THE DEVELOPMENT OF AN AUTOMATED S-PARAMETER MEASUREMENT SYSTEM

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EEAP 399
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Introduction

The aim of this project was to develop an automated measurement system, which measures the S-parameters of a two-port network with respect to frequency. The frequency range of the system is from 1 MHz to 1300 MHz. The system and accompanying software were developed to make the measuring and displaying of the parameters simple and still allow the user to select the frequency range of the measurements.

A step-by-step user's guide is included in the report to assist the user. This report will also discuss:

1) The properties of traveling waves and their relation to S-parameters, as well as other parameter sets;

2) The equipment used to measure S-parameters;

3) Automating the measurement process with a desktop computer;

4) The testing of the system with a resonsant circuit;

5) Possible ways of improving the accuracy of the system.

I. Parameter Sets

Parameter sets, such as the S, y, z, h and ABCD parameters, are a means of characterizing an n-port network. Based on one of these parameter sets and knowledge of the external loads applied to the ports of a network, one may determine how a network will respond to an input signal without knowing the internal structure of the network.

The most commonly used parameter sets are the y, h, z and ABCD parameters. These parameters are all based on the total voltages and total currents at the ports of a network. For example, the y-parameters of a two-port network (see Figure 1) are defined by equations 1 and 2. V_1 and V_2 are the total voltages and I_1 and I_2 are the total currents.

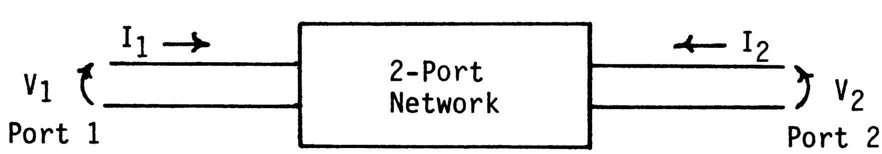


FIGURE 1

1) $I_1 = Y_{11} V_1 + Y_{12} V_2$

2) $I_2 = Y_{21} V_1 + Y_{22} V_2$

To measure the y-parameters of the two-port network, one of the two ports must be shorted and the voltage at the other port and the currents at both ports measured. The y-parameters are the ratios of the currents to the voltage. See the equations below:

$$Y_{11} = \frac{I_1}{V_1}\Bigg|_{V_2 = 0} \qquad Y_{12} = \frac{I_1}{V_2}\Bigg|_{V_1 = 0}$$

$$Y_{21} = \frac{I_2}{V_1}\Bigg|_{V_2 = 0} \qquad Y_{22} = \frac{I_2}{V_2}\Bigg|_{V_1 = 0}$$

As mentioned in the introduction, the objective is to characterize a network at higher frequencies (1 MHz - 1300 MHz). However, when attempting to measure the more commonly used parameters at these frequencies, several difficulties arise. The major problems are:

1) Equipment is not readily available to measure total voltages and total currents at the ports of the network.

2) Short and open circuits are difficult to achieve over a broadband of frequencies.

3) Active devices, such as transistors, very often will not be short or open circuit stable.

Therefore, at these frequencies a different means of characterizing the network must be used. The solution is the S-parameter set. These parameters are defined in terms of traveling voltage waves, which can be measured at the higher frequencies with a network analyzer.

II. Traveling Waves

Examine the two-port network diagrammed in Figure 2.

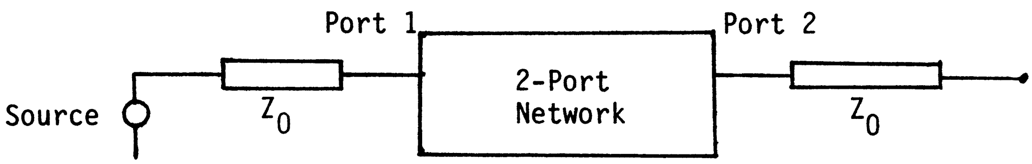


FIGURE 2

A traveling wave (Ei_1) generated at the source travels towards port 1 of the network through a transmission line of characteristic impedence Z_0 (neglect the effects of the transmission line). When the wave reaches the network, two new traveling waves are produced. One appears at port 2 traveling away from the network (Er_2) and the other appears at port 1 traveling back towards the source (Er_1). The S-parameters characterize the network by indicating the amount of power reflected from the network at both its ports ($Er_1/\sqrt{Z_0}$, $Er_2/\sqrt{Z_0}$) compared to the amount of power incident to its ports ($Ei_1/\sqrt{Z_0}$, $Ei_2/\sqrt{Z_0}$). The S-parameters for a two-port network are defined by equations 3 and 4.

3) $$\frac{Er_1}{\sqrt{Z_0}} = S_{11}\frac{Ei_1}{\sqrt{Z_0}} + S_{12}\frac{Ei_2}{\sqrt{Z_0}}$$

$$4) \quad \frac{Er_2}{\sqrt{Z_0}} = S_{21} \frac{Ei_1}{\sqrt{Z_0}} + S_{22} \frac{Ei_2}{\sqrt{Z_0}}$$

Each of the S-parameters may be independently defined in terms of a standing-wave-ratio (SWR); the ratio of the reflected traveling wave and the incident traveling wave. (Note the other incident signal must be zero.)

$$5) \quad S_{11} = \left. \frac{Er_1}{Ei_1} \right| Ei_2 = 0 \qquad 6) \quad S_{12} = \left. \frac{Er_1}{Ei_2} \right| Ei_1 = 0$$

$$7) \quad S_{21} = \left. \frac{Er_2}{Ei_1} \right| Ei_2 = 0 \qquad 8) \quad S_{22} = \left. \frac{Er_2}{Ei_2} \right| Ei_1 = 0$$

The total voltages and currents, mentioned earlier, are also functions of the traveling waves. Specifically, the total voltage at a port is equal to the sum of the two voltage traveling waves at the port.

$$9) \quad V_1 = Ei_1 + Er_1$$

$$10) \quad V_2 = Ei_2 + Er_2$$

The total current is the difference of the two current traveling waves.

$$11) \quad I_1 = Ii_1 - Ir_1 = \frac{Ei_1}{Z_0} - \frac{Er_1}{Z_0}$$

$$12) \quad I_2 = Ii_2 - Ir_2 = \frac{Ei_2}{Z_0} - \frac{Er_2}{Z_0}$$

Through this relationship other important relations may be developed.

The load at the end of a transmission line can be related to the SWR of the reflected and incident voltages.

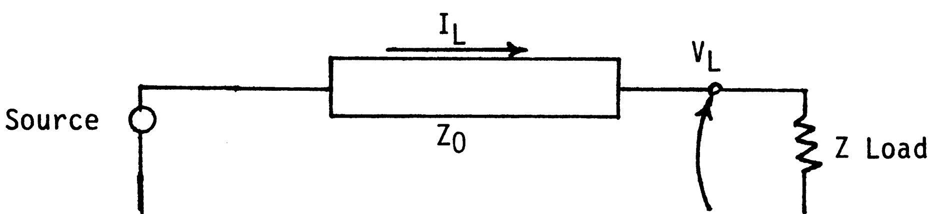


FIGURE 3

$$Z\ Load = \frac{V_L}{I_L} = \frac{Ei_L + Er_L}{Ii_L - Ir_L} = \frac{Z_0 \ (Ei_L + Er_L)}{(Ei_L - Er_L)} = Z_0 \ \frac{(1 + (SWR))}{(1 - (SWR))}$$

Based on this relation, if $Z_0 = Z_L$ (the load and transmission line are "matched") no reflected signal is generated. If the load is a short (Z load $= 0$) then the reflected wave is equal to the incident signal but travels in the opposite direction.

Also, because of the relation between the S-parameters and traveling waves; traveling waves and total voltages and currents; and total voltages and currents and the y, z, h and ABCD parameters, one can express the more commonly used parameters in terms of S-parameters. As mentioned before, it is difficult to measure these parameters, however, they can be calculated from the measured S-parameters.

As an example, let us calculate two of the y parameters based on the S-parameter values.

$$I_1 = Y_{11} V_1 + Y_{12} V_2$$

Matching the load at port 2 of the network reduces Ei_2 to zero (using equations 9, 10, 11, 12).

$$\frac{Ei_1 - Er_1}{Z_0} = Y_{11} (Ei_1 + Er_1) + Y_{12} (Er_2)$$

$$1 - \left.\frac{Er_1}{Ei_1}\right|_{Ei_2 = 0} = Y_{11} Z_0 \left(1 + \left.\frac{Er_1}{Ei_1}\right|_{Ei_2 = 0}\right) + Y_{12} Z_0 \left.\frac{Er_2}{Ei_1}\right|_{Ei_2 = 0}$$

Using equations 5 and 7

13) $I - S_{11} = Y_{11} Z_0 (1 + S_{11}) + Y_{12} Z_0 S_{21}$

There are still two unknowns. Another equation is generated by matching the load at port 1, eliminating Ei_1.

$$-\frac{Er_1}{Z_0} = Y_{11} (Er_1) + Y_{12} (Ei_2 + Er_2)$$

$$-\left.\frac{Er_1}{Ei_2}\right|_{Ei_1 = 0} = Y_{11} Z_0 \left.\frac{Er_1}{Ei_2}\right|_{Ei_1 = 0} + Y_{12} Z_0 \left(1 + \left.\frac{Er_2}{Ei_2}\right|_{Ei_1 = 0}\right)$$

Using equations 6 and 8

14) $-S_{12} = Y_{11} Z_0 S_{12} + Y_{12} Z_0 (1 + S_{22})$

Solving equations 13 and 14 simultaneously

$$Y_{11} = \frac{(1 - S_{11})(1 + S_{22}) + S_{12} S_{21}}{(1 + S_{11})(1 + S_{22}) - S_{12} S_{21}}$$

$$Y_{12} = \frac{-2\, S_{12}}{(1 + S_{11})\,(1 + S_{22}) - (S_{12}\, S_{21})}$$

Using this procedure, all the parameters derived from total voltages and currents may be defined in terms of the S-parameters. The conversion equations for each of the parameter sets y, h, z and ABCD are given in the Appendix of this report.

III. Measuring the S-Parameters

To measure the S-parameters of a two-port network, the load and transmission line at one of the ports is matched, an incident signal is generated and sent towards the other port, and the incident signal and reflected signals are measured. The ratio of the reflected signals to the incident signal yields two of the S-parameters. Matching the load and transmission line at port 2 yields:

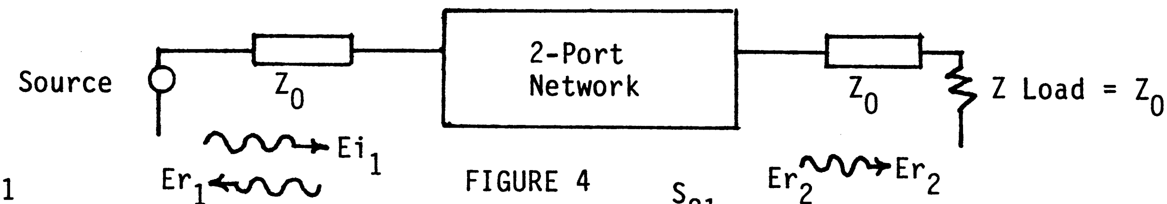


FIGURE 4

$$S_{11} = \frac{Er_1}{Ei_1} \qquad S_{21} = \frac{Er_2}{Ei_1}$$

To measure S_{12} and S_{22}, reverse the ports of the D.U.T. and repeat the same procedure.

The problem that arises when attempting to actually measure the traveling voltage waves is that the reflected and incident signals at port 1 travel along the same transmission line. The two signals must be separated so that each may be measured independent of each other.

An HP-8502A Transmission/Reflection test set is used for this purpose. The internal structure of the test set is diagrammed in Figure 5.

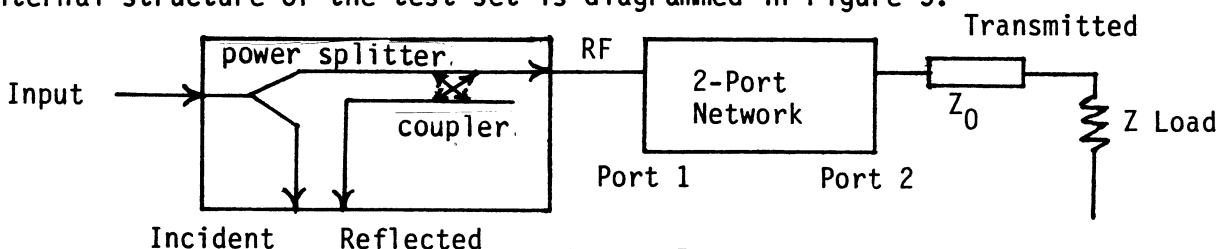


FIGURE 5

The incident signal is applied to the input port of the test set, and its power, is divided by a 3dB power splitter. Half of the signal is sent to the output port labeled "Incident" and the other half is sent to port 1 of the network. The signal reflected back from port 1 travels through a directional coupler, which separates it from the incident signal because it is traveling in the opposite direction. This reflected signal is available for measurement at the port labeled "Reflection". The signal reflected from port 2 of the network is the only signal on that transmission line, as long as the load at the end of the line is matched. It may be measured directly. Through the use of this instrument, each of the traveling wave signals can be measured. The test set's frequency range is 500 KHz - 1300 MHz; within the desired range of the system. Also, all the ports of the T/R test set are 50 ohm, which match the characteristic impedence of the transmission lines used.

In order to measure the SWRs with respect to frequency, an HP-8505A network analyzer is used.

IV. The Network Analyzer

The network analyzer measures both the magnitude and phase response of a network within the frequency range of 500 KHz to to 1300 MHz. A general description of the analyzer's capabilities and how these features can be used to measure the SWRs with respect to frequency will be discussed.

The complete analyzer can be thought of as three distinct but integrated units - the source/converter, the frequency controller, and the signal processor.

A. Source/Converter

The source is the signal generator which outputs sinusoidal signals at the port labeled "RF" (see Figure 6). The power level of the output signal can be adjusted from +10dBm to - 60dBm.

The converter consists of three 50 ohm input ports labeled R, A and B. The input level switch sets the maximum allowable power of the input signals. If the input power exceeds this level, an overload is indicated on the LEDs above.

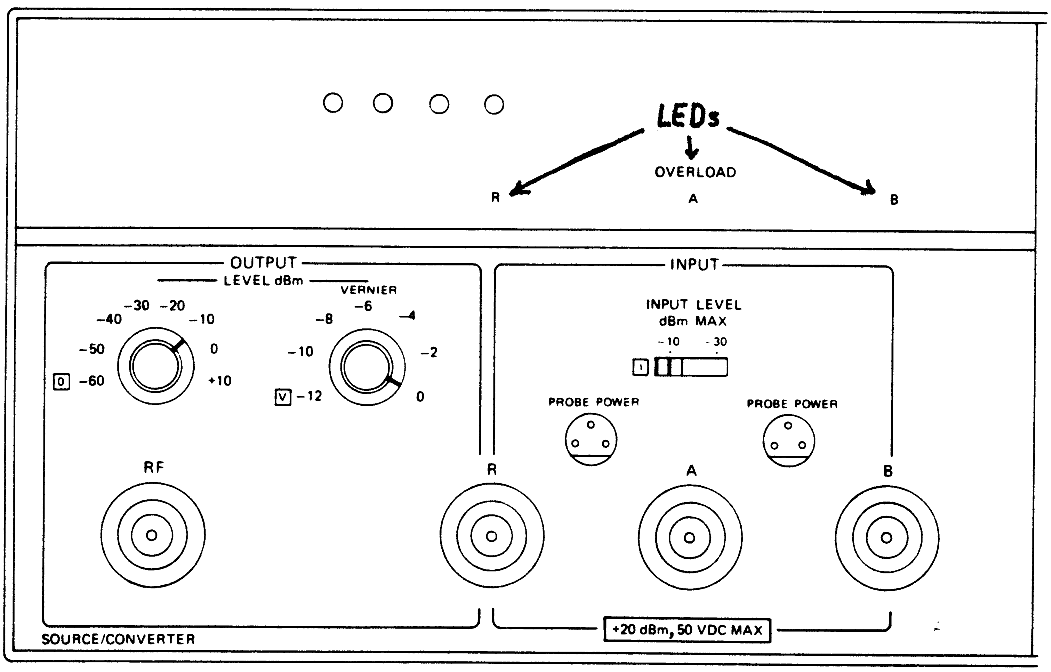


FIGURE 6

B. Frequency Controller

The frequency controller's main function is to set the frequency range of the response and to select the type of scaling to be used. There are three types of scaling; linear, logrythmic and expanded. The range of the linear and log scales are set by the RANGE switch (3 possible settings). The linear expanded scale allows a user to select a more specific range within one of the general range settings. The method used to set the range for this project was the start/stop method. The user sets the desired range by selecting the start frequency using the left-most frequency adjuster (FA in Figure 7) and the stop frequency using the frequency adjuster to the right (FB in Figure 7). When the RANGE switch is set to expanded scale, the range of the response is from the start to the stop frequency.

