USAF ACADEMY
DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING
LESSON 4 LAB - Impedance Measurement and Matching Networks
Fall 2026

Learning Objective 1.4: I can calculate input impedance, feed considerations, and the role of baluns in an antenna feed system.

COLLABORATION POLICY: The lab itself is a team assignment; each team should submit one combined lab report.

AUTHORIZED RESOURCES: Any resources are authorized.

DOCUMENTATION: You must include a documentation statement with each assignment in accordance with the course policy letter.

DUE DATES: The lab report will be due as indicated on Gradescope.

INSTRUCTIONS:

- Before lab: read entire lab packet.
- Before lab: read the VNA user's guide.
- Before lab: work the Part II design by hand (Question 7) so you arrive with component values in hand.
- During lab: complete the measurements as specified.

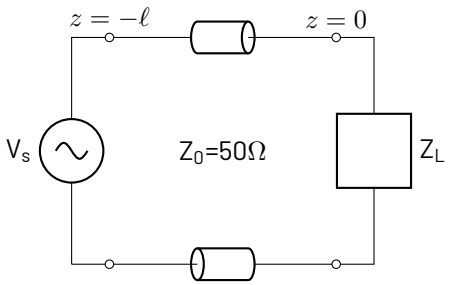
EQUIPMENT SAFETY:

- Equipment safety rules must be observed at all times and are for the safety of the students and protection of the equipment.
- No food or drink is allowed in the ECE labs while conducting measurements. Cadets are requested to finish their snacks outside the classroom and place all trash in the trash containers before class starts, and keep all drinks off work surfaces.
- At least two people (instructor/technician/cadet) must be in the room when equipment is in use.
- Cadets should return equipment to original configuration before leaving.
- Cadets must clean up their immediate area (return wires, pick up trash, etc.) before leaving.
- Cadets are to refrain from "playing" with the equipment, parts, and wires when there is no hands-on activity underway.
- When plugging in or unplugging wires, make sure any signal sources (AC or DC) are not transmitting.

1 Purpose

This lab comes in two parts. In **Part I** you will use a Vector Network Analyzer (VNA) to measure reflection and transmission coefficients in the transmission line system shown below: you will familiarize yourself with RF measurement technique, calibrate the VNA, measure several known load impedances, and characterize an unknown device.

In **Part II** you will put that skill to work. You will build a load that behaves like an electrically small antenna – a small resistance in series with a large capacitive reactance – measure how badly it is mismatched, then **design, build, and verify** an L-network that matches it to the 50Ω system. This is the measurement half of Lesson 4: the matching math you did on paper, checked against a real instrument.



2 Background

In this lab, we will measure the reflection and transmission coefficient for some devices over various frequency ranges. In these ranges, we can observe reflection and transmission as described in class. Recall that you find the reflection and transmission coefficients from:

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0}$$
$$T_L = 1 - \Gamma_L$$

In this lab, we won't be considering the length of our transmission lines (ℓ), because we will calibrate the length out of our calculations.

2.1 Matching, in two moves

An antenna is rarely 50Ω on its own, and an electrically small antenna is nowhere close. From Lesson 4: a short dipole of length ℓ carrying a triangular current has radiation resistance $R_{\text{rad}} = 20\pi^2(\ell/\lambda)^2$ – a fraction of an ohm for $\ell = 0.05\lambda$ – sitting in series with a large *capacitive* reactance. Small real part, big negative imaginary part. Connect that to a 50Ω radio and almost all of your power comes straight back at you.

The L-network fixes this in two moves, and the order matters:

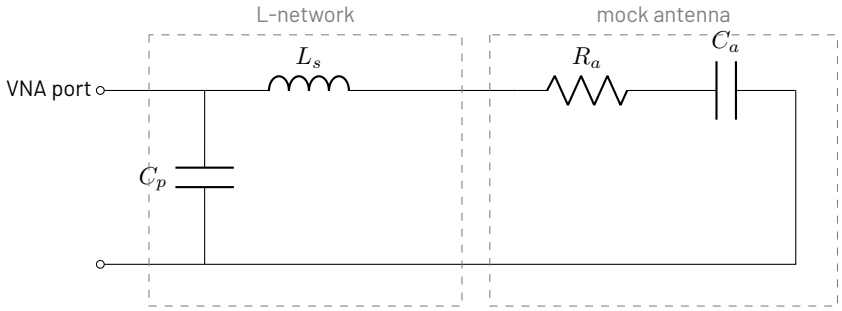
1. **Cancel the reactance.** Add a series element whose reactance is equal and opposite to the load's, so what remains is purely real.
2. **Transform the resistance.** Use the remaining series reactance plus a shunt element to turn that real value into 50Ω .

