

# Baba Yaga's Hut: A Laboratory Experience in Phasor Analysis

Kristina Collins, David Kazdan

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## Abstract

A laboratory exercise is presented for the examination of analog signals simultaneously in the time, frequency and phasor domains, as well as demodulated audio. A simulated transmitter, transmission medium, receiver front end and in-phase/quadrature demodulator are constructed using function generators, two oscilloscopes, and RF components. In this initial exercise, the focus is on the examination of an AM signal, which students vary in modulating frequency, amplitude, depth, etc. while making guided observations of the effects on each representation. This develops experiential understanding and intuition for examination of AM signals in the 3 domains, and offers a kinesthetic demonstration of concepts typically presented as blackboard exercises. The demonstration is extensible to frequency and phase modulation and QAM, and may form the basis for a semester course in modulation. The exercise has been successfully deployed in a junior-level electrical engineering class focusing on signal modulation. This work is supported by the Electrical Engineering and Computer Science department of Case Western Reserve University, through the Robert E. Collin Radiofrequency and Communications Laboratory and the Case Amateur Radio Club, W8EDU. Educational canon, including bill of materials, setup instructions, and lab exercises for this demonstration, is available at [cwrucommlab.wordpress.com](http://cwrucommlab.wordpress.com).

## Equipment:

1. 2 Oscilloscopes (One for time domain, one for phasor)
2. 2 Arbitrary waveform generators: Sigilent SDG2122X (2x)
3. Spectrum analyzer (SignalHound USB-SA44B)
4. Computer with Spike (SignalHound software) installed
5. 10 male/male BNC cables (Digikey P/N: ACX2316-ND)
6. 7 BNC tee connectors
7. 2 low pass filters (see below)
8. Splitter (MiniCircuits ZSC-2-2+)
9. 2 Mixers (MiniCircuits ZAD-6+)
10. Female BNC to banana adapter
11. Spool of wire
12. An AM Radio
13. An A440 tuning fork

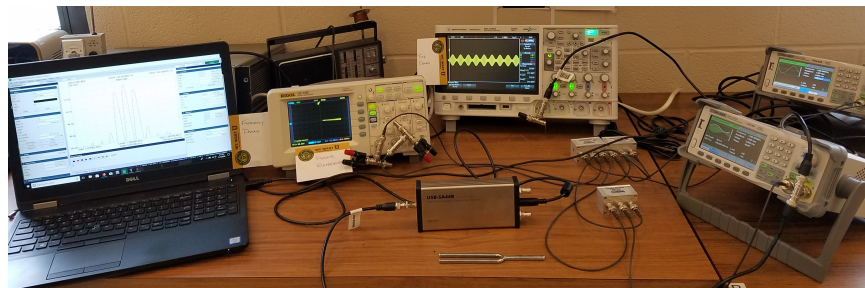


Figure 1: Lab apparatus, showing an AM signal in time domain, frequency domain and phasor representation simultaneously.

## 1. A Review of Phasors

We describe to students the notion of an analytic signal existing in vector space as a rotating vector and the Steiglitz view of synchronizing with the nominal rotating vector to examine the modulation. We recommend Eugene Khutoryansky's excellent visualization: <https://www.youtube.com/watch?v=r18Gi8lSkfM>

## 2. The Hut on Fowl's Legs

We press very hard for a memorable, visualizable metaphor for phasor analysis. Baba Yaga, in Russian folk tales<sup>1</sup>, was an old woman (witch?) living deep in the forest who sometimes helped and sometimes hindered those who encountered her. She lived in a hut that stood on fowl's legs; at her command, the hut would spin and fly. Our laboratory-grade version includes a glass floor and a wideband angular frequency knob; the received analytic signal's spinning vector is insisted to be on the lab floor, and the student is asked to envision entering the hut, commanding the spin, commanding the flight, flying over the vector disk, and adjusting frequency to enter phase lock (and therefore frequency lock) with the nominal carrier, as depicted in Figure 3. Now beneath the student's feet is the remaining phase vector (the phasor) from which modulation phenomenon may be observed. Students are reminded that centrifugal forces are as imaginary as the hut and they should not orchestrate the unRaveling of the Modestly-built apparatus.



