NBS TECHNICAL NOTE 663

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Characterization of a High Frequency Probe Assembly for Integrated Circuit Measurements

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CHARACTERIZATION OF A HIGH FREQUENCY PROBE ASSEMBLY FOR INTEGRATED CIRCUIT MEASUREMENTS

A detailed, applications-oriented description of a measurement technique that characterizes a high-frequency probe assembly for integrated circuit measurements is given along with the procedure that extracts the parasitic effects of the probe assembly from measurements made at the input connectors of the probe assembly. The scattering parameters of an integrated-circuit device or transistor can now be extracted and accurately determined up to 2 GHz at the wafer stage of assembly. This represents a significant advance over conventional techniques that enable only dc parameters to be measured. Measurement results using this technique are given along with the precision of values obtained as well as the nature of the measurement bias introduced by the probe assembly.

KEY WORDS: High frequency probe assembly; integrated circuit transistors; parasitic element; S-parameters.

1. INTRODUCTION

In response to a request from the Air Force Weapons Laboratory (AFWL), the National Bureau of Standards, in 1971, undertook a project to assist in improving instrumentation and procedures utilized in measurements associated with the prediction of the effects of nuclear radiation on semiconductor devices. The work performed during the period January 1971 to August 1972 was reported in AFWL Report AFWL-TR-73-54, "Measurement of Transit Time and Related Transistor Characteristics" [1].

That report discussed some of the causes of discrepancies in the measurement of transistor transit time. In addition, a test plan for an interlaboratory comparison of transistor S-parameter measurements was outlined, special high-frequency probe assemblies (see fig. 1) for measuring the characteristics of transistors in integrated-circuit wafers were described, and techniques were developed for determining the equivalent circuit representation of these probe assemblies in the 0.2 to 2 GHz frequency range.

The work performed during the period September 1972 to July 1973 was reported in NBS Special Publication 400-5, Semiconductor Measurement Technology: "Measurement of Transistor Scattering Parameters" [2]. This special publication describes the results of the interlaboratory comparison of transistor S-parameter measurements and shows how the equivalent circuit of the HF probe assemblies can be characterized by means of S-parameters using previously-described techniques.

The present report covers the work performed from January 1974 to July 1974. It describes a refined measurement technique that more accurately characterizes the probe assembly. The mathematical model used in the previous probe assembly work was not general enough to correctly describe the probe assembly, particularly at 1 GHz and above. Measurement results, and the technique for extracting the effects of the probe assembly from measurements made at the input connectors of the probe assembly, are given. The precision of the values obtained and the nature of the measurement bias introduced by the probe assembly are also shown.

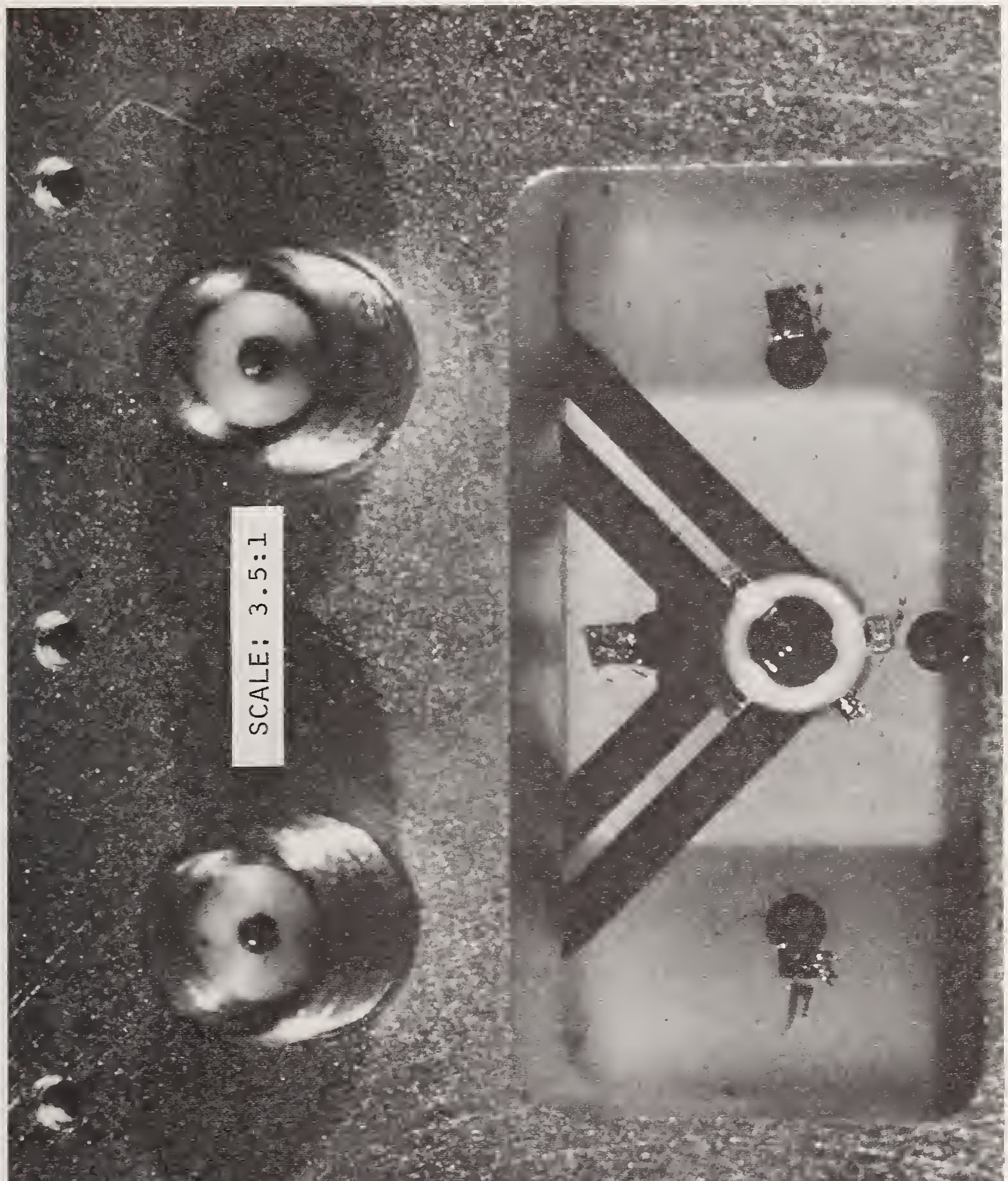


Figure 1. High frequency probe assembly

2. ELECTRICAL CHARACTERIZATION OF THE PROBE ASSEMBLY

2.1 Background

The probe assembly used for making measurements on integrated circuit devices and transistors is illustrated in figure 2. To determine the intrinsic characteristics

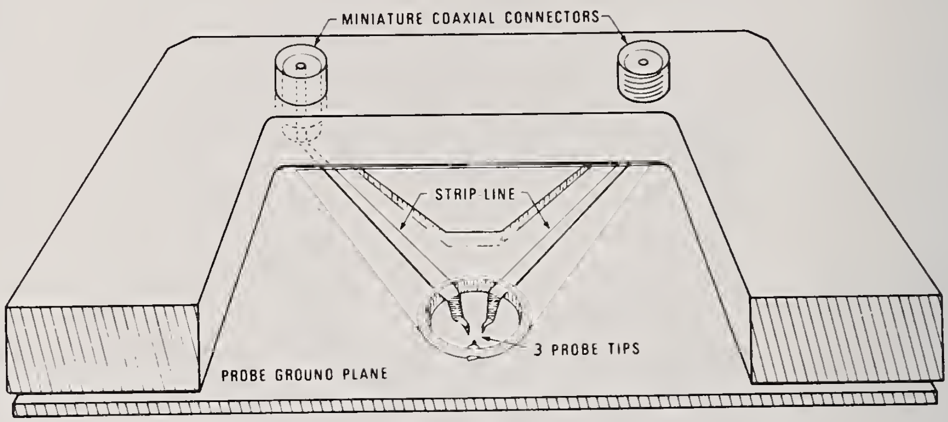


Figure 2. Probe assembly for integrated circuit measurements

of a device or transistor, the parameters of the probe assembly must be separated from the S-parameters measured at the miniature coaxial connectors. The parameters of the probe assembly can be determined by making measurements at the ports (miniature coaxial connectors) of the probe assembly, having the probe tips in contact with elements of known impedance values. Since each arm of the probe assembly network is represented by four (initially unknown) elements, four different probe tip terminations are required. In effect, the sequence of measurements yields four equations in the four probe-impedance unknowns, and so the unknowns may be determined simultaneously. Three of the electrical terminations chosen are an open-circuit, a short-circuit, and a resistor of known value, all of which are small contact pads that are 0.002 inch (0.05 mm) wide and 0.006 inch (0.15 mm) long deposited on an alumina substrate. The material used for the resistor is a layer of tantalum nitride that is chemically etched to achieve different resistance values which are measured by dc potentiometric (Kelvin) methods. These resistors can be shown to have values which are, to all practical purposes, independent of frequency to beyond 2 GHz. The fourth electrical termination is a large copper short circuit 1.375 inch (3.49 cm) long and 0.875 inch (2.22 cm) wide.

A work station equipped with a microscope is used that enables the probe assembly and terminations to be moved relative to each other so that a known termination such as a short, open or resistance can be placed across the appropriate probe tips.

2.2 Probe Assembly Evaluation

The probe assembly can be represented as two sections of transmission line with an additional element, y_p, that has been added to account for the finite impedance of the ground probe lead (fig. 3). This parasitic element and its measurement effects were summarized in an article in the GOMAC Digest [3]. The previous work also forms the basis for the procedures we used in this report to 1) characterize the probe assembly, and 2) extract the effects of the probe assembly and determine the S-parameters of the test device from measurements made at the probe assembly's input connectors.

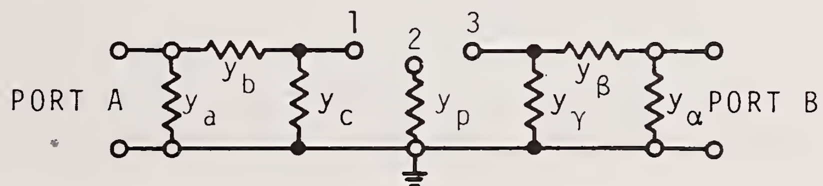


Figure 3. Probe assembly with parasitic element

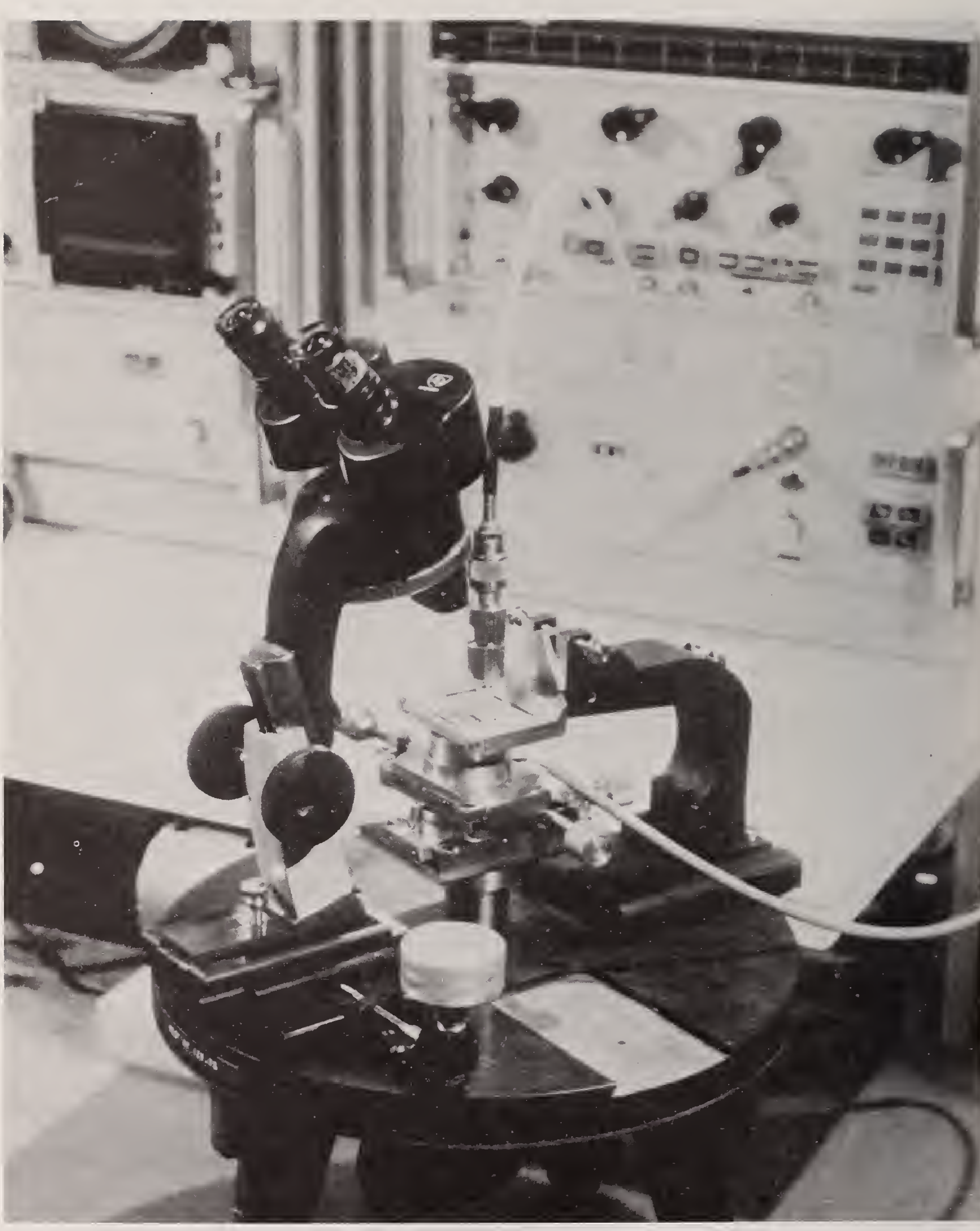


Figure 4. Measurement system for probe assembly measurements

To characterize the probe assembly, measurements are made at ports A and B with known terminations connected at probe tips, 1, 2 and 3. The probe assembly is connected to the NBS Automatic Network Analyzer as shown in figure 4. The inter-connecting cable and adapter are attached to the SMA connector on the probe assembly, which is the point designated as port A. Port B is left open. Measurements are made in terms of the magnitude of reflection coefficient and the phase angle, and are taken at 100 MHz increments starting with 0.2 and ending at 2 GHz, or at every discrete frequency of interest for each of the terminations. In order to achieve a short circuit between probe tip 2 and ground, a large copper plate is used as shown in figure 5. The copper plate short-circuits all the probe tips to the probe ground plane. This technique introduces a low impedance between the copper plate and the bottom of the probe ground plane, which is small enough to effectively short out the small, but finite impedance in the ground probe lead.