For a load resistance R_a smaller than Z_0, the series element goes on the *load* side and the shunt element on the *source* side, and the ratio you are transforming sets the network's quality factor entirely:

$$Q = \sqrt{\frac{Z_0}{R_a} - 1}$$

$$X_s = QR_a \qquad X_p = \frac{Z_0}{Q}$$

where X_s is the *total* series reactance the network needs to see – so the inductor you actually install must also make up for whatever reactance the load brought with it. Note what Q does not depend on: frequency. It is fixed by how far you are transforming, and it sets the bandwidth you get. You will measure exactly that in Question 9.



3 Equipment

3.1 Basic Familiarization

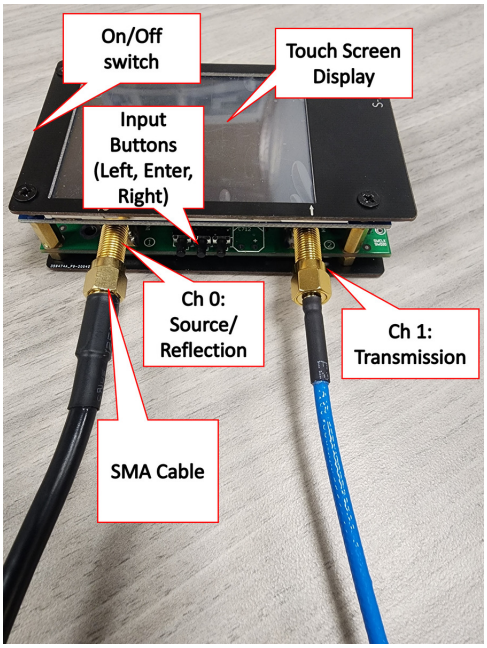
A full user's guide for the VNA is available online. Please familiarize yourself with this guide **before** the lab period. Figure 1a shows the VNA and calls out its key components.

We will use a VNA to measure S-parameters, which are essentially reflection and transmission coefficients. For a two-port network (which, in our case, are Channel 0 and Channel 1), we have 4 S-parameters: S_{11}, S_{21}, S_{12}, and S_{22}. The subscripts represent the receiving port and the source port, so S_{21} means the signal received at port 2 as a result of a source at port 1 – this is the transmission coefficient from port 1 to port 2.

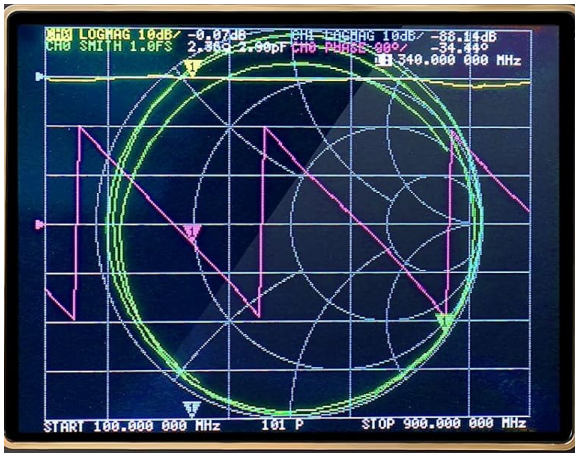
You can power these nano VNAs from the built-in battery or the micro-USB cable. To operate the VNA, turn on the device using the on/off slider on the left side of the device. Within a few seconds, you should see a display as shown in Figure 1b. At first, the display will appear cluttered, because you are actually looking at several plots overlayed on one another. The labels for each trace are at the very top of the screen and the default quantities are as follows:

- Yellow: Channel 0's magnitude in log format. This is the reflection coefficient, which the VNA plots on the rectangular grid. The default scale, as shown, is 10dB per division. Usually, 0dB is at the top of the screen.
- Blue: Channel 1's magnitude in log format. This is the transmission coefficient, which the VNA plots on the rectangular grid. The default scale, as shown, is 10dB per division. Usually, 0dB is at the top of the screen.
- Magenta: Channel 0's phase in degrees. The default scale is 90° per division.
- Green: This is the smith chart plot of the measured complex impedance of the load (Z_L). The VNA plots it "behind" the rectangular grid, on its own scale (normalized **impedance**).