Another feature of the frequency controller are the markers. These may be set to any frequency within the range.

The controller also has a scan-time and trigger control.

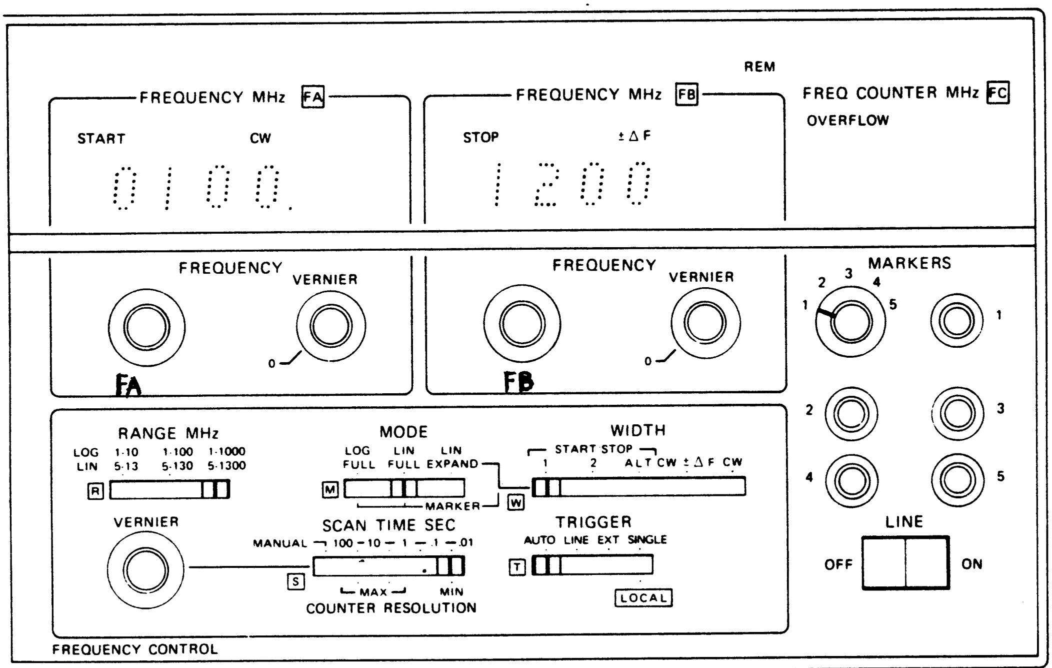


FIGURE 7

C. Signal Processor

The signal processor allows the user to view the response of a network on two independent, but identical channels. For each channel, the user selects the signal to be displayed; inputs A, B or R or ratios A/R or B/R. The magnitude or phase of the response may be displayed in either rectangular or polar coordinates. The scale division of the display is also controllable.

A digital readout is used to display either reference offsets, set by the user, or the magnitude or phase of the response at the marker frequency.

The signal processor also allows for the electric length of input A or B to be increased or decreased to eliminate phase discrepencies in SWR (A/R or B/R) measurements. The use of this feature will be discussed in more detail in the section titled "System Improvements."

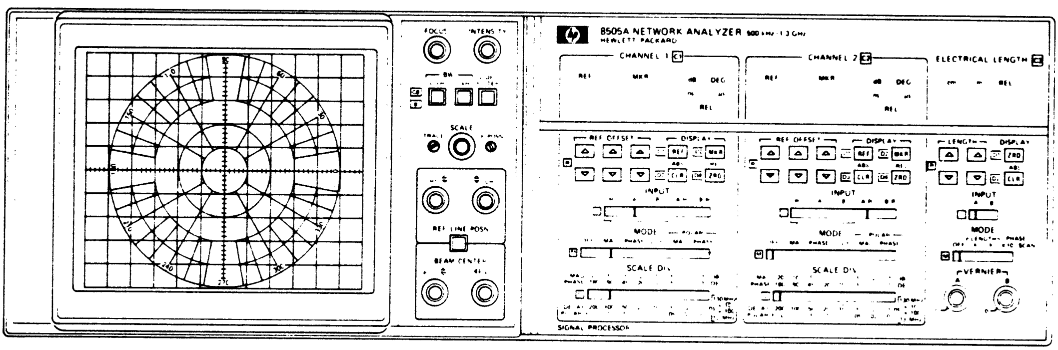


FIGURE 8

V. SWR Measurements

To measure the SWRs of the reflected signals and the incident signal, the following procedure was employed. Figure 9 illustrates how the DUT, transmission/reflection test set, and network analyzer are interconnected. The incident signal is measured at port R, the reflected signal at port A, and the transmitted signal at port B.

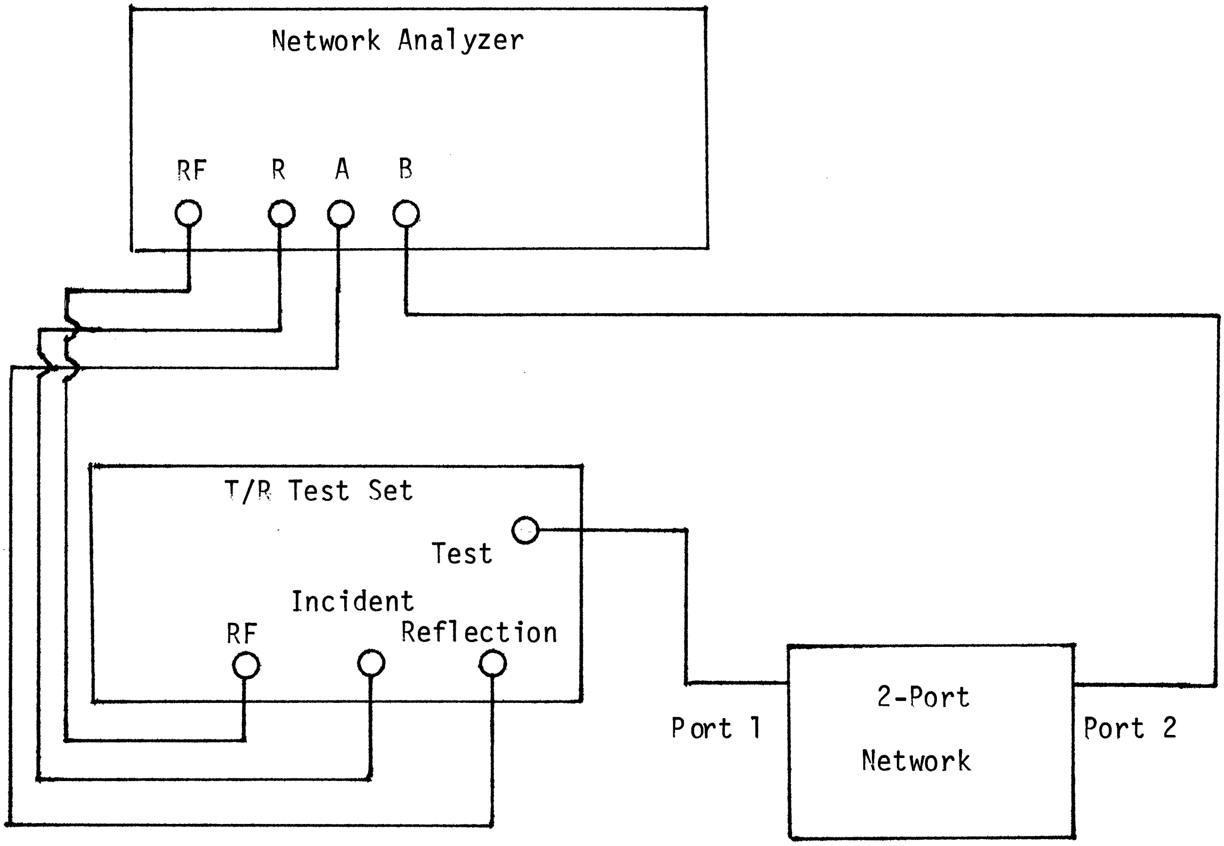


FIGURE 9

The transmission lines, connectors and ports are all 50 ohm impedence, therefore, all loads, due to the measuring of the signals, are matched to the transmission lines (no undesired reflections should occur).

By selecting the input A/R at channels 1 and 2, the magnitude mode at channel 1 and the phase mode at channel 2, the magnitude and phase of the S_{11} parameter is displayed. By selecting B/R the S_{21} parameter is displayed. Interchanging the two ports of the DUT, A/R displays S_{22} and B/R displays S_{12}. Therefore, the complex characteristics of all the S-parameters may be displayed in this manner.

VI. Programming the Network Analyzer

The 8505A Network Analyzer comes equipped with 001 option, which allows the front panel controls of the analyzer to be set automatically (remote mode), instead of manually (local mode). The analyzer's controls are set by receiving ASCII code via an HP-IB and data is transmitted from the analyzer using the same bus.

The source/converter/frequency controller and the signal processor are treated as two separate instruments, although they work together. Each of the instruments are addressed and programmed separately, and each has a different programming code.

The source/converter and frequency controller are programmed by a string of alphanumeric characters (in ASCII) received by the addressed instrument (addressing of instruments is discussed in the computer's I/O operations section). In general, the instrument interprets the received characters as follows. Any letter received, specifies one of the controls on the front panel of the instrument. For example, on "o" specifies the output level control. The setting of this control is specified by the first number received following the letter. Using the same example, a "1" following the "o", programs the output level to be set to -60dBm. The numbers used to specify the control settings range from 1 to the number of possible positions, with 1 specifying the left-most or most counter-clockwise position. Table 1 is provided to indicate which letter specifies each control and the code used to program each of the control's possible settings.

A series of these letter-number combinations are strung together to produce a programming code which sets all of the devices front panel controls. Every string of code must end with an end-of-data command (letter "E", carriage return, line feed) which not only indicates the end of the data string but also causes the controls to be set to the positions specified by the received code.

The only major exceptions in the programming code of the source/converter and frequency controllers are the programming of the start frequency, the stop frequency and the marker frequency. Each of these controls are specified by two letters (FA-start, FB-stop, FC-marker). The desired start and stop frequencies are specified by the four numbers following the letters, FA or FB, and the position of the RANGE switch. Range 1 (500KHz - 13MHz) implies XX.XX MHz, Range 2 (500KHz - 1.3MHz) implies XXX.X MHz and Range 3 (500HKz -1.3GHz) implies XXXX MHz.

The marker frequency is specified by a number 0-99. The marker frequency is a function of the width of the range and this number. Zero specifies the beginning of the range and 99 specifies the end of the range. Note: only one marker is available in the remote mode.

Signal processor is divided into four channels for programming purposes. Channel 0 is the display; Channel 1 is the left channel; Channel 2 is the right channel and Channel 3 is the electric length controller. The programming code for the signal processor consists of selecting a channel (C0, C1, C2, C3), selecting a control of that channel with a letter and selecting the position of that control with a number. This code is similar to the code for the source/converter and frequency controller except that the channel to which each control belongs must also be specified in the code. For example, the code "C1I2" sets the Input control of Channel 1 to the second position so that Channel 1 displays the response at input A. Table 2 gives a complete listing of the programming code for the signal processor.

The signal processor also outputs data in ASCII code, via an HP-IB. The data sent is the value of the response on Channel 1 and Channel 2 at the marker

Table 1

PROGRAMMING FOR 8505A OPTION 001 SOURCE/CONVERTER-FREQUENCY CONTROL			
Functions	**ASCII Code and Sequence**	**Comments**	**Position In Data String**
OUTPUT LEVEL dBm	O	RF Output, Coarse control in 10 dB steps	1-2
	O1	−60 dBm	
	O2	−50 dBm	
	O3	−40 dBm	
	O4	−30 dBm	
	O5	−20 dBm	
	O6	−10 dBm	
	O7	0 dBm	
	O8	+10 dBm	
OUTPUT LEVEL dBm Ø = −12 dB 99 = 0 dB	V	RF Output, Vernier control. LLO must be set (true) to program. Non−learned programming code.	
	VØ	−12 dB	
	V22	−10 dB (Approx. value in Remote).	
	V25	−9 dB	
	V50	−6 dB	
	V75	−3 dB	
	V99	0 dB	
INPUT LEVEL dBm MAX	I	Maximum input level before overload.	3-4
	I1	−10 dBm MAX	
	I2	−30 dBm MAX	
RANGE MHz	R	Frequency Range	5-6
	R1	.5 − 13 MHz	
	R2	.5 − 130 MHz	
	R3	.5 − 1300 MHz	
MODE	M	Sweep Mode	7-8
	M1	LOG FULL, sweeps full band	
	M2	LIN FULL, sweeps full band	
	M3	LIN EXPAND, WIDTH switch selects which Start/Stop sweep ranges or CW.	
WIDTH	W	Frequency displayed is between START & STOP Markers. Program M3 prior to a "W" code.	9-10
	W1	START/STOP 1	
	W2	START/STOP 2	
	W3	START/STOP ALTernately 1 and 2	
	W4	CW ±ΔF	
	W5	CW	

Table 1 (cont.)

PROGRAMMING FOR 8505A OPTION 001 SOURCE/CONVERTER-FREQUENCY CONTROL			
Functions	**ASCII Code and Sequence**	**Comments**	**Position In Data String**
SCAN TIME SEC	S	S1 – S5, SCAN TIME VERNIER defaults to maximum (CW) in Remote and LLO is set.	11-12
	S1	MANUAL	
	S2	100 – 10 Seconds	
	S3	10 – 1 Seconds	
	S4	1 – .1 Seconds	
	S5	.1 – .01 Seconds	
TRIGGER	T	SINGLE not programmable. Position is used to select LOCAL.	13-15
	T1	AUTO	
	T2	LINE	
	T3	EXTernal	
		NOTE **Range MHz, Mode, and Width should be programmed prior to START and STOP FREQUENCY MHz registers.**	
START FREQUENCY MHz	FA	Start and Stop FREQUENCY VERNIER controls default to minimum (CCW) when LLO is set. RANGE MHz codes determine placement of decimal point.	16-22
STOP FREQUENCY MHz	FB		23-29
Terminator (EXECUTE)	E	Followed by CR, LF	30

Table 1 (cont.)

PROGRAMMING FOR 8505A OPTION 001 SOURCE/CONVERTER-FREQUENCY CONTROL			
Function	**ASCII Code and Sequence**	**Comments**	**Position In Data String**
FREQ COUNTER MHz 0 = START 99 = STOP	FC	Non-learned programming code. Only one marker available in REMOTE. 0 – 99 = Percentage of Sweep Width: Sweep Width = FB-FA.	
		PROGRAMMING EXAMPLE	
	FC10	Start (FA) = 800 MHz and Stop (FB) = 1000 MHz therefore, Sweep Width = FB-FA = 200 MHz 200 X 10% = 20 MHz so the marker position is at 820 MHz.	

