Application Note

4-Port AutoCal®

Scorpion®

Automatic Calibrations for Two, Three and Four-Port S-parameter Applications

Introduction

Automatic calibration techniques for Vector Network Analyzers (VNAs) have long been known as convenient transfer-standard techniques for calibration that avoid many connections and user errors. With the advent of multiport VNAs, the need for automatic calibration increases since the number of manual cal connections increases. This application note will discuss a 4 port AutoCal® module (36584KF and 36584NF), how it works, how it can be practically used, and how uncertainties are affected.

The concept of transfer-standard calibrations in VNAs has been around for several years (e.g., [1]-[3]). In this process, a set of convenient standards is carefully characterized, often by a manufacturer. Later, the user re-measures these standards and the instrument uses that data together with the characterization data to generate a reasonable quality calibration. In essence, the calibration used during characterization is transferred to the user's instrument via these non-ideal but time-stable standards.

The prime motivation for using this AutoCal process is to avoid manual connection of ideal standards which can lead to errors (wrong standard connected), lost standards, damaged standards, and much lost time. In an AutoCal process, the standards are usually connected via a switch (usually electronic switches for repeatability but mechanical is a possibility) so only one cable connection is required. Thus the standards are protected, few connections are required, few errors are possible and time is saved.

As multiport VNAs and calibrations have become more popular and necessary, the desire for a multiport AutoCal process has increased. The number of standards connections has gone from a minimum of 7 for a two port SOLT (short-open-load thru) calibration to 15 for a four port calibration of the same type. A process with that many connections can be very time-consuming and error prone. The above transfer standard process can be easily extended to multiple ports and the following discussions will apply to a four port AutoCal module that can be used for two, three and four port calibrations. Some means of connecting an appropriate number of thru lines and providing three impedances (non-ideal standards) to each port is all that must be provided.

The 4-Port AutoCal Module

The switching to provide impedance standards to each port can be readily conceptualized. The implementation, however, is dependent on how one wants to configure the thru lines. As discussed elsewhere (e.g., [2]), the minimum number of thru lines required for an N port calibration is N-1. For this model, the structure chosen was to have one common node (labeled port X) to which all thrus are connected. This leads to the simple switch fabric shown in Figure 1. While not the most complex possible, it does benefit from minimal insertion loss which leads to more repeatable calibrations as will be discussed later.

The one port impedance standards are labeled as S, O, and L for short, open and load but the actual impedances are not that important. What is important is that the standards are sufficiently different in impedance that there are no numerical problems in applying the autocalibration. Details on this topic are in the appendix but the key point is that the design and factory testing processes are implemented to ensure sufficient differences.

An additional path, shown in Figure 1, is that of an assurance standard. This is a mismatched transmission line of intermediate insertion loss that can be used to judge the quality of a calibration. Its parameters are stored at the time of characterization. When the assurance standard is later measured, the new values are compared to the original characterization-time values and the differences judged against the measurement uncertainties.

Aside from the standards, switches and the controller/drivers for them, the other main portion of the autocalibration module is related to temperature control. A thermal sensor and heater are used to form a closed loop to keep the standards module at a very constant temperature and hence improve stability. The *operate* LED on the module is used to indicate when the module is at temperature. Characterization, calibrations and assurance measurements should not be made unless this LED is illuminated.

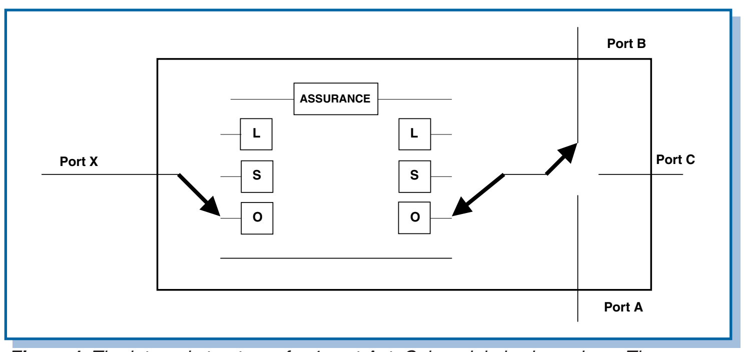

Figure 1. *The internal structure of a 4-port AutoCal module is shown here. The standards are switched to the various ports as required. The complete calibration requires only three thru lines so only those are provided internally to minimize insertion loss.*

