# ELEC 453/6391 Microwave Engineering

# Experiment #5

# HP8505 and HP8720 Network Analyzers

This experiment has two parts. In the first part you will use an HP8505 network analyzer (NA) to measure the reflection coefficient of the loads used in experiments 1 and 2: the standard loads; the "tee-50" and "tee-75" loads; and the resistors. In the second part the lab demonstrator will help you to measure the input impedance of the microstrip line of experiment 4, with no matching circuit, with a single-stub tuning stub, and with a double-stub tuning circuit. Your lab group has 90 minutes to work on the HP8505, and 90 minutes to work with the lab demonstrator on the HP8720.

## 1. Equipment

- HP8505A network analyzer with HP8501A storage normalizer.
- HP8503A S-parameter test set.
- APC-7 to N male adapter
- HP8720A network analyzer
- APC-7 to N male adapter
- N to SMA male adapter
- N-type tee junction, 50 $\Omega$ loads, 75 $\Omega$ loads, short circuit load, resistors mounted on N-type bulkhead connectors.
- Female to female SMA adapter, SMA short circuit with male connector
- Microstrip line with $Z_0 = 50\,\Omega$ on GML 1000 board, terminated with a load resistor.
- 3M 1183 conducting tape, X-acto knife (for cutting the tape), glass plate, steel ruler, magnifying glass, digital calipers

## 2. Introduction

In this experiment, you will use the HP8505 and the HP8720 network analyzers. These are more modern instruments than the HP8410 NA of Experiment 4. This section provides some basic information about what these instruments consist of, and how they are used. The Procedure section below has detailed instructions for calibration and measurement.

2.1 The HP8505 Network Analyzer

Fig. 5.1 is a photo of the HP8505 network analyzer (two center boxes), the HP8501A storage normalizer (top box), and the HP8503A S-parameter test set (bottom box). The HP8505[1] network analyzer itself has a CRT display, with controls for "channel 1" and "channel 2" of the display to the right of the screen. The swept-frequency source and the RF receiver are located

[1] HP8505A Network Analyzer Operating Manual, part number 08505-90072, Hewlett-Packard Company, 1976.

below the CRT, with the frequency controls to the right. The HP8505 uses a YIG-tuned, swept-frequency oscillator for the RF source, over the frequency range 500 kHz to 1.3 GHz. The sweeper accuracy is $\pm 1\%$ of the range of the sweep. The sweeper provides the RF signal to the S-parameter test set, which routes the power to a splitter. One branch of the splitter goes through a 20-dB attenuator to the reference channel or "R" channel of the HP8505's receiver. The other branch of the splitter is routed to a pair directional couplers and an RF switching arrangement. For reflection coefficient ($S_{11}$) measurement, a directional coupler samples the reflected voltage from the unknown load or "device under test" (DUT) and delivers it to channel A of the receiver. For transmission coefficient $(S_{21})$ measurement, the voltage transmitted through the DUT is routed into channel B of the receiver. In the receiver, the three channels (R, A and B) are down-converted to an intermediate frequency (IF) of 100 kHz. The receiver has a dynamic range from -10 dB to -110 dB, and more than 100 dB isolation between the three channels.

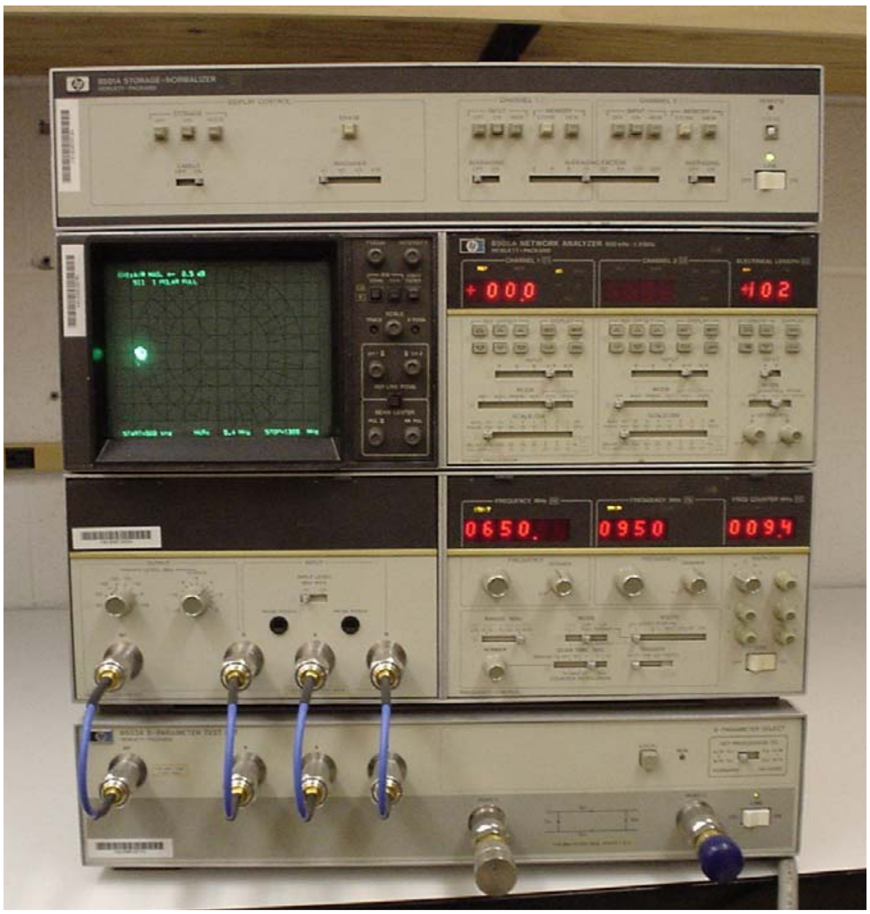

Figure 5.1 The HP8505A network analyzer (two center boxes), with the HP8501A storage normalizer (top) and the HP8503A S-parameter test set (bottom).

The CRT display has two channels, 1 and 2. Each channel can either display the signal at channel A of the receiver, or display the signal at channel B, or display the ratio of channel A to the reference channel (A/R), or display the ratio of channel B to the reference channel (B/R). The format of the CRT display can be selected as either Cartesian or polar. Each channel can display either magnitude or phase as a function of frequency, or can display both the magnitude and phase, on polar axes. In this experiment, we will measure the reflection coefficient using channel A of the receiver. Channel 1 of the CRT display will be used to show the magnitude ratio A/R as a function of frequency, and channel 2 of the display will show the angle of A/R as a function of frequency, both on Cartesian axes.

To operate the instrument the starting frequency and stopping frequency of the sweep are set with the knobs to the right of the blue jumper cables in Fig. 5.1. The NA measures A/R at 500 frequencies between the starting and stopping value. The NA has five “markers”, with the controls located to the right of the frequency controls. The markers are used to read back data from the CRT display: frequency, magnitude, and phase. Select marker 1, 2, 3, 4 or 5 using the rotary switch, and then set the marker frequency using the numbered knobs. The frequency of marker is shown above the marker controls, with a resolution of 100 kHz. On the CRT, the marker position is shown with a small diamond, and the value of the marker (magnitude or phase) is displayed in red digits above the panel for channel 1 or channel 2, and also on the CRT display.

We will use a short circuit load as a “reference standard” to calibrate the NA, by connecting it to Port 1 of the S-parameter test set. You must follow the calibration instructions given below in the Procedure section precisely. The instructions seem illogical and counter-intuitive! The calibration sequence uses marker #1 and corrects for path length differences and imperfections in the S-parameter test set at the frequency selected for marker 1. So set marker 1 to the middle of your frequency range before starting the calibration procedure. The HP8505 includes an electronic line stretcher that performs the same function as the mechanical line stretcher in the reflection/transmission test set used in experiment 4 with the HP8410. You will set the “length” of the line stretcher so that the angle of the reflection coefficient from the short-circuit load is 180 degrees, at the frequency of marker #1. Once the NA is calibrated, the unknown load is mounted on Port #1, and the NA reads the magnitude of the reflection coefficient in dB and the angle of the reflection coefficient in degrees, as a function of frequency from the start frequency to the stop frequency of the sweeper.

What the HP8505 actually measures is the ratio $r(f_k)$ of the “test” channel voltage (A or B) to the “reference” channel voltage (R), at 500 frequencies, $\{f_k : k = 1,...,500\}$, evenly-spaced from the start frequency to the stop frequency of the sweep. We can use this capability to measure the reflection coefficient of an unknown load by proper calibration with a “reference standard”, namely a short-circuit load. We need to find a calibration coefficient that changes the ratio $r(f_k)$ into the reflection coefficient,

$$\Gamma(f_k) = C_k r(f_k) \qquad \ldots(1)$$

at each frequency of the sweep. To find the calibration coefficients $\{C_k\}$, mount the short-circuit load, which has a reflection coefficient $\Gamma = -1$ independent of frequency, and measure the response $r_s(f_k)$. Then calculate the coefficient at each frequency by solving $-1 = C_k r_s(f_k)$ so

$$C_k = \frac{-1}{r_s(f_k)} \qquad \ldots(2)$$

Then the unknown load is mounted, and the NA measures the ratio of the channel A voltage to the reference channel voltage, $r_L(f_k)$, at each frequency. The reflection coefficient is calculated as

$$\Gamma_L(f_k) = C_k r_L(f_k) = \frac{-r_L(f_k)}{r_s(f_k)} \qquad \ldots(3)$$

The magnitude is $|\Gamma_L| = |r_L|/|r_s|$ and is given in dB by

$$|\Gamma_L(f_k)|(\text{dB}) = |r_L(f_k)|(\text{dB}) - |r_s(f_k)|(\text{dB}) \qquad \ldots(4)$$

The angle of the reflection coefficient $\theta_L$ is found from

$$|\Gamma_L| e^{j\theta_L} = \frac{|r_L| e^{j\phi_L} e^{j\pi}}{|r_s| e^{j\phi_s}}$$

where $-1 = e^{j\pi}$. Hence the angle is

$$\theta_L(f_k) = \phi_L(f_k) - \phi_s(f_k) + \pi \qquad \ldots(5)$$

We say that we "subtract" the calibration response $r_s$ from the load response $r_L$ to get the true reflection coefficient $\Gamma_L$.

