The Automatic Calibration Module - ACM

What is an ACM?

An Automatic Calibration Module, or ACM, is used to perform user calibration on a Copper Mountain Technologies Vector Network Analyzer (VNA). This is the calibration that is performed prior to making a series of measurements, not the one performed on an annual or semi-annual basis at a calibration laboratory. The ACM presents a series of calibration standards to the VNA – that is, one or more Opens, Shorts, Loads, and a Thru – to complete a SOLT (Short/Open/Load/Thru) full 2-port calibration, or a SOL 1-port calibration. A simplified block diagram is shown in Figure 1.
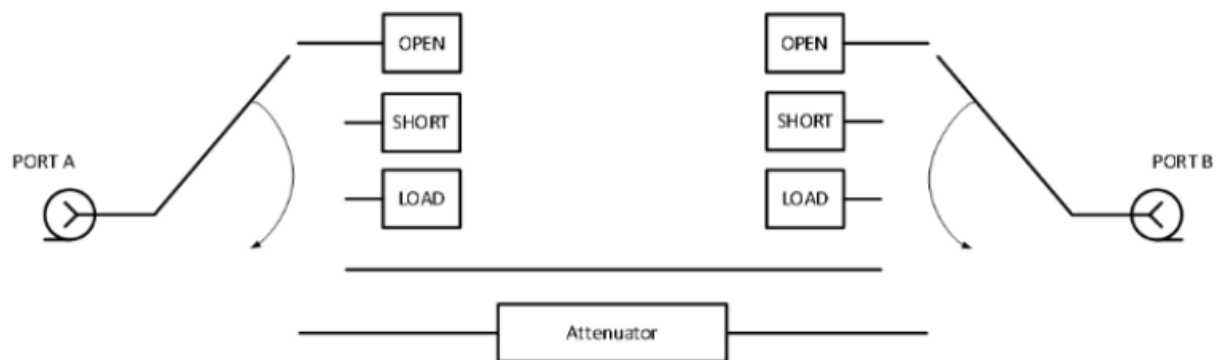

Figure 1 - ACM Block Diagram

A mechanical calibration kit contains individual Open, Short, Load, and Thru calibration pieces, which must be attached to the VNA one after another. A calibration kit definition file informs the VNA of what reflection coefficient each piece should exhibit at each frequency, and calibration is calculated by comparing measured values to actual values. In contrast, the Short, Open, Load, and Thru in the ACM have been precisely characterized at the CMT factory and the results are stored in its non-volatile memory. This is much more accurate than the typical polynomial curve fit definition of the mechanical kit. The ACM completes the calibration process with a single connection to the test cables, automatically cycling through the internal calibration standards.

How is it Used?

A USB cable must be connected between the ACM and the PC running the VNA software to use the ACM. The ACM is then attached to the test cables and either 1-port, 2-port, or 2-port one-path calibration methods are chosen under the Calibration/Autocal menu. The ACM may be attached to the test cables in either direction, with Port A on the Port 1 test cable, or with Port B when the orientation option is set to AUTO.

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The operating frequency range of the ACM is printed on the label. When using an ACM, make sure that the VNA frequency range is within the range printed on the ACM. Leave the thermo compensation function ON, as this will provide more accurate calibration when ambient conditions change.

Figure 2 - 8 GHz 2-Port ACM

Allow the calibration to complete, and then COR should appear in the lower-left corner of the VNA UI screen. The calibration type should be added at the end of the trace definition in the upper left corner – [F1], [F2], and [OP] for full 1-port, 2-port, and one-path 2-port calibration respectively.

For 4-port calibration, the ACM4509 AND ACM4520 are 9 and 20 GHz 4-port models respectively. They are capable of performing 1-, 2-, 3-, or 4-port calibration as needed.