Procedures

As might be expected, the parameters of all of the impedance standards (through all applicable paths) are measured at the time of characterization along with the parameters of all thru lines and all assurance paths. The characterization is performed while the instrument is carefully calibrated so that the actual S-parameters of the AutoCal module are now known. During calibration, the same standards are then measured while the user's instrument is in an uncalibrated state. Since the true S-parameters of those standards are known via the characterization file, a system of equations must simply be solved to generate the error coefficients for the user's system.

Characterization

This process of measuring the standards under calibrated conditions is usually performed by the manufacturer either at time of assembly or during subsequent recalibrations of the module. This process is done over the whole frequency range of the module (10 MHz-9 GHz) with the maximum number of points allowed in the host VNAs (1601 points for the MS462XX). When an auto calibration is performed over a narrower frequency range, interpolation is used. More details on this process are in the appendix.

If users frequently work in very small frequency ranges, they may want to perform their own characterization over just that range. This reduces the amount of interpolation involved, although the errors in that are quite small as will be demonstrated in the examples. There may also be cases when more frequent characterizations are desired and time does not permit a factory recharacterization; user characterizations are then also an option.

The process for performing a characterization is as follows. The power level is not extremely critical but would normally be set at 0 dBm for this process.

1. Perform a CAREFUL manual 4-port calibration over the desired frequency range with the desired number of points. Clean calibration standards and proper connector torquing are important. The use of a sliding load, or at least the high return loss load of the 375xLF or 375xR calibration kits, is recommended. Connector repeatability particularly with N connectors can be challenging. The use of phase equal insertables or non-zero length thru lines may be required to get the connectors types correct for use with the AutoCal module (see [4] for more information).
2. Connect the AutoCal module and select Utility/AutoCal Characterization on the Scorpion VNA. A menu is shown in Figure 2.
3. Select a 4 port module and select the port assignment (which VNA port is connected to which AutoCal port; may not have a choice depending on firmware version). Select an appropriate number of averages. The default is 4 for loads, reflections and thrus (averaging menu shown in Figure 3). This default will give a very low noise cal. If even less jitter is desired, consider increasing the number of averages (particularly load and thrus) to 8-10.
4. Start the Characterization. It may take awhile if many points and averages are used.
5. Store the characterization file (either now or from the save/recall menu later). The file name must begin with S and an extension of .ACD will automatically be added.
6. This characterization is automatically active now and can be immediately used to perform an auto calibration.

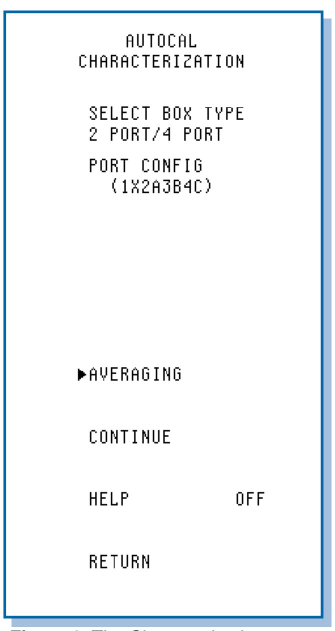

Figure 2. *The Characterization menu (firmware version 1.15) is shown here.*

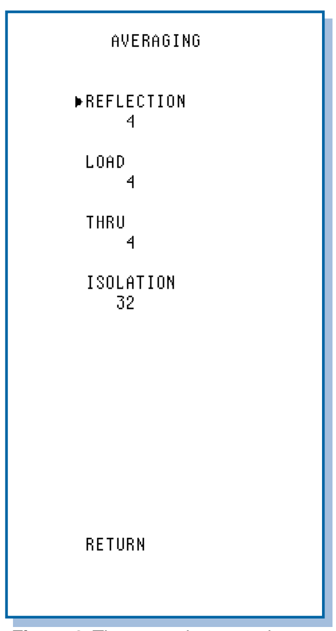

Figure 3*. The averaging menu in its default state is shown here. Isolation is not used during Characterization but this menu is shared with calibration.*

As a side note, the serial number of the AutoCal module is embedded in the characterization file. Thus when performing an auto calibration later, the VNA will check that the identity of the current AutoCal module matches that listed in the current characterization file. If an error is generated because these do not match, just reload the correct characterization file.