Table 2

PROGRAMMING FOR 8505A OPTION 001 SIGNAL PROCESSOR/DISPLAY			
Functions	**ASCII Code and Sequence**	**Comments**	**Position In Data String**
BW VIDEO FILTER (Display bandwidth)	CØB	Selects bandwidth and video filter IN or OUT.	1-5
	CØB1	BW = 10 kHz, Video Filter OUT	
	CØB2	BW = 1 kHz, Video Filter OUT	
	CØB3	BW = 10 kHz, Video Filter IN	
	CØB4	BW = 1 kHz, Video Filter IN	
SET CHANNEL 1 (Left Channel)	C1	All codes defined for Channel 1 apply also for Channel 2 and have the same meaning.	6-7
INPUT	I	Selects input port being processed.	8-9
	C1I1	R Input Connector	
	C1I2	A Input Connector	
	C1I3	B Input Connector	
	C1I4	A/R Input Connectors	
	C1I5	B/R Input Connectors	
MODE	M	Selects parameter being processed.	10-11
	C1M1	OFF	
	C1M2	MAGnitude	
	C1M3	PHASE	
	C1M4	DLY (Delay)	
	C1M5	POLAR MAGnitude	
	C1M6	POLAR PHASE	
Scale/DIV (Selects sensitivity or resolution for CRT display in units/division)	S	Values for positions S1 through S8 depend on MODE Selected. For group delay, Frequency RANGE is also determining factor.	12-13

PROGRAMMING FOR 8505A OPTION 001 SIGNAL PROCESSOR/DISPLAY			
Functions	**ASCII Code and Sequence**	**Comments**	**Position In Data String**
DISPLAY	D	Non-learned programming code.	
DISPLAY REF	C1D1	Display indicates value of REFerence line.	
DISPLAY MKR	C1D2	Display indicates parameter value at Marker frequency.	
ABS CLR	C1D3	ABSolute Clear; sets reference line to zero. **NOTE** **In Remote, D3 does not have the delayed-dual action of clearing the calibration register; to do this, enter O Ø.**	
REL ZRO	C1D4	Calibrate or normalize (zero). Stores current value of REF or MKR in zero calibration register. REL lights, when REL ZRO is pressed.	
REF OFFSET (UP/DOWN pushbuttons offset reference line)	R ±19999	Decimal position automatically inserted and depends on MODE and SCALE/DIV. Displayed resolution increases at S = >5. Up/Down pushbuttons are not programmable but position (valid value) at time of local-to-remote transition is loaded directly. **PROGRAMMING EXAMPLES**	14-21
	C1R45Ø C1R2ØØØ	45° in M3 Mode 20 dB in M2 Mode	
SET CHANNEL 2 (Right Channel)	C2	All codes defined for Channel 1 apply also for Channel 2 and have the same meaning.	22-23
INPUT	I		24-25
MODE	M		26-27
SCALE/DIV	S		28-29

Table 2 (cont.)

PROGRAMMING FOR 8505A OPTION 001 SIGNAL PROCESSOR/DISPLAY			
Functions	**ASCII Code and Sequence**	**Comments**	**Position In Data String**
DISPLAY	D	Non-learned programming code.	
REF OFFSET	R		30-37
SET ELECTRICAL LENGTH	C3	Amount of electrical length added is determined by position of RANGE MHz on Frequency Control panel. (When cm and m lights, electrical lengths displayed in centimeters and meters respectively.)	38-39
INPUT	I	Selects input port being processed.	40-41
	C3I1	A Input Connector	
	C3I2	B Input Connector	
MODE	M	Maximum value depends on frequency range.	42-43
	C3M1	OFF	
	C3M2	LENGTH x; minimum calibrated (length) range.	
	C3M3	LENGTH X; maximum calibrated (length) range.	
	C3M4	PHASE x10°/SCAN; uncalibrated X10°/SCAN.	
Other Port MODE	S	Mode of not selected input port.	44-45
DISPLAY	D	Non-learned programming code.	
DISPLAY ZRO	D2	Calibrate or normalize (zero). Stores current value of length reference in length offset register.	
ABS CLR	D1	ABSolute Clear; sets reference line to zero. **NOTE** **In Remote, D2 is not a two-function switch and does not clear the calibration register; to do this, enter O Ø.**	

Table 2 (cont.)

PROGRAMMING FOR 8505A OPTION 001 SIGNAL PROCESSOR/DISPLAY			
Functions	**ASCII Code and Sequence**	**Comments**	**Position In Data String**
LENGTH Offset	R ±nnn	Position of decimal point and lamps m or cm ON is determined by RANGE MHz switch and MODE LENGTH switch. Up/Down push-buttons are not programmable but position (valid value) at time of local-to-remote transition, is loaded directly. EXAMPLES of RANGE, MODE, and lamps lit: **RANGE MHz** — **C3M2** — **C3M3** R1 — XX.X m — XXX. m R2 — XXX. cm — XX.X m R3 — XX.X cm — XXX. cm	46-51
VERNIER A and B		Vernier controls for LENGTH Offset switches. (Length offset adjusted by VERNIER controls is not stored in length-offset register.) VERNIER A and B default to zero (CCW) in Remote and LLO set.	
TERMINATOR (EXECUTE)	E	Terminator is needed to avoid Rnn, Dnn, and Onn from being run together in a given channel. EXAMPLES: Incorrect: "C1D1R450O90E" Correct: "C1D1EC1R450EC1O90E"	52-53
RESET CHANNEL 1	C1		54-55
Calibration (Zero) Register	O ±19999	Not displayed on front panel. Value goes to reference offset register with REL ZRO pressed. Value equals zero with ABSolute CLR pressed.	56-63
CHANNEL 2	C2		64-65

frequency. The value is either in dB or degrees (magnitude or phase response) and the data is transmitted using the following format.

```
±DDDDE-D      ,      ±DDDDE-D
\________/           \________/
 Channel 1            Channel 2
```

The string of code used to program each of the instruments to measure the S-parameters will be discussed in the "Software" section.

VII. 9845C - Desktop Computer

The desktop computer is used as the main controller for the system. In conjunction with the software developed, it generates the network analyzer's programming code, sends the code to the analyzer, stores the measured results and displays these results in graphic form. The following is a brief discussion of the computer's features and how they are applied to satisfy the system's needs.

A. General Features

All programs are written in an HP enhanced form of BASIC and are stored in the computer's 56K bytes of R/W memory. Some of the more important HP-BASIC commands are discussed in the section titled "Software", however, for a complete description of all commands, consult the "9845C Operations and Programming Guide." This manual also discusses entering a program into memory and editting the program.

The computer also comes equipped with a built-in thermal printer, for making hardcopies of program listings or graphic displays, and two built-in tape drives which are used for mass-storage. Programs and data can be stored and retrieved from the tapes.

B. Graphics Rom

The computer also has two Graphics Rom chips which enhance the computer's capabilities to display plots, figures, pictures, etc. on the CRT. Some of the HP-Graphics commands are discussed in the "Software" section, but more detailed descriptions of the commands are available in the "9845C Graphics Rom" manual.

C. Communicating with the 9845C

One of the most important features of the 9845C are its enhanced Input/Output capabilities. The I/O Rom package adds extensive input, output and device control capabilities to the 45C System. The two Rom's add a total of 32K bytes to the system's memory, however, they also reserve 640 bytes of the computer's R/W memory which cannot be accessed by the user.

All of the computer's I/O operations use the three-wire "handshake" method to transmit and receive data. The general "handshake" method works as follows:

1. The receiver of the data signals the sender that it is ready to receive data.

2. The sender places the data on the bus lines and signals the receiver that the data is available.

3. The receiver sends a signal to the sender indicating it has received the data.

For any I/O operation to take place the sender and the receiver of the data must be specified. The computer accomplishes this through the use of the I/O Rom and the use of select codes. A select code is the number assigned to the bus which will act as the communication link between the computer's main processing unit and an external device. There are 17 different select codes used for interfacing, however, as one will notice from Table 3, 5 of the select codes have been used internally and should not be used for external interfacing.

Table 3
Select Code Assignments

Select Code	Device
0	Keyboard, Thermal Printer
1 ↓ 12	For external use
13	CRT Graphics Raster
14	Left Tape Drive
15	Right Tape Drive
16	CRT Alphanumeric Raster

All I/O statements are relative to the computer. The computer is the sender for output statements and the receiver for input statements. The I/O statements also requires a select code, so that the sender, the receiver, and the direction of data flow are inherent to an I/O statement and the data transaction can take place.

There are several output-type statements, OUTPUT, WRITEBIN AND EOL. The command of most concern is the OUTPUT statement. This command causes the computer to output data one ASCII character at a time, along the bus specified by the select code. A exemplatory statement is:

```
OUTPUT 7; A
       ↗  ↖
 select    variable
  code
```

This statement is an output statement, so the computer is automatically specified as the talker. The number following the statement is the select code (7). It specifies where the data is to be sent. Following the semicolon are the variables, which provide the data to be sent. These variables may be numeric or string variables.

More than one receiver may be specified.

OUTPUT 7, 4; A

This statement specifies two busses, with select codes 7 and 4.

The data can be transmitted in a formatted form if desired. A detailed discussion of formatting can be found in the 45C's "I/O ROM" programming guide. If a format is not specified the free-format mode is used. Using this mode, all the available data, provided by the variables, is sent and the ASCII Code for Carriage Return (CR) and Line Feed (LF) are sent indicating the end of the data.

The input statement, ENTER, is used so the computer can receive data from external devices.

ENTER 7; A

Based on the example statement, the device connected to the computer via the bus, with the select code 7, is specified as the sender. The computer is the listener. The value of the ASCII character on the data lines of the bus is stored in the computer as variable A. Depending on the type of data sent, the variable in the statement may be a numeric variable or a string variable or both. The information that is entered into the computer may also be formatted. A detailed discussion of formatting input statements is found in the 45C's "I/O ROM" programming guide.

D. <u>Communicating with the HP-IB</u>

The 98034A interface card, used in the system, is Hewlett-Packard's implementation of the IEEE standard 488-1975. It is commonly known as a Hewlett-Packard Interface Bus (HP-IB) and allows HP computers to be "plug-to-plug" compatable with many programmable instruments.

An important characteristic of the HP-IB is that more than one instrument can be connected to the bus. In fact, 13 different devices can be connected to one HP-IB at once. The select code only specifies which bus will be used to transmit the data. Therefore, there is a need to further specify exactly which of the devices, connected to the HP-IB, the computer wishes to communicate with.

Each device which uses HP-IB has, inherent to it, an address known as a device number. This number ranges from 0-30. It is through the use of this number that the computer can communicate directly with each device. An instrument's device number can be determined by consulting one of the instrument's manual.

Specifying a device as the talker and a device as the listener on the HP-IB is known as configuring the bus. With the use of the I/O Rom and knowledge of an instrument's device number, the process of configuring the bus and sending data requires only a minor addition to the previously discussed I/O statements.

OUTPUT 714; A
ENTER 714; A

The select code in this example is 7 and the device number is 14. The device number is represented as a two-digit number directly following the select code.

Communicating with the 8505A

The signal processor and source/converter/frequency controller are two separate instruments and are connected to the 9845C (via an HP-IB) in parallel. The 98034A interface card plugs directly into the 9845C in any one of the interface slots at the back of the computer and the HP-IB is connected to the signal processor and source/converter at the ports labeled "001 Option" located at the back of both of the instruments. The HP-IB has a select code of 7. The device number for the signal processor is 16, and the device number for the source/converter/frequency controller is 19. The programming code for each instrument is set equal to a string variable and is sent to the instruments using the OUTPUT statement.

```
OUTPUT 716; A$
```

programs the signal processor

```
OUTPUT 719; B$
```

programs the source/converter.

To retrieve information about the magnitude and phase of the response at the marker frequency, from the signal processor, the following statement is used.

```
ENTER 716; C$, D$
```

C$ contains the magnitude and D$ contains the phase. The only other external instrument used in the system that has not been mentioned is the Flexible Disk Drive. It is used to store the measured data collected by network analyzer. It is connected to the computer via a 98036A interface card. The card is inserted into one of the interface slots in the back of the computer. The select code for this bus is 8. The "software" section will discuss how to store and retrieve data from the disk drive.

VIII. Software

The software developed for the system has been divided into two programs. The measurement program generates the programming code for both the signal processor and source/converter, outputs this code to the analyzer, stores the measured values of the phase and magnitude response of the desired S-parameter on a floppy disk and loads the plotter program. The plotter program allows the user to display the measured responses in the three forms: magnitude vs. frequency, Phase vs. frequency, and on a Smith Chart. A complete listing and flowcharts are provided of each of the programs.

A. The Measurement Program

The measurement program's function is to measure either the reflection or transmission coefficient of a network within a user-defined frequency range. The magnitude and phase responses of the coefficient are measured at .5MHz intervals, by displaying 50 MHz sections at a time and incrementing the marker frequency from 0 to 99. Each of the 99 marker frequency positions constitute 1 percent of the total displayed range or .5MHz. The 50 MHz sections are produced by setting the frequency controller to the linear expanded mode and setting the start (FA) and stop (FB) frequencies 50 MHz apart. At each .5MHz interval, it is determined whether this frequency is within the user-defined frequency limits. If it is not, then the measurement process ends. If the marker frequency is not out of range and the stop frequency is reached, then the next 50 MHz section is displayed and the measurements continue.

The majority of the software is used to construct the alphanumeric strings which program the source/converter and the signal processor.

Most of the source/converter's controls are set automatically by the computer, however, the user does have control over the output power level and the maximum input power level. The position of these controls are set according to the selection chosen by the user from the menus displayed on the CRT.

The frequency range of the measurement is controlled by the user. The user enters a maximum and minimum frequency to set the range.

The signal processor is programmed to display the magnitude response of the chosen coefficient on Channel 1 and the phase response on Channel 2. No offsets are programmed on either of the channels and the electric length channel (C3) is turned off. After the programming strings have been received by the instruments, the magnitude and phase values at the marker frequency are outputted by the signal processor. These values are read by the computer using the "ENTER" statement. These values are read as strings and are converted to numeric values before storing them on the disk. The data is stored on the flexible disk using the "ASSIGN" and "PRINT" statements.

The "measure" subprogram sets the start, stop and marker frequencies, programs the network analyzer and stores the measured results on the disk. Although the analyzer outputs both the magnitude and phase together, the "measure" subprogram is called twice. The reason is that the magnitude and phase data are stored in two separate files, which have two different locations on the disk. It is quicker to run the subprogram once to measure and store the magnitude data and once to measure and store the phase data then to call the subprogram only once and jump back and forth between the files to store the data.

A third data file is created on the disk to store the maximum and minimum frequencies and magnitudes. This information is used by the plotter program set-up the axes of the plots.

The program's final command loads the plotter program.

B. The Plotter Program

The plotter program begins by retrieving the magnitude and phase data from the disk and storing it as variables; "magnitude (X)" and "Phase (X)". This data may be displayed on a magnitude vs. frequency plot, on a phase vs. frequency plot or on a Smith Chart.

Magnitude Plot

If the magnitude plot is chosen by the user, the highest and lowest magnitude values are used to call the subprogram "scale." This subprogram computes the scale size for an axis based on the highest and lowest values to be plotted. The highest and lowest markings on the axis are also computed. This same procedure is used to compute the scale size of the frequency axis.

The computer enters the graphics mode so that the plot can be drawn on the CRT. The labels for the plot and the axes are printed. The "LOCATE" statement is used to isolate an area of the screen where the plot will be drawn. This area is sealed and the axes are drawn and numbered. Finally, the magnitude response is plotted using the measured data. A hardcopy of the plot is made available using the "DUMP GRAPHICS" statement, which causes the thermal printer to make a copy of the drawing on the CRT.

Phase Plot

Before the phase data is plotted, it is increased or decreased by a factor of 360 degrees so that all the phase values fall between +180 degrees and -180 degrees. This makes the phase plots easier to construct and easier to understand.

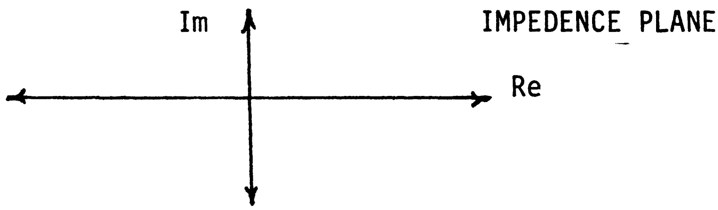
The phase plot is constructed in the same manner as the magnitude plot. The same scaling size is used for the frequency axis and the phase axis is always set-up the same way; ranging from +180 degrees to -180 degrees.