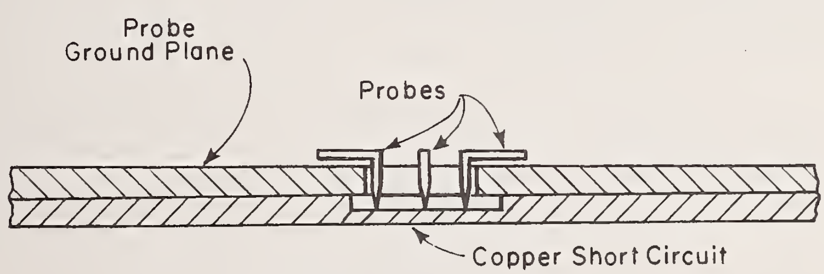


Figure 5. Method for achieving short circuit

With input at port A and electrical terminations between probe tips 1 and 2, the left side of the probe assembly (fig. 3) is characterized by measuring the admittance at port A under the following conditions:

$$Y_1 = y_a + y_b \qquad \begin{bmatrix}\text{Large Copper} \\ \text{Short Circuit} \\ \text{Tips 1, 2, \& 3}\end{bmatrix}, \qquad (1)$$

$$Y_2 = y_a + \frac{y_b y_c}{y_b + y_c} \qquad \begin{bmatrix}\text{Open Circuit} \\ \text{Tips 1 and 2}\end{bmatrix}, \qquad (2)$$

$$Y_3 = y_a + \frac{y_b (y_c + y_p)}{y_b + y_c + y_p} \qquad \begin{bmatrix}\text{Short Circuit} \\ \text{Tips 1 and 2}\end{bmatrix}, \qquad (3)$$

$$Y_4 = y_a + y_b \frac{y_c + \dfrac{Y_L y_p}{Y_L + y_p}}{y_b + y_c + \dfrac{Y_L y_p}{Y_L + y_p}} \qquad \begin{bmatrix}\text{Conductance } Y_L \\ \text{Tips 1 and 2}\end{bmatrix}, \qquad (4)$$

These values can be used to solve for the components of the equivalent network, y_a, y_b and y_c. Hence:

$$y_a = Y_1 - y_b \ , \qquad (5)$$

$$y_b = \sqrt{\frac{y_p \ (Y_1 - Y_2)(Y_1 - Y_3)}{Y_3 - Y_2}} \ , \qquad (6)$$

$$y_c = \frac{(Y_1 - Y_3) y_p}{Y_3 - Y_2} - y_b \ , \qquad (7)$$

$$y_p = \frac{Y_L (Y_1 - Y_2)(Y_3 - Y_4)}{(Y_1 - Y_3)(Y_4 - Y_2)} \ . \qquad (8)$$

From these admittances, the S-parameters of the probe assembly can be determined. Similarly, with input at port B and terminations at probe tips 2 and 3, solutions in terms of y_β, y_α and y_γ are found.

3. MATRIX SOLUTION FOR CHARACTERIZING AND EXTRACTING EFFECTS OF THE PROBE ASSEMBLY

3.1 Probe Assembly Characterization

The mathematics of characterizing the probe assembly and solving for the S-parameters of test devices or transistors can be simplified by using impedance and cascading parameters [4] instead of admittance and Pi-network parameters. Figure 6 shows the circuit representation of the

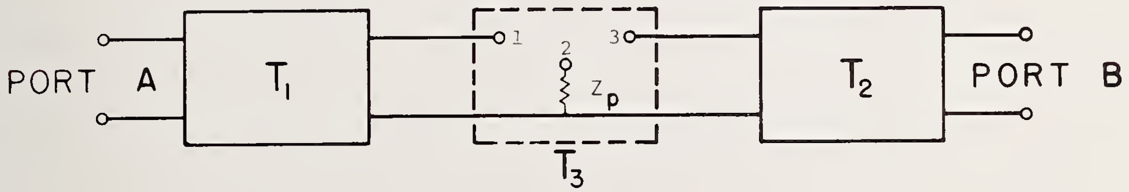


Figure 6. Circuit representation of probe assembly

probe assembly as two cascading matrices with the parasitic element $z_p = 1/y_p$. Figure 7 is the matrix representation

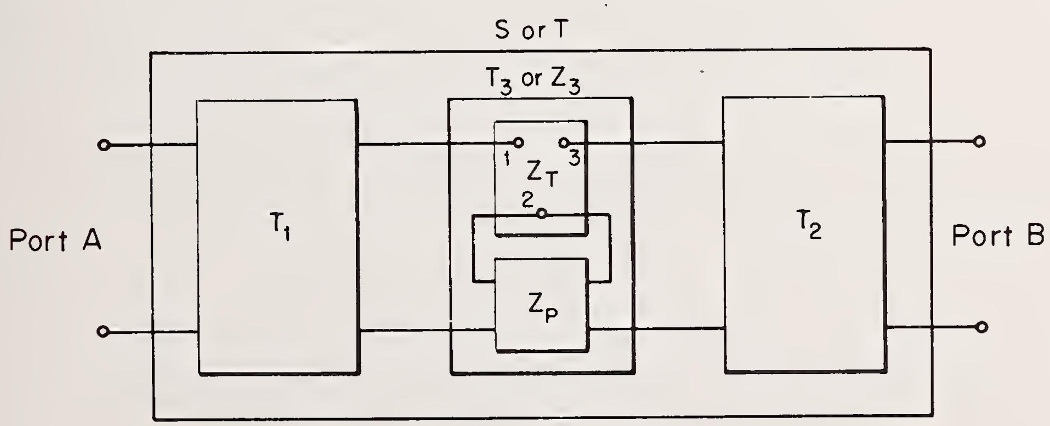


Figure 7. Matrix representation of the probe assembly, where S indicates scattering parameters, T represents v and i cascading parameters, and Z represents impedance parameters.

of the probe assembly where each section is represented by the v and i cascading matrix T,

$$T = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = D \begin{bmatrix} a & b \\ c & 1 \end{bmatrix} , \tag{9}$$

$$a \equiv \frac{A}{D} , \quad b \equiv \frac{B}{D} , \quad c \equiv \frac{C}{D} . \tag{10}$$

Let the voltages and currents be defined as indicated in figure 8. For arm A, the equations are

$$v_1 = Av_2 + Bi_2 , \tag{11}$$

$$i_1 = Cv_2 + Di_2 . \tag{12}$$

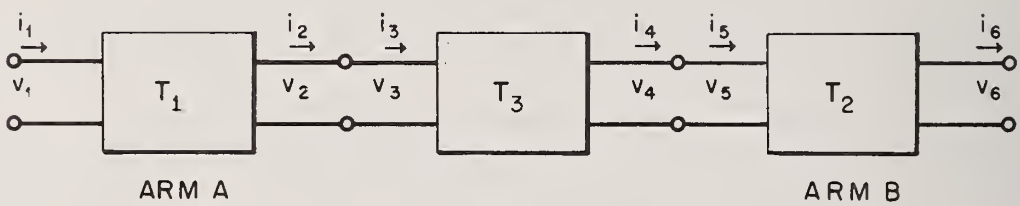


Figure 8. Defining the voltages and currents used with T_1, T_2, and T_3

If arm A is reciprocal, the complex constants are related by

$$AD - BC = 1 . \tag{13}$$

The cascade parameters of each arm can be obtained by using the same four load conditions in a manner similar to that used in section 2 to obtain the Pi-network parameters.

Define

$$Z_1 \equiv \frac{v_1}{i_1} \quad , \quad Z_2 \equiv \frac{v_2}{i_2} \quad . \tag{14}$$

Then (11) and (12) give

$$Z_1 = \frac{AZ_2 + B}{CZ_2 + D} \tag{15a}$$

$$= \frac{aZ_2 + b}{cZ_2 + 1} \quad . \tag{15b}$$

For the different load conditions, let Z_1 be:

Z_{1s} - for a short circuit between probe tip #1 and ground.

Z_{1o} - for an open circuit between probe tips #1 and #2.

Z_{1p} - for a short circuit between probe tips # 1 and #2.

Z_{1L} - for a resistive load, Z_L, between probe tips # 1 and 2.

For these four conditions, (15b) gives

$$Z_{1s} = b \tag{16}$$

$$c\, Z_{1o} = a \tag{17}$$

$$c\, Z_{1p}\, Z_p + Z_{1p} = a\, Z_p + b \tag{18}$$

$$c\, Z_{1L}\, (Z_L + Z_p) + Z_{1L} = a\, (Z_L + Z_p) + b \, . \tag{19}$$

Using (16) and (17) in (18) gives

$$c\, Z_{1p}\, Z_p + Z_{1p} = c\, Z_{1o}\, Z_p + Z_{1s} \quad , \tag{20}$$

or

$$c = \frac{Z_{1p} - Z_{1s}}{Z_p(Z_{1o} - Z_{1p})} \quad . \tag{21}$$

Using (16) and (17) in (19) gives

$$c\, Z_{1L}\,(Z_L + Z_p) + Z_{1L} = c\, Z_{1o}\,(Z_L + Z_p) + Z_{1s}\ , \qquad (22)$$

or

$$c = \frac{Z_{1L} - Z_{1s}}{(Z_L + Z_p)(Z_{1o} - Z_{1L})}\ . \qquad (23)$$

Equating (21) and (23) to eliminate c,

$$\frac{Z_L + Z_p}{Z_p} = \frac{(Z_{1L} - Z_{1s})(Z_{1o} - Z_{1p})}{(Z_{1o} - Z_{1L})(Z_{1p} - Z_{1s})}$$

$$\frac{Z_L}{Z_p} = \frac{(Z_{1L} - Z_{1s})(Z_{1o} - Z_{1p}) - (Z_{1o} - Z_{1L})(Z_{1p} - Z_{1s})}{(Z_{1o} - Z_{1L})(Z_{1p} - Z_{1s})}$$

which gives

$$Z_p = Z_L\ \frac{(Z_{1o} - Z_{1L})(Z_{1p} - Z_{1s})}{(Z_{1L} - Z_{1p})(Z_{1o} - Z_{1s})}\ , \qquad (24)$$

the parasitic element.

With Z_p known, c is obtained from (21) or (23). The program in Appendix I uses equation (21). Then a is obtained from (17), and b from (16). Knowing a, b, and c, D can be obtained from (13) which can be written

$$D = \frac{1}{\sqrt{\frac{A}{D} - \frac{B}{D}\frac{C}{D}}} = \frac{1}{\sqrt{a - bc}} \qquad (25)$$

and A, B, and C are obtained from (10). The cascading matrix T_1 for arm A is now known.

The same process is repeated for arm B to obtain a cascading matrix Q_2 which is not quite the same as T_2, shown in figures 7 and 8, because of the different direction in which T_2 is determined. Referring to figure 8,

$$\begin{bmatrix} v_5 \\ i_5 \end{bmatrix} = T_2 \begin{bmatrix} v_6 \\ i_6 \end{bmatrix} \tag{26}$$

whereas if arm B is evaluated from port B, one obtains

$$\begin{bmatrix} v_6 \\ -i_6 \end{bmatrix} = Q_2 \begin{bmatrix} v_5 \\ -i_5 \end{bmatrix} . \tag{27}$$

Let

$$N \equiv \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} . \tag{28}$$

Then

$$\begin{bmatrix} v_6 \\ -i_6 \end{bmatrix} = N \begin{bmatrix} v_6 \\ i_6 \end{bmatrix} \text{ and} \begin{bmatrix} v_5 \\ -i_5 \end{bmatrix} = N \begin{bmatrix} v_5 \\ i_5 \end{bmatrix} . \tag{29}$$

Using (29) in (27) gives

$$N \begin{bmatrix} v_6 \\ i_6 \end{bmatrix} = Q_2 N \begin{bmatrix} v_5 \\ i_5 \end{bmatrix} , \tag{30}$$

or

$$N^{-1} Q_2^{-1} N \begin{bmatrix} v_6 \\ i_6 \end{bmatrix} = \begin{bmatrix} v_5 \\ i_5 \end{bmatrix} . \tag{31}$$

Comparing (31) and (26) shows that

$$T_2 = N^{-1} \; Q_2^{-1} N , \tag{32}$$

or

$$T_2^{-1} = N^{-1} Q_2 N . \tag{33}$$

Since $N^{-1} = N$, (33) can be written

$$T_2^{-1} = NQ_2N \quad . \tag{34}$$

If

$$Q_2 = \begin{bmatrix} q_{11} & q_{12} \\ q_{21} & q_{22} \end{bmatrix} , \tag{35}$$

then

$$NQ_2N = T_2^{-1} = \begin{bmatrix} q_{11} & -q_{12} \\ -q_{21} & q_{22} \end{bmatrix} . \tag{36}$$

The probe assembly is now completely characterized.

Table I shows representative S-parameter and parasitic element values that were obtained from the measured data from arms A and B of Air Force probe assembly S/N 104. This information is especially useful in analyzing design properties of the probe assembly, by pointing out non-symmetrical variations between arms and showing resonant frequency points.

3.2 Extraction of the Probe Effects

When a test device or transistor is measured with the probe assembly, this measurement includes T_1, T_2 plus T_3. This is shown in figure 9 as the combined cascading matrix T:

$$T = T_1T_3T_2 \tag{37}$$

which gives

$$T_3 = T_1^{-1}TT_2^{-1} \quad . \tag{38}$$

Table I

Representative S-parameter and parasitic element values obtained from arms A and B of the probe assembly.