Figure 2: Baba Yaga.

## 3. Radio Topology

The simulated transmitter is straightforward: It is a carrier oscillator that can be amplitude modulated in AM (full carrier), AM (double-sideband suppressed carrier), FM, PM, binary phase-shift keying, and a few other modes.

The coaxial cable from the transmitter to the receiver simulates the transmitter's cable and antenna, free space, then the receiver's antenna and cable.

The simulated receiver boasts a direct-conversion, synchronous-vector topology. The input cable connects to a signal splitter. Each splitter output is led to a ring modulator. One ring modulator is fed by an oscillator; the other is fed by the same oscillator but phase-shifted  $90^\circ$ . A simple low-pass filter is on each modulator's output leaving demodulated in-phase and quadrature outputs separated. Those are cabled to the X and Y inputs of the phasor observation oscilloscope respectively. The connections are shown in Figure 4.

<sup>1</sup>For an academic analysis of her folklore, see ISBN 978-0820467696. We do not claim to have read this book. We are working from fondly remembered tales from childhood and do not wish to be told memory is faulty.

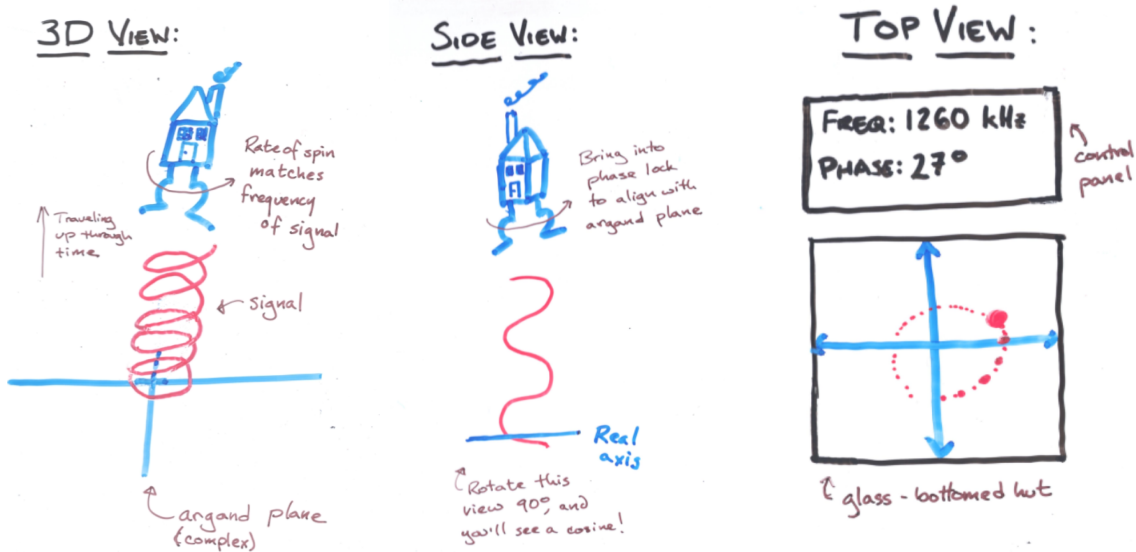


Figure 3: Illustration of the hut metaphor.