The HP8505 network analyzer itself cannot store an array of 500 calibration coefficients $\{C_k\}$. The instrument stores only one calibration coefficient, $C_M$, and the frequency at which this coefficient is found is the frequency of marker #1, $f_M$. So if you are working from 600 MHz to 1000 MHz, for calibration set the frequency of marker #1 to the middle of the band, $f_M = 800$ MHz. The calibration procedure evaluates the coefficient as

$$C_M = \frac{-1}{r_s(f_M)} \qquad \ldots(6)$$

Then the reflection coefficient of Eqn. (3) is approximated as

$$\Gamma_L(f_k) \approx C_M r_L(f_k) \qquad \ldots(7)$$

This is exact at the marker frequency, but at other frequencies is an approximation that does not obtain the best possible accuracy.

The purpose of the storage normalizer is to "subtract" the calibration curve from the measurement curve at all 500 measurement points. The normalizer stores 500 data values for Channel 1, which we will call $\{s_1(f_k)\}$, and 500 values for Channel 2, $\{s_2(f_k)\}$. The normalizer can display either the input from the 8505, $d_1(f_k)$ for channel 1 and $d_2(f_k)$ for channel 2, or "INPUT-MEM", the difference between the input and the stored values, which is $d_1(f_k) - s_1(f_k)$ for channel 1 and $d_2(f_k) - s_2(f_k)$ for channel 2. We can use this for calibration as follows. Start by using the ERASE key to clear the memory of the storage normalizer, and set storage normalizer so that both channel 1 and channel 2 display the INPUT, not INPUT-MEM. Then mount the short circuit load and carry out the calibration procedure for the 8505 in the usual way. Set up the 8505 to display magnitude on channel 1 and phase on channel 2, both on Cartesian axes. Then on the storage normalizer, press STORE for channel 1 and STORE for channel 2. This stores the curves in the normalizer's memory: channel 1 stores $s_1(f_k) = |r_s(f_k)|$ in dB, and channel 2 stores $s_2(f_k) = \phi_s(f_k)$, the angle of the response of the short-circuit "calibration standard". Then mount the unknown load, so that the input to the normalizer is $d_1(f_k) = |r_L(f_k)|$ in dB on channel 1 and $d_2(f_k) = \phi_L(f_k)$, the angle of the load, on channel 2. Then set the normalizer to display INPUT-MEM. For channel 1 the normalizer displays $d_1(f_k) - s_1(f_k) = |r_L(f_k)| - |r_s(f_k)|$ in dB, which is the "corrected" magnitude given by Eqn. (4), and $d_2(f_k) - s_2(f_k) = \phi_L(f_k) - \phi_s(f_k)$, which is not quite the corrected phase of Eqn. (5). We must add 180 degrees to the phase of channel 2 of the 8505 using the phase reference keys, so that the channel 2 data is $d_2(f_k) = \phi_L(f_k) + 180$, and then the storage normalizer displays the proper "corrected" phase, $d_2(f_k) - s_2(f_k) = \phi_L(f_k) + 180 - \phi_s(f_k)$.

Unfortunately, the software called "hp8505" on the lab's Linux computer is not set up to read the data output of the storage normalizer. So we can only read the approximate reflection coefficient of Eqn. (6). This deficiency will be fixed for next year! You can correct this yourself: save a data file with the response of the short circuit $r_s(f_k)$, and another data file with the response of the load, $r_L(f_k)$. Then write a short computer program to "subtract" $r_s(f_k)$ from $r_L(f_k)$ according to Eqns. (4) and (5).

Another function of the storage normalizer is to perform averaging over many measurements. RF measurements are often very noisy. By measuring the frequency response many times and averaging the measurements, the signal-to-noise ratio can be dramatically improved. The storage normalizer can keep a running average of the incoming data. Suppose the normalizer stores data $d_1(f_k)$ for channel 1 and $d_2(f_k)$ for channel 2, which are usually the magnitude and phase of the reflection coefficient, respectively. The sweeper performs a new frequency sweep, and supplies new data $d_{1new}(f_k)$ and $d_{2new}(f_k)$ to the normalizer. With the averaging factor set to $n$, the normalizer replaces $d_1(f_k)$ with $\frac{1}{n} d_{1new}(f_k) + \left(1 - \frac{1}{n}\right) d_1(f_k)$, and similarly replaces $d_2(f_k)$ with $\frac{1}{n} d_{2new}(f_k) + \left(1 - \frac{1}{n}\right) d_2(f_k)$. This improves the signal-to-noise ratio by a factor of $\sqrt{n}$. But it also "slows down" the measurement because with the averaging set to $n$, the data takes $2n$ sweeps of the sweeper for the data to reach 86% of its final value and $4n$ sweeps to reach 98% of the final value. We do not need to use averaging for the simple measurements that are done in this experiment.

## 2.2 The HP8720 Network Analyzer

The HP8720[2] shown in Fig. 5.2 is an early model of "modern" microprocessor-controlled network analyzers commonly found in industry. The HP8720 includes everything needed for reflection and transmission coefficient measurement in one instrument: synthesized frequency sweeper, S-parameter test set, receiver, microprocessor controller, storage normalizer, and CRT display. Unlike the HP8505, where many of the functions of the instrument are controlled by knobs and slide switches on the front panel, most of the HP8720's functions are controlled in software by computer-generated "soft key" menus that appear on the CRT screen and are accessed with the row of eight buttons located at the right edge of the screen in Fig. 5.2. Because the instrument's software includes many menus and sub-menus, the "learning curve" is steep: it takes about three months experience with the HP8720 to become a knowledgeable operator. In this experiment the lab demonstrator will operate the instrument, explain the calibration procedure to you, and help you to measure the reflection coefficient of your microstrip circuit.

[2] HP872A Microwave Network Analyzer - System Operating and Programming Manual, part number 08720-90002, Hewlett-Packard Company, 1988.


Figure 5.2 HP8720A network analyzer.

The HP8720 includes a synthesized source covering the frequency range from 130 MHz to 20 GHz, with a frequency resolution of 100 kHz. Some instruments include an "option" to increase the resolution to 1 Hz! The source generates either a single frequency ("continuous wave" or CW) or a frequency sweep. In the S-parameter test set a power splitter sends some of the input power to the reference channel and some to the DUT. Power sent to the reference channel is used to phase-lock the RF receiver and to provide the signal to the "reference" channel for amplitude and phase measurement. Power from the other splitter branch is routed to the unknown load. The S-parameter test set includes two directional couplers and RF switches that are arranged such that the 8720 can rapidly switch between measuring reflection coefficient $S_{11}$ and measuring transmission coefficient $S_{21}$ at each frequency in a frequency sweep. This allows $S_{11}$ and $S_{21}$ to be measured "simultaneously", actually alternately in rapid succession. The test set contains a 55-dB attenuator which allows the input power to the DUT to be adjusted in 5-dB steps.

The receiver has three channels: the reference channel, the "A" channel and the "B" channel. Each input signal is converted to a 4-kHz intermediate frequency (IF), preserving both the magnitude and the phase information of the original signal. The IF signals are multiplexed onto an analog-to-digital converter, and the digital outputs are measured and processed by the 8720's microprocessor for display on the CRT screen and for output to a computer via a gpib bus.

The calibration procedure for the HP8505 that was explained above uses only one "calibration standard": a short-circuit load. This procedure is available on the HP8720, and is called a "response" calibration. It is quick and simple and sufficiently accurate for many purposes. But much better accuracy can be obtained with an "$S_{11}$" calibration, which uses three calibration standards that are part of a "calibration kit'. The three standards are: a short circuit; an open circuit; and a broadband matched load.

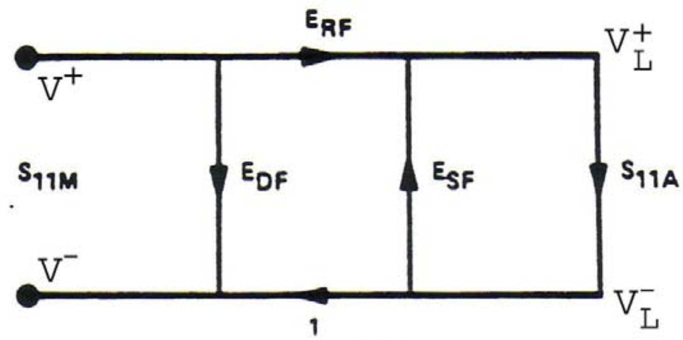


Figure 5.3 The "signal flow graph" for the S11 calibration[3].

