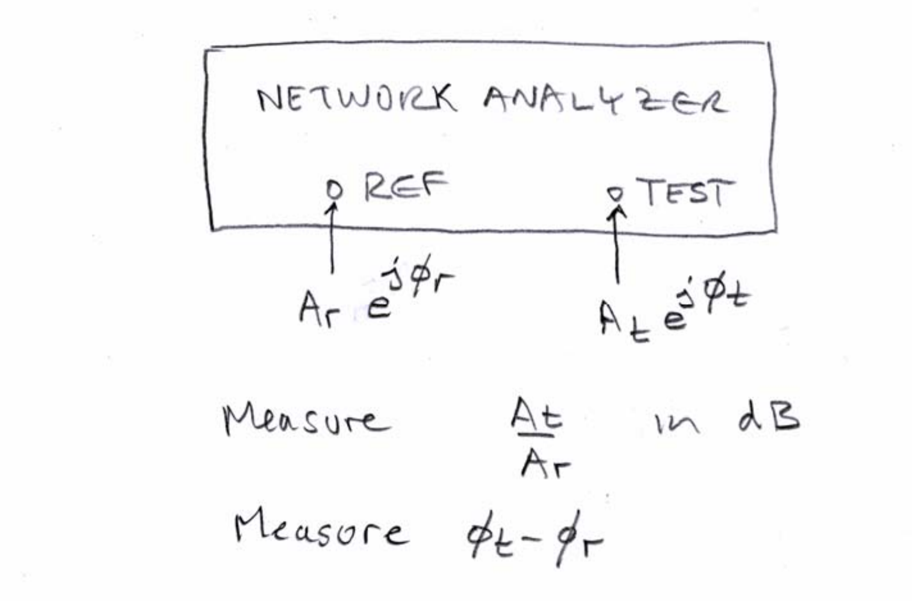
Guidelines for Writing Your Project Report

Network Analyzers



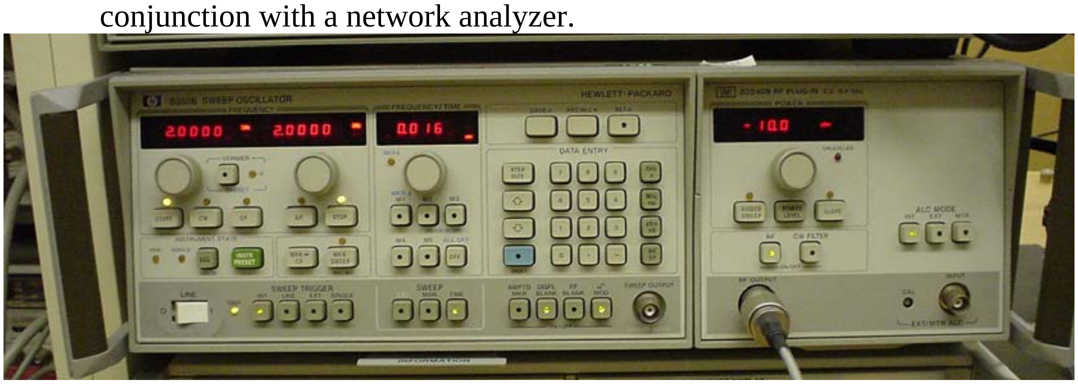
- A *Network Analyzer* is often used to measure the S-parameters of a component as a function of frequency.
- What does a Network Analyzer actually measure?
- A network analyzer has two channels:
  - a "reference" channel, where you input a signal $V_r = A_r e^{j\phi_r}$
  - a "test" channel, where you input another signal $V_t = A_t e^{j\phi_t}$
- The network analyzer measures:
  - the ratio of the amplitude at the test channel to the amplitude at the reference channel, $\frac{A_t}{A_r}$.
  - This is usually expressed in dB as $20\log\frac{A_t}{A_r}$
  - the phase difference between the test channel and the reference channel, $\phi_t - \phi_r$
- Hence the network analyzer measures $R = \frac{A_t e^{j\phi_t}}{A_r e^{j\phi_r}} = \frac{A_t}{A_r} e^{j(\phi_t - \phi_r)}$
- The output is often presented on a "polar" display showing the amplitude ratio $\frac{A_t}{A_r}$ on the radial axis and the phase difference $\phi_t - \phi_r$ on the angle axis.
- How do we use this to measure the scattering parameters:
  - S_{11} or Γ, the reflection coefficient
  - S_{21}, the transmission coefficient

