Measurements on a Tube Radio

Peter D. Hiscocks

Professor Emeritus, Electrical Engineering, Ryerson University

phiscock@ee.ryerson.ca

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1 Introduction

In this paper we show how a modern measuring instrument, the Syscomp CGR-101 oscilloscope-generator, can be used to view the operation of vacuum tube based equipment. We give an example, showing measurements on an *All American Five* tube radio, the Nipper II, made by RCA in Montreal, Canada. Modern instruments are very useful in diagnosing faults in vacuum tube based equipment, but there are some precautions that need to be observed – for the safety of the human being, and the preservation of the equipment.

1.1 Isolation Transformer

The All-American-Five has no transformer isolation from the AC power line. The electrical common connection in the radio, which connects to the metal chassis, is connected to one side of the AC line cord. The power cord on the AA5 is not polarized – it can be plugged into an AC outlet in two different ways. For one configuration, the radio common (and chassis) are connected to the AC line neutral, which is within a few volts of earth ground. For the other configuration, the circuit common and chassis are at AC line potential, 117VAC.

Now consider what happens when the AA5 common is at 117VAC and you connect an instrument ground (such as a CircuitGear oscilloscope probe) to the radio circuit common. In effect, there is a dead short across the AC line. This will put a momentary surge of tens of amperes through the circuit, vapourizing sections of circuitry and components. (Ultimately, the fuse breaker in the distribution panel may open, but that will be far too late to prevent damage.)

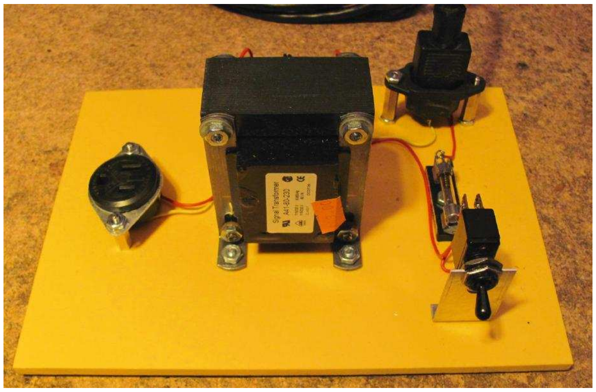


Figure 1: Isolation Transformer

Some people suggest *floating* the oscilloscope off ground. For example, if the host laptop is battery powered, then one can theoretically connect the oscilloscope ground to the radio ground. There will no longer be a dead short across the AC line, but any exposed metal parts of the oscilloscope and laptop can possibly be at a potential of 117VAC. A human operator is at great risk of serious shock or electrocution.

The safe way to work on such a radio is to power it from an *isolation transformer*. This is a 1:1 transformer that delivers 117VAC to the radio from a secondary that is totally isolated from ground. Consequently, either terminal of the secondary can be connected to an earth ground without risk.

One can buy a ready-made isolation transformer, for example, one of the the 171 series from Hammond Manufacturing [1]. The 100VA model is available from Digikey for $100. The 171 series is 'ready to go', with a primary circuit breaker, primary plug and secondary outlet wired in.

You can also build your own isolation transformer, as shown in figure 1. I used the Signal Transformer A41-80-230, an 80VA unit available from Digikey for $34. The AA5 radio requires 0.3 amps at 117V, or 35VA, so this transformer has an adequate power rating. The A41-80-230 transformer has dual primaries and dual secondaries. For 117VAC operation, the primaries are wired in parallel. Check the data sheet carefully: the dotted terminals must be connected together.

[1] http://www.hammondmfg.com/pdf/PB0231.pdf

The circuit is otherwise very straightforward: the primary is connected to the AC line, in series with a fuse and on-off switch. The secondary is connected to an AC outlet, which is now the source of isolated AC voltage.

A cautionary note: an *autotransformer* consists of one transformer winding tapped at various points to step up or step down the input voltage. A common example of autotransformer is the *Variac* adjustable transformer, which can be used to adjust line voltage. An autotransformer does **not** provide isolation from the AC line. If you want adjustable line voltage and isolation, you need both an autotransformer and an isolation transformer.

