Preliminary Draft

National Institute of Standards and Technology
De-embedding Software

Program MultiCal [1]

Revision 1.00

USER'S GUIDE

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[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.

While every effort has been made to ensure that this software is suitable for the purposes intended, NIST makes no warranty, expressed or implied, as to the correctness or fitness for a particular purpose and accepts no responsibility for direct or consequential damages which may result from its use.

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

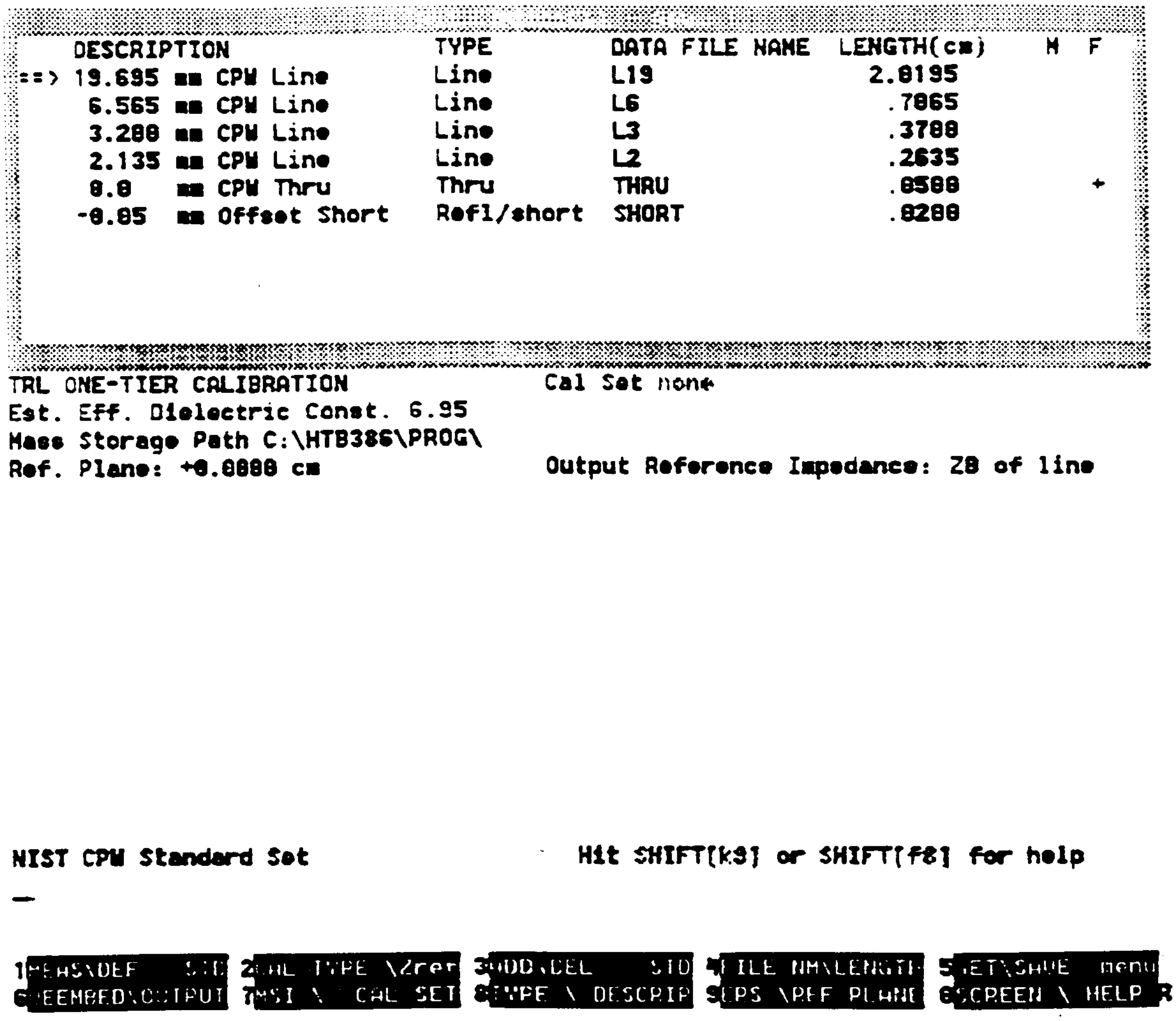
When MultiCal is loaded and run, a menu similar to that shown in Figure 1 will appear on the screen. The parameters displayed on the screen define the calibration procedure.

