RL-938

AN INTRODUCTION TO MultiCal

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PREFACE

The objective of this manual is to provide basic information necessary to run the National Institute of Standards and Technology (NIST) *MultiCal* software program. *MultiCal* is an alternative calibration routine that offers more accuracy as compared to the built in HP 8510C Automatic Network Analyzer (ANA) Thru-Reflect-Line (TRL) calibration. The user is assumed to be experienced with the HP 8510C ANA, particularly the TRL calibration. It should be noted here that the HP 8510C ANA setup can perform measurements in the frequency ranges of 2 - 60 GHz and 70 - 115 GHz.

INTRODUCTION

MultiCal is a software program developed by the National Institute of Standards and Technology (NIST) to perform scattering parameter (S-parameter) calibrations of the HP 8510C Automatic Network Analyzer (ANA). The software is located on the PC connected to the HP 8510C ANA and runs under HT_Basic in a Windows 3.11 environment..

MultiCal can be used with on-wafer standards, planar transmission lines, coaxial lines, and hollow waveguides. The basic de-embedding algorithm is based on the multiline Thru-Reflect-Line (TRL) algorithm and the standards required are one thru line, one longer line, and one pair of identical reflective loads at each port. The TRL calibration separates the effects of the transmission medium in which the circuit is embedded, from the circuit characteristics. The calibration essentially eliminates all effects of connector discontinuities so that the measured S-parameters solely characterize the device-under-test (DUT).

Rather than using discrete impedance standards, the TRL calibration uses tranmission line standards, such as a thru line, an open/short circuit, and delay lines. If the thru line is used as a reference, the reference plane is defined at the midpoint of the thru line. Therefore, the circuit to be measured should be designed such that the feedline is half the thru line length. The reference plane will thus be moved from the end of the coaxial cable, through the feed line, to the beginning of that particular DUT (see Fig. 1).

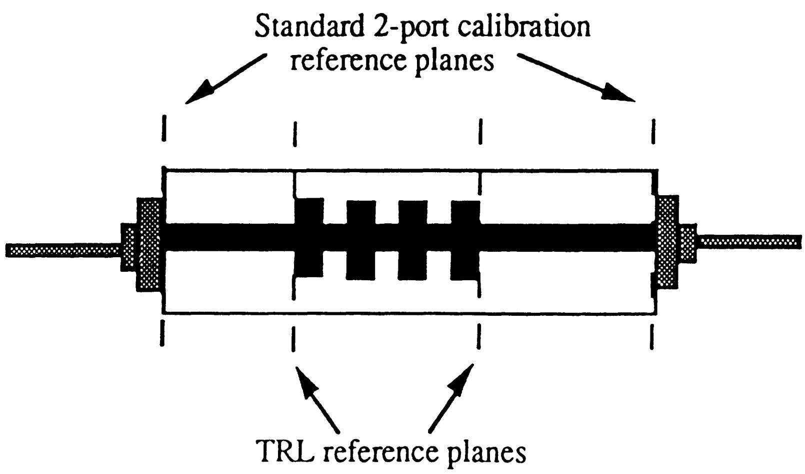

Figure 1: Top view of circuit in test fixture

MultiCal makes the TRL calibration faster and more convenient. Rather than defining standards on the HP 8510C ANA, the calibration standards are quickly defined on screen by editing a calibration menu. Mistakes made during measurements are easily corrected since intermediate data is saved. Finally, *MultiCal* can plot and analyze various data, including propagation constant, line-standard characteristic impedance, S-parameters, and impedance and admittance parameters.

LOADING *MultiCal*

To run *MultiCal* on the PC follow these steps:

(1) Turn PC on and enter Windows environment. If computer asks for password, type TICS1.

(2) Double-click with mouse on HT_Basic menu icon. Double-click on HT_Basic program icon.

(3) A HT_Basic screen should come up. Load the device driver for the HPIB interface card:

load bin "gpibh"

(4) Load *MultiCal* under the HT_Basic environment:

load "c:\multical\multical"

(5) Run *MultiCal*:

run

Once in *MultiCal*, the mass storage path can be changed to any drive or directory. The calibration menu will be up and the softkeys can be used to edit it and/or make measurements. After the menu has been edited: (1) connect a standard to the ANA, (2) select the standard on the menu with the arrow keys, (3) press the MEASURE softkey to measure and store the uncorrected S-parametes of the standard in the local directory specified by the mass storage path. This procedure must be repeated for each standard listed in the calibration menu.