The Confidence Check feature, which may be enabled in the Automatic Calibration menu, helps verify the integrity of the test cables. After pressing the Confidence Check button in the User Interface, an approximately 20 dB attenuator is connected internally between the A and B ports of the ACM and a precision factory measurement of that same attenuator is loaded into the active trace memory. The memory trace will normally be covered by the active measurement, so it is best to subtract the live measurement from the memory trace by navigating to Display>Memory>Data Math>Data / Memory. Set the scale to a low value, such as 0.05 dB/Div , for a magnitude reading and then move the ACM from side to side to flex the test cables slightly. There should be very

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little movement of the displayed difference. If wild movement is seen, then the test cables are either loose or defective. Defective cables should be discarded immediately.
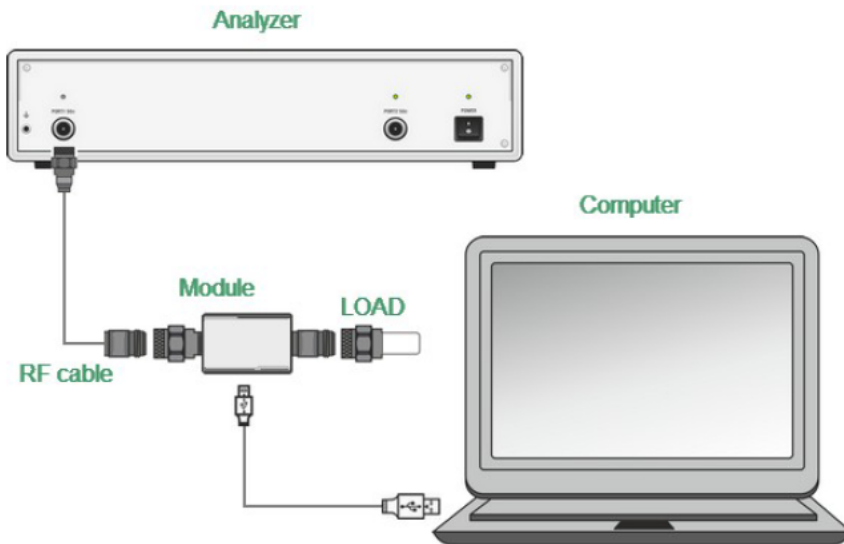

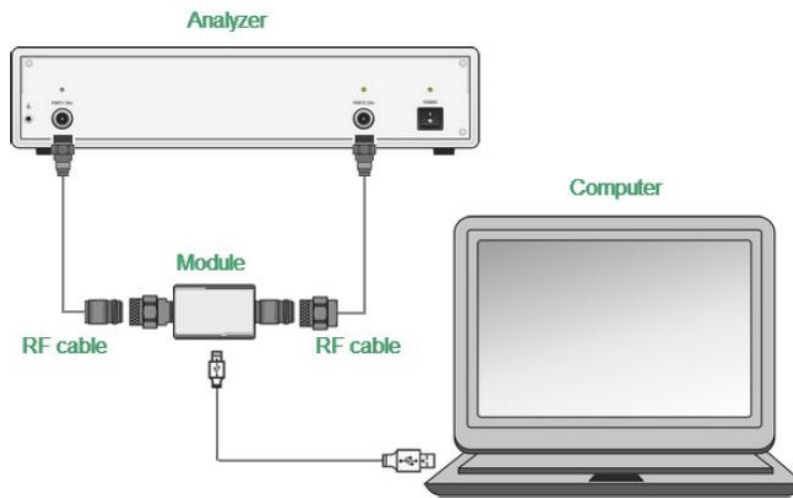Figure 3 - ACM Connection for 1-Port Calibration, Load Unused Port

Figure 4 - ACM Connection for 2 Port Calibration

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Why Use an ACM?