Auto Calibration

The actual calibration sequence will be employed by all users and is the most important. As summarized earlier, the calibration routine will measure the (non-ideal) standards in the AutoCal module and use that, together, with the characterization data stored previously to calculate the error coefficients. The choices to be made are limited to the standard ones for any calibration: number of ports, frequency range, number of points, power levels, etc.

1. Set up system parameters as desired (frequency range, point count, power levels, etc.)
2. Enter Calibration/AutoCal (menu in Figure 4) and select the type of calibration. The choices will depend on the firmware version but will at least include Full 2 port cal, Full 3 port cal, and full 4 port cal.
3. Select the port assignment (if available, depends on firmware version). Commonly, VNA port 1 will be connected to AutoCal port X, VNA port 2 to AutoCal port A, VNA port 3 to AutoCal port B and VNA port 4 to AutoCal port C for a full four port calibration. A typical setup is shown in Figure 5.

NOTE: If adapters are used to make these connections, the calibration will be at the adapter planes. Consider the use of phase equal insertables (e.g., [4]) if the DUT has different connector types.

4. Select the number of averages. The default is 4 for loads reflections and thru standards and this will allow for a very low noise cal. If cal speed is important and slightly higher trace noise is acceptable, these numbers can be safely reduced. Isolation uses external terminations to try to correct for internal VNA or test setup leakage. This is only available in some firmware versions and can almost always be skipped (enter 0 for number of averages) unless the test setup is quite unshielded.
5. Make sure the AutoCal module is connected (see Figure 5), the operate light is on and start the calibration. Save the calibration, if desired, at the end.

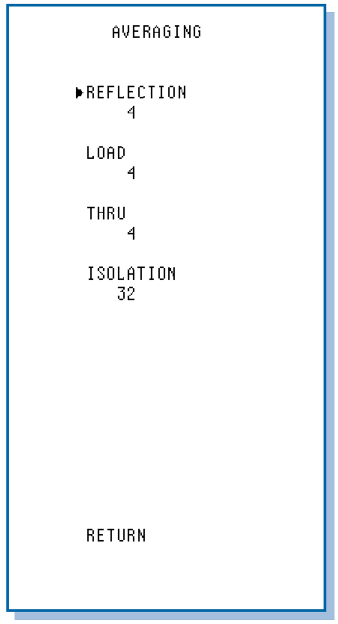

Figure 4. *The AutoCal menu (firmware version 1.15) is shown here. The calibration type and averaging can be selected before starting the calibration.*

AutoCal Assurance

(may not be available depending on firmware revision)

In this step, the assurance standard is measured using the current calibration and the results compared to those obtained during the characterization step. The objective is to compare any differences with measurement uncertainties to determine if the current cal is of expected quality. The uncertainties are computed using a simplified model based on that discussed in the next section and some of the parameters are editable. It is not suggested that the user edit these parameters unless very familiar with the calibration models and instrument behavior.