The Smith Chart

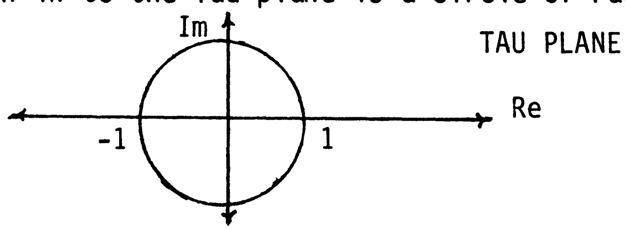
A Smith Chart is a method of plotting the characteristics of the reflection coefficient of a network. The reflection coefficient is plotted on a polar coordinate system and the relation between the plot and the chart provides information about the input impedence of the network. The concept of the Smith Chart is based on the following relationship.

$$T \text{ reflection} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0}$$

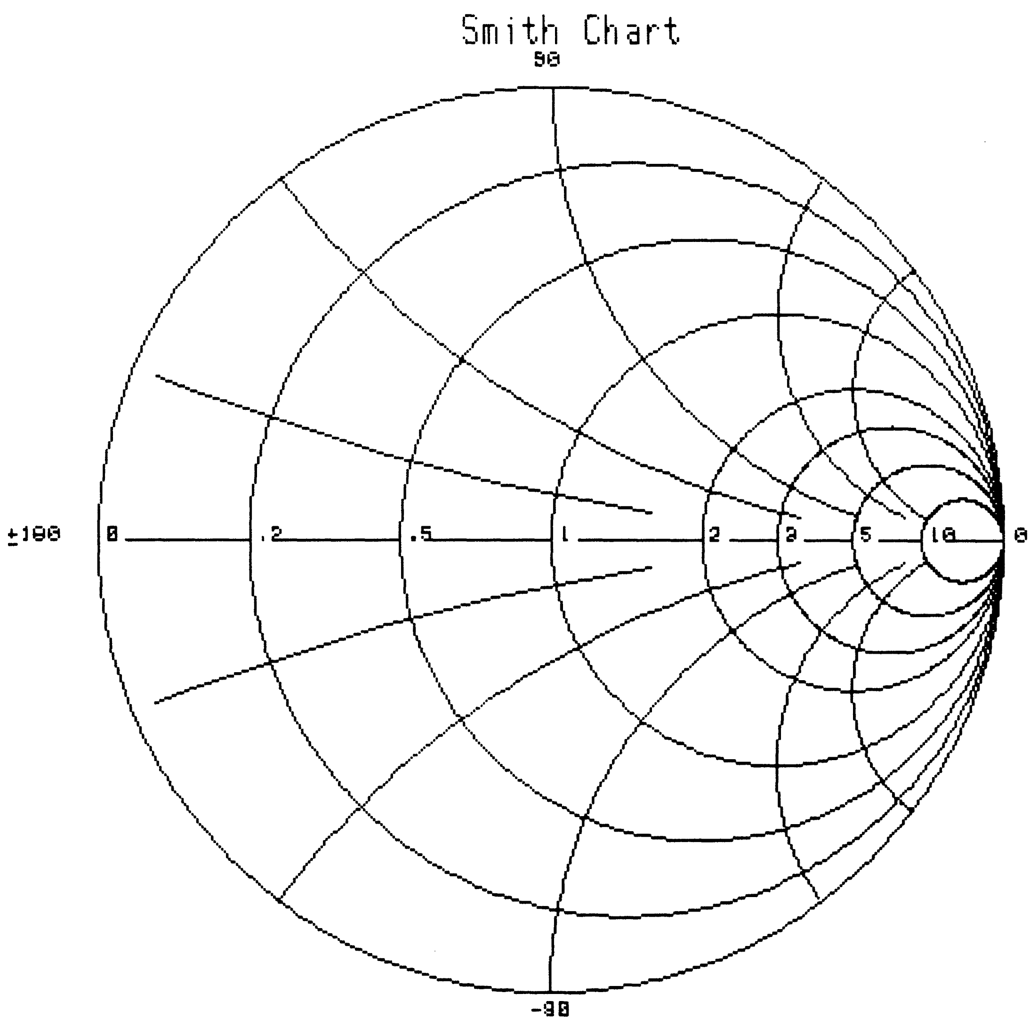
The reflection coefficient (T refl.) is a function of the input impedence (Zin) and the characteristic impedence of the transmission lines (Zo). The impedence of the lines used in this system are 50 ohms. Constant resistances and constant reactances in the impedence plane transform into circles in the Tau plan (reflection coefficient plane). For example, if the input resistance is 50 ohms and the reactance is allowed to vary from $-j\infty$ to $+j\infty$



its tranformation in to the Tau plane is a circle of radius 1.



Positive impedences map into the area within the circle and negative impedences map into the area outside the circle. The Smitn Chart is constructed by mapping a series of constant, positive resistances and constant reactances (positive and negative) into the Tau plane. The circles are labeled to indicate the impedence they are related to. An example of a Smith Chart is shown in the Figure below.



The measured reflection coefficient is also plotted in the Tau plane. By comparing the plot to the chart, one can estimate the input impedence of network over a range of frequencies. Also, using the chart, one may determine if a amplifier is stable over a range of frequencies. If the plot goes outside of the circle of radius 1, then the input impedence is negative and the amplifier is unstable.

The subprogram "Smith" creates the Smith Chart, labels the circles and plots the reflection coefficient in the Tau plane. The magnitude data must be converted from dBs to watts before the data can be plotted. The following equation is used for the conversion.

$$\text{Magnitude (watts)} = 10\wedge(\text{Magnitude (dB)}/20)$$

Next, the real and imaginary parts of the reflection coefficient are calculated, based on the magnitude and phase values. Solving equations 15 and 16 simultaneously yields the real and imaginary values.

$$(15)\ \tan(\text{Phase}) = \frac{Im}{Re}$$

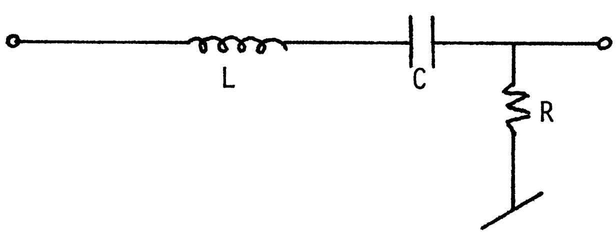
$$(16)\ \text{Magnitude (watts)} = [(Im)^2 + (Re)^2]^{1/2}$$

Finally, the imaginary and real values are plotted on the chart.

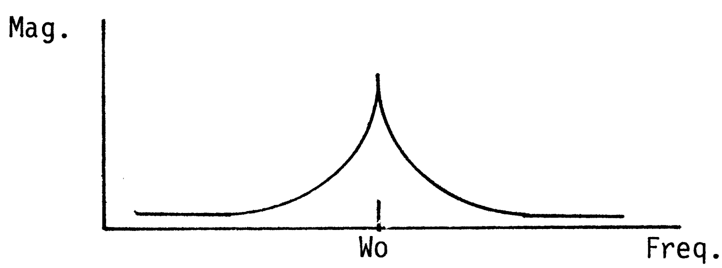
IX. Testing the Measurement System

The completed measurement system was tested by designing a circuit which has a predictable response within the frequency range of the system. The response of the circuit was measured and compared with the predicted response to determine the system's accuracy.

A series resonant circuit was designed to test the system. The circuit is diagrammed below.



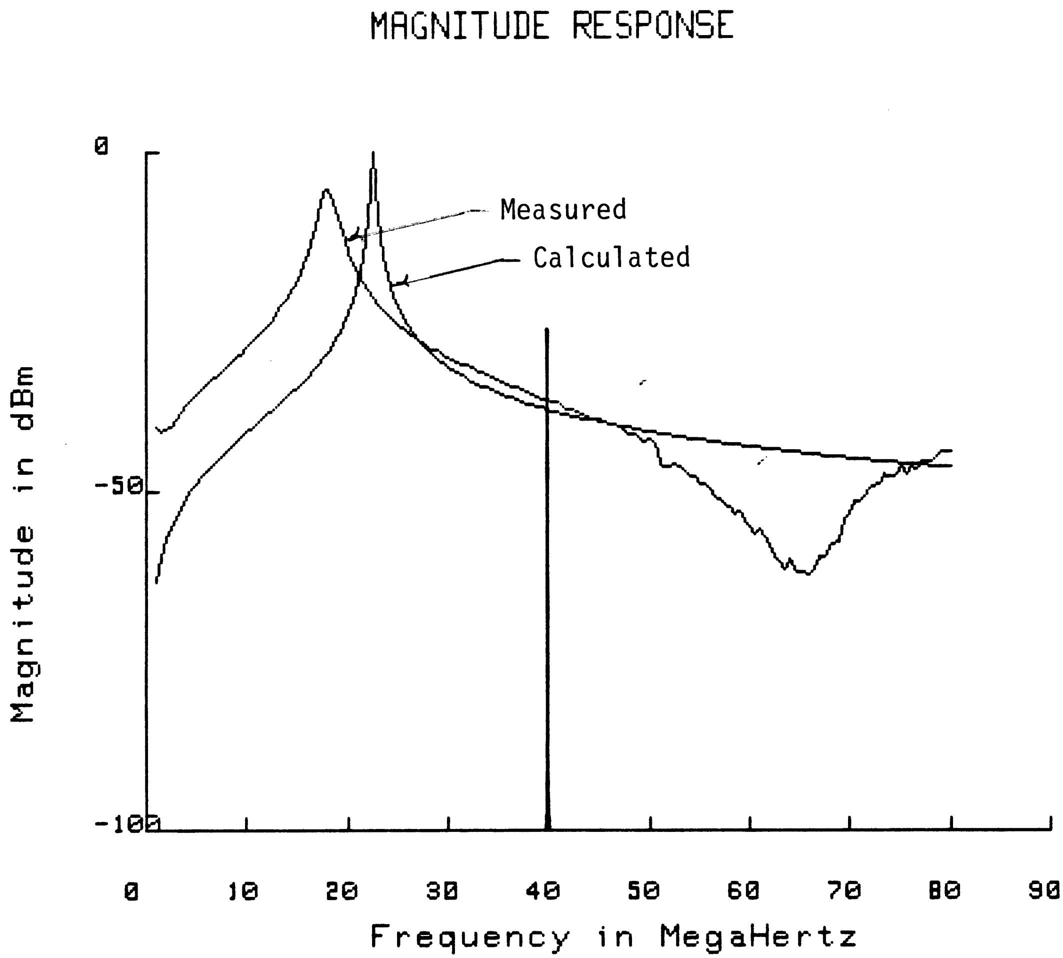
The circuit acts as spike filter, which has a peak at the resonant frequency,.



The resonant frequency (Wo) is controlled by the values of the inductor (L) and the capacitor (C) ($W_o = \sqrt{1/LC}$). The bandwidth of the filter is controlled by the resistance (R) and inductance ($B = L/2\pi R$). The resistance used was 22 ohms, the capacitance was 5 pF and the inductance was 10 mH. The resonant frequency was approximately 22MHz.

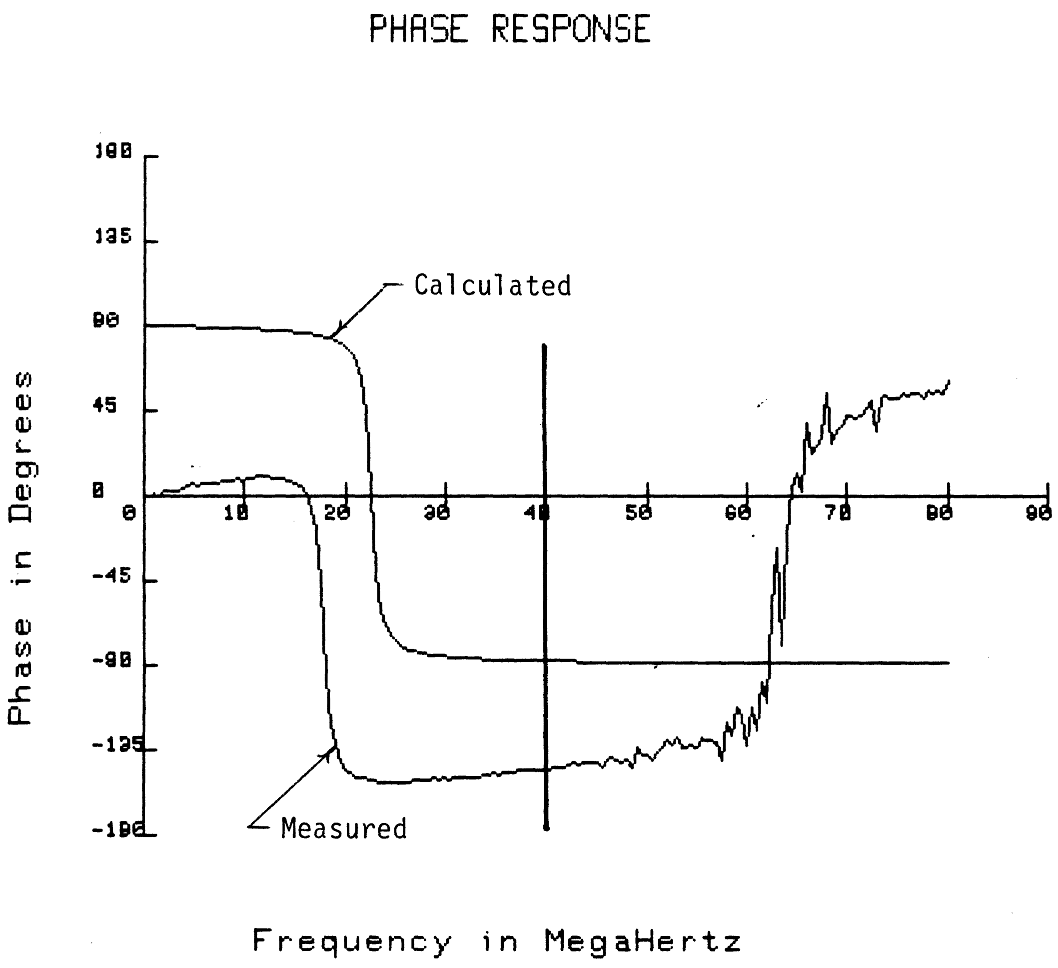
The circuit was connected to the system and the reflection and transmission coefficients were measured. Alterations were made in the plotter program so that the calculated response were drawn on the same plot as the measured responses, making them easy to compare.

The measured magnitude response of the transmission coefficient is similar to the expected results up to the frequency of 40MHz (see Plot 1). Past this frequency major deviations occur.



