Characterization of Microstrip Three Port Devices

by

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Abstract

GOLDBERG, STEVEN B. Characterization of Microstrip Three Port Devices

A method of characterizing three port devices is presented. It utilizes data extracted from raw measurements of the two port device simulated when one of the three ports is terminated with a known load. From two sets of data with two different terminations, the full three port scattering parameters was calculated from a closed form algorithm. It makes no assumptions upon the device and takes into account the influences of reflections from untested ports. Enhanced Through Symmetric Line deembedding techniques was utilized in the derivation of the three port characterization. A study of the symmetry of the coaxial-to-microstrip transitions and of ETSL sensitivity to line lengths was done. A comparison of this method with Wood's renormalization method was done with a marked improvement in accuracy. Three microstrip tees were characterized.

A study on smoothing or windowing of data was also done and it was concluded that this data should not be used in any subsequent calculations.
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Chapter 1

Introduction

1.1 Motivation

Since the modern computer is based upon digital technology, the circuitry involved was designed with the assumption that only two signal states would exist and that they are almost instantaneously sent to whatever components need them. The only timing considerations accounted for were delays in the IC circuitry and the rate of the clock pulse. With the build up of information and the subsequent need to process it, clock speeds were sped up and delays in the IC's were decreased and even transmission line propagation time was regarded in the system timing diagrams. However, since the basic design was still predicated upon instantaneous distribution of signals to all nodes, the signal lines branched off to wherever the signal would be needed. These "tees" are not well characterized at high frequencies and with the speedier clock rates the signals are not going to their desired destinations when they need to arrive.

To aid the computer designer in his quest for the faster, more powerful computer, the RF and microwave engineer needs to better characterize the multitude of discontinuities that exist upon a computer data bus line, of which the tee or three port
device is one. This thesis attempts to present an accurate method of measurement of three port devices, and an algorithm to characterize these three ports from which better models may be derived to aid the designer.

1.2 Thesis Overview

This thesis examines two areas. A thorough analysis of deembedding procedures is done for the purpose of removing measurement errors so that the network parameters of itself is extracted. From this data, a procedure is developed to fully characterize a three port device with reasonable confidence in its validity.

Chapter two traces the development of calibration and deembedding methods from the graphical era before accurate error correcting measurement equipment was available, through the introduction of the automatic network analyzer and the subsequent numerical error correcting methods. The concepts of noninsertable calibration standards and two tier error removal are cited. Finally the application of symmetry to reduce the number measurements are presented.

Chapter three includes a derivation of the algorithm used to fully characterize three port devices. Previous work by other authors is presented and analyzed. An improvement upon an existing symmetric deembedding method is presented in chapter four and experimental verification of the material from chapters three and four is in chapter six. Also included is an analysis on smoothing or windowing of data.
The computer program SPANA, signal processing of automatic network analysis, is discussed in chapter 5 with semantics included in the appendices. Chapter 7 summarizes the document and its accomplishments and suggests areas for further study.

1.3 Original Contributions

The original contributions reported here include:

- A three port deembedding procedure with verification,

- A study on windowing or data smoothing.
Chapter 2

Review of Calibration Theory

2.1 Literature Review

Techniques of measurement have evolved along with the development of more complex circuits and systems. This was driven by the need for more accurate and trustworthy experimental data upon which these complicated designs could be based. Errors of corrupted data can propagate and be multiplied by the errors from subsequent circuits until the overall system performance would only barely resemble the designed parameters. Calibration is a method to eliminate or at least minimize these measurement errors.

2.1.1 One Port Calibration

Each step toward the development of measurement technique in RF and microwave circuits has been based upon the achievements of prior investigators. In the 1950's, Dechamps' graphical method was used to determine the error corrected input impedance of a one port [1]. The graphical approach was developed further by others [2], [3] until the development of automatic network analysis made multiple frequency testing more feasible and graphical methods more bulky. Hackborn [4] was among the
first to develop a calibration technique for automatic network analyzers (ANA).

2.1.2 Two Port Calibration

With the coming of automatic network analysers (ANAs), numerical methods came to replace graphs and the full measurement of two ports became the goal. Rediscovery of the usefulness of scattering parameters (S parameters) opened up the way for numerical manipulation [5]. Hackborn developed a two port method by taking two of his one port models and placing them on both ports [4]. Shurmer's model looked at a two port with only one path of leakage [6]. Rehnmark took the leakage concept of Shurmer and applied it to Hackborn's model [7]. Whereas Fitzpatrick added reverse leakage to Shurmer's model [8]. Figures 2.1.1, 2.1.2, 2.1.3, 2.1.4 show each of these models.

Each of these models and, hence, calibration techniques removed the system errors of the ANA by lumping their effects into these error models. The core of each calibration procedure was to enumerate all known and unknown variables. To solve for various error parameters, calibration standards are determined to allow easy calculation. These standards are usually shorts, opens, and matched terminations, which are easily constructed for coaxial systems. The end result is a well defined measurement system.

However, most microwave circuits are not coaxial in construction, therefore transitions between the ANA coaxial line and the circuit microstrip, stripline, finline,
Figure 2.1.1: Hackborn's two port error model, after [4].
Figure 2.1.2: Shurmer's two port error model, after [6].
Figure 2.1.3: Rehnmark's two port error model. He applied Shurmer's concept to Hackborn's model, after [7].
Shurmer’s model with leakage was presented by Fitzpatrick, after [8].
etc. transmission lines add more errors. This is called fixturing and the process of eliminating these errors is referred to as deembedding [9].

Each transition from connector to circuit can be modelled as a passive, non-magnetic two port. Therefore, two networks, one at each end of the circuit, need to be compensated. Direct modeling from physical structure is difficult due to the complicated geometries involved. Difficulties also arise if standards are sought so that the fixture errors may be eliminated. Such standards are difficult to construct and model. They are also difficult to insert. Therefore, distributed standards and other calibration methodologies were developed.

TSD Thru Short Delay

In 1975, Franzen and Speciale [10] introduced the use of a distributed standard, a delay, in calibration. By use of a zero length through and shorts at both ports, the error networks can be completely described. The advantage of this technique is the use of a short versus a matched load, which is very difficult to construct. An assumption made, however, is that the delay is lossless and perfectly matched to the system. Also, there is a limit to the phase difference between the through and delay. Singularities occur in the algorithm when the phase difference is near zero or 180 degrees. The technique is rendered invalid when this happens.
L-OS-L Line Offset short Line

Bianco et al [11] based their work upon Franzen and Speciale and in 1976 applied their basic theory to microstrip line. In microstrip, however, a precise through is impossible due to the transition discontinuities and a second line is used. They both must be reflectionless, but not necessarily lossless. The propagation constants can be calculated from the information from the standards.

TRL Thru Reflect Line

Engen and Hoer [12] reintroduced Bianco’s results in 1979. The line they used need not be lossless, but reflectionless. The reflection standard could be arbitrary, but had to be repeatable. Opens and shorts fit the bill well. However, the singularities due to zero or 180 degree phase differences between the through and delay still exists.

O-S-5L Open Short Five line

Benet [13], in 1982, took a novel approach. He calibrated a universal MMIC test fixture and ANA together by using assorted lines and a short and open all in one tier. The open and short are used to determine the fixture’s reference planes. Then at least three lines are used to find the characteristic impedance. Two additional lines allow a least squares fit. Benet used the 12 term ANA error model. He showed that insertable distributed standards could be used for test fixtures.
2.1.3 Two Tiers

Most test fixtures cannot use insertable standards. They are usually transitions from connectors to transmission lines such as in microstrip. Since these fixtures cannot be separated in order to insert standards, Vaitkus and Sheitlin in 1982 [14] proposed a two-tier method of deembedding. First, the ANA is calibrated using O-S-L, open-short-line, establishing reference planes at the ends of the ANA ports. Then using a simplified version of Rehnmark's model, developed a twelve term error model where each port has an error network with two leakage terms, as shown in figure 2.1.5. This was reduced to seven terms by assuming the forward and reverse leakage would be the same and that the fixture itself is passive. An open and a short were the standards and a model was used to describe the bond wire used for the through measurement. Vaitkus used prior knowledge of propagation constant, open circuit inductance, and short circuit capacitance of the through in the same way as this model when he introduced the O-S-T, open-short-thru, calibration procedure in 1986 [15].

Double thru lines

Bianco et al stated in their introductions of L-OS-L calibration that transition parameters could be determined to within a multiplicative constant with only two through standards. These throughs were actually lines. This constant could not be determined, since a third through would only create a linear combination of the
Figure 2.1.5: Model of two tiered calibration system. The ANA reference plane is at the ports of the fixture and the deembedded reference plane is at the device, after [23].
equations from the other two standards.

Pennock et al [16] used this multiplicative constant, in 1987, to characterize transitions between novel transmission media. They used a six-term two-port error model and showed that the multiplicative constant of Bianco was a ratio of two error terms and close to unity for most transitions. However, since distributed standards were used, the throughs were assumed reflectionless and the attenuation constants needed to be known. There was also the singularity problems at half wavelengths.

TTT Triple-thrus

In 1988, Meys [17] introduced a deembedding method that uses an extra two port called network C along with the two two port halves of the embedded fixture, labeled networks A and B. By measuring the combination of AB, BC, and CA; almost all the necessary information to determine the error networks of the fixture is provided. See figure 2.1.6. If network C is assumed reflectionless, a matched load is needed. Since true throughs are used, this method is very broad banded. But the flexibility to create these precise throughs is not inherent in microstrip fixtures.

TMR Thru-Match-Reflect

In 1988, Eul and Schiek showed that at least three two ports needed to be measured for complete characterization of the embedding networks [18]. They showed that twelve parameters can be measured, but that only eight are linearly independent. This redundancy meant that less information about the standards was necessary
Figure 2.1.6: Triple through deembedding. Use of an additional 2 port with the error two ports give enough combinations to characterize the error.
and was the basis for their introduction of TMR. The only standard that required prior knowledge was the matched load. The reflection standard could be arbitrary and a true through provides this calibration scheme broad band validity.

### 2.1.4 Symmetry

While one group of investigators were working on calibration methods to compensate for imperfect standards and ANA errors, another group was focusing on decreasing the number of standards or measurements without degrading the accuracy of the calibration. A method of achieving this was to exploit the symmetric characteristics of the embedding fixture if they existed.

**First Order Symmetry**

Souza and Talboys used a first order symmetric assumption when they were characterizing coaxial to microstrip transitions in 1982 [19]. A first order symmetric fixture is one where the fixture halves are identical but are asymmetric, figure 2.1.7. Therefore, if the first fixture is denoted with an “a” subscript and the second half with a “b” subscript, then \( S_{11a}=S_{22b}, \ S_{22a}=S_{11b}, \) and \( S_{21a}S_{12a}=S_{21b}S_{12b} \) for the fixture. Of course, in most applications where the fixture halves are passive and therefore reciprocal, \( S_{21}=S_{12} \) and so \( S^2_{21a}=S^2_{21b} \).

Souza and Talboys, in their analysis, also made the assumptions that there is only one discontinuity between the coaxial connector and the microstrip line and that
Figure 2.1.7: Two port error model for a first order symmetric fixture. Fixture error networks are described by three s-parameters; $S_{21}$, $S_{11}$, $S_{22}$, after [23].
the reflection of this discontinuity is small. For these assumptions to be true, the microstrip impedance must be the same as the reference characteristic impedance of the measurement system, usually 50Ω. They showed that effective deembedding can be done with symmetry assumptions and with only two standards, a through and a line, but that they must be lossless.

In the calibration of their universal test fixture (for transmission), Pollard and Lane in 1983 [20] indirectly used a first order symmetry assumption by modeling their fixture half with a pi equivalent circuit with different shunt capacitances, figure 2.1.8. Their technique uses open, short, and through standards to get a best fit to the measured data for the three pi parameters and then does a best fit to the measured data for higher frequencies. Of course, this method used approximations and optimization to characterize the error network and it fails if the embedding fixture cannot be modeled with lumped elements or the fixture is very long. Also, three insertable standards are necessary.

Ehlers, in 1986, first looked at symmetry in a finline fixture without any additional assumptions [21]. He used a through with either a matched load or a matched line with unknown transmission characteristics. The transmission characteristics could be calculated from the measured parameters of the line and through. Although two possible solutions exist, the one that satisfies the phase constraints of the physical set up is chosen. However, the method breaks down if the line is more than λ/4 long. Ehlers had shown, however, that if the standards are reflectionless,
Figure 2.1.8: Error fixture half modeled by pi network with different shunt capacitances. This is an example of first order symmetry, after [23].
a transmission parameter may be found and only two standards are necessary for symmetrical deembedding.

Second Order Symmetry

In 1987, Martin and Dukeman introduced second order symmetry as an approach for two port deembedding [22]. A second order fixture has identical and symmetric parameters, figure 2.1.9. That is, the reflection parameters for both ports in each fixture half is equal ($S_{iia} = S_{iib} = S_{11}$) and all transmission parameters are equal as well ($S_{ija} = S_{jiib} = S_{21}$). Martin and Dukeman used a single standard, a through, and used extensive matrix manipulation to get their results. However, by their method, the precision of the raw measurements may have significant effect to the accuracy of the end result in some cases.

TSF Thru Symmetric Fixture

In 1989, Kasten [23] applied the second order symmetric argument from a signal flow approach and avoided the matrix manipulation. From the signal flow diagram of the circuit, figure 2.1.10 and applying Mason's non-touching loop rule, algebraic relationships can be found for the error network parameters and with only a single through standard necessary. The only assumption used is the second order symmetry and it is very sensitive to any variation from it. A solution choice is needed for $\alpha$, attenuation constant, but the physical constraints from the electrical length of the through make this choice easy as it did for Ehlers. Also, as with Ehlers, there exists
Figure 2.1.9: Two port error network for a second order symmetric fixture. Fixture error is described with two s-parameters, $S_{11}$ and $S_{21}$, after [23].
Figure 2.1.10: Signal flow diagram of Thru-Symmetric-Fixture. TSF takes advantage of second order symmetry to limit the necessary standards to one, after [23].
a singularity problem when the fixture is \( \lambda/2 \) long. Kasten avoided the extensive calculations that Martin and Dukeman used as well as the assumption that the fixture is matched to the system, but retained the advantage of a single standard.

**ETRL Enhanced Thru Reflect Line**

Kasten et al had also looked at Engen and Hoer's TRL (Thru Reflect Line) technique and introduced ETRL (Enhanced Thru Reflect Line) in 1990 [24]. Engen and Hoer's method used a transmission line's known length and known characteristic impedance. However, they assumed that the characteristic impedance is a constant across the frequency band. Kasten et al calculates the frequency dependent characteristic impedance from the free space capacitance of the line and the propagation constant. Both may be calculated without any additional standards or measurements.

**TSL and ETSL (Enhanced) Thru Symmetric Line**

Kasten combined the results from these last two papers and developed in his Masters thesis [23] in 1989, the calibration methods of TSL (Thru Symmetric Line) and ETSL (Enhanced Thru Symmetric Line). By applying first order symmetry arguments to Engen and Hoer's TRL, he showed that the reflection standard can be eliminated. By assuming the arbitrary reflection to be a perfect open or short at the end of a fixture half and using the measured data from the through, the measured reflection coefficients at the fixture port can be synthesized, figure 2.1.11. With the additional
Figure 2.1.11: Signal flow diagram of TSL circuit used to synthesize the reflection coefficient with a short or open termination, after [23].
information from measuring the transmission line, the error network can be fully characterized.

TSL still has the same shortcoming as TRL in that it assumes that the characteristic impedance of the through and line to be frequency independent. Using the techniques in [24], he got an accurate deembedding method with only two standards.

2.2 Conclusion

We see that extensive study on calibration and deembedding has been done with a focus on two port measurement systems. This is quite natural, since characterization of networks have been defined by ratios of two measured quantities. Techniques were developed to both increase accuracy as well as decrease necessary standards.

It would be fair to say that we can now characterize a device’s behavior between two ports with a reasonable amount of confidence. In the next chapter, we shall apply these same techniques to a three port device.
Chapter 3

Three Port Characterization

3.1 Introduction

This chapter will examine characterization of three port networks using the same basic assumptions and approaches of two port deembedding. It also ties in the importance of two port results with the three port procedure.

3.2 Previous Approaches

3.2.1 Transistor model

Anderson, in 1967, applied a three port network characterization to a transistor [25]. The transistor was modeled with a simple emitter conductance and a current gain model, figure 3.2.1. His method was to evaluate the admittance parameters \([Y]\) and then normalize and transform them to scattering parameters \([S]\). His objective was to show how scattering parameters can be interpreted to describe the ideal circuit performance of the transistor including circulation. Anderson also pointed out that development of the three port \(s\) parameters from two port measurements would have error due to the physical size of the device in relation to the wavelength. His method, however, used a simplistic network model and neglects the effect of
Figure 3.2.1: Anderson's transistor model used in characterization with s parameters, after [25].
impedance mismatch at the unmeasured port.

3.2.2 Renormalization

Woods, in 1976, compiled many of his short papers [26], [27], [28], [29], [30], [31], to a single treatise expounding the merits of complex normalization of N port networks [5]. He recognized the effect of the remaining ports on the data measured from two tested ports. His was a method of multiple renormalizations that involved extremely intensive matrix arithmetic to come up with the s parameters of the N-port. He gives examples with three ports.

3.2.3 Super TSD

Special applied TSD techniques, renamed Super TSD, to N port measurements in 1977 and included a leakage term in the error model [32]. The new model for the error network treats one path from an input to a single output as a direct path and all others paths from other input ports to the same output as leakage. This technique works well for network analyzer calibration when leakages do occur from the error network, but it does not directly account for mismatches at the unused ports during a two-port measurement. There are also limits due to the TSD standards in that a reflectionless line is required as a standard.
3.2.4 Desegmentation

In 1981, Sharma and Gupta used desegmentation techniques to deembed multiports [33]. They also used a large error network connected to all the ports of the multiport. However, unlike Speciale, they recognized that the large error network can be treated as a number of independent networks to simplify the algorithm, figure 3.2.2. This assumes that the connections between the device and the error network are matched. Yet again, mismatches at the untested ports are not directly reckoned with.

Speciale along with Sharma and Gupta used examples that were two port devices to check agreement with existing procedures. Unfortunately, this does not necessarily show three port or higher situations would be very accurate.

