FM Converter Based on Silicon Labs FM Tuner Chip (version 2 of the circuit board)

As seen in the AWA Journal!

Gord Rabjohn - V2 May 2026

This document describes my FM Converter project. Specifically, it refers to the second iteration of the circuit board. Please refer to an earlier version of this same document if you have the first iteration board

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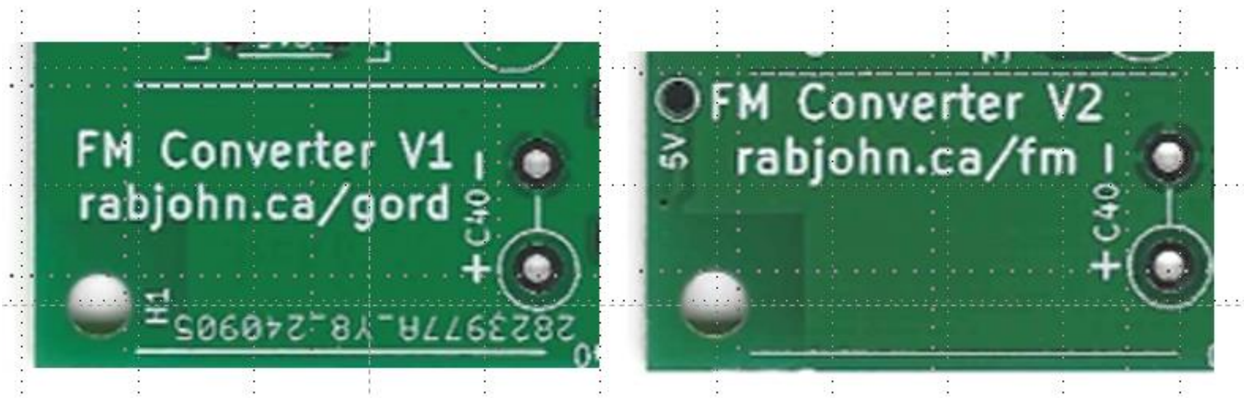

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1. Introduction

The AM band has become so devoid of interesting programing that it has become almost irrelevant. Unfortunately, most of our favorite radios receive only AM, and I am sure you have wondered if it is possible to convert an AM radio to FM. Although both AM and FM radios historically use the same superheterodyne architecture, it would be impossible to retune a traditional tube AM radio to receive FM. The frequency of the FM band is about 100X higher than AM. So, better active devices are required, and lead length becomes much more critical. The bandwidth of the FM signal is at least 10X wider, so the IF amplifier in an AM radio is far too narrow. Finally, a different detector is required for FM. Even if it was possible, permanently modifying a vintage radio seems wrong.

This FM converter circuit is intended to convert post-1932 tube AM radios to FM operation. A single band radio will operate just as it always did, only FM stations will be received. Although the tuning mechanism works as before, the tuning dial markings on the host radio become meaningless; it can be recalibrated for the FM band if desired. It will work on multiband radios, but the other bands will be disabled. This device will convert a radio by just connecting to the tube sockets. The radio is not permanently modified in any way: no soldering, no permanent radio changes, no need to realign. The adaptor can be removed without affecting the antique value or the authenticity of the radio in any way, just by pulling it out of the tube sockets. It will work with most tube superheterodyne radios, notably the very common “All American 5”.

I have been playing with different versions of this concept for years, and this is by far the best implementation. All of my previous versions except version 2 (that used a conventional FM tuner) used the Philips TDA7088 FM tuner integrated circuit. This is a very clever analog bipolar chip that uses unconventional tricks to receive FM. Its intended market is inexpensive toys and novelty radios that are tuned with 2 buttons: search and reset. I drove the radio’s varactor diode with the tuning voltage. These chips are not without their quirks. Tuning is tricky and sensitive and touchy. That makes them drift as they warm up. Fidelity is not fantastic. High frequency response is limited, and harmonic distortion (at low deviation) is specified at 1%. Some stations never tuned-in clearly. And it requires a large number of external capacitors. You were able to buy them in “Dollar Stores” and the like for a few dollars, but they are becoming less common. I built a tuner based on the original (Philips branded) TDA7000 using selected silvered mica capacitors, with pretty similar results to the dollar store versions. The TDA7088 chip is considered obsolete (though it is still widely available (as of fall 2024)) so it was time to try something new. I found the Silicon Labs Si48xx series of mechanical (actually, potentiometer) tuned chips, which turned to be ideal for this application. They offer excellent audio quality, such that the radio, not the converter, will almost always be the factor limiting audio performance.

In addition, in this version I used the 74HCT9046 (Philips) phase locked loop chip. This chip is an improvement on the standard 74HC4046 (they are almost pin-for-pin compatible), with improved stability, and an improved phase detector.

In addition to the other versions that I have made (see https://rabjohn.ca/gord/projects/fmconversion/ , I draw your attention to another ingenious approach out of France: https://www.paleophonies.com/FM-DW/FM-DW.htm They use a little microcontroller rather than my analog approach to achieve similar results.

If you are thinking of trying to convert a radio to FM, I recommend this, my most recent version over any of the TDA7088 versions, because a) a circuit board makes assembly easy, and building it straight-forward, b) the FM performance is better than earlier versions, and c) no permanent changes are required to the radio. For the sake of readability, I will refer to this circuit as the "FMC" (FM Converter) for the rest of this document.

