Restoration of a 1940s Emerson Radio

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Abstract

This paper details the restoration of an Emerson Model EC, an antique tube-based AM radio. First, I will explain the design of this radio, elaborating on the theory behind common components of radio circuits of the era. Next, I will discuss the modifications that were necessary to make the radio safe and return it to operating condition. The final section describes a set of measuments taken and their use in assessing the performance of the newly-restored radio.

1 Overview

1.1 History

The Model EC was produced by Emerson Radio & Phonograph in the years prior to WWII. It was obtained in unknown condition and with no labels or markings other than the manufacturer's name on the front. Its year of manufacture is thus unknown; however, several Internet sources suggest a date of 1940-1941.

Like many radios of the day, the EC is an All-American Five–one of the many low-budget AC/DC radios built in the 1930s and 1940s. The AA5 design was used by many manufacturers, with minor variations from one design to the next. The economic pressures of the era encouraged manufacturers to make significant cuts in radio price. Most of the design decisions were made with cost-efficiency in mind: radios with the fewest components and simplest assembly were the most inexpensive to produce.

2 Operation

The superheterodyne design used in the Emerson EC can be most easily described by breaking it into discrete blocks (see Figure 1).[1] The AA5 design is not as simple as this block diagram, however; the designers took

[1] Diagram borrowed from `http://www.vias.org/basicradio/basic_radio_33_06.html`.

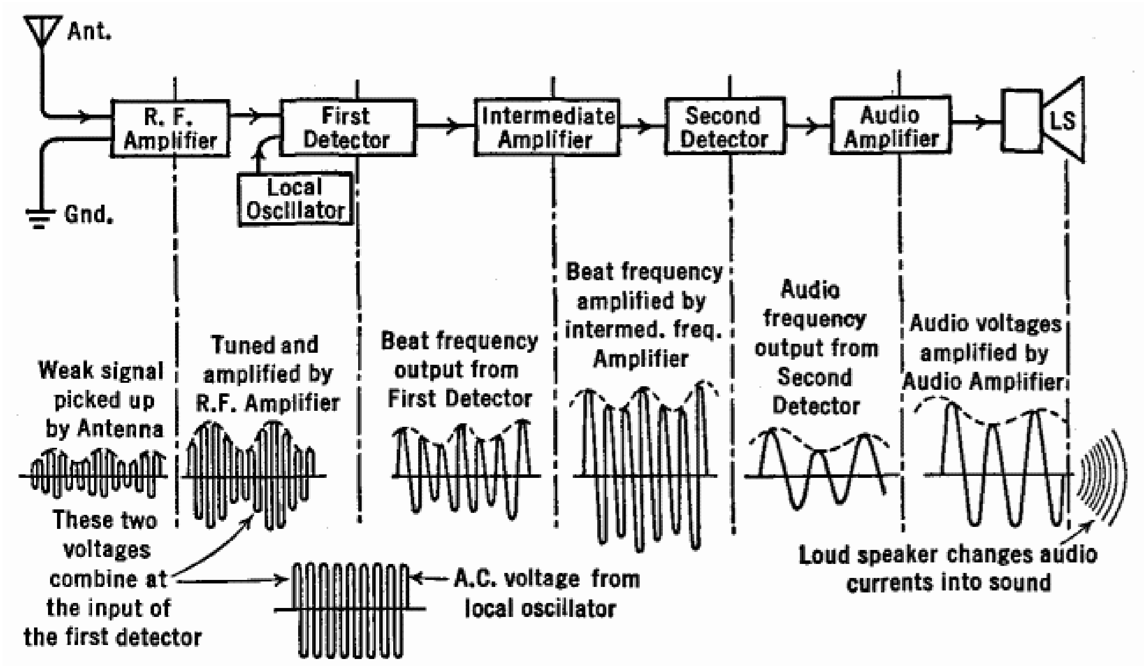

Figure 1: Block diagram of a superheterodyne radio

care to combine elements into a single tube whenever possible. The block diagram also neglects vital elements such as the power supply and AVC.

In this section, I will connect this theoretical model of a superheterodyne to the actual components in an All-American Five, focusing on a few of the subtleties that arise from the model EC's design choices.

2.1 Power supply

Before we begin to look at the components that directly modify the incoming signal, it is important to look at the power system. Like any tube-based electronic appliance, this radio must provide its tubes with three different supply voltages: filament power, B+ power, and grid bias. Let us examine the first two of these requirements—grid bias is connected to the discussion of AVC, so we will save it for later.