The measurement accuracy of the VNA depends on the quality of the user calibration. You can best understand the quality of calibration by examining the residual errors which remain after the calibration is performed. The 12-term error model is generally used to characterize these errors – six terms for forward measurements, such as S_{11} and S_{21}, and six for the reverse, S_{22} and S_{12}. These errors are depicted in the S-parameter network diagrams shown below.
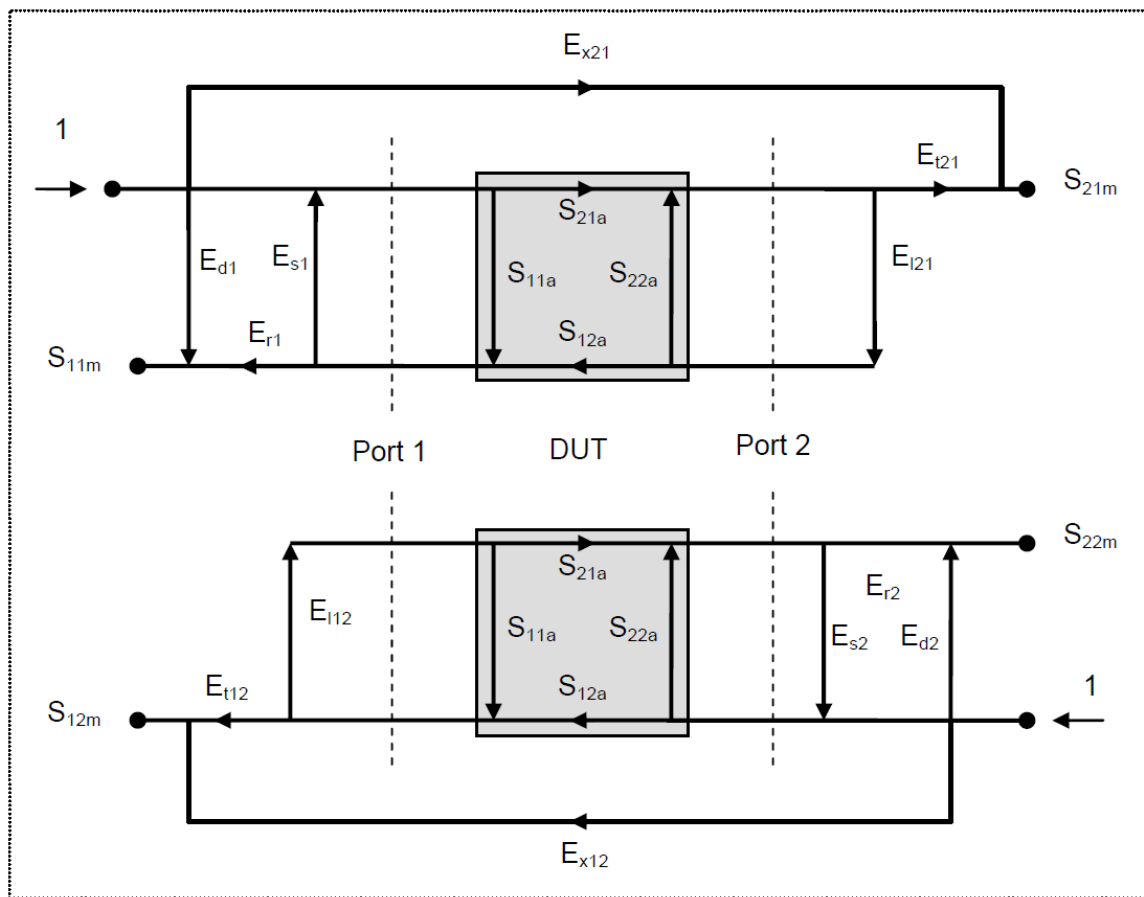

Figure 3 - 12 Term Error Model, Forward and Reverse

The actual Device Under Test (DUT) S-parameters are shown in the grey box, and the error vectors appear on either side of it.

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These errors are:

Description	Stimulus Source	
	Port 1	Port 2
Directivity	E_{d1}	E_{d2}
Source match	E_{s1}	$E_{s2,}$
Reflection tracking	E_{r1}	E_{r2}
Transmission tracking	E_{t1}	E_{t2}
Load match	E_{l1}	E_{l2}
Isolation	E_{x1}	E_{x2}

Table 1 - 12 Term Errors

After calibration, these errors are greatly reduced but are not zero. The remaining errors are called residual errors. For instance, the raw directivity of the directional bridge in the VNA might be 18 dB, but after calibration with an ACM, it might be 46.

The Importance of Residual Directivity

The directional bridge in the VNA has four ports: an input, an output, a forward sample port, and a reverse sample port. When a forward traveling signal passes through the bridge, the forward port should have an attenuated version of this signal exiting it, assuming 20 dB coupling attenuation for example. A reverse traveling signal should cause a 20 dB down signal to appear on the reverse sample port. Ideally, there would be no signal on the reverse sample port when there is only a forward traveling wave passing through the bridge. As no bridge is ideal, a leakage signal will be present as shown in Figure 4. If the normal coupling is 20 dB and the leakage signal is 35 dB, then we say the bridge has 15 dB of directivity.