3.2.5 Resonant and nonresonant measurement

Gruner in the same year, introduced resonant and nonresonant methods to measure parameters of multiports [34]. Though he derived his algorithm from definitions and properties of scattering parameter matrices, Gruner still assumed that transmission through any two ports is reciprocal, which is only true for passive nonmagnetic devices. Also, in a three port example, he found the phase of the transmission parameters indeterminant by $\pm \pi$. The measurement techniques involve the changing of the line lengths, which is not always feasible, as well as another assumption that there are negligible transitions in the input lines. This, of course, negates application to microstrip circuits where coaxial to microstrip transitions are significant.
Figure 3.2.2: Example of analyzing a circuit by the desegmentation method. \(\alpha\) is the device under test, \(\beta\) is embedding network, \(\gamma\) is the entire network made up of \(\alpha\) and \(\beta\), after [33].
Gruner had shown that closed form, linear equations could be found to characterize multiports with known terminations on the unused ports.

3.2.6 Incomplete characterization

Herscher, in developing a technique to calibrate power sensors, used a three port (a power splitter) and was aware of reflections from the terminated port [35]. Of course, he was interested in a scalar factor and did not try to develop the individual s parameters that characterized the power splitter.

We find many investigators take Herscher's approach [12] [36] [37] [38] [39] [40] [41] [42]. The multiport involved in their studies are characterized in scalar and complex calibration factors. These four and six port networks are part of a measurement system where most of the ports are permanently terminated by loads or detectors and can be simplified to smaller equivalent networks. These calibration factors are sufficient to compensate for errors in the highly specialized operation of these multiports in the measurement system, but do not fully characterize the network as well as an s parameter matrix.

We see that the majority of previous work has been on highly specialized uses of multiport devices and some do not fully characterize the network. In the next section, we shall present a method of measuring and calculating the scattering parameters of a non-descript three port device and thereby fully characterizing it.
3.3 Theory

Figure 3.3.1 is a simplistic representation of a three port device. Since only two port measurements are available, each of the ports must be terminated in a standard with known reflection coefficient for every combination of measurements. Figure 3.3.2 shows a full signal flowgraph for a three port. A partially terminated three port yields a relationship between the s parameters of the three port, $S_{ij}$, the measured two port s parameters, $S_{ij}^M$, and the reflections of the terminations $\Gamma_k$. Using Mason's non-touching loop theorem [43], the equation for the two port reflection s parameter at the $i^{th}$ node is:

$$m_k S_{ii}^M = S_{ii} + \frac{S_{kk} m \Gamma_k}{1 - S_{kk} m \Gamma_k}$$

(3.3.1)

or simplified

$$m_k S_{ii}^M = S_{ii} (1 - S_{kk} m \Gamma_k) + S_{ik} m \Gamma_k S_{ki} + S_{ii}^M S_{kk} m \Gamma_k$$

(3.3.2)

The measured two port transmission s parameter between nodes i and j can be found in the same way:

$$m_k S_{ij}^M = S_{ij} + \frac{S_{kj} m \Gamma_k S_{ik}}{1 - S_{kk} m \Gamma_k}$$

(3.3.3)

and simplified again

$$m_k S_{ij}^M = S_{ij} (1 - S_{kk} m \Gamma_k) + S_{kj} S_{ik} m \Gamma_k + S_{ij}^M m \Gamma_k S_{kk}$$

(3.3.4)
Figure 3.3.1: Simple model of a three port device
Figure 3.3.2: Signal flow graph of a three port device with port 3 terminated by reflection coefficient, $\Gamma$. 
In both equations, M indicates that the s parameter is a measured quantity, and m
and k are indices distinguishing different terminations \(^m\Gamma_k\) at port k. The equations
(3.3.2) and (3.3.4) describe 3 sets of two port S parameter measurements with i, j,
k = 1, 2, 3; i \neq j \neq k. This leads to 12 coupled nonlinear equations which have
multiple solutions. The equations can also be poorly conditioned as the measured
two port s parameters may only be determined to 1% accuracy. This is especially
so if the magnitude of one three port s parameter is much less than that of another
since then the small s parameters may be lost in the equation solution process. That
is, it may not be possible to determine s parameters that are small relative to other
s parameters.

In general, good accuracy is obtained when \(S_{ii}\) (\(S_{ij}\)) is evaluated solely in terms
of \(^m\Gamma_{ii}\) (\(^m\Gamma_{ij}\)) measurements as, usually, they are of the same order. This requires
that two different reflection standards be used at each port (so that m = 1,2) and
that two port s parameter measurements be taken for all two port combinations
(that is i, j, k = 1, 2, 3, i \neq j \neq k). This leads to 24 equations which can be solved
as a linear set of equations.

Multiplying the equation for \(^1S_{ii}^M\) ((3.3.2) with m = 1) by \(^2\Gamma_k\) and subtracting
this from the equation for \(^2S_{ii}^M\) ((3.3.2) with m = 2) multiplied by \(^1\Gamma_k\) gives

\[
\left( ^1\Gamma_k ^2S_{ii}^M - ^2\Gamma_k ^1S_{ii}^M \right) = S_{ii} \left( ^1\Gamma_k - ^2\Gamma_k \right) + S_{kk} ^1\Gamma_k ^2\Gamma_k \left( ^2S_{ii}^M - ^1S_{ii}^M \right) \quad (3.3.5)
\]

Similarly

\[
\left( ^1\Gamma_i ^2S_{kk}^M - ^2\Gamma_i ^1S_{kk}^M \right) = S_{kk} \left( ^1\Gamma_i - ^2\Gamma_i \right) + S_{ii} ^1\Gamma_i ^2\Gamma_i \left( ^2S_{kk}^M - ^1S_{kk}^M \right) \quad (3.3.6)
\]
Subtracting (3.3.5) times \((1\Gamma_i - 2\Gamma_i)\) from (3.3.6) times \(1\Gamma_k^2 \Gamma_k \left(2^k S'^M_{ii} - 1^k S'^M_{ii}\right)\) and rearranging yields the formula for \(S_{ii}\)

\[
S_{ii} = \frac{1\Gamma_i^2 \Gamma_i \left(2^k S'^M_{ii} - 1^k S'^M_{ii}\right) (1\Gamma_i - 2\Gamma_i) \left(\Gamma_k^2 \Gamma_k \left(2^k S'^M_{ii} - 1^k S'^M_{ii}\right) - (1\Gamma_i - 2\Gamma_i) (1\Gamma_k^2 \Gamma_k 2^k S'^M_{ii} - 1^k S'^M_{ii})\right)}{1\Gamma_i^2 \Gamma_i \left(2^k S'^M_{ii} - 1^k S'^M_{ii}\right) \Gamma_k^2 \Gamma_k \left(2^k S'^M_{ii} - 1^k S'^M_{ii}\right) - (1\Gamma_i - 2\Gamma_i) (1\Gamma_k^2 \Gamma_k \left(2^k S'^M_{ii} - 1^k S'^M_{ii}\right) - (1\Gamma_i - 2\Gamma_i) (1\Gamma_k^2 \Gamma_k 2^k S'^M_{ii} - 1^k S'^M_{ii})\right)}
\]

(3.3.7)

which as expected reduces to

\[
S_{ii} = 2^k S'^M_{ii}
\]

(3.3.8)

when \(2\Gamma_k = 0\). Equation (3.3.7) describes two \(S_{ii}\) solutions for each \(i\), as \(j\) can be substituted for \(k\).

The transmission parameters can be obtained following a similar approach. Combining the two equations obtained from (3.3.4) with \(m = 1\) and \(2\) and rearranging

\[
S_{ij} = \frac{(1\Gamma_k 2^k S'^M_{ij} - 1^k S'^M_{ij}) - S_{kk} 1\Gamma_k 2^k \Gamma_k \left(2^k S'^M_{ij} - 1^k S'^M_{ij}\right)}{1\Gamma_k - 2\Gamma_k}
\]

(3.3.9)

where \(S_{kk}\) is found from (3.3.7). Again, if \(2\Gamma_k = 0\), the \(s\) parameter is determined from a single measurement.

\[
S_{ij} = 2^k S'^M_{ij}
\]

(3.3.10)

The \(s\) parameters of a three port are found by multiple application of (3.3.7) and (3.3.9) for all combinations of \(i\), \(j\) and \(k\) such that \(i, j, k = 1, 2, 3\) and \(i \neq j \neq k\).
3.4 Conclusion

It has been shown that a closed form, linear expression can be used to find the s parameters of a three port. Using signal flow theory, no assumptions on the device's performance were made (i.e. reciprocal transmission characteristics) except that the network is linear. It is obvious, however, that the values for the reflection coefficients of the terminated ports are critical and the next chapter shall discuss the procedures used to acquire them as well as describe a procedure for accurate two port measurement extraction.
Chapter 4

Deembedding procedures

4.1 Introduction

Chapter 3 has shown that an expression of measured parameters and termination reflection coefficients can be used to determine each s parameter for characterizing any linear three port device. The measured parameters are easily available from existing measurement systems and existing deembedding techniques as outlined in chapter 2. The reflection coefficients, however, are less accessible since the direct measurement of the terminations do not account for the intervening fixture half present during three port measurements. Using procedures derived from existing techniques, the reflection coefficient seen by the extraneous port of the three port will be found in this chapter as well as an improvement on an existing method of two port deembedding will be presented.

4.2 De-termination

The goal of all the deembedding techniques described is to compensate for unwanted networks interspaced between the test ports of the measurement system and the input/output ports of the desired device. In order to do this, the intervening networks’
characteristics were determined and the resulting matrix used as a representative of the error network. Therefore, the removal, or the mathematical equivalent of removal, of the matrix, extracts the error network from our system.

In figure 4.2.1, we see the model of a three port device embedded in an error network with one port terminated. In figure 4.2.2, we see a model of a termination in the configuration for a measurement. Notice that both halves of the overall error network precede the actual termination. Comparison with figure 4.2.1, we see a partial deembedding is necessary on figure 4.2.2 to get the reflection coefficient as seen by the three port in fig 4.2.1 and, therefore, what is necessary for our algorithm. An accurate representation for the error network is obviously necessary.

4.2.1 ETSL

For microstrip applications, we see that the Enhanced Through Symmetric Line, ETSL,[23] suits our needs well. It can completely characterize the error matrix with the least number of standards and can be used to deembed the two port measurements of the three port device as well.

ETSL requires the characteristic impedance of the transmission line. This can be stated as a constant approximation over the frequency band or calculated from measured s parameters and the dimensions of the line. Type 4 DMB2 in SPANA, a computer program for computer aided microwave measurement (see chapter 5), calculates the complex characteristic impedance by finding the free space capaci-
Figure 4.2.1: Model of three port device embedded in independent error networks with one port terminated.
Figure 4.2.2: Model of measurement configuration of a termination.
the shunt conductance. These parameters correspond to those seen in the model of a transmission line in figure 4.2.3. At high frequencies \( G \) is much less than \( j\omega C \) and if we let \( R \) be equal to the DC resistance, \( C \) equal \( C_0 \), the free space capacitance, and \( L \) equal to \( L_o \), the free space inductance of the line, the expression becomes:

\[
Z_o^2 \mu_{eff} \epsilon_{eff} = \frac{R_{dc} + j\omega L_o}{j\omega C_0} \quad (4.2.5)
\]

It has previously been shown [3] that the free space characteristic impedance is:

\[
Z_o = \frac{1}{C_0 c} \quad (4.2.6)
\]

where \( c \) is the speed of light in a vacuum. Since free space is a lossless transmission line, the characteristic impedance may also be shown to be:

\[
Z_o = \sqrt{\frac{L_o}{C_0}} \quad (4.2.7)
\]

Substitution of (4.2.6) into (4.2.7) yields

\[
\frac{1}{C_0 c} = \sqrt{\frac{L_o}{C_0}} \quad (4.2.8)
\]

Rearranging, we have the free space inductance in terms of the free space capacitance.

\[
L_o = \frac{1}{C_0 c^2} \quad (4.2.9)
\]

or

\[
C_0 = \frac{1}{L_o c^2} \quad (4.2.10)
\]

Substituting (4.2.10) into (4.2.6) and setting \( \epsilon_{eff} = 1 \) in (4.2.5):

\[
L_o^2 c^2 \mu_{eff} = \frac{R_{dc} + j\omega L_o}{j\omega \frac{1}{L_o c^2}} \quad (4.2.11)
\]
Figure 4.2.3: Circuit schematic of a transmission line with per length parameters G, conductance, C, capacitance, R, resistance, and L, inductance.
Rearranging, we get an expression for $\mu_{eff}$:

$$\mu_{eff} = \frac{R_{dc} + j\omega L_o}{j\omega L_o}$$  \hspace{1cm} (4.2.12)

Now, with $\mu_{eff}$ and $\omega$ known and $\gamma$ measured, $\varepsilon_{eff}$ can be calculated from (4.2.3).

Then the characteristic impedance can be calculated from the left hand portion of (4.2.4).

$R_{dc}$ can be calculated from the dimensions and conductivity of the transmission line material or can be measured directly. $C_o$ can also be calculated from the dimensions using either full wave or effective area methods and $L_o$ can be found from $C_o$ using (4.2.9).

4.3 Procedure

The technique required for the removal of the necessary unwanted networks for our three port network characterization, entails a number of steps that must be carefully executed. Care must be made when measurements are taken. The connectors must be cleaned with swab and alcohol, all connections should be tightened to specification (8 in-lbs torque for SMA and 12 in-lbs for APC-7 mm), and the cables should not be bent with a radius less than 5 inches [44]. Following these warnings should insure good, repeatable results within the specification of the network analyzers.

Using the aforementioned cautions, the ANA was calibrated to the first tier. The reference plane should be well defined, therefore, sexless connectors are recommended. After calibration, raw data should be taken for a through standard, a line
standard, and both terminations. See figure 4.3.1. Also, all combinations between the three ports with each port terminated with both loads, see figure 4.3.2.

4.3.1 Standards

The choice for the through should have an electrical length long enough to cover the length of the error network 4.3.3. However, it should not be so long that the embedded three port measurement has a shorter electrical length.

The line standard must, of course, be longer than the through. In fact, it needs to be long enough to maintain resolution at low test frequencies. It also cannot be so long that multiple resonances mask the results. The best choice of length would be one that is larger than the through by the free space wavelength of the center frequency of the test bandwidth. This would give the most accurate characteristic impedance of a transmission line with those particular dimensions on that substrate.

Two port deembedding

Using the equations derived in section 4.2.1, calculate \( Z_c \). With this characteristic impedance and the symmetry arguments, the embedding error matrix can be found using ETSL.
Figure 4.3.1: Standards necessary for 3 port deembedding and characterization. a) Two fixture halves are to be determined. b) A through connection, c) a transmission line connection, and d) both 50Ω and short terminations are measured.
Figure 4.3.2: Configurations for full measurement of a three port device. Measurement of port 1-2 a), port 1-3 b), and port 2-3 c) combinations.
Figure 4.3.3: Model of through standard, after [23].
Terminations

Using the set up in figure 4.2.2, the raw data of the terminations may be represented by the product of cascaded matrices as follows:

\[ [\text{Load}_{\text{raw}}] = [\text{Error}_1] [\text{Error}_2] [\text{Load}] \]  \hspace{1cm} (4.3.1)

Since we are using symmetry arguments, \([\text{Error}_2] = [\text{Error}_1^{\text{flipped}}]\). Flipped is defined as where the parameters are related as follows:

\[ ^2P_{ij} = ^1P_{ji} \]

\[ ^2P_{11} = ^1P_{22} \]

\[ ^2P_{22} = ^1P_{11} \]  \hspace{1cm} (4.3.2)

for \(i,j=1,2\). Therefore, (4.3.1) can be rewritten as:

\[ [\text{Load}_{\text{raw}}] = [\text{Error}_1] [\text{Error}_1^{\text{flipped}}] [\text{Load}] \]  \hspace{1cm} (4.3.3)

The unused port of the three port device we wish to characterize would only see the second half of the error network and so the raw data needs to be multiplied by the inverse of \([\text{Error}_1]\). The resulting decascaded outcome is:

\[ [\text{Load}_{\text{3port}}] = [\text{Error}_1]^{-1} [\text{Error}_1] [\text{Error}_1^{\text{flipped}}] [\text{Load}] \]  \hspace{1cm} (4.3.4)

or

\[ [\text{Load}_{\text{3port}}] = [\text{Error}_1^{\text{flipped}}] [\text{Load}] \]  \hspace{1cm} (4.3.5)
4.4 Conclusion

We now have all the data necessary to characterize our three port using the equations of chapter 3. We have shown how two port deembedding techniques can be used to remove the fixture errors of our raw data and we have improved upon existing methods of finding the characteristic impedance of a transmission line using open space inductance. The following chapter is a brief description of a computer program that can do these calculations.
Chapter 5

SPANA: Computer Program for Computer Aided Microwave Measurement

5.1 Introduction to SPANA

Computer processing of microwave measurements is necessary to free the engineer from costly measurement time. It is very reasonable to assume that computer processing is needed since a single two port measurement can produce sixty four kilobytes (64K) of data. SPANA (Signal Processing for Automatic Network Analysis) has been developed to meet the needs of automatic microwave measuring systems.

SPANA is a tool to be used for processing measured S-parameter data and its prime use is to implement de-embedding algorithms. SPANA also performs various tasks such as input/output of data, data format conversions, and others. Written in FORTRAN in a modular fashion, SPANA is conducive to future expansion.

In SPANA, operations are carried out by using a command language. These commands allow the user to interact with the data freely. One of the most important assets of SPANA is that a series of commands can be sequentially read from a command file — a macro. SPANA is adaptable to outside programmers since it maintains all data I/O and frees the programmer to concentrate on the processing
of data.

5.2 Structure

SPANA has two program levels and each level has the capability to inform the user if a syntax error occurs. At the top is the command interpreter and its task is to determine which command is to be executed. The next layer is the actual command function which may in turn nest several sub-layers to complete the function. When a command is completed, control is returned back to the command interpreter for subsequent command processing. It is important to note that SPANA is not a menu driven program but rather a command interpreter. Commands available in SPANA are given in the next section.