2.1.1 Filament power

As is typical of All-American Five radios, the Emerson EC has a remarkably simple solution to filament supply: the five tubes are designed to be connected in series to unregulated line power. All five tubes are designed to draw 150 milliamps of current, and their voltage ratings sum to 121 volts.

The pilot light, a small bulb rated for 4.5V, is connected in parallel with a small segment of the filament of tube 35Z5. This creates a current divider between the bulb and the 35Z5 filament, allowing the bulb to run on less than the full 150 mA of filament current. Likewise, that smaller section of filament is thinner than the rest as it carries less current. This leads to an interesting (and common) failure mode: if the pilot light burns out, the thin section of 35Z5 filament must carry all 150 mA of current–well beyond its maximum rating. This leads quickly to tube failure, so one must be pay attention and turn the radio off immediately if its pilot light ever burns out.

2.1.2 Plate voltage

The plate supply, commonly known as B+, is produced by half-wave rectification of the AC line voltage. First, the 35Z5 diode is used to cut out the negative side of the AC; next, a large pi filter. This filter, composed of a pair of large (20 μF) capacitors and a large inductor (the speaker field coil), removes the AC components from the rectified line, giving a direct current B+ supply at the peak voltage of the incoming AC.

A more worrying aspect of the Emerson EC's power supply is its use of a hot chassis: that is, the metal chassis is tied directly to the B- supply. This is a potential shock hazard–an issue that I will discuss in depth in a later section.

2.2 Oscillator

2.2.1 Superheterodyne theory

The superheterodyne radio, patented by Armstrong in 1917, uses the nonlinear characteristics of a certain vacuum tube to 'mix'—that is, multiply—the incoming RF signal with a sinusoid from the local oscillator, producing sum-and-difference components. By adjusting the oscillator frequency, one can maintain a constant IF over a wide range of input RF frequencies.

The Emerson EC uses a Hartley oscillator configuration to produce its mixer frequency. This implementation has two interesting features: amplification using the first two grids of a heptode and the use of capacitive coupling between two coils wound around a transformer.

To understand this oscillator, it is instructive to consider the two necessary (Barkhausen) conditions for oscillation in steady state:

1. The total phase shift introduced in the feedback signal is $n \times 360°$.

2. The loop gain is equal to one.

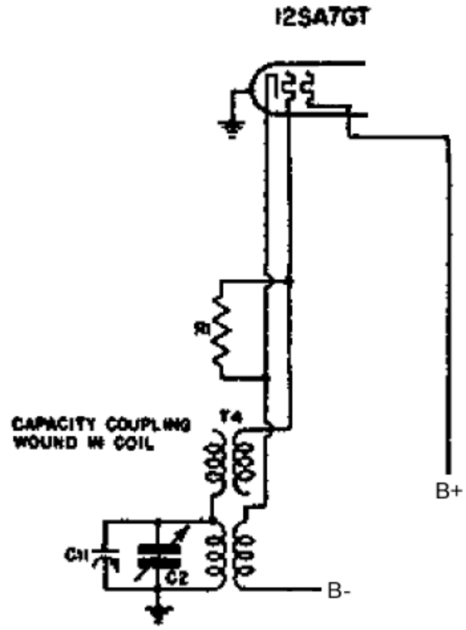

Figure 2: Emerson EC Hartley oscillator

First, note that the common-plate topology is non-inverting and the grid and cathode are tied to the same end of the transformer. Since no phase shift occurs, the first criterion is satisfied.

Second, consider the gain around the loop. The second grid, tied to B+, acts as a plate, creating a common-plate configuration with a gain of slightly less than one. For any signal that appears on the first grid, then, a slightly smaller signal appears on the cathode ($A_v < 1$). This signal is amplified as it passes through the transformer, as the winding on the left is larger than the one one on the right (see figure 2). This signal is capacitively coupled to the first grid, completing the loop. If the total gain around the loop is one, then the system will oscillate.

2.3 Signal path

After the converter, the signal passes through an IF tank and into 12SK7, a second IF pentode. From there it proceeds through another IF tank and into one of the diodes of 12SQ7, which acts to rectify the IF signal. C15 removes the high-frequency components of the IF, leaving only the audio signal and a small amount of sawtooth-shaped ripple. This signal passes through the triode part of 12SQ7, giving another increase in amplitude. The plate is capacitively coupled to the next audio stage, 50L6.