The signal flow graph of Fig. 5.3 is the model of the S-parameter test set used in the calibration procedure. The true reflection coefficient of the unknown load is $S_{11A} = \dfrac{V_L^+}{V_L^-}$. The network analyzer measures $S_{11M} = \dfrac{V^-}{V^+}$. The measured reflection coefficient $S_{11M}$ differs from the true reflection coefficient $S_{11A}$ because of imperfections in the S-parameter test set. The signal flow graph of Fig. 5.3 accounts for three kinds of errors. The directional coupler separates the forward-traveling wave from the backward-traveling wave. The "directivity" of the coupler[4] is a measure of the extent to which the backward wave is corrupted by the forward wave. This gives rise to the directivity error $E_{DF}$ : the directional coupler delivers a small part of the "incident" voltage directly to the "reflected" port. "Frequency tracking" refers to differences in path length and path loss between the test channel and the reference channel, which change as the frequency changes. The frequency-tracking error $E_{RF}$ accounts for these differences. The "source match" error $E_{SF}$ accounts for the small mismatch between the characteristic impedance of the components inside the S-parameter test set and the true value of 50 ohms. The signal flow graph of Fig. 5.3 can be solved to obtain

$$S_{11M} = E_{DF} + \frac{S_{11A}E_{RF}}{1 - E_{SF}S_{11A}} \qquad \ldots(8)$$

and then the true reflection coefficient of the load is

$$S_{11A} = \frac{S_{11M} - E_{DF}}{E_{SF}(S_{11M} - E_{DF}) + E_{RF}} \qquad \ldots(9)$$

To use this relation, we need to know the values of the three error terms $E_{DF}$, $E_{RF}$, and $E_{SF}$. The three calibration standards are used to find the values of these error terms as follows.

The first standard is the broadband matched load, for which $S_{11A} = 0$. The NA measures reflection coefficient

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[3] HP872A Microwave Network Analyzer - System Operating and Programming Manual, part number 08720-90002, Hewlett-Packard Company, 1988, Figure 5-26..

[4] Pozar, "Microwave Engineering", 3rd edition, Wiley, pp. 311-314.

$$S_{MA} = E_{DF} + \frac{0xE_{RF}}{1 - E_{SF}x0} = E_{DF} \qquad \ldots(10)$$

This determines the directivity error directly. The second standard is the "perfect" short circuit, which has $S_{11A} = -1$. The NA measures

$$S_{SC} = E_{DF} - \frac{E_{RF}}{1 + E_{SF}} \qquad \ldots(11)$$

This equation has two unknowns, $E_{RF}$ and $E_{SF}$, hence we need a second equation. The third reference standard is the "perfect" open circuit, which has $S_{11A} = 1$. Then

$$S_{OC} = E_{DF} + \frac{E_{RF}}{1 - E_{SF}} \qquad \ldots(12)$$

Equation (10) gives the value of $E_{DF}$. Equations (11) and (12) can be solved for the values of $E_{RF}$ and $E_{SF}$.

The NA is used to measure the reflection coefficient at many frequencies, typically 801 frequencies, in one frequency sweep. Mount the broadband matched load; then the NA measures and stores $S_{MA}$ at 801 frequencies. Then mount the short circuit; and the NA measures and stores $S_{SC}$ at 801 frequencies. Finally, mount the open circuit, and $S_{OC}$ is measured and saved at 801 frequencies. Incidentally, the RF generator must be able to return to precisely the same set of 801 frequencies in each case to make the calibration measningful! After the three standards have been measured, the NA's built-in software solves Eqns. (10), (11) and (12) at 801 frequencies, and saves the values of the "calibration coefficients" $E_{DF}$, $E_{RF}$ and $E_{SF}$ at 801 frequencies. Then the unknown is mounted on the test port, and the reflection coefficient $S_{11M}$ is measured at 801 frequencies. Then Eqn. (9) is used with the saved values of the calibration coefficients to find the actual reflection coefficient $S_{11A}$ at all 801 frequencies, and the result is displayed on the CRT screen of the network analyzer.

In practice, the three calibration standards are somewhat imperfect. The accuracy of the calibration can be substantially improved if the NA models each standard with an equivalent circuit that predicts its true reflection coefficient as a function of frequency. For example, it is not assumed that the short circuit standard has $S_{11} = -1$. Instead, an equivalent circuit is built-in to the NA' read-only memory for the short circuit standard, and the NA uses the actual reflection coefficient of the standard in Eqn. (11). Similarly, "corrected" versions of Eqns. (10) and (12) are used to account for the imperfect matched load and open circuit. The NA's equivalent circuit for each standard load can be modified by the user, but there is normally no reason to do this.

Frequently, network analyzers are used to measure low-level, noisy signals. As discussed above for the HP8505 NA, averaging over many frequency sweeps can be used to substantially improve the signal-to-noise ratio. The HP8720 includes averaging in its software system, and a soft key-controlled menu can be invoked to set the averaging factor.

## 3. Preliminary Exercise

Answer these questions before you come to the lab. The lab demonstrator will check that you have answered these questions before he permits you to do the experiment.

1. Derive Equations (8) and (9) from the signal flow graph of Fig. 5.3.

2. Solve Equations (10), (11) and (12) to find the values of $E_{DF}$, $E_{RF}$ and $E_{SF}$ in terms of the three "calibration" measurements $S_{MA}$, $S_{OC}$ and $S_{SC}$.
3. Design a double-stub tuner for the microstrip board that you used in Experiment 4. Use the actual load impedance that you measured in Experiment 4, at 3 GHz. Assume that one stub is located 1 cm from the load, and that the second stub is spaced by an eighth-wavelength at 3 GHz. The load that must be matched is the load impedance from experiment 4 shifted "toward the generator" by 1 cm. *The longest stub length that is practical on the microstrip boards is about 6 cm.* Your design consists of the lengths of the two stubs. There are two solutions: choose the solution with the shortest stub lengths.
4. Use the TRLINE program to find the bandwidth of your design, for a return loss better than 20 dB.

# 4. Procedure in the Laboratory

This experiment has two parts. In Part 1, you will use the HP8505 to measure the loads from Experiments 1 and 2. In Part 2, the lab demonstrator will use the HP8720, and explain to you how it is calibrated, and then measure the reflection coefficient of your microstrip line, without and with your tuning circuits.

Fig. 5.4 The sweeper controls and the marker controls.

### 4.1 The HP8505 Network Analyzer

**Operating the HP8505**

Set up the HP8505 for measurement as follows. Mount the N-type matched load on Port 1 of the NA. Adjust the trace position on the CRT. Press the REF LINE POSN button, located to the right of the CRT display. In the channel 1 control cluster to the right of the CRT, set the MODE slide switch to MAGNITUDE, and put channel 2 to OFF. Adjust the position of the line on the CRT screen so that it appears in the center of the screen. Then turn channel 1 OFF, set channel 2 to MAGNITUDE and adjust the trace position to the screen center. Next switch the MODE slide switch to POLAR MAG, and use the “BEAM CENTER” controls to the right of the CRT screen to move the beam to the center of the screen. Then disengage the ref line position button so that the reference line disappears.

On the storage normalizer, make sure that the Channel 1 INPUT is set to ON, and that the Channel 2 INPUT is also set to ON. These controls should NOT be set to “INPUT-MEM” because we have not stored anything in the memory of the normalizer! Also make sure the AVERAGING switch is set to OFF for both channel 1 and channel 2.

Set the INPUT LEVEL slide switch to -10 so that the power flowing from the sweeper into the S-parameter test set is -10 dBm. The INPUT LEVEL switch is located above the three blue jumper cables in Fig. 5.1. Set the OUTPUT level rotary switch to -30 dBm and the vernier to 0.

Set the starting frequency of the sweep to 600 MHz and the stopping frequency to 1000 MHz, using the knobs below the frequency readouts, shown in Fig. 5.4. Put the RANGE switch on 5-1300 MHz. Put the SCAN TIME SEC on 0.1 sec. Put the MODE on LIN EXPAND so that the CRT displays the selected frequency range. Put the WIDTH on START/STOP 1. Put the TRIGGER on AUTO. Then on the MARKERS panel, and set marker #1 to the desired calibration frequency. Use the rotary switch to select marker #1, and then use the knob for marker #1 to adjust its frequency to 800 MHz.


Fig. 5.5 Port #1 of the HP8505, with the short-circuit termination mounted for calibration.

**Calibration**

Calibrate the instrument as follows. Note that you must follow these instructions exactly as stated for a successful calibration.

Mount the short circuit on the PORT 1 connector, as shown in Fig. 5.5. We will calibrate the HP8505 using channel 1; this also calibrates channel 2 because the instrument stores only one calibration coefficient, $C_M$. Set the INPUT sliders for both channel 1 and channel 2 to measure

A/R. Turn channel 2 off. On channel 1, set the MODE slider to POLAR MAG. Set the SCALE/DIV POLAR FULL 1. Clear the previous calibration by pressing CLR on the channel 1 panel and CLR on the ELECTRICAL LENGTH panel to the right of the channel 2 panel.


Fig. 5.6 The polar display at the start of the calibration sequence.

The display shows a circle of magnitude somewhat less than unity, as in Fig. 5.6. At the end of the calibration procedure the display will show a reflection coefficient for the short-circuit load of approximately $\Gamma$=-1. The calibration sets the reflection coefficient to be precisely equal to -1 at the frequency of marker #1.


Fig. 5.7 Calibration adjusts the magnitude of the reflection coefficient of the short circuit to unity.

To adjust the magnitude of the reflection coefficient to unity, press MRK on the channel 1 panel, then press ZRO and hold it briefly until the numerical display reads 0 dB. The reflection coefficient circle expands to be equal to unity in value. Pressing ZRO actually adjusts the magnitude reflection coefficient to be unity only at the frequency of marker #1; it is approximately unity at other frequencies. The display should look like Fig. 5.7.


Fig. 5.8 Adjustment of the electronic line stretcher.

The next step is to adjust the electronic line stretcher, which is equivalent to turning the crank on the mechanical line stretcher on the HP8410's reflection/transmission test set. On the ELECTRICAL LENGTH panel, set the slide switch to A and the MODE slider to "x10". Use the LENGTH arrow pushbuttons on the ELECTRICAL LENGTH panel to get the smallest "cluster" that you can. Fig. 5.8 shows a small cluster near $\Gamma = -1$; but it does not matter where the cluster appears on the screen, as long as it is small. You can use the vernier knob at the lower left of the electrical length panel to make finer adjustments than are possible with the pushbuttons. Then press ZRO on the ELECTRICAL LENGTH panel; this lights up the REL indicator to show that a setting has been saved.