Next, the ANA may be de-embedded by pressing the DEEMBED softkey. The calibration constans are calculated from the measurement files stored on the mass storage path directory. These calibration coefficients are then automatically transferred back to the ANA. Then to measure the S-parameters follow these instructions:

(1) Press softkey **F3** to add a standard in the calmenu.

(2) Toggle softkey **F8** to change added standard to type **DUT**.

(3) Use the softkeys to change the filename **(F4)** and/or description (**Shift F8**) of standard.

(4) Press softkey **F1** to measure.

(5) Enter input filename (same as in the calmenu) for data to be stored in binary format.

(6) Enter **C** for corrected measurements.

(7) Press softkey **Shift F6** to go to output section.

(8) Enter number of frequency points from the HP 8510C ANA (usually 201).

(9) Press softkey **F1** for Data Menu.

(10) Choose measurement no. **9** for S-parameters from file (from calmenu).

(11) Save it to disk or directory in ASCII format.
Note: the S-parameter default format is real and imaginary values. Use Shift key to toggle to magnitude/phase format.

To quit *MultiCal* and return to the HT_Basic environment, just type **q**. Type **quit** to exit the HT_Basic environment and return to Windows.

The next section contains the NIST *MultiCal* Software User's Guide. In it, there is a detailed explanation of the several softkeys. A good understanding of the sofware will prove invaluable for an efficient and accurate use of the program in calibrating the HP 8510C ANA.

NIST *MultiCal* USER'S GUIDE

Preliminary Draft

National Institute of Standards and Technology
De-embedding Software

Program MultiCal [1]

Revision 1.00

USER'S GUIDE

[1] Trademark pending.

Contents

MultiCal[1] was developed with funds from the NIST/Industrial MMIC Consortium. New features are not available to the general public until one year after testing and release to Consortium members. Users of MultiCal and other National Institute of Standards and Technology (NIST) calibration software outside of the United States of America must complete the license agreement in Appendix 1. Questions concerning the Consortium should be directed to Mr. Gerry Reeve at (303)497-3557.

The authors of the software request that you refer to NIST in all publications making use of this software and that you specifically reference the relevant publications cited in this manual. A list of relevant publications can also be found by executing MultiCal's help command.

HOW TO GET HELP FROM NIST

Questions regarding user and equipment interfaces, measurement methodology, or de-embedding algorithms should be directed to Dr. Dylan Williams at (303)497-3138 (dylan@bldrdoc.gov) or to Dr. Roger Marks at (303)497-3037 (marks@boulder.nist.gov).

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1. Introduction

MultiCal performs scattering parameter (S-parameter) calibrations on the HP 8510B, HP 8510C, the HP 8700 series vector network analyzers, and the Wiltron 360 vector network analyzer. MultiCal runs on most Hewlett Packard 9000 series 200/300 computers under HP BASIC and on PCs under the Windows and DOS environments. MultiCal is not a standalone Windows or DOS product; to run on a PC it requires the commercial interpreter HTBasic, available from TransEra Corp., Orem, Utah at (801)224-6550 or HP Basic for Windows, available from Hewlett Packard, Inc. at (800)829-4444. While the software was developed for use with on-wafer standards, it can also be used with other planar transmission lines, with coaxial transmission lines, and with hollow metal waveguide.

The menu-driven software makes calibrating vector network analyzers using de-embedding algorithms developed at the National Institute of Standards and Technology (NIST) extremely easy. The basic de-embedding algorithm used in the software is based on the multiline Thru-Reflect-Line (TRL) algorithm developed by Marks [1]. If more standards than the minimum number are available, MultiCal will automatically and optimally weight the results for maximum accuracy; there is no need to partition the frequency band to eliminate the instability of the TRL algorithm near those frequencies where the difference in line lengths of one line pair approaches a multiple of a half wavelength. MultiCal's multiline TRL algorithm also optimally measures the propagation constant of the lines used in the calibration. MultiCal can determine and reset the calibration reference impedance using the method of [2], applicable to low loss substrates, or the method of [3], which is applicable to lossy and dispersive substrates.

MultiCal supports the line-reflect-match (LRM) calibration. If a line standard of moderate length is available, MultiCal can also accurately translate the reference plane and accurately reset the reference impedance to 50 Ω, even when the transmission lines are lossy and dispersive and the resistor standard has a significant reactance [4]. This requires the auxiliary program LRMCal.