In order to maximize power transfer into the speaker, it is important to match impedances between

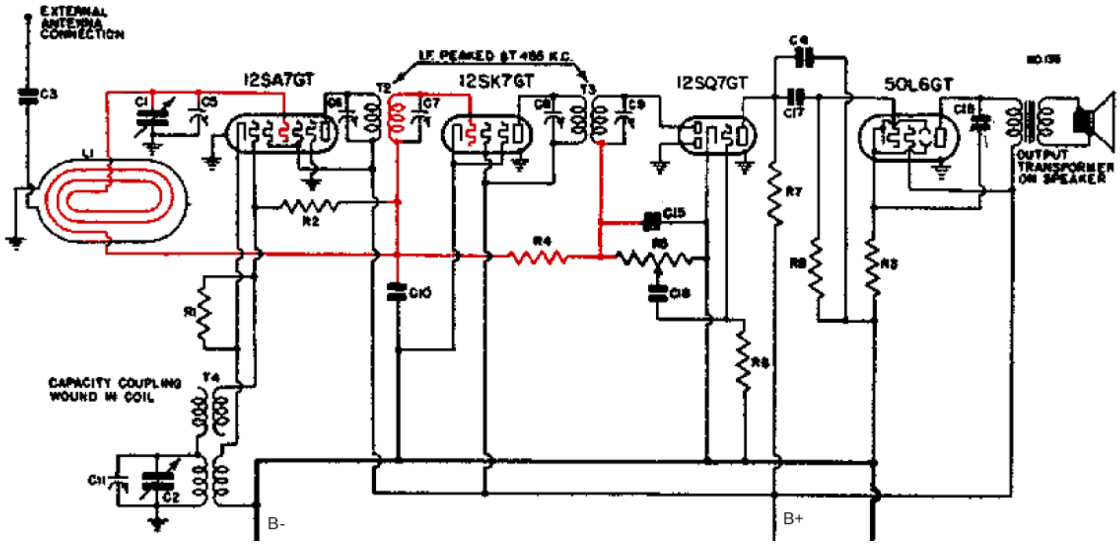

Figure 3: The automatic volume control bus, marked in red

the last tube and the speaker. Because the impedance of the speaker is very low compared to the output impedance of 50L6, an output transformer with a high turns ratio is placed between the two. This 'reflects' a much higher impedance back to 50L6, improving efficiency.

2.4 AVC

The AVC exists to maintain a constant volume level between stations of widely varying RF power. Amplifier gain can be adjusted by varying the grid bias on a tube: as the bias voltage becomes more negative, gain is reduced. This allows for a clever system of negative feedback, where the DC component of the detector output is used to control the gain of the previous stages.

In the Emerson EC, both the 12SA7 and 12SK7 are controlled by the AVC. This DC voltage is applied to the grid via the AVC bus (see figure 3), which is at a negative voltage relative to B-.

In order to be useful, the AVC voltage must vary quickly (to allow it to adjust to new stations while tuning), but not too quickly (such that it would vary in response to music or voice). This reaction time is controlled by an RC pair—C10 and R4 in this case, giving a time constant of 0.15 seconds.

3 Restoration

3.1 Initial state

Upon first inspection, the radio appeared in reasonably good condition. The knobs turned freely and the dial cord was intact; mechanically, everything appeared sound. Cosmetically, its exterior looked fine apart from a few shallow scratches. In short, the radio did not look abused; a further diagnosis was not possible without disassembly.

Upon removal of the case, several new problems were apparent. First of all, a tube was missing; its socket was clearly marked 12SQ7. A second tube, 50L6, had a cracked base but appeared to be otherwise intact; it would possibly also need to be replaced.