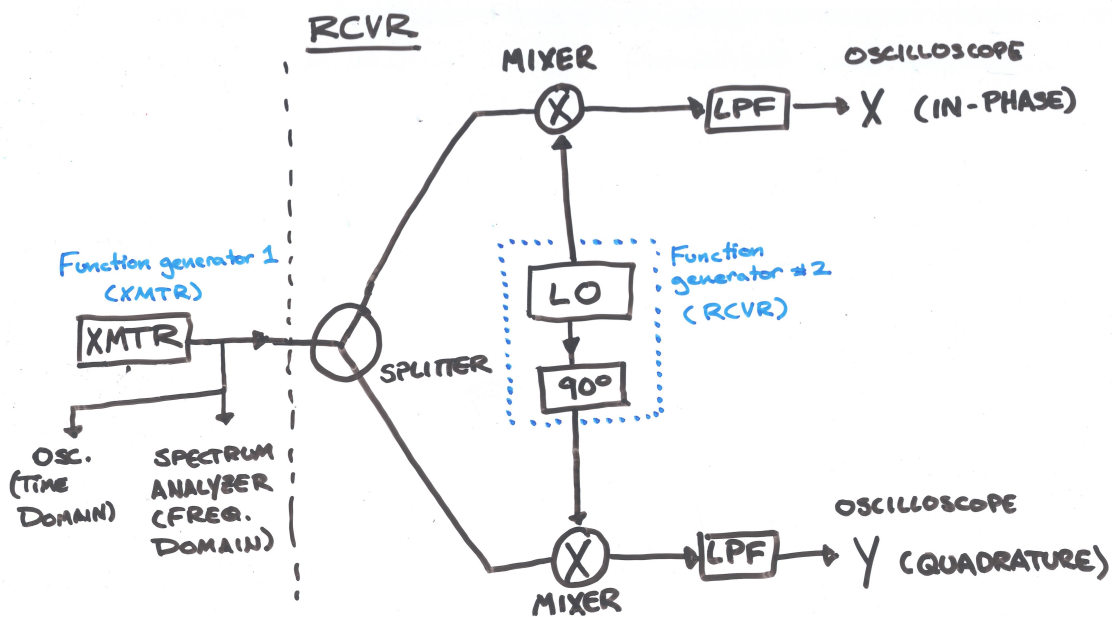


Figure 4: Schematic for the apparatus.

#### 4. Function Generator Settings

Recall that the function generators (one representing the transmitter and the other representing the local oscillator of the receiver) must be synchronized in frequency. If the function generators are turned off, the settings will not persist. Follow these steps to put the function generators in the correct settings. The generators are denoted XMTR, for "transmitter," and RCVR, for the local oscillator of the receiver.

##### 4.1. Clock Synchrony

A BNC cable must be used to connect the two "10 MHz In/Out" ports on the function generators. On the XMTR: Select Utility  $\mapsto$  Clock, and verify that the clock source is internal and that the 10 MHz clock out is enabled. On the RCVR, set the clock source to external. Both generators will now be synchronized according to the XMTR's clock.

##### 4.2. XMTR: Channel Sync

Both channels of the XMTR should have the same output. To achieve this, on the XMTR select Utility  $\mapsto$  CH Copy/Coupling  $\mapsto$  Track ON.

### 4.3. RCVR: Quadrature Channel Sync

We should achieve frequency synchrony for the RCVR, but the two channels must be 90° out of sync. On the RCVR, select Utility  $\mapsto$  CH Copy/Coupling  $\mapsto$  Track ON. Select PhaseDev and set the phase difference to 90°.

### 4.4. Parameter Settings

Using the Parameter menu on the RCVR, set the amplitude of the signal to  $1V_{pp}$ . Ensure that all outputs are on by pressing the Output button above each BNC connector on the function generators. Set the amplitude on both generators to 1V, and the frequency to somewhere in the AM broadcast band<sup>2</sup>. Put your oscilloscope in XY mode and ensure that the scales for X and Y are the same.

### 4.5. Store Settings

You can store the settings on each function generator by selecting Store/Recall  $\mapsto$  Filetype: State, and then reload this state file if the function generator is turned off. Ensure that the Output buttons on each generator are green and confirm functionality.

## 5. Construction Notes

### 5.1. BNC Cables

Not all BNC cables are created equal. We found that the BNC cables in our lab didn't produce a clean phasor picture. Switching to the ones listed in the BOM above worked much better.

### 5.2. Low Pass Filters

To ensure correct display of the phasor, low pass filtering on the oscilloscope inputs is a virtual necessity. We used the assembly shown in Figure 5, for each input of the oscilloscope used for the phasor display. The apparatus consists of two BNC tees, one 50Ω BNC terminator, one BNC to banana adapter, and one 1 μF capacitor.