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
     3.200 mm CPW Line           Line         L3                  .3700
     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 \Zref 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 **Zref**	Pressing this softkey toggles the calibration type. 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.

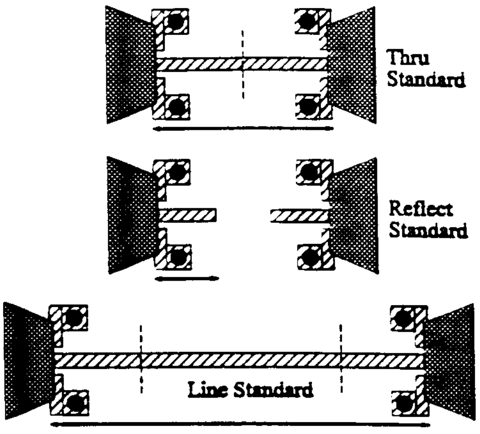


Figure 2. Physical lengths and measurement reference planes are illustrated for a microstrip line with via hole transitions. The lengths listed in the standards list are usually the physical lengths of the lines, indicated here by the arrows. The calibration reference planes, which have not been translated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

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Appendix 1. Foreign License Agreement

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Outside of Europe return completed agreements to Dylan Williams, NIST 813.00, 325 Broadway, Boulder CO, 80303-3328, USA. In the case of termination of this agreement, software and manuals should be returned to this address.

User's Manual

Program VERIFY Rev. 1.03

This software 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 National Institute of Standards and Technology (NIST) calibration software outside of the United States of America must complete a foreign license agreement. 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 in the 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).

Microwave Metrology Group, Electromagnetic Fields Division, National Institute of Standards and Technology, 325 Broadway, Boulder Colorado, 80303.

Introduction

Simple network analyzer calibrations based on lumped elements are quite common for everyday on-wafer scattering parameter measurements. Such "working" calibrations are easy to perform and often give good results. However, you may wish to check the accuracy of one of your working calibrations for a number of reasons. The reference impedance of the working calibration may be set to the load impedance of a small lumped resistor and may not be a constant, real 50 Ω. The reference plane position of the working calibration may be set by reflective terminations whose reactance may not be accurately known. The devices may be embedded in microstrip lines with via-hole or other transitions which are not accounted for by the working calibration. Finally, it is possible for some lumped element calibrations to be inconsistent. For instance, this might occur because of incorrect standard definitions (such as setting $\Gamma=1$ for an open which radiates energy), performing a Line-Reflect-Match (LRM) calibration in which there is coupling between the match standards, or using non-identical match standards in an LRM calibration.

Even if you are presently calibrating to 50 Ω using NIST's multiline Thru-Reflect-Line (TRL) calibration method [1] with reference impedance correction [2] you may be interested in the techniques described in this manual. For example, you may wish to quantify the effects of random errors due to probe placement or loose cables.

This manual describes a method for determining the accuracy of on-wafer calibrations and includes instructions for running the NIST/Industrial Consortium software to perform the required analysis. The verification procedure is described in [3], which we highly recommend reading. Applications of the verification procedure are described in [3], [4], and [5]. Applications of the method to the determination of characteristic impedance on lossy substrates are described in [6] and [7]. Application to calibrations on lossy substrates are described in [8].

Procedure

The calibration comparison procedure is straightforward. First you must have access to artifacts for a "benchmark" TRL calibration. Ideally these calibration artifacts should consist of a set of lines which are identical to the lines to which your device is connected. This is best accomplished by fabricating the calibration artifacts and the lines on the same wafer.

If you have not fabricated a set of lines on your wafer, it is possible to obtain a set of standard lines from NIST. These lines are fabricated to standard dimensions [9] and care has been taken to control linewidths and materials. However, even if you try to embed your devices in similar lines, the NIST lines may differ in a number of ways from those on your wafer; caution is always advisable when calibrating with a set of standard lines which differ from those on your test wafer.