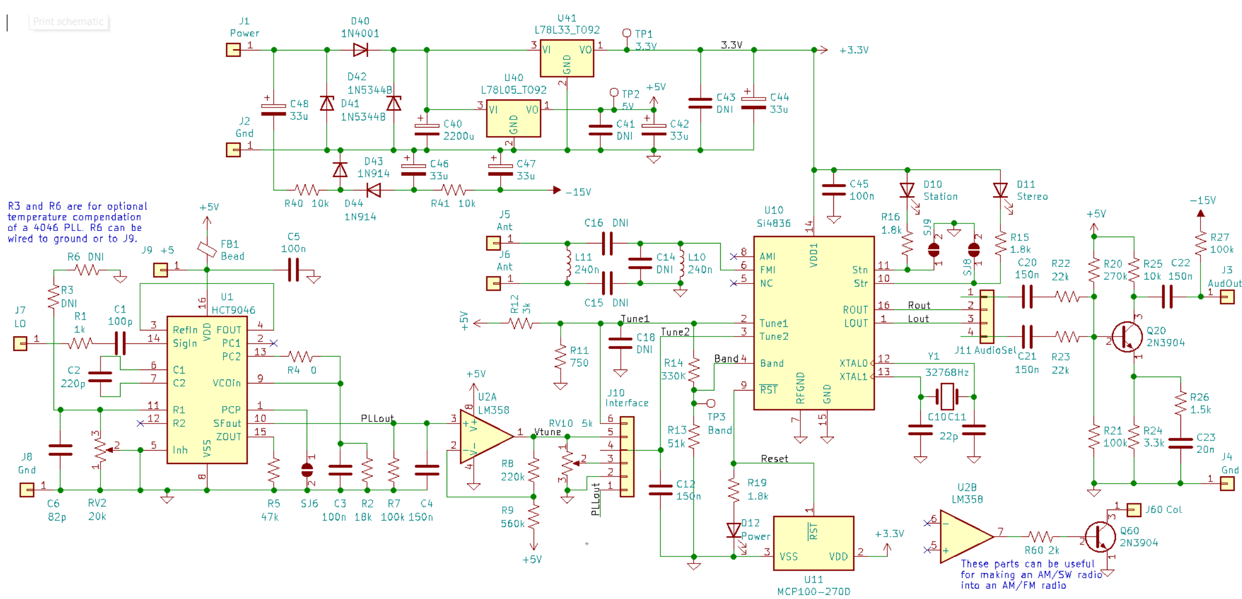
The first iteration of this board was fabricated in September 2024. It worked really well, and about 20 were sold all over the world. There were some minor edits that I wanted to do, and these were fabricated in April 2026. The changes to the board include:
-Enlarge the solder holes for the external connections
-Place a hole behind the two potentiometers so they can be adjusted from either side of the board.
-Add provisions for temperature compensation of the 4046 PLL.
-Add a few test points.
-Make a place for a resistor from VCO pin 9 to ground (see discussion of PLL stability).
-Add Q60 and R60 which can be used by the advanced experimenter to make a converter that turns an AM/SW radio into an AM/FM radio (there is a separate document that describes this).
-Make the negative voltage supply a doubler to make it more effective as an artificial AGC voltage.
-Change layout around PLL to reduce noise coupled into the PLL input terminal.
-To make room, some components that were never used in the first version were removed.

It looks like a long list, but the changes are all small, mostly cosmetic. At a glance, the board looks the same as V1 and has a very similar BOM. The physical size, mounting hole location, general layout, block diagram, main components, and alignment procedure all remain the same. The only significant change to the schematic is the doubler for the negative supply (and this can be populated either way). The changes to the layout of the PLL, reducing the noise into the PLL input, has improved its performance somewhat but has not obviated the need for the extra stability components. The performance of the version 2 board is similar to the version 1 board, so if you have the first iteration board, don't despair. As long as you have built it to the latest version (added the stability components) you are not missing anything. This document describes only the 2nd iteration. If you have the 1st iteration, please refer to the earlier version of this document.

2. FMC Circuit Description

In a typical superhetrodyne AM tube radio, a local oscillator (LO) that runs between about 1MHz and 2MHz is mixed with the signal from the antenna, producing an IF signal (the difference frequency: the LO frequency minus radio station frequency) at typically about 455kHz. This IF signal is amplified and detected and fed to an audio amplifier. As the LO frequency is adjusted, specific stations in the AM band are converted to the IF frequency and tuned in. When the FMC is used, the same LO frequency is used to tune an FM radio in the converter. The audio output of the FMC is fed directly to the radio's audio amplifier, skipping the IF amplifier and detector. This way, the radio appears to operate just as it had when it received AM, but FM stations are received instead.

Refer to the schematic diagram of the FMC below. U1 is a phase locked loop (PLL) operating as a frequency-to-voltage converter. It converts the host radio's variable LO frequency (about 1MHz to 2MHz) to a variable voltage. As you tune the host radio across the band, this voltage tracks. This voltage is level shifted by U2 to a level suitable for tuning U10, a single-chip FM tuner with "mechanical" (actually, voltage) tuning. It is designed for use with potentiometer tuning, but in this design, it will tune with the voltage generated by U2. Q1 provides about 10dB of audio amplification, and the whole circuit is supported with 2 voltage regulators.



Phase Locked Loop (PLL) Section

One way to translate a variable frequency to a variable voltage is with a Phase Locked Loop (PLL). My earlier FM converters used a 74HC4046 PLL chip for the frequency-to-voltage converter. This chip is not very stable (over temperature or voltage) and earlier designs of the FM converter circuit drifted as they warmed up. An improved chip, the 74HCT9046 PLL (similar but not identical pin-out and functionality to the standard HC4046) has superior VCO stability and a better phase detector. However, it is discontinued (while the HC4046 is not) (which is a shame) which makes it more difficult to find, so the circuit board has been designed to accommodate either a HCT9046 or a HC4046. See page 8 for thermal compensation tips if you must use a 4046.