MultiCal supports the off-wafer calibration method of [5], which corrects for differences in substrate dielectric constants.

MultiCal performs both one-tier and two-tier de-embedding. The two-tier algorithms can be used to electrically characterize probe heads and other components, and to implement the calibration comparison and verification methods described in [6], [7], and [8]. MultiCal also supports a second-tier "transition de-embed" calibration based on 3 or more known but otherwise arbitrary one-port standards [9].

After de-embedding, MultiCal can plot and analyze various data, including propagation constant, line-standard characteristic impedance, S-parameters, impedance parameters, and admittance parameters.

2. Program Organization

When MultiCal is loaded and run, a menu similar to that shown in Figure 1 will appear on the screen. The parameters displayed on the screen define the calibration procedure.

The MultiCal menu contains a list of the calibration standards, followed by a list of the essential parameters defining the calibration. Softkeys displayed at the bottom of the screen are used to edit the menu and give the user control over de-embedding and measurement. Edited menus may be saved on disk and recalled later. This makes it easy to completely specify a de-embedding or measurement procedure for another user. Using the default file name "**CALMENU**" is convenient as this menu is automatically loaded when MultiCal is restarted. If MultiCal cannot find the file **CALMENU**, it will start with a default menu set up for calibration with NIST coplanar waveguide standards.

Pressing the up-arrow and down-arrow keys moves the arrow (==>) at the left of the list of standards. Properties of the standards are changed by selecting the standard with the arrow and using the softkeys to modify the standard attributes. Other softkeys modify the information on the menu below the standard list.

After the menu has been edited, the uncorrected S-parameters of each standard may be measured and stored on disk by selecting the appropriate standard with the up-arrow and down-arrow keys and pressing the **MEASURE** softkey. Once the uncorrected S-parameters of each standard have been measured and stored on disk, the analyzer may be de-embedded by pressing the **DEEMBED** softkey. To exit the program and restore your CRT settings, hit "Q" or "X" from the main menu.

Mistakes are easy to correct because all of the intermediate measurements are stored on disk; changing menu parameters, remeasuring a single standard, or even adding a standard does not require restarting the calibration process from the beginning. However, some care must be taken if type definitions are changed. Extra data is taken with the thru line to determine the switching error terms in the analyzer. Data is also taken differently when the one-tier and two-tier algorithms are specified.

```
    DESCRIPTION                   TYPE          DATA FILE NAME  LENGTH(cm)     M  F
==> 19.695 mm CPW Line            Line          L19                 2.0195
     6.565 mm CPW Line            Line          L6                   .7065
     3.280 mm CPW Line            Line          L3                   .3780
     2.135 mm CPW Line            Line          L2                   .2635
     0.0   mm CPW Thru            Thru          THRU                 .0500        +
    -0.05  mm Offset Short        Refl/short    SHORT                .0200

TRL ONE-TIER CALIBRATION                      Cal Set none
Est. Eff. Dielectric Const. 6.95
Mass Storage Path C:\HTB386\PROG\
Ref. Plane: +0.0000 cm                        Output Reference Impedance: Z0 of line




NIST CPW Standard Set                          Hit SHIFT[k3] or SHIFT[f8] for help
_

1MEAS\DEF   STD 2CAL TYPE \Zrer 3ADD\DEL    STD 4FILE NM\LENGTH 5GET\SAVE  menu
6DEEMBED\OUTPUT 7MSI \   CAL SET 8TYPE \ DESCRIP 9EPS \REF PLANE 0SCREEN \ HELP R
```

Figure 1. The menu as seen on the screen after loading and running MultiCal. The standards and their various descriptors are listed at the top of the menu. The calibration type, effective dielectric constant, mass storage device, and other parameters defining the calibration are listed below. The softkey definitions are displayed at the bottom of the screen.

3. An Overview of MultiCal's Main Menu

The top half of the computer screen contains a list of calibration standards. The arrow (= = >) at the left of the list of calibration standards is moved by the wheel, mouse, or arrow keys on your computer, and selects the standard to be edited or measured.

The first column of the list of calibration standards contains a general description of the standard. The purpose of this description is solely to help the user identify the standard.