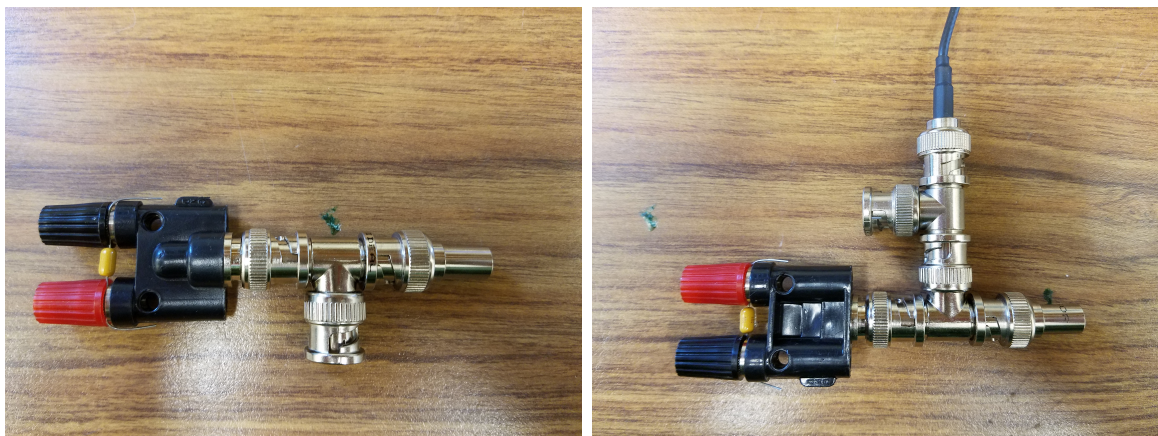


Figure 5: Lowpass filters. The image on the left depicts the filter by itself, while the image on the right shows how it connects to the phasor input and oscilloscope using a BNC tee.

### 5.3. RF Coupling to Radio

Including demodulated audio in the exercise is a very helpful touch. Our method for coupling to the radio, shown in Figure 6, was to use a spool of copper wire connected to the time domain oscilloscope input.

## Acknowledgment

The authors gratefully acknowledge the prior work of Alan Wolke, W2AEW. His phasor demonstration, on which ours is based, can be viewed at <https://www.youtube.com/watch?v=5GGD99Qi1PA>.

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<sup>2</sup>We used 1260 kHz, but you may want to select a frequency corresponding to a broadcast station you can hear, in order to demonstrate capture - or rather, lack thereof.

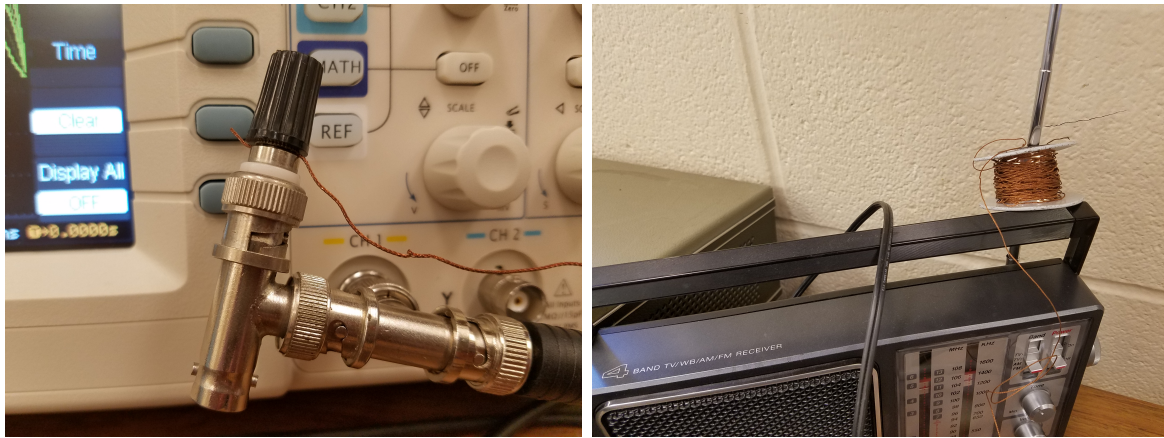


Figure 6: Our chosen method of coupling the modulated signal into an AM radio.