5.3 Tools available in SPANA

To use SPANA, data is input to the program by “GETting” a measurement set. After this it is available for processing by executing other commands. Finally, the results of data manipulation can be “PUT” to a file. For example, calibration using TSF requires a measurement for the through standard and the embedded device. Two “GETs” and a call to DMB2 (with appropriate TYPE) will calculate the error networks and the de-embedded device. “PUTting” these results will save them for later use. Below is a list of the functions and a brief description of their purpose. The reader is directed to Appendix B for a complete discussion of the semantics of
Rearranging, we get an expression for $\mu_{eff}$:

$$\mu_{eff} = \frac{R_{dc} + j\omega L_o}{j\omega L_o}$$  \hspace{1cm} (4.2.12)

Now, with $\mu_{eff}$ and $\omega$ known and $\gamma$ measured, $\varepsilon_{eff}$ can be calculated from (4.2.3). Then the characteristic impedance can be calculated from the left hand portion of (4.2.4).

$R_{dc}$ can be calculated from the dimensions and conductivity of the transmission line material or can be measured directly. $C_o$ can also be calculated from the dimensions using either full wave or effective area methods and $L_o$ can be found from $C_o$ using (4.2.9).

### 4.3 Procedure

The technique required for the removal of the necessary unwanted networks for our three port network characterization, entails a number of steps that must be carefully executed. Care must be made when measurements are taken. The connectors must be cleaned with swab and alcohol, all connections should be tightened to specification (8 in-lbs torque for SMA and 12 in-lbs for APC-7 mm), and the cables should not be bent with a radius less than 5 inches [44]. Following these warnings should insure good, repeatable results within the specification of the network analyzers.

Using the aforementioned cautions, the ANA was calibrated to the first tier. The reference plane should be well defined, therefore, sexless connectors are recommended. After calibration, raw data should be taken for a through standard, a line
each command and Appendix C where the "SHELL" command is example for the potential programmer.
<table>
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<td>Function</td>
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<td>ERRor thru</td>
<td>Creates thru data for TSF</td>
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<td>WOOD3</td>
<td>Uses Wood’s method to de-embed 3 port</td>
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</tbody>
</table>

### 5.4 Conclusion

This chapter introduces SPANA with its purpose to aid microwave measurements. The ability to execute command macros is essential to extensive measurement calculations and SPANA can be modified by adding command to the interpreter and writing the appropriate sub-layers.
Chapter 6

Results and Discussions

6.1 Introduction

In this chapter, the three-port characterization techniques are applied to microstrip tee structures. A verification of the characteristic impedance of the line from ETSL with free space inductance is done and an examination of its limits is performed. An examination of smoothing is also done with respect to transmission line deembedding. Two port deembedding of three port data is executed using the ETSL algorithm and the decascading of the terminations is performed using the ETSL calculated error network. A comparison with Wood's renormalization technique is also examined. A number of microstrip tee structures are characterized and presented.

The measurement system used is a Hewlett-Packard 8510A Automatic Network Analyzer, figure 6.1.1. The data is transferred to a MICROVAX II where the calculations are executed using SPANA (see chapter 5). The system was calibrated to the ports of the ANA with the O-S-L calibration procedure, as required in any two tier procedure. Since precise definition of the reference plane is required, the sexless APC-7 mm connector was used.
Figure 6.1.1: S parameter measurement setup. The HP 8510 measures the device's parameters under control of the controller, then the data is transmitted to the MicroVax for further processing, after [23].
6.2 Characteristic Impedance

6.2.1 Introduction

The following sections shall show the steps and results of the utilization of free space inductance and capacitance in the determination of the characteristic impedance of a transmission line. Comparison of results with and without $L_o$ is shown and effects of different lengths between through and line standards are presented.

6.2.2 Measurement and circuit description

As cautioned in chapter 4, care in cleanliness and tightness of the connectors was maintained throughout the measurement process.

Figure (6.2.1) represents the microstrip transmission line standard used. The designed characteristic impedance of the line is 50Ω. The dimensions are width (w) = 8 mils (0.2032 mm), height (h) = 5.6 mils (0.1422 mm), metal thickness (t) = 3.6 mils (0.09144 mm), and the conformal coat dielectric layer is approximately 4 mils (0.1016 mm) thick. Figure (6.2.2) shows the cross sectional detail of the circuit. These dimensions were used because PCB manufacturing resources required them. The through standard is 1000 mils (2.54 cm) which is long enough to contain the error network but short enough not to interfere in any of the test circuits. The line standard was chosen to be 3000 mils (7.62 cm) long for an electrical length difference from the through standard of 2000 mils (5.08 cm) which is the wavelength of the
Figure 6.2.1: Transmission line standard. The deembedded reference plane is found from the through standard, after [23].
Figure 6.2.2: Detail cross section of embedded microstrip, after [23].
midpoint of the frequency band, 5977 GHz. The measurements were made every
118 MHz from 45 MHz to 12 GHz for 103 points.

6.2.3 Symmetry

Full two port scattering parameters were taken from both the through and line
standards. The phase and magnitudes are shown in figures 6.2.3, 6.2.4, 6.2.5, 6.2.6.

Notice that in both the through and line cases, the networks are not quite
symmetric with differences at resonant frequencies. These differences may be due
to the quality of the solder connections, the amount of solder used, or variances in
the right angle of the microstrip-coaxial transition.

Figures 6.2.7 and 6.2.8 show the real and imaginary impedance of the transmis-
sion line with the slightly assymmetric standards and figures (6.2.9) and (6.2.10)
are the real and imaginary impedance when the standards are “symmetricized.”
That is, the reflection parameters and the transmission parameters are averaged and
used as both the forward and reverse data. The procedure used was the algorithm
without free space inductance.

Notice the impedance with symmetric standards is slightly smoother than with
asymmetric standards. At high frequencies, it is a little flatter. The impedance drops
at low frequencies because resolution at those frequencies is decreasing. A more
obvious contrast is evident when the impedance data is utilized in a deembedding
procedure.
Figure 6.2.3: Embedded transmission line with length 3000 mils s parameters. Magnitude of (○) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.2.4: Cont. Embedded transmission line with length 3000 mils s parameters. Angle of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.2.5: Embedded through line with length 1000 mils s parameters. Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.2.6: Cont. Embedded through line with length 1000 mils s parameters. Angle of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.2.7: Characteristic impedance real part of a 3000 mil transmission line using asymmetric standards.
Figure 6.2.8: Cont. characteristic impedance imaginary part of a 3000 mil transmission line using asymmetric standards.
Figure 6.2.9: Characteristic impedance real part of a 3000 mil transmission line using symmetric standards.
Figure 6.2.10: Cont. characteristic impedance imaginary part of a 3000 mil transmission line using symmetric standards.
Still using the unimproved version of ETSL, the through standard was deembedded using symmetric and assymmetric standards. Note that the raw through data for the symmetric case was also symmetricized. Figures (6.2.11 and 6.2.12) show the results of the assymmetric and the symmetric cases, respectively. In figure 6.2.11 we see that $S_{11} \neq S_{22}$ and many singularities exist. Also we see that $S_{21}, S_{12}$ have values that exceed 1.0 which indicates a gain condition compared to the standard. However, this is the standard. Figure (6.2.12) is more indicative of our initial assumptions, this is a through standard and is symmetrical. We see that $S_{11} = S_{22}$ and $S_{21} = S_{12}$ and that they are perfectly flat across the frequency band with the ideal values of 1.0 for transmission parameters and 0.0 for reflection parameters. Figure 6.2.13 shows the unsymmetricized through deembedded with symmetric standards. This is an indication of the difference between the symmetricized and raw data and perhaps even a measure of the error from our symmetric assumption.

6.2.4 Different lengths

It has been stated in chapter 4 section 4.3.1 that the optimum electrical length difference ($\Delta l$) is the wavelength of the center frequency of the test band. This requires that $\Delta l$ be long enough to include the fixture errors with a transmission line buffer and short enough to not interfere with the desired circuit response. Figures (6.2.14, 6.2.15, 6.2.16, 6.2.17, 6.2.18) show the measured real part of the charac-
Figure 6.2.11: Deembedded asymmetric microstrip through standard S parameters with asymmetric standards. Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.2.12: Deembedded symmetric microstrip through standard s parameters with symmetric standards. Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.2.13: Deembedded asymmetric microstrip through standard s parameters with symmetric standards. Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.2.14: Real part of characteristic impedance of 268 mil transmission line.
Figure 6.2.15: Real part of characteristic impedance of 348 mil transmission line.
Figure 6.2.16: Real part of characteristic impedance of 536 mil transmission line.
Figure 6.2.17: Real part of characteristic impedance of 696 mil transmission line.
Figure 6.2.18: Real part of characteristic impedance of 10000 mil transmission line.
teristic impedance for Δl's of, respectively, 268 mils, 348 mils, 536 mils, 696 mils, and 10,000 mils. We see at the shorter lines, figure 6.2.14, that the impedance does not behave anywhere near as expected. This can be attributed to the lack of resolution for much of the frequency band. Also, the impedance of a transmission line at that short a length would not dominate the effects of any asymmetry that exists at the coaxial-microstrip transitions. That is, if the transitions are modeled as discontinuity capacitances of different value at each port, the impedance mismatches from this imbalance would dominate the overall response of the network only if the transmission line was so short that its contribution to the mismatch was minimal. Figure 6.2.15 is somewhat flat and indicates that the asymmetric impedance and the line impedance is almost balanced. The dip at the end of the band is probably from a bad root choice in the algorithm.

If we examine figures 6.2.16 and 6.2.17 just up to 5 GHz, we can see what begins to be the shape of the curve in the corresponding frequency range in figure 6.2.9. At these lengths, the impedance is beginning to dominate the system. Finally, Zc in figure 6.2.18 obtained with a very long Δl is erratic. The spikes are probably due to root choices in the algorithm which is confused by frequency steps that are too wide for the response. Also the assumption that the transmission line is uniform along its entire length may be false. Variances in the dielectric constant in the board as well as manufacturing tolerances for long lengths contribute to a uniformity that cannot be guaranteed.
It appears that our length choice of $\Delta l = 2000$ mils is a compromise in resolution, line impedance domination, and minimization of uniformity variance. It also is conveniently the wavelength of the center frequency of our test band.

### 6.2.5 Addition of free space inductance

With the establishment of line lengths and the use of symmetricized standards, the addition of free space inductance, $L_o$, was implemented in the calculation of the characteristic impedance as described in chapter 4. The free space capacitance was found to be $37.21 \text{ pF/m}$ using a full wave three dimensional calculation method from another computer program using Greenfield's method [45]. We avoided using the Bahl-Stuckly method [46] in SPANA because it involves approximation. The DC resistance was calculated to be $1.37 \text{ } \Omega /\text{m}$ where the conductor is copper and the designed dimensions in figure 6.2.2 were used. Figures 6.2.19 and 6.2.20 show the resulting real and imaginary characteristic impedance of the transmission line. Notice that the data of the real part is very much smoother and flatter than our previous results as well as the stable value of the magnitude is very close to $50\Omega$, the designed value. The ripples in both figures 6.2.19 and 6.2.20 are due to $180$ degree phase points that plague TRL methods. It is at these points that the phase becomes indeterminant and root choices in the algorithm becomes difficult. Note that the $\Delta l$ of the line is $5 \text{ cm}$ which is an integer multiple of a half wavelength at the following frequencies: $1.5, 3, 4.5, 6$, and $7 \text{ GHz}$; all frequencies where a ripple
Figure 6.2.19: Real part of characteristic impedance of a 3000 mil transmission line with free space inductance included.
Figure 6.2.20: Cont. imaginary part of characteristic impedance of a 3000 mil transmission line with free space inductance included.
occurs. The higher harmonics are probably attenuated by the loss and dispersion of the line. However, in both real and imaginary cases, the variance is only about 0.2 ohms, only 0.4% of the nominal value.

The magnitude of the imaginary part has significance. The nominal value of \( \approx 0.7\Omega \) or about 1.5% accounts for the loss in the through measurement and avoids the common and frustrating result of device transmission parameters being measured greater than unity. The peak at about 4000 MHz is just a single point anomaly.

6.3 Two Port Deembedding

6.3.1 Measurement and circuit description

With the characteristic impedance including the free space inductance calculated, ETSL two port deembedding was done on a series of simple transmission lines. The lines had \( \Delta l \)'s of 268, 348, 536, and 10,000 mils the same as was used in the characteristic impedance study in the last section. Figures 6.3.1, 6.3.2, 6.3.3, and 6.3.4 show the data of the deembedded lines while figures 6.3.6, 6.3.7, 6.3.8, and 6.3.9 show the raw data. Figure 6.3.5 is the deembedded version of the 2000 mil transmission line used in section 6.2.3. We see that only in figure 6.3.5 does the result resemble a theoretical ideal. Since the characteristic impedance that was used was calculated from the transmission line in figure 6.3.5, this was not a surprise. However, in figures 6.3.10, 6.3.11, and 6.3.12 where the algorithm used the characteristic impedances calculated for each individual line as shown in the last
Figure 6.3.1: Deembedded 268 mil transmission line s parameters. Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$.
Figure 6.3.2: Deembedded 348 mil transmission line’s parameters. Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.3.3: Deembedded 536 mil transmission line s parameters. Magnitude of (□) $S_{11}$, (Δ) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.3.4: Deembedded 10000 mil transmission line S parameters. Magnitude of (□) \(S_{11}\), (△) \(S_{21}\), (+) \(S_{12}\), and (×) \(S_{22}\).
Figure 6.3.5: Deembedded 2000 mil transmission line s parameters. Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.3.6: Embedded 268 mil transmission line s parameters. Magnitude of (□) \( S_{11} \), (△) \( S_{21} \), (+) \( S_{12} \), and (×) \( S_{22} \).
Figure 6.3.7: Embedded 348 mil transmission line s parameters. Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.3.8: Embedded 536 mil transmission line's parameters. Magnitude of (□) $S_{11}$, (Δ) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.3.9: Embedded 10000 mil transmission line s parameters. Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (∗) $S_{22}$. 
Figure 6.3.10: Deembedded 348 mil transmission line's parameters with itself as the line standard. Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.3.11: Deembedded 536 mil transmission line s parameters with itself as the line standard. Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 


Figure 6.3.12: Deembedded 10000 mil transmission line s parameters with itself as the line standard. Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
section, we observe in all the figures that the reflection is very high at low frequency. This may be attributed to the lack of resolution of the $\Delta l$ length at those frequencies. Figure 6.3.12 is highly distorted due to the same reasons its characteristic impedance data is deformed. A long transmission line is not uniform because of manufacturing tolerancing and dielectric variances.

It is interesting to note that, except in figure 6.3.12, the nulls in the reflection parameters all occur at integer multiples of a half wavelength. In figure 6.3.10 one occurs at about 8.5 GHz, where the length is a full wavelength and in figure 6.3.11, two occur at approximately 5.5 GHz and 11.03 GHz, where the length is a full wavelength and a half wavelength, respectively.

It appears that the most accurate way to deembed two ports is by using the calculated impedance of the embedded device itself. This is due to the variance of the characteristic impedance, circuit to circuit. This is caused, once again, by tolerances and dielectric inhomogeneity with additional factors from the dissimilarity of the coaxial-to-microstrip transitions. This, of course, fits into the continual metrological anxiety about the quality of standards.

6.3.2 Smoothing

We see that in the plots of characteristic impedance, deembedded data, and error fixture halves, the results all have discontinuities. A common practise for presenters is to smooth or window their results. This makes for pretty pictures and removes
unexplainable glitches and minor resonances. Their points may be made, but the question of how much smoothing should be done without distorting the outcome must be examined.

First, the definition of smoothing or windowing is the running averaging of data within a specified independent variable range. See figure 6.3.13. However, since we are dealing with complex numbers, we have a choice of what to average, real and imaginary parts or magnitudes and angles. To decide which option would be correct, examine figures 6.3.14 and 6.3.15. Each figure shows the effect of the increasing averaging in each case. The variances in the original data are usually due to minor resonances around some point as represented by the circle in figure 6.3.16. In figure 6.3.15, it is obvious that that method will result in the center. (Manufacturers of ANA's use the same concept when using a sliding load during O-S-L calibration [44].)

From these figures, it is obvious that the number of points used in the averaging window can greatly affect the outcome. If too many points are used, information outside the resonant circle can skew the average and effectively mask or alias the desired result. To avoid this predicament, it should be recognized that each resonant circle represents a half wavelength. Therefore, the maximum limit of points in a window should cover no more than an octave. The optimum number would be such that it would only cover the circle itself. Unfortunately, the number of points in a circle is dependent on its bandwidth or Q. This may vary depending on the cause
Figure 6.3.13: Definition of smoothing. A running average of the data within the window as it moves across the band.
Figure 6.3.14: Averaging of complex data by real and imaginary parts. Notice the result gets closer to the center of the circle.
Figure 6.3.15: Averaging of complex data by magnitude and angle parts. Notice the result is offset from the center of the circle.
Figure 6.3.16: Circles along a plot on a Smith chart represent minor resonances which give variances in measured data.
of the minor resonance. Trial and error seems to be the only method to find this optimum number. Figures 6.3.17, 6.3.18, 6.3.19 and 6.3.20, 6.3.21, 6.3.22 show the effect of different window ranges on characteristic impedance and magnitude of $S_{21}$ of a 2 inch transmission line, respectively.

Besides having an ascetic quality, can smoothed data also be utilized for continued calculations? Figure 6.3.23 shows a simplified flow diagram of the procedure for two port deembedding. If smoothed data can be used, we shall show the likely spots that it may be allowed to enter into the calculation. Raw data should not be smoothed because it may indicate any true variation due to the actual physical circuit. $Z_c$ may be smoothed since impedance is expected to be continuous. The error matrix, also, may be smoothed for the same reason and because it is passive. These are all very subjective justifications and based on intuition.