8410 Network Analyzer

- The HP8410 network analyzer with the HP8412 rectangular display.
- HP8410 Network Analyzer: 2-12 or 2-18 GHz (depends on which model)
- The 8410 is an "older" version of the 8510, before internal microprocessor control was available.
- The 8410 is much, much easier to use than an 8510 or an 8720!
  - you can learn the 8410 in one lab session
  - it takes a lot of time to learn to use an 8510 or 8720 well…up to 3 months!
- The left-hand unit is the processor which includes the phase-locked receiver and the controls.
- The right-hand unit is the "rectangular" display:
  - it shows the magnitude of the reflection coefficient in dB and the angle of the reflection coefficient in degrees, both as a function of frequency.

Measurement as a Function of Frequency

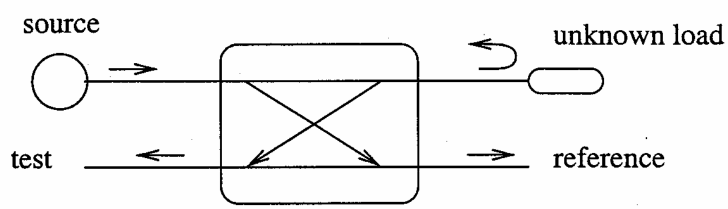
- Microwave engineers frequently need to measure $S_{11}(f)$ and $S_{21}(f)$ over a specified frequency bandwidth from say f_1 to f_2.
- This is done by using a "sweeper" or "swept-frequency generator" in conjunction with a network analyzer.



- The HP8410 is used with a "sweeper":
  - this is an RF generator which sweeps the frequency from a pre-set starting frequency to a pre-set ending frequency.
- The generator has controls to set the starting frequency f_1 and the stopping frequency f_2.
- When the generator is triggered to start, the frequency increases from f_1 to f_2 at a slow rate.

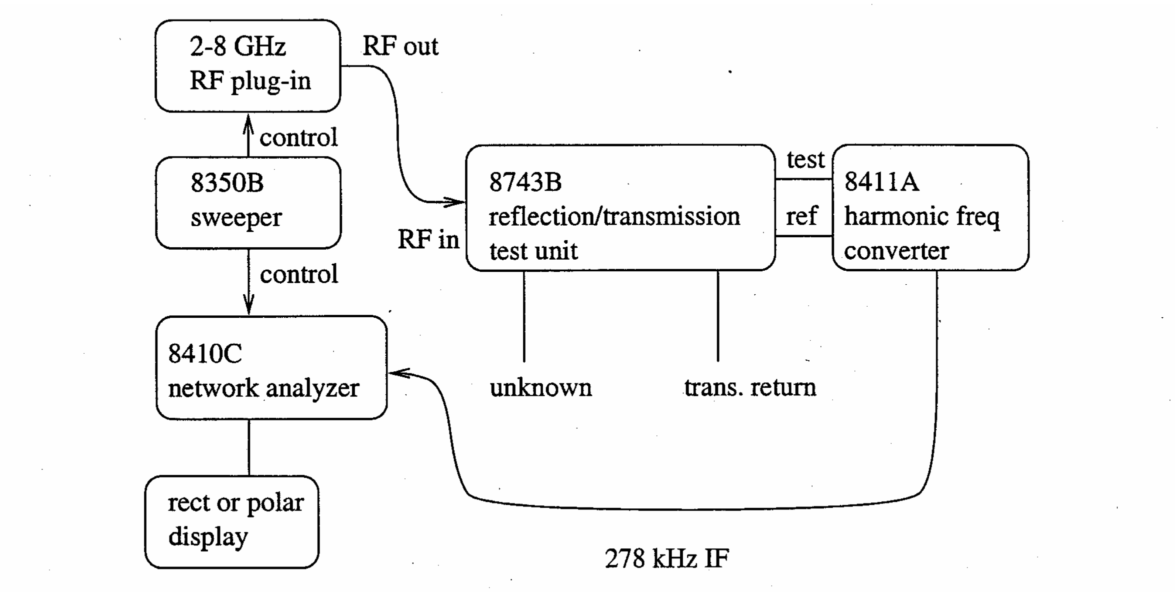
- The sweep rate can be controlled:
  - it must be slow enough that the HP8410 can remain phase-locked as the frequency changes
  - The “stability” of the generator is an issue.
    - How accurate is the frequency?
    - Does it “drift” with time?
  - There are two modes:
    - “CW” mode where the frequency increases linearly with time.
    - The “step mode” or frequency-stepped mode where the frequency increases in discrete steps and remains constant at each step for a period of time, controlled by the sweep rate.
    - The step mode is much more accurate for measurement.
  - How reproducible is the frequency sweep?
- A cable delivers a “sample” of the sweeper’s output to the NA which is used by the NA to phase-lock the receiver.
  - the sweep rate must be slow enough that the receiver can track the changing frequency.
- The network analyzer measures ratio $R = \frac{A_t}{A_r} e^{j(\phi_t - \phi_r)}$ at each frequency.
- “Modern” network analyzers are computer-controlled:
  - The network analyzer can do the “arithmetic” associated with calibration and so compute S_{11} and S_{12} at each frequency.
  - The NA can make a data file of frequency and the value of S_{11} and S_{12} at each frequency
  - This is available on a diskette or over an IEEE488 bus to a computer.
- In Experiment 4 you will use the sweeper and HP8410 under computer control.
  - the computer operates the sweeper in the “step” mode, which is more accurate than the CW mode.
  - the computer makes a paper copy of the display on the HP8410’s screen.
  - you can include the paper copy in your lab report.