# AM Lab

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## Abstract

This lab will help you get familiar with amplitude modulated signals. The equipment is set up in the Glennan 709 lab. When done, leave your lab papers in the dropbox.

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## 1. Equipment Setup

This should be done already when you get to the lab. Refer to this section if you need to troubleshoot things.

### 1.1. Output Lock (Transmitter)

Select Utility  $\mapsto$  CH Coupling  $\mapsto$  Tracking ON.

### 1.2. Baba Yaga's Hut (Receiver)

The two channels of this generator should be coupled together, with a  $+90^\circ$  phase shift between Channel 2 and Channel 1. The frequency should match the frequency of the transmitter. Use the Utility  $\mapsto$  CH Coupling menu to couple both channels and add the requisite phase shift.

## 2. Set up AM on Generator

Let's mimic the AM broadcast band (560-1600 kHz) with the function generator setup used in the previous lab. Set your function generator to 1260 kHz (WIXY 1260!) and use the "Mod" functions to modulate it with a 440 Hz<sup>3</sup> sine wave. Start with an AM depth of 75%.

## 3. Time Domain

Tweak the knobs on the oscilloscope until you see a picture similar to Figure 8. (Hint: Make good use of the trigger settings.)

## 4. Frequency Domain

We'll be using a USB<sup>4</sup> spectrum analyzer. Open Spike.exe on the lab computer and play around with the settings until you have a waveform you're happy with.

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<sup>3</sup>Remember, the human hearing range is roughly 20 Hz to 20 kHz, so this is near the middle of the road, logarithmically speaking.

<sup>4</sup>Expect to see this trend in a lot of test equipment in the future: a USB-connected box that outsources processing to the computer. Cheaper, easier to offload data, and easier to upgrade.