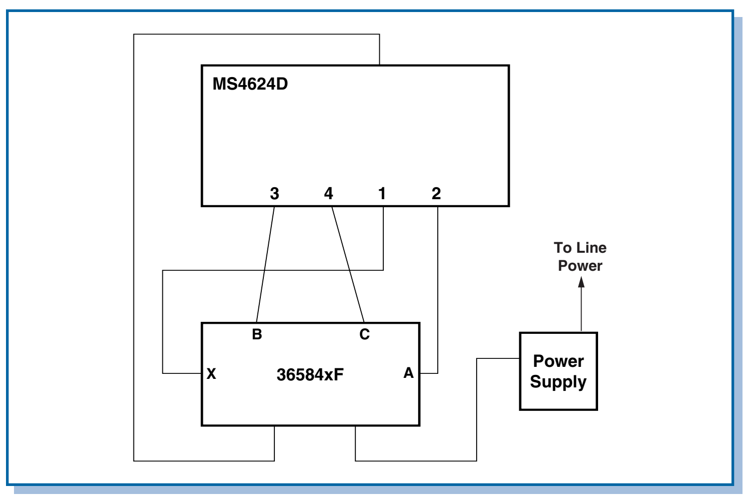

Figure 5. *A typical setup for a full four port autocalibration is shown here. For a full two port cal between ports 1 and 2, typically 1 would be connected to X and VNA port 2 connected to A. For a full three port cal (of VNA ports 1,2 and 3), the cable between VNA port 3 and B would be added.*

Using AutoCal as Part of a General Protocol

While there are many ways that autocalibration can be used as part of an overall calibration protocol, the following is meant to provide some guidance on benefits and costs that are associated.

- Calibration errors and connector repeatability problems are greatly reduced through the use of autocalibration. Calibration speed can be increased by an order of magnitude or more. Full four port calibrations with 401 points can take about 50 seconds as opposed to 5-10 minutes for a typical, careful manual cal.
- For a fixtured or on-wafer environment, autocalibration is only appropriate if the test port-to-DUT plane path can be readily de-embedded. This is relatively easy in a switch matrix test environment. More information is available in [5] on the de-embedding process.
- Uncertainties are degraded only slightly relative to a very good manual cal (a few hundredths of a dB in passband transmission) due to long term drift and minor connector issues during characterization. Uncertainties will generally be much better than a mediocre manual cal.
- User characterizations can be performed but are normally not required. If uncertainty shifts of a few hundredths of a dB are an issue and the desired step size is about 2 MHz or less, it could be considered.
- The official recharacterization interval is currently 6 months.

Uncertainty Analysis and Comparison Examples

It is assumed that the reader is familiar with basic VNA uncertainty analysis (if not, a simple treatment is available in [6]). The analysis is based on a fairly common error model including terms such as residual directivity, residual source and load match, tracking errors, noise floor, crosstalk, compression, and other terms. The original calibration used for characterization forms the starting point for many of these parameters. In the process of using the AutoCal module, additional terms for drift of the standards, connector repeatability, and numerical effects must be included. This is usually done indirectly by studying the effects on the other terms and buffering the tolerances appropriately. The new set of model terms can then be processed using software such as Exact Uncertainty to come up with expected uncertainties on common S-parameter measurements. Since these uncertainties are dependent on what is being measured, the values are usually plotted as a function of device match or transmission. Some example AutoCal curves are shown in Figure 6.