- The HP8410 works with an "S-parameter test set", which is called the "reflection/transmission" test set.
- The crank adjusts the length of the "line stretcher", which is described in the following notes.
- Set the buttons at right to "REFL" to measure the reflection coefficient S_{11}
- In this picture a coax-to-waveguide adaptor is mounted on the test port.



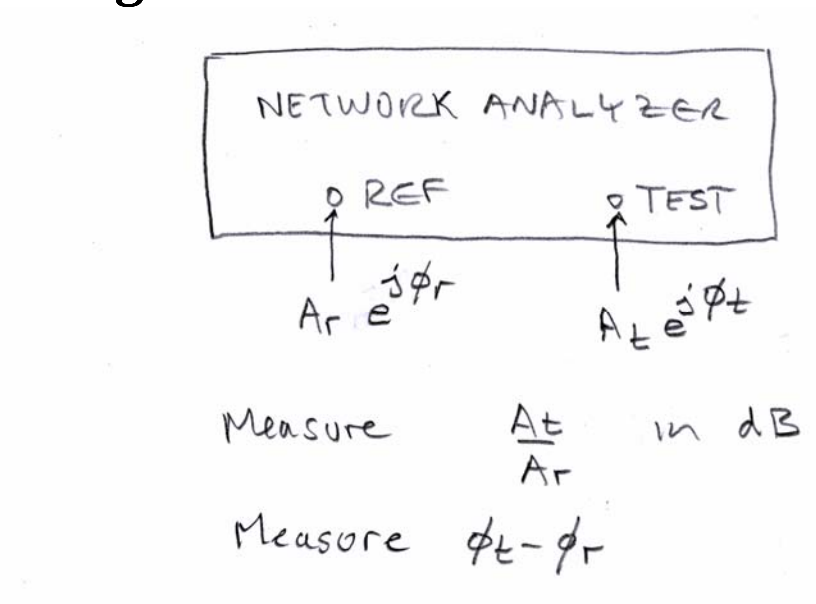
directional coupler (inside 8743B)

- Simplified block diagram of the HP8743B "reflection/transmission test set".