1.2 Caution: Lethal Voltages

Modern solid-state equipment uses supply voltages typically in the range of 3 to 15 volts. Tube equipment supply voltages start at 100 volts and go up from there. The supply voltages in a tube power amp may be something like +350 volts. In an RF linear amplifier or microwave oven, thousands of volts are not unusual. The casual approach to safety that works for a 3.3 volt op-amp could result in deadly harm from a vacuum tube based unit.

The radio used as an example in this note has a relatively modest supply voltage - under 170 volts. However, this is still high enough to cause a nasty shock or even, under the right circumstances, cardiac arrest. The isolation transformer minimizes the chance for a supply-to-earth-ground shock, but it can still happen if one hand is on the chassis common and the other touches a high voltage.

- Work slowly, deliberately and carefully.
- Shut off the power when making changes to the circuitry or measuring configuration.
- When using the oscilloscope to measure a signal, first use a DC multimeter (such as the Syscomp DVM-101) to measure the DC voltage at that point. If you need to observe a small AC voltage riding on top of a large DC value, block the DC value with a capacitor. Make sure the capacitor has the necessary voltage rating.
- If the scope probe has a switchable $\times 1/\times 10$ setting, start the measurement in the $\times 10$ position.
- When injecting a signal from the generator, bear in mind that the low internal resistance of the generator will short out any DC or AC voltage at that point in the circuit. Use a blocking capacitor to prevent the DC from flowing through the generator.

1.3 Thermal Shock and the Adjustable Line Transformer

Vacuum tubes are heated by a *filament*. The resistance of the filament is low when the filament is cold. As a result, there is a large inrush of current through the filaments when the radio is first switched on, especially if the moment of switch-on coincides to a peak in the AC line voltage. (The same effect is at work with incandescent lamps, which tend to burn out at the time they are switched on.) There may be some mechanism in the radio to minimize this inrush current. If not, or if you wish to be cautious, you should apply line voltage from an adjustable transformer (figure 2). Turn on the power switches and increase the supply voltage up to 117 volts.

Figure 2: Line Voltage Autotransformer

1.4 Being Paranoid: First Time Operation

The first time you operate the radio from the isolated supply, it's a good idea to measure the isolation between the radio chassis and the ground point of the measuring instrument. With the radio plugged into its power source (the isolation transformer) and power off, use an ohmmeter to measure the resistance between the radio chassis and the measuring instrument ground (such as the barrel of a BNC connector). The reading should show *open circuit*.

Now enable power to the radio. With a voltmeter on the AC voltage range, measure the potential between a ground point on the oscilloscope and the chassis of the radio. The voltmeter should read zero volts.

If the system passes both these tests, it's safe to work on.

2 The All American Five AM Radio

The All American Five (AA5) is a 5 tube AM band radio that was produced in great numbers for the consumer market in North America. The background, history and some technical information on the AA5 is available here: [1], [2], [3]. Description and technical information is in RCA Receiving Tube Manuals, [4] [5].

This particular radio has a label on the bottom of the case which states the requirement for a license, according to the Radio Telegraph Act (Canada) of 1938. Mandatory licensing of 'private receiving stations' was abolished in 1952, [6] so this set was sold some time between those two dates. It's still operating properly in 2011, some 60 years later.

(a) Case

(b) Chassis Front

(c) Chassis Top

(d) Chassis Wiring

Figure 3: Nipper II

2.1 The Schematic

It's often helpful when trying to understand some new circuit to redraw the diagram from scratch. Ideally, the most positive power supply voltage should be at the top of the page, and the signal should flow from left to right. Compare the original schematic of figure 12 on page 11 with the redrawn schematic of figure 4 on page 5. It's *much* simpler to trace the power supply wiring and some of the signal connections on the redrawn version.

Throughout our exploration of the radio operation, we will refer to the redrawn schematic.