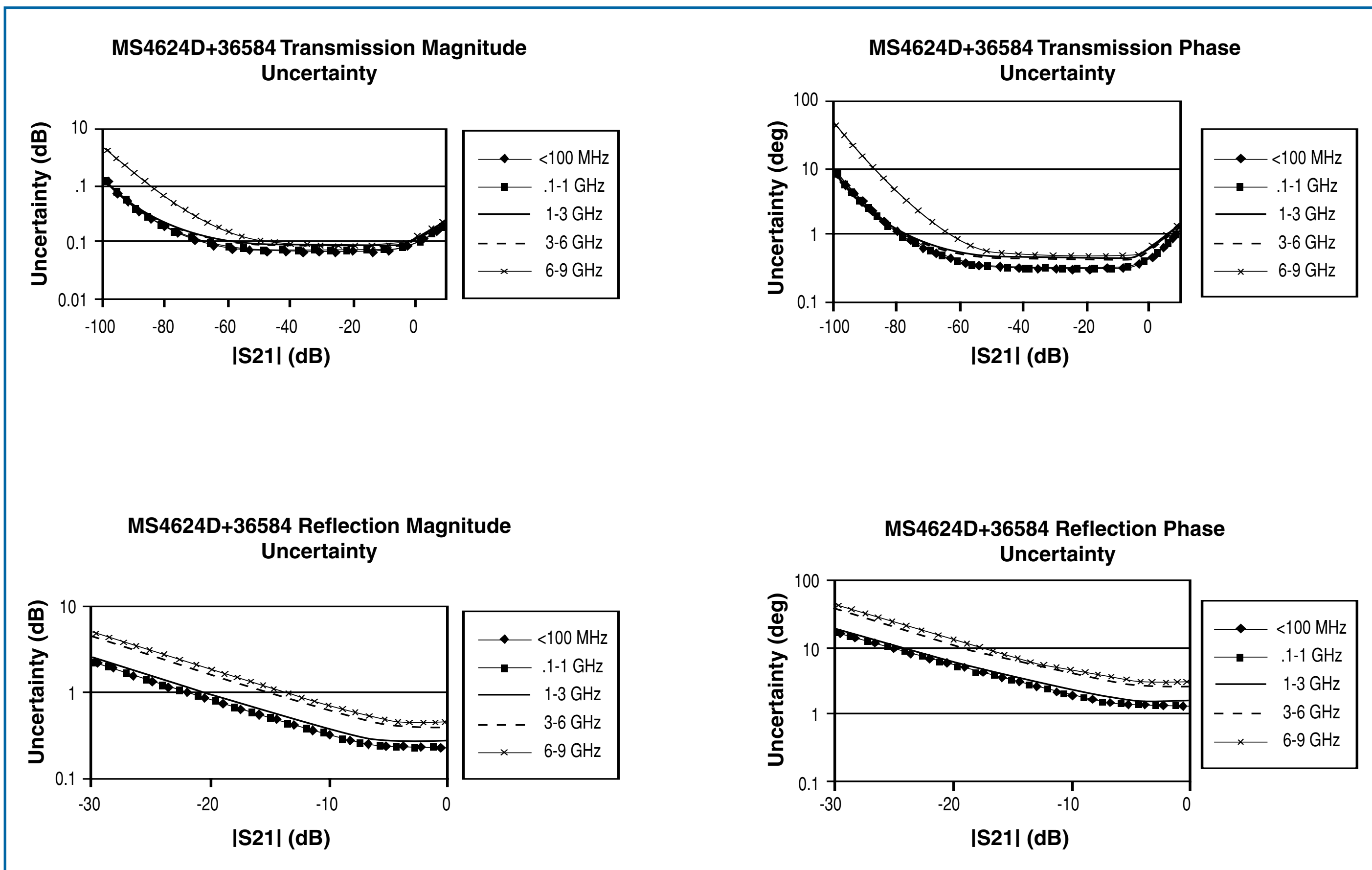

Figure 6. *Example uncertainty curves for an autocalibrated MS4624D are shown here. The calculations are based on a common error model, the specifications for the VNA, and the specifications for the AutoCal module 36584.*

Examples

While it may appear obvious that the accuracy of the original calibration is being transferred to the final instrument, some comparison examples may help to illustrate the process. The first example is that of a simple one port airline measurement and it is shown in Figure 7. As this is often used to measure corrected source match of a VNA, it is quite important. A manual cal and an AutoCal performed over the same frequency range with the same number of points are shown. Since these parameters match the characterization range, no interpolation was involved although that made no perceptible difference in this case.

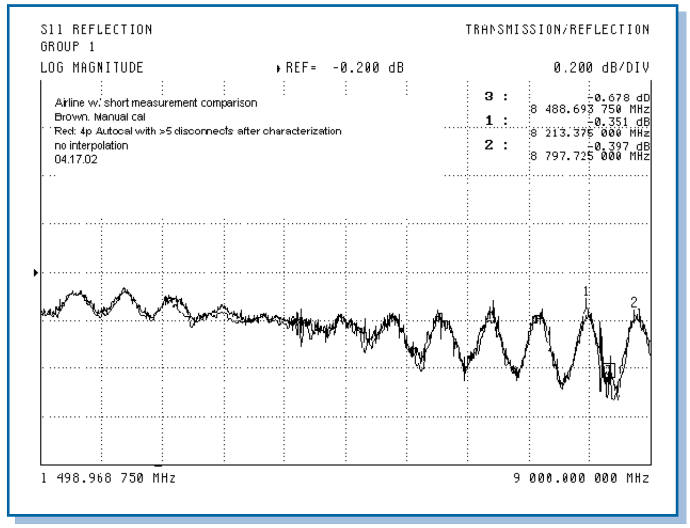

Figure 7. Comparison airline measurements (unsupported coax line with very low reflections connected to port 1) with a manual cal and an autocalibration are shown here.