These hypotheses were tested using various window ranges (odd numbered only, because SPANA's algorithm requires it). Figures 6.3.24, 6.3.25, and 6.3.26 show the deembedded results of a 2000 mil transmission line as the window decreased in the smoothing of the characteristic impedance. It is obvious that smoothing the characteristic impedance has little effect on the deembedding process. Figures 6.3.27, 6.3.28, and 6.3.29 show the deembedded results of the same line, but with the intervening error fixture half smoothed. Notice that as the window decreases from 7 points (826 MHz bandwidth), the curve gets more continuous until the limit of a single point window gives the best result. In other word, the raw data of the
Figure 6.3.17: Smoothed (7 points) real part of characteristic impedance of a 3000 mil transmission line.
Figure 6.3.18: Smoothed (5 points) real part of characteristic impedance of a 3000 mil transmission line.
Figure 6.3.19: Smoothed (3 points) real part of characteristic impedance of a 3000 mil transmission line.
Figure 6.3.20: Smoothed (7 points) magnitude of transmission a parameter ($S_{21}$) of a 3000 mil transmission line.
Figure 6.3.21: Smoothed (5 points) magnitude of transmission $s$ parameter ($S_{21}$) of a 3000 mil transmission line.
Figure 6.3.22: Smoothed (3 points) magnitude of transmission s parameter ($S_{21}$) of a 3000 mil transmission line.
Figure 6.3.23: Simple flowchart of the sequence for ETSL deembedding
Figure 6.3.24: Deembedded 2000 mil transmission line s parameters with characteristic impedance smoothed (7 points). Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.3.25: Deembedded 2000 mil transmission line s parameters with characteristic impedance smoothed (5 points). Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.3.26: Deembedded 2000 mil transmission line s parameters with characteristic impedance smoothed (3 points). Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.3.27: Deembedded s parameters of 2000 mil transmission line when the embedding error fixture half is smoothed (7 points). Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.3.28: Deembedded parameters of 2000 mil transmission line when the embedding error fixture half is smoothed (5 points). Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.3.29: Deembedded s parameters of 2000 mil transmission line when the embedding error fixture half is smoothed (3 points). Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
error fixture half is the best data for deembedding.

6.4 Three Port Characterization

6.4.1 Measurement and circuit description

A microstrip tee in the configuration in figure 6.4.1 was measured two ports at a time with the unused port terminated in either 50Ω or a short. The data is in figures 6.4.2, 6.4.3, 6.4.4, 6.4.5, 6.4.6, and 6.4.7. This data was deembedded with ETSL and the raw $Z_c$ as described above. The results are in figures 6.4.9, 6.4.8, 6.4.11, 6.4.10, 6.4.13, and 6.4.12. Note that $S_{11}$ and $S_{22}$ is the same as is $S_{13} = S_{21}$; $S_{23} = S_{32}$. This is expected since the tee is passive. Also $S_{13}(S_{31}) \approx S_{33}(S_{32})$, which shows that the tee is balanced.

6.4.2 Terminations

With the error fixture half matrix properly calculated using ETSL and the aforementioned standards and heeding all cautions, the decascading of the termination measurements can easily be done. Recall that the three port device only sees half of the total intervening error network at the unused port during measurement. However, the full error is present when the termination is tested. See figure 6.4.14.

Figures 6.4.15 and 6.4.16 show the raw data of a 50Ω load and a short when measured through the fixture. Figures 6.4.17 and 6.4.18 are the decascaded results that the three port sees on its unused port.
Figure 6.4.1: Configuration of a microstrip tee with all arms on same plane of PCB.
Figure 6.4.2: Embedded $s$ parameters of a microstrip tee with port 1 terminated with a short measured between ports 2 and 3. Magnitude of $(\Box) S_{11}$, $(\triangle) S_{21}$, $(\ast)$ $S_{12}$, and $(\times) S_{22}$. 
Figure 6.4.3: Cont. embedded s parameters of a microstrip tee with port 1 terminated with a 50 ohm load measured between ports 2 and 3. Magnitude of (□) $S_{11}$, ($\triangle$) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.4.4: Cont. embedded s parameters of a microstrip tee with port 2 terminated with a short measured between ports 1 and 3. Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.4.5: Cont. embedded s parameters of a microstrip tee with port 2 terminated with a 50 ohm load measured between ports 1 and 3. Magnitude of (□) $S_{11}$, ($\triangle$) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.4.6: Cont. embedded s parameters of a microstrip tee with port 3 terminated with a short measured between ports 1 and 2. Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.4.7: Cont. embedded s parameters of a microstrip tee with port 3 terminated with a 50 ohm load measured between ports 1 and 2. Magnitude of (□) $S_{11}$, ($\triangle$) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.4.8: Deembedded $s$ parameters of a microstrip tee with port 1 terminated with a short measured between ports 2 and 3. Magnitude of (□) $S_{11}$, (∆) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.4.9: Cont. deembedded s parameters of a microstrip tee with port 1 terminated with a 50 ohm load measured between ports 2 and 3. Magnitude of (□) $S_{11}$, (Δ) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.4.10: Cont. deembedded s parameters of a microstrip tee with port 2 terminated with a short measured between ports 1 and 3. Magnitude of (□) $S_{11}$, ($\Delta$) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.4.11: Cont. deembedded $s$ parameters of a microstrip tee with port 2 terminated with a 50 ohm load measured between ports 1 and 3. Magnitude of (□) $S_{11}$, (∆) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.4.12: Cont. deembedded s parameters of a microstrip tee with port 3 terminated with a short measured between ports 1 and 2. Magnitude of (□) $S_{11}$, ($\Delta$) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.4.13: Cont. deembedded s parameters of a microstrip tee with port 3 terminated with a 50 ohm load measured between ports 1 and 2. Magnitude of (□) $S_{11}$, (△) $S_{21}$, (+) $S_{12}$, and (×) $S_{22}$. 
Figure 6.4.14: Model of measurement configuration of a termination.
Figure 6.4.15: Raw magnitude of reflection data of a 50 ohm load at the end of the through standard.
Figure 6.4.16: Raw magnitude of reflection data of a short at the end of the through standard.
Figure 6.4.17: Decascaded magnitude of reflection data of a 50 ohm load at the end of the through standard. Note that half of the error fixture is still embedded.
Figure 6.4.18: Decascaded magnitude of reflection data of a short at the end of the through standard. Note that half of the error fixture is still embedded.
To verify that this method is accurate, the data is further de-cascaded to the termination itself. Figures 6.4.19 and 6.4.20 show the end product and we observe that both plots closely resemble the theoretical expectation.

### 6.4.3 Implementation of Algorithm

We now have all the data required and with all measured and residual errors removed. The data consists of two port measurements in every port combination (3 measurements recognizing that transmission is reciprocal) and reflection measurements with one port terminated (3 measurements) all done with the used port terminated in both a standard 50Ω and a short (multiplied by two). This totals to 12 measurements of the device. The standard terminations are also measured for an additional two measurements and a grand total of 14 measurements. These were placed into the algorithm described in chapter three.

Figures 6.4.21 through 6.4.26 are the results that characterize the microstrip tee in the configuration of figure 6.4.1. It is interesting to note that the reflection parameters are around a value of approximately 0.33 which coincides with a 50Ω transmission line looking into parallel 50Ω loads. Also note that $S_{11}$ and $S_{22}$ track together closely while $S_{33}$ loosely follows. This mimicry decreases with frequency, probably due to the increasing coupling of the base arm with the two cross arms. The reciprocity detected in the two port de-embedded measurements still holds true. The spikes that appear are probably due to resonances from the transmission line.
Figure 6.4.19: Fully decascaded magnitude of reflection data of a 50 ohm load at the end of the through standard.
Figure 6.4.20: Fully decascaded magnitude of reflection data of a short at the end of the through standard.
Figure 6.4.21: Characterized microstrip tee's parameters. Magnitude of (□) $S_{11}$, ($\triangle$) $S_{22}$, and (+) $S_{33}$. 
Figure 6.4.22: Cont. characterized microstrip tee's parameters. Magnitude of (□) $S_{21}$, (△) $S_{12}$. 
Figure 6.4.23: Cont. characterized microstrip tee's parameters. Magnitude of (□) $S_{31}$, (△) $S_{13}$, (+) $S_{33}$, and (×) $S_{23}$. 
Figure 6.4.24: Cont. characterized microstrip tee s parameters. Angle of (∆) $S_{11}$, (£) $S_{22}$, and (+) $S_{33}$. 
Figure 6.4.25: Cont. characterized microstrip tee's parameters. Angle of (□) $S_{21}$, ($\triangle$) $S_{12}$. 
Figure 6.4.26: Cont. characterized microstrip tee s parameters. Angle of (□) $S_{21}$, ($\triangle$) $S_{13}$, (+) $S_{22}$, and (×) $S_{23}$. 
lengths of the arms in the tee as well as interactions of the inductive and capacitive coupling in the arms. These inductive and capacitive differences are more evident at the high frequencies.

6.4.4 Comparison with Renormalization Method

The raw data from the microstrip tee was also processed using algorithms developed by Wood [5]. He utilized multiple renormalization schemes that evolved into extensive matrix manipulations. Figures 6.4.27 through 6.4.32 are the results with a 50Ω termination at the unused port. The technique was also used with a nominal short for a termination, but the resulting deembedded s parameters were erratic. By the algorithm, the results should have given the same outcome regardless of the termination. A possible reason for this is that in renormalizing to an impedance with a large reactive component, the s parameters would have large uncertainty errors.

The reflection results from the renormalization with the 50 Ω termination are generally similar to our outcome up to 4.8 Ghz. Past that point, the data diverges greatly. A possible cause for this variance is Wood's dependence on the measurement of the termination. In figure 6.4.17, we see that the termination does not remain constant with frequency. Therefore, the reference impedance in Woods algorithm is frequency dependent. Our method uses two terminations and calculates to a universal 50 Ω reference and therefore is not as dependent upon any single
Figure 6.4.27: Characterized microstrip tee's parameters using renormalization and with nominal 50 ohm load on unused port. Magnitude of (□) $S_{11}$, (△) $S_{22}$, and (+) $S_{33}$.
Figure 6.4.28: Cont. characterized microstrip tee s parameters using renormalization and with nominal 50 ohm load on unused port. Magnitude of (□) $S_{21}$ and (△) $S_{12}$.
Figure 6.4.29: Cont. characterized microstrip tee s parameters using renormalization and with nominal 50 ohm load on unused port. Magnitude of (□) $S_{31}$, (△) $S_{13}$, (+) $S_{32}$, and (×) $S_{23}$. 
Figure 6.4.30: Cont. characterized microstrip tee's parameters using renormalization and with nominal 50 ohm load on unused port. Angle of (□) $S_{11}$, (△) $S_{22}$, and (+) $S_{33}$. 
Figure 6.4.31: Cont. characterized microstrip tee s parameters using renormalization and with nominal 50 ohm load on unused port. Angle of (□) $S_{21}$ and (△) $S_{12}$
Figure 6.4.32: Cont. characterized microstrip tee's parameters using renormalization and with nominal 50 ohm load on unused port. Angle of (□) $S_{21}$, (△) $S_{13}$, (+) $S_{32}$, and (×) $S_{23}$. 
measurement of a termination.

Although the presented method is more accurate than any previous technique, it still has its limitations. As formerly pointed out, the reflection coefficients of the two terminations must be very different or else the algorithm fails. Also the process is only as good as the data used, therefore reliable methods must be used to measure and deembed the device. ETSI, in microstrip applications, is recommended.

6.4.5 Microstrip Tees

Figures 6.4.33, 6.4.34, and 6.4.35 are the configurations for three more microstrip tees. Each involve a via through the dielectric and a continuation of the transmission line on the reverse side of the board. Figure 6.4.34 has a transitional step before the via. This prevents the base line from being directly under the cross arms, as in figure 6.4.33. Figure 6.4.35 is similar to figure 6.4.33 except that the base transmission line is designed to have a characteristic impedance of 25Ω.

The same steps of the procedure described for the characterization of the tee in the last section were performed on the above tees. The results are in figures 6.4.36 through 6.4.41 for the tee of figure 6.4.33, figures 6.4.42 through 6.4.47 for the tee of figure 6.4.34, and figures 6.4.48 through 6.4.53 are for the tee of figure 6.4.35.

It is interesting to note that in the configuration of figure 6.4.34, all three ports track each other relatively closely along the entire band up to 8 GHz. The overall performance is even better than that of the figure 6.4.1 configuration. The configu-
Figure 6.4.41: Configuration of a microstrip tee with base arm on reverse plane of PCB from cross arms.
Figure 6.4.34: Configuration of a microstrip tee with base arm on reverse plane of PCB from cross arms with transitional steps.
Figure 6.4.35: Configuration of a microstrip tee with base arm of 25 ohms on reverse plane of PCB from cross arms of 50 ohms.
Figure 6.4.36: Characterized microstrip tee with base arm on reverse plane of PCB's parameters. Magnitude of (□) $S_{11}$, (△) $S_{22}$, and (+) $S_{33}$. 
Figure 6.4.37: Cont. characterized microstrip tee with base arm on reverse plane of PCB s parameters. Magnitude of (□) $S_{21}$ and ($\Delta$) $S_{12}$. 
Figure 6.4.38: Cont. characterized microstrip tee with base arm on reverse plane of PCB's parameters. Magnitude of (□) $S_{31}$, (△) $S_{13}$, (+) $S_{22}$, and (×) $S_{23}$. 
Figure 6.4.39: Cont. characterized microstrip tee with base arm on reverse plane of PCB's parameters. Angle of (□) $S_{11}$, ($\triangle$) $S_{12}$, and (+) $S_{33}$. 
Figure 6.4.40: Cont. characterized microstrip tee with base arm on reverse plane of PCB's parameters. Angle of (□) $S_{21}$ and (△) $S_{12}$. 
Figure 6.4.41: Cont. characterized microstrip tee with base arm on reverse plane of PCB's parameters. Angle of (□) $S_{31}$, (Δ) $S_{13}$, (+) $S_{32}$, and (×) $S_{23}$. 
Figure 6.4.42: Characterized microstrip tee with base arm on reverse plane of PCB and cross arms with transitional steps s parameters. Magnitude of (□) $S_{11}$, (△) $S_{22}$, (+) $S_{33}$. 
Figure 6.4.43: Cont. characterized microstrip tee with base arm on reverse plane of PCB and cross arms with transitional steps s parameters. Magnitude of (□) $S_{21}$ and (△) $S_{12}$.
Figure 6.4.44: Cont. characterized microstrip tee with base arm on reverse plane of PCB and cross arms with transitional steps s parameters. Magnitude of (□) $S_{31}$, ($\triangle$) $S_{13}$, (+) $S_{22}$, and (×) $S_{23}$. 
ration of figure 6.4.33 has each port performing together until about 4 GHz. From 4 GHz, two ports stay together until all three diverge at about 10 GHz. The figure 6.4.35 configuration has, except for a small band, a single port divergent from the two remaining ports.

The interesting part is in the comparison of each configuration's results. Configurations of figures 6.4.34 and 6.4.33 have similar responses at low frequency, up to 3 GHz. The layouts looking similar at low frequency contributes to this and the divergence is probably due to the increasing coupling with frequency of the cross arms to the base in figure 6.4.33 compared to figure 6.4.34. The responses of the configurations of figures 6.4.33 and 6.4.35 are totally different although the physical layout is very similar. This is unexpected since the base of figure 6.4.35 was designed to be 25Ω in order to improve performance. It, in fact, achieves better match of that port at low frequency, but to the detriment of the match at the other two ports. The transmission has little or no improvement. We also see that at very low frequency, all the tees, except for figure 6.4.35 perform alike.

6.4.6 Conclusion

We can now see that variances in configuration can have major and minor effect on the performance of a microstrip tee. The varying magnitudes of these effects can be the basis of more effective modeling of tees. Some models of tees have already been presented [47],[48]. However, the measured data upon which these equivalent
circuits were based, were not deembedded and did not account for reflections from the unused port.

6.5 Conclusion

This chapter has exhibited the experimental data for a procedure to characterize a three port device, step by step. Along the way, effects of symmetry and electrical length has been examined and a study in smoothing or averaging has shown that no improvement and even degradation of the output results if it is used in further calculation. Experimental results using an improvement to the ETLS technique of deembedding, where the free space inductance is included in the characteristic impedance calculation, was presented. The procedure was also shown to be more accurate than Wood’s method of multiple renormalization. Finally, various microstrip tees were characterized using the procedure.
Figure 6.4.45: Cont. characterized microstrip tee with base arm on reverse plane of PCB and cross arms with transitional steps s parameters. Angle of (□) $S_{11}$, (△) $S_{22}$, and (⁺) $S_{33}$. 
Figure 6.4.46: Cont. characterized microstrip tee with base arm on reverse plane of PCB and cross arms with transitional steps s parameters. Angle of (□) $S_{21}$ and (△) $S_{12}$
Figure 6.4.47: Cont. characterized microstrip tee with base arm on reverse plane of PCB and cross arms with transitional steps s parameters. Angle of (□) $S_{31}$, (△) $S_{13}$, (+) $S_{32}$, and (×) $S_{23}$. 
Figure 6.4.48: Characterized microstrip tee with 25 ohm base arm on reverse plane of PCB's parameters. Magnitude of (□) $S_{11}$, (△) $S_{22}$, and (+) $S_{33}$. 
Figure 6.4.49: Cont. characterized microstrip tee with 25 ohm base arm on reverse plane of PCB's parameters. Magnitude of (□) $S_{21}$ and (△) $S_{12}$
Figure 6.4.50: Cont. characterized microstrip tee with 25 ohm base arm on reverse plane of PCB's parameters. Magnitude of (□) $S_{31}$, (△) $S_{13}$, (+) $S_{32}$, and (×) $S_{23}$. 
Figure 6.4.51: Cont. characterized microstrip tee with 25 ohm base arm on reverse plane of PCB's parameters. Angle of (□) $S_{11}$, (△) $S_{22}$, and $S_{33}$. 
Figure 6.4.52: Cont. characterized microstrip tee with 25 ohm base arm on reverse plane of PCB s parameters. Angle of (□) $S_{21}$ and ($\triangle$) $S_{12}$
Figure 6.4.53: Cont. characterized microstrip tee with 25 ohm base arm on reverse plane of PCB s parameters. Angle of (□) $S_{31}$, (△) $S_{13}$, (+) $S_{32}$, and (×) $S_{23}$. 
Chapter 7

Conclusion

7.1 Summary

The characterization of three-port devices has two important areas, deembedding of the raw measurement data and the inclusion of the influence of reflection from untested ports. Both have been examined and analyzed in this document.

In the area of deembedding, a compilation of the chronological development of calibration and deembedding was done and two trends of evolution of measuring techniques were noticed. One was to decrease the number and dependence upon calibration standards and another was to increase the accuracy. Symmetric assumptions attempts to do both and the ETSL method was chosen as the best system for the applications in this study. An enhancement was made to ETSL by including free space inductance in the calculation of the characteristic impedance of the transmission line standard. The dependence upon the transmission line length and the validity of the symmetry argument upon ETSL was also studied.