Fig. 5.9 Adjust the position of the cluster to angle zero degrees.

The next step is to adjust the reflection coefficient of the short circuit to be 180 degrees. This is done in two steps: first adjust the position to zero degrees, and then to 180 degrees. Do this as follows. Set the channel 1 MODE slider switch to POLAR PHASE. Press MRK to be sure the marker phase is displayed. Under DISPLAY, press and briefly hold the ZRO button, until the numeric display reads zero degrees. Then press the REF button. The REF indicator lights up. The display should look like Fig. 5.9.


Fig. 5.10 Adjust channel 1 to put the cluster at angle 180 degrees.

The final calibration step is to adjust the angle of the short-circuit load to 180 degrees. Use the REF OFFSET buttons on the channel 1 panel to move the cluster to 180 degrees; you can watch the numeric display and simply use the buttons to make the display read “180”. Then press ZRO again. The display should look like Fig. 5.10. Then press MRK to turn on the marker for measurement. Calibration is complete.

**Measuring an Unknown Load**

To measure the reflection coefficient of an unknown load, mount the load on the measurement port. Remember: connectors should be “finger tight”: turn the nut gently with your fingers until there is some small resistance, and that is tight enough! Set the MODE switch for channel 1 to MAGNITUDE and the MODE switch for channel 2 to PHASE. To transfer the data from the HP8505 to the lab computer, log in as maxwell with no password, type startx to open a couple of X-windows, then in one of the windows type “hp8505”. The program fetches the *magnitude* data from *channel 1* of the HP8505, and the *phase* data from *channel 2* of the HP8505, which is why we must set the controls of the 8505 to show magnitude on channel 1 and phase on channel 2! The computer starts a plotting program and graphs the magnitude in one window and the phase in another. Verify that the graphs on the computer look like the HP8505’s CRT screen, then type “return” on the computer to close the graphics windows. Copy the data file to your diskette with the command

mcopy –t hp8505.dat a:filename

where “filename” is a descriptive name such as “resistor1.gam”. You can put the diskette into the drive on the “DARWIN” computer and display it with SMTHCHT. As you know from previous labs, SMTHCHT can convert the reflection coefficient data to input impedance, and display the resistance and reactance using RPLOT. You can also use RPLOT directly with input file resistor1.gam to graph the magnitude or the angle of the reflection coefficient as a function of frequency, on rectangular axes.

**4.1.1 Calibration**

Calibrate the HP8505 by following the procedure described above. When you are done, then run “hp8505” on the lab computer and save the “calibration” data file on your diskette. Enter the file name in Table 4.1 in Section 6, below. This data file contains the “short circuit” reflection coefficient magnitude $|r_s(f_k)|$ and angle $\phi_s(f_k)$. When a load is connected to the test port, the NA measures the load reflection coefficient magnitude $|r_L(f_k)|$ and angle $\phi_L(f_k)$. You can use your data file for the short circuit to implement Eqns. (4) and (5) and correct the load reflection coefficient frequency-by-frequency. Since it is tedious to correct 500 frequencies manually, a short computer program can read the data files, evaluate Eqns (4) and (5), and write a “corrected” data file.

**4.1.2 Confidence Checks**

Use the HP8505 to measure the reflection coefficient of the matched load, the 2:1 load and the 1.2:1 load. Save each data file to your diskette, and record the names of the data files in Table 4.1. Note that you do *not* have to recalibrate the HP8505 for each load, so measuring several loads can be done very quickly.

**4.1.2 Reflection Coefficient of Various Loads**

Use the HP8505 to measure the reflection coefficient of the loads of experiments 1 and 2. Measure the reflection coefficient of the “tee 50” load, the “tee 75” load, and of each of the two resistors mounted on bulkhead connectors. Record the name of the data file in each case in Table 4.1.

**4.1.4 Storage Normalizer**

Because the “hp8505” software on the lab computer does not read the output of the storage normalizer, we cannot use the normalizer to correct the measured reflection coefficient for this experiment. (We are hoping to fix this for next year!) If you want to try the normalizer, here’s how to do it. On the HP8505, set the MODE slider for channel 1 to display MAGNITUDE and the MODE slider for channel 2 to display phase. Then on the storage normalizer, press ERASE to erase the memory of the normalizer. Mount the short-circuit on the measurement port, and press STORE on channel 1 and STORE on channel 2, to store the short-circuit’s magnitude response and angle response. Then on the normalizer set channel 1 and channel 2 to display INPUT-MEM to subtract the stored data from the input data. On the CRT the magnitude trace shows 0 dB, and the angle trace shows 0 degrees, across the full frequency band. To shift the angle to 180 degrees, on the channel 2 panel, use the REF OFFSET arrow buttons to move the phase trace up to 180 degrees. Then take the short circuit load off, and mount an unknown load. The HP8505 measures the A/R response of the unknown load, and the normalizer “subtracts” the calibration values at all 500 frequencies and displays the result on the CRT screen. As mentioned above, the “hp8505” software cannot read the data from the storage normalizer, so we cannot save the data to a diskette.

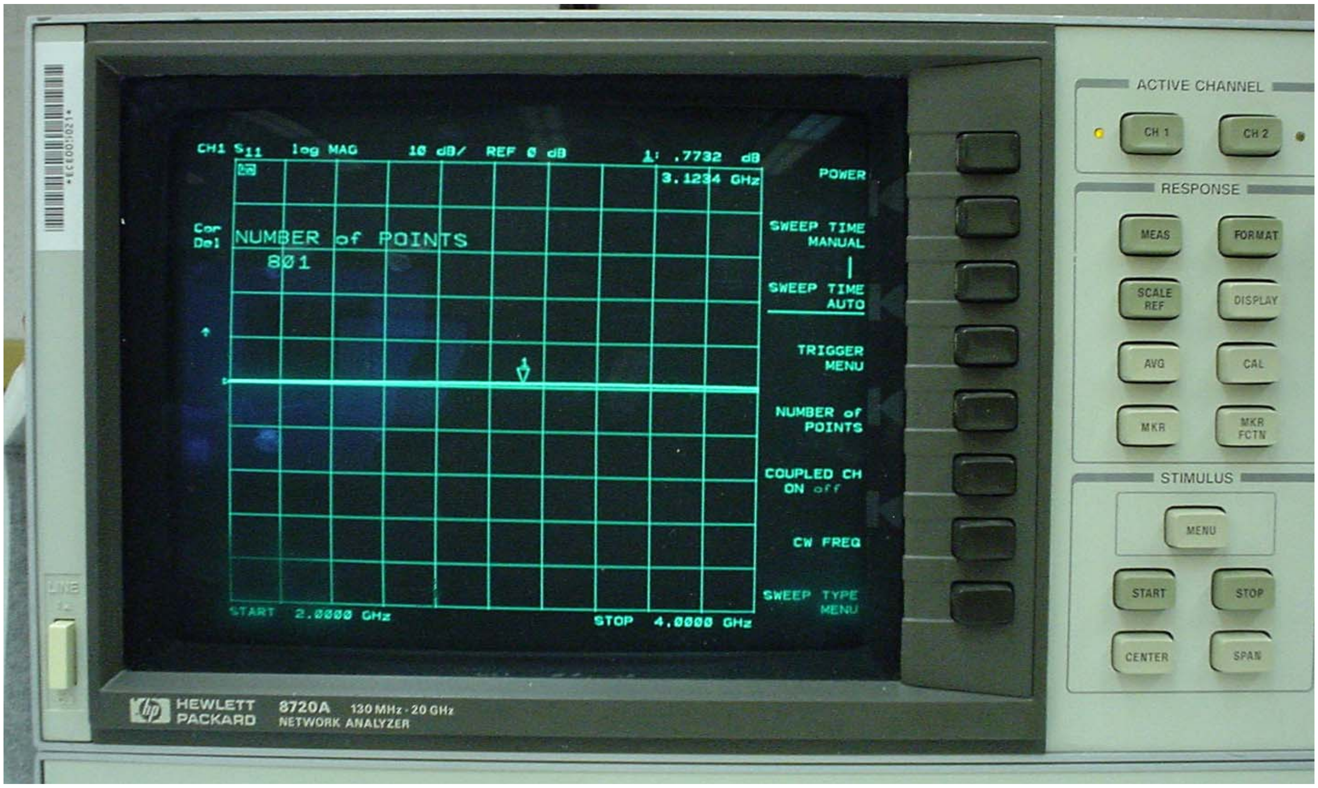

Fig. 5.11 The MENU soft key choices on the HP8720.

**4.2 The HP8720 Network Analyzer**

*The lab demonstrator will operate the HP8720. He will explain the three-standard calibration sequence to you, and then measure the reflection coefficient of your microstrip circuit.*

**Operating the HP8720**

The HP8720 is set up for you with a 3.5 mm to N-type adapter on Port 1 of the S-parameter test set. On the STIMULUS panel to the lower right of the CRT screen, press MENU to obtain the list of soft-keys shown in Fig. 5.11. Press NUMBER of POINTS then use the large knob at the upper right side of the instrument to increase the number of points from 201 to 801. Note that the number of points is shown on the CRT screen. The measurements will be done with 801 points in each frequency sweep. Then set the starting and stopping frequency of the sweep. Press START on the STIMULUS panel and use the key pad to key in “2”, and then press the GHz button. Note that START 2 GHz appears on the CRT screen. Press STOP and key in 4, and press GHz. The frequency range is now set.