The next example is that of a three port bandpass filter and is shown in Figures. 8-9. In this case, a significant amount of interpolation was used in the AutoCal due to the much smaller 700-1200 MHz frequency range. This measurement also involves the use of an arbitrary impedance transformation (see [7] or [8] for example) and mixed-mode S-parameters since it is a differential output device (single-ended in). This particular filter had relatively poor return loss (stripped of its normal matching networks) but the agreement between the calibrations was well within uncertainties.

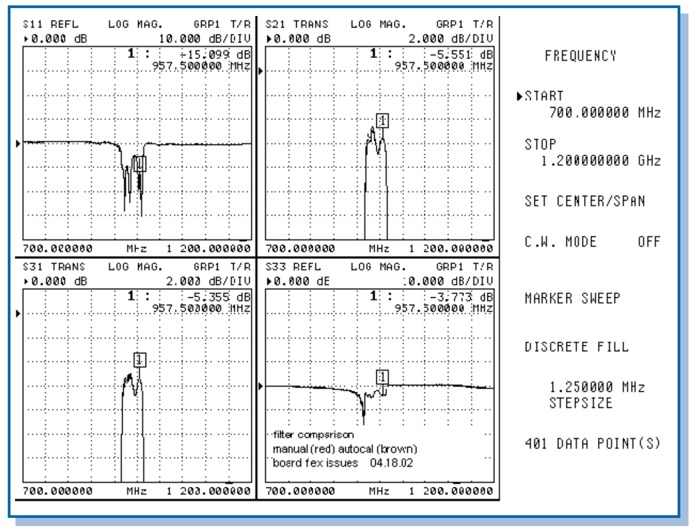

Figure 8. Comparison measurements of a single ended-to-balanced bandpass filter are shown here with manual and automatic calibrations. The filter is on a PC board and board line lengths have been removed. The output differential impedance is 150 ohms and this was used for the data shown.

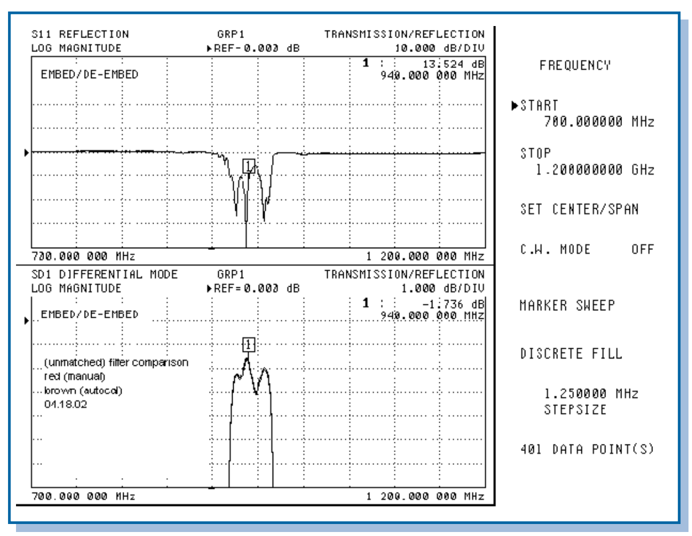

Figure 9. An expanded view of the data in Figure 8 is shown here. The agreement is good as might be expected from the uncertainty analysis.