A step-by-step procedure was introduced with appropriate warnings and lab technique guidelines to achieve accurate and repeatable deembedded data. An analysis on the concept of smoothing or data averaging was done with the conclusion that it
is purely cosmetic and should not be used for any subsequent calculations.

An algorithm that accurately characterizes any three-port device was introduced. It is closed form and makes no assumptions upon the device under test. It takes into consideration the influences of reflections from untested ports and returns a full characterization of the device as it is seen in the circuit. A comparison with a previous method is done and its improvement upon accuracy is confirmed. Finally, a number of microstrip tees in various configurations were characterized.

7.2 Application

The impact of this procedure of characterization is enormous if the practical applications are examined. Not only can any three-port device now be measured, but accurate models can be synthesized to fit the data. This is beneficial to the computer designer, the communication system engineer, and the transistor design engineer. The algorithm does not involve complicated test schemes or equipment except for an ANA, a common item many high frequency labs, and is, therefore, very accessible to anyone with a computer. With multiport measurement system being developed, such as the 4 and 6 port ANA, the complete characterization of its components with make for better error models and, therefore, more accurate calibration and better measurement data. This is only a glimpse of the possibilities that arise from full three port characterization.
7.3 Suggestions for Further Study

Additional areas of study include:

i) exploration of algorithm sensitivity,

ii) quantitative study on ETSL sensitivity to symmetric assumptions,

iii) effective modeling of a number of three port devices using data acquired from this algorithm,

iv) expansion of algorithm to larger port devices.
References


Appendix A

SPANA Semantic Command Description

This appendix is a user's manual for SPANA. Its purpose is to inform the user of the command syntax and the required command line parameters. SPANA is not case sensitive and for clarity this appendix will use bold face characters to indicate command syntax.

Some of the functions require command parameters in addition to the command itself for example.

\texttt{dmb2 meas=1 type=1 dest=2 stan=3}

The command parameters provide the function with information. Each command parameter is separated with a space and the argument to the right of the parameter is the data to be passed to the function. The order of command parameters is not important but a complete command line is required. The arguments can be delimited with any white space character. If a command syntax occurs the line will be aborted and a message given.

A.1 help

Example: \texttt{help more}

Purpose. HELP is the on-line help facility for listing the commands that are available in SPANA as well as a brief description of each command. The possible help arguments are shown below.

Arguments.

\texttt{more}

\texttt{page2}

* help
Command Available:

<table>
<thead>
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<th>COMMAND</th>
<th>KEYWORD</th>
<th>DESCRIPTION</th>
<th>CONTACT</th>
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<td>Describes Data</td>
<td>Steer</td>
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<td>EXT</td>
<td>Extrapolates Data</td>
<td>Steer</td>
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<td>FPT</td>
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<td>Does FFT on Data</td>
<td>Steer</td>
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<td>GET</td>
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<td>S/K</td>
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<td>Displays this help file</td>
<td>S/K</td>
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<tr>
<td>PUT</td>
<td>PUT</td>
<td>Outputs data</td>
<td>Steer</td>
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</table>

For more information on a command type "keyword" HELP
More information is available by typing HELP MORE
or by typing HELP PAGE2
Commands Available:

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<td>De-embeds DUT data</td>
<td>S/K</td>
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<td>BUILD</td>
<td>BLD</td>
<td>Makes standard from data</td>
<td>Kasten</td>
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<td>DECAS</td>
<td>Matrix from prod of matrices</td>
<td>Goldberg</td>
</tr>
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</table>

For more information on a command type "keyword" HELP
More information is available by typing HELP MORE

The following input/output commands are available:

- **read filename**: the file filename is opened for input
- **read**: the previously opened file is now used for input
- **write filename**: the file filename is opened for output
- **eof**: the input data file is closed
- **end**: the input data file is temporarily closed
- **title**: write line to output file
- **prompt**: write line to terminal
- **echo on**: the flag prt is set
- **echo off**: the flag prt is cleared

If prt is set all lines input are echoed.
A.2 get

Example: get meas=1 file=dut.s2p format=magang

Purpose. GET is used to input a measurement set into SPANA.

Arguments.

help

meas = n1

file = filename

format = magang

= a+jb

= 3port

MEAS designates the measurement set (n1) that the data will be loaded into. The argument must be less than the maximum number of measurement sets. GET will overwrite an existing measurement set. Be careful in that three port data uses three measurement sets.

FILE designates the filename from which the data will be read from. The filename can be any acceptable name including a directory path provided the total number of characters is less than thirty.

SPANA allows for text information to be placed above the data. Each line of this text must begin with a comment delimiter (! or #) in the first or second column however the first line in the file is taken as the data identifier and it is used in the PUT and DISPlay functions. Any subsequent comment lines will be ignored and GET will begin reading the data when it encounters the first uncommented line. The data is read in until the end of file is encountered. Below is an example file.
! S parameters for DUT (This is an example data identifier)

! This line will be ignored

1.500 0.015 35.5 0.995 95.4 0.995 95.4 0.02 20.5

If the data is in the frequency or time domain than the independent variable is assumed to be in megahertz or nanoseconds respectively.
FORMAT is an optional parameter that designates the data format in the file. It can be either magnitude-angle form (magang), real-imaginary (a+jb), or three port (3port). GET defaults to magnitude-angle form if format is not specified. ZC format is used when a characteristic impedance, gamma, permittivity, and permeability file is to be read in. It is assumed that the input values are in real-imaginary form.

The command get help will give the on-line help information about the get function. Reprinted below.

################################################################### GET ###################################################################

Usage:

GET HELP
  : This Message

GET MEASurement_set = n1 FILE=ssssss FORMAT=a+jb
  : GETs MEASurement set n1 from FILE sssss
  : Input is is Real-Imaginary format

GET MEASurement_set = n1 FILE=ssssss FORMAT=time
  : GETs MEASurement set n1 from FILE sssss
  : Input is Magnitude format

GET MEASurement_set = n1 FILE=ssssss FORMAT=z
  : GETs MEASurement set n1 from FILE sssss
  : Input is is Real-Imaginary format

GET MEASurement_set = n1 FILE=ssssss FORMAT=3port
  : GETs MEASurement set n1 from FILE sssss
  : Input is is Magnitude-Angle format

Note: 1. If no FORMAT is given magang is assumed
       2. Default units are MHz and nanoseconds

###################################################################
A.3 put

Example: put meas=n file=dut.s2p

Purpose. PUT is used to output a measurement set to the terminal screen or to a specified filename.

Arguments.

```
help

meas = n1

file = filename

inline = n2

option = 1 for option
```

MEAS designates the measurement set (n1) that will be processed. The argument must be less than the maximum number of measurement sets. If MEAS is the only argument then the measurement set will be put to the terminal screen and attached to the beginning of the data will be the PUT banner.

FILE designates the filename to which the data will be written to. The filename just as for GET can be any acceptable name including a directory path provided the total number of characters is less than thirty. Below are two banners that PUT would attach to the beginning of PUT file.

```
! S parameters for DUT
-------------------------------
! MEASUREMENT SET 1
! Two-port S parameters
! Frequency-Domain Data: Magnitude-Angle Form
! Number of Frequency points: 1
! Frequency Interval: 0.  MHz
! Low Frequency: 1000.00  MHz
! High Frequency: 1000.00  MHz
! Valid Measurement Data
! Characteristic Impedance: 50.0000
! Identifier:
! S parameters for DUT
!
! FREQ  S11   S21   S12   S22
! (MHz)  Mag Angle Mag Angle Mag Angle Mag Angle
```
<p>| | | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1000.0</td>
<td>0.01944</td>
<td>-151.31</td>
<td>0.97351</td>
<td>-102.56</td>
<td>0.97470</td>
<td>-102.43</td>
<td>0.01784</td>
<td>136.54</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Three port de-embedded result (DM3). Part 1 of 3.

MEASUREMENT SET 9

Three-port S parameters
Frequency-Domain Data: Magnitude-Angle Form
Number of Frequency Points: 1
Frequency Interval: 0.0 MHz
Low Frequency: 1000.00 MHz
High Frequency: 1000.00 MHz
Valid De-embedded Data
Characteristic Impedance: 50.0000

Identifier:

Three port de-embedded result (DM3). Part 1 of 3.

<table>
<thead>
<tr>
<th>FREQ (MHz)</th>
<th>Mag</th>
<th>Angle</th>
<th>Mag</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000.0000</td>
<td>0.59842</td>
<td>-169.85</td>
<td>0.22104</td>
<td>-33.48</td>
</tr>
<tr>
<td>0.22104</td>
<td>-33.48</td>
<td>0.75168</td>
<td>-167.80</td>
<td>0.30034</td>
</tr>
<tr>
<td>0.21382</td>
<td>-33.49</td>
<td>0.30034</td>
<td>-30.96</td>
<td>0.72729</td>
</tr>
</tbody>
</table>

The banner that precedes the data depends on measurement statistics (see display command for information about possible statistics) with the above examples showing two and three port data. The file format (magang, a+jb, zc or time) is specified by the format type of the measurement set to be written out.

The INLINE argument is used to place the data on one line with the line containing all the data for one frequency or time point. This is default for two port data but may be used for three and four port data output.

OPTION can be used to reduce a ZC format measurement set to only the characteristic impedance and gamma. The option is default to zero and does not reduce if an option value of one is entered the option is executed.

The command put help will give the on-line help information about the put function. Reprinted below.
Usage:

PUT HELP
  : This Message

PUT MEASurement_set = n1
  : Types MEASurement on terminal

PUT MEASurement_set = n1 INLINE
  : Puts results on a single line used with three ports and higher

PUT MEASurement_set = n1 OPTION = n2
  : Outputs results using special option

PUT MEASurement_set = n1 FILE=ssssss
  : PUTs MEASurement set n1 in FILE sssss
A.4 disp

Example: disp=1

Purpose. Display is used to list measurement parameters for one set or all.
Arguments.
  help
  all
  n1

If a measurement set number (n1) is given then the measurement statistics will be displayed. Statistics available include the following.

1, 2, 3 or 4 port S or Y parameters
System characteristic impedance
Start/Stop frequency or time
Number of data points
Data status (measured, converted or de-embedded)
Domain of data (frequency or time)
Data format (magang, a+jb)

If the all argument is given then statistics will be displayed for all available measurement sets. Below is a sample display output and the on-line help for disp (disp help).
MEASUREMENT SET 1
Two-port S parameters
Frequency-Domain Data: Magnitude-Angle Form
Number of Frequency points: 1
Frequency Interval: 0.00 MHz
Low Frequency: 1000.00 MHz
High Frequency: 1000.00 MHz
Valid Measurement Data
Characteristic Impedance: 50.0000
Identifier:
S parameters for DUT

*************************************************************************
DISPlay

Usage:

DISP HELP
   : This Message
DISP
   : DISPlay data about all Measurement sets
DISP n
   : DISPlay data about Measurement set n

*************************************************************************
A.5 refl

Example: refl meas=1 dest=2

Purpose. Reflect takes s-parameter data of a load and puts the reflection data into the format for three port deembedding.

Arguments.

help

meas= n1

dest= n2

SPANA will take the $S_{11}$ data from the measurement set n1 and place it into n2 in columns 1, 2, and 3. Three port deembedding (dmb3) requires this format. If refl help is entered, the on-line help for reflect will be displayed and is reprinted below.

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! REFLection !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!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A.6  err

Example: err meas=1 dest=2

Purpose. Error takes the error fixture half data and calculates the through data necessary for TSF deembedding.

Arguments.

   help

   meas= n1

   dest= n2

   The error fixture half data in n1 is matrically multiplied with its flipped conjugate to create a through standard that can be used in Thru-Symmetric-Fixture,TSF, deembedding (dmb2 type 2). If err help is entered, the on-line help for error will be displayed and is reprinted below.

   ######################## ERROR THRU ########################
   Usage:

   err meas=n1 dest=n2

   #########################
A.7 decas

Example: decas meas=1 dest=2 mata=3

Purpose. Decascade allows the pulling out of a matrix from a cascaded matrix when one of the multipiers is known.

Arguments.

help

meas= n1
dest= n2
mata= n3
matb= n3

The cascaded matrix is in n1 and either the first matrix (mata) from the multipication or the last matrix (matb) from the multiplication is in n3. By multiplying n1 by the inverse, or flipped inverse, of n3 the desired matrix is placed into n2. If decas help is entered, the on-line help for decascade will be displayed and is reprinted below.

############################################################################### DECAScade ##############################################################################

Usage:

  decas meas=n1 dest=n2 mata=n3 or matb=n3 flip (OPTIONAL)

mata is the known first matrix
matb is the known last matrix
flip inverts mata or matb

###############################################################################
A.8  del

Example: del meas=1

Purpose. Delete is a house cleaning tool and is used to delete an exiting measurement set making it available for reuse.

Arguments.

    help

    meas= n1

SPANA will delete the measurement set designated by n1. This deletion is permanent and should be used with caution. Note: del does not delete files stored on disk. If del help is entered, the on-line help for delete will be displayed and is reprinted below.

******************************************************************************

Usage:

    DEL HELP
         : This Message

    DEL MEASurement_set = n1
         : DELetes MEASurement set n1

******************************************************************************
A.9 ptor

Example: ptor meas=1

Purpose. PTOR is for conversion from polar to rectangular format.

Arguments.

  help

  meas = n1

  MEAS designates the measurement set that is to be converted. This is destructive since the measurement set is overwritten. PTOR will not convert a measurement set if it is currently in magang format. Note: ZC format can be converted however time format can not.

  On-line help is available for PTOR by entering ptor help. The help message is reprinted below.

   **************************************** PTOR ****************************************

Usage:

  PTOR HELP
     : This Message

  PTOR MEAS_set = n1

   *********************************************************************************
A.10 rtop

Example: rtop meas=1

Purpose. RTOP is for conversion from rectangular to polar format.

Arguments.

    help

    meas = n1

MEAS designates the measurement set that is to be converted. This is destructive since the measurement set is overwritten. RTOP will not convert a measurement set if it is currently in a+jb format. Note: ZC format can be converted however time format cannot.

On-line help is available for RTOP by entering rtop help. The help message is reprinted below.

******************** RTOP ********************

Usage:

    RTOP HELP
    : This Message

    RTOP MEAS_set = n1

*****************************************************************************
A.11  dbtop

Example: dbtop meas=1

Purpose. DBTOP is for conversion from log magnitude to polar format.

Arguments.

  help

    meas = n1

  MEAS designates the measurement set that is to be converted. This is destruc-
tive since the measurement set is overwritten. DBTOP will not convert a mea-
surement set if it is currently in a+jb format. Note: ZC format can be converted
however time format can not.

  On-line help is available for DBTOP by entering dbtop help. The help message
is reprinted below.

# DBTOP #

Usage:

    DBTOP HELP
         : This Message

    DBTOP MEAS_set = n1

#
A.12  stoy

Example: stoy meas=1 dest=2 rect

Purpose. STOY is used to convert S parameter sets to Y parameters.

Arguments.

  help

  meas = n1

  dest = n2

  rect

  magang

  MEAS designates the measurement set that is to be converted and the result is
place in the DEST measurement set. The default format is that of the MEAS set
however by using either RECT or MAGANG arguments the result format can be
forced accordingly. Note: This conversion is only valid for S parameter measurement
sets.

  On-line help is available for STOY by entering stoy help. The help message is
reprinted below.

############################################################################
STOY  ####################################################################

Usage:

STOY HELP
  : This Message

STOY MEAS_set = n1 DEST_set = n2
  : Convert S parameters data to Y parameters
    : using current format.

STOY MEAS_set = n1 DEST_set = n2 RECTangular
  : Convert S parameters data to Y parameters
    : outputting data in complex rectangular form.

STOY MEAS_set = n1 DEST_set = n2 MAGANG
  : Convert S parameters data to Y parameters
    : outputting data in magnitude-angle form.

############################################################################
A.13 sym

Example: sym meas=1 dest=2

Purpose. SYM is used to symmetrize the specified measurement set.

Arguments.

help

meas = n1

dest = n2

Symmetrization of a MEAS set is done by replacing 11 and 22 and 21 and 12 with the respective average of the two. The format of the DEST set will be that of the MEAS.

On-line help is available for SYM by entering sym help. The help message is reprinted below.

############################# SYMmetrize #############################

Usage:

SYM HELP
: This Message

SYM MEAS_set = n1 DEST_set = n2
: Averages data in measurement set n1 and puts output in measurement set n2
Output in columns 1 and 4 = average of data in input columns 1 and 4
Output in columns 2 and 3 = average of data in input columns 2 and 3
Averaging is done in real imaginary form and data is returned in the input format.

#############################
A.14 pul

Example: pul meas=1 dest=2 every=10

Purpose. PUL is used to reduce the size of a measurement set.

Arguments.

help

meas= n1

dest= n2

every= n3

MEAS signifies the measurement set to be reduced and DEST set will contain
the result. EVERY specifies which data points to take, ie. take EVERY 8th one.
Number of DEST points equals integer(number/every).

################################################### PUL1 ###################################################

Usage:

PUL HELP
    : This Message

    PUL MEAS_set = n1 DEST_set = n2 EVERY = n3

###################################################
A.15 win

Example: win meas=1 dest=2 parm=11 size=81

Purpose. Windowing is used to smooth a parameter in an existing measurement set.

Arguments.

help

meas = n1

dest = n2

parm = 11

    = 21

    = 12

    = 22

size = n3

MEAS designates the measurement set that will be smoothed with the result to be placed in the DEST measurement set. Windowing is done on the a+jb form of the PARM that is specified so both real and imaginary or magnitude and phase are smoothed together. The argument PARM is needed to designate which columns of data within the measurement set are to be smoothed. 11, 21, 12, and 22 correspond respectively to columns 1-2, 3-4, 5-6, and 7-8 of the measurement set. This is done so that any data format can be windowed.

SIZE is the width of the window and it is a number of samples and needs to be odd.

On-line help is available for WIN by entering win help. The help message is reprinted below.

################################################## WINDOW ##################################################
Usage:

WIN HELP
: This Message

WIN MEASurement_set = n1 DESTination_set = n2
PARAMeter = ?? window SIZE = n3

Note: Window size is an odd number of samples.
A.16  **strp**

Example: **strp** meas=1 type=logmag file=temp.stp parm=21

Purpose. STRP is used to generate X-Y data from a specified measurement set.