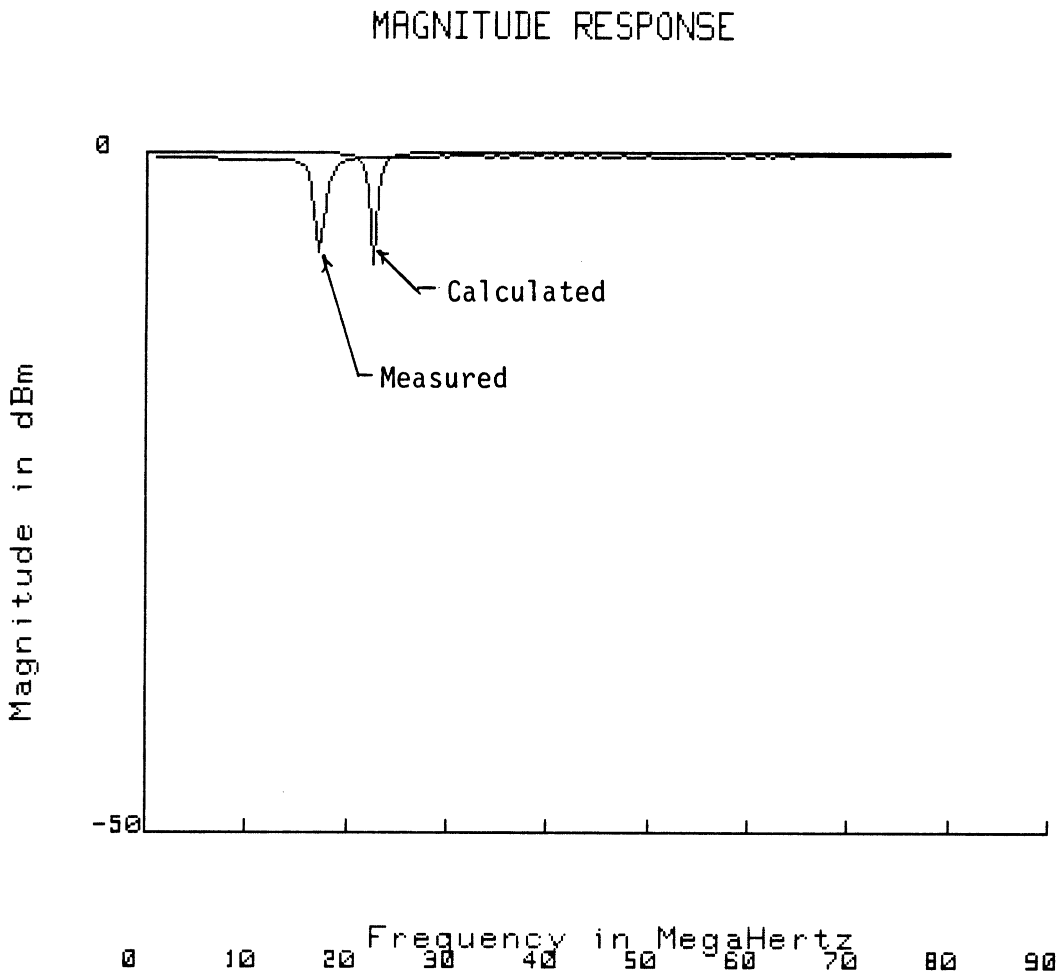
Plot 1

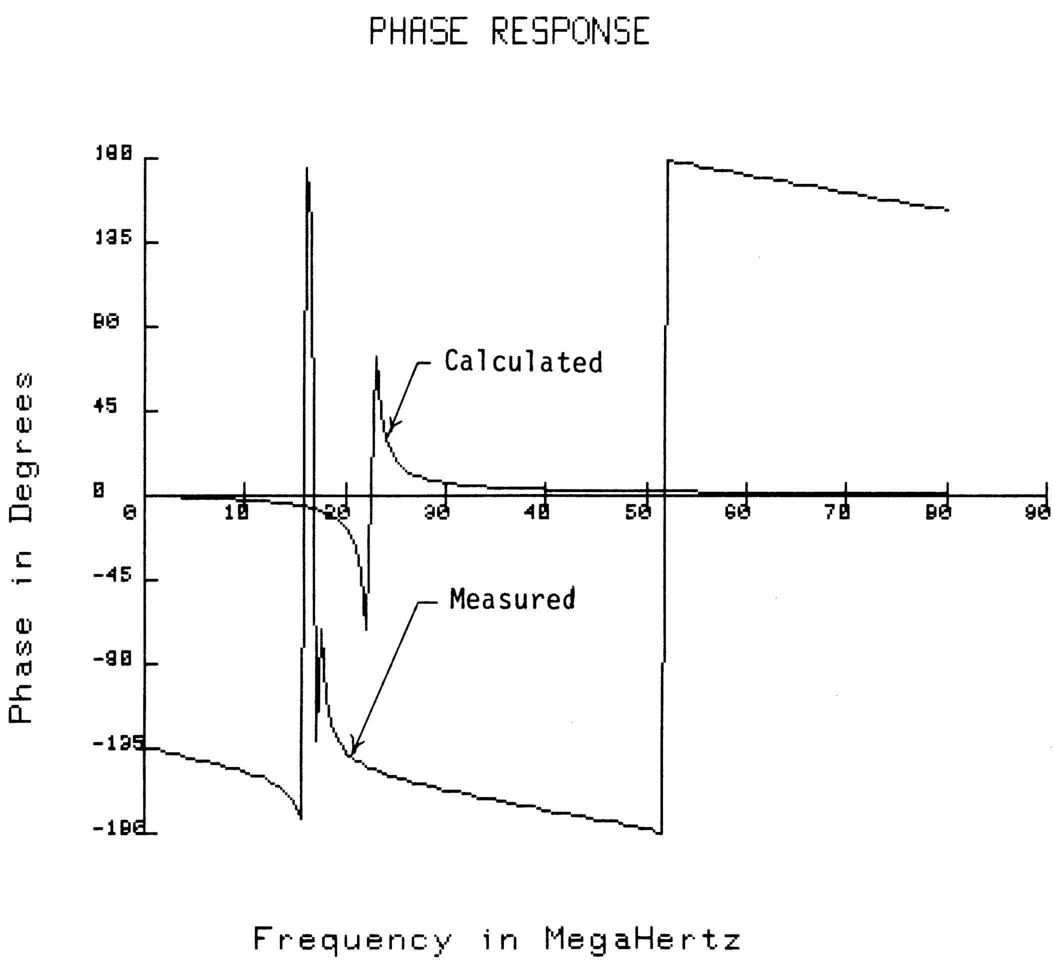
The measured phase response has about the same shape as the calculated response, up to 40MHz (see Plot 2). However, there is constant 15 degree phase difference between the two responses.



Plot 2

Comparing the measured and calculated responses of the reflection coefficient reveal the same conclusions. The limit of the system is approximately 40MHz, and the measured phase values are approximately 15 degrees less than the actual phase.


MAGNITUDE RESPONSE
0
-50
Calculated
Measured
Magnitude in dBm
Frequency in MegaHertz
0
10
20
30
40
50
60
70
80
90


PHASE RESPONSE
180
135
90
45
0
-45
-90
-135
-180
Calculated
Measured
Phase in Degrees
0
10
20
30
40
50
60
70
80
90
Frequency in MegaHertz

XI. Improving the Measurement System

It is apparent from the plots in the previous section, that significant error is present at the higher frequencies of the S-parameter measurements. The errors are believed to be caused by imperfections in the instruments used to make the measurements. These errors are classified as "systematic" errors, which are repeatable and can be measured by the system.

The most important advantage of automating a measurement system is that these systematic errors can be stored in memory. When a future measurement is made, the error terms can be factored out of the measured value to produce a more accurate result.

The Hewlett Packard Company provides, in their Application Note 221A, a method of measuring systematic errors and also provides equations which relate the error terms to the actual result and the measured result.

Let's first consider the measurement of the transmission coefficient. The major source of error that affects this measurement is the Forward Transmission Tracking term (ETR). This error is caused by variations in the magnitude and phase flatness vs. frequency. It is related to the actual S_{21} value and the measured S_{21} value by the following equation.

$$S_{21}M = ETR\ S_{21A}$$

This error term is measured by connecting the input port directly to the output port ($S_{21} = 1$ with no phase shift). The measured transmission coefficient is equal to ETR. This term must be measured over the complete frequency range of the system. When an S_{21} parameter is measured, the ETR term is factored out of the measured value.

$$S_{21A} = \frac{S_{21M}}{ETR}$$

Notice that all the quantities are complex and this fact must be taken into account when the calculations are made.

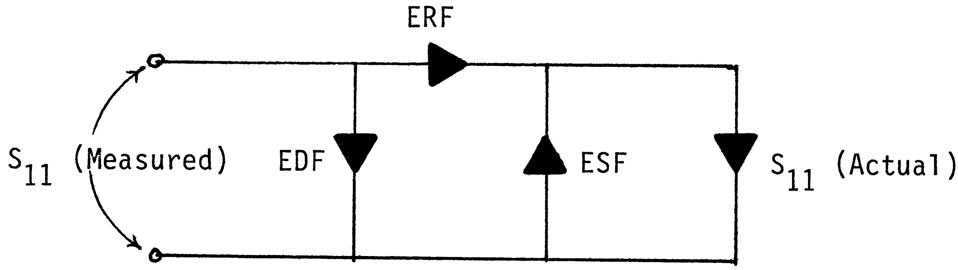
The three sources of error that affect the measurement of the reflection coefficient are the Effective Directivity, the Effective Source Match and Tracking.

The Effective Directivity (EDF) of a system refers to the amount of incident signal that leaks through the signal separation device (the coupler of the T/R test set) and appears as part of the reflected signal.

The Effective Source match refers to the amount of the reflection signal that is re-reflected due to a mismatch at the port that measures the reflected signal. This re-reflected signal passes through the coupler and appears as part of the incident signal.

The tracking error (ERF) is caused by variations in the magnitude and phase responses due to changes in frequency.

Suppose that the reflection coefficient represents the S_{11} parameter. The diagram below is helpful in illustrating the effect of the error terms on the system.



This relation is represented mathematically by Equation 15.

$$(15) \quad S_{11M} = EDF + \frac{S_{11A}\,(ERF)}{1 - ESF\, S_{11A}}$$

To measure the EDF term, a "perfect" load is applied to the measurement port. For this system a 50 ohm load is used. This makes S_{11A} equal to zero. Applying this to the equation above, the measured S_{11} value, under these conditions, is equal to tne EDF term.

To measure the two other error terms, a short ($S_{11}4 = -1$) and an open ($S_{11} = 1$) are applied to the measurement port. This produces the following two equations.

$$S_{11M} = EDF + \frac{(-1)\ ERF}{1 - ESF\ (-1)}$$

$$S_{11M} = EDF + \frac{ERF}{1 - ESF}$$

By solving these two equations simultaneously, the values for ESF an ERF can be calculated.

After all the error terms are measured, they can be used to correct any future measurements using the system. Rearranging equation 15 so that S_{11} actually is isolated yields the following equation.

$$S_{11A} = \frac{S_{11M} - EDF}{ESF\ (S_{11M} - EDF) + ERF}$$

The corrected S_{11} value is calculated from tnis equation. All tne values of the equation are known.

Tnis project did not include implementing the accuracy ennancement technique on the system, however, if one wished to use this method it should not be too difficult to implement. Tne disk drive can be used to store the measured error data and a separate program can be written which reads the measured coefficient data and the error data from the disk and calculates the adjusted results. The corrected results can be stored in the same data files as before, therefore no major changes need to be added to the "measurement" and "plotter" programs.

The system should be tested again to examine the improvements due to enhancement technique. It would be advisable to test the system with an active circuit as well as a passive circuit.

XII. Problems Encountered

The major problems I encountered during this project were hardware related.

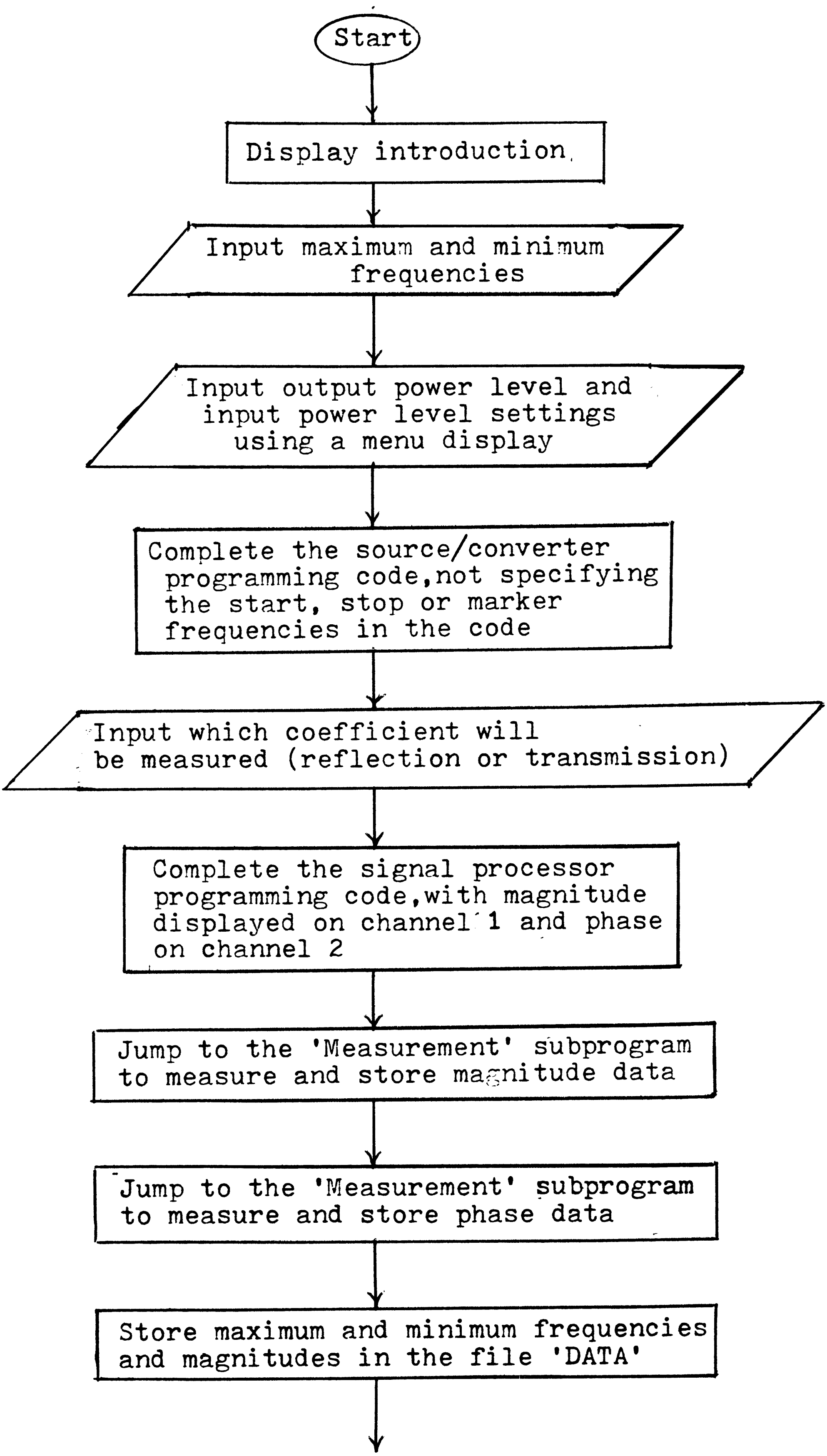
The first problem that arose and continued to crop up throughout the project was the connection between the computer and the CRT. The CRT is separate from the computer; it is connected to the computer when it is positioned properly on top of the computer. If there is a problem with this connection, the computer will not become active, and this problem occurred quite often. The only way to get the computer to work again was to lift the CRT off the computer and re-position it. Sometimes, the re-positioning of the CRT relieved the problem and sometimes it didn't. I continued to lift the CRT off the computer and set it back down until the connection was made. I don't know what can be done to prevent this problem from occurring in the future.

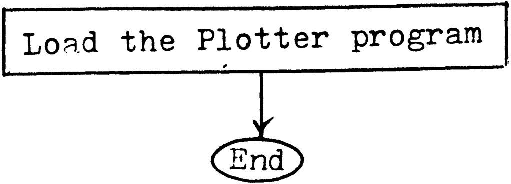
The other major problem was the addressing of the network analyzer. When I first attempted to output the programming strings to the signal processor and source/converter, the information was never transmitted. The problem was either due to the computer's I/O operations or due to the analyzer's inability to receive the data.

A plotter was connected to the HP-IB. A short program was written to program the plotter to print a message. This test was successful, therefore, the problem was related to the analyzer. The problem was eventually traced to a set of DIP switches within the analyzer. These switches determine the device number of the instruments. The analyzer's manual indicated that the switches were pre-set to 16, for the signal processor, and 19, for the source/converter.