You can customize each scale – the user's manual describes how – but this lab does not need it.



(a) An annotated overview of the VNA.



(b) An initial view of the nano VNA screen.

Figure 1: Familiarization views of the nano VNA.

3.2 VNA Setup

To bring up the menu, tap the screen (it helps to use a passive stylus) or press the middle tactile button. Your first task should be to flip the display, which will allow you to turn the ports away from you. To do this, tap the screen, then tap "Display" at the top of the menu. At the bottom, you should then see "Flip Display" – tap this button and the screen should invert. You should also tap the "Pause Sweep" button – this pauses the frequency sweep and measurement cycle of the VNA. Take some time to explore the menu structure – a full map is available in the user's guide.

3.3 Parts for Part II

Beyond the VNA and its cables, each team builds a mock antenna from two components:

Part	Marked	Role
15Ω resistor	15Ω	mock antenna, radiation resistance
1 nF capacitor	0.001 μF	mock antenna, series reactance

Those two values are the whole input to the Question 7 design, which you do **before** lab. The matching network's inductor and capacitor come out of that calculation – you draw them from the bench kit in Question 8, and picking the nearest stocked value to what you computed is part of the exercise.

Keep your leads **short**: at these frequencies a few centimeters of wire is a small but measurable inductance, and it is one of the reasons your built network will not perform quite as well as your arithmetic promises.

4 Part I – Measurement

4.1 Calibration

When performing RF measurements, you **always** need to calibrate your device to your particular configuration. You must recalibrate every time you connect a cable or change the frequency range. First, connect the SMA cables to each port (SMA cables are the smaller coax connectors). On channel 0 (which is confusingly labeled "1" on the circuit board), connect the black SMA-BNC connector, then connect the BNC-grabber clips cable to the open end. On channel 1 (labeled "2" on the circuit board), connect the blue SMA-SMA cable. Don't worry about the different colors or lengths of the cables at this time. RF connectors are sensitive, so when connecting them **DO NOT** overtighten the connectors or cross-thread them. Finger tight is just right in this case.

Before we calibrate the device, you will need to set your frequency range.

1. Tap **Stimulus** from the main menu.
2. Set your frequency range from 50kHz to 5MHz using the **Start** and **Stop** buttons.

You will now follow the calibration procedure using an open, short, and load calibration standard.

1. Connect every calibration standard to channel 0, and leave channel 1's SMA cable disconnected.
2. Bring up the menu and tap **Cal**.
3. Reset the calibration by tapping **Reset**.
4. Leave the grabber clips disconnected from any load. This is an open circuit.
5. Now, under the **Calibration** pane, tap **Open**. The calibration is complete when the background of the text turns black.
6. Connect the grabber clips to form a short circuit.
7. Under the **Calibration** pane, tap **Short**.
8. Once the calibration is complete, move on to the **Load** calibration. In this case, you will connect the grabber clips to a matched load of 50Ω – a simple resistor.
9. Do not conduct a **Thru** measurement. This involves adding another length of transmission line between channel 0 and channel 1.
10. Tap **Done** at the bottom of the **Calibration** pane.
11. If you wish, you may save your calibration by tapping "Save 0". You will be able to recall these calibration settings later.
12. From the **Cal** pane, ensure **Correction** is highlighted in black.
13. Calibration is now complete – tap any portion of the plots to close the menu.

Note the reference plane. Everything you just did tells the VNA to call the *tips of the grabber clips* the place where $z = 0$. Every impedance you report from here on is the impedance seen at those clips. You will rely on this in Part II.

4.2 Measurement

When making measurements, be sure to pause the sweep while changing physical connections. Additionally, you may read values for the marker positions at the top of the screen. You can move the markers by tapping/holding and dragging (this requires a stylus), or by choosing **Markers → Select Markers → Marker X** and then using the left/right tactile buttons to move the marker location. Figure 2 shows an annotated example.