Arguments.

  help

  meas = n1

  parm = 11

  = 21

  = 12

  = 22

  file = filename

  type = logmag

  = linmag

  = ang

  = real

  = imag

MEAS designates the measurement set where the Y data is located with the 
X data assumed frequency or time depending on the measurement set domain. 
PARM specifies which column pair to use 11, 21, 12 and 22 for 1-2, 3-4, 5-6 and 
7-8 respectively and finally TYPE gives the output format of the Y data. Note: 
Linmag, logmag and ang types apply to magnitude-angle format data and real and 
imag types correspond to a+jb format. Time format is either linmag, logmag or 
real type.

On-line help is available for STRP by entering **strp help**. The help message is 
reprinted below.
Usage:

STRP HELP
: This Message

STRP MEASurement set = n1 FILE = sssss
  PARM = n2 TYPE = n3
: Strips parameter either magnitude or phase
  and places along with frequency (x,y) in the
  file designated
A.17  dmb2

Example: dmb2 meas=1 dest=2 type=4 h=5.6 l=2000 w=8 t=3.6

Purpose. DMB2 contains all the two port de-embedding routines and their purpose is to do error correction.

Arguments.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>help</td>
<td></td>
</tr>
<tr>
<td>meas</td>
<td>n1</td>
</tr>
<tr>
<td>dest</td>
<td>n2</td>
</tr>
<tr>
<td>error</td>
<td>n3</td>
</tr>
<tr>
<td>stan</td>
<td>n4</td>
</tr>
<tr>
<td>thru</td>
<td>n5</td>
</tr>
<tr>
<td>line</td>
<td>n6</td>
</tr>
<tr>
<td>zmeas</td>
<td>n7</td>
</tr>
<tr>
<td>zdest</td>
<td>n8</td>
</tr>
<tr>
<td>reflect</td>
<td>n7</td>
</tr>
<tr>
<td>type</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td>t</td>
<td>?</td>
</tr>
<tr>
<td>w</td>
<td>?</td>
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<tr>
<td>h</td>
<td>?</td>
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<td>l</td>
<td>?</td>
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<tr>
<td>eps</td>
<td>?</td>
</tr>
<tr>
<td>zc</td>
<td>?</td>
</tr>
<tr>
<td>c</td>
<td>?</td>
</tr>
<tr>
<td>rdc</td>
<td>?</td>
</tr>
</tbody>
</table>
The de-embedding routines are executed by providing the required arguments and possibly some optional arguments. The de-embedding types 1-4 require the following; MEAS set, DEST set and TYPE choice and some form of standard information. The MEAS set contains the raw S parameters of the device under test (dut) and the result or error corrected parameters are placed in the DEST set. If the ERROR set is specified the de-embedding routines will place the error two-port to this measurement set. Only argument semantics will be discussed here with a detail discussion of de-embedding techniques left to the De-embedding Theory section of this manual.
A.17.1 type 1 Microstrip Open-Short-Load

Required arguments.

\[ \text{stan} = \text{n4} \]

Type 1 (Microstrip Open-Short-Load) requires a STAN measurement set that contains the reflection coefficients for the three standards (open, short and load or matched termination). This STAN set is generated using the BLD command (see BLD for further information). Of course the result is placed in the MEAS set.

A.17.2 type 2 Through-Symmetric-Fixture

Required arguments.

\[ \text{stan} = \text{n4} \]

Type 2 (Through-Symmetric-Fixture) requires a STAN measurement set that contains the through connection measurement of the embedding fixture. STAN can be generated using the \texttt{err} command.

A.17.3 type 3 Through-Symmetric-Line [enhanced]

Required arguments \hspace{1cm} Optional arguments

\[ \text{thru} = \text{n5} \]

\[ \text{line} = \text{n6} \]

\[ \text{zmeas} = \text{n7} \]

\[ \text{t} = ? \]

\[ \text{short} = \text{n7} \]

\[ \text{w} = ? \]

\[ \text{zc} = ? \]

\[ \text{h} = ? \]

\[ \text{eps} = ? \]

Type 3 (Through-Symmetric-Line [enhanced]) is a combination of type 3 de-embedding routines. The combinations exist because of the optional arguments.
First the required arguments, type 3 needs two S parameter measurements, THRU set and LINE set, and some physical information; \( w \) = microstrip width, \( t \) = metal thickness, \( h \) = dielectric height and \( \text{eps} \) = dielectric constant. Note: All dimensions are in mils. The default type 3 calculates the microstrip characteristic impedance (\( Z_{\text{cmic}} \)) based on the physical parameters. This \( Z_{\text{cmic}} \) can be replaced by a fixed impedance \( Z_C=?? \) or a measurement set \( Z_{\text{MEAS}} \). The \( Z_{\text{MEAS}} \) characteristic impedance is contained in position 11 of the measurement set and is usually generated by type 4 de-embedding. If \( Z_{\text{cmic}} \) is not used \( w, t, h, \text{eps} \) need not be specified.

The SHORT argument specifies a measurement set that contains the measured reflection coefficient (in the \( S_{11} \) position) with a physical short placed at the microstrip port of the embedding fixture. If SHORT is not specified then the symmetrical option is used. See the De-embedding Theory section for more information.

### A.17.4 type 4 Through-Symmetric-Line

**Required arguments.**

- \( \text{thru} = n4 \)
- \( \text{line} = n5 \)
- \( t = ? \)
- \( w = ? \)
- \( h = ? \)
- \( l = ? \)
- \( c = ? \)
- \( \text{rdc} = ? \)
- \( \text{zdest} = n6 \)

Type 4 (Through-Symmetric-Line) is used generally to determine the character-
istic impedance of the microstrip. This in turn is used with type 3 de-embedding. Type 4 requires two S parameter measurement sets, THRU set and LINE set as well as the physical parameters \( w = \text{microstrip width}, t = \text{metal thickness}, h = \text{dielectric height}, \) and \( l = \text{difference between the physical lengths of the line and thru standards}. \) Reminder, all dimensions are in mils. For example if the thru microstrip is 1000 mils long and the line strip is 3000 mils long one would use 2000 mils as the length \( (l) \). The free space capacitance may be input as an option instead of having SPANA calculate it. \( R_{dc} \), the dc resistance, may also be input or the material of the etch may be typed. Examples of circuit material are copper, gold, or aluminum.

The characteristic impedance, propagation factor \( (\gamma) \), effective dielectric constant, and effective permeability are outputs of type 4 and are placed in the last available measurement set as a default if zdest is not specified. Typing disp all will inform the user what measurement set this is. This measurement set is assumed empty at all times and any data that may exist there is overwritten by type 4. This measurement set can be PUT just as any normal measurement set however if it is subsequently read in by GET the user will have to specify the FORMAT=ZC option to correctly input the data. See the command descriptions for PUT and GET for further information about this I/O operation.

This finishes the argument semantics discussion and below is a reprint of the on-line help that is available for DMB2 (type dmb2 help).

```
# Two Port Dembedding (DMB2) ##############
Usage:

DMB MEAS = n1 DEST = n2 TYPE = n3

Type 0: Given symmetric error network
      NETWK = n4
Type 1: Microstrip Open-Short-Load
      STAN = n4
Type 2: Through-Symmetric-Fixture
      STAN = n4
Type 3: Through-Symmetric-Line (enhanced)
      THRU = n4 LINE = n5 Width = ? H(eight) = ?
      T(hickness) = ? EPSilon = ? ZC = optional
      ZMEAS = n6 (optional) SHORT = n7 (optional)
Type 4: Through-Symmetric-Line
      THRU = n4 LINE = n5 [ Width = ? H(eight) = ?
```
\[ T(\text{hickness}) = ? \text{[length]} = ? \text{ or [CO = ? (F/m)]}\]
\[ [\text{rdc} = ? \text{Ohm/m}] \text{ or [rdc = copper] or [rdc = gold]}\]
\[ \text{or [rdc = aluminum]}
\[ \text{[zdest = ni]}\]

\text{Note: All dimensions are metric}

*******************************************************************************
A.18  bld

Example: bld open=1 shor=2 term=3 dest=4

Purpose. BLD is used to build the three termination standard needed for TYPE 1
de-embedding.

Arguments.

  help

  dest  =  n1
  open  =  n2
  shor  =  n3
  term  =  n4

OPEN, SHOR and TERM designate the measurement sets that contain open,
short and matched termination reflection coefficient measurements respectively. These
measurements are located in the S11 position for all three standards.

#############################################################################
Build #############################################################################

Usage:

BLD HELP
: This Message

BLD OPEN_set = n1 SHOR_set = n2 TERM_set = n3
  DEST_set = n4

#############################################################################
A.19  **stop/quit**

Example: `stop quit`  Purpose. Stop is used to exit SPANA
A.20  dm3

Example: dm3 measa1=1 measa2=2 measb1=3 measb2=4 measc1=5 measc2=6
load1=7 load2=8 dest=9

Purpose. Three port characterization

Arguments.

\[
\begin{align*}
\text{measa1} &= n1 \\
\text{measa2} &= n2 \\
\text{measb1} &= n3 \\
\text{measb2} &= n4 \\
\text{measc1} &= n5 \\
\text{measc2} &= n6 \\
\text{load1} &= n7 \\
\text{load2} &= n8 \\
\text{dest} &= n9
\end{align*}
\]

Six two port measurements are required for maximum accuracy.

\text{measa1}:  Two port between ports 2 and 3 with a termination at port 1 of reflection coefficient \( \Gamma_1 \).

Port 2 of the three port is connected to port 1 of the network analyzer.

\text{measa2}:  Two port between ports 2 and 3 with a termination at port 1 of reflection coefficient \( \Gamma_2 \).

Port 2 of the three port is connected to port 1 of the network analyzer.
measb1: Two port between ports 1 and 3 with a termination at port 2 of reflection coefficient \( f_{gamb} \).
Port 1 of the three port is connected to port 1 of the network analyzer.

measa2: Two port between ports 1 and 3 with a termination at port 2 of reflection coefficient \( s_{gamb} \).
Port 1 of the three port is connected to port 1 of the network analyzer.

measc1: Two port between ports 1 and 2 with a termination at port 3 of reflection coefficient \( f_{gamc} \).
Port 1 of the three port is connected to port 1 of the network analyzer.

measc2: Two port between ports 1 and 2 with a termination at port 3 of reflection coefficient \( s_{gamc} \).
Port 1 of the three port is connected to port 1 of the network analyzer.

The reflection coefficient is passed in two 2 port measurement sets arranged as follows.

load1:

\[
\text{freq. } |f_{gama}| / |f_{gamb}| / f_{gamb} / f_{gamc} / f_{gamc}
\]

load2:

\[
\text{freq. } |s_{gama}| / |s_{gamb}| / s_{gamb} / s_{gamc} / s_{gamc}
\]
The deembedded result will be written onto the dest designated measurement set and the two sets following it. Therefore, dest must be at least 3 sets less than the maximum number allowed. Any measurement sets used will be overwritten. The displayed output will have the following format.

<table>
<thead>
<tr>
<th>FREQ</th>
<th>S11</th>
<th>S12</th>
<th>S13</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S21</td>
<td>S22</td>
<td>S23</td>
</tr>
<tr>
<td></td>
<td>S31</td>
<td>S32</td>
<td>S33</td>
</tr>
</tbody>
</table>

If dmb3 help is typed, the following will be displayed onto the screen.

######## DMB3  De-embedding of Three Ports ########

Usage:

DMB3 HELP
: This Message
DMB3 MEASA1 = n1 MEASB1 = n2 MEASC1 = n3 LOAD1 = n4
     MEASA2 = n5 MEASB2 = n6 MEASC2 = n7 LOAD2 = n8
     DEST   = n9

Note: The output will be a three port. Three measurement sets are required to store all of the parameters. n9, (n9+1) and (n9+2) are used to store the output

*****************************************************************************
A.21 gain

Example: Incomplete write up.

############################ GAIN ###########################

Usage:

GAIN HELP
: This Message

GAIN MEAS_set = n1 [GAIN = n2] [MERIT = n3] [NOISE = n4]
: Get gain, noise and figure of merit information
 : of a device described by the two-port measurement
 : S parameters in measurement set n1.
 : The gain information is put in set n2 and the
 : figure of merit information in set n3 and the
 : noise information in set n4.
 : The parameters in [] s are optional.

###############################
A.22 sigma

Example: Incomplete write up.

************************************************** SIGMA **************************************************

Usage:

SIGMA HELP
  : This Message

SIGMA MEAS = n1 X = n2 XX = n3 mean = n4 stddev = n5
  : Each entry of measurement set n1 is added to set n2 and its square is added to set n3. From these accumulated values the mean (put in set n4) and standard deviation (put in set n5) are calculated.
SIGMA CLEAR X = n2 XX = n3
  : Clears measurement sets n2 and n3

**************************************************
A.23 pie

Example: pie meas=1 dest=2

Purpose. PIE is used to calculate a pi equivalent circuit for a given S parameter measurement set.

Arguments.

  help

  meas = n1

  dest = n2

MEAS specifies the S parameter measurement set to be converted and the result is placed in the DEST measurement set. It is important to note that the S parameters must be of a network that is accurately modeled by a pi circuit or the results will be erroneous. Below is a reprint of the on-line help that is available for PIE (pie help).

***************************************************************************** PIE *****************************************************************************

Usage:

  PIE HELP
    : This Message

  PIE MEAS_set = n1 DEST_set = n2

*****************************************************************************
A.24 wood3

Example: wood3 meas1=1 meas2=2 meas3=3 dest=4 stan=5

Purpose. Characterize three port device using renormalization techniques.

Arguments.

help

meas1 = n1
meas2 = n2
meas3 = n3
dest = n4
stan = n5

MEAS1 is the two port data between ports 2 and 3 with port 1 terminated.
MEAS2 is the two port data between ports 1 and 3 with port 2 terminated. MEAS3
is the two port data between ports 1 and 2 with port 3 terminated. STAN is the
reflection coefficients of the termination at each port. The resulting three port data
is placed in the three subsequent measurement sets starting with n4.

## Three Port Dembedding Using Wood's Method (WOOD3) ##

Usage:

WOOD3 MEAS1 = n1 MEAS2 = n2 MEAS3 = n3
DEST = n4 STAN = n5

*****************************************************************************
Appendix B

SPANA Three Port Deembedding Code

SPDMB3

PURPOSE:
De-embeds a three port.

Six two port measurements are required for maximum accuracy.

meas1: Two port between ports 2 and 3 with a termination at port 1 of reflection coefficient f gamma.
Port 2 of the three port is connected to port 1 of the network analyzer.

meas2: Two port between ports 2 and 3 with a termination at port 1 of reflection coefficient f gamma.
Port 2 of the three port is connected to port 1 of the network analyzer.

meas1b: Two port between ports 1 and 3 with a termination at port 2 of reflection coefficient f gamma.
Port 1 of the three port is connected to port 1 of the network analyzer.

meas2b: Two port between ports 1 and 3 with a termination at port 2 of reflection coefficient f gamma.
Port 1 of the three port is connected to port 1 of the network analyzer.

meas1c: Two port between ports 1 and 2 with a termination at port 3 of reflection coefficient f gamma.
Port 1 of the three port is connected to port 1 of the network analyzer.

meas2c: Two port between ports 1 and 2 with a termination at port 3 of reflection coefficient f gamma.

---

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Port 1 of the three port is connected to port 1 of the network analyzer.

The reflection coefficient is passed in two 2 port measurement sets arranged as follows.

load1:

freq. \([fgama] / \_fgama \| fgamb \| / \_fgamb \| fgamc \| / \_fgamc\)

load2:

freq. \([sgama] / \_sgama \| sgamb \| / \_sgamb \| sgamc \| / \_sgamc\)

\[\text{e.g.} \quad 1000.0, 0.090909, 0.0, -0.666666, 0.0, -0.7857, 0.0, 0.0\]

VARIABLES: (Related to user's guide variables -- in LaTeX form)

\(\{\_\text{subscript} \quad \text{superscript} \quad \{\}\_\text{groups}\}\)

- \(fsija \quad ^{-15} A_{ij}\), \(i, j = 2, 3\)
- \(fsij \quad ^{-15} B_{ij}\), \(i, j = 3, 1\)
- \(fsij \quad ^{-15} B_{ij}\), \(i, j = 2, 1\)
- \(ssij \quad ^{-25} A_{ij}\), \(i, j = 3, 2\)
- \(ssij \quad ^{-25} B_{ij}\), \(i, j = 3, 1\)
- \(ssij \quad ^{-25} C_{ij}\), \(i, j = 2, 1\)
- \(fgam\quad ^{-i\text{gamma}}A\)
- \(fgamb \quad ^{-i\text{gamma}}B\)
- \(fgamc \quad ^{-i\text{gamma}}C\)
- \(sgam\quad ^{-2\text{gamma}}A\)
- \(sgamb \quad ^{-2\text{gamma}}B\)
- \(sgamc \quad ^{-2\text{gamma}}C\)

Verification:

(Note testing only complete for reciprocal networks.)

c three.ckt
C ! FILE FOR TESTING THREE PORT DEEMBEDDING
C DIM
C FREQ MHZ
C CKT
C PRC 1 0 R=50 C=1
C PRC 2 0 R=30 C=10
C PRC 3 0 R=100 C=.1
C RES 1 2 R=10
C RES 3 2 R=1
C RES 1 3 R=1000
C DEF3P 1 2 3 THREE THREE.S3P
C OUT
C THREE MAG[S11]
C THREE MAG[S11]
C THREE MAG[S21]
THREE ANG[521]
THREE MAG[512]
THREE ANG[512]
THREE MAG[522]
THREE ANG[522]
FREQ
STEP 1000

This generated the three port S parameters.

```
three.s3p:
1000.00  0.599 -169.851  0.221 -33.476  0.214 -33.475
0.221 -33.476  0.752 -167.835  0.299 -30.961
0.214 -33.475  0.299 -30.961  0.728 -168.129
```

A 60 ohm resistor was placed at port 1 to get the S parameters of measurement configuration A. The circuit file then looked like

```
PRC 1 0 R=50 C=1
PRC 2 0 R=30 C=10
PRC 3 0 R=100 C=.1
RES 1 2 R=10
RES 3 2 R=1
RES 1 3 R=1000
RES 1 0 R=60
DEF3P 2 3 THREE MEASA1.S2P
```