The 4046/9046 family of chips has a voltage-controlled oscillator (VCO) and two different phase detectors. The phase detector outputs are at pin 2 and 13, and I have had good success with the phase detector at pin 13. C3 is the loop filter; a simple first order loop is used. Any of the 4046/9046 datasheets will describe the loop filter design. The 9046 uses an external resistor, R5, to set the charge pump current, so R4 is 0 ohms. If the HC4046 is used, R4 determines the charge pump current and R5 is not used. Pin 1 is ground on a HCT9046 and open-circuited when a HC4046 is used. The VCO frequency is set by C2 and RV2, so these must be stable parts. The VCO operates without an offset (so 0V input would theoretically produce a 0Hz output) so a resistor is not required on pin 12.

I found that the 9046 PLL had some issues (actually probably one issue). This manifests itself when driven at lower amplitude (under about -15dBm (measured across 50 ohms), which is about 0.04V RMS. This is measured at the small capacitor near the LO tube; the amplitude at the board is about a fifth of this, depending on cable length). When driven with a 50 ohm generator, the issues are small; them are more noticeable when driven thru a small capacitor. At higher amplitudes, it behaves as one would expect. The symptoms are:

-it is sometimes unstable (oscillates at just over 10kHz). This is not in itself a big issue because the oscillation will be filtered out by C4/C12, however it causes hysteresis when it starts or stops. The oscillation can be seen with an oscilloscope on pin 13/9 on the 9046.

-The PLL voltage output depends on LO input amplitude. Ideally, the output tuning voltage (VCO voltage) should have no LO amplitude dependence (you would expect it to be either locked, or become unlocked and go to a rail).

-The PLL not as sensitive as expected (because either of the above issues starts at low power).

I found that as adding a small (33-100pF) capacitor in parallel with RV2, and adding a resistor (18k) parallel with C3 makes a huge improvement. There does not seem to be a down-side to adding these parts, but I cannot explain why it is necessary. The 4046 seems to have a similar issue, but I have not played with it as much.

When the fix is applied, the PLL output remains absolutely steady over a >40dB range of input power when driven from a 50 ohm lab-grade generator (until the PLL falls out of lock at low power). It remains in lock even when the LO drive is reduced to 0.005V RMS . When driven from a higher impedance source (like thru the 5pF capacitor), there is some LO amplitude dependence at low drive, which may suggest a sensitivity to noise.

If there is adequate LO drive from the host radio (and most radios have plenty), this should not be a problem. If a problem is suspected, then extracting the LO using a larger capacitor (larger than 5pF) will also help. But nipping it in the bud (by adding R2 and C6) is good practice and recommended.

The input to the phase detector from the host radio is brought in through R1 and C1 which provide a DC block, and some protection from overdrive. (Note that only 5-10pF series capacitance is needed. I generally populate 100pF on the board, and use a smaller capacitor (or “gimmick” capacitor made from wire) close to the tube. More details are mentioned in section 5.1). Since U1 is fundamentally a digital chip (which could interfere with the operation of the FM tuner), provision has been made to block noise from the supply lines with extra decoupling and a ferrite bead, FB1 and C5. For the same reason, there is a provision for a shield around this section of the circuit. I experienced no interference, so FB1 and the shield were not used.

The HCT9046 VCO control voltage (and therefore the voltage output, proportional to the input frequency) is specified to operate from about 1V to about 4V (with a 5V supply). This must be scaled down to the 0V to 1V required by the FM tuner chip. This scaling is done with U2A, R8, R9 and RV10, using the 5V supply as a reference voltage. (R7 is the VCO buffer load as specified by the data sheet. C4 filters any noise coming from the PLL) With a 1MHz to 2MHz LO, this circuit is designed so the VCO control voltage will be about 1.5V to 3V. At Pin 1 of U2, this voltage is 0 to 2.2V which is scaled down to 0 to 1V with RV10.

RV2 and RV10 are adjusted so that the host radio tunes the FM band. The host radio is set to the low end of the band (where the bottom end of the FM band should start, say 540kHz). RV2 is adjusted until the voltage at pin 5 of J10 is just above 0V (as RV2 is adjusted, the voltage at pin 5 will be 0V over part of the rotational range of RV2, and increasing over the other part of the range. It should be set at the inflection point). Then, the host radio is set to the upper end of the band (where the upper end of the FM band stops, say 1600kHz), and RV10 is adjusted until 1V is seen on pin 3 of J10. That should set the range correctly; as the host radio is tuned across the band, the voltage at pin 3 should vary from 0 to 1 volt. There should be enough tuning range so that IF frequencies of 175kHz to 500kHz can be accommodated. In operation, pin 3 and 4 of J10 are jumpered together.

Tuner Section

U10 is a single-chip FM tuner, which was developed at Silicon Labs. This product line was acquired by Skyworks (my former employer) in 2021. It is available at Digikey and Mouser among other suppliers. It employs a synthesized local oscillator (based on the 32kHz crystal) and digital signal processing to demodulate the FM. There is a family of these chips available in 2 package styles, some with AM and shortwave tuners, some with stereo demodulators. The FMC board is compatible (with minor changes) with the monaural Si4825, or the stereo Si4836.

