} G_{11}a_{G2} + G_{12}b_{G2} & G_{11}a_{G2'} + G_{12}b_{G2'} \\ H_{21}a_{H2} + H_{22}b_{H2} & H_{21}a_{H2'} + H_{22}b_{H2'} \end{pmatrix} \begin{pmatrix} G_{21}a_{G2} + G_{22}b_{G2} & G_{21}a_{G2'} + G_{22}b_{G2'} \\ H_{11}a_{H2} + H_{12}b_{H2} & H_{11}a_{H2'} + H_{12}b_{H2'} \end{pmatrix}^{-1} \quad (9)$$

Here, again, apostrophes designate values measured in reverse direction.

Modifying the tracking term e_{10} changes G_{21} , therefore an effect on all S-parameters should result. Simulation shows, however, that if the device under test is matched at its input ($S_{11} = 0$), the corrected parameters S_{11}

and S_{12} are not affected by altering G_{21} . From that it must be concluded that the small deviations of those parameters are caused by bad numerical conditioning. Nevertheless, the nonidealities of S_{21} and S_{22} must be attributed to the influence of G_{21} .

The second example demonstrates the effect of modifying the forward directivity term e_{00} . After a TOM calibration an offset of $0.3 + 0.3j$ was added to e_{00} . Fig. 7 shows the reflection coefficient of the MATCH that had been used as a calibration standard, measured at test port 1. One might believe that the directivity term is just an additive offset, which means that the reflection coefficient of a MATCH should now be $0.3 + 0.3j$ instead of 0. However, e_{00} does not just add to the corrected reflection coefficient Γ , but also appears in the denominator of the corrected value (Note that in the case of a one-port DUT, the same error correction formula holds for 7-term, 3-term and 12-term calibration):

$$\Gamma = \frac{\Gamma_M - e_{00}}{e_{11}(\Gamma_M - e_{00}) + e_{01}e_{10}}$$

Γ_M is the raw measured value. So the resulting trace is not just a point, but spreads to a “cloud” when frequency is swept. Improving the source match e_{11} reduces the size of this cloud. The position of the center of the cloud is mainly determined by the offset value and the reflection tracking term $e_{01}e_{10}$.

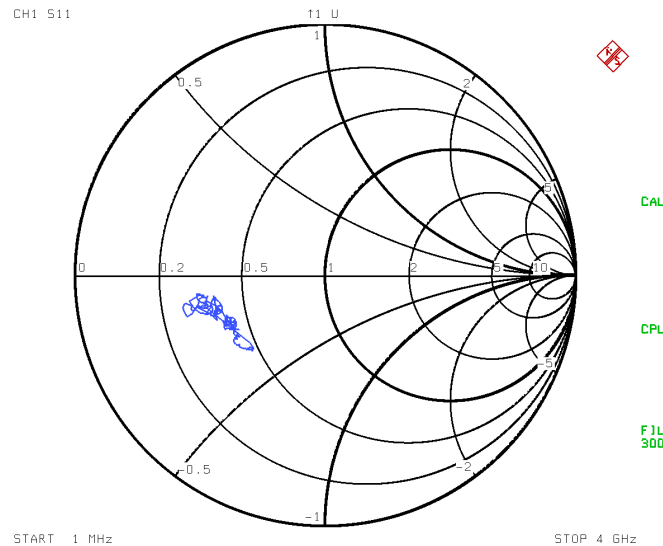


Fig. 7 Measured reflection of a MATCH after modification of forward directivity term

6 Power Correction Data

User defined power correction is available only if option ZVR-B7 is installed. Correction data is organized in data sets that refer to a specific wave quantity each and that are stored as part of a file. The VNAs of the ZVR family have 4 internal wave quantities: a_1 , b_1 , a_2 and b_2 (see Fig. 1). For a_1 and a_2 there are two types of data sets: Generator and receiver correction data. a_1 IF REF POWER CAL (this requires option ZVR-B6 to be installed for ZVRx and ZVCx) results in a separate receiver correction data set for a_1 . For b_1 and b_2 there are only receiver correction data available. If the VNA is a ZVM or ZVK and if INPUT b_1 or INPUT b_2 is active during calibration, separate receiver correction data sets for b_1 or b_2 are created.

Generator Correction

The purpose of generator correction is to compensate for frequency flatness errors of the generator. When the nominal (desired) power and the correction value are given, the power that is adjusted at the VNA generator results from:

$$\text{adjusted power} = \text{nominal power} + (\text{correction value} * 0.01),$$

where the power values are given in dB. The correction value is an additive offset, which is stored in 0.01 dB units. The correction values are determined for each sweep point by iteratively comparing the adjusted power to the reading of a power meter, which is connected to the desired reference plane, and increasing or decreasing the adjusted power according to difference between nominal and measured power.