Before beginning, you must know the capacitance per unit length C of the lines in your benchmark standard set. If you are using NIST lines, C is printed on the glass slide to which the standard set is mounted. If you are using your own lines, C must be measured. We recommend using the NIST procedures found in [10] to determine C for your lines. The programs **CAP** and **CAP NIST**, available from NIST, handle the calculations and make the determination of C easy.

Once you have selected the benchmark standard set and know the capacitance per unit length of the lines, simply perform the following steps:

1) Perform the working calibration whose accuracy you wish to verify.

2) Load and run program **MultiCal**. Load the menu appropriate to your benchmark calibration off of the disk by pressing the **GET\SAVE menu** softkey. Chose "TWO-TIER TRL" by pressing the **CAL TYPE** softkey. Set the first tier cal set on the main menu to the cal set you used for your working calibration by pressing the **CAL SET** softkey. Set the second tier cal set to any other unused cal set in the analyzer.

3) The benchmark may be performed either with respect to the characteristic impedance of the line or with respect to 50 Ω. If you select a 50 Ω calibration, be sure to input the correct capacitance and set the reference impedance to 50 Ω. The capacitance is modified by pressing the **Zref** softkey to enter the capacitance menu, and then pressing the **SET C** softkey to modify the capacitance. The reference impedance can now be set to 50 Ω by pressing the **Zref** softkey. After editing the sub-menu is exited by pressing the **RETURN** softkey to return to the main menu. After editing the menu, you may wish to save the menu by pressing the **SAVE menu** softkey.

4) Contact each standard listed in **MultiCal**'s main menu file list and press the **MEAS** softkey. **MultiCal** will take data for each standard and store it on the disk in the appropriate disk file.

5) After storing all of the data on the disk, press the **DEEMBED** softkey. The program will calculate the error coefficients, put them in the analyzer; and place you in the output section.

6) Press the **Data Menu** softkey and store the following information in the BDAT format:
    a) S-parameters of probe 1 [store in file S P1].
    b) S-parameters of probe 2 [store in file S P2].
    c) Effective dielectric constant (mean) [store in file EPS].

7) Exit **MultiCal** and load and run program **VERIFY**. After running **VERIFY** you will enter the main menu. Enter the capacitance of the lines used in the benchmark calibration by pressing the **cap** softkey. At this point you may also change file names and alter various parameters of the analysis (see section on main menu below). If you have followed the above procedure, however, you need not modify the menu. Simply press the **start** softkey and the analysis will begin.

8) After the analysis is complete, the program will enter an output menu. From this menu you may print, view, or plot a variety of calibration diagnostics.

The Main Menu

All of the input parameters for program **VERIFY** may be modified from the main menu by pressing the softkeys:

Softkey	Effect
port 1	Specify the file containing the S-parameters of the probe connected to port 1.
port 2	Specify the file containing the S-parameters of the probe connected to port 2.
eps eff	Specify the file containing the effective dielectric constant of the lines in the benchmark calibration standard set.
cap	Specify the capacitance per unit length of the lines used in the benchmark calibration.
Zref	Specify the reference impedance used in the benchmark calibration. Pressing the softkey toggles between 50 Ω and Z_0.
order	Toggle the order in which your calibration and the benchmark calibration were performed. Usually the benchmark calibration is performed after the working calibration and all of the measurements for the benchmark are performed with respect to the working calibration. In this case choose "second tier". Choose "first tier" if the benchmark was performed first and the working calibration performed with respect to the benchmark calibration. (In this case, the working calibration must determine the S-parameters of the probe head.)
menu	The main menu may be stored or retrieved from disk.
select S	Selects which worst case deviations are be determined. The default is the worst case deviation of any of the four S-parameters. The worst case deviations for any single S-parameter may be selected with this softkey.
screen	Refresh the screen.
start	Begin the calculations and then enter the output menu.

The program may be exited by pressing Q or X.