Further examination of the various connections underneath made it clear that my radio was hot chassis—the B- bus consisted of numerous solder points where wires were tied directly to the steel chassis. This was a common design decision at the time; it saved the expense of running a wire between the dozen or so components that connect to B-. (The cost of a foot of wire, of course, is small compared to the savings in assembly cost—a much more significant factor.) Unfortunately, however, it has the notorious side-effect of making contact with the metal chassis a significant safety hazard.[2]

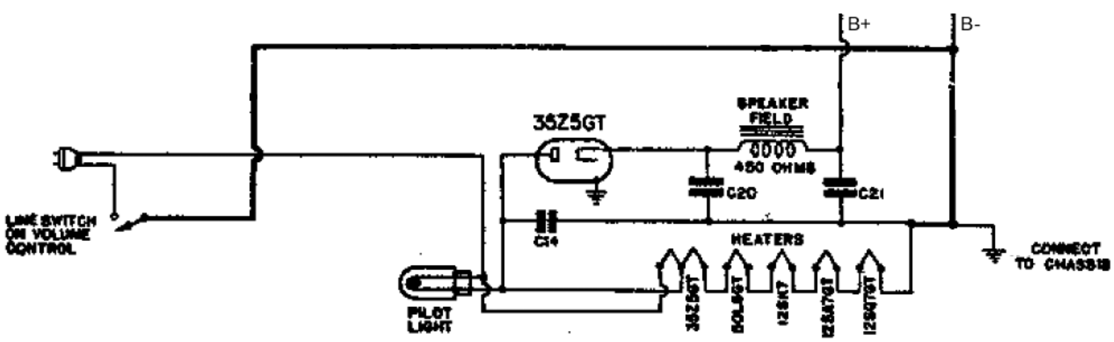

Figure 4: Emerson EC power supply prior to safety modifications

3.2 Safety modifications

Before the radio could be turned on for the first time, several modifications had to be made. The first goal was to replace the dangerous nonpolarized line cord with a new polarized one and move the switch from

[2]The March 1998 issue of *Radio Age* has a great article entitled "Making AC-DC Radios Safe" that explains this problem in detail and suggests the method I've used to correct it.

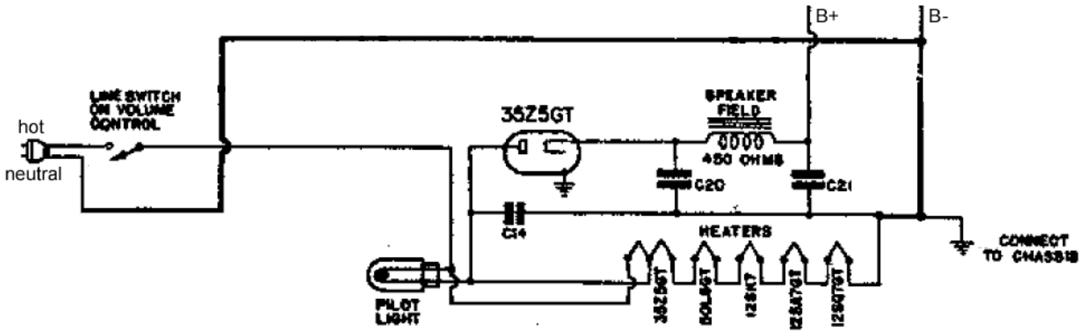

Figure 5: Emerson EC power supply with rewired plug

the neutral to the hot side of the circuit. With this modification, one terminal of the switch is the only electrically live component in the entire radio is hot when it is turned off.

The original line cord was attached to the switch and one pin of the 35Z5's heater—the chassis was connected directly to the other terminal of the switch. I first clipped out the existing line cord and replaced it with a polarized plug, taking care to tie the neutral pin to the chassis and the hot pin to the switch. I then used heavy stranded wire to tie the other side of the switch to the 35Z5.

After making this modification and testing for continuity between the chassis and neutral pin, it was time to attempt powering things up for the first time. I borrowed a 12SQ7 tube from another radio, plugged my radio into an isolation transformer and variac, and slowly applied power. Nothing caught fire—in fact, the radio began to crackle slightly and play talk radio! Encouraged by the lack of total failure, I moved on to the next step of my restoration.

3.3 Maintenance

Several steps were taken to clean up the internal workings of the radio. First, I used a paintbrush and compressed air to blow accumulated dust out of the chassis and gently scoured the tubes with steel wool. Next, I applied a layer of DeoxIT to the tube sockets to clean the socket and tube pins. To reduce the rough crackling that occured upon turning the volume knob, I injected a blast of DeoxIT into the potentiometer to break up corrosion.

A small amount of repair was necessary to repair damage to the speaker I'd unintentionally caused while cleaning; I managed to tear one edge of the paper cone. By carefully pushing the torn paper back into place and soaking it in superglue, I was able to create a solid bond that held together better than the original paper. This same superglue was also used to reattach the dial indicator, which had come unglued during disassembly.