- Simplified block diagram of the HP8410 Vector Network Analyzer

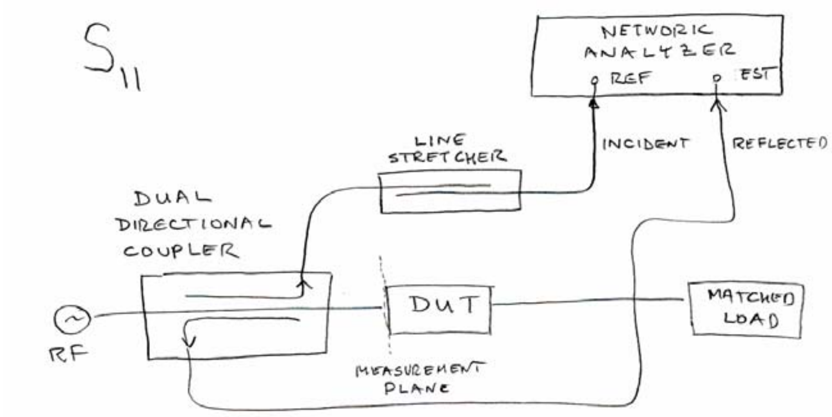
Using the HP8410 Network Analyzer



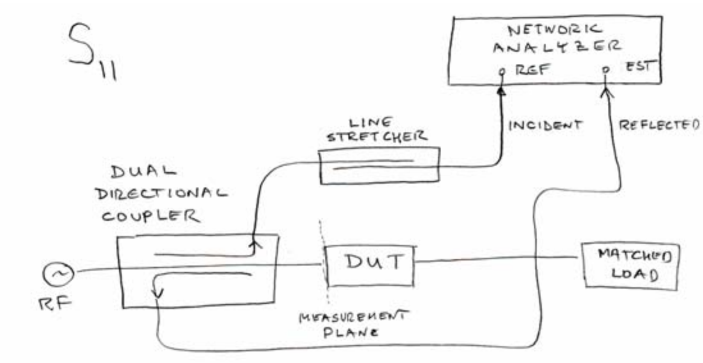
- Recall that a *Network Analyzer* has two channels:
  - a "reference" channel, where you input a signal $V_r = A_r e^{j\phi_r}$
  - a "test" channel, where you input another signal $V_t = A_t e^{j\phi_t}$
- The network analyzer measures: $R = \frac{A_t e^{j\phi_t}}{A_r e^{j\phi_r}} = \frac{A_t}{A_r} e^{j(\phi_t - \phi_r)}$

- o the ratio of the amplitude at the test channel to the amplitude at the reference channel, $\frac{A_t}{A_r}$. This is usually expressed in dB as $20\log\frac{A_t}{A_r}$
- o the phase difference between the test channel and the reference channel, $\phi_t - \phi_r$

Measurement of the Reflection Coefficient



- An RF generator supplies a signal to the "Device Under Test" (DUT) which is terminated with a matched load.
- The "reference plane" is $z = 0$ and the voltage at the reference plane is
  $$V(0) = V^+ + V^-$$
- We want to measure $S_{11} = \frac{V^-}{V^+}$ evaluated at the measurement plane.



- A dual directional coupler is used to take a sample of the incident voltage V^+ and of the reflected voltage V^-.
  - o The voltage on the dual directional coupler "transmission line" is
    $$V(z) = V^+ e^{-j\beta z} + V^- e^{j\beta z}$$
  - o Let the measurement plane be at $z = 0$.
  - o Let L be the distance from the RF generator to the reference plane.
  - o Then the generator is located at $z = -L$.
  - o The voltage at the generator is
    $$V(-L) = V^+ e^{-j\beta(-L)} + V^- e^{j\beta(-L)} = V^+ e^{j\beta L} + V^- e^{-j\beta L}$$

- The voltage at the "ref" connector is $(V^+ e^{j\beta L})A_1 e^{-j\beta L_1}$ where A_1 is the coupling coefficient of the directional coupler, and L_1 is the total path length from the generator to the reference channel connector.
- Similarly, the voltage at the "test" connector is $(V^- e^{-j\beta L})A_2 e^{-j\beta L_2}$ where A_2 is the coupling coefficient of the directional coupler, and L_2 is the total path length of the reference channel.

- The Network Analyzer measures the ratio of the voltage at the "test" connector to the voltage at the "reference" connector:

$$R = \frac{V^- e^{-j\beta L} A_2 e^{-j\beta L_2}}{V^+ e^{j\beta L} A_1 e^{-j\beta L_1}} = \frac{V^-}{V^+}\frac{A_2}{A_1} e^{-j2\beta L} e^{-j\beta(L_2-L_1)} = C\frac{V^-}{V^+}$$

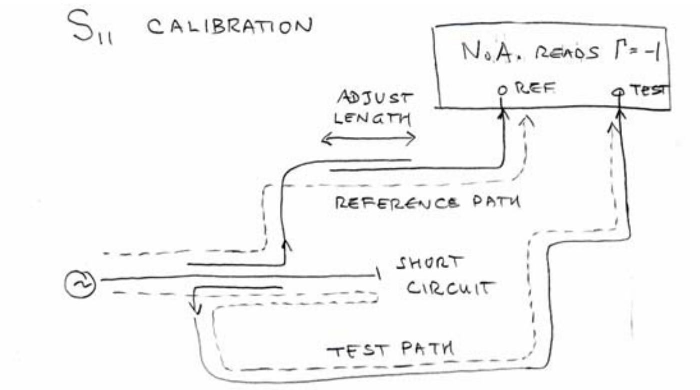
  where the proportionality constant is

$$C = \frac{A_2}{A_1} e^{-j2\beta L} e^{-j\beta(L_2-L_1)}$$

- We need to do a "calibration" measurement with a short circuit to find the value of the proportionality constant C as described in the following.
- Once C is known, then

$$S_{11} = \frac{V^-}{V^+} = \frac{R}{C}$$

- Calibration: We can "calibrate" the NA so that $C = 1$.