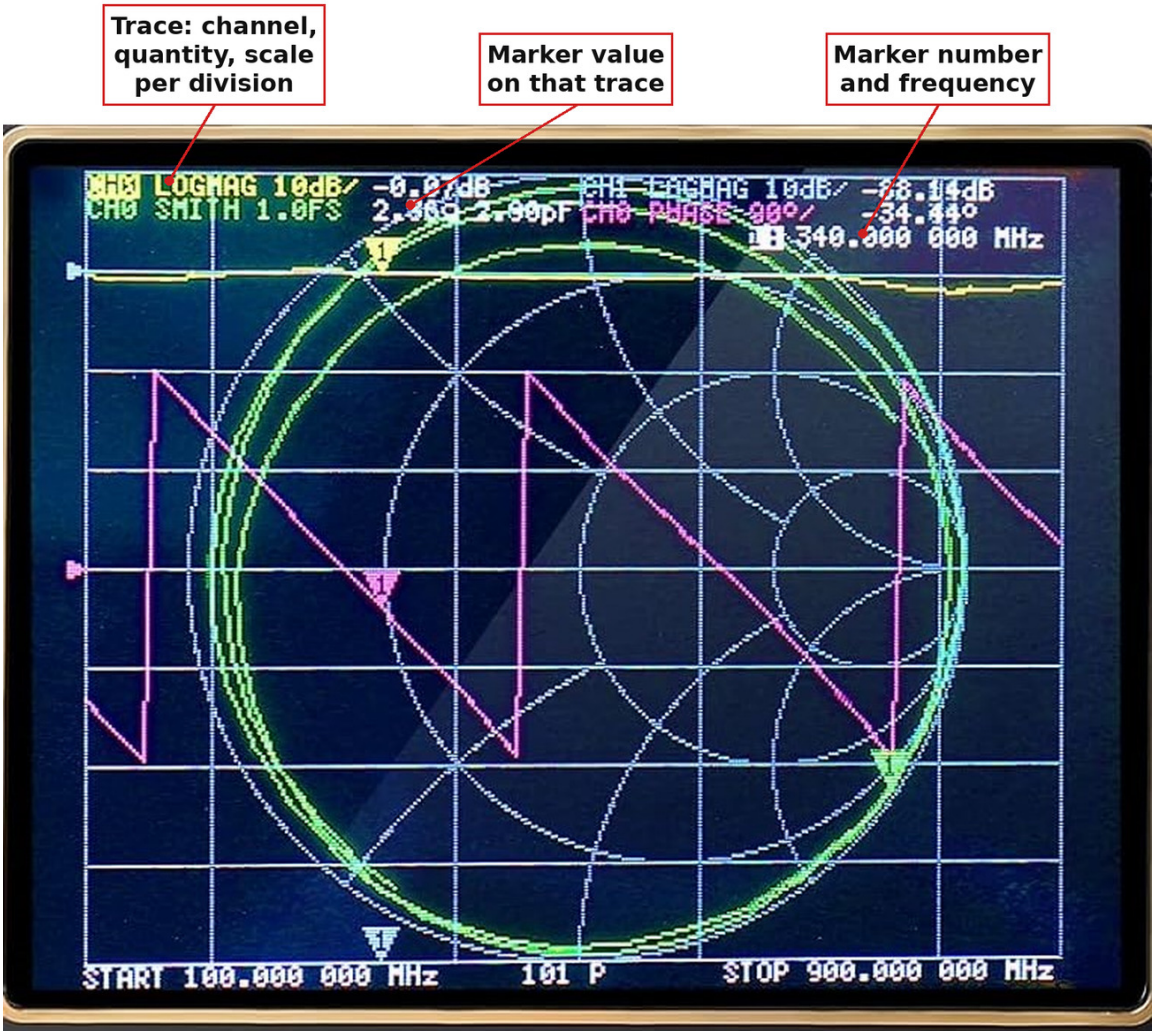


Figure 2: An example readout of a VNA measurement showing the location of Marker position information.

1. Given an open circuit load, what type of reflection would you expect to see, in terms of the reflection magnitude and phase? Use the reflection coefficient equation to inform your answer. It may also help to include a screenshot of the resultant plot.

(a) What amplitude and phase do you observe?

Amplitude = Phase =

(b) What position is the open circuit indicating on the Smith Chart? Does this make sense, based on your understanding of the Smith Chart?