After this mostly cosmetic maintenance, the radio appeared to be in good shape; it received audio and no longer crackled badly when I turned the volume knob. There was a slight hum to the audio, however—a sure sign of degraded capacitors. These would be the next things to go.

3.4 Replacement parts

The radio had capacitor of a variety of types: dry electrolytics, wax-moulded paper, and mica. Only the first two types needed to be replaced; mica capacitors are not in danger of failing with time. Table 1 shows the substitutions I made.

Reference	Existing part			Replacement part		
number	capacitance	rating	material	capacitance	rating	Other comments
C4	.0002 μF	600 V	tubular	220 pF	???	Ceramic replacement; unknown rating
C10	.01 μF	200 V	tubular	.068 μF	630 V	Schematic suggests .05 μF
C16	.002 μF	600 V	tubular	.0022 μF	630 V	
C17	.02 μF	400 V	tubular	.022 μF	630 V	
C19	.02 μF	400 V	tubular	.022 μF	630 V	Schematic suggests .03 μF
C20	20 μF	150 V	dry	33 μF	160 V	Dual electrolytic
C21	20 μF	150 V	dry	33 μF	160 V	Dual electrolytic

Table 1: These fixed-value capacitors were replaced in the Emerson EC radio.

3.5 Tuning

The schematic gives instructions for IF alignment. I followed them verbatim, being sure to adjust from right to left down the signal path:

> Swing the variable condenser to the minimum capacity position. Feed 455 kc to the grid of the 12SA7 tube through a .01 mf condenser and adjust the four i-f trimmers for maximum response.

I also adjusted the oscillator to correct the position and spacing of the indicator dial. Indicator dial calibration can be modified in two ways: by adjusting the position of the needle on the shaft and by adjusting the capacitance of the circuit to adjust spacing. Both adjustments are necessary to correct the dial reading.

Since the oscillator is most affected by capacitance at high frequency, I began by tuning to a 600 KHz AM signal and adjusting the needle to match. With the lower end of the dial fixed, I proceeded to adjust the capacitance at the high end of the dial. This was accomplished by generating a 1600 KHz signal, adjusting the dial to 160, and turning the trimmer capacitor until the signal peaked. After these adjustments were made, I confirmed that the dial correctly displayed the frequency of incoming radio stations.

3.6 Cosmetics

As the radio's plastic case was in good condition to begin with, very little effort was required. I scraped off a few specks of what looked like white paint with my fingernail. I then polished the exterior with two coats of NOVUS Fine Scratch Remover, followed by a fine spray of Plastic Clean & Shine.

With this final touch, the Emerson EC was finally ready for reassembly and display. Not only did it receive great-sounding audio, it looked fantastic—a true piece of art!

4 Measurements

4.1 Capacitors

Reference number	Marked capacitance	Measured capacitance	Measured D	Measured series resistance
C10	10 nF	164.6 nF	.2081	38.7 kΩ
C17	20 nF	24.63 nF	.0632	855 kΩ
C20	20 μF	28.05 μF	.0732	3.47 Ω
C21	20 μF	24.91 μF	.1132	6.02 Ω

Table 2: Measurements of four removed capacitors using the HP 4192A impedance meter

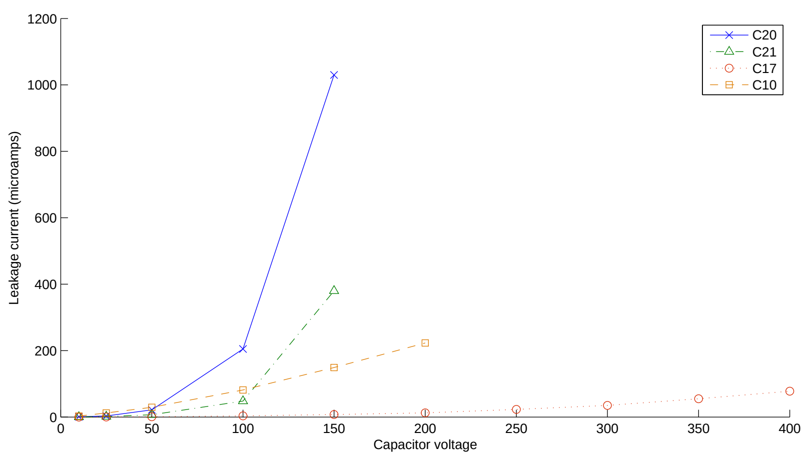

Figure 6: Leakage current from four removed capacitors

4.2 Tubes

Two of the original tubes needed to be replaced. 50L6, the audio output pentode, tested slightly below par. It was still amplifying fine, however—perhaps slightly less efficiently than might be expected. It also had a cracked base, however, making it a sure candidate for replacement.