S-Parameters for Arm A

FREQ.	S11 MAG.	S11 ANG.	S12 MAG.	S12 ANG.	S21 MAG.	S21 ANG.	S22 MAG.	S22 ANG.
200.000	0.009	-172.2	0.998	-12.7	0.998	-12.7	0.025	21.9
300.000	0.008	174.8	0.993	-18.9	0.993	-18.9	0.023	15.6
400.000	0.003	155.2	0.994	-24.8	0.994	-24.8	0.022	17.0
500.000	0.001	-25.0	0.999	-31.1	0.999	-31.1	0.022	19.1
600.000	0.007	-41.9	1.000	-37.8	1.000	-37.8	0.023	37.2
700.000	0.014	-49.2	0.990	-44.0	0.990	-44.0	0.027	23.4
800.000	0.021	-61.4	0.991	-49.7	0.991	-49.7	0.027	23.9
900.000	0.026	-67.8	0.998	-56.0	0.998	-56.0	0.027	-1.2
1000.000	0.032	-76.7	0.997	-62.8	0.997	-62.8	0.017	1.2
1100.000	0.039	-83.3	0.991	-69.0	0.991	-69.0	0.011	4.0
1200.000	0.047	-87.5	0.991	-75.1	0.991	-75.1	0.004	53.9
1300.000	0.057	-96.3	0.994	-81.4	0.994	-81.4	0.012	86.7
1400.000	0.055	-104.7	0.993	-87.4	0.993	-87.4	0.005	135.1
1500.000	0.063	-93.6	0.991	-94.2	0.991	-94.2	0.004	36.7
1600.000	0.087	-124.6	0.993	-99.8	0.993	-99.8	0.044	148.5
1700.000	0.092	-130.5	0.990	-106.5	0.990	-106.5	0.057	133.9
1800.000	0.091	-137.9	0.988	-112.4	0.988	-112.4	0.065	121.6
1900.000	0.097	-143.6	0.991	-118.6	0.991	-118.6	0.070	118.7
2000.000	0.101	-151.1	0.994	-125.2	0.994	-125.2	0.081	115.6

S-Parameters for Arm B

FREQ.	S11 MAG.	S11 ANG.	S12 MAG.	S12 ANG.	S21 MAG.	S21 ANG.	S22 MAG.	S22 ANG.
200.000	0.009	163.8	0.999	-12.7	0.999	-12.7	0.025	17.7
300.000	0.007	156.3	0.993	-19.0	0.993	-19.0	0.022	18.0
400.000	0.004	103.0	0.995	-24.9	0.995	-24.9	0.021	16.9
500.000	0.005	16.2	1.000	-31.3	1.000	-31.3	0.021	21.7
600.000	0.009	-14.1	1.000	-38.0	1.000	-38.0	0.024	39.6
700.000	0.017	-35.1	0.991	-44.2	0.991	-44.2	0.028	25.3
800.000	0.025	-49.4	0.992	-50.0	0.992	-50.0	0.027	25.8
900.000	0.029	-55.7	0.998	-56.3	0.998	-56.3	0.029	0.0
1000.000	0.035	-67.9	0.998	-63.0	0.998	-63.0	0.019	5.0
1100.000	0.044	-75.2	0.993	-69.3	0.993	-69.3	0.012	6.3
1200.000	0.052	-81.0	0.993	-75.4	0.993	-75.4	0.007	38.7
1300.000	0.063	-89.8	0.995	-81.8	0.995	-81.8	0.012	75.0
1400.000	0.062	-98.8	0.992	-87.7	0.992	-87.7	0.002	-27.8
1500.000	0.071	-91.0	0.991	-94.8	0.991	-94.8	0.005	-23.3
1600.000	0.095	-121.4	0.993	-100.3	0.993	-100.3	0.041	147.9
1700.000	0.100	-128.5	0.990	-107.0	0.990	-107.0	0.055	133.2
1800.000	0.100	-136.7	0.988	-113.1	0.988	-113.1	0.062	120.6
1900.000	0.106	-140.5	0.991	-119.2	0.991	-119.2	0.067	114.8
2000.000	0.113	-148.4	0.994	-126.0	0.994	-126.0	0.077	111.1

Average Z_p from Arms A & B

FREQ.	REAL	IMAGINARY	MAGNITUDE	PHASE
200.000	0.1489	1.6686	1.6752	84.90
300.000	0.2233	2.5174	2.5273	84.93
400.000	0.2450	3.1555	3.1650	85.56
500.000	0.2413	3.8789	3.8864	86.44
600.000	0.1836	4.6648	4.6648	87.75
700.000	0.1570	5.5210	5.5233	88.37
800.000	0.2240	6.3835	6.3874	87.99
900.000	0.3442	7.0214	7.0299	87.19
1000.000	0.3042	7.7741	7.7800	87.76
1100.000	0.2019	8.5858	8.5881	88.65
1200.000	0.2982	9.4594	9.4641	88.19
1300.000	0.2704	10.1261	10.1297	88.47
1400.000	0.2653	11.7516	11.7546	88.71
1500.000	0.5721	12.8007	12.8135	87.44
1600.000	0.2682	12.1024	12.1054	88.73
1700.000	0.2271	13.3697	13.3716	89.03
1800.000	0.3076	14.5672	14.5704	88.79
1900.000	0.5706	15.1212	15.1320	87.84
2000.000	0.4274	15.8854	15.8911	88.46

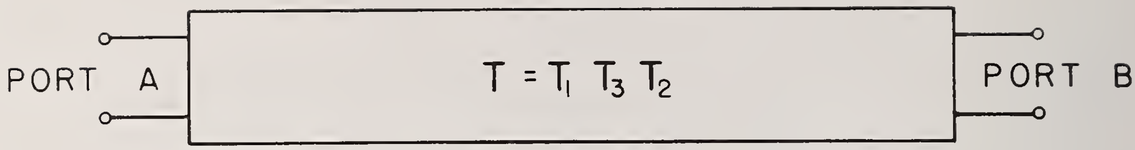


Figure 9. Combined cascading matrix T

As shown in figure 7, T_3 includes the parameters of the test device and also the parasitic impedance Z_p. To extract the transistor parameters from T_3, it is best to express these parameters in terms of impedances;

$$Z_t = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} . \qquad (39)$$

The parasitic impedance can be expressed as an impedance matrix whose elements are all z_p;

$$Z_p = \begin{bmatrix} z_p & z_p \\ z_p & z_p \end{bmatrix} . \qquad (40)$$

Then

$$Z_t = Z_3 - Z_p \qquad (41)$$

where Z_3 is the center matrix, T_3, converted to Z parameters,

$$Z_3 = \frac{1}{C_3}\begin{bmatrix} A_3 & A_3D_3 - B_3C_3 \\ 1 & D_3 \end{bmatrix} , \qquad (42)$$

and where A_3, B_3, C_3, and D_3 are elements of T_3. One can then obtain the S-parameters directly from the impedance matrix representing the test device or transistor,

$$Z_t \rightarrow S_t \quad . \tag{43}$$

A listing of the computer program is given in Appendix I for calibrating the probe assembly and also for calculating the S-parameters of a test device or transistor measured with the calibrated probe assembly.

4. RESULTS OF TEST DEVICE MEASUREMENTS

To determine the soundness and accuracy of this measurement technique, a series of measurements of the probe assembly were made with two test devices having known calculable S-parameters. This measurement treats the probe assembly as a two-port device and enables the S-parameters of the two test devices to be determined experimentally by the method described in section 3. The first test device was a small pad that shorted probe tips 1, 2, and 3 together as shown in figure 10.

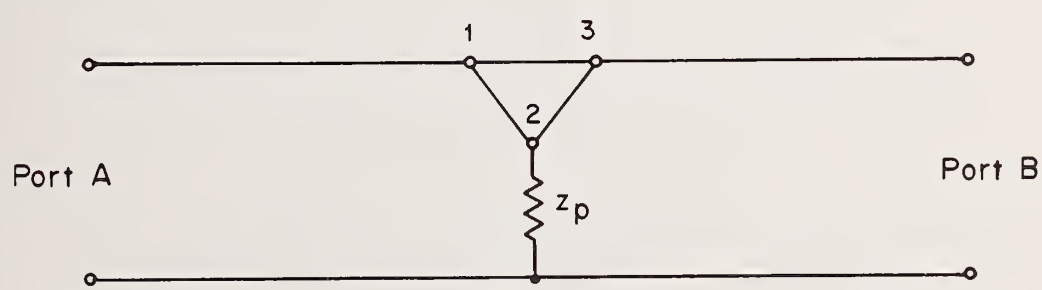


Figure 10. Shorted configuration

The residual inductance of this pad was calculated to be approximately two pico-henries or 0.01 ohms reactance at 1 GHz.

This particular load configuration, with all probe tips shorted provides an exacting test for this measurement technique. The parasitic element of the ground probe lead becomes an integral part of the load configuration and, therefore, has the greatest effect on the measurement.

The S-parameters for all probe tips shorted for any frequency are

$$S_{11} = S_{22} = 1 \underline{/\ 180°} \quad ,$$

$$|S_{12}| = |S_{21}| = 0 \quad .$$

By using these known values as the basis for a standard, one can readily establish how accurately the S-parameter values, determined experimentally, compare with the above standard.

The second test device is a thru-line configuration as shown in figure 11, where probe tips 1 and 3 are shorted, but 2 is open.

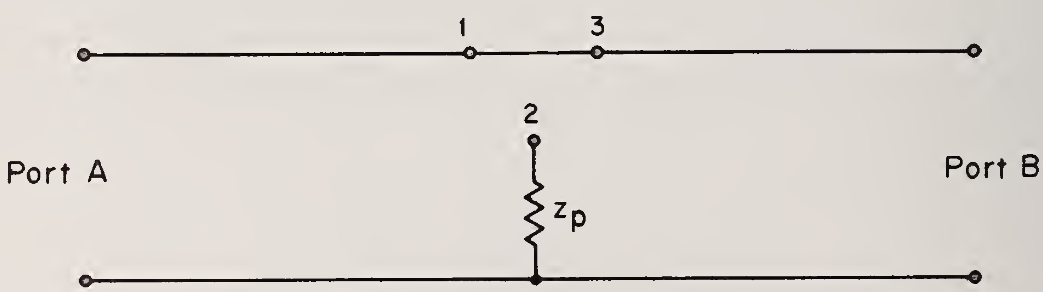


Figure 11. Thru-line configuration

The S-parameters of the thru-line for any frequency are

$$|S_{11}| = |S_{22}| = 0$$

$$S_{12} = S_{21} = 1 \underline{/\ 0°} \quad .$$

Again, this forms the basis for another standard that can be used for comparison purposes.

Tables II and III show the S-parameters obtained experimentally for both test devices by utilizing the measurement technique described in the preceding sections. Observing the values listed in tables II and III, the S-parameters of major interest for test device No. 1 are S_{11} and S_{22}; for test device No. 2, S_{12} and S_{21}. While the other S-parameters should not be overlooked, it is felt that these are the ones most likely to reflect measurement error in characterizing the probe assembly.

The values shown in tables II and III are representative of measurement data taken over a two-month interval. The accuracy of the measurements is discussed in section 5.

5. DATA ANALYSIS

5.1 Background

Measurements were made at nineteen frequencies in 100 MHz increments between 200 and 2000 MHz on an automatic network analyzer (ANA) having an accuracy ±0.003 in magnitude and ± 0.5 degree in phase angle. These measurements were made to experimentally establish the S-parameters for the two electrical configurations using the probe assembly. This was done on five different "occasions". The first three occasions were close in time--within a two day period. Each set of measurements made on an occasion was preceded by a calibration of the ANA. These first measurements were made using SMA connectors. Some weeks following, two additional replications of the measurements were made, one using SMA connectors, and one using 7 mm precision connectors.

Table II

Experimental S-parameters obtained from measurements made on two test devices, "all probe tips shorted" and "thru-line".

S-Parameters for Test Device No. 1

(All Probe Tips Shorted)

	S11		S12		S21		S22	
FREQ.	MAG.	ANG.	MAG.	ANG.	MAG.	ANG.	MAG.	ANG.
200.000	1.002	-179.9	0.002	-124.6	0.002	-125.6	0.998	180.0
300.000	1.002	-179.9	0.004	-157.3	0.004	-158.7	1.001	179.9
400.000	1.003	-179.8	0.001	-91.6	0.001	-135.4	1.003	-179.7
500.000	1.004	-180.0	0.002	-146.2	0.003	-166.3	1.005	-179.4
600.000	1.000	-179.8	0.004	-105.4	0.004	-113.3	0.997	-179.2
700.000	1.005	-179.6	0.003	-146.3	0.005	-135.7	0.993	-179.0
800.000	1.002	-179.6	0.008	-134.0	0.010	-117.7	0.995	-179.2
900.000	1.006	-179.5	0.003	170.1	0.003	-116.8	0.999	-179.3
1000.000	1.004	-179.6	0.002	-35.7	0.004	-53.7	1.003	-179.4
1100.000	1.000	-179.4	0.011	-46.3	0.011	-38.1	0.998	-178.8
1200.000	1.002	-179.3	0.007	-55.9	0.006	-38.4	0.999	-178.6
1300.000	1.001	-178.8	0.007	52.7	0.011	61.3	0.994	-178.8
1400.000	0.990	-178.8	0.050	-70.8	0.045	-70.5	0.985	-179.4
1500.000	0.928	-177.4	0.129	-71.8	0.128	-73.5	1.145	-177.5
1600.000	0.982	-178.8	0.052	-84.9	0.050	-91.5	0.995	-178.5
1700.000	0.988	-178.7	0.050	-94.6	0.051	-100.0	0.989	-177.6
1800.000	0.988	-178.9	0.061	-99.1	0.061	-99.2	0.976	-177.6
1900.000	0.984	-178.7	0.051	-103.5	0.053	-97.0	0.975	-178.4
1999.990	0.986	-178.4	0.057	-111.7	0.055	-103.0	0.983	-178.8

S-Parameters for Test Device No. 2

(Thru-Line)

	S11		S12		S21		S22	
FREQ.	MAG.	ANG.	MAG.	ANG.	MAG.	ANG.	MAG.	ANG.
200.000	0.006	-172.3	1.002	0.4	1.001	0.4	0.007	175.6
300.000	0.008	-175.2	0.999	0.0	0.999	0.0	0.007	176.3
400.000	0.005	144.7	0.999	0.1	0.996	0.2	0.011	162.2
500.000	0.007	141.9	1.000	0.1	1.000	0.1	0.008	-177.5
600.000	0.003	-71.4	0.992	0.2	0.994	0.3	0.009	-75.1
700.000	0.012	-144.4	0.991	0.7	0.991	0.7	0.009	-93.6
800.000	0.021	-152.3	0.993	0.9	0.991	0.8	0.008	-143.2
900.000	0.029	178.6	0.995	1.2	0.992	1.2	0.023	147.0
1000.000	0.026	156.3	1.006	1.0	1.007	1.2	0.029	139.7
1100.000	0.027	138.5	1.002	0.6	1.001	0.6	0.031	139.1
1200.000	0.021	121.1	1.000	0.5	0.999	0.4	0.017	138.1
1300.000	0.010	159.4	0.998	1.1	1.000	1.0	0.006	-115.7
1400.000	0.034	96.7	0.998	-0.8	1.000	-0.8	0.029	85.3
1500.000	0.011	-20.4	1.062	-1.8	1.061	-1.8	0.136	92.2
1600.000	0.061	78.1	0.980	1.7	0.982	1.7	0.061	81.6
1700.000	0.060	54.5	0.998	1.9	1.002	2.0	0.050	49.8
1800.000	0.055	36.8	1.002	1.0	1.004	1.1	0.052	35.9
1900.000	0.054	28.6	1.001	0.8	0.998	0.8	0.060	35.2
1999.990	0.055	20.1	1.001	0.8	1.005	0.5	0.054	39.9

Table III

Experimental S-parameters obtained from measurements made on two test devices, "all probe tips shorted" and "thru-line".