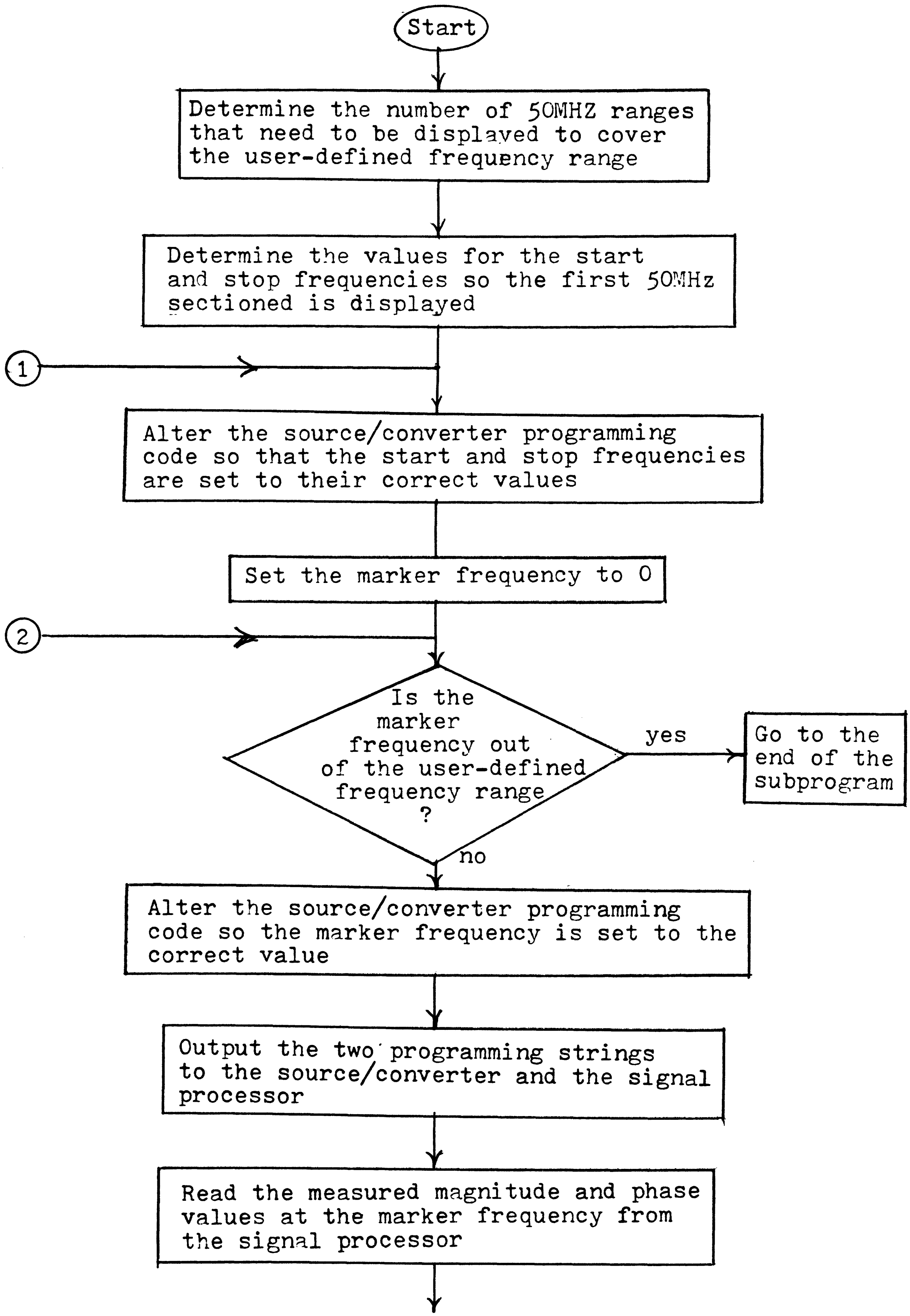
After removing the outer cases of the instruments, I found the switches were not set to these values. The switches were reset to 16 and 19 and after this adjustment all the communications between the computer and signal processor worked properly.

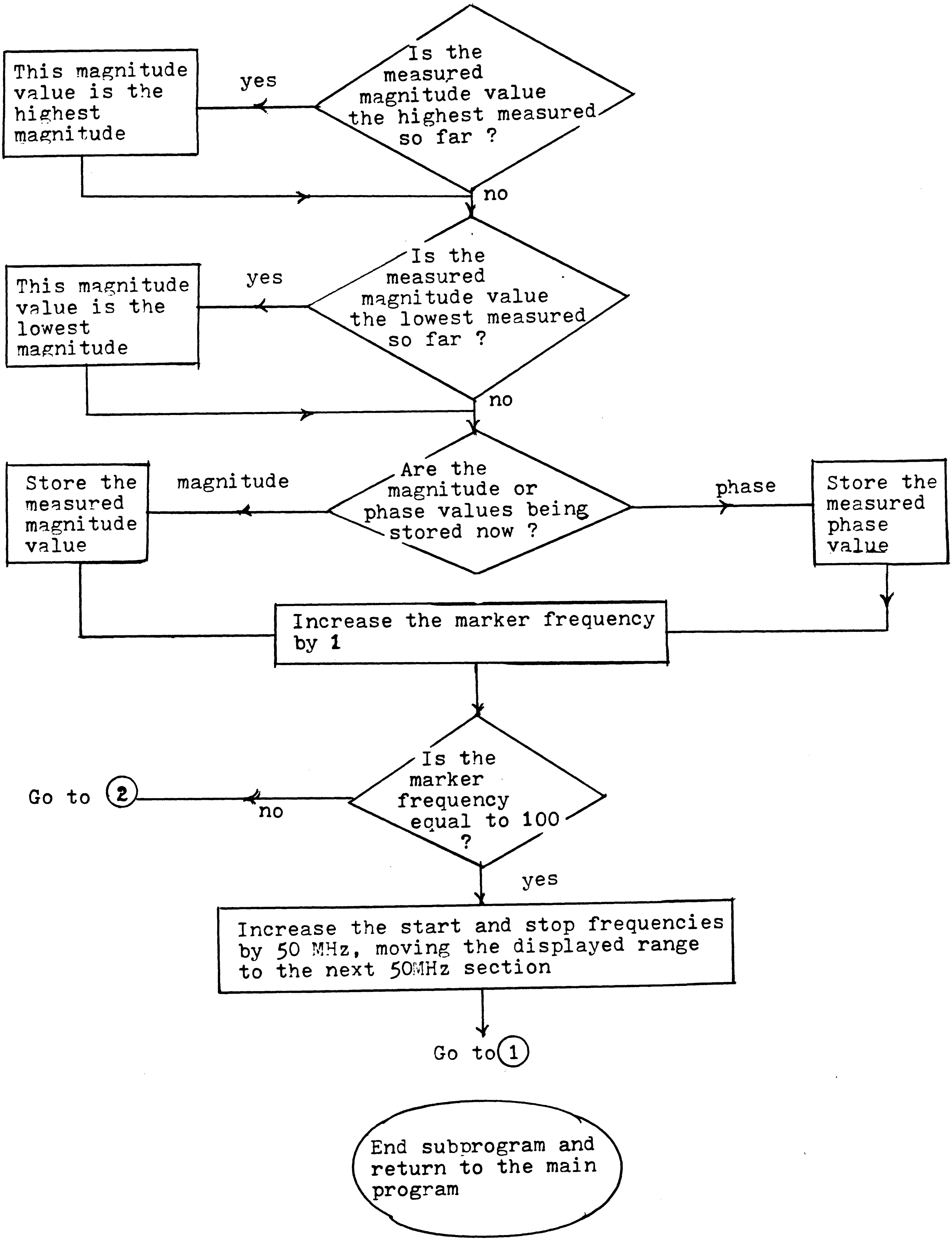
The Measurement Program Flowchart




Load the Plotter program
End

The Measurement Subprogram Flowchart



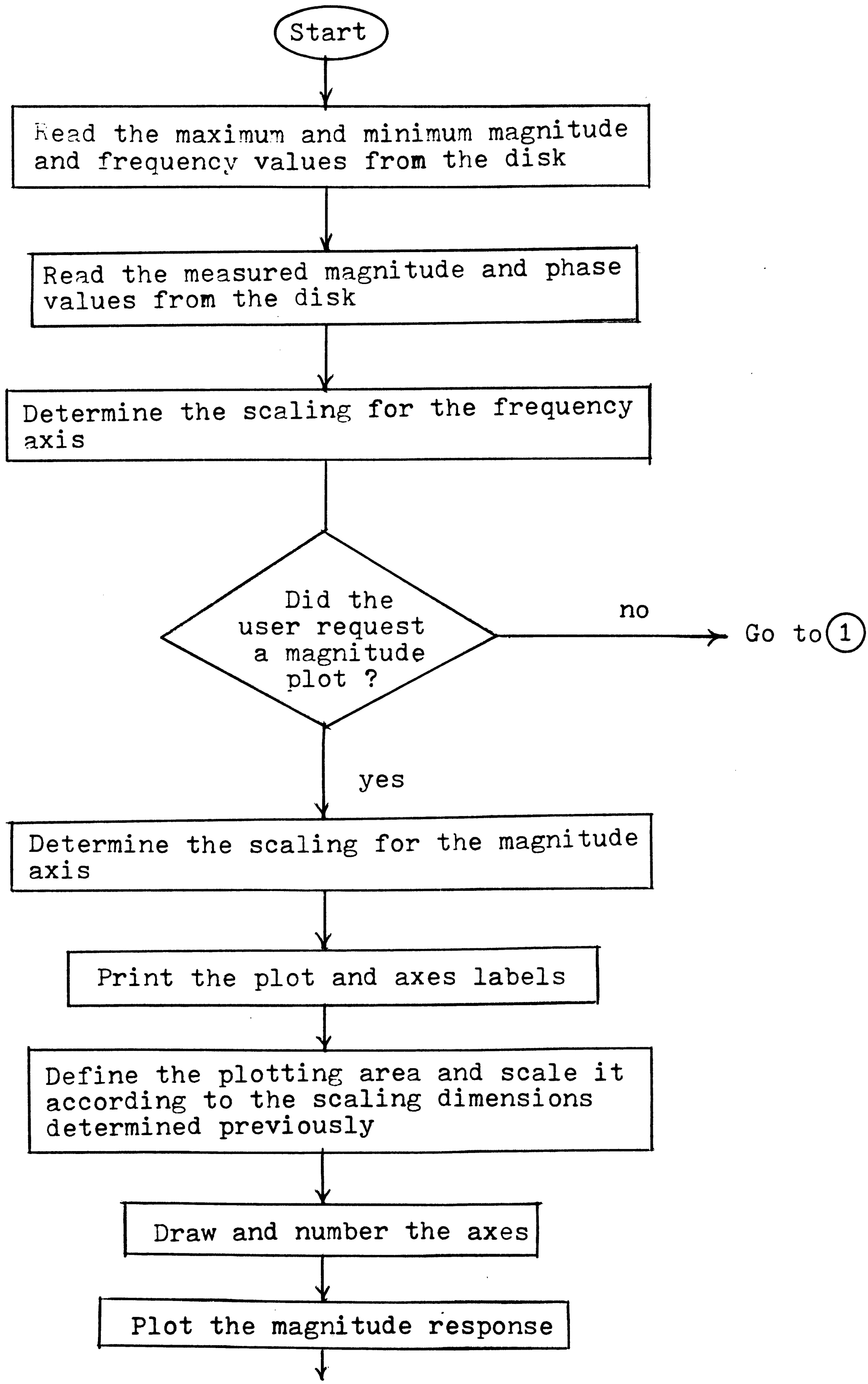

This magnitude value is the highest magnitude
yes
Is the measured magnitude value the highest measured so far ?
no
This magnitude value is the lowest magnitude
yes
Is the measured magnitude value the lowest measured so far ?
no
Store the measured magnitude value
magnitude
Are the magnitude or phase values being stored now ?
phase
Store the measured phase value
Increase the marker frequency by 1
Go to 2
no
Is the marker frequency equal to 100 ?
yes
Increase the start and stop frequencies by 50 MHz, moving the displayed range to the next 50MHz section
Go to 1
End subprogram and return to the main program

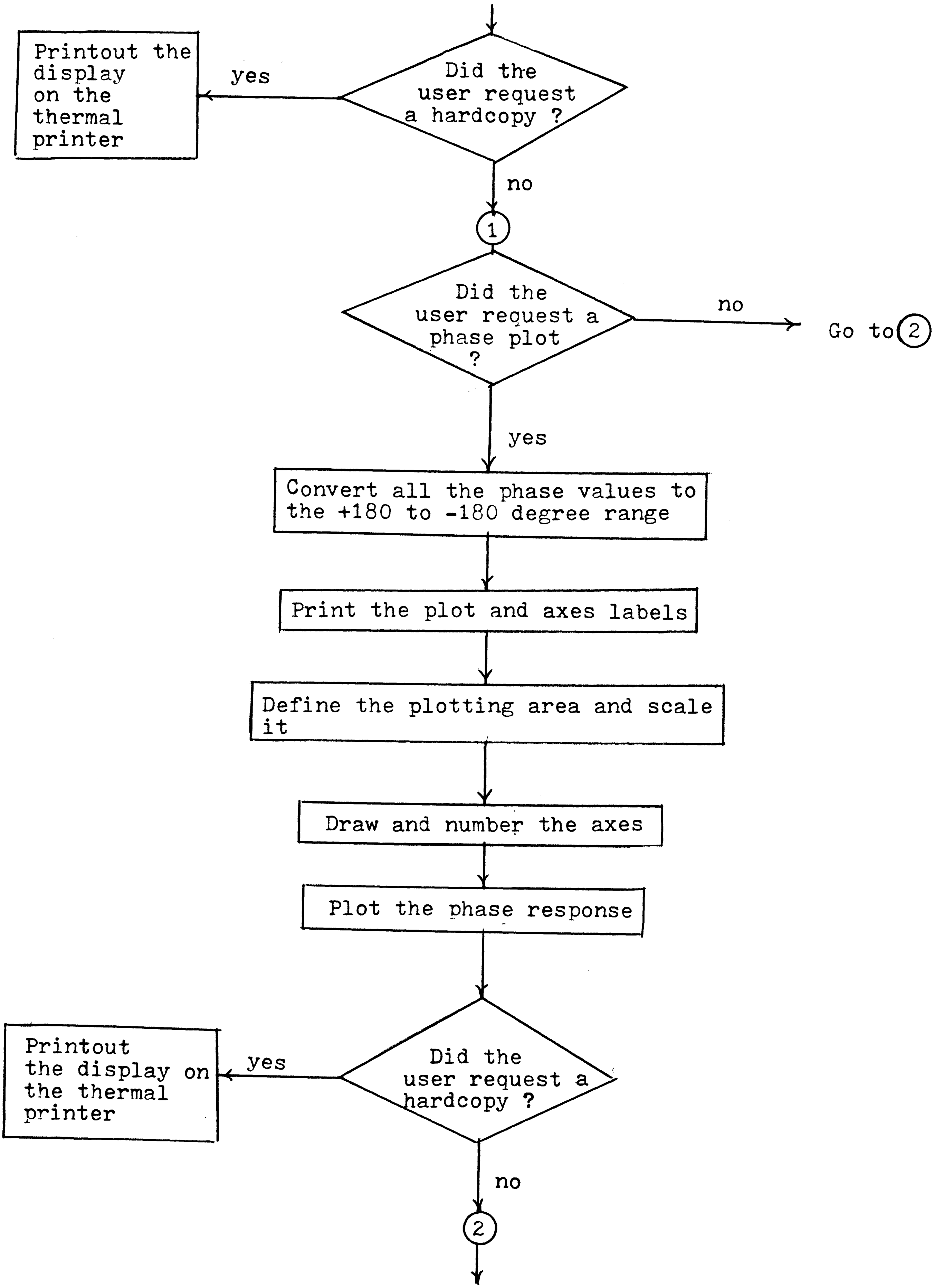
```
1      ! THE MEASUREMENT PROGRAM
10     ! Clear screen.
20     PLOTTER IS 13,"GRAPHICS"
30     PRINT PAGE
40     ! Display an introduction of the program.
50     PRINT "This program measures and plots the reflection and transmission"
60     PRINT "coefficients for a two-port network. Connect your circuit to"
70     PRINT "the network analyzer,using the transmission/reflection test set"
80     PRINT "so that the incident signal is at port R, the refected signal"
90     PRINT "is at port A, and the transmitted signal is at port B."
100    PRINT "Press the (CONT) key to continue."
110    PAUSE
120    PRINT PAGE
130    ! Allow the user to specify the frequency range of the measurement.
140    PRINT "Enter your maximum and minimum frequencies in Megahertz."
150    PRINT "The largest available frequency is 1300 MHz."
160    PRINT "The smallest available frequency is 1 MHz."
170    INPUT "Maximum Frequency=",Maxf,"Minimum Frequency=",Minf
180    PRINT PAGE
190    ! Enter the graphics mode so that the menus may be displayed.
200    PLOTTER IS 13,"GRAPHICS"
210    GRAPHICS
220    LOCATE 0,120,0,100
230    SCALE 0,12,0,10
240    FRAME
250    ! User selects the output level of the signals using a menu.
260    MOVE 2,9
270    LABEL "OUTPUT LEVEL SELECTIONS IN dBm"
280    DATA -60,-50,-40,-30,-20,-10,0,10
290    FOR X=8 TO 1 STEP -1
300        READ Y
310        MOVE 3,X
320        LABEL "( )          ";Y;"dBm"
330    NEXT X
340    POINTER 3,8,2
350    DIGITIZE X,Y
360    Y=(9.2-Y) DIV 1
370    DIM Source$[49],Signalp$[49],Freq$[9],Mag$[8],Phase$[8],C$[1]
380    ! Begin construction of the Source/converter programming code.
390    Source$="O"&VAL$(Y)
400    GCLEAR
410    ! User selects the max input level using a menu.
420    MOVE 3,9
430    LABEL "MAXIMUM INPUT LEVEL"
440    FRAME
450    MOVE 3,8
460    LABEL "( )          -10dBm"
470    MOVE 3,7
480    LABEL "( )          -30dBm"
490    POINTER 3,8,2
500    DIGITIZE X,Y
510    Y=(9.2-Y) DIV 1
520    Source$=Source$&"I"&VAL$(Y)
530    GCLEAR
540    Source$=Source$&"R3"
550    ! Complete the Source string zeroing out the start,stop and marker
560    ! frequencies.
570 Skip:Source$=Source$&"M3S5W1T1FA0000FB0000FC00E"
580    ! User selects the S-parameter to be measured using a menu.
```