2. Given a short circuit load, what type of reflection would you expect to see, in terms of the reflection magnitude and phase? Use the reflection coefficient equation to inform your answer. It may also help to include a screenshot of the resultant plot.

(a) What amplitude and phase do you observe?

Amplitude = Phase =

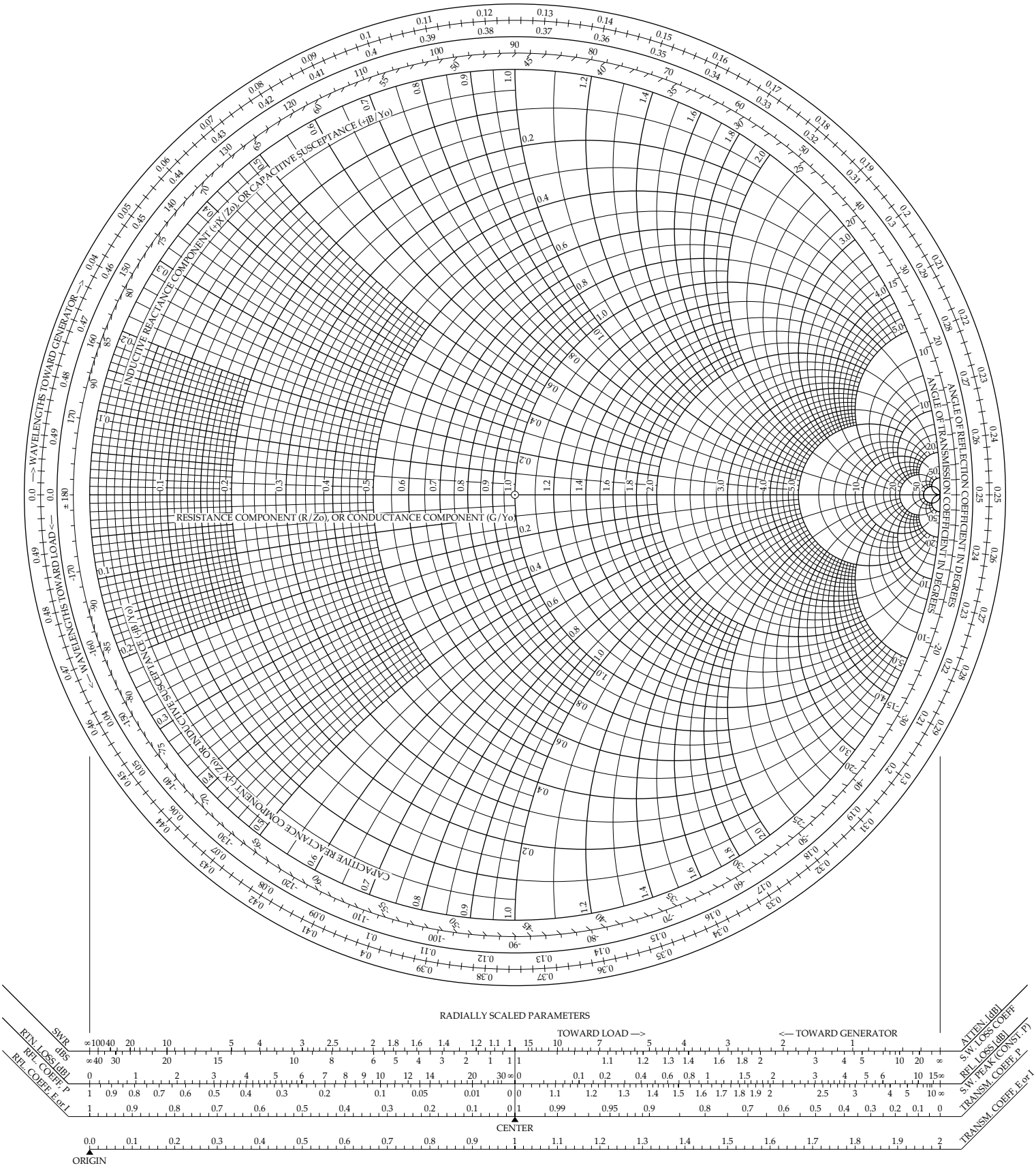
(b) What position is the short circuit indicating on the Smith Chart? Does this make sense, based on your understanding of the Smith Chart?

3. **Impedance Measurement:** Given a capacitor of value 470 pF, calculate the impedance for the frequency ranges shown in the table below. Plot these values on the smith chart and compare the measurement results – do they agree?