- To establish the location of the "measurement plane", replace the DUT with a short-circuit load which has reflection coefficient $\Gamma = -1 = \frac{V^-}{V^+}$
- The NA measures

$$R_c = \frac{V^-}{V^+}\frac{A_2}{A_1} e^{-j2\beta L} e^{-j\beta(L_2-L_1)} = (-1)\frac{A_2}{A_1} e^{-j2\beta L} e^{-j\beta(L_2-L_1)} = (-1)\frac{A_2}{A_1} e^{-j\beta(2L-(L_2-L_1))}$$

- If the directional coupler is well designed, then $A_1 = A_2$

$$R_c = (-1)e^{-j\beta(2L-(L_2-L_1))}$$

- Adjust the length of the **"line stretcher"** so that the path length factor $2L-(L_2-L_1)$ is equal to zero. Then

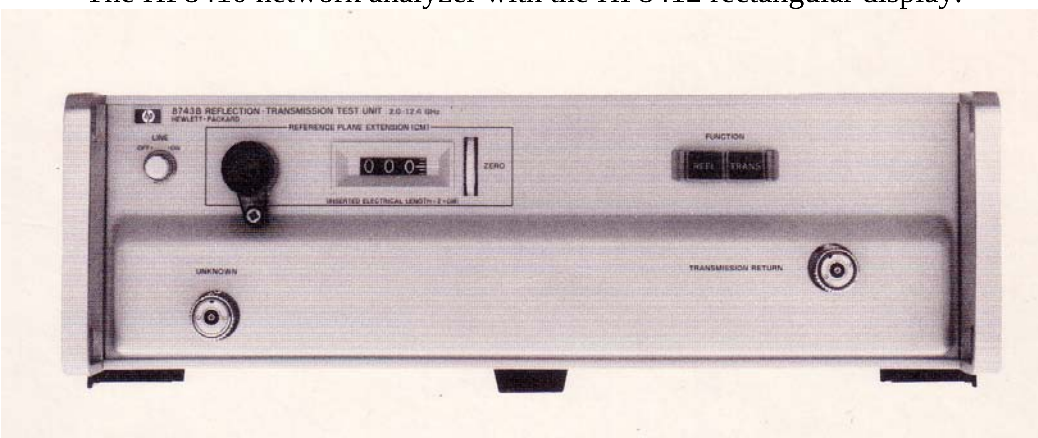
$$R_c = -1$$

- *This is easy*: adjust the line stretcher until the Network Analyzer reads $R = -1 = 1\angle 180°$

- Note that the "line stretcher" could be put in the "test" channel instead of in the reference channel.
- This calibration procedure sets $C = 1$ in the foregoing.
- After the network analyzer is calibrated by adjusting the line stretcher with a short-circuit load, the DUT is put back into the circuit, and the NA reads