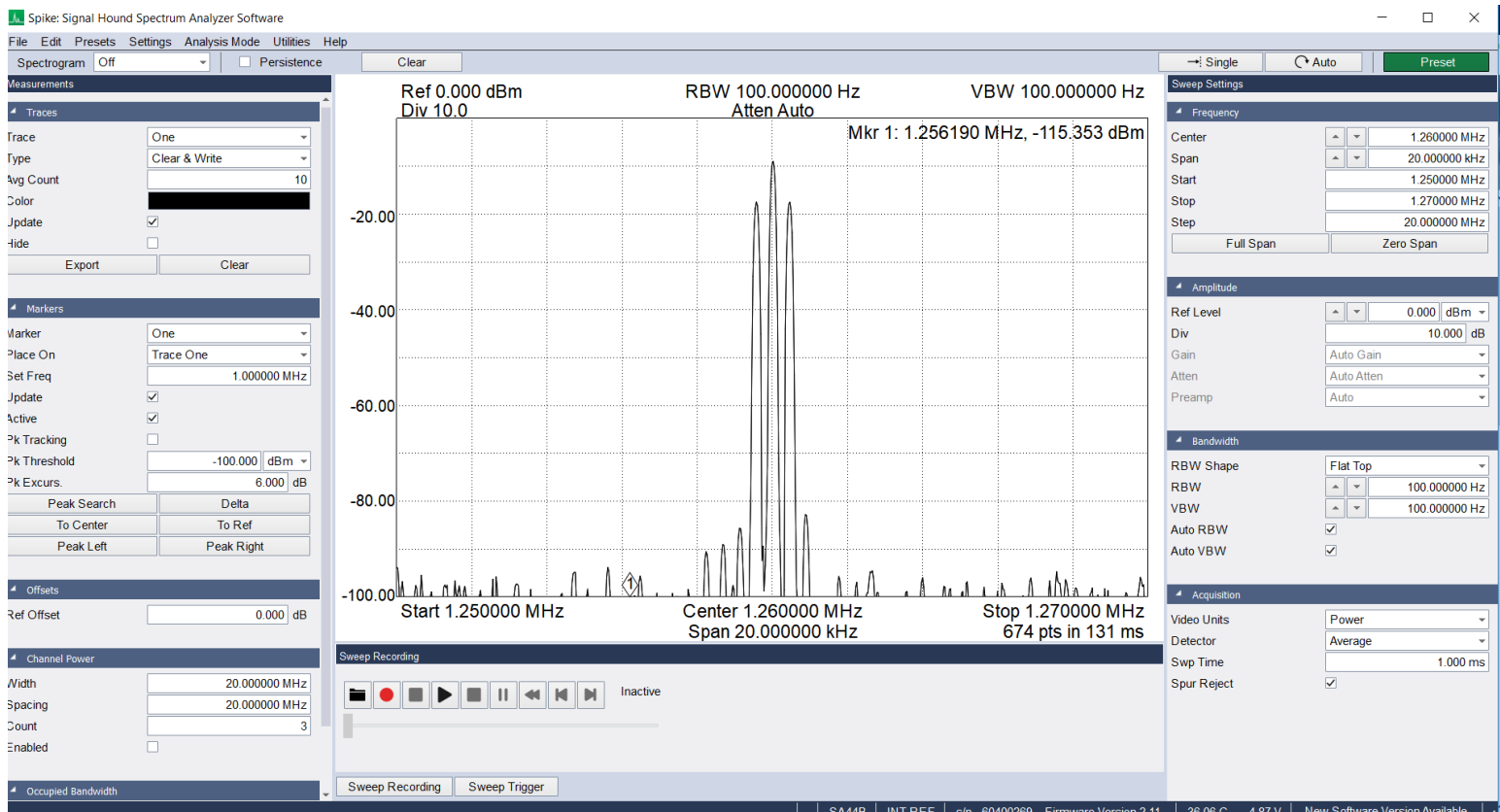


Figure 7: Example screenshot of Spike, the SignalHound software.

## 5. Phasor Representation

Now we must calibrate our simulated direct conversion receiver, henceforth referred to as Baba Yaga's hut. Typically you would use a modulation analyzer for this, but those cost more than a car, so we've constructed a system using the other waveform generator. Details of how this system works are available upon request, but the important details right now are these: *The receiver must be synchronized with the transmitter in frequency and in phase.* Frequency shouldn't be a big deal: we're planning to keep the carrier frequency at 1260 kHz for the entire lab. Phase will be a little trickier: Because the arbgens work through direct digital synthesis, you'll need to repeat this process occasionally<sup>5</sup> throughout the lab.

Let's practice.

In general, it's okay if you aren't phase-locked; just know that they should be.

**Vary the modulation depth from 10% to 120%. What do you observe in the phasor diagram? Describe with a labeled drawing. When done, return it to 75%.**



**With persistence on<sup>6</sup>, vary the phase on the transmitter from 0° to 90°. (For best results, change**

<sup>5</sup>By "occasionally," we mean whenever you change modulation mode. If the phase jumps around every time you change frequency or modulation depth, it's a sign that the transmitter generator's tracking is off. Select Utility  $\mapsto$  CH Coupling  $\mapsto$  Tracking ON and make a note in the margin here to let us know if that fixes the problem.

<sup>6</sup>On the Rigol: Menu  $\mapsto$  Display.

10 degrees at a time.) What do you observe in the phasor diagram? Describe with a labeled drawing. When done, return it to  $0^\circ$ .

Vary the carrier voltage from from  $1V_{pp}$  to  $0.5 V_{pp}$ . What do you observe in the phasor diagram? Describe with a labeled drawing. When done, return it to  $1 V_{pp}$ .