The next example is that of a surface mount narrowband balun (see Figure 10). Again this is a three-port mixed mode measurement with impedance transformations and interpolation but also with de-embedding of the PC board transmission lines linking the part to the coaxial connectors. The low insertion loss and good match of this device make it a good test of calibration quality and the agreement is again well within expectations. As might have been surmised from the uncertainty curves earlier, match uncertainties increase fairly substantially as the match improves. This makes sense from a signal level argument: as the match becomes very good, the signal level reflected becomes very small…to the point where it is much smaller than the raw directivity signal that is being corrected. This becomes a classical subtraction-of-nearly-equal numbers problem (e.g., [9]) so the uncertainty will become large. Thus it may be expected to see greater divergences as the match descends to the –30 dB level or below.

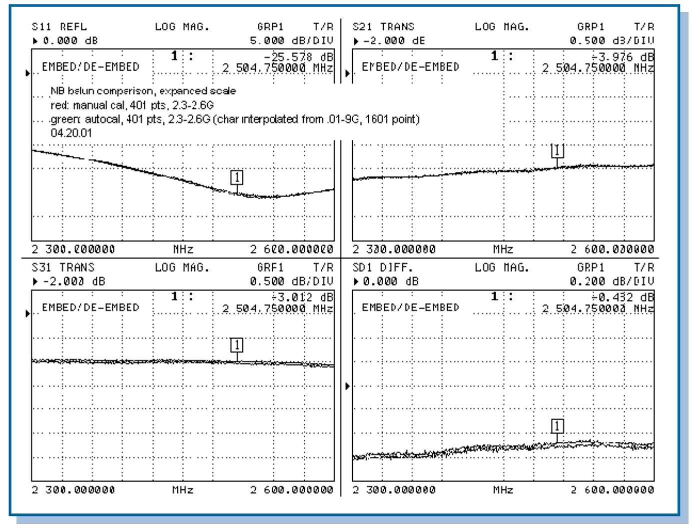

Figure 10. *Comparison measurements of a narrowband balun are shown here. Impedance transformations and PC board de-embedding were used on both manual and automatic measurements.*

The final example is that of a double balun (a pair of coaxial baluns back-to-back). This is a four port mixed mode measurement with interpolation. The data are shown in Figures 11-12. As in the previous examples, the agreement is as expected with some slight residual due to cable flex.

While more information can be found elsewhere on the mixed-mode S-parameters (e.g., [4], [10]), a few salient features will be pointed out. As might be expected, S_{d1d1} is the differential input match. S_{c2c1} is perhaps less obvious: it is the transmission through the device of common-mode signals. Since this is a pair of baluns, each using 180 degree out-of-phase differential signals, one would expect the common-mode transmission to be very low. The common-mode transmission is calculated from four single-ended S-parameters via the following:

$$S_{c2c1} = \frac{1}{2}\left(S_{31} + S_{41} + S_{32} + S_{42}\right)$$

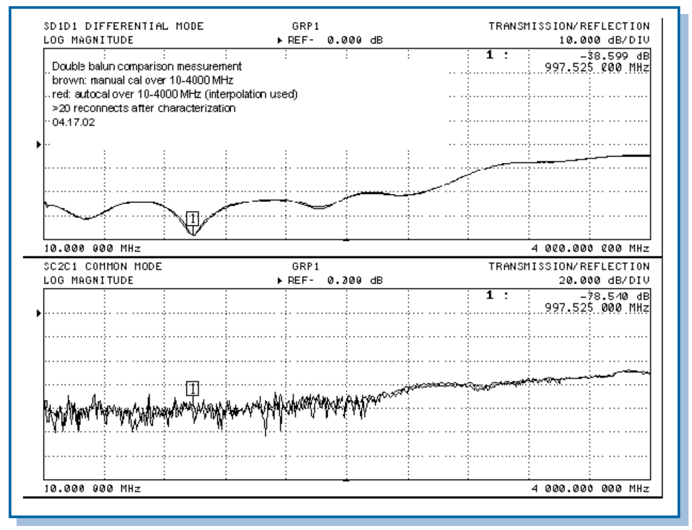

Figure 11. *Comparison measurements of a pair of back-to-back baluns (treated as a single four port) are shown here. Agreement is good even on the very demanding common-mode measurement shown in the lower frame.*

Assuming the baluns are well-balanced, all four of the S-parameters above will be of about the same magnitude. S_{31} and S_{42} will be of about the same phase and the other two will be about 180 degrees out of phase with S_{31} and S_{42}. This S_{c2c1} is a subtraction of basically equal numbers in this case. This situation places strong demands on the calibrations and the agreement in Figure 8 illustrates that the calibrations are nearly identical in terms of measuring these four S-parameters.