The second column contains the standard type. The standard type is used by the software to determine how to handle the measured data. Each calibration must have a single thru standard, and the position of the calibration reference plane is always referred to the center of this thru. Pressing the "I" key toggles the isolation correction on and off. Unless an isolation standard is explicitly chosen, the first reflect is used to determine the isolation error terms when isolation correction is toggled on. For on-wafer measurements it is usually best to toggle the isolation correction off (the default state), which sets the isolation error terms to zero.

The third column contains the name of the disk file in which uncalibrated S-parameter data for that standard will be stored.

The fourth column contains information defining the standard. If the standard is a transmission line, its length in cm is listed in this column; this length is usually the physical length of the standard (see section 6). Other standards often list a file name defining its properties in this column: the calibration methods of [4], [3] and [9] require such standards with known properties.

A "*" is placed next to each standard in the fifth column if that standard has been measured if the measurements were performed before the start of the program. A "+" is placed next to each standard in the sixth column if the data file associated with the standard already exists on the computer's mass storage unit.

Below the list of standards are several lines of additional information. The first line lists the type of calibration to be performed and the first and, if applicable, second tier network analyzer calibration sets.

The second line lists the estimated effective dielectric constant. This information, together with the physical lengths of each standard, is required to allow the program to make the correct root choices during TRL calibrations. Only an estimate of the effective dielectric constant is required. Not shown is the imaginary part of the effective dielectric constant, which is modified by holding the control key and pressing the "EPS" softkey. For calibrations in hollow metal waveguide, the waveguide cutoff frequency replaces the estimated effective dielectric constant.

For second-tier calibrations, the second line also lists estimates of the lengths of the fixtures or probes being de-embedded. The electrical length of the fixtures or probes are calculated from the estimated effective dielectric constant and the lengths listed on this line, and is used to determine the sign choice of the fixture or probe transmission parameters. MultiCal will require a very accurate estimate of this length if the electrical length of the fixture or probe is large at the lowest calibration frequency. This difficulty can be circumvented by including low frequencies in the calibration even when only high-frequency data is required.

The third line below the list of standards contains the path and mass storage device on which all data is stored.

The fourth line lists the reference plane position with respect to the center of the thru line standard and the output reference impedance for the calibration. Positive reference plane positions refer to locations beyond the center of the thru line, negative reference plane positions to locations nearer to the analyzer.

The fifth line lists the line capacitance or other line parameters used to determine the initial reference impedance of TRL calibrations, which is equal to the lines' characteristic impedance.

4. Editing the Main Menu

The softkeys are used to edit the menu. These softkeys and their functions are listed below. If the softkey affects a standard definition, only the standard selected by the arrow is effected.

CAL TYPE Pressing this softkey toggles the calibration type.
Zref Possible types are one-tier, two-tier, and transition de-embed calibrations.

Press the shift key and this softkey simultaneously to enter the reference impedance sub-menu. The reference impedance sub-menu defines the properties of the transmission lines used in the calibration. If the line capacitance and conductance [10] are specified, MultiCal uses the propagation constant to determine the characteristic impedance [2]. The characteristic impedance and propagation constant may also be specified directly. This allows the reference plane of LRM calibrations to be accurately translated even when the transmission lines are lossy and dispersive [4].

The reference impedance of the calibration is also selected from this menu.

ADD STD Pressing this softkey adds or deletes standards from the list.

DEL STD The "Insert line" and "Delete line" keys perform the identical functions.

FILE NM
LENGTH Press this softkey to change the file name for data storage for the standard selected by the arrow.

Press the shift key and this softkey simultaneously to change the length or the definition file of the standard.

GETMENU
SAVEMEN Press this softkey to save or retrieve an edited menu from mass storage. Upon saving a menu, you will be asked whether you wish to store the volume number. If you answer "yes", the volume number of the disk on which the data is saved will be stored. This can be useful if you use many floppy disks with volume labels.

MSI
CAL SET Press this softkey to change the mass storage or path names used for data storage. The mass storage path is listed three lines below the list of standards. A storage device must be specified, but a path location is optional. If the data disks were formatted in LIF format, the path must be omitted entirely.

Pressing the shift key and this softkey simultaneously allows the default calibration set on the analyzer to be selected. For one-tier calibrations, this is simply the calibration set in the analyzer to which the calibration coefficients will be written.

If the two-tier or the deembed transition calibration type is selected, then this softkey allows both the first-tier and second-tier calibration sets to be chosen. The estimated lengths of the transitions on each port between the first-tier and second-tier calibration reference planes must also be specified for two-tier calibrations. This is accomplished with the **EPS** and **REF PLN** softkeys.