## 6. Demodulating to Audio

Note that the second BNC tee on the transmitter is connected to a spool of wire, sitting next to the antenna of an AM radio. Through RF coupling, the radio's antenna will pick up the signal from the function generator. Turn the radio on, and turn the volume up a bit. You should hear the 1 Hz signal. **On the transmitter arbggen, turn off the output of Channel 2 by hitting the button above the BNC port. Then turn the channel back on again. What do you hear?**

Now hit the "Mod" button on the transmitter arbggen to turn the modulation off. You're now sending the radio an unmodulated AM carrier. What do you hear? You'll be able to verify on the oscilloscope that the carrier drops out momentarily when you make this adjustment. (Note that you can use this trick to silence the radio in the next few steps.)



Explain how the radio's automatic gain control circuit may have affected these results. How might your observations have sounded different if this radio didn't have a working AGC?<sup>7</sup>

Change the modulating frequency (using the dial on the function generator, by about a Hz at a time) and write down your observations.

Set the modulating frequency to 440 Hz. There's a tuning fork<sup>8</sup> on the bench. Do you detect any pitch difference?

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<sup>7</sup>We're sorry we don't have the ability to turn the AGC off. We found a radio with a broken AGC, and it was all ready to go, but then the rest of it broke too. In future iterations of this lab, we'll have a radio with a switch to turn the AGC on and off.

<sup>8</sup>Practice good tuning fork discipline — thwack it against something soft, like your hand or clavicle, not the edge of the table.

Change the modulating frequency (using the dial on the function generator, by about 10 Hz at a time) and write down your observations.

## 7. Varying Parameters: Modulation Depth

At this point you'll need to perform the phase shift on Baba Yaga's hut (our receiver, remember) and possibly adjust the scaling on the oscilloscope and spectrum analyzer to make sure the envelope and peaks, respectively, are visible. On the function generator, vary the modulation parameters as listed in Table 1. **Fill out Table 1, sketching the effect of the parameter changes on the time domain (oscilloscope), frequency domain (spectrum analyzer) and phasor views of the signal. Use color coding.** You've got a lot of screens to keep track of, so you may want to go through this once for each. Qualitative is fine. Remember that you'll have to repeat the hut orientation process each time you turn the modulation off, so expect to have the radio on this entire time. You should probably turn the volume on the radio down to a level you can hear, but that doesn't drive anyone too crazy.

## 8. Varying Modulation Frequency

**Fill out Table 2, sketching the effect of the parameter changes on the time domain (oscilloscope), frequency domain (spectrum analyzer) and phasor views of the signal. Use color coding.** You should be quantitative, but not necessarily precise.

## 9. Double Sideband Suppressed Carrier

Return the modulating frequency to 440 Hz. Change the modulation type from AM to DSB-AM<sup>9</sup>. Reorient the hut as needed. **Fill out Table 3.**

**Which version of 440 Hz sounds closer to the correct pitch? (You may want to use the tuning fork, or an online tone generator—[onlinetonegenerator.com](http://onlinetonegenerator.com), for instance—to gauge this.)**

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<sup>9</sup>DSB-SC, really — double sideband, suppressed carrier

Table 1: Varying modulation depth. *Default Parameters: Carrier frequency of 1260 kHz, carrier amplitude of 1 V<sub>pp</sub>, modulating frequency of 440 Hz.*

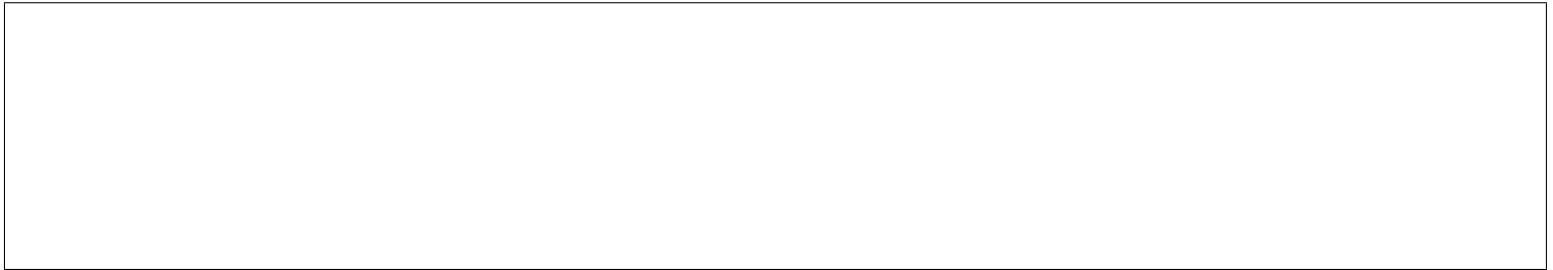
Depth	Time Domain	Freq Domain	Phasor	Audio Description
0%				
33%				
66%				
100%				
120%				