S-Parameters for Test Device No. 1

(All Probe Tips Shorted)

	S11		S12		S21		S22	
FREQ.	MAG.	ANG.	MAG.	ANG.	MAG.	ANG.	MAG.	ANG.
200.000	1.000	178.6	0.002	139.9	0.002	156.9	1.000	178.8
300.000	0.998	177.9	0.001	-161.3	0.002	-152.5	1.000	178.4
400.000	0.989	176.7	0.004	72.4	0.003	87.1	0.996	177.7
500.000	0.984	175.8	0.002	38.4	0.001	82.7	1.000	177.3
600.000	0.989	176.2	0.003	-65.2	0.002	-120.3	1.002	177.6
700.000	1.001	177.0	0.005	-52.1	0.004	-78.1	1.006	177.8
800.000	0.996	176.9	0.010	-48.0	0.008	-48.7	1.003	177.4
900.000	0.982	176.4	0.012	-23.9	0.012	-17.6	1.000	176.9
1000.000	0.977	176.6	0.019	-52.7	0.019	-53.3	1.001	177.4
1100.000	0.991	178.0	0.033	-58.2	0.030	-58.7	0.997	178.9
1200.000	1.001	179.5	0.038	-60.3	0.033	-60.1	0.997	179.6
1300.000	0.991	179.9	0.038	-54.4	0.034	-47.7	0.989	179.4
1400.000	0.970	179.6	0.071	-63.1	0.073	-61.7	0.978	177.5
1500.000	0.973	-178.9	0.079	-76.9	0.083	-73.5	0.979	179.4
1600.000	0.983	-178.6	0.077	-69.8	0.078	-69.6	0.982	-177.7
1700.000	1.001	-177.0	0.071	-72.2	0.069	-71.1	0.963	-174.7
1800.000	0.990	-177.9	0.063	-71.4	0.066	-67.3	0.950	-177.9
1900.000	0.968	-179.1	0.049	-75.8	0.055	-71.5	0.975	178.2
1999.990	0.969	-179.0	0.063	-75.4	0.071	-81.4	0.988	-179.0

S-Parameters for Test Device No. 2

(Thru-Line)

	S11		S12		S21		S22	
FREQ.	MAG.	ANG.	MAG.	ANG.	MAG.	ANG.	MAG.	ANG.
200.000	0.023	120.2	0.998	-0.4	0.998	-0.4	0.012	137.7
300.000	0.024	101.4	0.988	-1.2	0.995	-1.1	0.025	115.7
400.000	0.035	91.7	0.993	-1.3	0.992	-1.2	0.036	106.2
500.000	0.049	96.6	0.993	-1.5	0.994	-1.5	0.041	104.1
600.000	0.051	106.5	0.990	-1.5	0.990	-1.5	0.029	110.2
700.000	0.054	122.8	0.994	-1.5	0.993	-1.5	0.036	137.2
800.000	0.052	126.0	0.988	-1.8	0.990	-1.8	0.048	131.9
900.000	0.070	112.9	0.990	-1.6	0.991	-1.6	0.073	113.4
1000.000	0.081	104.2	0.998	-2.1	0.996	-2.1	0.074	105.6
1100.000	0.082	104.9	0.998	-2.8	0.995	-2.6	0.056	110.3
1200.000	0.061	109.9	0.986	-3.1	0.987	-3.1	0.037	110.8
1300.000	0.042	112.8	0.986	-2.5	0.986	-2.6	0.033	108.6
1400.000	0.070	93.7	0.990	-4.3	0.987	-4.3	0.065	79.5
1500.000	0.071	78.5	0.987	-3.8	0.988	-3.8	0.061	65.7
1600.000	0.081	78.9	0.979	-1.3	0.979	-1.2	0.056	76.6
1700.000	0.030	11.5	0.999	-2.1	0.998	-2.0	0.023	-38.7
1800.000	0.029	-24.4	0.990	-3.9	0.990	-3.8	0.027	-22.6
1900.000	0.038	-2.3	0.989	-4.4	0.988	-4.3	0.036	12.4
1999.990	0.049	6.0	0.997	-4.0	0.995	-4.3	0.046	-15.0

These measurements shed some light on the precision of values obtained using the probe assembly, as well as on the nature of the bias introduced by the measurement system. The eight components of each of the S-parameter matrices were determined separately, frequency by frequency. The reduced data consist of averages for the S-parameter values obtained at each of the 19 frequencies, using the SMA connectors and estimates of the standard deviations of the values going into these averages. Two types of typewriter plots were prepared for the more important S-parameters (magnitude and phase) of each of the two configurations. These parameters are S_{11} and S_{22} for all probe tips shorted, and S_{12} and S_{21} for thru-line. The first type of plot consists of a point plot of the average values versus frequency, as shown in figures 12 thru 15. A "95 percent confidence" interval is also shown with each of the average values. These intervals are calculated on the assumption that the distributions of the components at each frequency are Gaussian; this is an untested assumption. An additional caveat is that the estimated deviations are based equally on all four SMA occasions, even though the first three are very close in time relative to the fourth. There is no basis at present for weighting the individual occasions, however. The second type plot is that of the estimated standard deviations of individual determinations of a particular component versus frequency, as shown in figures 16 thru 19.

On the plots of the mean values as shown in figures 12 thru 15, the symbol "*" represents the mean value as defined for the tables; the symbol ($) represents the upper limit of the "95 percent confidence" interval for the mean, and the symbol "0" represents the lower limit. When plotting positions are so close as not to be distinguishable for plotting purposes, the number of points "coincident" are printed rather than any of the above-mentioned symbols. The confidence intervals are symmetric about the mean value, plus or minus the resolution of the printer. Comments and conclusions about these plots are stated in section 5.2.

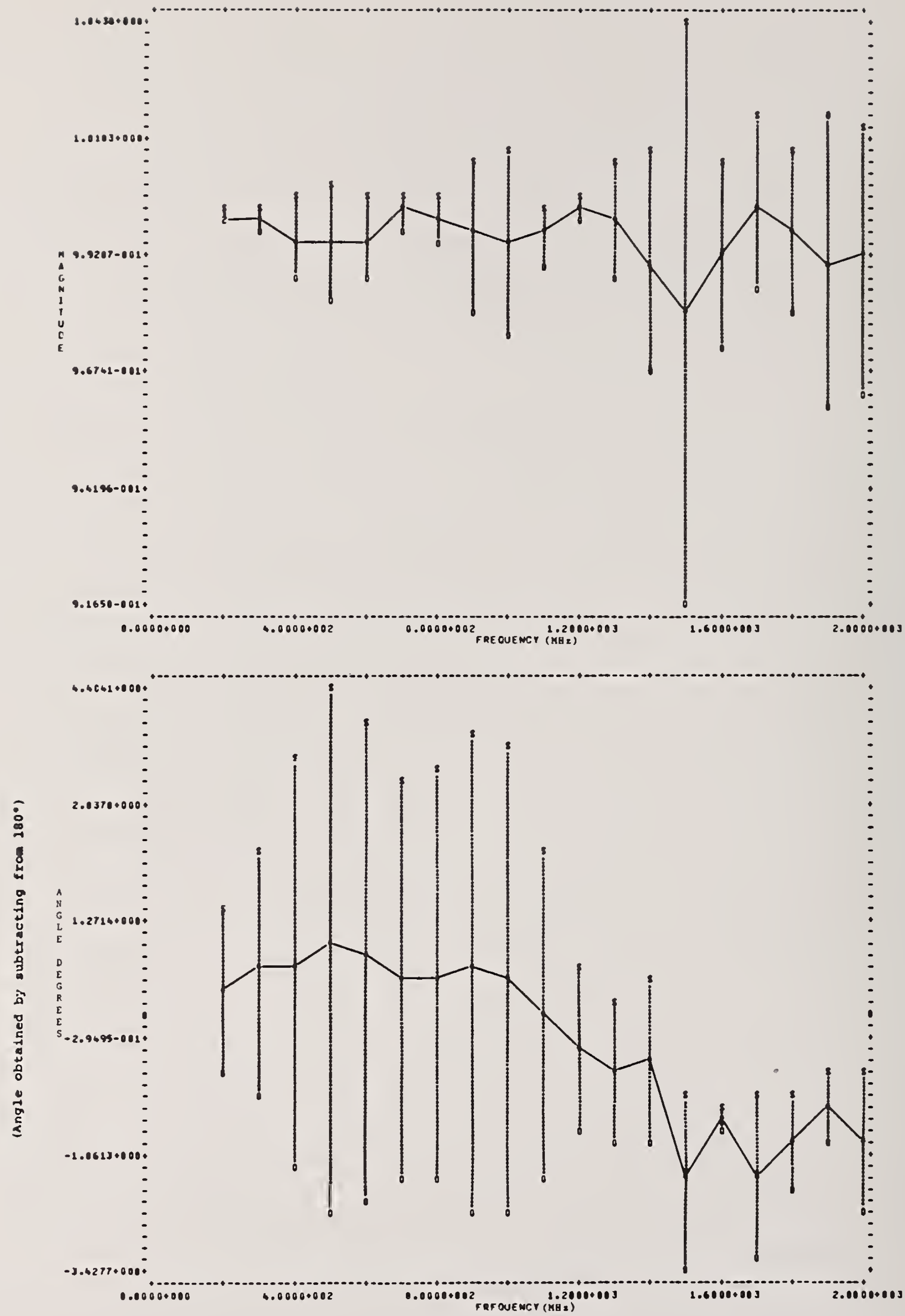


Figure 12. All probe tips shorted S_{11} magnitude and phase with 95 percent confidence intervals for four SMA occasions

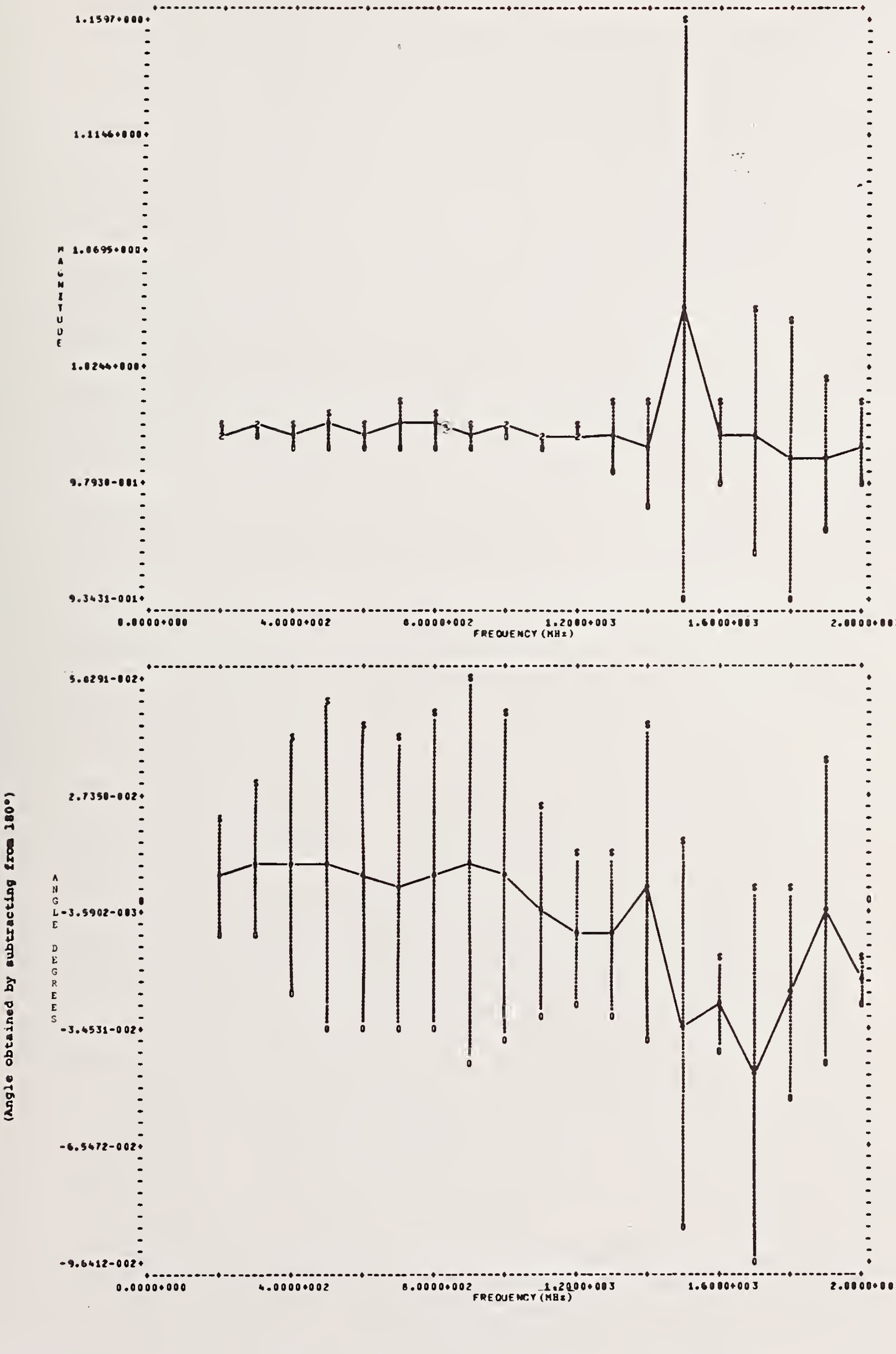


Figure 13. All probe tips shorted S_{22} magnitude and phase with 95 percent confidence intervals for four SMA occasions

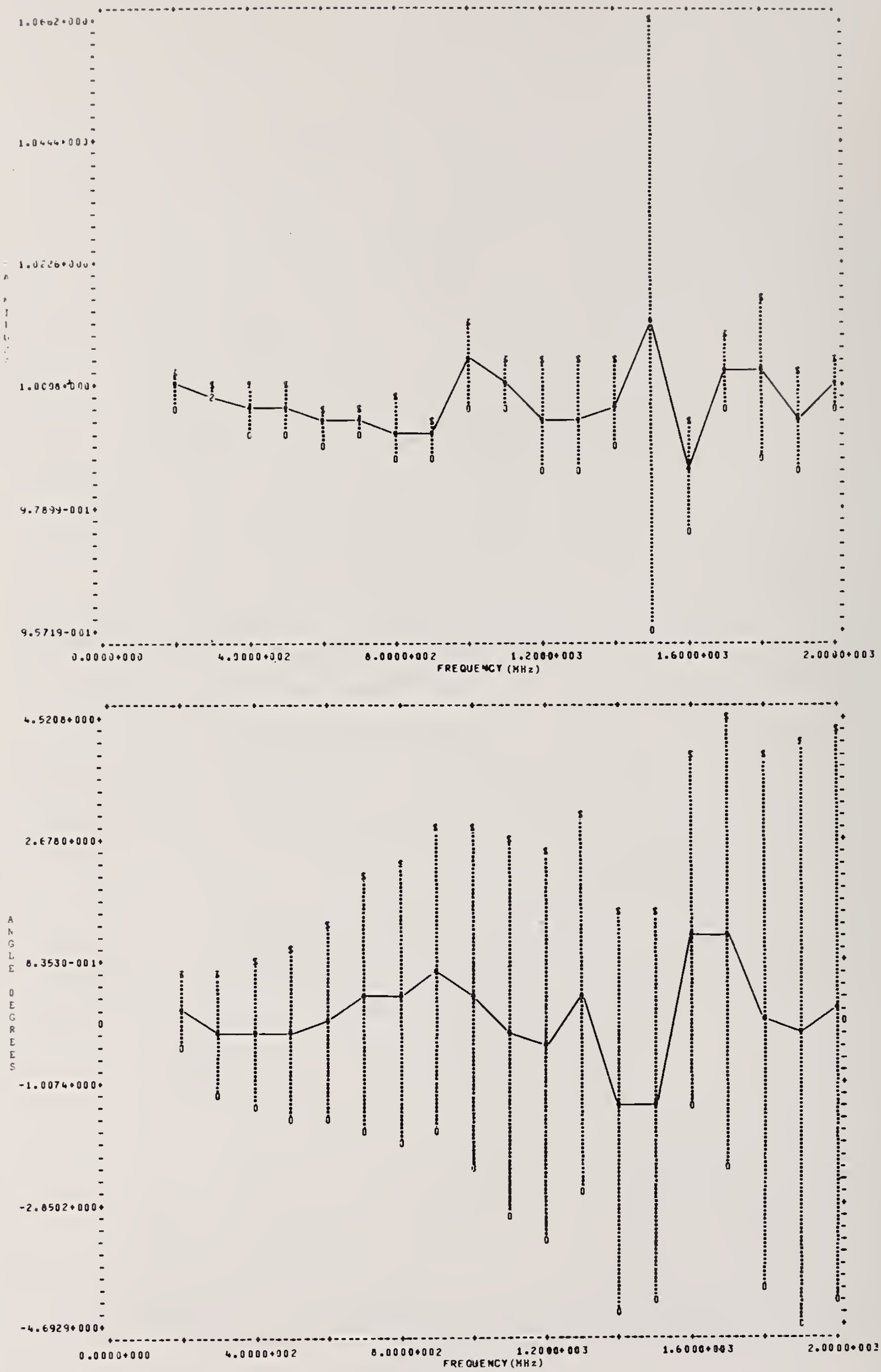


Figure 14. Thru-line S_{12} magnitude and phase with 95 percent confidence intervals for four SMA occasions