To understand the importance of the quality of the calibration kit, consider the following: to improve the directivity, you would have the VNA produce a signal and terminate it by attaching the calibration load to the output port. Theoretically, there would be only a forward traveling signal leaving the VNA and no reflection from the load, hence no reverse traveling signal. The leakage signal could then be measured on the reverse sample port and simply subtracted from all subsequent measurements. The residual (corrected) directivity would be infinite! Unfortunately, the assumption that there is no

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reflection from the calibration load is incorrect. A very expensive (~$6k) 26 GHz, 3.5mm calibration load will have worst case return loss of about 30 dB, so there will be a reflected signal, 30 dB down entering the port. This will show on the reverse sample port. The residual directivity of the bridge after calibration will therefore be no better than 30 dB.
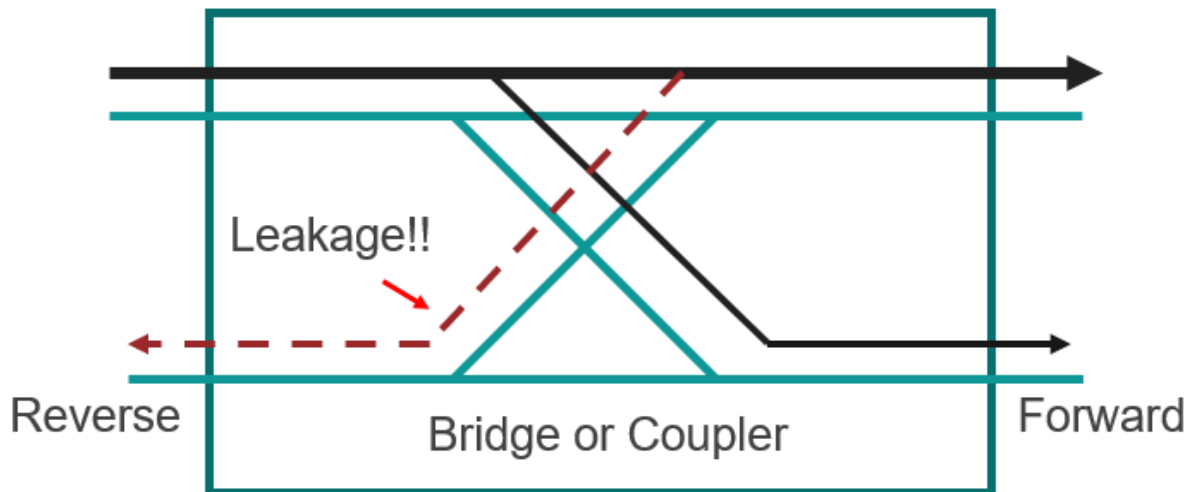

Figure 4 - Bridge with Leakage Signal

Because the ACM has a stable, temperature-compensated, data-based calibration load, the residual directivity after calibration is 46 dB, much better than 30 dB.

Residual Errors and Reflection Uncertainty

The other error terms are corrected to the much smaller residual values based on the quality of the calibration standards within the ACM. The uncertainty of VNA measurements depends on the values of these residual errors. A typical reflection uncertainty chart after ACM calibration is shown in Figure 5.
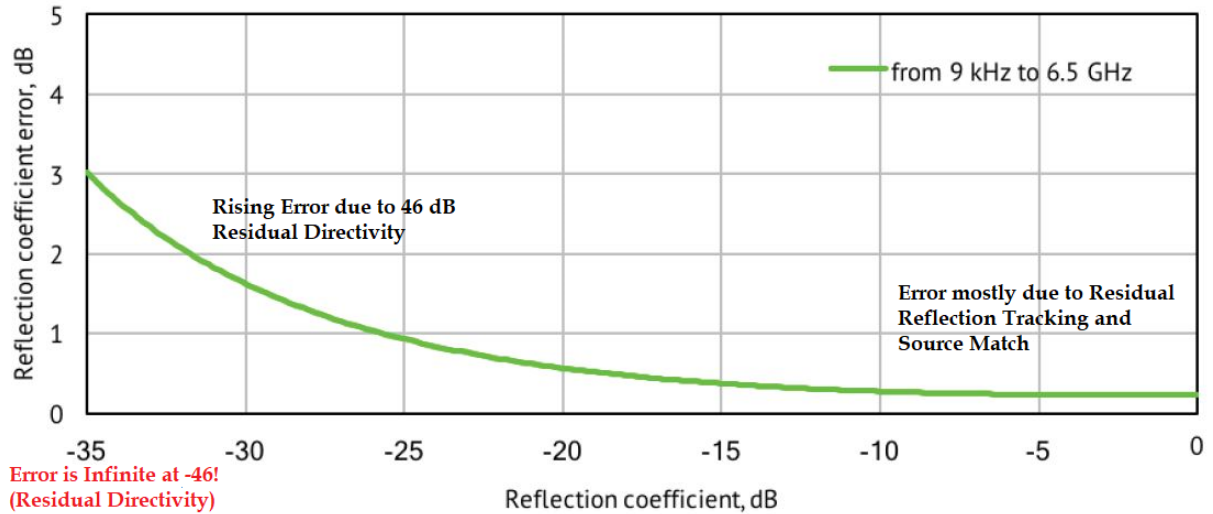
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Figure 5 - Reflection Uncertainty