Table 2: Varying modulation frequency. *Default Parameters: Carrier frequency of 1260 kHz, carrier amplitude of 1 V<sub>pp</sub>, modulation depth of 75%.*

Frequency	Time Domain	Freq Domain	Phasor	Audio Description
1 Hz				
440 Hz				
1 kHz				
5 kHz				
10 kHz				



Figure 8: The USPS Amateur Radio stamp showcases the classic face of an AM radio signal in the time domain: a stationary envelope with the modulation fuzz inside.



With a modulating frequency of 440 Hz, tune the radio a bit above and below the carrier frequency (or lack thereof) of the radio. **What happens to the audio in each case?**

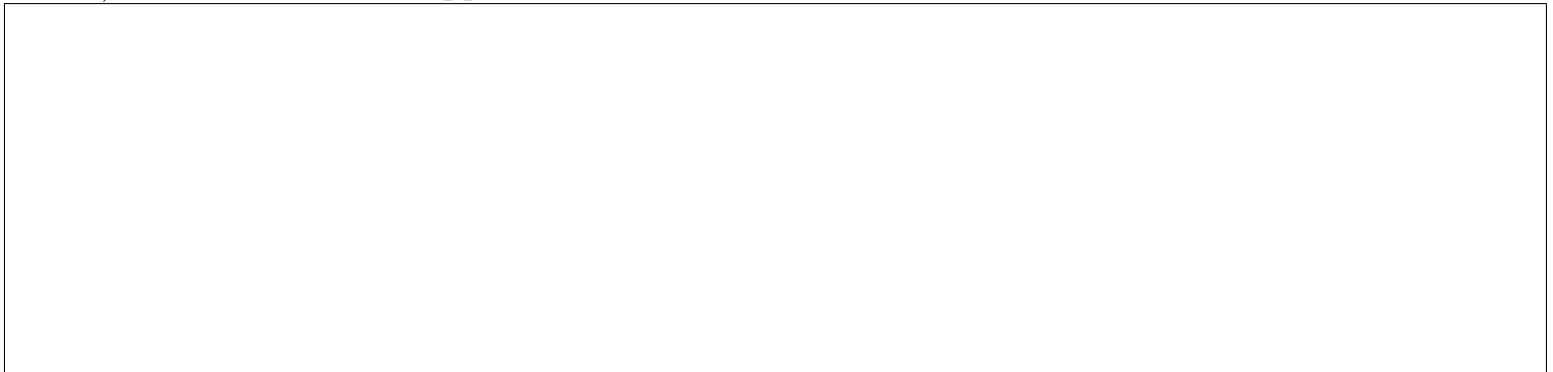


Table 3: AM (DSB-FC) versus AM (DSB-SC). *Default Parameters: Carrier frequency of 1260 kHz, carrier amplitude of 1 V<sub>pp</sub>, modulation depth of 75%.*

Scheme	Time Domain	Freq Domain	Phasor	Audio Description
DSB-FC				
DSB-SC				

Table 4: Tools

Tool	Oscilloscope	Spectrum An.	Modulation An.	AM Receiver
Domain	Time Domain	Frequency	Phasor	Demod. Audio
DSB-FC or DSB-SC? <sup>10</sup>				
Carrier amplitude?				
Carrier frequency?				
Modulating frequency?				
Modulating amplitude?				

## 10. Selecting Tools

Here's where we summarize the salient parts of the lab: figuring out which tool you should use to determine relevant information. **In Table 4, note which tools can be used to answer each question. Highlight your favorites.**