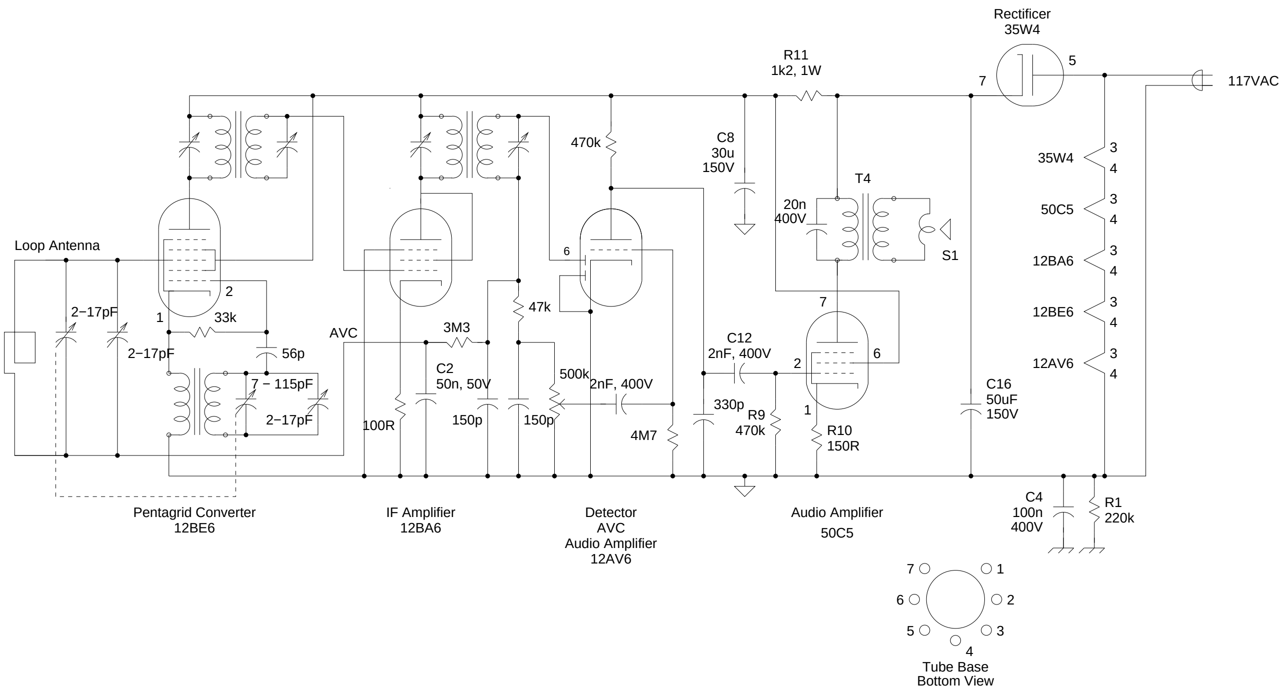


Figure 4: Redrawn Schematic

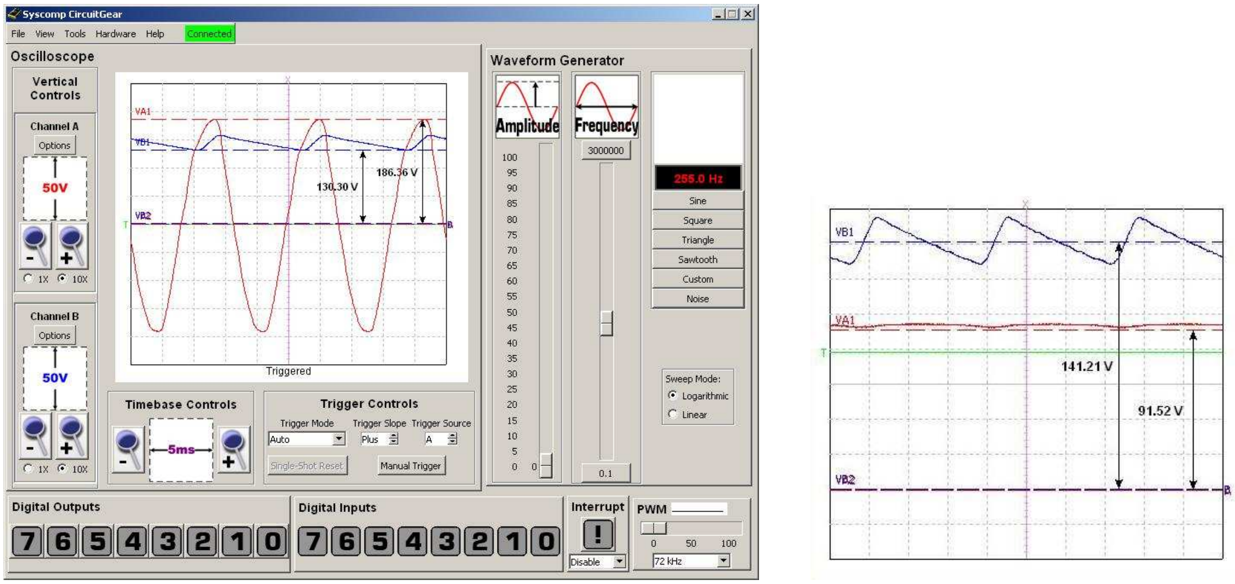
2.2 Chassis Connection

The metal chassis is connected to the power supply common (which is one side of the AC line!) via 220k resistor R1 in parallel with 100nF capacitor C4. It would be convenient to use the chassis as the ground point for our measurements. Then this resistor and capacitor will appear in series with our measurement probles. Will that work?

The input resistance of the Syscomp DVM-101 digital voltmeter is 10MΩ. Consequently, the 0.22MΩ resistance will introduce a 2.2% loading error, which is negligible in this application.

The Syscomp CGR-101 CircuitGear oscilloscope has a maximum input range of ± 25 volts, well below what is required to measure the AA5 supply voltages. We will need to use a $\times 10$ oscilloscope probe, which extends the range to ± 250 volts. Again, the 0.22MΩ resistance has very little effect in this application.

What is the effect of the bypass capacitor C4? Consulting a reactance slide rule, the capacitance is equal to the resistance at 7Hz. Above that frequency, its impedance is less than the resistance. At the 60Hz power supply



(a) Input & Output

(b) Output & 2nd Filter

Figure 5: Power Supply Measurements

frequency, the impedance will be roughly 25kΩ. At the RF frequencies of the radio (540 to 1600 kHz), this capacitance will appear essentially as a short circuit. In either case, the capacitor impedance is much less than the instrument impedance and it will not affect the voltmeter or oscilloscope.

So: The measuring instrument ground (voltmeter or oscilloscope) can be connected to the chassis.

2.3 Input, Rectifier and First Filter

Referring to the schematic of figure 4, the line voltage is connected to the 35W4 half wave rectifier. The rectifier conducts on positive half cycles of the line voltage. These pulses are filtered first in 50μF capacitor C16. The waveforms of the input voltage and capacitor voltage are shown in figure 5(a)[2].

There are several interesting features in these waveforms:

- The supply voltage has a peak value of around 186 volts.