The Output Menu

The various options accessible from the output menu:

Softkey	Description
50 ohm	Worst case deviations of measurements of passive devices from the benchmark calibration. The reference impedance of the benchmark calibration is set to 50 Ω, even if the reference impedance of the benchmark calibration was initially set to the characteristic impedance of the benchmark lines. After pressing this softkey you will be given options for data output format. (See Viewing, Storing, or Plotting the Data below.) The data will be labeled as follows:

Label	Data description.
initial	Direct comparison of calibrations. The plotted quantity is $\epsilon(50\Omega, l_0)$ or $\epsilon_{ij}(50\Omega, l_0)$ of [3]. The working calibration is compared to the benchmark calibration with a 50 Ω reference impedance and a reference plane which has not been translated.

Softkey	Description
Fit 50	Worst case deviations of measurements of passive devices from the benchmark calibration. After pressing this softkey you will be given options for data output format. (See Viewing, Storing, or Plotting the Data below.) The data will be labeled as follows:

Label	Data description.
initial	Direct comparison of calibrations. The plotted quantity is $\epsilon(50\Omega, l_0)$ or $\epsilon_{ij}(50\Omega, l_0)$ of [3]. The working calibration is compared to the benchmark calibration with a 50 Ω reference impedance and a reference plane which has not been translated.
impedance	Worst case deviation after an impedance transformation to the best estimate of the reference impedance of the working calibration is applied to the benchmark calibration. The plotted quantities are the $\epsilon(\hat{Z}, l_0)$ or $\epsilon_{ij}(\hat{Z}, l_0)$ of [3]. The working calibration is compared to the benchmark calibration with a reference impedance which has been adjusted at each frequency to best match that of the working calibration and a reference plane which has not been translated.
offset	Worst case deviation after reference plane of benchmark calibration is adjusted to most nearly equal the reference plane of the working calibration. The plotted quantities are the $\epsilon(50\Omega, l_M)$ or $\epsilon_{ij}(50\Omega, l_M)$ of [3]. The working calibration is compared to the

	benchmark calibration with a 50 Ω reference impedance and a reference plane which has been translated to a fixed position which best matches the *average* reference plane position of the working calibration.
imp+off	Worst case deviation after the reference impedance and reference plane of the benchmark calibration have been adjusted to be as close as possible to those of the working calibration. The plotted quantities are the $\epsilon(\hat{Z},l_M)$ or $\epsilon_{ij}(\hat{Z},l_M)$ of [3]. The working calibration is compared to the benchmark calibration with a reference impedance which has been adjusted to best match the reference impedance of the working calibration at each frequency and a reference plane which has been translated to a fixed position which best matches the *average* reference plane position of the working calibration.

Fit Z0 Worst case deviations of measurements of passive devices from the benchmark TRL calibration. The **50 ohm** and **All** options, in which worst case deviations from the 50 Ω benchmark calibration are determined, are usually more informative than this option. After pressing this softkey you will be given options for data output format. (See Viewing, Storing, or Plotting the Data below.) The data will be labeled as follows:

Label	Data description.
initial	Direct comparison of calibrations. The plotted quantities are the $\epsilon(Z_0,l_0)$ or $\epsilon_{ij}(Z_0,l_0)$ of [3]. The working calibration is compared to the benchmark calibration with the reference impedance equal to the characteristic impedance of the lines in the benchmark calibration set and a reference plane which has not been translated.
impedance	Worst case deviation after an impedance transformation to the best estimate of the reference impedance of the working calibration is applied to the benchmark calibration. The plotted quantities are the $\epsilon(\hat{Z},l_0)$ or $\epsilon_{ij}(\hat{Z},l_0)$ of [3]. The working calibration is compared to the benchmark calibration with a reference impedance which has been adjusted at each frequency to best match that of the working calibration and a reference plane which has not been translated. This parameter is the same quantity labeled "impedance" obtained by pressing the **Fit 50** softkey.
offset	Worst case deviation after reference plane of benchmark calibration is adjusted to be as close as possible to reference plane of the working calibration. The plotted quantities are the $\epsilon(Z_0,\hat{l})$ or $\epsilon_{ij}(Z_0,\hat{l})$ of [3]. The working calibration is compared to the

	benchmark calibration with a reference impedance equal to the characteristic impedance of the lines in the benchmark calibration set and a reference plane which has been translated *at each frequency* to a position which best matches the estimated reference plane position of the working calibration.
imp+off	Worst case deviation after the reference impedance and reference plane of the benchmark calibration have been adjusted to be as close as possible to those of the working calibration. The plotted quantities are the $\epsilon(\hat{Z},\hat{l})$ or $\epsilon_{ij}(\hat{Z},\hat{l})$ of [3]. The working calibration is compared to the benchmark calibration with a reference impedance and a reference plane which have been translated *at each frequency* so as to best matches the estimated reference impedance and reference plane position of the working calibration.