More surprising, however, was the case of 12SQ7. Originally borrowed from another (untested) radio, the tube seemed to be in perfect working order; it detected well, and the amplification seemed more than sufficient. According to the tube tester, however, the tube was a total dud—the triode was far below standards, and the diodes appeared to be completely nonconducting. It was promptly replaced with a new tube, to no great effect—the new tube passes all tests easily, but the sound is indistinguishable from before.

Tube	Test type	Measured transconductance	Expected transconductance	Result?
35Z5	diode	[3]	[3]	pass
Old 50L6	triode	4800 $\mu℧$	5650 $\mu℧$	fail
New 50L6	triode	10500 $\mu℧$	5650 $\mu℧$	pass
Old 12SQ7	diode 1	[3]	[3]	fail
Old 12SQ7	diode 2	[3]	[3]	fail
Old 12SQ7	triode	200$\mu℧$	1850$\mu℧$	fail
New 12SQ7	diode 1	[3]	[3]	pass
New 12SQ7	diode 2	[3]	[3]	pass
New 12SQ7	triode	3500$\mu℧$	1850$\mu℧$	pass
12SK7	pentode	2650$\mu℧$	1260$\mu℧$	pass
12SA7	amplifier	2750$\mu℧$	760$\mu℧$	pass
12SA7	oscillator	7500$\mu℧$	2840$\mu℧$	pass

Table 3: Tube tester data for Emerson EC, including replacement tubes

4.3 Audio characteristics

I replaced the speaker with a five-watt 8.2Ω resistor and fed the radio 400 Hz audio at 50% modulation on 1.0 MHz carrier. I then examined the audio output with an oscilloscope. As the volume was increased, clipping began to occur on the upper edge of the signal at 2.38 V. With the signal amplitude reduced to slightly below this value, I used the distortion meter to calculate the percentage of total distortion. The result was 0.013% distortion—a remarkably low figure.

[3] The diode test does not measure transconductance; it requires a minimum needle deflection to pass.

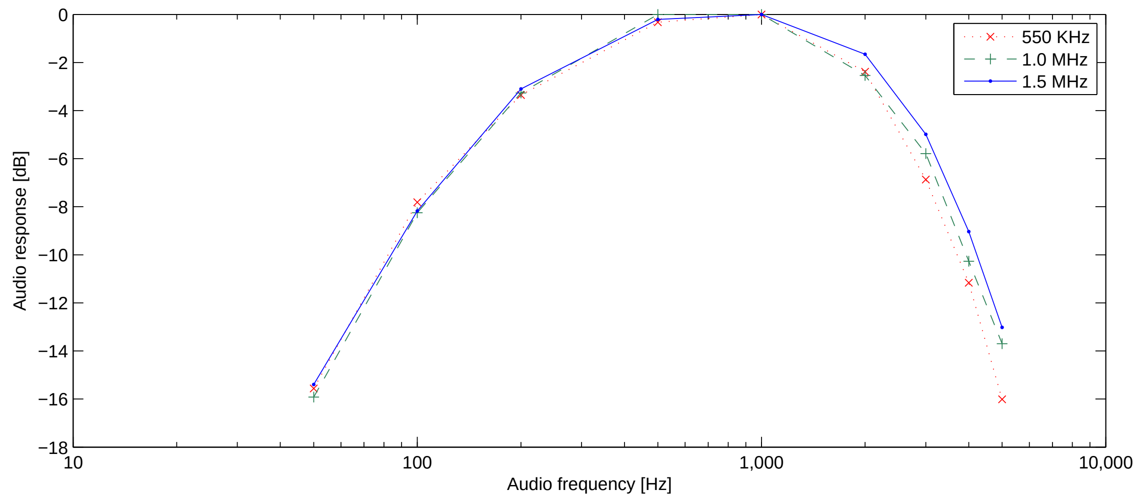

Figure 7: Audio bandwidth response to AM signal at three carrier frequencies

4.4 Measured voltages

The schematic gave a set of nominal DC voltages for various parts of the radio, including B+ at the plates of each tube. All voltages are given for a line voltage of 117.5 V_{rms}. Since the radio received a line voltage of 121.6 V_{rms}, I have renormalized these voltages to obtain expected values. All values are taken with the antenna shorted.