- The voltage drop across the rectifier diode, when conducting, is about 3 minor divisions on the screen, or 30 volts. That compares to about 0.7 volts for a modern silicon rectifier diode. (This is a reason to be careful in replacing a tube type diode with a semiconductor diode. The output voltage will be larger and may exceed the voltage rating of other components.)
- The input sine wave is slightly distorted during the conduction interval of the diode. The current flow during that interval creates a voltage drop in the isolation transformer.

[2]Figure 5(a) shows the complete GUI (graphical user interface) for the Syscomp CircuitGear oscilloscope used in these measurements. Figure 5(b) and subsequent figures just show the waveform display area.

- The peak to peak ripple across the filter capacitor is about 30V. Knowing the time interval of the discharge and the change in voltage, one could calculate the current drain in that section of the power supply.

  Alternatively, one could measure the current at that point using an ammeter and then calculate the actual filter capacitance.

The filtered power supply voltage is used to power the 50C5 audio power amplifier stage. One might reasonably expect the 30 volt ripple on the supply voltage to show up as a nasty hum in the loudspeaker. However, the 50C5 is a *pentode* (ie, 5 element) tube, and so the output is relatively high incremental output impedance. In other words, the pentode behaves as a voltage-controlled current source, and the value of the plate voltage has little effect on the plate current. Consequently, the ripple is largely ignored.

2.4 Second Filter

The rectified and filtered power supply voltage is then further smoothed in RC lowpass filter R11 and C8. The input and output voltages are compared in figure figure 5(b).

- There is a 50 volt drop between the average input voltage to this filter and the output.
- This supply voltage, which is used for the remaining stages of the radio, is about 91 volts.
- The R11, C8 filter is very effective in removing ripple from this much lower supply voltage. The peak-peak ripple is about one minor division, or 4 volts.