**Calibration**

A three-standard or “$S_{11}$” calibration is carried out as follows. You will need the N-type broadband matched load, short-circuit load and open-circuit load from the calibration kit. Press the CAL key in the RESPONSE panel to the right of the CRT screen to obtain the calibration menu shown in Fig. 5.12. Press the CAL KIT soft key to select a calibration kit from the menu shown in Fig. 5.13. Select the “N 50 $\Omega$” soft key to choose the calibration kit with N-type connectors, then press the RETURN soft key at the bottom to exit from the CAL KIT menu and return to the CAL menu of Fig. 5.12. Then press the CALIBRATE MENU soft key in the CAL menu in Fig. 5.12 to get the CALIBRATE menu of Fig. 5.14.

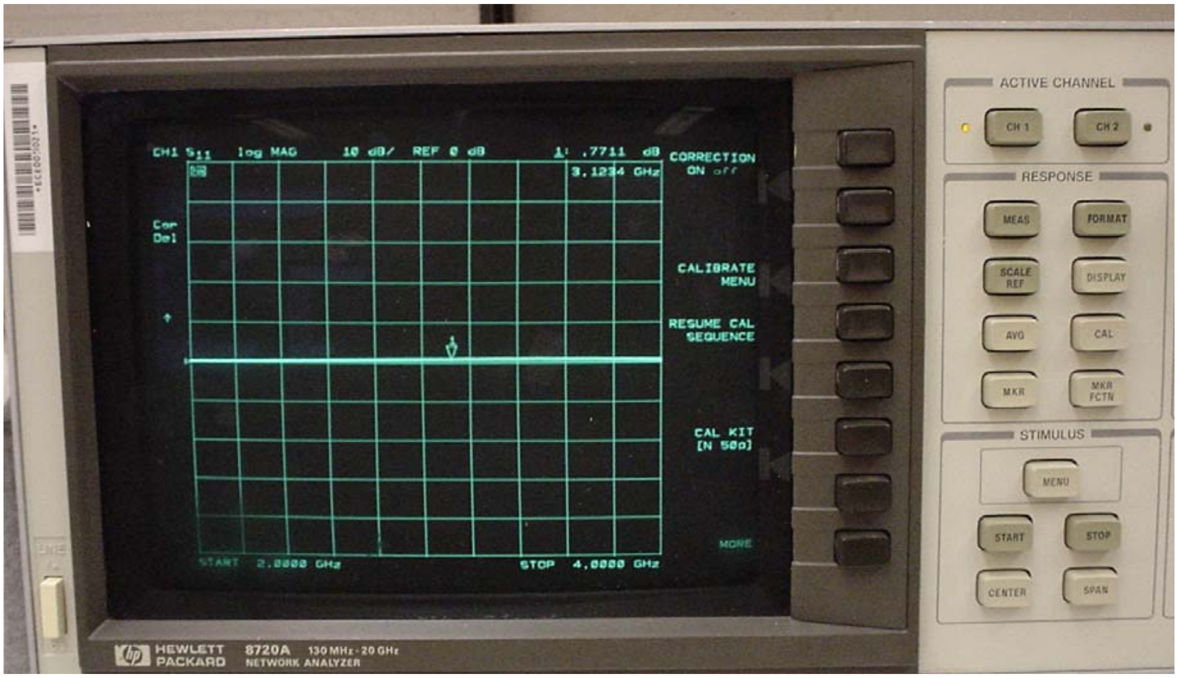

Fig. 5.12 The CAL menu.

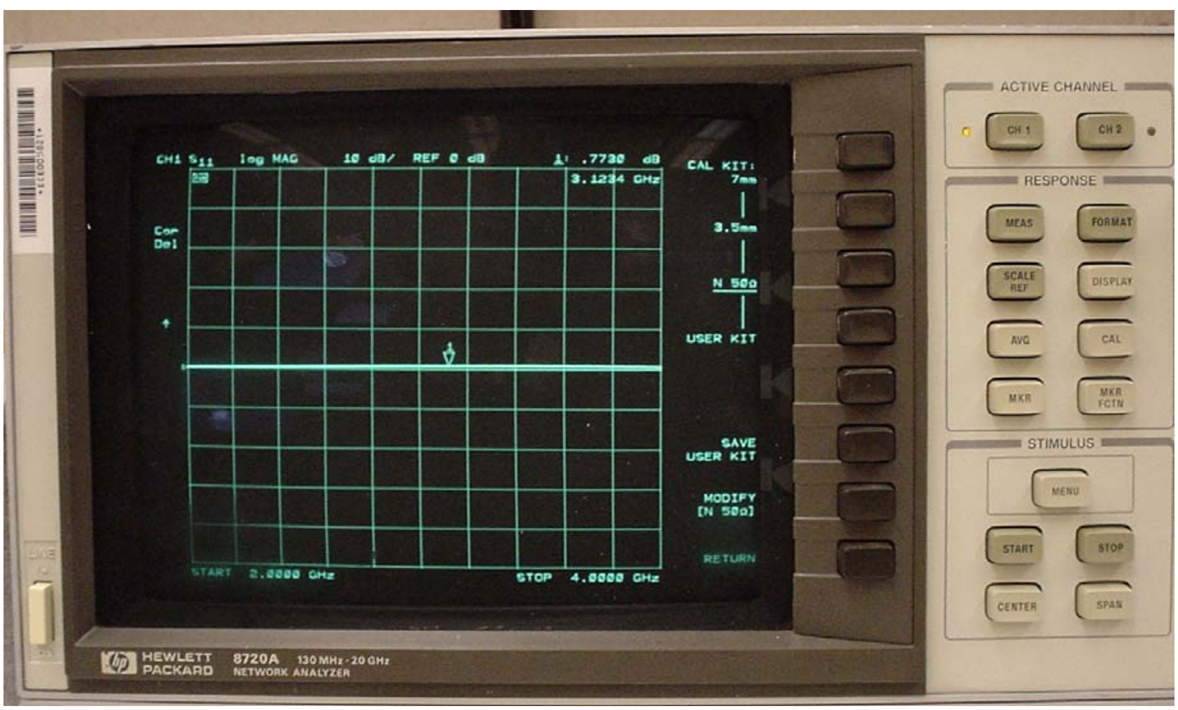

Fig. 5.13 The CAL KIT menu.

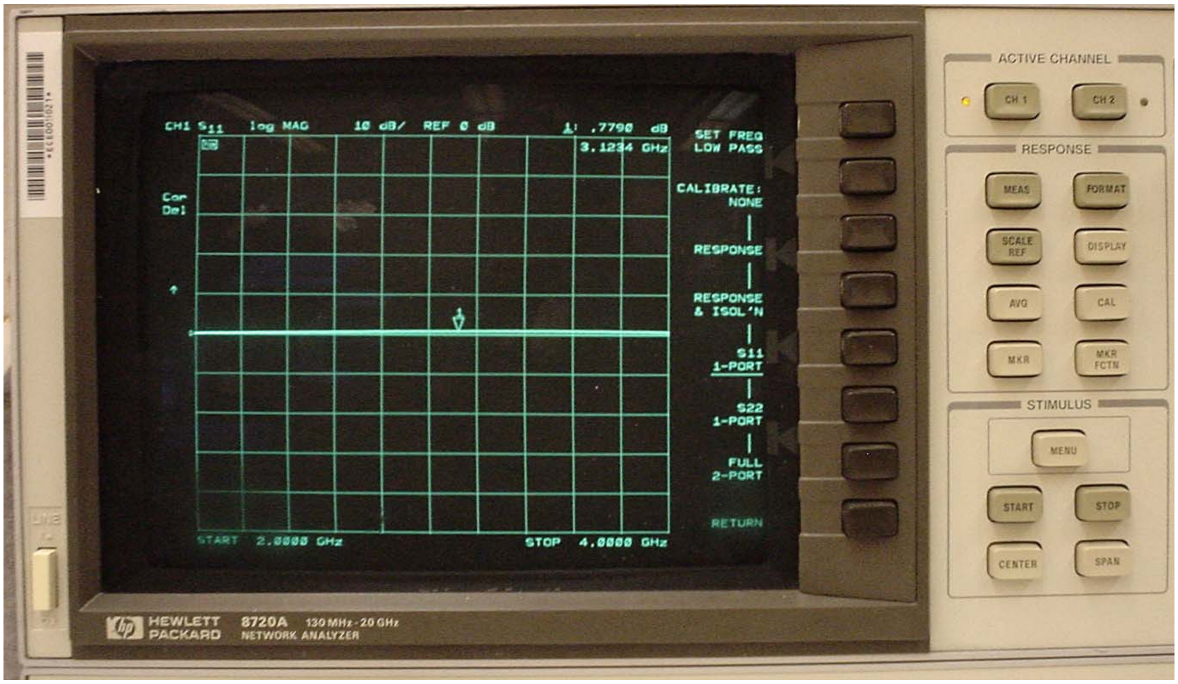

Fig. 5.14 The CALIBRATE menu.