DC voltage to be measured	Measured value	Expected value (renormalized)
12SK7 plate	86.2 V	99.1 V
12SK7 screen	86.2 V	99.1 V
12SA7 plate	86.2 V	99.1 V
12SA7 screen	86.2 V	99.1 V
12SQ7 plate	46.7 V	31.0 V
12SQ7 screen	46.7 V	31.0 V
50L6 plate	79.6 V	84.9 V
50L6 cathode	5.8 V	5.8 V

Table 4: Comparison of measured DC voltages to nominal values

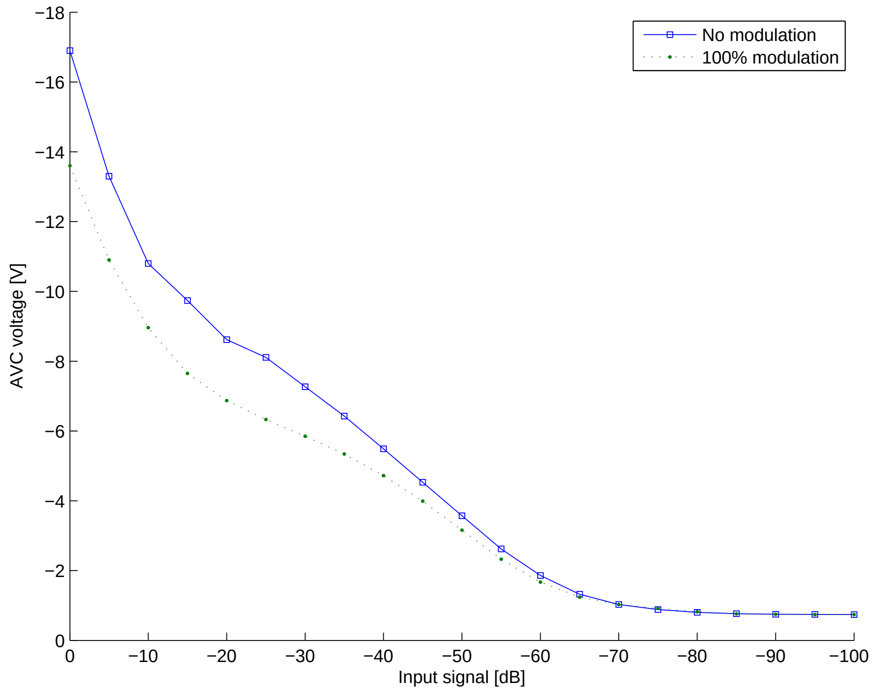

Figure 8: AVC voltage vs. signal applied. Decibels measured relative to $2V_{pp}$ applied to antenna

5 Evaluation

This radio came out of restoration in great condition. Everything seems to work properly: tuning works flawless, the AVC operates over many orders of magnitude in signal, and the audio response is quite good. As long as the volume level is kept below clipping, distortion is remarkably low—only a tiny fraction of a percent of the total signal.

One possible improvement would be widening the bandwidth to receive the full 5 KHz. There are several 'bottlenecks' in the signal path that could contribute to this narrowing in bandwidth, including the following:

1. The sharply-tuned IF tanks
2. Capacitive coupling between 12SQ7 and 50L6
3. Poor response of the output transformer and speaker

Of these, the second is likely the most significant—and certainly the easiest to fix.[4] A future modification to try, then, would be replacing C4 with a smaller value to decrease the amount of signal shunted to B-.

Another puzzling issue that was never resolved involves the behavior of the oscillator in low-signal conditions. In areas with no signal to receive, especiallymy home at East Campus, the radio will occasionally emit an audible tone that changes in pitch as you sweep across the band. This is never a problem in good receiving conditions, such as in the 34-600 hallway. Indeed, the primary reason this behavior has not been resolved is simply that it disappeared again before I could try to fix it!

These are but minor contentions, of course—this is a fantastic radio. In truth, it performs far beyond my expectations–for casual listening, this radio is about as good as it gets.

[4]This came up in conversation during my radio presentation on Friday, 5/9/08. Thanks to Ron for the tip.