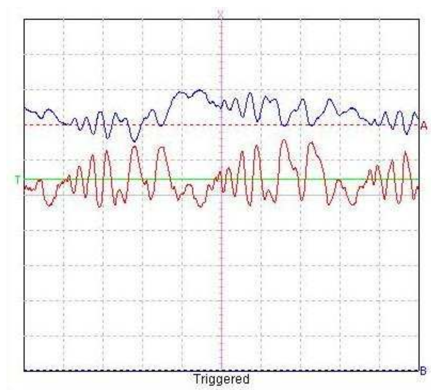


Figure 6: Audio Power Amplifier. Upper trace, Plate voltage, 20V/div. Lower trace grid voltage, 2 volts/div

2.5 Audio Power Amplifier

The input to the audio power amplifier stage is the grid terminal at pin 2. The output is on the plate terminal at pin 7. Figure 6 shows the signals on the two terminals.

The top trace is the plate voltage which shows some of the low frequency undulation due to the ripple on the power supply voltage, as mentioned earlier. The smaller undulations are the audio signal.

The lower trace is the grid voltage. Notice that the grid voltage signal and plate voltage signal are out of phase: as one increases, the other decreases.

Comparing the amplitudes of the two audio signals and allowing for the scale factors, the amplifier voltage gain is approximately 5 volts/volt.

Now look at the positioning of the zero voltage points for both traces. Zero voltage for the plate signal is at the bottom of the screen (the small B to the right of the display area), indicating that the signal is sitting on a large positive DC voltage.

Zero voltage for the grid signal is *above* the trace, indicating that the signal is sitting on a negative voltage. This negative voltage is caused by electrons that hit the grid while flowing from cathode to plate in the tube. The electrons flow out of the grid negative voltage and establish a negative voltage across the grid resistor R9.

(Alternatively, think of current flowing into the grid, which makes the grid terminal negative with respect to ground.) This current is known as *grid leak* current[3].

The cathode terminal at pin 1 is biased to about +10 volts, which is supposed to make the grid-cathode voltage negative by the same amount.

Amplifier Frequency Response

The audio amplifier frequency response was measured using the network analyser function of the CGR-101. The result is shown in figure 7. This is the relative amplitude of signals between the input to the volume control and the output across the loudspeaker.

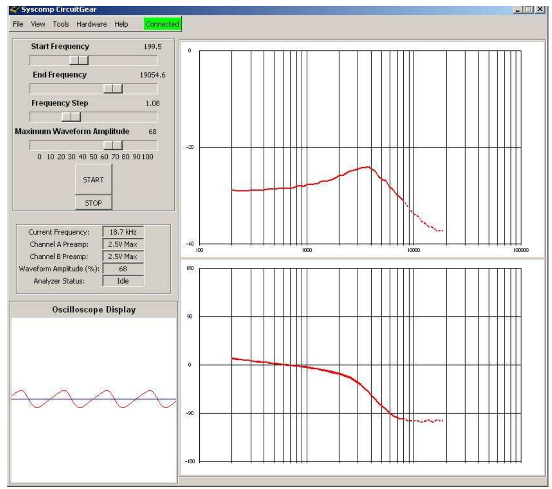


Figure 7: Amplifier Frequency Response

The input signal was applied from the CGR-101 generator output to the top of the volume control. The oscilloscope channel A, which is the reference input for the network analyser function, was connected to the same point. The oscilloscope channel B was connected across the loudspeaker terminals. The voltage at the top of the volume control is the negative half-wave rectified signal from the previous intermediate-frequency amplifier. As a result, the top terminal of the valume control is sitting at a negative potential that depends on the magnitude of the received radio signal. If we connect the generator output of the CGR-101 to that point, the low internal resistance of the generator (150Ω) will shunt that voltage to ground. This is not particularly harmful, but just to be safe we put a 680nF DC blocking capacitor between the output of the generator and the volume control terminal.

The frequency response shows a 5db rise, peaking around 4KHz. This may or may not be reflected in the actual acoustic output, which depends on the response of the loudspeaker. In any case, no one would mistake this for a high-fidelity device.

Audio Output Transformer

Curious about the turns ratio of the audio output transformer, I injected a signal into the volume control and measured the voltage at the primary (red trace) and secondary (blue trace), as shown in figure 8.

The turns ratio is about $N = 20 : 1$. This is usually expressed as the ratio of impedances, which is $N^2 = 400$. Then an 8 ohm speaker would appear as 3200 ohms in the primary of the transformer.