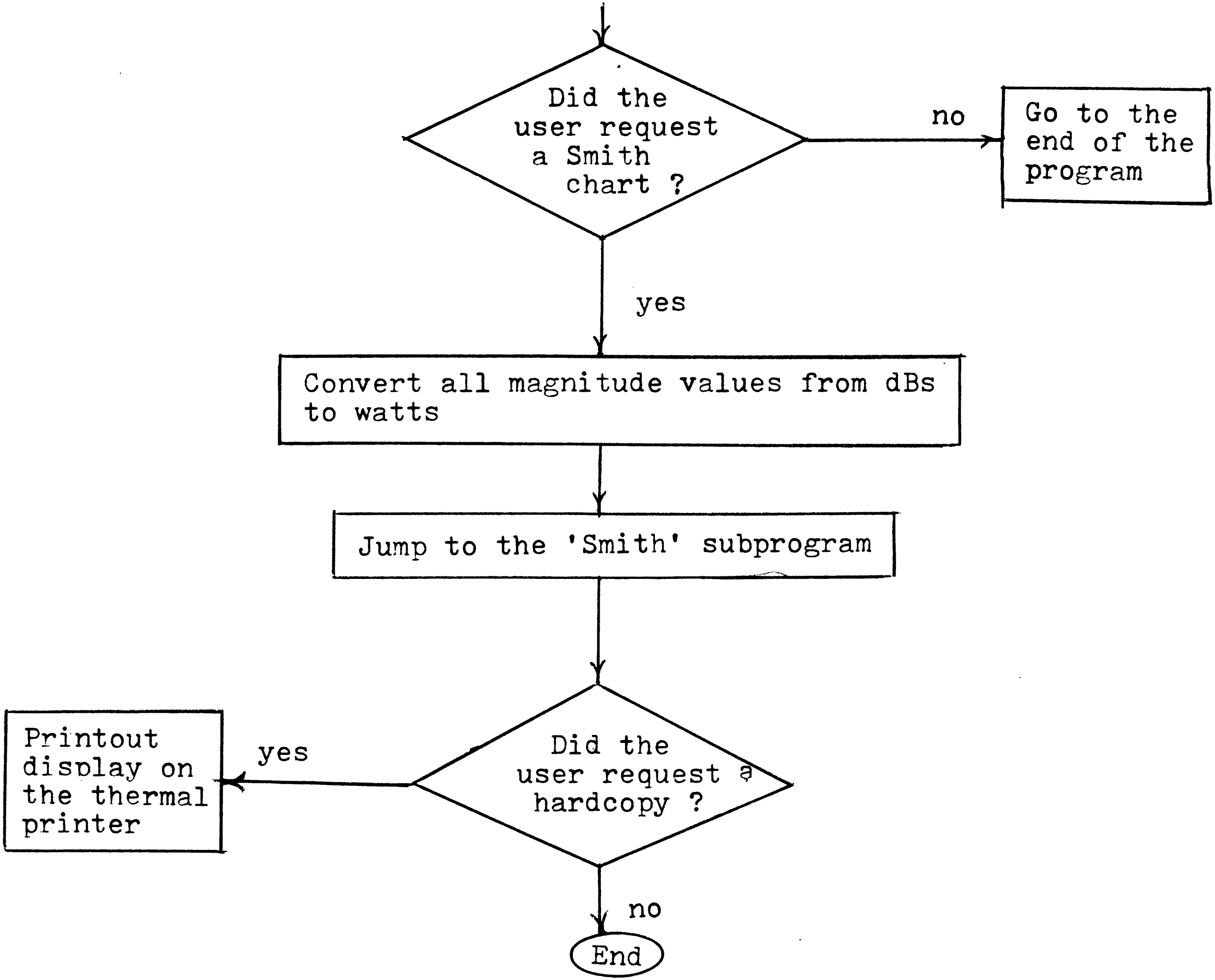
```
590    MOVE 2,9
600    LABEL "TRANSMISSION OR RELECTION CHARACTERISTICS"
610    FRAME
620    MOVE 3,8
630    LABEL "( )    Transmission"
640    MOVE 3,7
650    LABEL "( )    Reflection"
660    POINTER 3,8,2
670    DIGITIZE X,Y
680    GCLEAR
690    Y=(Y-3) DIV 1
700    ! Construct the programming code for the signal processor.
710    Signalp$="C0B1C1I"&VAL$(Y)&"C1M2C1S2C1D2C2I"&VAL$(Y)&"C2M3C2S3C2D2C3M1E"
720    ! Measure the magnitude response and store values on the disk.
730    CALL Measure(1,(Maxf),(Minf),(Source$),(Signalp$),Hmag,Lmag)
740    ! Measure the phase response and store values on the disk.
750    CALL Measure(2,(Maxf),(Minf),(Source$),(Signalp$),Hmag,Lmag)
751    ! Store the frequency range and magnitude range in this file for
752    ! plotting purposes.
760    ASSIGN "Data:F8" TO #3
770    PRINT #3;Maxf,Minf,Hmag,Lmag
771    ! Load the plotter program.
780    LOAD "Plot:T15"
790    END
800    !
810    !
820    !
830    !
840    !
841    ! The following subprogram displays the magnitude and phase response of
842    ! the S-parameter in sections of 50MHz ranges. The marker frequency
850    ! starts at the beginning of the response and is increased .5MHz each
851    ! time. The magnitude or phase value (depending on the fileno.) is
852    ! measured and stored for each of the marker frequencies.
853    !
860    SUB Measure(Fileno,Maf,Mif,A$,B$,Hmag,Lmag)
861    ! Assigns #1 to the file to store the magnitude values and #2 to
862    ! the file to store phase values.
870    ASSIGN "Mdata:F8" TO #1
880    ASSIGN "Pdata:F8" TO #2
890    DIM Mag$[8],Freq$[9],Phase$[8],C$[1]
891    ! Compute the number of 50MHz sections to be displayed for the
892    ! desired frequency range.
900    Ftotal=(Maf-Mif) DIV 50+1
930    Hmag=-10000
940    Lmag=10000
950    FOR X=1 TO Ftotal
951        ! Setup the 50MHz section.
960        Start=Mif
970        Stop=Mif+50
971     ! Determine the number of digits needed to represent the start and stop
972     ! frequencies and reconstruct the Source code to produce this range.
980     IF Start>9 THEN GOTO Above9
990        A$[20]=VAL$(Start)&"FB0000"
1000       A$[25]=VAL$(Stop)&"FC00"
1010       GOTO Done
1020 Above9:IF (Start>99) OR (Stop>99) THEN GOTO Above99
1030       A$[23]=VAL$(Stop)&"FC00"
1040       A$[25]=VAL$(Stop)&"FC00"
1050       GOTO Done
1060 Above99:IF Start>99 THEN GOTO Above992
```

```
1060 Above99:IF Start>99 THEN GOTO Above992
1070       A$[19]=VAL$(Start)&"FB0000"
1080       A$[24]=VAL$(Stop)&"FC00"
1090       GOTO Done
1100 Above992:IF (Start>999) OR (Stop>999) THEN GOTO Above999
1110       A$[18]=VAL$(Start)&"FB0000"
1120       A$[24]=VAL$(Stop)&"FC00"
1130       GOTO Done
1140 Above999:IF Start>999 THEN GOTO Above9992
1150       A$[18]=VAL$(Start)&"FB0000"
1160       A$[23]=VAL$(Stop)&"FC00"
1170       GOTO Done
1180 Above9992:A$[17]=VAL$(Start)&"FB0000"
1190       A$[23]=VAL$(Stop)&"FC00"
1191 ! Adjust the two digits in the code which control the marker frequency
1192 ! so that the marker frequency increases by .5MHz steps.
1200 Done:FOR Z=0 TO 99
1210       IF 50*Z*.01+Mif>Maf THEN GOTO Over
1211       ! Reconstruct Source code.
1220       IF Z>9 THEN GOTO Over9
1230       A$[29]="0"&VAL$(Z)&"E"
1240       GOTO Jump
1250 Over9:A$[29]=VAL$(Z)&"E"
1251 ! Output the appropriate programming code to each of the instuments.
1260 Jump:OUTPUT 719;A$
1270       OUTPUT 716;B$
1271 ! Store the measured magnitude and phase values as string variables.
1290       ENTER 716;Mag$,C$,Phase$
1291 ! Convert the results to numeric values, and determine if the
1292 ! magnitude is the highest or lowest measured.
1300       Mag=VAL(Mag$)
1310       IF Mag<Lmag THEN Lmag=Mag
1320       IF Mag>Hmag THEN Hmag=Mag
1330       Phase=VAL(Phase$)
1331 ! Store the appropriate value (mag or phase) on the disk.
1360       IF Fileno=2 THEN GOTO File2
1370         PRINT #1;Mag
1380         GOTO Over
1390 File2: PRINT #2;Phase
1400 Over:NEXT Z      ! Move to the next marker frequency(.5MHz)
1410       Mif=Mif+50
1420       NEXT X      ! Move to the next 50MHz frequency range.
1440       SUBEND
```

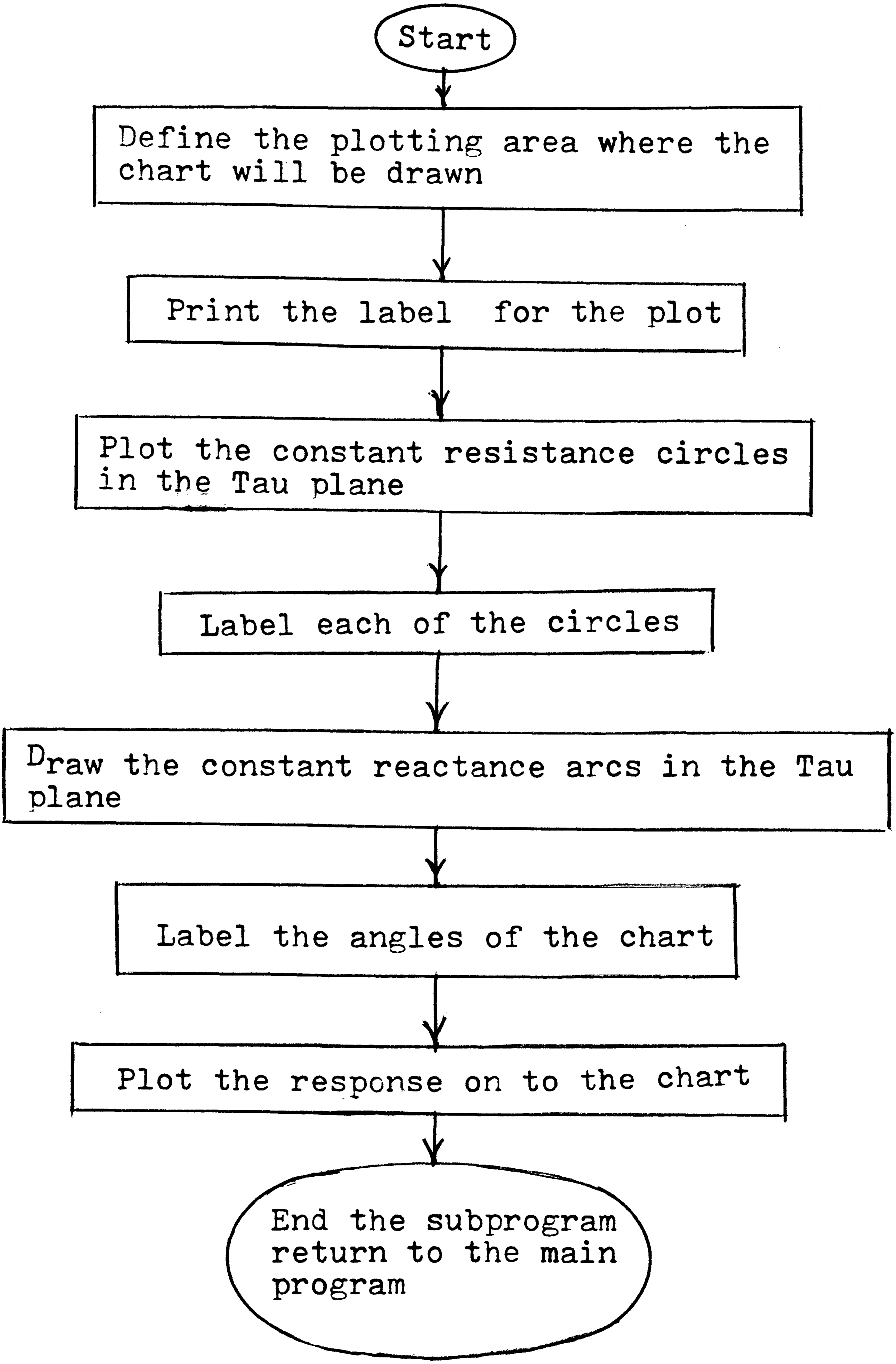
The Plotter Program Flowchart




Printout the display on the thermal printer
yes
Did the user request a hardcopy ?
no
1
Did the user request a phase plot ?
no
Go to 2
yes
Convert all the phase values to the +180 to -180 degree range
Print the plot and axes labels
Define the plotting area and scale it
Draw and number the axes
Plot the phase response
Printout the display on the thermal printer
yes
Did the user request a hardcopy ?
no
2


Did the user request a Smith chart ?
no
Go to the end of the program
yes
Convert all magnitude values from dBs to watts
Jump to the 'Smith' subprogram
Did the user request a hardcopy ?
yes
Printout display on the thermal printer
no
End