I still marvel at how compact FM tuners have become. “In the old days”, a mono FM tuner required a chassis with at least 4 tubes, and often more. Stereo added 2 or more tubes. The alignment procedure required numerous adjustments and required a sweep generator and oscilloscope for a proper alignment. Transistors made everything smaller, but did little to simplify alignment. These tiny Silicon Lab integrated circuits require only a crystal (and crystal load capacitors), 2 resistors, decoupling capacitors, a tuning potentiometer, and a capacitor and inductor at the antenna input. They require no alignment, and the Si4836 provides a stereo output. Add a few more parts, and they receive AM and short wave! Remarkable.

The chips are designed to be tuned with a potentiometer supplied by an internally generated reference voltage on pin 2, with the tuning voltage (the “wiper” of the tuning pot) on pin 3. The actual value of the reference voltage is not critical; it can be varied by 0.2V without affecting the tuning. That is, this voltage is used both as a reference for internal ADCs and the tuning potentiometer. However, for this circuit to work predictably with the PLL, this reference voltage needs to be fixed. I do not know how the reference voltage varies over temperature or device-to-device, so I use R11 and R12 to fix it at 1.0V (based on the 5V regulator). These 2 resistors may not be necessary. The band is selected by the voltage (relative to the reference voltage on pin 2) on pin 4. The chip documentation shows 41 bands! The “bands” differ by the exact frequency extents, the threshold that activates the stereo and station tuning lights, AM vs. FM demodulation, and the FM deemphasis. North American FM standards require a deemphasis network with a time constant of 75us, most of the rest of the world uses 50us. The default 87-108MHz band is in use in most parts of the world. Other bands can be selected by changing the values of R13 and R14. 1% resistors (standard “E24” resistor values have been selected) are necessary to ensure that the correct band is selected.

Band	Deemphasis	R13	R14
87-108MHz	50us	16k	150k
87-108MHz	**75us**	**51k**	**330k**
86.5-109MHz	50us	82k	390k
87.3-108.25MHz	50us	82k	300k
87.3-108.25MHz	75us	160k	470k
76-90MHz	50us	150k	360k
64-87MHz	50us	150k	300k
76-108MHz	50us	120k	200k
64-108MHz	50us	360k	510k

The antenna input circuitry is designed for flexibility. The default, as suggested by the data sheet, is just L10, and C16 connecting to an antenna. However, better electrical isolation (very important for AC-DC sets) will be achieved if the antenna is coupled with a transformer, with L10 and L11 forming the transformer (in which case C14, C15, C16 are not used). The transformer allows operation with a balanced antenna like a folded dipole.

The Si4836 has provisions for a station tuning light that illuminates when a station is correctly tuned, and a stereo indicator. Si4825 does not support these indicators, and pins 10 and 11 must be grounded.

There is an internal Digital Signal Processing engine in these chips (strictly internal, software cannot be loaded onto these chips) that must be reset at power-up. A surveillance chip, U11, keeps the chip in a reset state until the power supply voltage has stabilized. The crystal supplies the clock for the digital circuitry and provides a reference for the internal synthesizer.

The Si4836 includes a stereo decoder, and there are 2 outputs which generally must be combined using two jumpers on J11. Alternatively, 2 converters and 2 host radios can be employed, one on the left and one on the right. The Si4825 does not have a stereo decoder, and only pin 16 is used for the audio output. In either case the audio output is lower than a typical AM radio tuner, so a simple amplifier using Q20 boosts the audio by about 10dB. R26, C23 provide an optional treble boost, in case your vintage radio has weak treble. The amplifier may not always be necessary, and it may be possible to eliminate the circuitry surrounding Q20 if your radio has adequate gain.

Power Supply

The power supply is a simple half wave rectifier with three-terminal regulators. The PLL requires 5V for operation and the tuner chips require 3.3V. Since there are many different power supply scenarios depending on the host receiver, there are several options for the power supply implementation. There is also a simple unregulated negative supply (a voltage doubler) which is used to reduce the gain of the host receiver's IF amplifier (an artificial AVC voltage), and to reverse-bias the host receiver's detector diode. Reverse biasing the detector diode reduces distortion if the detector diode remains connected. In installations where the converter runs off of DC voltage, this circuit (D43, D44, C46, C47, C48, R40, R41, R27) does nothing and can be skipped. In this case, disconnecting the detector diode is recommended.

Thermal Stability

We would like the tuner to stay correctly tuned as the radio heats up, and as ambient temperature changes. Temperature induced drift can occur in several places:
-The host radio LO could drift.
-The voltage-to-frequency characteristics of the VCO in the PLL could drift. This could be caused by the VCO itself (or the VCO timing elements: C2, RV2) or the PLL power supply.
-The VCO buffer offset voltage could drift.
-The op-amp level shifter could drift. Changes in the 5V supply will also cause drift.
-The FM tuner itself could drift.

The AM band (in North America, at least) is divided into 10kHz channels, and there are a little over 100 channels in the band. The FM band is divided into 200kHz channels, and there are about 100 channels in the FM band. So, conveniently, one channel of drift in the host AM radio is roughly equivalent to one channel of drift in the FM radio, and this is about a 1% (specifically, 1% of the width of the entire band) frequency change. Note that the FM radio has powerful AFC which will track drift. This is very useful, but also causes some unexpected results. If there are 2 adjacent stations, the AFC will tend to grab onto the stronger of the two. You can tune in the weaker one, but AFC may cause the tuner to switch to the stronger one if there is drift (especially at turn-on). So, drift should be minimized.

I measured several tube AM radios, and found in every case that the LO was very stable at the low end of the band, but tended to drift down in frequency (typically 8kHz in a half hour. Interestingly, my old Philco 71 was the best at 3kHz, possibly all the metal gives it a longer time constant). The temperature rise depends on the radio, and where in the radio the temperature is being measured, but I was seeing about 10C rise.