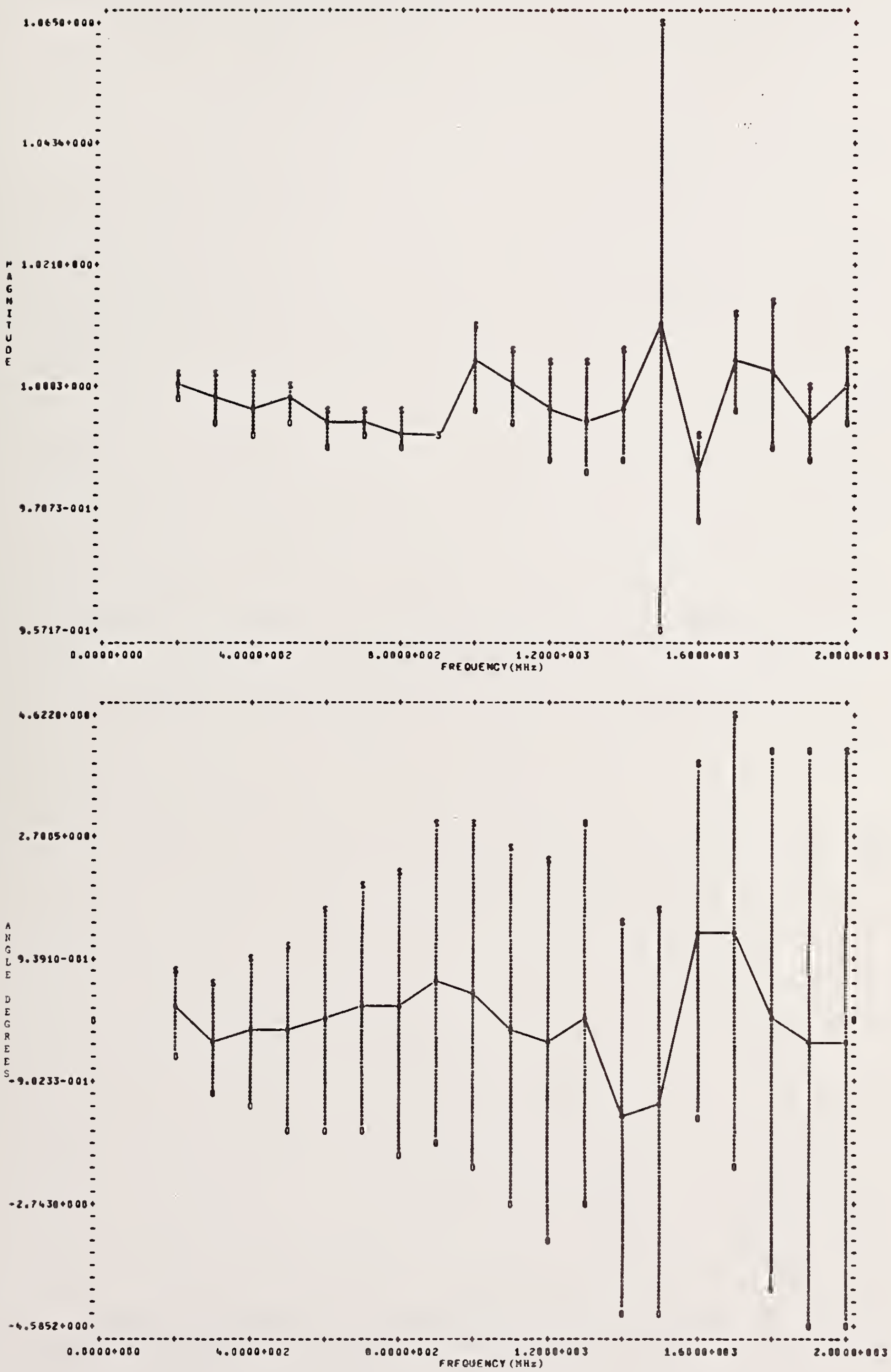


Figure 15. Thru-line S_{21} magnitude and phase with 95 percent confidence intervals for four SMA occasions

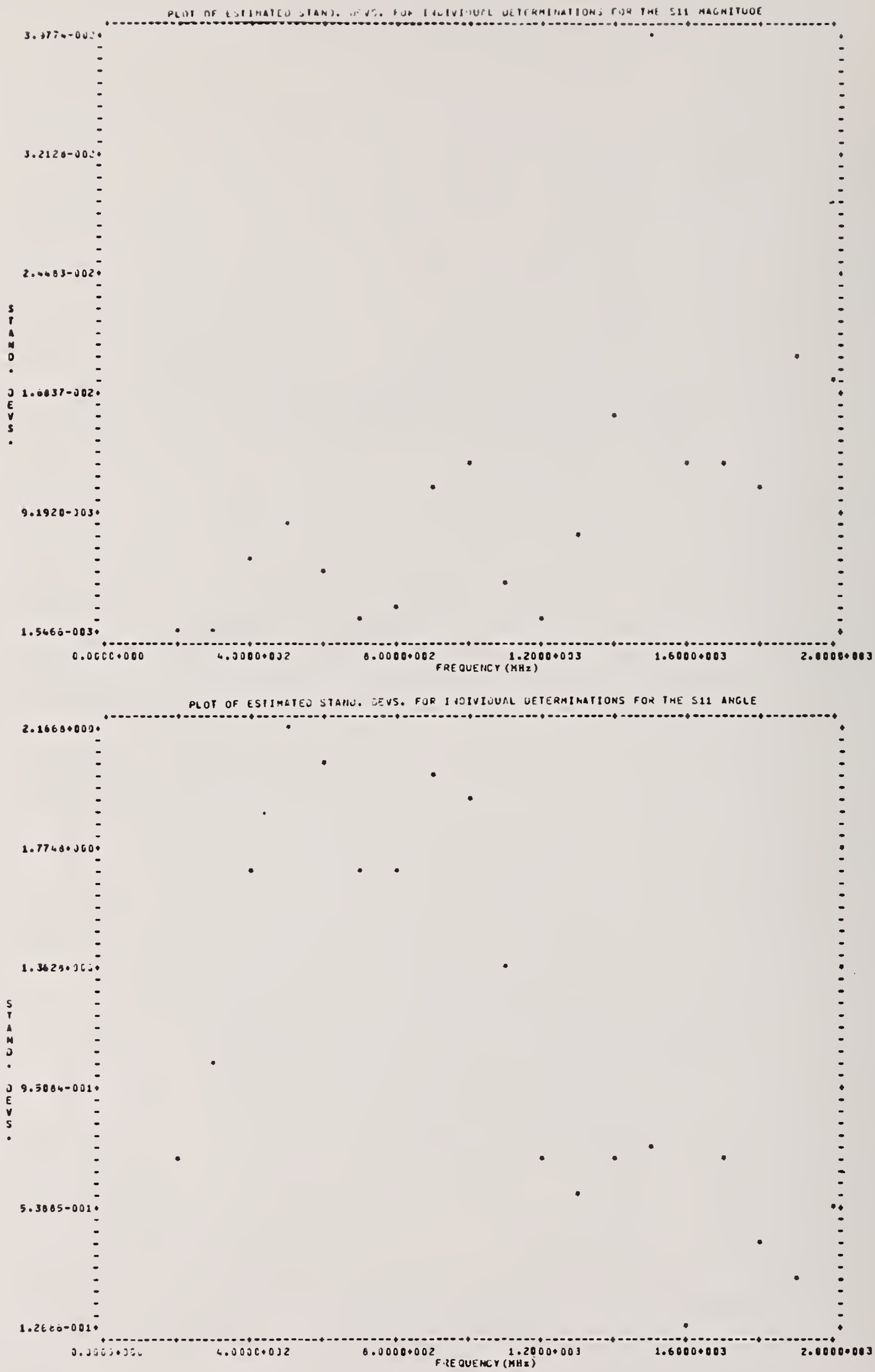
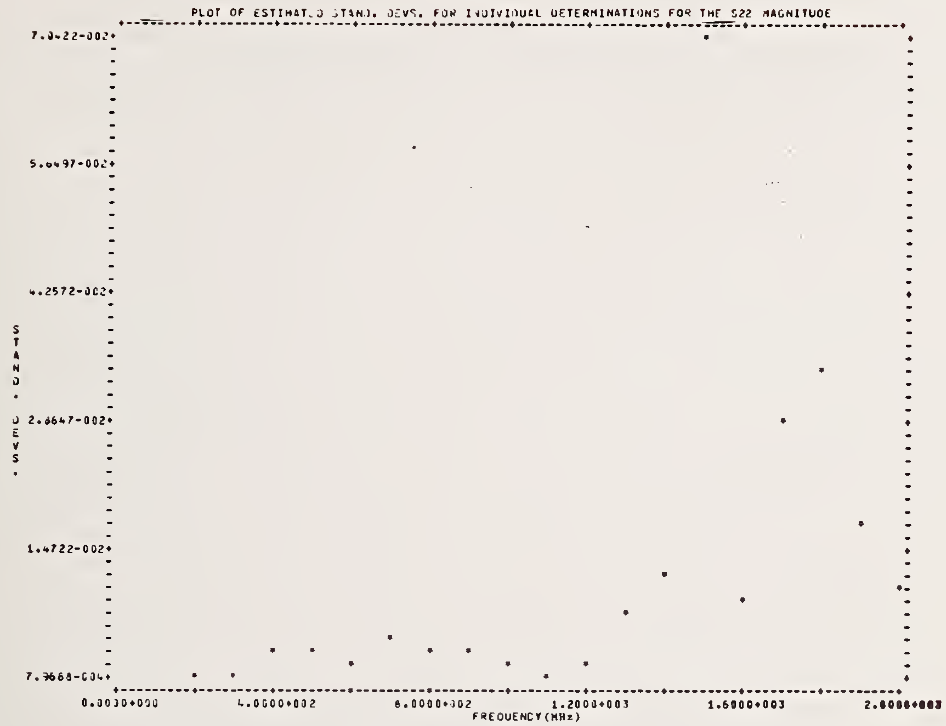


Figure 16. All probe tips shorted S_{11} magnitude and phase standard deviation for four SMA occasions



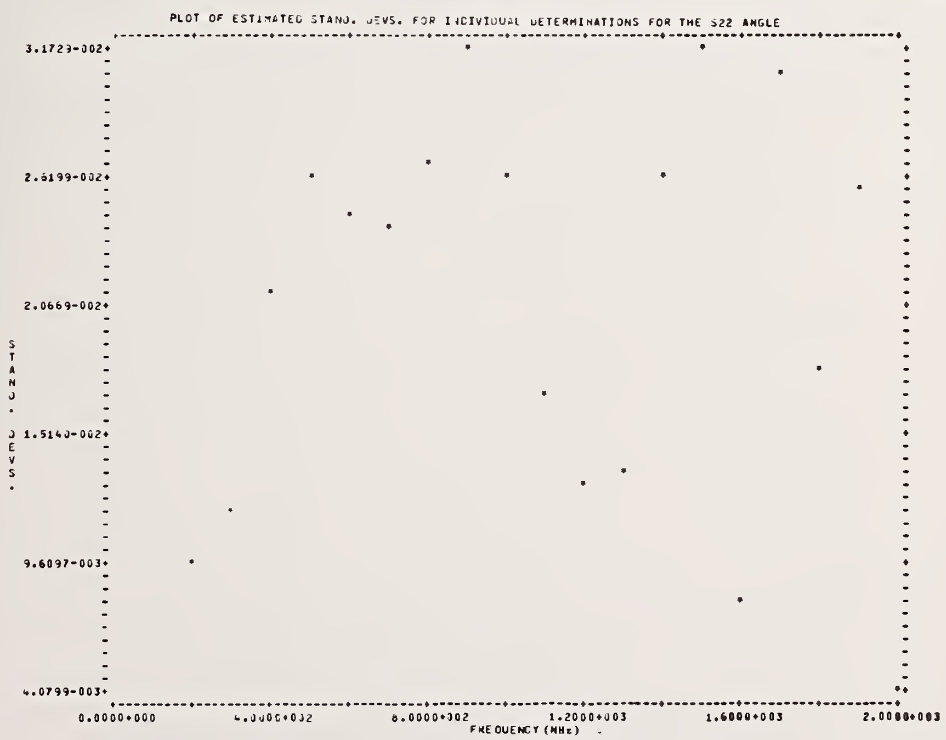


Figure 17. All probe tips shorted S_{22} magnitude and phase standard deviation for four SMA occasions