Similarly 70 ohms was placed at port 1 to get measa2.s2p
Similarly 10 ohms was placed at port 2 to get measb1.s2p
Similarly 5 ohms was placed at port 2 to get measb2.s2p
Similarly 6 ohms was placed at port 3 to get measc1.s2p
Similarly 45 ohms was placed at port 3 to get measc2.s2p

```
load1.s2p:
1000.  0.090909  0. -0.666666  0. -0.7857  0.  0.  0.
```

```
load2.s2p:
1000.  0.16666  0. -0.818181  0. -0.5263  0.  0.  0.
```

```
measa1.s2p:
1000.00  0.752 -167.520  0.303 -31.421  0.303 -31.421  0.727 -167.821
```

```
measa2.s2p:
1000.00  0.751 -167.280  0.305 -31.770  0.305 -31.770  0.726 -167.587
```

```
measb1.s2p:
1000.00  0.627 -175.038  0.137 -21.762  0.137 -21.762  0.788 -175.525
```

```
measb2.s2p:
1000.00  0.653 -177.033  0.093 -15.439  0.093 -15.439  0.839 -178.065
```

```
measc1.s2p:
1000.00  0.639 -176.141  0.118 -18.531  0.118 -18.531  0.842 -176.896
```
C measc2.s2p:
C 1000.00 0.599 -170.085 0.218 -33.007 0.218 -33.007 0.754 -168.193
C
C
C C
C **************************** SPANA ****************************
C
C get meas 1 file=load1.s2p
C  Default input format is MAGANG
C get meas 2 file=load2.s2p
C  Default input format is MAGANG
C get meas 3 file=meas1.s2p
C  Default input format is MAGANG
C get meas 4 file=meas2.s2p
C  Default input format is MAGANG
C get meas 5 file=measb1.s2p
C  Default input format is MAGANG
C get meas 6 file=measb2.s2p
C  Default input format is MAGANG
C get meas 7 file=measc1.s2p
C  Default input format is MAGANG
C get meas 8 file=measc2.s2p
C  Default input format is MAGANG
C dmb3 measa1=3 measa2=4 measb1=5 measb2=6 measc1=7 measc2=8 \nC load1=1 load2=2 dest=9
C
C * put meas 9
C  1000.0000 0.59842 -169.85 0.22104 -33.48 0.21382 -33.49
C   0.22104 -33.48 0.75168 -167.80 0.30034 -30.96
C   0.21382 -33.49 0.30034 -30.96 0.72729 -168.10
C
C * stop
C
C subroutine spdb3(parmx,parmy,parmf,arg,noarg,ident)
C
C real parmX(mxarg,mxparm,mxmeas),parmy(mxarg,mxparm,mxmeas)
C real arg(mxarg,mxmeas),parmf(mxform,mxmeas)
C integer noarg(mxmeas)
C common/parmax/mxarg,mxmeas,mxparm,mxform
C character*80 ident(mxmeas)
C character*40 str
C logical kf,fin,prt,ofile,rfile,pecho
C common/freerd/write,ntype,avai,ival,ich,kf,fin,prt
C + ,ofile,rfile,pecho,str
C logical lmeas1,lmeasb1,lmeasc1,load1
C logical lmeas2,lmeasb2,lmeasc2,load2
C logical ldest
C integer meas1,measb1,measc1,meas2,measb2,measc2,load1,load2
integer dest, destp1, destp2
complex ptor, sdm\(b\)(3,3)
complex f\(s2\)a, f\(s3\)a, f\(s3\)d, f\(s2\)a, s\(s2\)a, s\(s3\)a, s\(s3\)a, s\(s2\)a, s\(s2\)a
complex f\(s1\)b, f\(s3\)b, f\(s3\)b, f\(s1\)b, s\(s1\)b, s\(s3\)b, s\(s3\)b, s\(s1\)b, s\(s1\)b
complex f\(s1\)c, f\(s2\)c, f\(s2\)c, f\(s1\)c, s\(s1\)c, s\(s2\)c, s\(s2\)c, s\(s1\)c, s\(s1\)c
complex fgama, fgam\(b\), fgam\(c\), sgama, sgam\(b\), sgam\(c\)
complex a, b, c, d, e, f, g, h, i, j, k, l, m, n, o
complex num\(i\), denom\(i\), num\(2\), denom\(2\), num\(3\), denom\(3\)
complex one
data one/(1.0, 0.0)/
c
pi=3.1415927
r\(t\)d=180./pi
c
call fre\(d\)
c
if(str(1:4).eq.'HELP'.or.str(1:4).eq.'help')then
c  call qsmode(2)
write(ntype,50)
if(prt)write(nwrite,50)
50 format(''
  + '#### DMB3  Deembedding of Three Ports############',/',
  + 'Usage:','/',
  + '  DMB3 HELP','/',
  + '    : This Message','/',
  + '    DMB3 MEAS\(A\)= n1 MEAS\(B\)= n2 MEASC\(1\)= n3 LOAD\(1\)= n4 ','/
  + '    MEAS\(A\)= n5 MEAS\(B\)= n6 MEAS\(C\)= n7 LOAD\(2\)= n8 ','/
  + '    DEST = n9 ','/
  + '    Note: The output will be a three port. Three ','/
    measurement sets are required to store all','/
    of the parameters. n9, (n9+1) and (n9+2) are','/
    used to store the output','/"
)
return
endif
c
RESET PARAMETER FLAGS (used to test that all parameters have been input)
c
lmeas\(a\)=.false.
lmeas\(b\)=.false.
lmeas\(c\)=.false.
lmeas\(a\)=.false.
lmeas\(b\)=.false.
lmeas\(c\)=.false.
ldest=.false.
lload\(1\)=.false.
lload\(2\)=.false.
c
PARSE REST OF COMMAND LINE
c
100 if(fin)goto 150
if(str(1:6).eq.'MEAS\(A\)'.or.str(1:6).eq.'meas\(a\)')then
call fre\(d\)
meas\(a\)=.ival
if(meas\(a\).lt.1.or.meas\(a\).gt.mrmeas.or.parmf(3,meas\(a\)).eq.0.)then
write(notype,*)' Measurement set not available'
goto 600
endif
lmeas1=.true.
elseif(str(1:6).eq.'MEASA2'.or.str(1:6).eq.'measa2')then
call fread
measa2=ival
if(measa2.lt.1.or.measa2.gt.mxmeas.or.parmf(3,measa2).eq.0.)then
  write(notype,*)' Measurement set not available'
goto 600
endif
lmeas2=.true.
elseif(str(1:6).eq.'MEASB1'.or.str(1:6).eq.'measb1')then
call fread
measb1=ival
if(measb1.lt.1.or.measb1.gt.mxmeas.or.parmf(3,measb1).eq.0.)then
  write(notype,*)' Measurement set not available'
goto 600
endif
lmeasb1=.true.
elseif(str(1:6).eq.'MEASB2'.or.str(1:6).eq.'measb2')then
call fread
measb2=ival
if(measb2.lt.1.or.measb2.gt.mxmeas.or.parmf(3,measb2).eq.0.)then
  write(notype,*)' Measurement set not available'
goto 600
endif
lmeasb2=.true.
elseif(str(1:6).eq.'MEASC1'.or.str(1:6).eq.'measc1')then
call fread
measc1=ival
if(measc1.lt.1.or.measc1.gt.mxmeas.or.parmf(3,measc1).eq.0.)then
  write(notype,*)' Measurement set not available'
goto 600
endif
lmeasc1=.true.
elseif(str(1:6).eq.'MEASC2'.or.str(1:6).eq.'measc2')then
call fread
measc2=ival
if(measc2.lt.1.or.measc2.gt.mxmeas.or.parmf(3,measc2).eq.0.)then
  write(notype,*)' Measurement set not available'
goto 600
endif
lmeasc2=.true.
elseif(str(1:5).eq.'LOAD1'.or.str(1:5).eq.'load1')then
call fread
load1=ival
if(load1.lt.1.or.load1.gt.mxmeas.or.parmf(3,load1).eq.0.)then
  write(notype,*)' Measurement set not available'
goto 600
endif
lload1=.true.
elseif(str(1:5).eq.'LOAD2'.or.str(1:5).eq.'load2')then
call fread
load2=ival
if(load2.lt.1.or.load2.gt.mxmeas.or.parmf(3,load2).eq.0.)then
  write(ntype,*)' Measurement set not available'
goto 600
endif
llload2=.true.
elseif(str(1:4).eq.'DEST'.or.str(1:4).eq.'dest')then
  call fread
dest=ival
destp1=dest+1
destp2=dest+2
if(destp2.gt.mxmeas)then
  write(ntype,*)' Destination Measurement Set not available'
  write(ntype,*)' Three consecutive Measurement Sets must be'
  write(ntype,*)' available for three port deembedding.'
goto 600
endif
if(dest.lt.1)then
  write(ntype,*)' Destination Measurement Set not available'
goto 600
endif
if(parmf(3,dest).ne.0.)
  write(ntype,*)'Measurement set ',dest,' will be overwritten.'
if(parmf(3,destp1).ne.0.)
  write(ntype,*)'Measurement set ',dest,' will be overwritten.'
if(parmf(3,destp2).ne.0.)
  write(ntype,*)'Measurement set ',dest,' will be overwritten.'
dest=.true.
endif
call fread
goto 100

c Check that all parameters have been specified

150 if(lmeas1.eqv..false..or.
  + lmeas1.eqv..false..or.
  + lmeas1.eqv..false..or.
  + lmeas1.eqv..false..or.
  + lmeas1.eqv..false..or.
  + lmeas1.eqv..false..or.
  + lmeas1.eqv..false..or.
  + lmeas1.eqv..false..or.
  + lmeas1.eqv..false..or.
  + llload2.eqv..false..or.
  + llload1.eqv..false.)then
  write(ntype,*)' Not enough parameters specified in command line'
goto 600
endif

c Test status of input measurement set

c if (parmf(2,measai).ne.1..or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
  + parmfi(measai).ne.1. .or. parmfi(measai).ne.1. .or.
  + parmfi(measai).eq.0..or.
parmf(3,measc1).eq.0 . or.
+ parmf(2,measc2).ne.1 . or. parmf(1,measc2).ne.1 . or.
+ parmf(3,measc2).eq.0 . or.
+ parmf(2,load1).ne.1 . or. parmf(1,load1).ne.1 . or.
+ parmf(3,load1).eq.0 . or.
+ parmf(2,load2).ne.1 . or. parmf(1,load2).ne.1 . or.
+ parmf(3,load2).eq.0 .)

write(notype,*)' Invalid input measurement set(s). Two port S'
write(notype,*)' parameters in angle magnitude form required.'
endif

ccccc

NOW IMPLEMENT THREE PORT DEEMBEDDING

De-embedding loop, cycle through the frequencies.
do 10 nn=1,noarg(meas1)
  Prepare standard for calculation
    fgam1=ptor(parmx(nn,1,load1),parmx(nn,1,load1))
    fgam2=ptor(parmx(nn,2,load1),parmx(nn,2,load1))
    fgam3=ptor(parmx(nn,3,load1),parmx(nn,3,load1))
    sgam1=ptor(parmx(nn,1,load2),parmx(nn,1,load2))
    sgam2=ptor(parmx(nn,2,load2),parmx(nn,2,load2))
    sgam3=ptor(parmx(nn,3,load2),parmx(nn,3,load2))

    fs11c=ptor(parmx(nn,1,measc1),parmx(nn,1,measc1))
    fs21c=ptor(parmx(nn,2,measc1),parmx(nn,2,measc1))
    fs31c=ptor(parmx(nn,3,measc1),parmx(nn,3,measc1))
    fs11b=ptor(parmx(nn,1,measb1),parmx(nn,1,measb1))
    fs21b=ptor(parmx(nn,2,measb1),parmx(nn,2,measb1))
    fs31b=ptor(parmx(nn,3,measb1),parmx(nn,3,measb1))
    fs33b=ptor(parmx(nn,4,measb1),parmx(nn,4,measb1))
    fs22a=ptor(parmx(nn,1,meas1),parmx(nn,1,meas1))
    fs32a=ptor(parmx(nn,2,meas1),parmx(nn,2,meas1))
    fs33a=ptor(parmx(nn,3,meas1),parmx(nn,3,meas1))

    ss11c=ptor(parmx(nn,1,measc2),parmx(nn,1,measc2))
    ss21c=ptor(parmx(nn,2,measc2),parmx(nn,2,measc2))
    ss31c=ptor(parmx(nn,3,measc2),parmx(nn,3,measc2))
    ss11b=ptor(parmx(nn,1,measb2),parmx(nn,1,measb2))
    ss31b=ptor(parmx(nn,2,measb2),parmx(nn,2,measb2))
    ss33b=ptor(parmx(nn,4,measb2),parmx(nn,4,measb2))
    ss22a=ptor(parmx(nn,1,meas2),parmx(nn,1,meas2))
    ss32a=ptor(parmx(nn,2,meas2),parmx(nn,2,meas2))
    ss33a=ptor(parmx(nn,3,meas2),parmx(nn,3,meas2))
  ss33a=ptor(parmx(nn,4,meas2),parmx(nn,4,meas2))
a = fgama*fs11c - fgamc*fs33a
b = fgamc * (fgama*fs11c - one)
c = fgama * (one - fgamc*fs33a)
d = fgamb*fs22c - fgamc*fs33b
e = fgamc * (fgamb*fs22c - one)
f = fgamb * (one - fgamc*fs33b)
g = fgama*fs11b - fgamb*fs22a
h = fgamb * (fgama*fs11b - one)
i = fgama * (one - fgamb*fs22a)
j = fgama*ss11c - sgamc*fs33a
k = sgamc * (fgama*ss11c - one)
l = fgama * (one - sgamc*fs33a)
m = sgamb*fs22c - fgamc*ss33b
n = fgamc * (sgamb*fs22c - one)
o = sgamb * (one - fgamc*fs33b)

cnum1 = k*a - b*j
denom1 = k*c - b*l
num2 = n*d - m*e
denom2 = f*n - e*o
num3 = o*d - m*f
denom3 = o*e - n*f
c
if(denom1.ne.(0.,0.) .and. denom2.ne.(0.,0.) .and. 
   + denom3.ne.(0.,0.) .and. sgamc.ne.fgama .and. 
   + sgamb.ne.fgamb .and. sgama.ne.fgama)then

sdmb(1,1) = num1 / denom1 
sdmb(2,2) = num2 / denom2 
sdmb(3,3) = num3 / denom3

c
else

sdmb(1,1)=(0.,0.)
sdmb(1,2)=(0.,0.)
sdmb(1,3)=(0.,0.)
sdmb(2,1)=(0.,0.)
sdmb(2,2)=(0.,0.)
sdmb(2,3)=(0.,0.)
sdmb(3,1)=(0.,0.)
sdmb(3,2)=(0.,0.)
sdmb(3,3)=(0.,0.)

write(*,*)'Insufficient resolution to deembed at frequency', 
   + 'arg(un,measal)
goto 399
endif
c
sdmb(1,2) = (sgamc*fs12c - fgamc*ss12c 
   + fgamc*sgamc*sdmb(3,3)*c*ss12c)/(sgmc-fgmc)

sdmb(2,1) = (sgamc*fs21c - fgamc*ss21c 
   + fgamc*sgamc*sdmb(3,3)*c*ss21c)/(sgmc-fgmc)

sdmb(2,3) = (sgama*fs31a - fgama*ss31a 
   + fgama*sgama*sdmb(1,1)*c*ss31a)/(sgama-fgama)

sdmb(3,2) = (sgama*fs32a - fgama*ss32a
\[ sdbm(3,1) = \frac{(sgamb*fsi3b - fgamb*ss3ib) + (sgamb*ss3ib - fsi3b)}{(sgamb*fgamb)} \]

\[ sdbm(1,3) = \frac{(sgamb*ss3ib - fsi3b) + (fgamb*sgamb*sdbm(2,2)*(ss13b-fsi13b))}{(sgamb*fgamb)} \]

Output De-embedded result to destination set

399 do 401 jj=1,3
do 400 ii=1,3
  parmx(nn,ii,dest+jj-1)=cabs(sdbm(ii,jj))
  parmy(nn,ii,dest+jj-1)=atan2(imag(sdbm(ii,jj)),
               real(sdbm(ii,jj)))*rtd
400 continue
  parmx(nn,4,dest+jj-1)=0.0
  parmy(nn,4,dest+jj-1)=0.0
401 continue

Transfer frequency array from measurement to destination

arg(nn,dest)=arg(nn,meas1)

Zero frequency entries of auxiliary destination measurement sets as a reminder.

arg(nn,destp1)=0.0
arg(nn,destp1)=0.0
10 continue

Set-up descriptors

parmf(1,dest)=3.
parmf(1,destp1)=4.
parmf(1,destp2)=5.
parmf(2,dest)=1.
parmf(2,destp1)=1.
parmf(2,destp2)=1.
parmf(3,dest)=3.
parmf(3,destp1)=3.
parmf(3,destp2)=3.
parmf(4,dest)=parmf(4,meas1)
parmf(4,destp1)=parmf(4,meas1)
parmf(4,destp2)=parmf(4,meas1)
parmf(5,dest)=1.
parmf(5,destp1)=2.
parmf(5,destp2)=3.