The PLL VCO in the 4046 is quite different than the improved 9046. The 9046 is quite good, exhibiting an increase in voltage (tuning drifts up as it warms up) at a given VCO frequency of about 1 channel width at the high end of the band (20C increase in temperature), and almost none at the low end. It is serendipitous that this compliments the host radio characteristics, making the 9046 a very good choice. The 4046 does not fare as well. It drifts down (adding to the drift in the host radio) by well over 2 channel widths (a little less at the low end of the band). If the 4046 must be used, then some form of temperature compensation should be considered. My RCA “Little Master” (5-tube AC-DC set with a wooden back that tends to keep the heat in) using a FMC (situated inside the radio) built with a 4046 requires a couple of re-tunes over 1 hour of operation when tuned to a station at the high end of the FM band. The same radio using an FMC with a 9046 does not need retuning.

In more rigorous tests in a temperature chamber (with an excursion from 20C to 60C), the voltage output of the 9046 (at the high end of the band) increased by about 2%, whereas the output voltage of the 4046 decreased by over 7%. At the low end of the band, the 9046 drops by under 1%, and the 4046 drops almost 5%.

I temperature compensated a 4046 (specifically a TI 74HC4046A) by adding a thermistor. With trial and error, I found that a 100K NTC thermistor (a Murata 0603 with a B value of 4250) in series with an 47K resistor pulling up on pin 11 did the trick. You may need to experiment with the value of the 47K series resistor to get flat temperature performance. Lower values cause more compensation so tend to make the tuning voltage increase as temperature rises. There are provisions for these resistors on the board, (R3 and R6) and they can be populated to pull to ground or +5 to provide compensation in either direction. Having done this, I still believe the 9046 is more stable with temperature, does not need the compensation, and easier to implement.

3. Construction

Skills and Tools Needed to Construct the Board

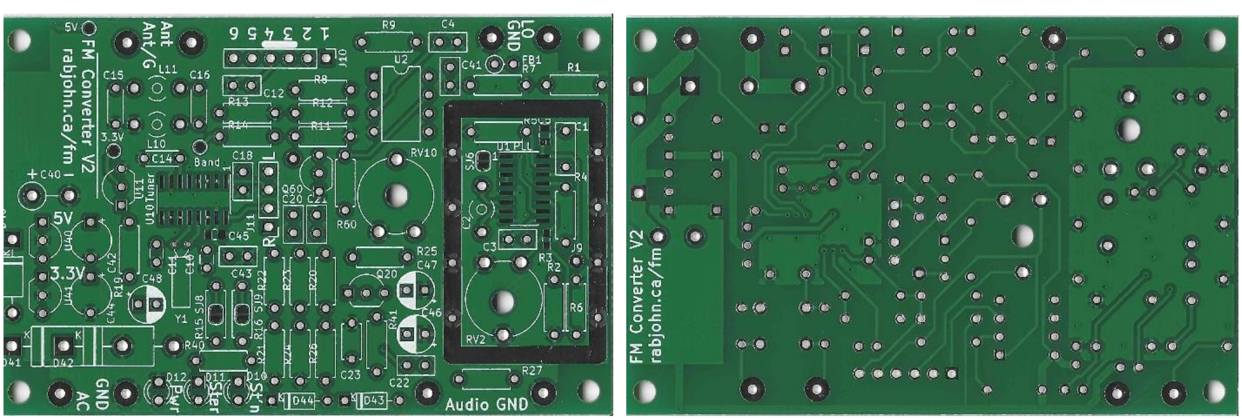
You will need a basic understanding of electronics. Familiarity with circuit board assembly techniques is necessary, but there are lots of resources describing these. You will need to be able to identify electronic parts: capacitors, resistors, ICs (be able to find pin 1), diodes. You will need a voltmeter and likely an ohmmeter. Mounting the surface-mount parts (16 leads at a 0.05” lead pitch) will require solder paste, a microscope, fine tweezers, and either a hot-plate, heat gun, or an oven to reflow the solder paste.