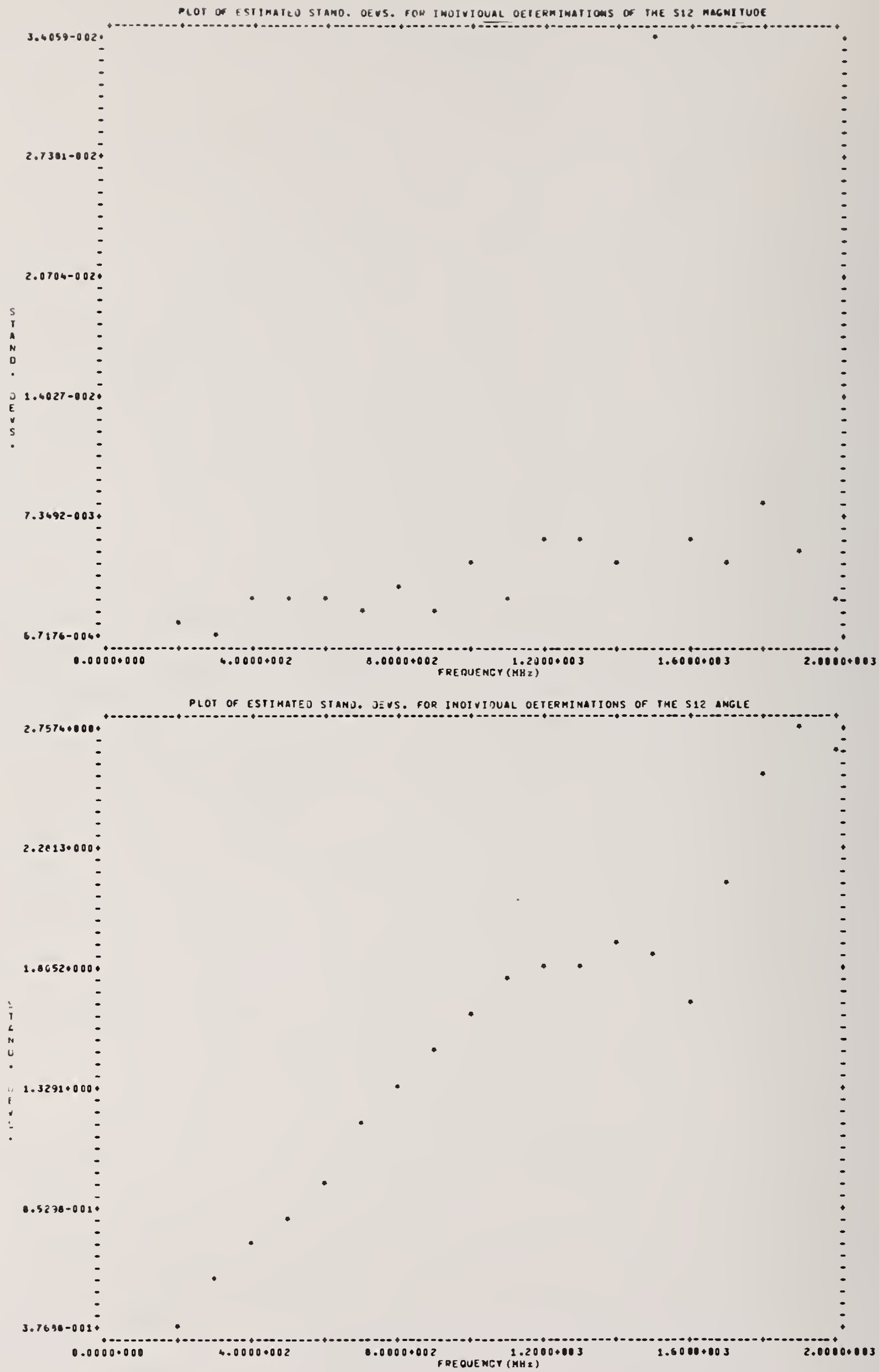


Figure 18. Thru-line S_{12} magnitude and phase standard deviation for four SMA occasions

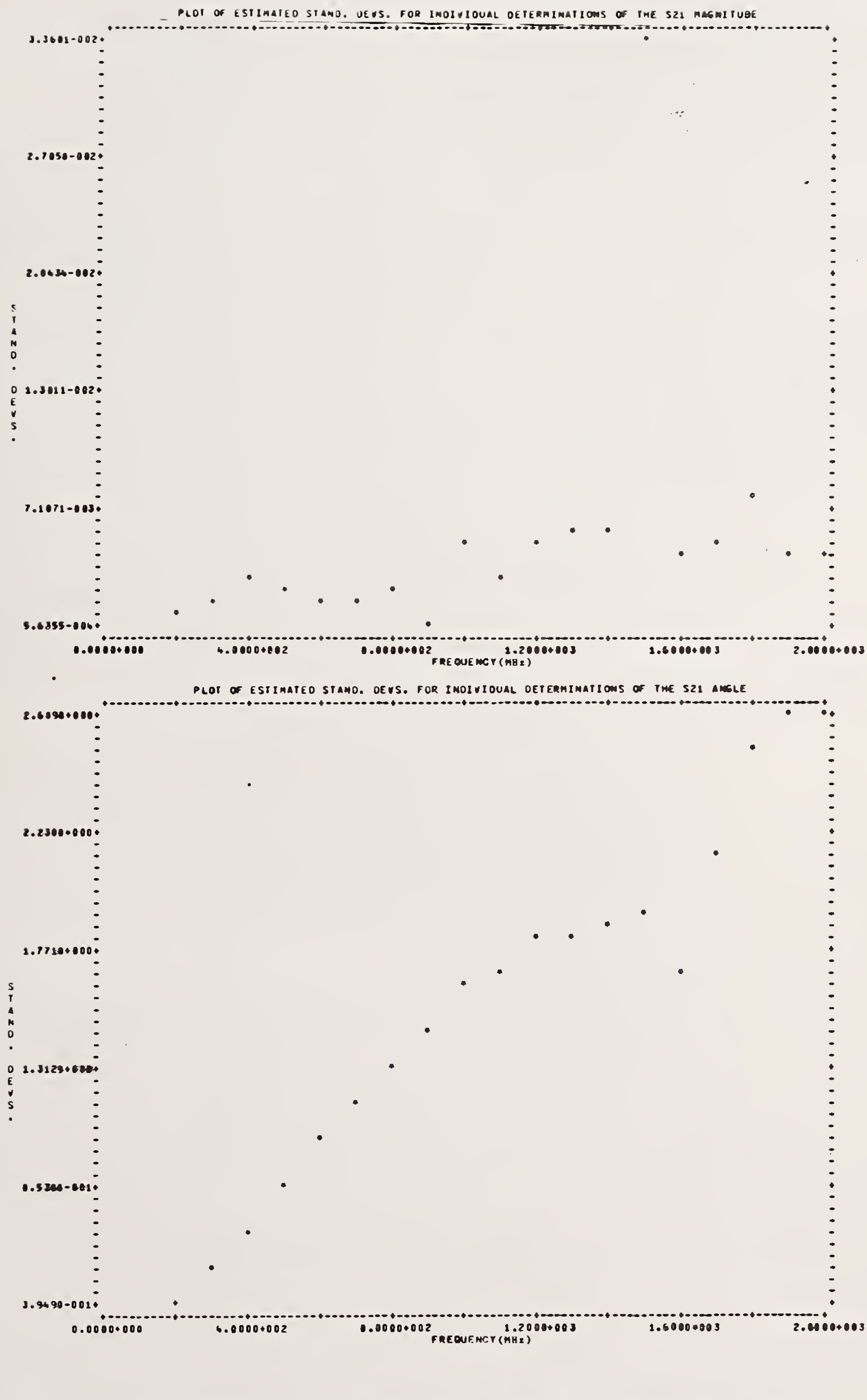


Figure 19. Thru-line S_{21} magnitude and phase standard deviation for four SMA occasions

5.2 General Comments

<u>All Probe Tips Shorted</u>

Mag(S_{11})

1. No evidence of bias is apparent.
2. The standard deviations seem to be sensitive to frequency, but the estimated value of 0.04 at 1500 MHz is disproportionately large. The next largest estimated standard deviation is 0.02 at 1900 MHz.
3. Largest average value: 1.004 at 1700 MHz
   Largest value recorded: 1.022 at 1500 MHz
   Smallest average value: 0.980 at 1500 MHz
   Smallest value recorded: 0.928 at 1500 MHz
4. The 7 mm values were close to the SMA averages below 1400 MHz; largest positive difference was 0.012. The largest positive difference overall was 0.03 at 1800 MHz.

Mag(S_{22})

1. As with the data for mag(S_{11}), there is no evidence of any bias.
2. Again, there is evidence that the standard deviation is sensitive to changes in frequency. The largest estimated value is 0.07 at 1500 MHz; the next largest is 0.03 at 1800 MHz.
3. Largest average value: 1.047 at 1500 MHz
   Largest value recorded: 1.145 at 1500 MHz
   Smallest average value: 0.990 at 1800 MHz
   Smallest value recorded: 0.095 at 1800 MHz
4. The largest positive difference between the 7 mm data and the SMA averages is 0.05 at 1500 MHz. The other differences are within 0.01.

<u>All Probe Tips Shorted</u> (contd.)

Mag(S_{12})
1. Some evidence of bias can be seen, especially for the higher frequencies.
2. The standard deviation tends to increase with frequency; the largest estimated standard deviation is 0.027 at 1500 MHz.
3. Largest average: 0.091 at 1500 MHz
   Largest value recorded: 0.129 at 1500 MHz
   Smallest average value: 0.002 at 400 MHz
   Smallest value recorded: 0.0005 at 400 MHz
4. The 7 mm data are within 0.006 below 1500 MHz.
   The largest positive difference (at 1500 MHz) is about 0.03.

Mag(S_{21})
1. There is evidence of bias.
2. The standard deviation increases with frequency. The largest estimate is 0.025 at 1500 MHz.
3. Largest average value: 0.093 at 1500 MHz
   Largest value recorded: 0.128 at 1500 MHz
   Smallest average value: 0.0015 at 400 MHz
   Smallest value recorded: 0.0006 at 400 MHz
4. The 7 mm values of mag(S_{21}) are within 0.001 for frequencies less than 1400 MHz. At 1500 MHz the positive difference is 0.04.

Angle(S_{11})
1. Some evidence of an increasing negative bias for frequencies above 1400 MHz is present.
2. There are also indications that the precision may be better for frequencies above 1200 MHz. The largest estimated standard deviation was 22 degrees at 500 MHz; value 0.12 at 1600 MHz.

<u>All Probe Tips Shorted</u> (contd.)

Angle(S_{11}) (contd.)

3. Largest average value: 0.905 at 500 MHz
   Largest value recorded: 4.18 at 500 MHz
   Smallest average value: -2.23 at 1500 MHz
   Smallest value recorded: -3.01 at 1700 MHz
4. The largest positive difference of the 7 mm values from the SMA averages was 2.1 degrees at 1600 MHz.

Angle(S_{22})

1. There is no evidence of any bias. This is in contrast to what was noted about angle(S_{11}).
2. The standard deviation did not appear to be sensitive to frequency and the precision seemed two orders of magnitude better than what was apparent for angle (S_{11}). The largest estimated standard deviation was 0.032 at 1500 MHz.
3. Largest average value: 0.010 at 300 MHz
   Largest value recorded: 0.055 at 900 MHz
   Smallest average value: -0.047 at 1700 MHz
   Smallest value recorded: -0.092 at 1700 MHz
4. The largest positive difference from the 7 mm data was 2.8 degrees.

Thru-Line

Mag(S_{11}): 1. There was some evidence of positive bias for values of mag(S_{11}) above 1100 MHz; but the values tended to rise with frequency.

2. On the basis of the estimated standard deviations, the standard deviations of the measured values of mag(S_{11}) did not appear to be sensitive to frequency changes. The largest standard deviation estimated was 0.03 at 1000 MHz.

3. Largest average value recorded: 0.063 at 1600 MHz
Largest value recorded: 0.082 at 1100 MHz
Smallest average value recorded: 0.01 at 200 MHz
Smallest value recorded: 0.003 at 600 MHz

4. The values of mag(S_{11}) obtained using the 7 mm connections tended to be less (but greater than zero) than the average values of mag(S_{11}) obtained using the SMA connectors. The largest positive difference is 0.033 at 1700 MHz. The largest value of mag(S_{11}) recorded for the 7 mm data was 0.053 at 1600 MHz.

Mag(S_{22}): 1. As with mag(S_{11}), the values of mag(S_{22}) rise with frequency.

2. The estimated standard deviation of mag(S_{22}) at 1500 MHz (.04) was relatively large. The next largest value was 0.03 at 1000 MHz.

3. Largest average value: 0.07 at 1500 MHz.
Smallest average value: 0.009 at 200 MHz.
Smallest value recorded: 0.003 at 400 MHz.

Thru-Line (contd.)

Mag(S_{22}) (contd.)

4. The largest positive difference from the 7 mm data was 0.04 at 1500 MHz. The largest 7 mm value for mag(S_{22}) is 0.044 at 1600 MHz.

Mag(S_{12})

1. No evidence of any bias was apparent from the data.
2. There appeared, however, to be a tendency for the standard deviation to increase with frequency especially after 1100 MHz. The largest standard deviation estimated was 0.034 at 1500 MHz; next largest was 0.008 at 1800 MHz. The instability exhibited here and elsewhere at 1500 MHz appears to affect only the first three SMA "occasions".
3. Largest average value: 1.012 at 1500 MHz
   Next largest average value: 1.002 at 1700 MHz
   Largest value recorded: 1.062 at 1500 MHz
   Smallest average value: 0.985 at 1600 MHz
   Smallest value: 0.979 at 1600 MHz.
4. The 7 mm values of mag(S_{12}) were generally within 0.01 of the average SMA values. The largest positive difference 0.011 at 1500 MHz.

Mag(S_{21})

1. No real evidence of bias was apparent.
2. With respect to the estimated standard deviations, those below 1000 MHz were generally smaller than those above; range of .0006 to .003 below and range of .004 to .008 above if one leaves out the value of .034 at 1500 MHz.

Thru-Line (contd.)

$Mag(S_{21})$ (contd.)

3. Largest average value: 1.011 at 1500 MHz
   Next largest average value: 1.004 at 1700 MHz
   Largest value recorded: 1.061 at 1500 MHz
   Smallest average value: 0.984 at 1600 MHz
   Smallest value recorded: 0.979 at 1600 MHz
4. The 7 mm values were generally within 0.01 of the SMA averages. The largest positive difference was 0.017 at 1700 MHz.

$Angle(S_{12})$

1. No evidence of bias apparent from the data.
2. Clearly there is a tendency for the standard deviations to increase with frequency. The low value of the estimated standard deviation of $angle(S_{12})$ is 0.4 at 200 MHz, and the high value is 2.8 at 1900 MHz.
3. Largest average value: 1.22 at 1600 MHz
   Largest value recorded: 2.32 at 1700 MHz
   Smallest average value: -1.47 at 1400 MHz
   smallest value recorded: -4.41 at 1900 MHz
4. The 7 mm data were within two degrees of the average SMA averages.

$Angle(S_{21})$

1. Again, no bias is evident.
2. As with $angle(S_{21})$, standard deviations increase with frequency.
3. Largest average value: 1.29 at 1600 MHz
   Largest value recorded: 2.42 at 1700 MHz
   Smallest average value: -1.47 at 1400 MHz
   Smallest value recorded: -4.31 at 1900 MHz
4. The 7 mm data were within two degrees of the average SMA values. The differences became larger with frequency.

6. CONCLUSIONS

A measurement technique has been described that demonstrates the practicality of making accurate measurements on integrated circuit devices up to 2 GHz with this probe assembly. The accuracy of this technique is best illustrated by figures 20 and 21 that show plots of measured and corrected data for the two test devices measured, i.e., all probe tips shorted and thru-line.