R(imp)	Estimated real part of the reference impedance of the working calibration as a function of frequency.
L(imp)	The inductance associated with the estimated imaginary part of reference impedance of the working calibration as a function of frequency.
d(off)	The estimated position of the reference plane of the working calibration in microns with respect to that of the benchmark calibration as a function of frequency.
EXIT	Return to the main menu. All data is lost.

Viewing, Storing, or Plotting the Data

After selecting the data type by pressing one of the softkeys you will enter a second sub-menu. From this menu you can view, plot, or store the data with the following softkeys.

Softkey	Description
PLOT	The data will be plotted on the screen. After scaling and other manipulations, it can be plotted on a pen plotter or printed on your printer.
BDAT	The data will be saved in a BDAT file.
ASCII	The data will be saved in an ASCII file. This format is not recommended for transferring files between systems.
HP-UX	The data will be saved in an HP-UX ascii file. This format is recommended for transferring files between systems.
CRT	The data will be printed on the screen.
PRT	The data will be printed on the printer.
RETURN	Return to the previous menu.

File Formats

Input parameters must be in the BDAT format. The order of the parameters in the S-parameter file is:

Freq Re(S_{11}) Im(S_{11}) Re(S_{21}) Im(S_{21}) Re(S_{22}) Im(S_{22}) Re(S_{12}) Im(S_{12})

where the frequency is given in GHz. The order of the parameters in the effective dielectric constant file is:

Freq Re(eps eff) Im(eps eff)

where the frequency is given in GHz.

References

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

2. R. B. Marks and D. F. Williams, “Characteristic Impedance Determination using Propagation Constant Measurement,” *IEEE Microwave and Guided Wave Letters* 1, pp. 141-143, June 1991.

3. D. F. Williams, R. B. Marks, and A. Davidson, “Comparison of On-wafer Calibrations,” *38th ARFTG Conf. Dig.* (San Diego CA), Dec. 5-6, 1991.

4. D. F. Williams and R. B. Marks, “Calibrating On-Wafer Probes to the Probe Tips,” 40th ARFTG Conference Digest, pp. 136-143, Dec. 1992.

5. R. B. Marks and D. F. Williams, “Verification of Commercial Probe-Tip Calibrations,” 42nd ARFTG Conference Digest, pp. 37-44, Dec. 1993.

6. D. F. Williams and R. B. Marks, “Accurate Transmission Line Characterization,” *IEEE Microwave and Guided Wave Letters* 3, pp. 247-249, Aug. 1993.

7. R. B. Marks and D. F. Williams, "Accurate Experimental Characterization of Interconnects,” *IEEE Transactions on Components, Hybrids, and Manufacturing Technology* 15, pp. 601-602, Aug. 1992.

8. D. F. Williams and R. B. Marks, “On-Wafer Impedance Measurement on Lossy Substrates,” *IEEE Microwave and Guided Wave Letters* 4, pp. 175-176, June 1994.

9. D. F. Williams and R. B. Marks, “Progress toward on-wafer standards,” *36th ARFTG Conf. Dig.* (Monterey CA), Nov. 1990.

10. D. F. Williams and R. B. Marks, “Transmission line capacitance measurement,” *IEEE Microwave and Guided Wave Letters*, vol. 1, no. 9, pp. 243-245, September 1991.

User's Manual

Program CAP Rev. 1.31

This software 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 National Institute of Standards and Technology (NIST) calibration software outside of the United States of America must complete a foreign license agreement. 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 in the help command.

HOW TO GET HELP FROM NIST

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Microwave Metrology Group, Electromagnetic Fields Division, National Institute of Standards and Technology, 325 Broadway, Boulder Colorado, 80303.