S_{d2d1} is differential transmission and the calibrations agree quite well on this measurement as well. This insertion loss is fairly high since these baluns are very broadband. The phase agreement was better than one degree as well.

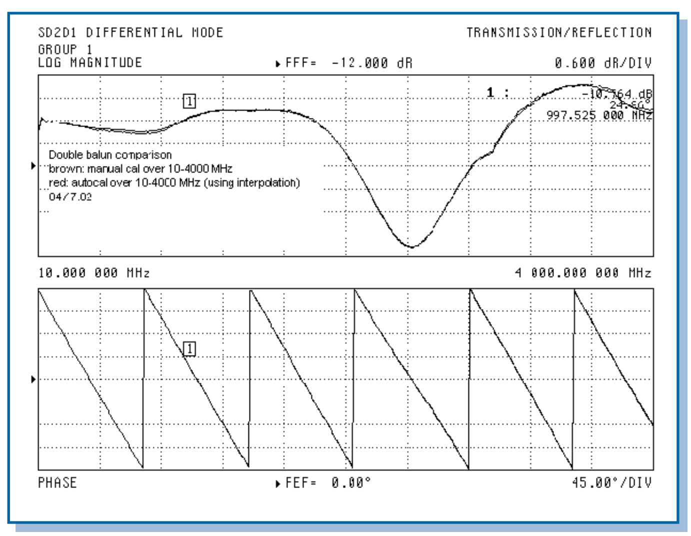

Figure 12. *Additional data on the device of Figure 11 are shown here. The differential transmission shows good agreement as well.*

Conclusion

A method for automatically calibrating multiport VNAs has been presented including a description of the autocalibration module, its principles and practicalities of operation, and how it fits into a calibration protocol. In addition, a simplified uncertainty analysis of this process has been discussed and a number of examples comparing automatic and manual calibration results on one through four port devices were presented. In all of the comparison examples, differences were less than would be computed from the uncertainties.

Appendix

To help understand the requirement for sufficient differences between one port impedance standards, consider the below equation for the directivity error term on the n^{th} port:

$$edn = \frac{cl_n \cdot mo_n \cdot ms_n (cs_n - co_n) + cs_n \cdot mo_n \cdot ml_n (co_n - cl_n) + co_n \cdot ms_n \cdot ml_n (cl_n - cs_n)}{co_n \cdot mo_n (cs_n - cl_n) - cs_n \cdot ms_n (co_n - cl_n) + cl_n \cdot ml_n (co_n - cs_n)}$$

Here cx_n refers to the characterization file value for standard x on the n^{th} port and mx_n is the measured (during the user calibration procedure) value for standard x on the n^{th} port ($x=o$, s or l). In the equation, one can see terms of the form (cx_n-cy_n) where x and y are different standards. If these difference terms get too small, loss of numerical resolution occurs or, in some, cases, the denominator goes to zero. Thus a goal is to keep these difference terms sufficiently large under all circumstances that the calibration will not fail for numerical reasons.

Interpolation is another computational issue. Since the characterization is often performed over the full frequency range of the module, a user calibration is rarely performed at exactly those same frequency points. Thus the system will interpolate the characterization values as appropriate. Since the frequency step in the factory characterization file is about 5.6 MHz and the interpolation is done in an energy conserving fashion (as is appropriate for S-parameters in general), the potential errors are small. Only if the line lengths involved (in the AutoCal module) are so long that a standing wave pattern could shift significantly over half this step size should one be very concerned. For a 10 degree shift, the line lengths would have to be on the order of 3m, far longer than anything within the module.

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