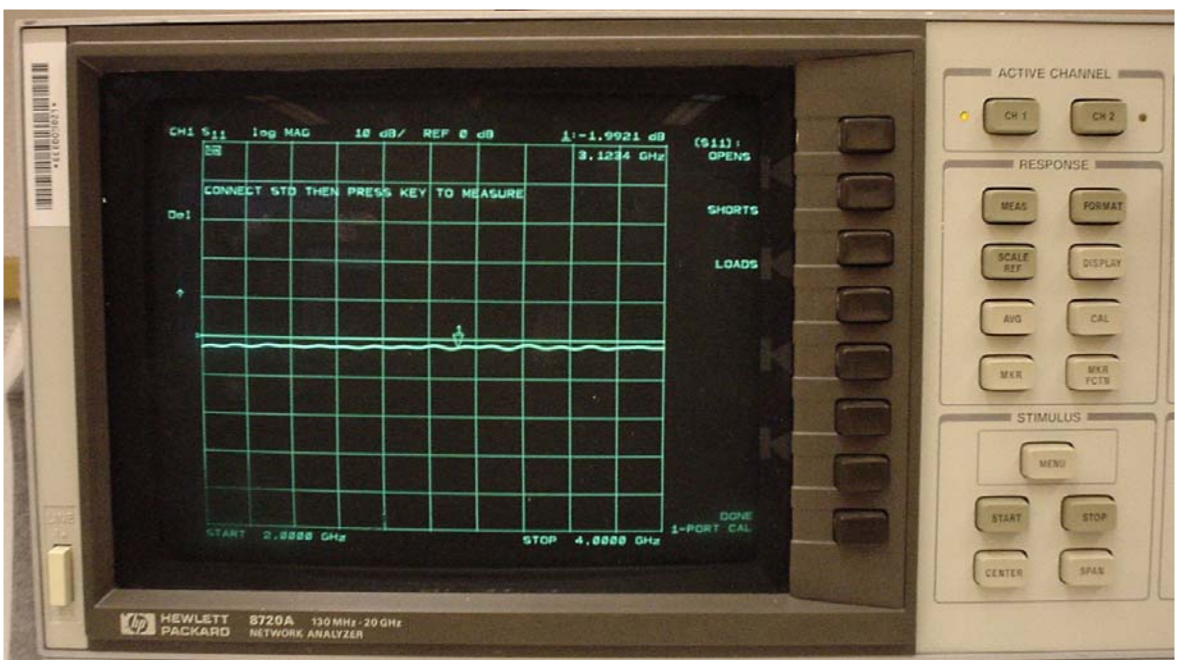

Fig. 5.15 The S11 1-PORT calibration menu.


Fig.5.16 The OPEN standard mounted on the test port.

In the CALIBRATE menu of Fig. 5.14, select the “S11 1-PORT” soft key to get the menu of Fig. 5.15. This menu invites you to mount the three standards on the test port, one by one, and record the response of each. Mount the open-circuit standard on the test port. When you mount the standard loads, hold the standard in your left hand but *do not turn it*. Turn the nut on the mating connector until it is “finger tight”. *Never turn the standard.* Then press the OPENS soft key in the menu of Fig. 5.15. This obtains a menu with two choices: OPEN(M) and OPEN(F). The “sex” refers to the connector on the measurement port, not to the calibration standard. Select OPEN(M) since the connector on the measurement port is male. Then press the DONE OPENS soft key to return to S11 1-PORT calibration menu. The HP8720 records the response and underlines OPENS to remind you that you have done this test.

Mount the short-circuit standard on the test port. Press the SHORTS soft key; a menu appears with the choices SHORT(M) and SHORT(F); press SHORT(M) and then the DONE SHORTS soft key to return to the S11 1-PORT calibration menu. Now SHORTS is underlined and the only test left uses the broadband matched load.

Mount the broadband matched load on the test port. Then press the LOADS key in the menu of Fig. 5.18. This gets a menu with three choices: BROADBAND, SLIDING, and LOWBAND. Press BROADBAND; the HP8720 measures the reflection coefficient for the broadband matched load. Press DONE LOADS to return to the S11 1-PORT menu; now all three tests are underlined so the calibration is complete. Press the DONE 1-PORT CAL soft key. The HP8720 reports COMPUTING CAL COEFFICIENTS while it does the arithmetic associated with Eqns. (10), (11), and (12).

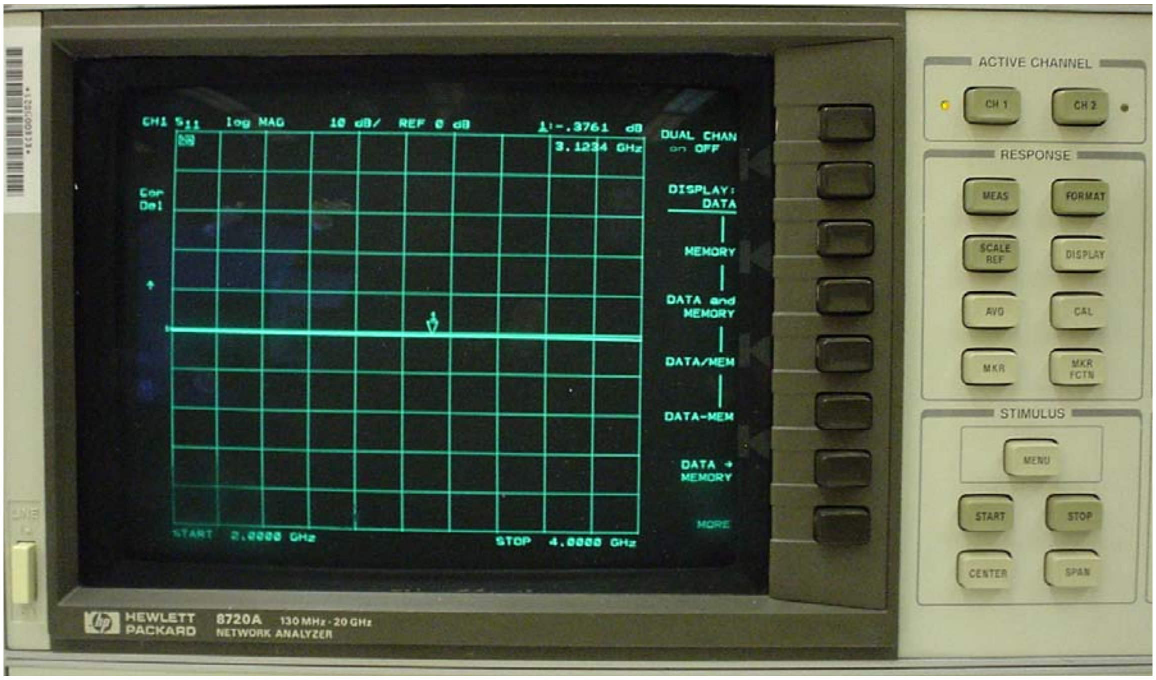


Fig. 5.17 The DISPLAY menu.

To complete the calibration push the DISPLAY key on the RESPONSE cluster of keys to the right of the screen. This gives the list of soft key choices shown in Fig. 5.17 which control what is shown on the screen. The HP8720 has a "memory" register that can store a frequency sweep for a component. This is useful for comparing the performance of two similar components: measure the first and save the response by pushing DATA>MEMORY. Then measure the second component. Then display DATA-MEM to see the difference between the two responses. For our purposes push DISPLAY:DATA to show the measured reflection coefficient of the load connected to port 1.


Fig. 5.18 Port 1 with the adapters, SMA bullet and short circuit.

Measuring an Unknown Load

To measure the reflection coefficient of a microstrip circuit board, mount an N to SMA adapter on the N connector. Then mount the SMA bullet and short circuit on the connector, as shown in Fig. 5.18. Remember, the connectors need to be “finger tight” but no tigheter! Use the FORMAT key in the RESPONSE cluster to get the soft-key FORMAT menu shown in Fig.5.19. Choose POLAR to show the measured data on polar axes as in Fig. 5.20. The reflection coefficient in Fig. 5.20 has a magnitude of approximately 1 but the angle is not -180 degrees. This is because the measurement plane is not at the location of the SMA short circuit. The HP8720’s electronic line stretcher must be adjusted to put the measurement plane at the location of the short circuit. Choose the SCALE REF menu in the response cluster, to get the menu of Fig. 5.20. Then press the ELECTRICAL DELAY soft key. Use the large knob to add electrical delay until the CRT shows a spot at $\Gamma = -1$ on the polar display, as in Fig. 5.21. The HP8720 is now calibrated and is ready to measure the reflection coefficient of the microstrip circuit.

To measure the reflection coefficient of an unknown load, mount it on the SMA adapter in place of the bullet and short circuit. The HP8720 sweeps the frequency from 2 to 4 GHz, records the measured reflection coefficient and corrects it with the calibration data using Eqn. (9). The corrected reflection coefficient is shown on the CRT screen in the format you choose with the display menu: either in Cartesian coordinates or on polar axes or Smith Chart axes.