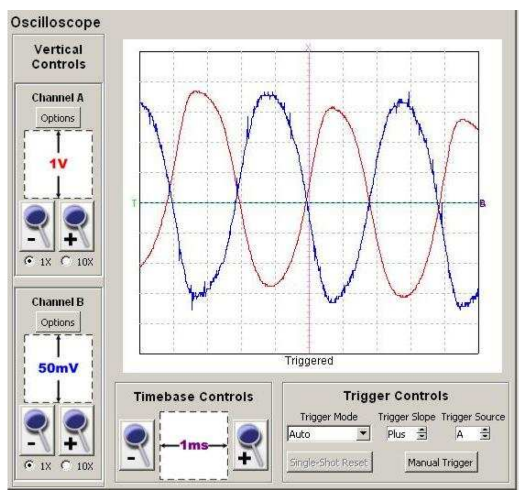


Figure 8: Output Transformer Ratio

[3]When first measured, the grid voltage was sitting about +9.5 volts. Looking at the schematic, almost no current should be flowing in the grid resistor R9, and the voltage should be around zero. The fact that it was positive suggested that C12 is leaking current from the very large voltage at the plate of the preceeding 12AV6. Capacitors do tend to deteriorate with time, and this one is over 60 years old, so it's not surprising that it would be come leaky. Replacing the capacitor stopped the leakage current and allowed the audio volume to increase *substantially*.

2.6 IF Amplifier Output

The IF (intermediate frequency) signal should consist of an RF carrier at the IF centre frequency (455kHz), amplitude modulated by the audio signal. This isn't clearly evident from an oscilloscope waveform trace, but it shows up nicely on a spectrum display (figure 9). The trace near the cursor is the IF centre frequency at 455 kHz. Notice that there is some slightly observable width to this signal, caused by the audio modulation. The low-frequency spectrum is the demodulated audio. The other spectrum spikes are other radio stations.

As the radio is tuned, the radio stations move left or right on the spectrum display, giving a simple panadaptor readout.

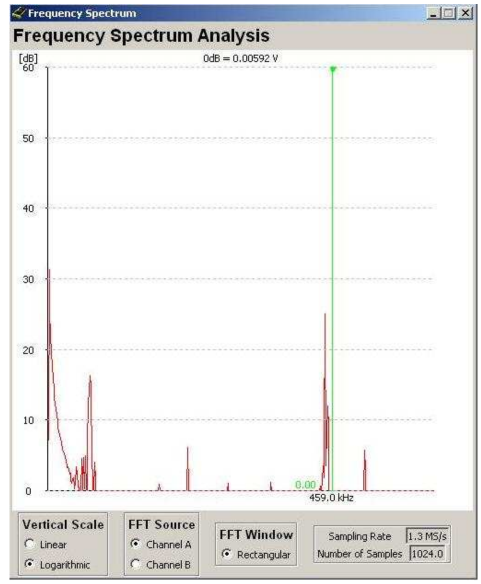
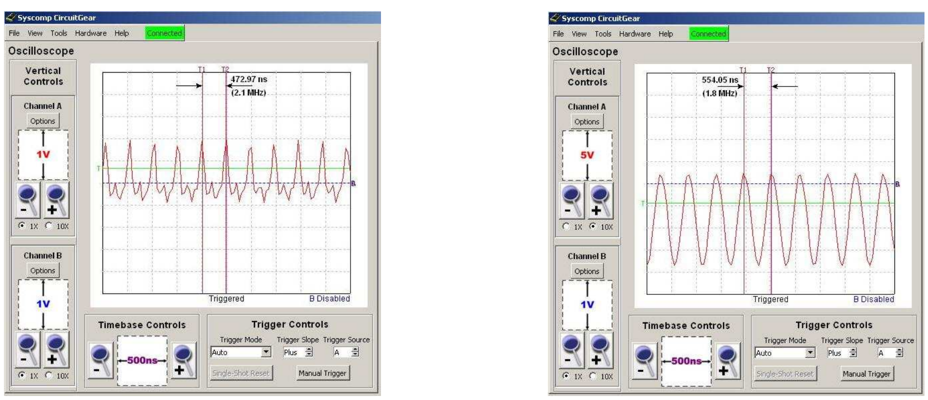


Figure 9: IF Amplifier Output

2.7 Local Oscillator



(a) Cathode (Pin 2)

(b) Grid (Pin 1)

Figure 10: Local Oscillator Waveforms

In a superheterodyne radio such as this one, the RF tuning and the local oscillator track each other so that the local oscillator frequency is different from the signal frequency by a fixed amount, the IF frequency. The two signals are mixed (multiplied) and the output frequency is then fed into the IF (intermediate frequency) amplifier. As a consequence, the selective amplification of the signal can take place at a fixed frequency.