Skills and Tools Needed to Install the Board

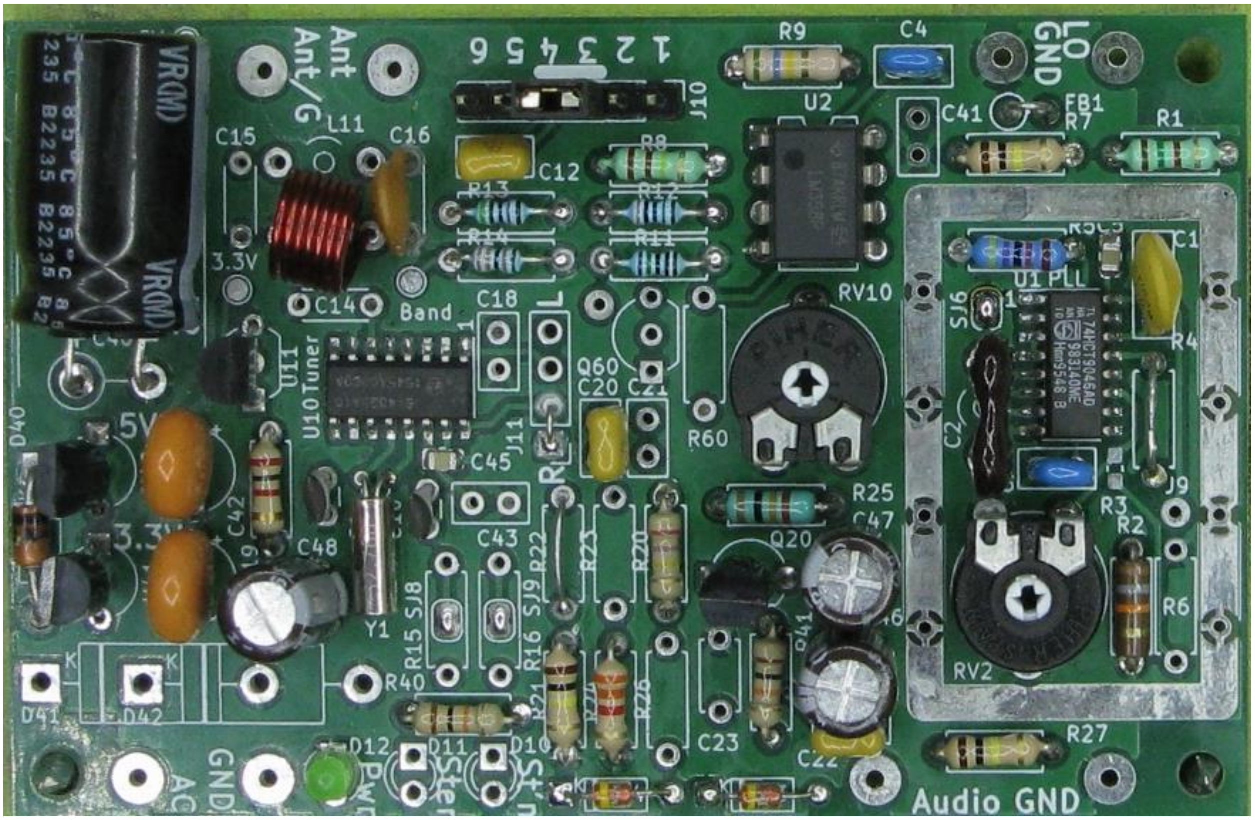
You will need a basic understanding of electronics. You will need to know the difference between parallel and series circuits. You will need to know enough about vintage radios to know if your radio is working properly, and to identify parts in the radio. You will need a voltmeter. As you will probably be making socket adaptors, you will need to be able to solder. Having access to dud tubes and tube sockets may be necessary.

Constructing the Board

A double-sided board has been designed and fabricated for the FMC, and I have bare boards available for sale.



Unpopulated board, version 2



A version 2 board populated with the Si4825 and 74HCT9046, with the negative voltage supply.

I have made a detailed document describing board assembly and parts procurement at https://rabjohn.ca/gord/projects/fmconversion/ . See FM_Converter_PCB_assembly_V2.pdf . Most parts use through-hole technology, but the two main ICs are available only in surface-mount packages, and should be soldered down first. First mount U1, U10, C5, and C45; the surface-mount parts. I place solder paste on the 16 pads on the board with a toothpick, then push the IC into the soler paste. I used a hot plate to reflow the solder, but an oven or a hot air gun can work too. Another technique I have used is to warm the board to ~100-150C (apply the solder paste before heating the board) , then use a fine soldering iron to locally heat each lead one at a time. The leads are at a 0.05” pitch, so definitely use solder paste and a microscope. I have seen very skilled technicians install these parts with a fine soldering iron and a simple magnifier, but if you are not skilled, I think you’ll need a microscope.

After assembling the surface mount parts, install the power supply parts and verify that the power supply generates the correct voltages. (apply 9V to the AC and Ground terminal (-ve to ground), and measure 3.3V and 5V at C41 and C42) Then, install the parts surrounding the tuner chip, U10, and make sure the tuner works (I connect a potentiometer (anything over 50K) to pins 2, 4, and 6 of J10 (wiper on pin 4) to allow me to tune it manually. Check for audio on J11). Then, install the parts around the PLL (U1). To test the PLL, set RV2 mid-way, and make sure the output voltage (pin 1 of J10) tracks when a variable frequency (1MHz to 2 MHz) RF signal generator is connected to the LO input. There are provisions for a shield around the PLL, but I have found it unnecessary. Finally, install the rest of the parts. Place a jumper on pin 3 to 4 of J10, and 2 jumpers on J11 (if present). Audio should now be present on the Audio Output pads on the board.

Note that not all parts need to be populated; there will be some empty footprints on the board.

Bill Of Materials for area around PLL. BOM depends on which PLL chip is used. DNI=Do Not Install

Ref	Value		Tolerance	Note	Purpose
U1	**4046**	**9046**		Part number of PLL chip	
C1	100pF		Not critical	Use >200V cap.	LO input DC blocking capacitor
C2	220pF		10%	Use a good, very stable cap. Mica preferred.	VCO timing cap.
C3	100nF		Not critical	Use a good cap.	PLL loop filter
C4	100nF		Not critical		PLL output smoothing
C5	100nF		Not critical	SMT : 0805 size	Local 5V decoupling
C6	33-100pF		Not critical		Stability
FB1	Short		Not needed		PLL supply filtering
R1	1k		Not critical		LO input protection
R2		18K			Improves PLL stability
R4	100K	Short	10%		PC2 loop filter
R5	DNI	47K	10%		PC2 current
SJ6	DNI	Short			Second ground for 9046
R7	100K		Not critical		Demod load
RV2	20K or 22K		Pot	Piher PT-10-LV10 series	Sets VCO Frequency
R3	100K?		Murata 0603	Footprint only on ver 2 board	Temp compensating thermistor
R6	47K?		Custom	Footprint only on ver 2 board	In series with thermistor
U1	74HC4046 or 74HCT9046			SMT: 16 pin SOIC	9046 is the preferred part

BOM for area around tuner IC. BOM depends on which tuner chip is used.