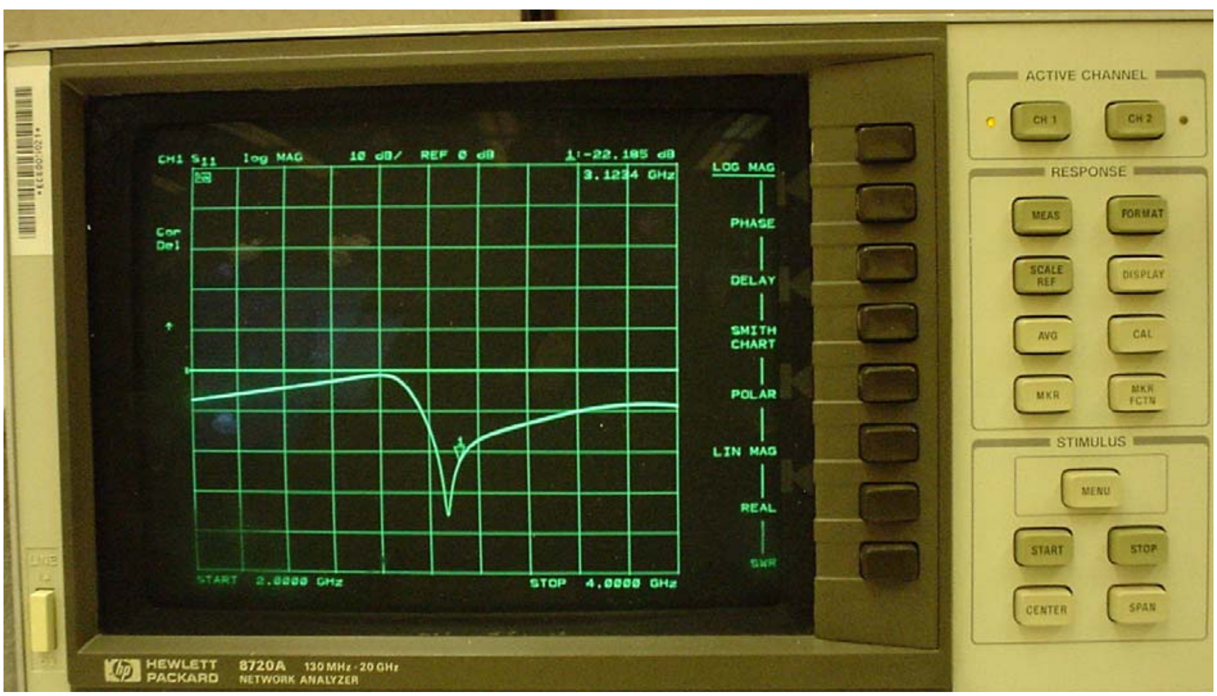


Fig. 5.19 The DISPLAY menu

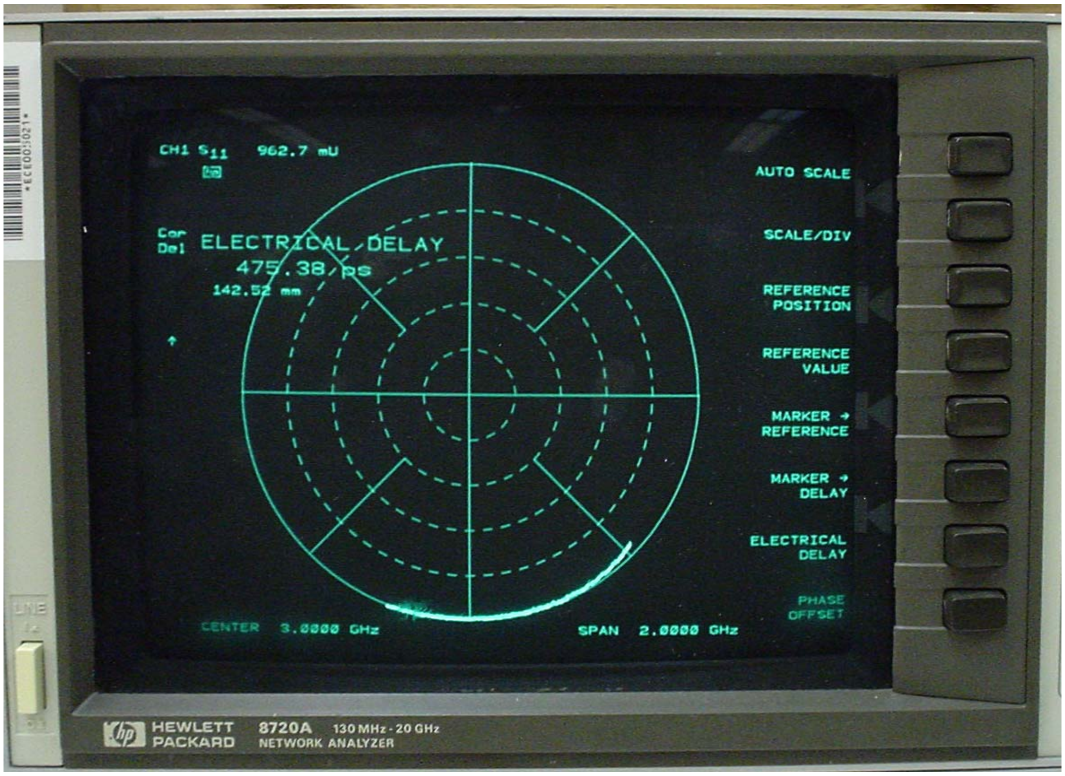

Fig. 5.20 The polar display, with the reflection coefficient of the SMA short circuit.

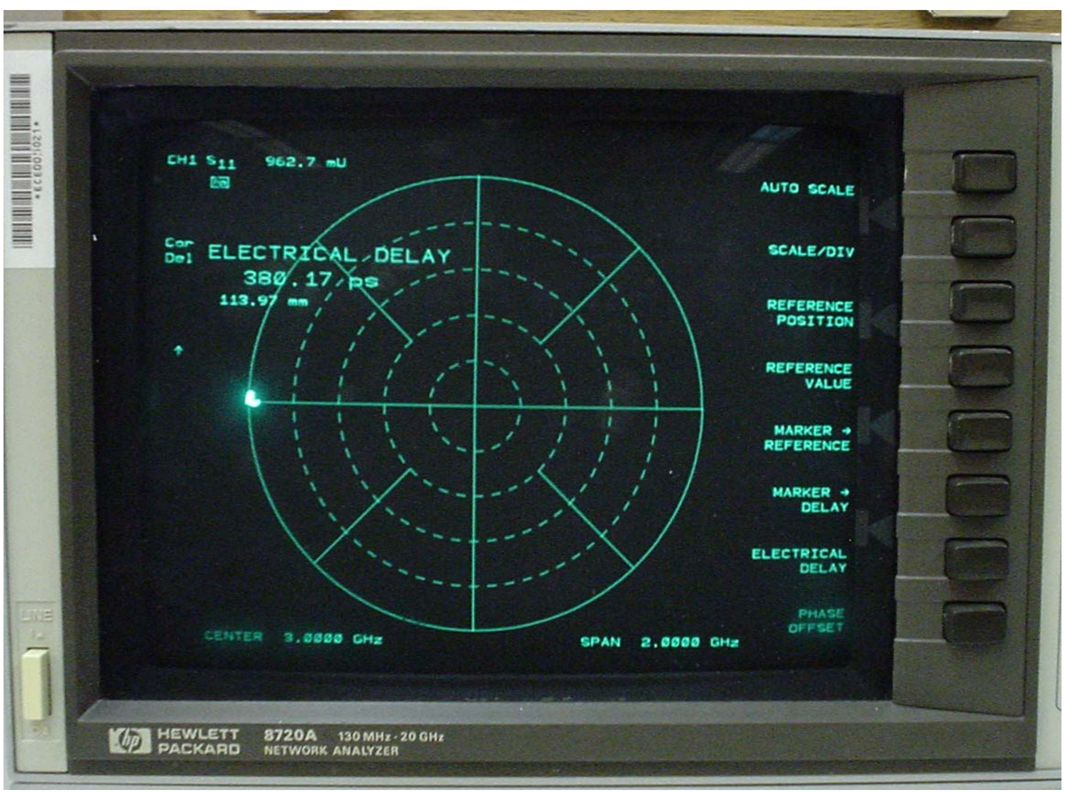

Fig. 5.21 Adjustment of the electrical delay.

4.2.1 Calibration and Confidence Check

Calibrate the HP8720 as described above. Save the calibration data to your diskette by typing “hp8720” on the computer keyboard. The computer takes control of the 8720 via the gpib bus and downloads the magnitude and phase of the reflection coefficient at each frequency. The data file is called “hp8720.dat”; copy it to your diskette with “mcopy –t hp8720.dat a:”, and record the name of the data file in Table 4.2. Then mount the SMA matched load on the bullet. Use the “hp8720” program to make a data file of the measurement and record the file name in Table 4.2.

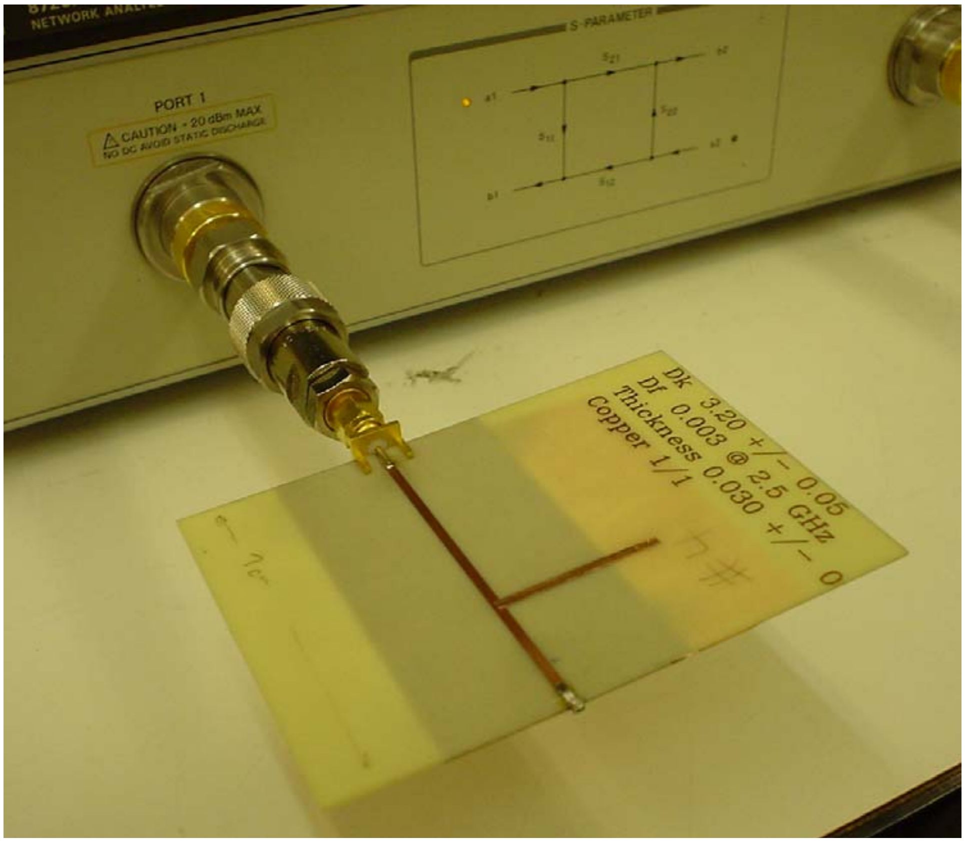

Fig. 5.22 The microstrip board mounted on the 8720’s test port.