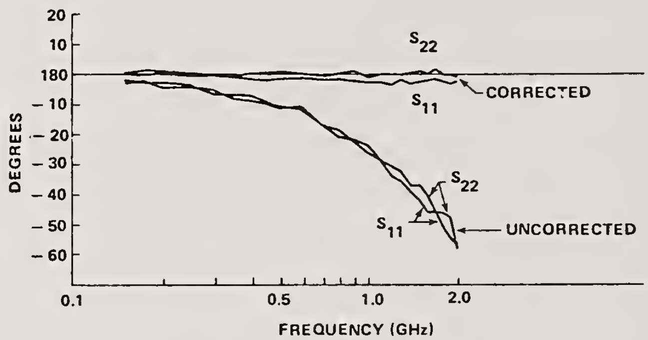


Figure 20. All probe tips shorted measurements

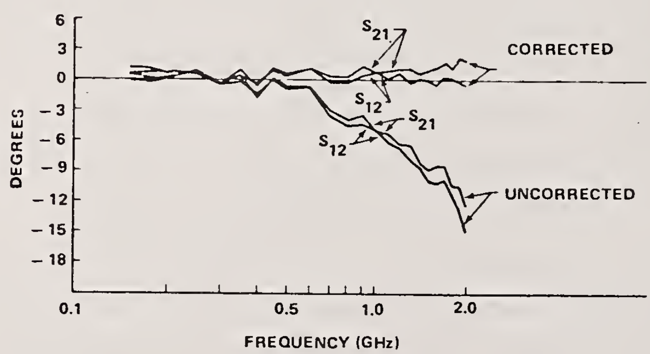


Figure 21. Thru-line measurements

Early in the program, it was seen that a possible limiting factor of this measurement technique was how well we could achieve a good short circuit between the probe tips and ground. This problem was solved by physically contacting the large copper short circuit to the bottom of the probe ground plane, and removing some material from the large copper short circuit to accommodate the probe tips, as shown in figure 5.

Stray (probably capacitive) coupling between the ungrounded conductors, probe tips 1 and 3, was shown to be neglibigle and does not affect the measurement results.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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APPENDIX I

LISTING OF COMPUTER PROGRAM WRITTEN IN BASIC

File 0

INSTRUCTIONS

```
100 REM  THIS CASSETTE CONTAINS ALL THE PROGRAMS & DATA FILES FOR CALIBRATING
110 REM  AND USING THE S/N 104 TRANSISTOR PROBE ASSEMBLY. THE FILE CONTENTS ARE:
120 REM
130 REM   0  INSTRUCTIONS
140 REM   1  PROGRAM FOR GETTING DATA OFF TAPE & INTO PROPER FILES
150 REM   2  PROGRAM FOR CALIBRATING ARMS A & B
160 REM   3  DATA FOR CALIBRATING ARM A
170 REM   4  S-PARAMETERS FOR ARM A
180 REM   5  ZP VALUES FROM ARM A
190 REM   6  DATA FOR CALIBRATING ARM B
200 REM   7  S-PARAMETERS FOR ARM B
210 REM   8  AVERAGE ZP VALUES FROM ARMS A & B
220 REM   9  T1 INVERSE
230 REM  10  T2 INVERSE
240 REM  11  PROGRAM FOR EVALUATING TEST ITEM(TRANSISTOR)
250 REM  12  DATA FOR EVALUATING TEST ITEM #1
260 REM  13  S-PARAMETERS FOR TEST ITEM #1
270 REM              ...
290 REM  50  DATA FOR EVALUATING TEST ITEM #20
300 REM  51  S-PARAMETERS FOR TEST ITEM #20
310 REM
320 REM DATA FOR CALIBRATING ARM A OF THE PROBE ASSEMBLY MUST BE LOADED
330 REM INTO FILE 3 IN THE FOLLOWING ORDER:
340 REM    FREQ,MO,PO,MS,PS,MZ,PZ,ML,PL
350 REM WHERE THE 1ST LETTER
360 REM    M=MAGNITUDE
370 REM    P=PHASE IN DEGREES
380 REM AND WHERE THE 2ND LETTER
390 REM    O=OPEN CIRCUIT
400 REM    S=SHORT TO GROUND
410 REM    Z=SHORT TO ZP
420 REM    L=LOAD
430 REM UP TO 20 LINES OF DATA (DIFFERENT FREQUENCIES) CAN BE STORED IN FILE 3
440 REM USING A SEMIPRECISION DIMENSION STATEMENT:    DS(20,9)
460 REM DATA FOR CALIBRATING ARM B IS LOADED INTO FILE 6 SAME AS FOR FILE 3
470 REM
480 REM DATA FOR UP TO 20 TEST ITEMS IS LOADED INTO FILE 12,14,...,50.
490 REM THE DATA IN EACH FILE HAS THE FOLLOWING ORDER:
500 REM    FREQ,MS11,PS11,MS12,PS12,MS21,PS21,MS22,PS22
510 REM WHERE MS11=MAGNITUDE OF S11, PS11=PHASE OF S11 IN DEGREES, ETC.
520 REM UP TO 20 LINES OF DATA (FREQUENCIES) CAN BE STORED FOR EACH TEST ITEM.
530 REM THE FREQUENCIES SHOULD CORRESPOND TO THOSE AT WHICH ARMS A & B
540 REM HAVE BEEN CALIBRATED.
550 REM
560 REM THE PROGRAM IN FILE 1 CAN BE USED TO LOAD DATA INTO THE FILES FROM
570 REM PAPER TAPE IF THE DATA ON THE TAPE IS IN THE PROPER ORDER. SEE FILE 1.
580 REM
590 REM TO CALIBRATE THE PROBE ASSEMBLY, FIRST LOAD THE DATA FOR ARMS A & B INTO
600 REM FILES 3 & 6, AND THE DATA FOR THE TEST ITEMS INTO FILES 12,14,...50.
610 REM     LOAD FILE 2 AND RUN.
620 REM THE PROGRAM WILL ASK FOR THE VALUE OF THE STANDARD LOAD RESISTOR USED IN
630 REM CALIBRATING ARMS A & B. TYPE IN THE VALUE, ASSUMED REAL. IT WILL THEN
640 REM ASK FOR THE # OF FREQUENCIES AND # OF TEST ITEMS TO BE EVALUATED.
650 REM TO CALIBRATE ONLY, TYPE 0 FOR THE # OF TEST ITEMS.
660 REM THE PROGRAM THEN CALCULATES T1 INVERSE & T2 INVERSE FOR EACH FREQUENCY
670 REM AND STORES THEM IN FILES 9 & 10.
680 REM IF THERE ARE TEST ITEMS TO BE EVALUATED, THIS PROGREM THEN LOADS IN
690 REM PROGRAM 11 WHICH EVALUATES THE TEST ITEMS. S-PARAMETERS FOR TEST ITEM #1
700 REM ARE STORED IN FILE 13, FOR ITEM #2 IN 15, AND FOR ITEM #N IN FILE 11+2N.
710 REM
720 REM TO EVALUATE THE TEST ITEMS WITHOUT RECALIBRATING, LOAD DATA FOR THE TEST
730 REM ITEMS INTO FILES 12,14,...,50 AS DESCRIBED ABOVE. THEN
740 REM     SCRATCH
750 REM     1 COM F3,F9,DS(20,9),RS(20,9),ZS(20,2)
760 REM     LOAD11,100,1
780 REM PROGRAM 11 WILL GO TO FILE 9 & 10 TO GET EXISTING CALIBRATION CONSTANTS
790 REM AND THEN EVALUATE THE TEST ITEMS.
```

File 1

```
10 REM:TAKING DATA FROM PAPER TAPE & STORING IN FILES
12 REM: TO READ IN PAPER TAPE TYPE  PTAPE # 7
14 REM
16 REM  DATA ON PAPER TAPE SHOULD BEGIN AT THE FOLLOWING LINE NUMBERS:
18 REM
20 REM  ARM A OPEN CIRCUIT DATA;     300 DATA FREQ,MAGNITUDE,PHASE(DEGREES)
22 REM  ARM A SHORT TO GROUND DATA; 400 DATA      "
24 REM  ARM A SHORT TO ZP DATA;     500 DATA      "
26 REM  ARM A LOAD DATA;            600 DATA      "
28 REM
30 REM  ARM B OPEN CIRCUIT DATA;     700 DATA FREQ,MAGNITUDE,PHASE(DEGREES)
32 REM  ARM B SHORT TO GROUND DATA; 800 DATA      "
34 REM  ARM B SHORT TO ZP DATA;     900 DATA      "
36 REM  ARM B LOAD DATA;           1000 DATA      "
38 REM
40 REM  S-PARAMETERS OF PROBE ASSEMBLY CONTAINING TEST ITEM #1 IN THE ORDER:
42 REM    1100 DATA FREQ,MS11,PS11,MS12,PS12,MS21,PS21,MS22,PS22
44 REM  WHERE MS11=MAGNITUDE OF S11, PS11=PHASE(DEG) OF S11, ETC.
46 REM  S-PARAMETERS OF PROBE ASSEMBLY CONTAINING TEST ITEM #2
48 REM    1200 DATA ...
50 REM    ...
52 DIM QS[20,9],C[19],A$[20]
54 FORMAT F9.3,F7.3,F8.1,F7.3,F8.1,F7.3,F8.1,F7.3,F8.1
56 PRINT "TO STORE ONLY CALIBRATION DATA, ENTER 1"
58 PRINT "TO STORE ONLY TEST ITEM DATA,    ENTER 2"
60 PRINT
62 PRINT
64 DISP "SEE NOTE ON PRINTER                ";
66 INPUT L
68 GOTO L OF 70,114


70 REM: STORING CALIBRATION DATA
72 PRINT "READ ALL OF CALIBRATION TAPE (TYPE: PTAPE # 7), THEN PRESS RUN 80"
74 PRINT
76 DISP "SEE NOTE ON PRINTER"
78 STOP
80 DISP "NO. OF FREQUENCIES(1 TO 20)=";
82 INPUT F9
84 FOR F0=3 TO 6 STEP 3
86 FIND F0
88 K2=2
90 FOR K=1 TO 4
92 K3=K2+1
94 FOR F=1 TO F9
96 READ Q[F,1],Q[F,K2],Q[F,K3]
98 NEXT F
100 K2=K2+2
102 NEXT K
104 GOSUB 154
106 STORE  DATA F0,Q
108 NEXT F0
110 PRINT "CALIBRATION DATA STORED"
112 END
```

File 1 (contd.)

```
114 REM: STORING TEST ITEM DATA
116 DISP "NO. OF TEST ITEMS = ";
118 INPUT F3
120 DISP "NO. OF FREQUENCIES(1 TO 20)=";
122 INPUT F9
124 F2=11+2*F3
126 F0=12
128 FIND F0
130 X=RBYTE7
132 IF X=0 THEN 130
134 FOR F=1 TO F9
136 ENTER (7,*)A$[1,10],(FORK=1TO9,Q[F,K])
138 NEXT F
140 GOSUB 154
142 STORE  DATA F0,Q
144 F0=F0+2
146 IF F0<F2 THEN 128
148 PRINT "ALL STORED"
150 PRINT
152 END


154 PRINT
156 PRINT " DATA ABOUT TO BE STORED IN FILE"F0;"IS"
158 PRINT
160 FOR F=1 TO F9
162 WRITE (15,54)Q[F,1],Q[F,2],Q[F,3],Q[F,4],Q[F,5],Q[F,6],Q[F,7],Q[F,8],Q[F,9]
164 NEXT F
166 PRINT
168 PRINT "IF DATA LOOKS OK, PRESS CONT"
170 PRINT "TO REJECT CAL DATA, START OVER. TO REJECT A TEST ITEM, PRESS CONT 130
172 PRINT
174 PRINT
176 STOP
178 RETURN
```

File 2

```
1 COM F3,F9,QS[20,9],RS[20,9],ZS[20,2]
2 REM
100 REM: CALIBRATING TRANSISTOR PROBE ASSEMBLY, ONE ARM AT A TIME
110 DIM X[9],Y[9],M[9],P[9],WS[20,9]
115 FORMAT F9.3,F7.3,F8.1,F7.3,F8.1,F7.3,F8.1,F7.3,F8.1
120 DEG
130 X[5]=1
140 Y[5]=Y[6]=0
145 DISP "VALUE OF STANDARD LOAD = ";
150 INPUT X[6]
160 PRINT "STANDARD LOAD = "X[6];"OHMS"
170 DISP "NO. OF FREQUENCIES(1 TO 20)=";
172 INPUT F9
174 DISP "NO. OF TEST ITEMS(1 TO 20)=";
176 INPUT F3
```

```
190 FOR F0=3 TO 6 STEP 3
192 LOAD  DATA F0,W
193 PRINT
194 PRINT
195 IF F0=6 THEN 200
196 PRINT "S PARAMETERS FOR ARM A"
198 GOTO 202
200 PRINT "S PARAMETERS FOR ARM B"
202 PRINT
204 PRINT "                        S11              S12              S21              S22"
206 PRINT "    FREQ    MAG    ANG     MAG    ANG     MAG    ANG     MAG    ANG"
208 PRINT
```

FØ = 3 for Arm A, 6 for Arm B

```
209 FOR F=1 TO F9
210 RESTORE 3000
250 FOR K=1 TO 4
252 L=2*K
255 M=W[F,L]
260 P=W[F,L+1]
270 D=(1+M*M-2*M*COS(P))/50
280 X[K]=(1-M*M)/D
290 Y[K]=2*M*SIN(P)/D
310 NEXT K
```

Converting reflection coefficient magnitude (M) and phase (P) input data to impedance $Z = Z_0 \frac{1+\Gamma}{1-\Gamma} \equiv X + jy$

```
330 FOR L=1 TO 15
340 GOSUB 1000
350 NEXT L
410 K=4
420 GOSUB 1200
430 M[4]=SQR(M[4])
440 P[4]=P[4]/2
450 GOSUB 1275
460 FOR L=1 TO 3
470 GOSUB 1000
480 NEXT L
```

Calculating the ABCD Cascading Matrix T_1 or T_2; and also Z_P

File 2 (contd.)