TYPE
DESCRIP Pressing this softkey will scroll through the standard types. Holding the control key while pressing "TYPE" will scroll the standard types in reverse order. The standard types are discussed in section 5.

Press the shift key and this softkey simultaneously to change the description of the standard. This description labels and helps differentiate the standards; it is not used in the calibration.

EPS EFF
REF PLN Press this softkey to change the estimated effective dielectric constant displayed on the second line below the list of standards. Hold the control key and press this softkey to set the imaginary part of the estimated effective dielectric constant. Good estimates for the real and imaginary part of the effective dielectric constant ensure that the algorithm correctly makes certain

root choices. This softkey also may be used to set the estimated lengths of the transitions to be de-embedded in a two-tier technique.

Press the shift key and this softkey to change the position of the electrical reference plane along the line. (See section 6.)

SCREEN HELP Press this softkey to refresh the screen. Press the shift key and this softkey to see a help menu. The help menu contains a list of references for the algorithms implemented in this software.

Keyboard strokes are used to accomplish several other functions: press "T" to change the title of the menu, press "A" to toggle the network analyzer interface on and off, press "D" to toggle the debugging option (see section 10) on and off, press "I" to toggle the isolation correction on and off, press "P" to toggle the direction of the pointer movement after each measurement, and press "Q" or "X" to exit the program.

5. Standard Types

The user may select from among eleven standard types. Different measurements are performed for the thru standard type and during first and second tier calibrations, so some care must be made when changing standard and calibration types after measurements have been made. The possible standard types are listed below.

Thru The shortest transmission line used in the calibration. The user may only select one thru line. The position of the calibration reference plane is always referred to the center of this thru line. If a one-tier de-embedding scheme is selected, switching error terms are measured when the thru measurement is made. These are stored in a disk file with the same name as that of the thru line, but with the prefix "G" added to the beginning of the file name.

Line A transmission line of construction identical to that of the thru line but of a different length used for the multiline TRL calibration method [1].

Match A two port with identical loads at each port. The output reference impedance may be set to the impedance of the load or, if the impedance of the load is known, it may be set to a real and constant value. In this latter case, a file containing the reflection coefficient of the load measured in a 50 ohm system must be placed in the standard definition column.

Refl/open A two-port with identical reflective loads connected at each port. The reflective load is assumed to have a reflection coefficient of approximately 1. Capacitive loads can be accommodated by increasing the length of the standard. When the isolation correction is toggled on, the isolation error terms are calculated from the first reflection in the standard list unless an **Isolation** standard is included in the standard list.

Refl/short Similar to the **Refl/open** except that the reflection coefficient is assumed to be approximately -1. Inductive standards can be accommodated by increasing the length of the standard.

Isolation When the isolation correction is toggled on (this correction is toggled on and off with the "I" key), the isolation error terms are calculated from this standard if it is included in the list. If it is not included, the isolation error terms are calculated from the transmission parameters of the first reflect in the standard list.

Load A standard whose reflection coefficients have been measured. The file containing the S-parameters of the **Load** standard is listed in the length column on the menu. The **Load** standard is used only with the two-tier "**De-embed Transition**" calibration. This calibration method is described in [9].

DUT This is provided for the user's convenience and allows both corrected and uncorrected device data to be stored on disk. The program will prompt for the file name when you press the measure softkey before taking data.

Adapt on both An adaptor is added to both ports of the calibration model. The file containing the S-parameters of the adaptor are listed in the DATA FILE NAME column of the standard list. If the adaptor is a simple shunt capacitance, the value of that capacitance in fF may be listed in the place of the file name containing the S-parameters of the adaptor. This is useful when implementing the method of [5], which corrects for differences in calibration and measurement substrates.

Adapt on 1 The same as **Adapt on both**, except that the adaptor is added only to port 1.

Adapt on 2 The same as **Adapt on both**, except that the adaptor is added only to port 2. In contrast to **Adapt on both**, the adaptor S-parameters are reversed before they are added to the port 2 error model; port 2 of the adaptor should be connected to the second port of the network analyzer during both the adaptor and DUT measurements.

6. Reference Plane and Line Length Definitions

The electrical reference plane to which all of the de-embedded measurements are referred is, by default, placed in the middle of the thru line. This reference plane can be moved with respect to this default position using the **REF PLN** softkey.