4.2.2 Single-Stub Matching Circuit

Ask the lab demonstrator for the microstrip board that you used in Experiment 4. Install your stub tuner from Experiment 4. Be careful to set the distance from the load resistor to the stub, and the length of the stub, to be exactly as they were in Experiment 4. Then calibrate the HP8410 network analyzer following the procedure used in Experiment 4. Then mount the microstrip board on the SMA connector on the HP8410. Remember to do this properly: hold the board in your left hand, and gently turn the nut on the SMA connector until it is “finger tight”. Measure the input reflection coefficient of your board with the stub tuner, and adjust the length of the stub to get a similar return loss to what you had in Experiment 4. Then use the lab computer to make a hard-copy of the return loss, and record the name of the data in Table 4.3.

Ask the lab demonstrator to mount the microstrip board with the stub tuner on the SMA connector on the HP8720 network analyzer. Fig. 5.22 shows a microstrip board (with a stub tuner) mounted on the 8720’s test port. The HP8720 measures the reflection coefficient at the input of the microstrip board. Copy the measured data to your diskette and record the file name in Table 4.3, and make a paper copy of the response.

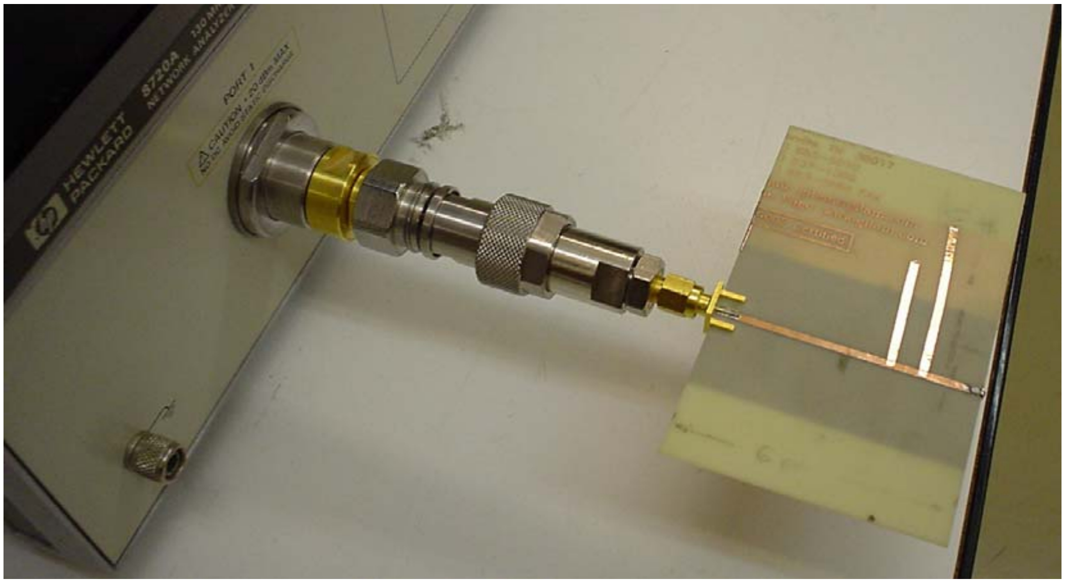


Fig. 5.23 The microstrip board with a double-stub tuning circuit.

4.2.3 Double-Stub Tuner

Build the double-stub tuner that you designed in the preliminary exercises in Part 3 above. *The longest stub length that is practical on the microstrip boards is about 6 cm.* One stub is located 1 cm from the load, and the second stub is spaced by an eighth-wavelength at 3 GHz. Install the two stubs on the microstrip board using the lengths that you choose in the pre-lab exercise. Then mount the microstrip board on the HP8720, as shown in Fig. 5.23, and measure the reflection coefficient. Record the data file name in Table 4.3.

## 5. Using the Linux Computer

The lab's Linux computer communicates with each of the network analyzers via a gpib card and cable. Log in to the computer with user name "maxwell" and no password. Type "startx" to create some X-windows. Run program "hp8505" to read data from the HP8505 network analyzer and create a file called "hp8505.dat". Copy the file to the diskette with "mcopy –t hp8505.dat a:". Or run "hp8720" to read data from the HP8720 network analyzer, and make a file called "hp8720.dat". Type "mcopy –t hp8505.dat a:/filename.dat" to copy the data to your diskette. Don't forget the "-t" switch, which fixes the ends of the lines in the data file so that they can be read on a Windows computer. Type "mcopy –t hp8720.dat a:/filename.dat" to copy data from the HP8720 NA.

On the Windows XP computer, log in as Maxwell with no password. Copy your data file from the diskette and rename it to have extension "gam". Give it a file name that identifies the contents. For example

Copy a:\hp8505.dat 8505tee50.gam

copies a data file for the "tee-50" load measured onto the HP8505 to a file named "8505tee50.gam", clearly identifying the data as measured on the 8505 for the "tee-50" load. Use SMTHCHT to display the measured reflection coefficient. You can compare with your measured data from Experiment 1 or 2 by typing the file names into the main menu in SMTHCHT.

## 6. Tables of Data

| | |
|---|---|
| Student name: | |
| Student I.D.: | |
| Lab Section: | |
| | |
| Lab Instructor's Signature: | |

**Table 4.1**
**File Names for the HP8505 Measurements**

| Case | File Name |
|---|---|
| Calibration of the HP8505 | |
| Matched Load | |
| 2:1 Load | |
| 1.2:1 Load | |
| "tee 50" load | |
| "tee 75" load | |
| Large resistor | |
| Small resistor | |

**Table 4.2**
**File Names for Calibration and Confidence Check on the HP8720.**

| Case | File Name |
|---|---|
| Calibration of the HP8720 with the SMA short circuit. | |
| Reflection Coefficient of the SMA matched load. | |

**Table 4.3**
**File Names for the Microstrip Measurements on the HP8720.**

| Case | File Name |
|---|---|
| Microstrip board on the HP8720. | |
| Microstrip board with single-stub tuner on the HP8410. | |
| Microstrip board with single-stub tuner on the HP8720. | |
| Microstrip board with double-stub tuner. | |

## 7. Questions to Answer in your Lab Report

Your lab report must include a signed “Expectations of Originality” form.

Your lab report must include the tables from Section 6, filled in with your data, and “signed off” by your lab demonstrator at the end of the lab session.

Your lab report will consist of the answers to the following questions:

1) Use SMTHCHT to graph the calibration curve for the HP8505 network analyzer. How close is the reflection coefficient of the short circuit to the “ideal” value of -1? This is a measure of the accuracy of the data for the “unknown” loads.
2) Use SMTHCHT to graph the reflection coefficient of the N-type matched load. Compare with your measured values from Experiment 1 and 2, using the “gam” files that you created in those experiments. Repeat for the 2:1 load and the 1.2:1 load. This is a three-way comparison: slotted line, vector voltmeter, and HP8505 NA. Do the three methods agree?
3) Plot the reflection coefficient of the “tee-50” load with SMTHCHT. Model the “tee-50” with the TRLINE program and calculate its reflection coefficient from 600 MHz to 1000 MHz. Plot the calculated value on the same axes and show that the measured data and the simulation agree quite well. Repeat for the “tee-75” load.
4) In Experiments 1 and 2, you measured the reflection coefficient of either the “tee-50” or the “tee-75” load. Plot your measured data from those experiments on the same Smith Chart as your HP8505 measurement. This is a three-way comparison. Do the three methods agree? Repeat for the resistor that you measured in Experiments 1 and 2.
5) Plot the reflection coefficient of the SMA short circuit that you measured on the HP8720 on a Smith Chart. The response is not precisely -1; this is a measure of the accuracy of the reflection coefficient measured for the microstrip board. Plot the reflection coefficient of the SMA matched load on rectangular axes. The return loss should be 40 dB or better from 2 to 4 GHz.
6) Plot the reflection coefficient of the microstrip board without the tuner on a Smith Chart, and compare with your measurement from Experiment 4. Is there agreement?
7) Plot the reflection coefficient of the microstrip board with the single-stub tuner, measured on the HP8410, on a Smith Chart, and compare with your measurement from Experiment 4. To obtain agreement, the length of the stub and the spacing of the stub to the load have to be very close to the values used in Experiment 4; this depends on how precisely you can “re-install” the stub that you saved from Experiment 4.
8) Compare the reflection coefficient of the board with the tuner measured on the HP8410 and on the HP8720, by plotting them on a Smith Chart. Comment on any differences.
9) Plot the measured reflection coefficient of the double-stub tuner on a Smith Chart. Compare with the reflection coefficient calculated with TRLINE. Do you obtain the expected bandwidth?

Optional question for expert users:

10) Write a short program in your favorite programming language (BASIC, c++, Java, or matlab) that “calibrates” the HP8505 data. The program should read the “calibration curve” measured with the short-circuit load on the HP8505, then read a measured curve for an

unknown load. The program must then calculate a corrected reflection coefficient by "subtracting" the calibration curve from the measured curve using Eqns. (4) and (5).

Use your program to-recalibrate the measured data for the reference loads (matched load, 2:1 load and 1.2:1 load). Plot the re-calibrated data in comparison to the "raw" data. Is the response improved?

Re-calibrate the "tee-50" and "tee-75" data. Are the re-calibrated curves closer to the simulations using TRLINE?

You can use the same program to re-calibrate the HP8720 data. The "calibration curve" is the curve measured with the SMA short circuit. You can correct the data measured for the microstrip board without and with the tuners. Does re-calibration improve the agreement?

Acknowledgement
Thanks to Wadah Muneer and Ibrahem Abdalla for their excellent contribution to this laboratory.