Ref	Value		Tolerance	Note	Purpose
U10	**4825**	**4836**		Part number of FM chip	
C10	22pF		10%		Crystal Load Cap
C11	22pF		10%		Crystal Load Cap
C12	100nF		Not critical		Tune 2 smoothing
C14	DNI				RF input shunt tuning
C15	DNI				RF input grounding
C16	33pF		Not critical	See text	RF input blocking
C17	DNI		Not needed		Tune1 decoupling as per DS
C18	DNI		Not needed		Tune1 decoupling as per DS
C20	100-470nF		Not critical		Audio DC block.
C21	DNI	470nF	Not critical		Audio DC block. 100nF OK too
C45	100nF		Not critical	SMT: 0805	3.3V decoupling at tuner
D10	DNI	LED	Vf <2.5V	Optional	Station indicator
D11	DNI	LED	Vf <2.5V	Optional	Stereo indicator
J11	DNI	4-pin		Short pin 1 to 2 4 pin header, 0.1” spacing	Not needed with 4825. Short pin 1 to 2 Selects right or left or both
L1	240n			See text	RF tuning couple to L2
L2	240n			See Text	Antenna tuning
R11	750ohm		1%		Reference voltage setting
R12	3K		1%		Reference voltage setting
R13	51k		1%		Channel selection
R14	330K		1%		Channel selection
R15	DNI	1.8K	Not critical	Optional	LED current setting
R16	DNI	1.8K	Not critical	Optional	LED current setting
R17	short	DNI			Jump for 4825
R18	short	DNI			Jump for 4825
R22	short	22K	10%		Audio input mix
R23	DNI	22K	10%		Audio input mix
U10	Si4825	Si4836		SMT: 16 pin SOIC package	See text for selection
U11	MCP100-300D			TO92	Power-on reset circuit
Y1	32768 Hz crystal		12.5pF load	8.3 X 3.2mm package	Main Clock. Any common 32768 Hz crystal should work

BOM for power supply and op-amp circuit

Ref	Value	Tolerance	Note	Purpose
C40	2200uF	not critical	16V or more. Bigger is better	Filter cap
C41	DNI			5V decoupling
C42	33u	not critical	6V or more	5V decoupling
C43	DNI			3.3V decoupling
C44	33u	not critical	6V or more	3.3V decoupling
D12	LED	Vf <2.5V	Optional	Power Indicator
D40	Rectifier: like 1N4001 or 1N5817 (which is Schottky)			Rectifier
D41	1N5344B		8.2V 5W zener	Protection, depends on application
D42	1N5357		20V 5W zener	Protection, depends on application
J10	6-pin 0.1" male header. One jumper will be required.			Interface
R8	220k	10%		Op amp feedback
R9	560k	10%		Op amp feedback
RV10	4.7 or 5k	Pot.	Piher PT-10-LV10 series	Range setting
R19	1.8k	10%	Optional	D12 LED current setting
U2	LM358		8-pin DIP	Level-shifting circuit
U40	LP2950-50 (TO-92)		Or in a pinch 78L05	5V regulator
U41	78L33_TO92			3.3V regulator

BOM for audio amplifier

Ref	Value	Tolerance	Note	Purpose
C22	470n	Not critical		Audio DC block. 150nF OK too.
C23	20n		optional	Treble boost
Q20	2N3904 or any silicon NPN transistor			Amplifier
R20	270k	5%		Base bias
R21	100k	5%		Base bias
R24	3.3K	5%		Emitter bias
R25	10k	5%		Collector bias
R26	1.8K	10%	optional	Treble boost

BOM for negative supply. May not be required.

Ref	Value	Tolerance	Note	Purpose
C46	33uF	Not Critical	16V minimum	Filter
C47	33uF	Not Critical	16V minimum	Filter
C48	33uF	Not Critical	16V minimum	Doubler capacitor
D43	1N914 or any silicon diode			Rectifier
D44	1N914 or any silicon diode			Rectifier
R27	100K	Not Critical		Current into radio
R40	10K	Not Critical		Filter
R41	10K	Not Critical		Filter

3.1 Construction Options

U1: 74HC4046 vs. 74HCT9046

If you are using the 74HCT9046 (recommended), populate R5. FB1, R4, and SJ6 are all shorts.

If you are using the 74HC4046B, populate R4. R5, SJ6 are not used. FB1 is a short. Some temperature compensation is recommended, footprints at R3 and R6 are there for your experimentation. A 100K NTC thermistor in series with a 47K resistor, these connected between +5V and pin 11, is a good place to start.

There is a provision for a shield around the PLL, however this has been found to be unnecessary.

U10: Si4825 vs. Si4836

The Si4825 is mono, and does not have the outputs for the signal strength LED or the stereo LED, and is slightly less sensitive. The Si4836 is stereo and has the LED indicators, and is more expensive. Otherwise, they are similar. (You probably only need a mono chip, and the LEDs will probably be hidden, and the difference in sensitivity is tiny, so the Si4825 will do just fine. Use what you can get.)

For the Si4825, the J11 header is unnecessary, just jumper pin 1 and 2. Do not populate D10, D11, R15, R16. Blob solder on the pads under R15, R16 (SJ8, SJ9).