Introduction

Program **CAP** determines the dc capacitance of on-wafer quasi-TEM transmission lines fabricated on lowloss substrates from measurements of lumped loads or from measurements of the dc resistance per unit length of the line. The dc capacitance of the lines is used in program MultiCal[1] to determine their characteristic impedance, and to reset the reference impedance of MultiCal's multiline Thru-Reflect-Line (TRL) calibration [1] with the method of [2]. Transmission lines printed on high loss substrates can be characterized by the methods described in [3], [4], and [5].

If the dc capacitance of your line is determined from the measurement of a lumped load the program requires as input the measured S-parameters of the load and the measured effective dielectric constant of your line. If the capacitance of your line is determined from the measured dc resistance per unit length of the line then only the measured effective dielectric constant of your line is required. The two solution algorithms are described in [6].

Program **CAP** 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 and with coaxial transmission lines.

Running CAP

Before running program **CAP** you must load the BASIC operating system. Once the BASIC operating system has been loaded, you can load program **CAP** by placing the program disk in the system drive and typing **LOAD "CAP"**. The program is executed by typing **RUN**. The menu shown in Figure 1 will then be displayed on the screen. The menu contains all of the information required to determine the dc capacitance of your lines. The menu may be refreshed by pressing the **SCREEN** softkey. The menu may be saved on disk or retrieved from disk by pressing the **MENU** softkey (shift **SCREEN** softkey).

The upper portion of the menu consists of a file list. Two files are shown. In the first row is the file with the measured S-parameters of your lumped load. In the second row is the file containing the effective dielectric constant of your line. In the third row is the file containing the weighting function for the capacitance data. Usually this is the relative standard deviation file produced by program **MultiCal**. If no file is specified, uniform weighting is used, as is the case upon loading and running the program.

The first column contains a description of the file. The second column contains the file names of each file. The third column lists the mass storage unit on which the file is or will reside and the fourth column gives the path name (HFS formatted disks only). The fifth column gives the file type, which can be either ASCII or BDAT.

The light bar on the file list may be moved either by pressing the arrow keys on the keyboard, rotating the knob on your keyboard, or moving your mouse. The file list is edited by selecting a file from the file list with the light bar and then pressing the softkeys. Use the **NAME** softkey to change the file name, the **LOC.** softkey to change mass storage unit, the **PATH** softkey to change the path name, and the **TYPE** softkey to change the file type. Pressing the **NAME** softkey will catalog the mass storage unit and then prompt you for the file name. Pressing the shift key and the **NAME** softkey will prompt you directly for the file name.

The capacitance of your line may be determined from a lumped load or the resistance of your line per unit length. The type of calculation is toggled by pressing the **MODE** softkey.

When the mode is toggled so that the capacitance of the line is to calculated from a lumped load, the dc resistance of the load is set by pressing the **SET R** softkey. The reference plane of the load measurement may be shifted along your line by pressing the **REF PLANE** softkey.

When the mode is toggled so that the capacitance of the line is calculated from the propagation constant and a dc measurement of the resistance per unit length of the line, the resistance of the line may be set by holding the shift key and pressing the **SET R** softkey. Pressing the **SET R** softkey loads the calculation sub menu. This menu allows the resistance per unit length of the line to be calculated from a set of measurements of the total resistance of the lines. The resistance may also be set directly by pressing the **SET R** softkey from within this sub menu.

To calculate the resistance per unit length of your line from within the sub menu, the individual measurements of line resistance must be entered into the list displayed on the screen. Lengths and resistances may be added by pressing the **ADD** softkey. Lengths and resistances may be modified by selecting the measurement with the light bar and pressing either the **L(I)** or the **R(I)** softkeys. The order of entry is immaterial.

Once the measurements have been entered into the menu, the resistance per unit length of the line may be found by pressing the **FIND R** softkey. A least squares fit to the data is performed to find the resistance per unit length of the probe heads. Incomplete data is subtracted from the list and ignored.