<u>The Smith Subprogram Flowchart</u>



```
1   !  THE PLOTTER PROGRAM
10  REM   This program displays the S-parameter data gathered by the
20  REM   previous program. This data is diplayed in the form of a
30  REM   magnitude response, a phase response, and on a Smith Chart.
40  ASSIGN "Mdata:F8" TO #1
50  ASSIGN "Pdata:F8" TO #2
60  ASSIGN "Data:F8" TO #3
70  DIM Magnitude(2600),Phase(2600),Real(2600),Imag(2600)
71  REM   Retrieve magnitude and phase data from the disk.
80  READ #3;Maxf,Minf,Hmag,Lmag
90  FOR W=Minf TO Maxf STEP .5
100   READ #1;Magnitude(X)
110   READ #2;Phase(X)
120   X=X+1
130 NEXT W
140 DATA 1,5,10,50,100                    ! Calculate the frequency scaling
150 FOR A=1 TO 5                          ! to be used.
160   READ Scale
170   CALL Scaling(Maxf,Minf,Xmax,Xmin,Scale,Xscale)
180   IF Xscale<>0 THEN GOTO Cont1
190 NEXT A
191 REM   Determine whether a magnitude vs. frequency plot desired by the user.
200 Cont1:INPUT "Magnitude plot?  Enter (Y or N)",Response$
210 IF Response$<>"Y" THEN GOTO Phase
220 DATA .1,.5,1,5,10                     ! Calculate the magnitude scaling
230 FOR A=1 TO 5                          ! to be used.
240   READ Scale
250   CALL Scaling(Hmag,Lmag,Ymax,Ymin,Scale,Yscale)
260   IF Yscale<>0 THEN GOTO Cont2
270 NEXT A
290 Cont2:PLOTTER IS 13,"GRAPHICS"        ! Enter the graphics mode.
300 GRAPHICS
310 MOVE 40,90
320 CSIZE 4.5,6/15
330 LABEL "MAGNITUDE RESPONSE"            ! Print the plot and axes labels.
340 MOVE 40,10                            !
350 CSIZE 3.3,9/15                        !
360 LABEL "Frequency in MegaHertz"        !
370 MOVE 10,30                            !
380 LDIR PI/2                             !
390 LABEL "Magnitude in dBm"              !
400 LDIR 0                                !
410 LOCATE 20,100,20,80                   ! Define an area on the screen
420 SCALE Xmin,Xmax,Ymin,Ymax             ! where the plot will be drawn.
430 AXES Xscale,Yscale,Xmin,Ymin          ! Draw the axes.
440 CSIZE 2.5                             !
450 FOR Z=Xmin TO Xmax STEP Xscale        ! Number the magnitude and frequency
460   MOVE Z-.2*Xscale,Ymin-.2*Yscale     ! axes.
470   LABEL VAL$(Z)                       !
480 NEXT Z                                !
490 FOR Z=Ymin TO Ymax STEP Yscale        !
500   MOVE Xmin-.5*Xscale,Z               !
510   LABEL VAL$(Z)                       !
520 NEXT Z                                !
530 PEN 2                                 !
540 FOR W=Minf TO Maxf STEP .5            ! Plot the magnitude response on the
550     PLOT W,Magnitude(I)               ! graph.
560     LET I=I+1                         !
570 NEXT W                                !
571 INPUT "Hardcopy?",Response$           ! Provide a hardcopy if requested.
572 IF Response$<>"Y" THEN GOTO Phase     !
573 DUMP GRAPHICS                         !
574 REM  Determine whether a phase vs. frequency plot is desired.
580 Phase:  INPUT "Phase plot?",Response$
590 IF Response$<>"Y" THEN GOTO Smithc
```

```
590 IF Response$<>"Y" THEN GOTO Smithc
600 I=0
610 FOR W=Minf TO Maxf STEP .5                    ! Place each phase value within
620 Repeat:IF Phase(I)<=180 THEN GOTO Negphase    ! the +180 to -180 range.
630    Phase(I)=Phase(I)-360                      !
640    GOTO Repeat                                !
650 Negphase:IF Phase(I)>=-180 THEN GOTO Done     !
660    Phase(I)=Phase(I)+360                      !
670    GOTO Repeat                                !
680 Done:I=I+1                                    !
690 NEXT W                                        !
700 PLOTTER IS 13,"GRAPHICS"                      ! Enter the graphics mode.
710 MOVE 40,90                                    !
720 CSIZE 4.5,6/15                                !
730 LABEL "PHASE RESPONSE"                        ! Print the plot and axes
740 MOVE 30,10                                    ! labels.
750 CSIZE 3.3,9/15                                !
760 LABEL "Frequency in MegaHertz"                !
770 MOVE 10,30                                    !
780 LDIR PI/2                                     !
790 LABEL "Phase in Degrees"                      !
800 LDIR 0                                        !
810 LOCATE 20,100,20,80                           ! Define an area on the screen
820 SCALE Xmin,Xmax,-180,180                      ! where the plot will be drawn.
830 AXES Xscale,45,Xmin,0                         ! Draw the axes.
831 CSIZE 2                                       ! Number the phase and frequency
840 FOR Degree=-180 TO 180 STEP 45                ! axes.
850   MOVE Xmin-.5*Xscale,Degree                  !
860   LABEL VAL$(Degree)                          !
870 NEXT Degree                                   !
880 FOR Freq=Xmin TO Xmax STEP Xscale             !
890   MOVE Freq-.2*Xscale,-12                     !
900   LABEL VAL$(Freq)                            !
910 NEXT Freq                                     !
920 PEN 2                                         !
930 I=0                                           !
940 FOR W=Minf TO Maxf STEP .5                    ! Plot the phase response.
950      PLOT W,Phase(I)                          !
960      LET I=I+1                                !
970 NEXT W                                        !
971 INPUT "Hardcopy?",Response$                   ! Provide a hardcopy if
972 IF Response$<>"Y" THEN GOTO Smithc            ! requested.
973 DUMP GRAPHICS                                 !
974 REM  Determine if the response plotted on a Smith chart is desired.
980 Smithc:  INPUT "Smith Chart?",Response$
990 IF Response$<>"Y" THEN GOTO End
1005 I=0
1006 DEG
1010 FOR W=Minf TO Maxf STEP .5                 !
1011  Magnitude(I)=10^(Magnitude(I)/20)        ! Convert the magnitude values
1020  A=TAN(Phase(I))                          ! from dB to Watts.
1030  Real(I)=Magnitude(I)/SQR(1+A^2)          ! Compute the real and imaginary
1040  Imag(I)=Real(I)*TAN(Phase(I))            ! values from the mag and phase
1050  I=I+1                                    ! values.
1060 NEXT W                                     !
1070 CALL Smith(Real(*),Imag(*),Maxf,Minf)      ! Call the subprogram to print
1071 INPUT "Hardcopy?",Response$                ! the chart. Provide a hardcopy if
1072 IF Response$<>"Y" THEN GOTO End            ! requested.
1073 DUMP GRAPHICS
```

```
1073 DUMP GRAPHICS
1080 End: END
1090 !
1100 !
1110 !
1120 !
1130 !
1140 !
1141 ! The following subprogram constructs a Smith chart and plots the measured
1142 ! response on the chart.
1150 SUB Smith(Real(*),Imag(*),Maxf,Minf)
1220  PLOTTER IS 13,"GRAPHICS"            ! Enter the graphics mode.
1230  GRAPHICS                            !
1240  LOCATE 10,90,10,90                  ! Define an area where the chart will
1250  SCALE -1,1,-1,1                     ! be drawn.
1260  MOVE -.2,1.1                        !
1270  CSIZE 4.5,6/15                      !
1280  LABEL "Smith Chart"                 ! Label the chart.
1290  CSIZE 2,9/15                        !
1300  Nx=1                                 !
1310  DEG                                   !
1320  DATA 10,5,3,2,1,.5,.2,0,-5              !
1330 Start:    READ Resistance                   ! Plot the constant resistances
1340           IF Resistance<0 THEN GOTO Overn    ! circles in the Tau plane.
1350           IF Resistance=0 THEN PEN 4          !
1360           Reflection=(Resistance-1)/(Resistance+1) !
1370           Radius=ABS((Reflection-1)/2)          !
1380           Center=1-Radius                      !
1390           MOVE Center,0                       !
1400           FOR Angle=0 TO 360                  ! Draw the circles.
1410               PDIR Angle                      !
1420               RPLOT Radius,0                  !
1430           NEXT Angle                          !
1440           IF Resistance=0 THEN PEN 1          !
1450           MOVE Nx,0                           !
1460           PLOT 1-(2*Radius-.06),0,-1          !
1470           Nx=1-2*Radius                       !
1480           MOVE Nx+.02,0                       !
1490           PEN 2                               !
1500           LABEL VAL$(Resistance)              ! Label each of the circles.
1510           PEN 1                               !
1520           GOTO Start                          !
1530 Over:     LET Angle=0                         !
1540           DATA .2,.5,1,2,3,-.2,-.5,-1,-2,-3,-5 !
1550 Again:    READ Reactance                      ! Draw the constant
1560           IF Reactance<-4 THEN GOTO End       ! reactance arcs in the Tau
1570           PENUP                               ! plane.
1580           LET Displacement=1/Reactance        !
1590           LET Radius=ABS(1/Reactance)
1600           IF Reactance<0 THEN GOTO Neg
1610           FOR Angle=-90 TO -270 STEP -1
1620              X=Radius*COS(Angle)+1
1630              Y=Radius*SIN(Angle)+Displacement
1640              IF Y<.05 THEN GOTO Angle
1650              IF X^2+Y^2>1 THEN GOTO Again
1660              PLOT X,Y
1670 Angle:    NEXT Angle
1680           GOTO Again
1690 Neg:      FOR Nangle=90 TO 270
1700              X=Radius*COS(Nangle)+1
1710              Y=Radius*SIN(Nangle)+Displacement
1720              IF Y>-.05 THEN GOTO Nangle
1730              IF X^2+Y^2>1 THEN GOTO Again
1740              PLOT X,Y
1750 Nangle:   NEXT Nangle
```

```
1750 Nangle:  NEXT Nangle
1760          GOTO Again
1770 End:     MOVE -.04,1.05                   ! Label the angles of the chart.
1780          LABEL "90"
1790          MOVE -1.2,0
1800          LABEL "±180"
1810          MOVE -.04,-1.05
1820          LABEL "-90"
1830          MOVE 1.03,0
1840          LABEL "0"
1850          Y=0
1860          PEN 2
1870          FOR W=Minf TO Maxf STEP .5       ! Plot the response.
1880            PLOT Real(Y),Imag(Y)
1890            Y=Y+1
1900          NEXT W
1910 Quit:  SUBEND                             ! End of the 'Smithc' subprogram.
1920   !
1930   !
1940   !
1950   !
1951   ! The following subprogram computes the scaling and the high and low
1952   ! marks on the axis based on the highest and lowest positions to be
1953   ! plotted.
1960   SUB Scaling(High,Low,Hscale,Lscale,Scale,Poscale)
1970       IF (High-Low)/(Scale*10)>1 THEN GOTO End
1980         Poscale=Scale
1990         IF High<0 THEN Hscale=High DIV Scale*Scale
2000         IF High>0 THEN Hscale=(High DIV Scale+1)*Scale
2010         IF Low<0 THEN Lscale=(Low DIV Scale-1)*Scale
2020         IF Low>0 THEN Lscale=Low DIV Scale*Scale
2030 End:SUBEND
```

USER'S GUIDE

Connecting the device-under-test (D.U.T.) to the network analyzer and transmission/reflection test set, for measurement of its S-parameters.

- -- All connections are made with 6", 50 ohm coaxial cables.
- -- Connect the analyzer's output port, labeled "RF", to the input port of the transmission/reflection test set, labeled "RF". The input port of the T/R test set is located at the instrument's rear panel.
- -- Connect the T/R test set's output port, labeled "TEST", to the input port of the D.U.T.
- -- Connect the output port labeled "INCIDENT", located at the T/R test set's rear panel, to the analyzer's input port labeled "R".
- -- Connect the output port labeled "REFLECTION" located at the T/R test set's rear panel, to the analyzer's input port labeled "A".
- -- Finally, connect the output port of the D.U.T. to the analyzer's input port labeled "B".

Note 1: Using this procedure to connect the D.V.T. to the measurement system, the reflection coefficient corresponds to S-parameter S_{11} and the transmission coefficient corresponds to S_{21}. The two other S-parameters may be measured by interchanging the input and output port of the D.V.T. (S_{22} = reflection, S_{12} = transmission).

Before turning on the computer.

- -- Check to see that both of the interface cards are properly inserted into their respective slots. The slots are located at the back of the computer.
- -- Check to see that the 98034A interface card (number indicated on the card) is properly connected to both of the network analyzer's units, and the 98032A interface card is properly connected to the disk drive.
- -- Turn on the analyzer and the disk drive.
- -- Insert the disk, labeled "S-parameter Data", into the disk drive.
- -- Insert the cassette tape, labeled "S-parameter Measurement", into the tape drive at the right-side of the computer keyboard.

Loading the measurement program.

- -- Turn on the computer. The screen should display

  MEMORY TEST IN PROGRESS.

  Once the computer's self-test has been completed, the screen should read

  9845C READY FOR USE.

- -- Type in the following statement to load the measurement program,

  LOAD "Meas: T15"

  Press the "EXECUTE" key.

-- After the program has been loaded into the computer's memory, press the "RUN" key to initiate the program's execution.

The measurement program.

-- An introduction to the program will be displayed. Press the "CONT" key to continue the program's execution.
-- The computer then asks the user to enter a maximum and minimum frequency to specify the range of the measurement. Enter each in MHz and press the "CONT" key.
-- Next, the screen will display three menus, one at a time. Use the arrow keys at the top of the keyboard to position the cursor, "+", between the parentheses, left of the desired selection. Press the "CONT" key.

Note 2: When choosing the reflection or transmission coefficient see Note 1 to determine which of the S-parameters each corresponds to.

-- If the user has made an error in selecting one of the menu's choices or the maximum and minimum frequencies, stop the program using the "STOP" key. Press the "RUN" again to restart the program.
-- The program will gather the necessary data and will automatically load the plotter program. While the measurements are being taken, the response of the parameter is displayed at the analyzer.

Displaying the measured data.

-- The user will be asked if he wishes a plot. For example,

Magnitude Plot

will appear on the CRT.
-- Type "Y" and the "CONT" key if a display of the plot is desired, and an "N" and the "CONT" key if not.
-- After the plot has been displayed, the user will be asked if he wants a hardcopy of the display. Type "Y" for yes and "N" for no.
-- The hardcopy will be generated by the thermal printer.
-- A phase plot and Smith Chart are also available.

Appendix

Conversions from S-parameters to other two-port parameters.

Y

$$Y_{11} = \frac{(1 - S_{11})(1 + S_{22}) + S_{12} S_{21}}{(1 + S_{11})(1 + S_{22}) - S_{12} S_{21}}$$

$$Y_{12} = \frac{-2 S_{12}}{(1 + S_{11})(1 + S_{22}) - S_{12} S_{21}}$$

$$Y_{21} = \frac{-2 S_{21}}{(1 + S_{11})(1 + S_{22}) - S_{12} S_{21}}$$

$$Y_{22} = \frac{(1 + S_{11})(1 - S_{22}) + S_{12} S_{21}}{(1 + S_{11})(1 + S_{22}) - S_{12} S_{21}}$$

Z

$$Z_{11} = \frac{(1 + S_{11})(1 - S_{22}) + S_{12} S_{21}}{(1 - S_{11})(1 - S_{22}) - S_{12} S_{21}}$$

$$Z_{12} = \frac{2 S_{12}}{(1 - S_{11})(1 - S_{22}) - S_{12} S_{21}}$$

$$Z_{21} = \frac{2 S_{21}}{(1 - S_{11})(1 - S_{22}) - S_{12} S_{21}}$$

$$Z_{22} = \frac{(1 - S_{11})(1 + S_{22}) + S_{12} S_{21}}{(1 - S_{11})(1 - S_{22}) - S_{12} S_{21}}$$

H

$$h_{11} = \frac{(1 + S_{11})(1 + S_{22}) - S_{12} S_{21}}{(1 - S_{11})(1 + S_{22}) + S_{12} S_{21}}$$

$$h_{12} = \frac{2 S_{12}}{(1 - S_{11})(1 + S_{22}) + S_{12} S_{21}}$$

$$h_{21} = \frac{-2 S_{21}}{(1 - S_{11})(1 + S_{22}) + S_{12} S_{21}}$$

$$h_{22} = \frac{(1 - S_{11})(1 - S_{22}) - S_{12} S_{21}}{(1 - S_{11})(1 + S_{22}) + S_{12} S_{21}}$$

A
B
C
D

$$A = \frac{(1 + S_{11})(1 - S_{22}) + S_{12} S_{21}}{2 S_{21}}$$

$$B = \frac{(1 + S_{11})(1 + S_{22}) - S_{12} S_{21}}{2 S_{21}}$$

$$C = \frac{(1 - S_{11})(1 - S_{22}) - S_{12} S_{21}}{2 S_{21}}$$

$$D = \frac{(1 - S_{11})(1 + S_{22}) + S_{12} S_{21}}{2 S_{21}}$$

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