The tuning of the RF circuit and the local oscillator is by two air-variable capacitors, which can be seen in figure 3(c).

In AM band radios, the input frequency tunes over the AM broadcast band, 540 to 1600 kHz (or kilocycles, as it used to be called). The intermediate frequency is 455 kHz. The local oscillator (LO) uses *high side injection*, so it is always 455 kHz higher than the input frequency. Consequently, we should see the frequency of the LO vary between 995kHz and 2055kHz.

The local oscillator is the transformer-variable capacitor network connected between the cathode (pin 2) and first grid (pin 1) of the 12BE6 Pentagrid Converter. The waveforms are shown in figure 10.

The cathode waveform shows a series of pulses. As the radio is tuned, their frequency varies from 987 to 2100kHz. This measurement was taken with the probe on the x10 setting, so that it presents 10MΩ in parallel with approximately 2 picofarads of capacitance. The cathode of the tube is a relatively low impedance point, so that helps to minimize the effect of attaching the scope probe. However, radio frequency circuits are exquisitely sensitive to loading, and the probe has enough of an effect to shift the frequency of operation slightly. Changing the probe to its x1 setting causes a much larger error in the measured frequencies.

The grid waveform shows a sine wave at the local oscillator frequency. The tuned network in the local oscillator has removed the higher order harmonics so that the injected signal into the mixer is relatively clean. This is a higher impedance point than the cathode and the probe has a substantial effect on frequency.

2.8 IF Amplifier Response

For best operation, the IF frequency should be centred on 455kHz, have the proper bandwidth, and be symmetrical in shape. At the time this radio was constructed, the IF response was measured by what the British called a *wobbulator*: an RF signal generator that could be swept over a range of frequencies. The output of the IF amplifier was sent to the vertical plates of an oscilloscope. At the same time, the signal sweeping the RF was applied to the horizontal plates of the scope. The result was an amplitude vs frequency display of the IF response. In order to calibrate the display, there were *frequency markers* generated by crystal frequency standards that showed up as bumps on the display[4].

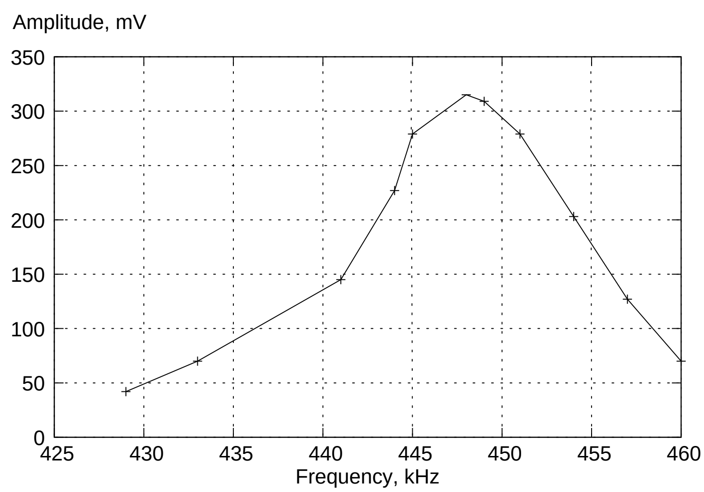


Figure 11: IF Amplifier Response

That technique is not possible with the CGR-101, but there is an alternative. The CGR-101 oscillator frequency can be set to a precision of 0.1Hz, so the RF input to the radio can be set very precisely. This can be used to sweep the IF frequency over a range, while measuring the output voltage from the IF amplifier. The exact IF frequency of a waveform can be measured quickly and accurately using the CGR-101 oscilloscope Automeasure facility.

The CGR-101 generator output was connected to the antenna terminal of the radio. Channel A of the CGR-101 scope was connected to the IF amplifier output, at pin 6 of the 12AV6. The automatic level control loop was disabled by short-circuiting capacitor C3[5].