Example: PORT 1 of a ZVR is connected to an input port of a power combiner in order to combine the VNA output with a signal from another generator. The other input port of the combiner should be terminated. The default factory power calibration of the ZVR has been disabled. At 1 GHz, the desired output power at the combiner output is -10 dBm. When the ZVR output power is set to -10 dBm via the softkey *SOURCE: POWER*, an output power of -18.4 dBm can be measured at the combiner output. This means that the ZVR power must be increased by 8.4 dB to reach the desired power level. In this case, the correction value for 1 GHz would be 840.

Receiver Correction

In a similar way, receiver correction data is used to compensate for flatness errors in the receiver path. When the power that is determined by the VNA hardware (measured power) and the correction value are given, the power that is displayed on the VNA screen results from:

$$\text{displayed power} = \text{measured power} + (\text{correction value} * 0.01)$$

Again, the powers are in dB and the correction value is an additive offset in 0.01 dB units. Correction values are determined by comparing the power that is measured by the receiver to the receiver input power, which is nominally known from a previous generator calibration.

Example: At PORT 1 of a ZVR, a generator power calibration for a desired level of -5 dBm has been performed. With a lossless through connection between PORT 1 and PORT 2, receiver channel b_2 displays -10.1 dBm at 1 GHz. For this frequency, the resulting correction value is 510.

7 Power Correction Data Files

Like system error correction data, power correction data is stored in files. Conventions for file names and paths are similar to system error correction. New correction data is stored in the file *user.pcX*. Here *X* stands for the letter *c*, if the display channels were coupled at calibration time. If they were decoupled, *X* is a number between 1 and 4, expressing the active display channel. If the calibration data file relates to external generators, *X* is substituted by the letter *e*.

The path of new correction data (after calibration) depends on whether the VNA runs under Windows NT (these instruments have a blue bezel around the screen, e.g. all ZVMs and ZVKs) or is an older one (red bezel around the screen). In the latter case the path is *d:\runtime\cal*, for NT instruments it is *c:\r_s\instr\cal*.

Please note that preceding holds only for the case that no *SAVE* operation has been performed. A *SAVE* that includes calibration data (this is the default setting, which may be changed via *SEL ITEMS TO SAVE*) moves the correction data file to the specified name and path. For example, performing a power calibration with coupled channels and saving the default setup items under the name *set_1* in the default path, results in the correction data file being stored under *c:\user\config\set_1.pcc*.

Power correction data files are organized in two blocks: header and body. The header contains statistical information as well as the most important hardware settings of the VNA at calibration time. This is needed for several reasons, e.g. when a calibration is activated and the original sweep settings are to be restored.

Do not change the header. Otherwise, data consistency problems may lead to a system crash.

Due to the complexity of the subject and mutual dependencies that are not obvious, the structure of the header will not be described here in detail. However, some information that is not included in the file body may be interesting for users who intend to modify power correction data. One such information is frequency. Knowing about the overall frequency grid of a power correction data file as well as the consecutive number of a certain frequency point in the file, the individual frequency of this point can be calculated. Frequency grid information can be interrogated from the VNA via IEC bus.

In the file body, power correction data is stored separately for each calibrated wave quantity. The position of the first byte of such a wave quantity data set, relative to the first byte of the file at position 0, can be obtained from a dedicated offset entry in the file. The byte positions are stored as 2-byte unsigned integer values. If such an offset entry equals 0, no correction data is available for the respective wave quantity. The positions of the first bytes of the offset entries are listed in the following table as decimal numbers:

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Position of First Byte of Offset Entry	Entry Indicates Position of First Byte of Correction Data Set for
2256	a ₁ generator correction
2260	a ₂ generator correction
2262	a ₁ receiver correction
2264	a ₁ IF REF POWER CAL receiver correction (ZVRx and ZVCx only)
2268	a ₂ receiver correction
2270	b ₁ receiver correction
2272	b ₂ receiver correction
2278	b ₁ INPUT b1 receiver correction (ZVM and ZVK only)
2280	b ₂ INPUT b2 receiver correction (ZVM and ZVK only)

Correction values are stored successively in the order of increasing frequency, beginning at the offset indicated in the preceding table. Each correction value is a 2-byte signed integer, covering a range of about ± 320 dB, with 0.01 dB resolution. Within a file, the frequency grid of the correction data is the same for all wave quantities.

8 Further Application Notes

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9 Ordering information

Vector Network Analyzer ZVK	10 MHz to 40 GHz	1127.8651.60
Vector Network Analyzer ZVM	10 MHz to 20 GHz	1127.8500.60
Vector Network Analyzer ZVC	20 kHz to 8 GHz	1127.8600.60/61/62
Vector Network Analyzer ZVCE	20 kHz to 8 GHz	1127.8600.50/52
Vector Network Analyzer ZVR	9 kHz to 4 GHz	1127.8551.61/62
Vector Network Analyzer ZVRE	9 kHz to 4 GHz	1127.8551.51/52
Vector Network Analyzer ZVRL	9 kHz to 4 GHz	1127.8551.14



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