In either mode, the best estimate of the capacitance of your line is found by fitting a quadratic to the measured estimates of the capacitance and extrapolating the result to dc. The frequencies used in fit are listed on the screen as **Fmax** and **Fmin**. These frequencies can be modified by holding the shift key and pressing the **PRINT \F(fit)** softkey. As a general rule the best measurements are low frequency measurements. The calculation is performed by editing the menu as described above and pressing the **FIND C** softkey. The results may be printed by pressing the **PRINT** softkey.

Measurement of dc Parameters

The resistance of the lumped load and resistance per unit length of the line can be measured easily through the bias ports and wafer probe heads on your analyzer. To measure the resistance of a lumped load, first measure the resistance of the probe and section of line connected to the load. Then measure the resistance of the probe and section of line terminated by an offset short placed at approximately the same location as the load, as illustrated in Figure 2. The difference of these two measurements gives the desired result.

The series resistance of the line includes not only the resistance of the center conductor, but the resistance of the ground planes as well. There are several ways to measure this resistance. A simple and accurate method is to terminate one probe head with a short at its coaxial port and connect an ohm meter to the other bias port, as illustrated in Figure 3. In order to assure that the resistance of the ground planes are properly accounted for the ground of the shorted probe head must be isolated from the ground of the probe head to which the ohm meter is connected. Several lines of different lengths must be contacted and the measured resistances recorded. The resistance per unit length of the line can then be determined in the **SET R** sub menu.

File Formats

The ASCII format of the S-parameter file is as follows:

Freq Re(S_{11}) Im(S_{11}) Re(S_{21}) Im(S_{21}) Re(S_{12}) Im(S_{12}) Re(S_{22}) Im(S_{22})

where the frequency is given in GHz. This format is compatible with the Touchstone data format. The BDAT format of the S-parameter file is as follows:

Freq Re(S_{11}) Im(S_{11}) Re(S_{21}) Im(S_{21}) Re(S_{22}) Im(S_{22}) Re(S_{12}) Im(S_{12})

where the frequency is given in GHz. In both cases the S-parameter data must be in the real-imaginary format.

Both the ASCII and BDAT formats of the effective dielectric constants are as follows:

Freq Re(epsilon effective) Im(epsilon effective)

where the frequency is given in GHz. The ASCII and BDAT formats of the weighting function files are as follows:

Freq sigma X

where the frequency is given in GHz, sigma is the normalized standard deviation of the measurement, and X is not used.

References

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

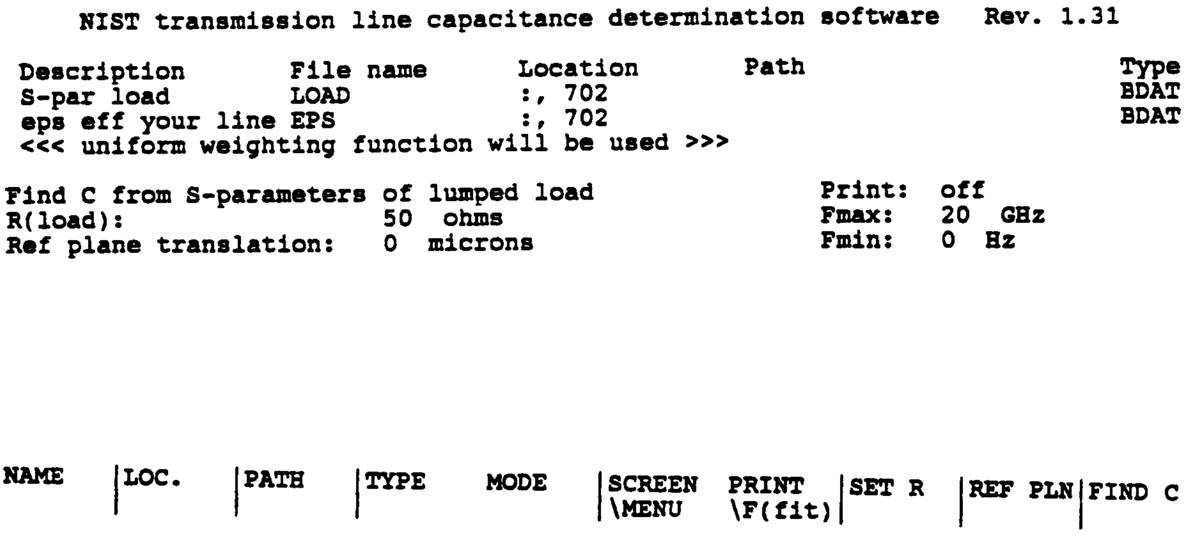
[2] R. B. Marks and D. F. Williams, “Characteristic Impedance Determination using Propagation Constant Measurement,” *IEEE Microwave and Guided Wave Letters* 1, pp. 141-143, June 1991.