Referring to figure 5, there are some features of the CGR-101 generator that make this measurement straightforward. The labels at the top and the bottom of the frequency slider are *clickable*. When mouse-clicked, an entry

[4]The author recalls visiting a radio factory in Toronto in the 70's, where a row of workers adjusted the responses according to a grease-pencil template on the oscilloscope screen.

[5]This appeared to have no effect on the amplitude of the signal, so it may be that the ALC is defective on this radio.

widget opens up and one can enter a new value. You can narrow down the range of the frequency slider to the RF frequency of the radio: 540kHz to 1600kHz. As well, the frequency readout display is clickable and one can enter a specific frequency.

For this measurement, set the frequency of the radio to some spot on the dial where there are no major radio stations. Slowly sweep the radio frequency over its range, watching the signal amplitude on the oscilloscope. At some point, you will see an increase in the signal.

Zero in the frequency limits to bracket the region where the IF amplitude ranges from a small value, to maximum, back to small amplitude. This is the region of measurement.

Step the frequency through this region. At each frequency, use the Automeasure facility of the scope to measure the IF frequency. Use the amplitude cursors to measure the amplitude of the sine wave.

Figure 11 shows the result for this radio. The response peaks at 448kHz rather than 455kHz and is rather unsymmetrical. It could probably be improved. However, before moving the centre of the IF, it would be wise to check on the relationship of the local oscillator and signal frequencies. It may be that the LO is offset by 448kHz, in which case the radio is tuned correctly. Re-aligning an IF amplifier is not for the faint hearted - adjustments require special tools, a non-magnetic slug adjustment tool for the IF transformers and a non-magnetic miniature screwdriver for the capacitors. Furthermore, all the adjustments interact. You need to be able to read out the frequency of the local oscillator accurately, without affecting it.

2.9 All American Five Schematic: Original

Figure 12 is a copy of the original schematic, from reference [4].

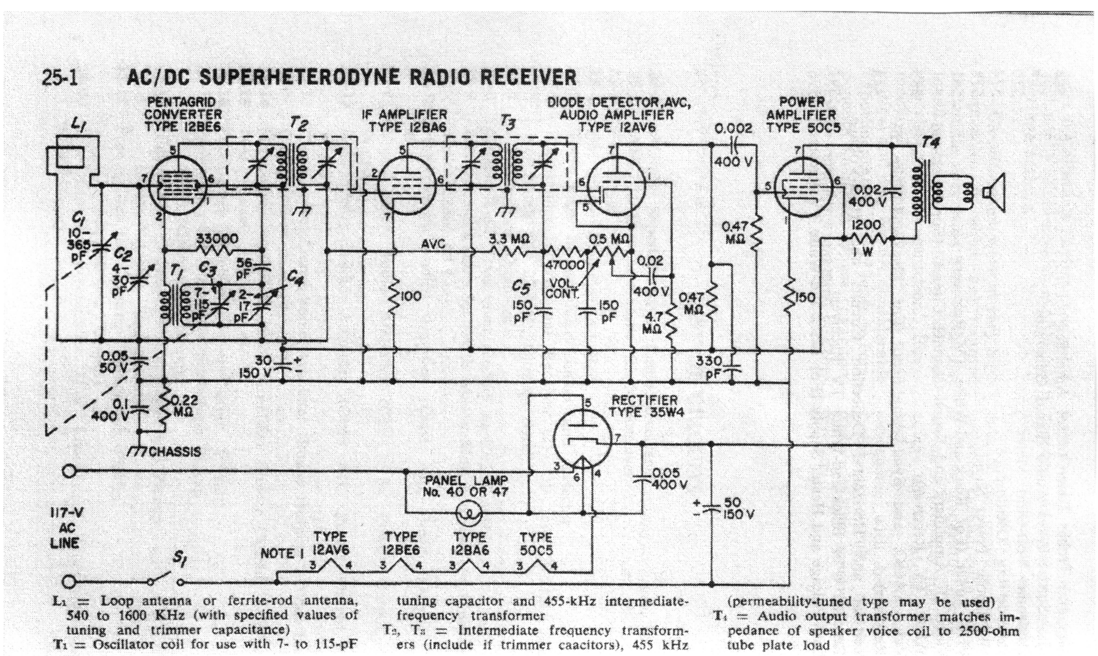


Figure 12: Original Schematic

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