The lengths of the standards listed in the standards menu refer to the physical distance between probe contacts where, in the multiline TRL algorithm, all contact errors are assumed to occur. These lengths define standard lengths for purposes of de-embedding and allow for proper averaging of errors. Since the probes typically contact the standards at their physical beginning, these lengths are usually just set to the physical lengths of the standards. This is illustrated in Figure 2.

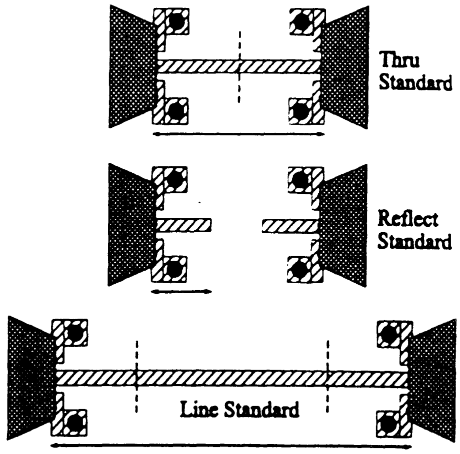

Figure 2. Physical lengths and measurement reference planes are illustrated for a microstrip line with via hole transitions. The lengths listed in the standards list are usually the physical lengths of the lines, indicated here by the arrows. The calibration reference planes, which have not been translated in this example, are shown in dashed lines.

7. Setting the Output Reference Impedance

Calibrated S-parameter measurements are always referred to an output reference impedance. The value of this reference impedance is set in the reference impedance sub-menu, entered by pressing the **Zref** softkey.

In the TRL calibration the output reference impedance can be set equal to the characteristic impedance of the line or, if the capacitance of the line [10] is know, to a real and constant reference impedance (usually 50 Ω) [2]. If the characteristic impedance of the line has been determined by the calibration comparison method, the calibration reference impedance can also be reset to a real and constant reference impedance [3]. The output reference impedance of an LRM calibration can be either set equal to the impedance of the match standard or, if the impedance of the match standard has already been measured, to a real and constant impedance [4].

8. Measuring the S-Parameters of a Standard

The uncorrected S-parameters of each standard are measured and stored on disk by contacting or connecting the appropriate standard, moving the arrow to the standard on the menu, and then pressing the **MEASURE** softkey. After all of the standards have been measured, the analyzer can be de-embedded. In some situations, such as LRM, it is convenient to measure the S-parameters of only one port at a time. Holding the control key and pressing the **MEASURE** softkey allows the standard to be measured first on port 1, and then on port 2. In this case, the program pauses between the port 1 and port 2 measurements to allow the standard to be connected to port two before completing the measurement.

9. De-embedding the Analyzer

The analyzer is de-embedded by pressing the **DEEMBED** softkey. The measurement files stored on disk are then retrieved and the calibration coefficients calculated by the de-embedding algorithm. MultiCal can load these coefficients directly into the network analyzer (the "A" key toggles this network analyzer interface on and off), or it can correct data stored on disk in its output section (see section 10).

Because the data is stored on disk, the menu may be edited and another attempt made at de-embedding if a mistake is made. Also, if a single connection is the reason for a bad calibration, that measurement can be repeated and the data file for that standard written over.

Three types of de-embedding algorithms are supported. The one-tier calibration is the most accurate and the quickest way to calibrate the analyzer. The entire analyzer is calibrated in the one-tier method in a single step. The position of the electrical reference plane is referred to the center of the thru line.

The two-tier calibration is a more complicated process, but more information is obtained. Before beginning a two-tier calibration, the analyzer is calibrated at some intermediate electrical reference plane, often in a coaxial line. Then an adapter, often a test fixture or probe head, is added to the analyzer at the intermediate electrical reference plane and the two-tier algorithm is used to perform a second calibration on the far side of the adaptor. The two-tier algorithm determines the S-parameters of the adapter and uses them to move the measurement reference plane to its far side. These S-parameters are available for output after de-embedding, and are referred to as the "S-parameters of the probe head" in MultiCal's output section. In order for the program to successfully resolve the signs of the adaptor transmission parameters accurate estimates of their electrical lengths must be provided. Two-tier calibrations can also be used to compare and determine the accuracy of calibrations; this is discussed in [6], [7], and [8].

A third calibration type, **DEEMBED TRANSITION**, is also a second-tier calibration. It requires only known one-port standards. This calibration uses the "load" standard type.