Frequency	**Expected Z_C**
50 kHZ	
100 kHz	
500 kHz	
700 kHz	
900 kHz	
1 MHz	
2 MHz	
3 MHz	
4 MHz	
5 MHz	

The Complete Smith Chart

Black Magic Design



4. **Matched Load Measurement:** Now, you will measure a matched load of 50Ω . Simply connect the grabbers to each side of the same 50Ω resistor used during calibration.

   (a) What is the predicted magnitude of the matched load reflection coefficient, in dB? Remember, you are measuring **Voltages**.

   (b) What is the measured magnitude of the matched load reflection coefficient.

   (c) Identify the resistance value from the marker readout and the Smith Chart.

   (d) Make at least one observation about your measurements.

5. **Mismatched Load Measurement (Resistive):** Now you will measure a purely resistive mismatch. Connect the 1 kΩ resistor to the mini grabbers and answer the following questions.

   (a) What is the predicted magnitude and phase of the reflection coefficient for this system, in dB? Remember, you are measuring **Voltages**.

   (b) What is the measured magnitude/phase of the load reflection coefficient.

   Amplitude = Phase =

   (c) Identify the resistance value from the marker readout and the Smith Chart.

   (d) Make at least one observation about your measurements.

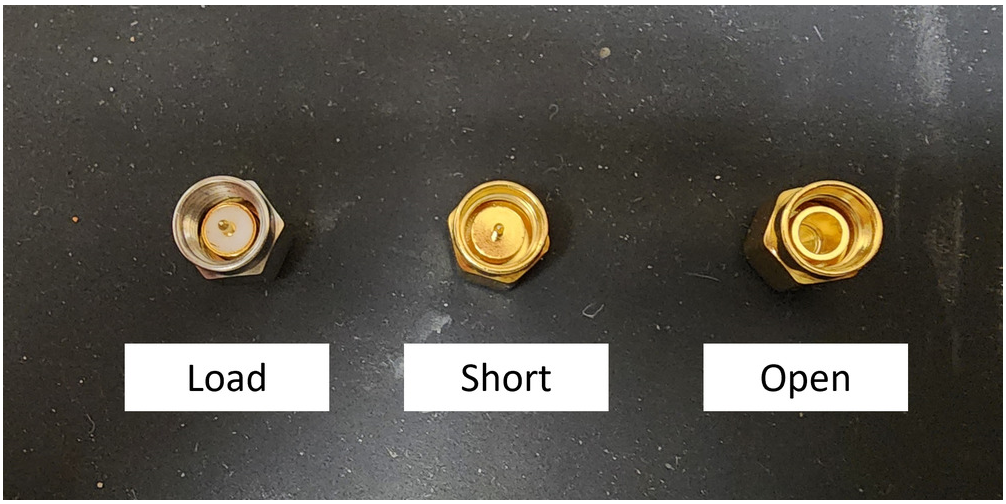


Figure 3: The RF calibration standards for this VNA, used in Part 6.

6. Black Box Measurement

Now, you will measure an unknown device, often called the "Device Under Test" (DUT). Tape covers the DUT's label – do not remove it! Also, note the DUT has SMA connectors – disconnect the BNC cable with the minigrabbers. Due to the operational bandwidth of the DUT, you will need to adjust the frequency range to correlate to your specific filter and recalibrate. The calibration procedure is slightly different, in that SMA cables use different calibration standards (as shown in Figure 3). Please use the short, open, and load connectors. This time, you may also perform a thru calibration by connecting channel 0 and channel 1 using a coupler, but this is optional. Now, connect the DUT to the VNA using the appropriate cables and restart the sweep.

(a) Looking at the plot of the transmission and reflection coefficient, what type of filter do you have? How do you know?

(b) Determine the cutoff frequency (or frequencies) of the filter (remember, this is the -3dB point).

(c) Using the Smith Chart display, observe whether the DUT is capacitive or inductive over certain frequency ranges. If you move the Smith Chart marker, you will see the reactance change – can you correlate that change with a value of capacitance or inductance?

(d) Make at least one additional observation about your measurements.

5 Part II – Design a Matching Network

Reconnect the BNC-to-grabber cable to channel 0 and **recalibrate** over 50kHz to 5MHz (open, short, load) if you changed anything for the black-box measurement. Your reference plane is back at the grabber clips.