[3] D. F. Williams and R. B. Marks, “Accurate Transmission Line Characterization,” *IEEE Microwave and Guided Wave Letters* 3, pp. 247-249, Aug. 1993.

[4] R. B. Marks and D. F. Williams, "Accurate Experimental Characterization of Interconnects,” *IEEE Transactions on Components, Hybrids, and Manufacturing Technology* 15, pp. 601-602, Aug. 1992.

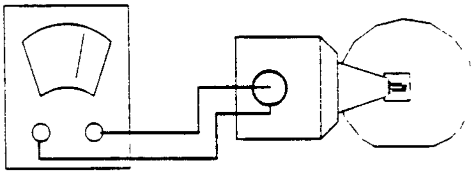
[5] D. F. Williams and R. B. Marks, “On-Wafer Impedance Measurement on Lossy Substrates,” *IEEE Microwave and Guided Wave Letters* 4, pp. 175-176, June 1994.

[6] D. F. Williams and R. B. Marks, "Transmission line capacitance measurement," IEEE Microwave and Guided Wave Letters, pp. 243-245, September 1991.

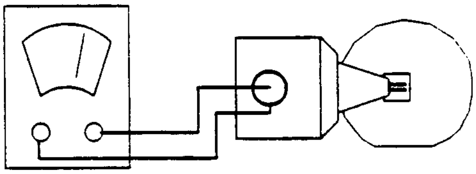


```
     NIST transmission line capacitance determination software   Rev. 1.31

  Description        File name      Location       Path                       Type
  S-par load         LOAD           :, 702                                    BDAT
  eps eff your line  EPS            :, 702                                    BDAT
  <<< uniform weighting function will be used >>>

 Find C from S-parameters of lumped load                 Print:  off
 R(load):                 50  ohms                       Fmax:   20  GHz
 Ref plane translation:   0   microns                    Fmin:   0   Hz




 NAME    |LOC.   |PATH   |TYPE    MODE   |SCREEN  PRINT  |SET R   |REF PLN|FIND C
         |       |       |               |\MENU   \F(fit)|        |       |
```

Figure 1. The **CAP** menu. The file list is edited by selecting the appropriate file with the light bar and using the softkeys.

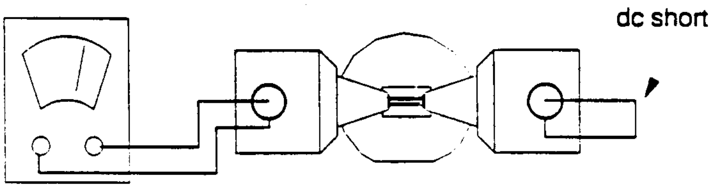


Measure resistance of probe heads and lumped load.

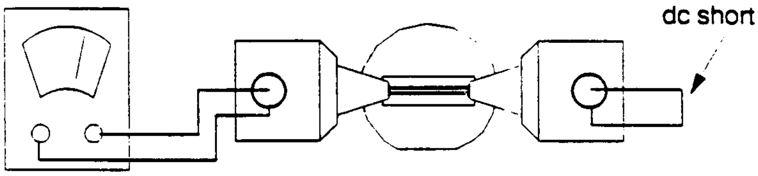


Measure resistance of probe heads and planar short.

Figure 2. The dc resistance of a lumped load can be measured accurately by measuring the resistance of a short placed near the position of the load and subtracting this result from the measured resistance of the load.



Measure resistance of probe heads and short line.



Measure resistance of probe heads and long line.

Figure 3. The dc resistance per unit length of the line can be measured accurately by shorting one of the probe heads and measuring the resistance of two lines through the bias port of the second probe head. The difference of the measured resistances is divided by the difference of the lengths of the lines to find the series resistance per unit length.