Copy number of data points to destination and error sets

noarg(dest)=noarg(meas1)
noarg(destp1)=noarg(meas1)
oarg(destp2)=noarg(meas1)

Copy number of data points to destination and error sets

ident(dest)= 'Three port deembedded result (DMB3). Part 1 of 3.'
ident(destp1)= 'Three port deembedded result (DMB3). Part 2 of 3.'
ident(destp2)=' Three port deembedded result (DMB3). Part 3 of 3.'
return
600 write(ntype,*)' Command Error -- Command Ignored'
return
end
Appendix C

SPANA Woods Renormalization Code for 3 Port

Deembedding

```
c........................................................................
c  SPWOOD3
c  PURPOSE:
c  De-embeds a three port using Wood's method.
c  METHOD:
c  D. Woods, "Multi-port network analysis by matrix
  renormalization employing voltage-wave S-parameters with
c  
  VARIABLES:
c  
  subroutine spwood3(parmx,parmy,parmf,arg,noarg,ident)
c  real parmx(mxarg,mxparm,mxmeas),parmy(mxarg,mxparm,mxmeas)
c  real arg(mxarg,mxmeas),parmf(mxform,mxmeas)
c  integer noarg(mxmeas)
c  common/parmx,mxarg,mxmeas,mxparm,mxform
  character*80 ident(mxmeas)
c  character*40 str
  logical kf,fin,prt,ofile,rfile,pecho
  common/freerd/nwrite,ntype,aval,ival,ich,kf,fin,pnt
  +ofile,rfile,pecho,str
  logical lmeas1,lmeas2,lmeas3,ldest,lstan
  integer meas1,meas2,meas3,dest,stan
c  call fread
c  if(str(1:4).eq.'HELP'.or.str(1:4).eq.'help')then
c    call qsmode(2)
c  call write(ntype,50)
c  if(prt)write(nwrite,50)
c50 format(
c    +'## Three Port Deembedding Using Wood’s Method (WOOD3) ##',/,
c    +'Usage:/',/,
c    +'WOOD3 MEAS1 = n1 MEAS2 = n2 MEAS3 = n3 ',/,
c```

c    + ' DEST = n4 STAN = n5 ',//,
c    + ' #aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa')
return
endif

c RESET PARAMETER FLAGS (used to test that all parameters have been input)
c lmeas1=.false.
lmeas2=.false.
lmeas3=.false.
ldest=.false.
lstan=.false.
c PARSE REST OF COMMAND LINE
c
100 if(fin)goto 150
if(str(1:5).eq.'MEAS1'.or.str(1:5).eq.'meas1')then
call fread
meas1=ival
if(meas1.lt.1.or.meas1.gt.mxmeas.or.parmf(3,meas1).eq.0.)then
    write(*,*)' Measurement set not available'
go to 600
endif
lmeas1=.true.
elseif(str(1:5).eq.'MEAS2'.or.str(1:5).eq.'meas2')then
call fread
meas2=ival
if(meas2.lt.1.or.meas2.gt.mxmeas.or.parmf(3,meas2).eq.0.)then
    write(*,*)' Measurement set not available'
go to 600
endif
lmeas2=.true.
elseif(str(1:5).eq.'MEAS3'.or.str(1:5).eq.'meas3')then
call fread
meas3=ival
if(meas3.lt.1.or.meas3.gt.mxmeas.or.parmf(3,meas3).eq.0.)then
    write(*,*)' Measurement set not available'
go to 600
endif
lmeas3=.true.
elseif(str(1:4).eq.'DEST'.or.str(1:4).eq.'dest')then
call fread
dest=ival
if(dest.lt.1.or.dest.gt.mxmeas)then
    write(*,*)' Destination Measurement Set not available'
go to 600
endif
ldest=.true.
elseif(str(1:4).eq.'STAN'.or.str(1:4).eq.'stan')then
call fread
stan=ival
if(stan.lt.1.or.stan.gt.mxmeas)then
    write(*,*)' Standard set not available'
go to 600
endif
lstan=.true.
endif
call fread
goto 100
c
c Check that all parameters have been specified
c
if(lstan .eqv. .false. .or. 
   ldest .eqv. .false. .or. 
   lmeas1 .eqv. .false. .or. 
   lmeas2 .eqv. .false. .or. 
   lmeas3 .eqv. .false.) then
   write(ntype,*) 'Not enough parameters specified in command line'
goto 600
endif
c
if(meas1.eq.dest .or. meas1.eq.dest+1 .or. meas1.eq.dest+2 .or. 
   meas2.eq.dest .or. meas2.eq.dest+1 .or. meas2.eq.dest+2 .or. 
   meas3.eq.dest .or. meas3.eq.dest+1 .or. meas3.eq.dest+2) then
   write(ntype,*) 'Measurement and Destination sets conflict'
   write(*,*) 'Three consecutive locations required to store three port'
   write(*,*) 'deembedded result.'
goto 600
endif
c
Test status of input measurement set
c
if (parmf(2,meas1).ne.1. .or. parmf(1,meas1).ne.1. .or. 
   parmf(3,meas1).eq.0. .or. 
   parmf(2,meas2).ne.1. .or. parmf(1,meas2).ne.1. .or. 
   parmf(3,meas2).eq.0. .or. 
   parmf(2,meas3).ne.1. .or. parmf(1,meas3).ne.1. .or. 
   parmf(3,meas3).eq.0. .or. 
   parmf(2,stan).ne.1. .or. parmf(1,stan).ne.1. .or. 
   parmf(3,stan).eq.0.) then
   write(ntype,*) 'Invalid input measurement set(s). Two port S'
   write(ntype,*) 'parameters in angle magnitude form required.'
goto 600
endif
c
Test status of destination measurement set
c
if(dest+2 .gt. mxmeas) then
   write(*,*) 'Not enough room to store three port deembedded result.'
   write(*,*) 'Three consecutive locations required.'
goto 600
endif
if(parmf(3,dest).ne.0.)
   write(ntype,*) 'Measurement set ',dest,' will be overwritten.'
if(parmf(3,dest+1).ne.0.)
   write(ntype,*) 'Measurement set ',dest+1,' will be overwritten.'
if(parmf(3,dest+2).ne.0.)
   write(ntype,*) 'Measurement set ',dest+2,' will be overwritten.'
c Clear Destination Set
do 170 i=1,mxparm
do 170 j=1,mxarg
  parmz(j,i,dest)=0.0
  parmx(j,i,dest)=0.0
  parmx(j,i,dest+1)=0.0
  parmx(j,i,dest+1)=0.0
  parmx(j,i,dest+2)=0.0
  parmx(j,i,dest+2)=0.0
  continue

call wood3x(meas1,meas2,meas3,stan,dest,parmx,parmx,parmx,arg, +
             noarg,ident)
return

600 write(ntype,*)' Command Error -- Command Ignored'
return
end

WOOD3X

PURPOSE:
De-embeds a three port using Wood's method.

\[ \begin{array}{cc}
\begin{array}{ccc}
3 & & \\
\multicolumn{2}{c}{o} & o \\
\multicolumn{2}{c}{|} & | \\
\multicolumn{2}{c}{o----|} & \|
\end{array}
\end{array} \]

\[ \begin{array}{cc}
1 & & 2 \\
\multicolumn{2}{c}{|} & | \\
\multicolumn{2}{c}{|-----o} & \|
\end{array} \]

Three two port measurements are required.

meas1: Two port between ports 2 and 3 with a termination at port 1
       the reflection coefficient contained in the 11 position of
       the stan measurements set.

meas2: Two port between ports 1 and 3 with a termination at port 2
       the reflection coefficient contained in the 12 position of
       the stan measurements set.

meas3: Two port between ports 1 and 2 with a termination at port 3
       the reflection coefficient contained in the 21 position of
       the stan measurements set.

VARIABLES: (Related to user's guide variables -- in \LaTeX\ form)

( _ subscript \quad ^ superscript \quad \{ \} groups )
subroutine wood3x(meas1, meas2, meas3, stan, dest, parmx, parmy, parmf, arg, 
                noarg, ident)
  c
real parmx(mxarg, mxparm, mxmeas), parmy(mxarg, mxparm, mxmeas)
real arg(mxarg, mxmeas), parmf(mxform, mxmeas)
integer noarg(mxmeas)
common/parmax/mxarg, mxmeas, mxparm, mxform
  c
character*80 ident(mxmeas)
integer meas1, meas2, meas3, stan, dest
complex ptor, s(3,3)
complex gamma1, gamma2, gamma3, zi, z2, z3, d, c44
complex delta1, delta21, delta31
complex delta12, delta22, delta32
complex delta13, delta23, delta33
complex s11, s21, s31, s12, s22, s32, s13, s23, s33
complex sr11, sr21, sr31, sr12, sr22, sr32, sr13, sr23, sr33
complex one, zo
real pi
data one, pi/(1.0, 0.0), 3.1415927/
  c
rtd=180./pi
  c
define measurement reference impedance
zo = (50., 0.)
  c
  c
  c
NOW IMPLEMENT THREE PORT DEEMBEDDING
  c
  c
---------------------------------------------------------------------------------
  c
De-embedding loop, cycle through the frequencies.
  c
do 10 nn=1, noarg(measi)
  c
Prepare standard for calculation
  c
c get normalizing impedances
  gamma1=ptor(parmx(nn, 1, stan), parmy(nn, 1, stan))
  z1 = zo * ( one + gamma1) / (one - gamma1)
  gamma2=ptor(parmx(nn, 2, stan), parmy(nn, 2, stan))
  z2 = zo * ( one + gamma2) / (one - gamma2)
  gamma3=ptor(parmx(nn, 3, stan), parmy(nn, 3, stan))
  z3 = zo * ( one + gamma3) / (one - gamma3)
  c
normalize port 2 - port 3 measurement
  s(1,1)=ptor(parmx(nn, 1, meas1), parmy(nn, 1, meas1))
  s(1,2)=ptor(parmx(nn, 3, meas1), parmy(nn, 3, meas1))
  s(2,1)=ptor(parmx(nn, 2, meas1), parmy(nn, 2, meas1))
  s(2,2)=ptor(parmx(nn, 4, meas1), parmy(nn, 4, meas1))
call wood2(s, zo, zo, z2, z3)
s22 = s(1,1)
s23 = s(1,2)
s32 = s(2,1)
\( s_{33} = s(2,2) \)

c normalize port 1 - port 3 measurement
\[
\begin{align*}
    s(1,1) &= \text{ptor}(\text{parmx}(mn,1,\text{meas2}),\text{parmy}(mn,1,\text{meas2})) \\
    s(1,2) &= \text{ptor}(\text{parmx}(mn,3,\text{meas2}),\text{parmy}(mn,3,\text{meas2})) \\
    s(2,1) &= \text{ptor}(\text{parmx}(mn,2,\text{meas2}),\text{parmy}(mn,2,\text{meas2})) \\
    s(2,2) &= \text{ptor}(\text{parmx}(mn,4,\text{meas2}),\text{parmy}(mn,4,\text{meas2})) \\
\end{align*}
\]
call \text{wood2}(s,zo,zo,z1,z3)
\[
\begin{align*}
    s11 &= s(1,1) \\
    s13 &= s(1,2) \\
    s31 &= s(2,1) \\
    s33 &= s(2,2) \\
\end{align*}
\]
c normalize port 1 - port 2 measurement
\[
\begin{align*}
    s(1,1) &= \text{ptor}(\text{parmx}(mn,1,\text{meas3}),\text{parmy}(mn,1,\text{meas3})) \\
    s(1,2) &= \text{ptor}(\text{parmx}(mn,3,\text{meas3}),\text{parmy}(mn,3,\text{meas3})) \\
    s(2,1) &= \text{ptor}(\text{parmx}(mn,2,\text{meas3}),\text{parmy}(mn,2,\text{meas3})) \\
    s(2,2) &= \text{ptor}(\text{parmx}(mn,4,\text{meas3}),\text{parmy}(mn,4,\text{meas3})) \\
\end{align*}
\]
call \text{wood2}(s,zo,zo,z1,z2)
\[
\begin{align*}
    s11 &= s(1,1) \\
    s12 &= s(1,2) \\
    s21 &= s(2,1) \\
\end{align*}
\]
c \text{******************************************************************************}
\text{c}
\text{c Implement woods transformation to convert to a 50 ohm system}
\[
\begin{align*}
    \text{delta11} &= s22*s33 - s23*s32 \\
    \text{delta12} &= s23*s31 - s21*s33 \\
    \text{delta13} &= s21*s32 - s22*s31 \\
    \text{delta21} &= s13*s32 - s12*s33 \\
    \text{delta22} &= s11*s33 - s13*s31 \\
    \text{delta23} &= s12*s31 - s11*s32 \\
    \text{delta31} &= s12*s23 - s13*s22 \\
    \text{delta32} &= s13*s21 - s11*s23 \\
    \text{delta33} &= s11*s22 - s12*s21 \\
\end{align*}
\]
\[
\begin{align*}
    c44 &= s11*\text{delta11} + s12*\text{delta12} + s13*\text{delta13} \\
    d &= 1 - \text{gamma1}*s11 - \text{gamma2}*s22 - \text{gamma3}*s33 + \text{gamma2*gamma3*delta11} \\
        &+ \text{gamma1*gamma2*gamma3*delta22} + \text{gamma1*gamma2*delta33} \\
        &+ \text{gamma1*gamma2*gamma3*c44} \\
\end{align*}
\]
dinv = (1.,0.)/d
\[
\begin{align*}
    \text{c get renormalized s parameters}
\end{align*}
\]
\[
\begin{align*}
    \text{sr11} &= \text{dinv} * (s11 - \text{gamma1} - \gammaa*\gammab*\gammac*\deltaa11 \\
        &+ \gammaa*\deltaaa22 - \gammaa*\deltaaa33 + \gammaa*\gammab*\gammac*\s22 \\
        &+ \gammaa*\gammab*\gammac*\s33 + \gammaa*\gammab*\gammac*\s44) \\
    \text{sr22} &= \text{dinv} * (s22 - \gammaa*\gammab*\gammac*\deltab22 \\
        &+ \gammaa*\deltab33 - \gammaa*\deltab11 + \gammaa*\gammab*\s11 \\
        &+ \gammaa*\gammab*\s33 + \gammaa*\gammab*\s44) \\
    \text{sr33} &= \text{dinv} * (s33 - \gammaa*\gammab*\gammac*\deltac33 \\
        &+ \gammaa*\deltac11 - \gammaa*\deltac22 + \gammaa*\gammab*\gammac*\s11 \\
        &+ \gammaa*\gammab*\s22 + \gammaa*\gammab*\s44) \\
\end{align*}
\]
\[
\begin{align*}
    \text{sr12} &= \text{dinv} * (\gammaa*\gammab*\gammac*\s12 + \gammaa*\gammab*\gammac*\s11 \\
    \text{sr13} &= \text{dinv} * (\gammaa*\gammab*\gammac*\s13 + \gammaa*\gammab*\gammac*\s11 \\
    \text{sr21} &= \text{dinv} * (\gammaa*\gammab*\gammac*\s21 + \gammaa*\gammab*\gammac*\s12 \\
    \text{sr23} &= \text{dinv} * (\gammaa*\gammab*\gammac*\s23 + \gammaa*\gammab*\gammac*\s12 \\
    \text{sr31} &= \text{dinv} * (\gammaa*\gammab*\gammac*\s31 + \gammaa*\gammab*\gammac*\s13 \\
\end{align*}
\]
sr32 = dinv*(one - gamma2)*(one + gamma3)*(s32 + gamma1*delta23)
c c Output De-embedded result to destination set
c
c parms(n,1,dest)=cabs(sr11)
parmy(n,1,dest)=atan2(aimag(sr11),real(sr11))*rtd
parm(n,2,dest)=cabs(sr12)
parmy(n,2,dest)=atan2(aimag(sr12),real(sr12))*rtd
parm(n,3,dest)=cabs(sr13)
parmy(n,3,dest)=atan2(aimag(sr13),real(sr13))*rtd
parm(n,1,dest+1)=cabs(sr21)
parmy(n,1,dest+1)=atan2(aimag(sr21),real(sr21))*rtd
parm(n,2,dest+1)=cabs(sr22)
parmy(n,2,dest+1)=atan2(aimag(sr22),real(sr22))*rtd
parm(n,3,dest+1)=cabs(sr23)
parmy(n,3,dest+1)=atan2(aimag(sr23),real(sr23))*rtd
parm(n,1,dest+2)=cabs(sr31)
parmy(n,1,dest+2)=atan2(aimag(sr31),real(sr31))*rtd
parm(n,2,dest+2)=cabs(sr32)
parmy(n,2,dest+2)=atan2(aimag(sr32),real(sr32))*rtd
parm(n,3,dest+2)=cabs(sr33)
parmy(n,3,dest+2)=atan2(aimag(sr33),real(sr33))*rtd
c c Transfer frequency array from measurement to destination
c
c arg(n,dest)=arg(n,meas1)
c c Zero frequency entries of auxilliary destination measurement sets as a
 c reminder:
 arg(n,dest+1)=0.0
c arg(n,dest+2)=0.0
10 continue

c c Set-up descriptors
c
c parmf(1,dest)=3.
parmf(1,dest+1)=4.
parmf(1,dest+2)=5.
parmf(2,dest)=1.
parmf(2,dest+1)=1.
parmf(2,dest+2)=1.
parmf(3,dest)=3.
parmf(3,dest+1)=3.
parmf(3,dest+2)=3.
parmf(4,dest)=parmf(4,meas1)
parmf(4,dest+1)=parmf(4,meas1)
parmf(4,dest+2)=parmf(4,meas1)
parmf(5,dest)=1.
parmf(5,dest+1)=2.
parmf(5,dest+2)=3.
c c Copy number of data points to destination and error sets
c
noarg(dest)=noarg(meas1)
noarg(dest+1)=noarg(meas1)
noarg(dest+2)=noarg(meas1)
Copy number of data points to destination and error sets

ident(dest)="Three port deembedded result (WOOD3). Part 1 of 3."
ident(dest+1)="Three port deembedded result (WOOD3). Part 2 of 3."
ident(dest+2)="Three port deembedded result (WOOD3). Part 3 of 3."

return

cccc

600 write(notype,*), 'Command Error -- Command Ignored'
return
end

*****************************************************************************
Wood2

Transforms 2 port data with different port impedances
to 2 port data with other port impedances

*****************************************************************************

subroutine wood2(s,z1,z2,zo1,zo2)

complex s(2,2),z1,z2,zo1,zo2
complex one,demn,gam1,gam2,del33,z11,z12,z21,z22
c
one=(1.0,0.0)
gam1=(z1-zo1)/(z1+zo1)
gam2=(z2-zo2)/(z2+zo2)
del33=s(1,1)*s(2,2)-s(1,2)*s(2,1)
demn=one-gam1*s(1,1)-gam2*s(2,2)+gam1*gam2*del33
c
z11=(s(1,1)-gam1-gam2*del33+gam1*gam2*s(2,2))/demn
z12=(one+gam1)*(1-gam2)*s(1,2)/demn
z21=(one-gam1)*(1+gam2)*s(2,1)/demn
z22=(s(2,2)-gam2-gam1*del33+gam1*gam2*s(1,1))/demn
c
s(1,1)=z11
s(1,2)=z12
s(2,1)=z21
s(2,2)=z22
c
return
end