7. Design (do this before lab).

You are handed an "antenna": a 15Ω resistor in series with a 1 nF capacitor. It is a stand-in for an electrically small antenna – a small radiation resistance in series with a large capacitive reactance – and your job is to feed it from a 50Ω source at $f_0 = 2$ MHz.

(a) Compute the antenna impedance Z_a at f_0. Express it as $R_a + jX_a$.

Z_a =

(b) Before matching, what are $|\Gamma|$ and the VSWR at f_0?

$|\Gamma|$ = VSWR =

(c) Design the L-network of Section 2.1. Find Q, the total series reactance X_s, and the shunt reactance X_p; then convert to an inductance and a capacitance at f_0. **Careful:** the series inductor has to cancel X_a *and* supply X_s.

L_s = C_p =

(d) Check your design in the `feed-match` widget on the Lesson 4 page: set R and X to your antenna impedance and confirm the point sits where you expect on the Smith chart. Sketch or screenshot where the load starts and where you expect it to end up.

8. Build and verify.

Now go and find the parts. The inductor and capacitor you calculated in Question 7 are not on your bench – they are across the hallway in the electronics lab, in whatever bins happen to be stocked. Nobody has laid out a kit for you.

Take the closest thing you can find to each of your two values, and write down all four numbers: what you calculated, and what you actually came back with. Measure the capacitor on the bench LCR meter while you are at it – a marked value and a measured value are not the same thing, and part (e) turns on the difference.

You will not get exactly what you asked for. That is the normal case in this line of work, and the useful question is not whether the match is perfect but whether it is **good enough** for what the radio needs. Part (f) asks you to answer that.

Watch which capacitor is which. One is the antenna's series capacitor from the table in Section 3.3; the other is the matching capacitor you just fetched. They differ by roughly a factor of two, and swapping them will not work.

Build the mock antenna first, measure it, then add the network. Keep leads short.

(a) Clip the mock antenna to the grabbers. Measure R and X at f_0 from the Smith Chart marker. How well does it agree with your prediction?

R measured = _____ X measured = _____

(b) Record $|\Gamma|$, VSWR, and return loss at f_0 for the unmatched antenna.

$|\Gamma|$ = _____ VSWR = _____ RL = _____

(c) Now build the L-network and connect it between the clips and the antenna. Re-measure at f_0 and fill in the table.

	$\lvert\Gamma\rvert$	VSWR	Return loss
Unmatched			
Matched (predicted)			
Matched (measured)			

(d) Where did the operating point move on the Smith Chart? Describe the path in terms of the two design moves.

(e) Your measured match is almost certainly worse than your Question 7 design predicted. Recompute the prediction using the parts you actually came back with – the marked inductance and your measured capacitance – and see how much of the gap that alone explains. Name two further physical reasons for whatever is left over.

(f) **Is it good enough?** You did not get the parts you designed for, and you will not next time either. State the VSWR your network actually holds at f_0, and the mismatch loss that costs in dB. Then take a position: for a transmitter that wants VSWR $\leqslant 2$, would you ship this network, go back across the hallway for a better part, or redesign around what the bins actually carry? Defend the answer with your two numbers, not with a preference.

(g) **Optional – trim it.** If small capacitors are available, add one in parallel with your C_p to make up a

shortfall and re-measure. What value do you need, and what does it buy you?

9. Bandwidth – what the match cost you.

Restart the sweep and look at the return-loss trace across the full 50kHz–5MHz span.

(a) Over what frequency range does your matched antenna hold VSWR $\leqslant 2$? Report the band edges and the fractional bandwidth.

f_{low} = f_{high} = FBW =

(b) The network Q you computed in Question 7 was 1.53. Explain, in one or two sentences, the connection between that number and the bandwidth you just measured.

(c) A real 0.05λ dipole would have R_{rad} well under an ohm rather than 15Ω. What does that do to the required Q, and therefore to the bandwidth? Connect your answer to the Chu-Harrington bound from Lesson 3.

(d) Why did we not use a quarter-wave transformer here? One tempting answer – "the load is complex" – is not by itself a reason. Explain why that objection does not hold, then give the two things that actually rule the transformer out at this frequency.

(e) Make at least one additional observation about your measurements.

Documentation: _____