The floor for reflection measurement accuracy is determined by the residual directivity error. The quality of the calibration load is very important. To put it another way, 1-port reflection measurements are not noise limited, but rather interference limited by the residual directivity.

The reflection uncertainty curve above is only valid for calibration with an ACM. If using a mechanical kit with a 30 dB return loss calibration load instead, the above curve would be shifted 16 dB to the right and the uncertainty for a -20 dB reflection measurement would be about ± 3 dB instead of ± 0.6.

From EUROMET [1], the equation for the approximate uncertainty of a reflection measurement in terms of the residual errors is (in linear terms):

$$\Delta S_{ii} = D + T * S_{ii} + M * S_{ii}^2 + L * S_{21} * S_{12} + R$$

Where S_{ii} is the measured reflection
T is the Residual Reflection Tracking
M is the Residual Source Match
L is the Residual Load Match
And R accounts for random factors such as connector repeatability

The Load match term, L, only applies for reflection measurements of a DUT, which is terminated on the other side by the opposite port of the VNA and insertion loss through

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the DUT is low (S12 = S21≈1). Residual reflection tracking and source match dominate for high reflection, and residual directivity dominates for low reflection measurements.

Residual directivity, D, is approximately equal to the calibration load uncertainty; 30 dB for the expensive mechanical kit and 46 dB for the ACM.

$$D \cong \Delta\Gamma_L$$

Residual source match is approximately equal to the weighted square root of the sum of the squares of the calibration load uncertainty and the angular phase error (radians) of the Open and Short calibration standards.

$$M \approx \sqrt{\Delta\Gamma_L^2 + \frac{\varepsilon_s^2}{4} + \frac{\varepsilon_o^2}{4}}$$

Residual load match is approximately equal to the residual source match for a 2-port calibration with unknown thru.

The uncertainties of the calibration standards determine the residual errors and how those residual errors affect the final reflection measurement uncertainty. A more thorough treatment of VNA metrology is given in [2].

Residual Errors and Transmission Uncertainty

A typical transmission measurement uncertainty chart after ACM calibration (CMT Model SC5065) is shown in Figure *6*.

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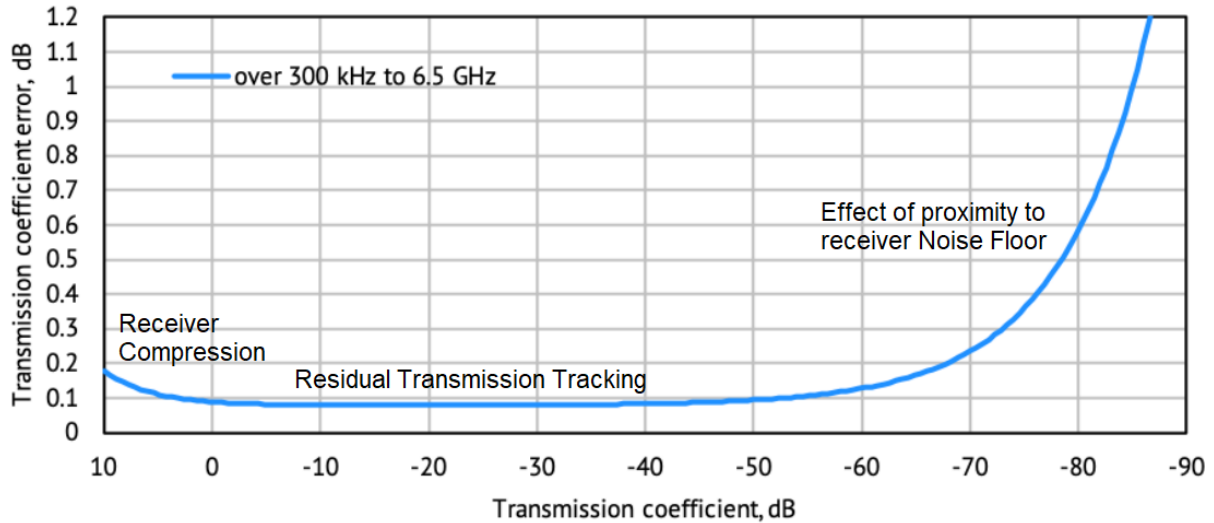
Specifications are based on matched DUT, and IF bandwidth of 10 Hz
Figure 6 - Transmission Uncertainty, Model SC5065