10. MultiCal's Output Section

The output section may be entered immediately after the de-embedding process is finished by pressing the **data menu** softkey. At this point, you can plot or store to disk the line's effective dielectric constant, attenuation constant, relative phase constant, or characteristic impedance. You may also plot or save the S-parameters of either of the adaptors if a two-tier procedure was used. You can also plot the normalized standard deviation and effective phase delay of the best line pair [1]. This data can be useful in evaluating the quality of the calibration as a function of frequency. The output section also has a submenu which calculates the capacitances needed to correct for differences of calibration and measurement substrates using the method of [5]. Finally, it is possible to read in data, calibrate it, and display or store it back to disk.

After the desired data has been selected, the data can be viewed on the screen's of some network analyzers by pressing the **ANA** softkey, in a frequency table on the computer's CRT by pressing the **CRT** softkey, or on paper by pressing the **paper** softkey. Data can be plotted on the screen by pressing the **Plot** softkey. The data can also be stored on disk in either BDAT format by pressing the **BDAT** softkey, in a TOUCHSTONE compatible HP format by pressing the **ASCII** softkey, in the HPUX file format by pressing the **HPUX** softkey, or in a DOS format by pressing the **DOS** softkey.

Stored data files may be read from disk using the **Get data** softkey. The number of frequency points in the file must match the number of frequencies in the de-embedded data.

MultiCal's multiline TRL algorithm will calculate the propagation constant of the lines used in the calibration, which MultiCal expresses as an effective dielectric constant. The values are frequency-dependent, but should be smooth and close to the expected value of the effective dielectric constant of the transmission line for reasonably high frequencies. Often problems in the calibration can be detected by comparing the different propagation constants calculated for each line pair. The "d" key toggles between an optimum averaging scheme (the default mode) and a debugging mode, in which each line pair consists of a fixed line and the thru line. This debugging mode is useful for detecting errors in a particular line measurement as it allows the propagation constants determined for each line pair to be compared.

The choice "Propagation constant and attenuation" includes the relative phase constant (the "slow-wave factor") and the loss in dB/cm of the line standards. The propagation constant is sent to the ANA as the real part of the "user 1" parameter, the attenuation constant as the imaginary part.

Another valuable parameter is the effective phase delay. This quantity is also frequency dependent. Its value is the effective phase delay at each frequency of the optimum set of lines used in the calibration. This quantity is always between 0 degrees and 90 degrees: 90 degrees provides the minimum sensitivity to error. This quantity can be used to determine whether the calibration standards effectively cover the frequency band desired, as discussed in reference 2. Reference 2 also describes the normalized standard deviation, a second criteria for judging the error sensitivity of the TRL calibrations. This quantity reflects the relative error expected for the calibration. A value of 1 corresponds to the error of a standard TRL calibration with a single line one-quarter wavelength longer than the thru line. When multiple lines are used this quantity may be significantly less than one, indicating the improvement gained from the redundant measurements.

If the reference impedance was set real in a TRL calibration the characteristic impedance may be plotted or saved. The characteristic impedance of the line is determined from the propagation constant and the capacitance of the line.

The output section contains the algorithms described in [5] for determining the excess probe-tip capacitance due by differences in the calibration and measurement substrates.

The output section contains the S-parameters of the adapter, test fixture, or probe heads determined by the de-embedding algorithm.

The S-parameters stored on disk can also be loaded and, if desired, corrected in the output section. If the reference impedance of the S-parameters is known, impedance and admittance parameters may also be plotted or stored to disk. S-parameters stored in BDAT format are ordered with frequency (in GHz) in the first column followed by the real and imaginary parts of S_{11}, S_{21}, S_{22}, and S_{12} . S-parameters stored in ASCII, HPUX, or DOS formats comply with the TOUCHSTONE compatible ordering frequency, S_{11}, S_{21}, S_{12}, S_{22}.

Once the calibration data has been viewed or stored, press the **Data Menu** softkey to display more data, press the **Deembed Menu** softkey to return to the main menu, or press the "Q" or "X" key to terminate the program. It is also possible to get directly to the output section from the main menu by pressing the **OUTPUT** softkey. At this point, no data is available. However, you may make use of the features of the output section after loading data from disk using the **Get data** softkey.

References

1. R. B. Marks, "A multiline method of network analyzer calibration," *IEEE Trans. Microwave Theory Tech.*, Vol. 39, pp. 1205-1215, July 1991.

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APPENDIX

HP 8510C Automatic Network Analyzer Connection Diagram