$$R = \frac{V^-}{V^+} = S_{11}$$

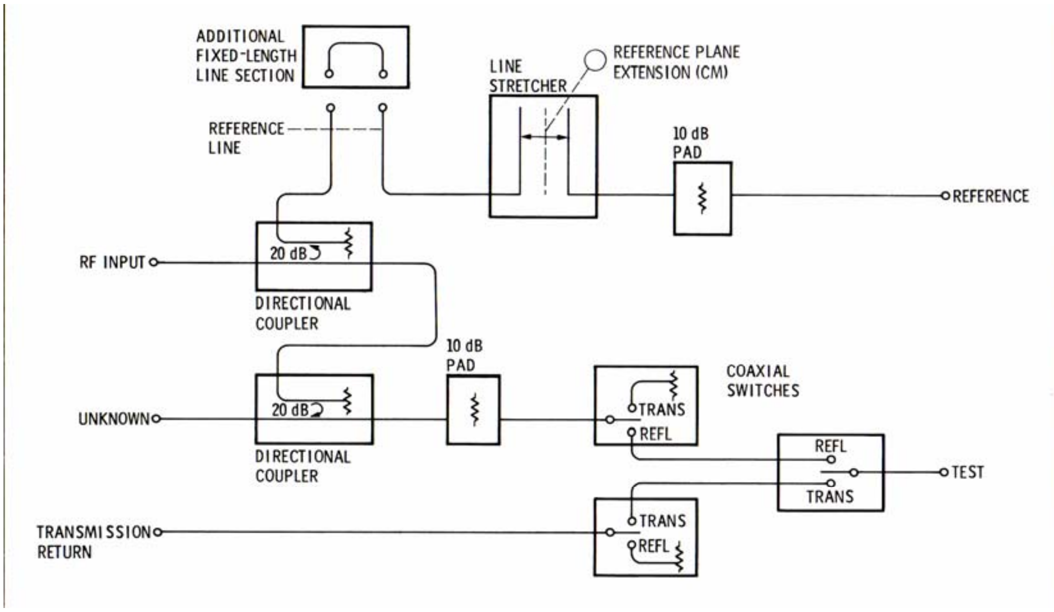
The HP8410 network analyzer with the HP8412 rectangular display.



Reflection/Transmission Test Set (S-parameter test set)

S-Parameter Test Set or "Reflection/Transmission Test Set

- Network Analyzers are usually used with an "S-parameter test set", called an HP8743B "reflection/transmission test set" for the 8410.

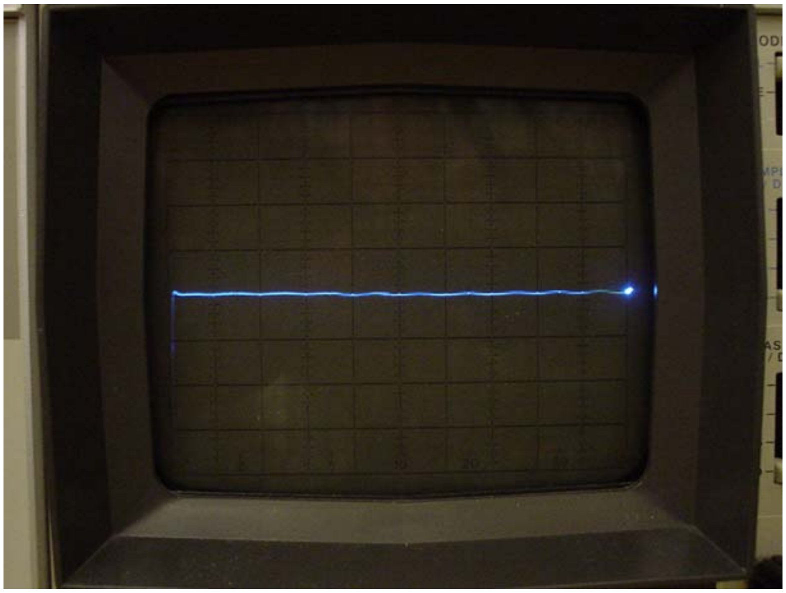


(from the HP8743B manual)

- This contains two directional couplers and RF switches to switch between the “reflection” mode and the “transmission’ mode.
- On newer Network Analyzers the “line stretcher” is implemented in software!
- The circuit implemented by the S-parameter test set is somewhat different from that given above:
    - Note in particular that the “transmission return” port is routed by the switches directly to the “test” port on the network analyzer, which must behave as a “matched” load and absorb the power transmitted through the unknown.
    - Although this eliminates one directional coupler, it severely limits the power level at which measurements can be made!
    - Hence to test high-power devices, an external directional coupler and high-power load can be used.

Calibration of the HP8410 with a Short Circuit

The SMA short circuit on the “unknown” port.



Adjust the magnitude offset and vernier to make the reflection coefficient of the short-circuit load equal to 0 dB on a scale from -40 dB to 40 dB.

Adjust the mechanical line stretcher and the phase offset so that the phase jumps back and forth between -180 degrees and 180 degrees.

- Remark: *much* more elaborate calibration procedures are often used that can account for:
    - directional coupler differences: $A_1 \neq A_2$; in fact A_1 and A_2 have different *magnitudes* and *angles*.
    - attenuation in cables
    - connector mismatch (each connector is modeled as having a reflection coefficient).
    - "Calibration kits" are sold which contain precision components used in a "*calibration procedure*".