For transmission measurements, the approximate measurement uncertainty is given by:

$$\Delta S_{ij} = T + M + I + R$$

Where:

T is the Residual Transmission Tracking error
M is a residual error due to DUT mismatch
I is the residual Isolation error
R includes a number of random factors but is dominated by the noise floor for small reflections

Residual transmission tracking is proportional to the product:

$$T \approx \mu_1 L_2 + \mu_2 L_1$$

Where:
μ_1 is Residual Source Match
L_2 is Raw Load Match
μ_2 is Residual Load Match
L_1 is Raw Source Match

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Raw source and load match are properties of the VNA hardware, and residual source and load match are approximately equal to the uncertainty of the calibration load standard. The raw source and load match of the VNA should be reasonable, but the two products above are dominated by the small residual values.

For a well-matched DUT, the M term may be ignored, and the port-to-port isolation of the VNA is normally below thermal noise in 10 Hz bandwidth, so it can also be ignored. The R term is mostly trace noise due to proximity of the measurement to the receiver noise floor.

The uncertainties of the calibration standards affect uncertainty of transmission measurements over a broad range from about 0 to -60 dB. Below -60 dB, random noise introduced by the receiver noise floor dominates, and above 0 dB, receiver compression introduces errors. Receiver compression errors may be avoided by reducing the stimulus power for amplifier measurements. Again, the quality of the calibration kit is important for precise transmission measurements.

Adding Adapters to the ACM

Normally, you would use an ACM that matches the connectors of the test cables. For instance, an ACM with female-to-female N connectors would be selected for use with test cables having male N connectors. Sometimes, adapters are added to the ACM to allow for calibration using test cables with non-matching connectors. User Characterization can be performed on the ACM to allow for this.

As an example, use test cables that have 3.5mm male connectors and an ACM that has female N connectors. Place the N Male to 3.5mm female adaptors on the ACM and torque them appropriately. Calibrate the ends of the test cables using a 3.5mm calibration kit, another ACM, or a good mechanical kit. Make sure the frequency range is appropriate for the adapters and set the number of points to 1601. Attach the test cables to the ACM with adapters using proper torque. In the VNA User Interface under Calibration/AutoCal, select Characterization and change it from "factory" to one of three user characterizations. Press the Characterize AutoCal Module button, allow the calibration to complete, then fill out the information on the dialogue screen which will automatically appear.

After User Characterization, the adapters should be left on the ACM. If they need to be removed and then re-attached, the user characterization should be repeated.

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Conclusion

The accuracy of the VNA measurement greatly depends on the quality of the calibration kit in use, especially for 1-port reflection measurements. Because of its thermally compensated, data-based internal calibration standards, the ACM delivers consistently superior results as compared to calibration using even a very high-grade mechanical calibration kit. In addition, the Confidence Check feature provides a fast and easy method to verify the robustness of the calibration and test set-up. For precision VNA measurement, an ACM is required.

Two and Four-Port ACM modules can be found on the CMT website here.

References

[1] EURAMET, "Guidelines on the Evaluation of Vector Network Analyzers", Euramet cg-12 Version 2.0, 3/2011.

[2] Brian Walker, Copper Mountain Technologies, "Introduction to the Metrology of VNA Measurement", May 31st, 2022.