Setting T_1 or T_2 = E + jF = A + jB

```
490 K=1
500 FOR I=1 TO 2
510 FOR J=1 TO 2
520 E[I,J]=A[I,J]=X[K]
530 F[I,J]=B[I,J]=Y[K]
540 K=K+1
550 NEXT J
560 NEXT I
```

For Arm B data, go to 950

```
565 IF F0=6 THEN 950
```

Storing Z_p at frequency F in matrix Z

```
570 Z[F,1]=X[7]
580 Z[F,2]=Y[7]
```

Calculate T_1 inverse = C + jD

```
590 GOSUB 2100
```

Storing T_1 inverse at frequency F in matrix Q

```
591 K=2
592 FOR I=1 TO 2
593 FOR J=1 TO 2
594 Q[F,K]=C[I,J]
595 Q[F,K+1]=D[I,J]
596 K=K+2
597 NEXT J
598 NEXT I
```

Converting Cascade parameters to S-parameters and printing results

```
660 GOSUB 1700
670 GOSUB 1600
690 GOSUB 2500
710 NEXT F
```

Printing Z_p values

```
715 PRINT
716 PRINT
720 IF F0=6 THEN 750
730 PRINT "ZP FROM ARM A"
740 GOTO 760
750 PRINT "AVERAGE ZP FROM ARMS A & B"
760 PRINT
770 PRINT "   FREQ         REAL       IMAGINARY   MAGNITUDE     PHASE"
780 PRINT
790 FOR F=1 TO F9
800 K=7
810 X[7]=Z[F,1]
820 Y[7]=Z[F,2]
830 GOSUB 1200
840 WRITE (15,845)W[F,1];X[7];Y[7];M[7];P[7]
845 FORMAT F9.3,3F12.4,F12.2
850 NEXT F
852 FOR I=1 TO 4
854 PRINT
856 NEXT I
```

Converting Z_p = X + jY to magnitude and phase (line 830)

File 2 (contd.)

```
860 STORE  DATA F0+1,W
870 STORE  DATA F0+2,Z
880 NEXT F0
```

Storing S-parameters
Storing Z_p values

```
885 PRINT
890 STORE  DATA 9,Q
900 STORE  DATA 10,R
905 IF F3=0 THEN 930
910 LOAD 11,100,245
920 END
930 REWIND
940 END
```

Storing all T_1^{-1} matrices in file 9
Storing all T_2^{-1} matrices in file 10

Loading in program to evaluate test items

```
950 Z[F,1]=(Z[F,1]+X[7])/2
953 Z[F,2]=(Z[F,2]+Y[7])/2
```

Calculating average Z_p from Arms A and B

```
956 FOR K=1 TO 4
960 READ J
965 L=2*K
970 R[F,L]=J*X[K]
980 R[F,L+1]=J*Y[K]
990 NEXT K
999 GOTO 660
```

Calculating T_2 inverse at frequency F, storing in matrix R.

File 2 (contd.)

Subroutines

Complex Math Subroutine

```
1000 REM: COMPLEX +,-,*,&/
1005 READ I,J,K
1010 IF I>0 THEN 1075
1015 I=-I
1020 IF J>0 THEN 1055
```

Z_i/Z_j

```
1025 J=-J
1030 D=X[J]*X[J]+Y[J]*Y[J]
1035 X=(X[I]*X[J]+Y[I]*Y[J])/D
1040 Y[K]=(Y[I]*X[J]-X[I]*Y[J])/D
1045 X[K]=X
1050 RETURN
```

Z_i*Z_j

```
1055 X=X[I]*X[J]-Y[I]*Y[J]
1060 Y[K]=Y[I]*X[J]+X[I]*Y[J]
1065 X[K]=X
1070 RETURN
1075 IF J>0 THEN 1100
```

Z_i-Z_j

```
1080 J=-J
1085 X[K]=X[I]-X[J]
1090 Y[K]=Y[I]-Y[J]
1095 RETURN
```

Z_i+Z_j

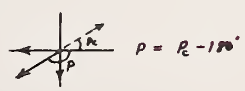
```
1100 X[K]=X[I]+X[J]
1105 Y[K]=Y[I]+Y[J]
1110 RETURN
```

Code

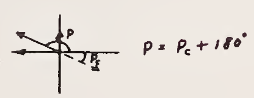
I	J	Z_k =
+	+	$Z_i + Z_j$
+	-	$Z_i - Z_j$
-	+	$Z_i * Z_j$
-	-	Z_y / Z_j

```
1200 REM: CONVERTING X+JY TO M & P
1205 X=X[K]
1210 Y=Y[K]
1215 M[K]=SQR(X*X+Y*Y)
1220 P=ATN(Y/X)
1225 IF X>0 THEN 1250
1230 IF Y>0 THEN 1245
1235 P=P-180
1240 GOTO 1250
1245 P=P+180
1250 P[K]=P
1255 RETURN
```

← **X neg, y neg** →



← **X neg, y pos** →




```
1275 REM: CONVERTING M & P TO X+JY
1280 X[K]=M[K]*COS(P[K])
1285 Y[K]=M[K]*SIN(P[K])
1290 RETURN
```

```
1600 REM: CONVERTING Z TO S PARAMETERS; GIVEN Z=E+JF, GIVES S=E+JF
1610 MAT I=IDN[2,2]
1620 MAT E=(0.02)*E
1630 MAT A=E+I
1640 MAT B=(0.02)*F
1650 GOSUB 2100
1660 MAT A=E-I
1670 GOSUB 2000
1680 RETURN
```

File 2 (contd.)

```
1700 REM: CONVERTING Z TO T OR T TO Z PARAMETERS
1710 REM: GIVEN Z=E+JF, GIVES T=E+JF. GIVEN T=E+JF, GIVES Z=E+JF
1720 E2=E[1,1]*E[2,2]-F[1,1]*F[2,2]-E[1,2]*E[2,1]+F[1,2]*F[2,1]
1730 F[1,2]=E[1,1]*F[2,2]+F[1,1]*E[2,2]-E[1,2]*F[2,1]-F[1,2]*E[2,1]
1740 E[1,2]=E2
1750 C0=E[2,1]*E[2,1]+F[2,1]*F[2,1]
1760 MAT I=IDN[2,2]
1770 MAT A=(E[2,1]/C0)*I
1780 MAT B=(-F[2,1]/C0)*I
1790 E[2,1]=1
1800 F[2,1]=0
1810 MAT C=E
1820 MAT D=F
1830 GOSUB 2000
1840 RETURN


2000 REM:MULTIPLYING 2 COMPLEX MATRICES E+JF=(A+JB)*(C+JD)
2010 MAT G=B*D
2020 MAT E=A*C
2030 MAT E=E-G
2040 MAT G=B*C
2050 MAT F=A*D
2060 MAT F=F+G
2070 RETURN


2100 REM: INVERTING A COMPLEX MATRIX  C+JD=INV(A+JB)
2110 MAT G=INV(A)
2120 MAT H=G*B
2130 MAT C=B*H
2140 MAT C=A+C
2150 MAT C=INV(C)
2160 MAT D=H*C
2170 MAT D=(-1)*D
2180 RETURN
2190 DIM A[2,2],B[2,2],C[2,2],D[2,2],E[2,2],F[2,2],G[2,2],H[2,2]


2500 REM: CONVERT ELEMENTS OF E+JF TO MAGNITUDE & PHASE, STORE IN W, PRINT
2520 K=1
2530 FOR I=1 TO 2
2540 FOR J=1 TO 2
2550 X=E[I,J]
2560 Y=F[I,J]
2570 GOSUB 1215
2580 L=2*K
2590 W[F,L]=M[K]
2600 W[F,L+1]=P[K]
2610 K=K+1
2620 NEXT J
2630 NEXT I
2640 WRITE (15,115)W[F,1],M[1],P[1],M[2],P[2],M[3],P[3],M[4],P[4]
2650 RETURN


3000 DATA 1,-4,7,4,-3,4,3,-2,8,1,-2,9,1,-3,3,-7,8,7,-4,9,4,-7,-4,7,-7,6,7
3010 DATA -8,-3,3,-3,-7,3,-3,1,1,-2,3,4,1,-4,4,-5,-4,4,-1,4,1,-2,4,2,-3,4,3
3020 DATA 1,-1,-1,1
```

File 11

```
100 REM: EVALUATING TRANSISTOR IN PROBE ASSEMBLY
110 DIM M[4],P[4],S[2,2],T[2,2],U[2,2],V[2,2],WS[20,9]
115 FORMAT F9.3,F7.3,F8.1,F7.3,F8.1,F7.3,F8.1,F7.3,F8.1
200 LOAD  DATA 8,Z
210 LOAD  DATA 9,Q
220 LOAD  DATA 10,R
225 DISP "NO. OF FREQUENCIES(1 TO 20)=";
226 INPUT F9
230 DISP "NO. OF TEST ITEMS(1 TO 20)=";
240 INPUT F3
245 DEG
250 F2=11+2*F3
255 F4=0
260 FOR F1=12 TO F2 STEP 2
262 F4=F4+1
264 PRINT "S PARAMETERS FOR TEST ITEM NO. "F4
266 N=3
268 GOSUB 1000
270 LOAD  DATA F1,W
272 PRINT "                   .S11              S12              S21              S22"
274 PRINT "    FREQ    MAG    ANG     MAG    ANG     MAG    ANG     MAG    ANG"
276 PRINT
280 FOR F=1 TO F9                  For each frequency F, set:
290 K=2
300 FOR I=1 TO 2
310 FOR J=1 TO 2
320 S[I,J]=Q[F,K]                  T1^-1 = S + jT
330 T[I,J]=Q[F,K+1]
340 U[I,J]=R[F,K]                  T2^-1 = U + jV
350 V[I,J]=R[F,K+1]
360 E[I,J]=W[F,K]*COS(W[F,K+1])    S-parameters of probe assembly = E + jF
370 F[I,J]=W[F,K]*SIN(W[F,K+1])
380 K=K+2
390 NEXT J
400 NEXT I
460 GOSUB 1500                     Convert S to T parameters
470 GOSUB 1700                     Cascade parameters of probe assembly = E + jF
480 MAT A=E  }
490 MAT B=F  }    = T
500 MAT C=U  }
510 MAT D=V  }    = T2^-1
520 GOSUB 2000                     Calculate TT2^-1 = E + jF
530 MAT C=E  }
540 MAT D=F  }    = TT2^-1
550 MAT A=S  }
560 MAT B=T  }    = T1^-1
570 GOSUB 2000                     Calculate T1^-1 TT2^-1 = E + jF ≡ T3
580 GOSUB 1700                     Converts T3 to Z3, impedance parameters
590 MAT C=CON
600 MAT G=(Z[F,1])*C }
610 MAT H=(Z[F,2])*C }  = Zp = G +jH
620 MAT E=E-G  }
630 MAT F=F-H  }   Zt = Z3 - Zp = transistor impedance parameters
640 GOSUB 1600                     Converts Zt to St, S-parameters
660 GOSUB 2500                     Prints S-parameters
760 NEXT F
770 STORE  DATA F1+1,W             Store S-parameter of transistor
773 PRINT
776 PRINT "STORED IN FILE "F1+1
780 N=4
790 GOSUB 1000
810 NEXT F1
820 REWIND
830 END
```

File 11 (contd.)

Subroutines

```
1000 REM: SKIPPING N LINES
1010 FOR I=1 TO N
1020 PRINT
1030 NEXT I
1040 RETURN


1200 REM: CONVERTING X+JY TO M & P
1205 X=X[K]
1210 Y=Y[K]
1215 M[K]=SQR(X*X+Y*Y)
1220 P=ATN(Y/X)
1225 IF X>0 THEN 1250
1230 IF Y>0 THEN 1245
1235 P=P-180
1240 GOTO 1250
1245 P=P+180
1250 P[K]=P
1255 RETURN


1275 REM: CONVERTING M & P TO X+JY
1280 X[K]=M[K]*COS(P[K])
1285 Y[K]=M[K]*SIN(P[K])
1290 RETURN


1500 REM: CONVERTING S TO Z PARAMETERS; GIVEN S=E+JF, GIVES Z=E+JF
1510 MAT I=IDN[2,2]
1520 MAT A=I-E
1530 MAT B=(-1)*F
1540 GOSUB 2100
1550 MAT A=I+E
1560 MAT B=F
1570 GOSUB 2000
1580 MAT E=(50)*E
1590 MAT F=(50)*F
1599 RETURN


1600 REM: CONVERTING Z TO S PARAMETERS; GIVEN Z=E+JF, GIVES S=E+JF
1610 MAT I=IDN[2,2]
1620 MAT E=(0.02)*E
1630 MAT A=E+I
1640 MAT B=(0.02)*F
1650 GOSUB 2100
1660 MAT A=E-I
1670 GOSUB 2000
1680 RETURN


1700 REM: CONVERTING Z TO T OR T TO Z PARAMETERS
1710 REM: GIVEN Z=E+JF, GIVES T=E+JF. GIVEN T=E+JF, GIVES Z=E+JF
1720 E2=E[1,1]*E[2,2]-F[1,1]*F[2,2]-E[1,2]*E[2,1]+F[1,2]*F[2,1]
1730 F[1,2]=E[1,1]*F[2,2]+F[1,1]*E[2,2]-E[1,2]*F[2,1]-F[1,2]*E[2,1]
1740 E[1,2]=E2
1750 C0=E[2,1]*E[2,1]+F[2,1]*F[2,1]
1760 MAT I=IDN[2,2]
1770 MAT A=(E[2,1]/C0)*I
1780 MAT B=(-F[2,1]/C0)*I
1790 E[2,1]=1
1800 F[2,1]=0
1810 MAT C=E
1820 MAT D=F
1830 GOSUB 2000
1840 RETURN
```

File 11 (contd.)

```
2000 REM:MULTIPLYING 2 COMPLEX MATRICES E+JF=(A+JB)*(C+JD)
2010 MAT G=B*D
2020 MAT E=A*C
2030 MAT E=E-G
2040 MAT G=B*C
2050 MAT F=A*D
2060 MAT F=F+G
2070 RETURN

2100 REM: INVERTING A COMPLEX MATRIX  C+JD=INV(A+JB)
2110 MAT G=INV(A)
2120 MAT H=G*B
2130 MAT C=B*H
2140 MAT C=A+C
2150 MAT C=INV(C)
2160 MAT D=H*C
2170 MAT D=(-1)*D
2180 RETURN
2190 DIM A[2,2],B[2,2],C[2,2],D[2,2],E[2,2],F[2,2],G[2,2],H[2,2]

2200 REM: PRINTING ELEMENTS OF E+JF                    not used
2210 PRINT "PARAMETERS (REAL & IMAGINARY) ARE"
2220 PRINT
2230 PRINT "(11) = "E[1,1];F[1,1];"(12) = "E[1,2];F[1,2]
2240 PRINT "(21) = "E[2,1];F[2,1];"(22) = "E[2,2];F[2,2]
2250 PRINT
2260 RETURN

2300 REM: READ MATRIX E+JF IN ORDER 11,12,21,22        not used
2310 FOR I=1 TO 2
2320 FOR J=1 TO 2
2330 READ E[I,J],F[I,J]
2340 NEXT J
2350 NEXT I
2360 RETURN

2500 REM: CONVERT ELEMENTS OF E+JF TO MAGNITUDE & PHASE, PRINT
2520 K=1
2530 FOR I=1 TO 2
2540 FOR J=1 TO 2
2550 X=E[I,J]
2560 Y=F[I,J]
2570 GOSUB 1215
2580 L=2*K
2590 W[F,L]=M[K]
2600 W[F,L+1]=P[K]
2610 K=K+1
2620 NEXT J
2630 NEXT I
2640 WRITE (15,115)W[F,1],M[1],P[1],M[2],P[2],M[3],P[3],M[4],P[4]
2650 RETURN
```

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A detailed, applications-oriented description of a measurement technique that characterizes a high-frequency probe assembly for integrated circuit measurements is given along with the procedure that extracts the parasitic effects of the probe assembly from measurements made at the input connectors of the probe assembly. The scattering parameters of an integrated-circuit device or transistor can now be extracted and accurately determined up to 2 GHz at the wafer stage of assembly. This represents a significant advance over conventional techniques that enable only dc parameters to be measured. Measurement results using this technique are given along with the precision of values obtained as well as the nature of the measurement bias introduced by the probe assembly.

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