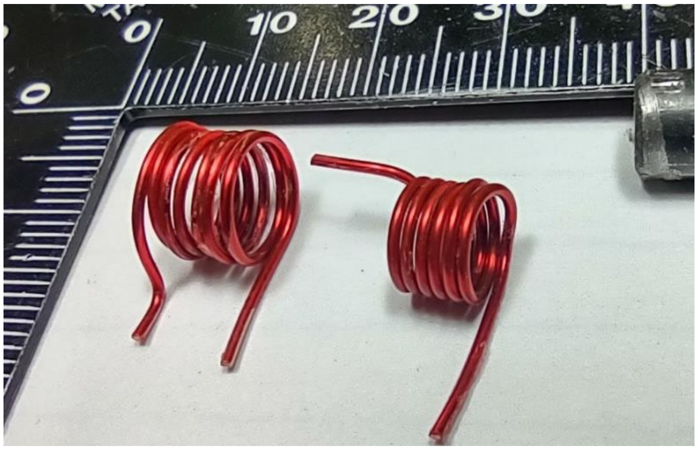
For the Si4836, populate J11 (and use slide-on shorts to bridge 1 to 2 and 3 to 4). D10, D11, R15, R16 are optional if you want the signal strength and stereo indicator. Do not blob the contacts under R15 and R16 (SJ8, SJ9).

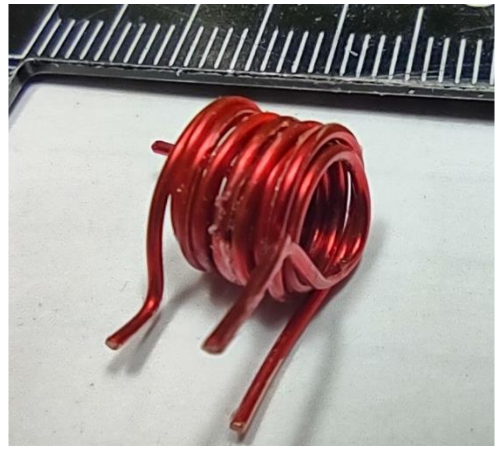
Antenna coupling options

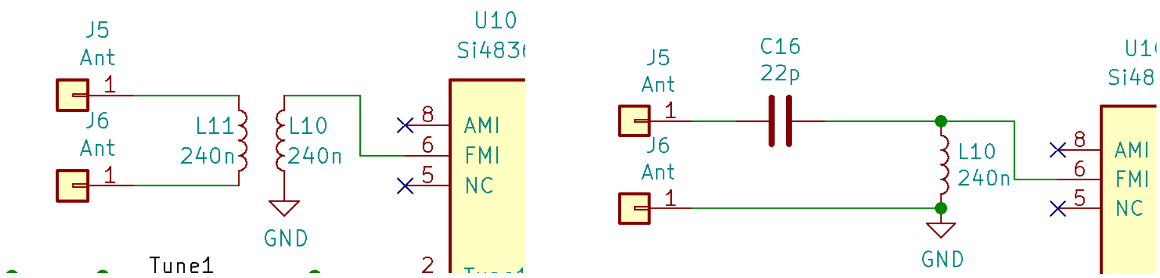
An inductor of about 0.25uH is required at L10. This can be 7 turns of #20 enameled wire, close wound (I wind it on a 1/4” drill bit, but it springs out to be about 9/32”. Sorry for the archaic “imperial” measurements, but I don’t have metric drill bits), or use a chip or thru-hole inductor.

Single ended capacitance coupling: The data sheets recommend coupling the antenna to pin 6 of the Si4836 through a capacitor of about 22pF (C16). In AC/DC sets, this should be a good quality high voltage capacitor to lower the risk of shocks from the antenna.

Transformer coupling: I use a second inductor (L11) tightly coupled to L10. This allows a balanced antenna to be used, and the antenna is isolated from ground, making it particularly suitable for AC/DC radios. I did not populate any capacitors. In this case, L10 is the larger: 7 turns on #20 wire on a 9/32” drill bit. L11 is the smaller, (inside L10): 7 turns of #20 wire on a 7/32” drill bit.







Transformer coupling (left) and capacitive coupling (right).

Power Supply Options

C40 is specified with a 16V rating. If more than 10VAC or 16VDC is applied, this capacitor should have a higher voltage rating. C46, C47, C48 are specified with a 16V rating. If more than 16VDC or 6.3VAC is supplied to the board, then their voltage rating should be increased. If a DC supply is used (for example in a car radio), then the negative supply will not work and D43, D44, R40, R41, R27, C46, C47 and C48 are unnecessary.

A low-drop high precision 5V regulator, the LP2950-50 is specified by default. It offers +/- 1% tolerance voltage tolerance which makes alignment easier (it makes the 1V reference voltage at pin 2 of the tuner accurate) The less precise and more common 78L05 works fine, too, but it needs a minimum input of about 6.5VDC for proper operation (6.3VAC from a filament circuit is fine), and alignment instructions need to be tweaked because the regulated supply voltage may deviate slightly from 5.0V. If the power supply voltage is limited (like in a 6V car radio), stick to the low-drop regulator.

The FMC has provisions for Zener diodes at the AC input. If the host radio has a parallel heater circuit, then there should be no need for a Zener diode in either position. Series heater circuits **must** use a Zener diode at D41 to limit the voltage seen by the circuit. (failure to do so will destroy the FMC) If the FMC is in parallel with a heater in a series string set (only realistic in sets with 300mA heaters) then D42 protects the FMC in case the heater fails open. See section 5 on implementation.

4. Suitable Radios

In order to determine if a radio is suitable for the FMC, one needs to consider A) the radio architecture; generally, only superheterodyne radios are easy to accommodate; B) whether an appropriate voltage is available to run the converter, and this is generally pulled from the filament supply, so the filament circuitry matters; C) the IF frequency of the host radio; and D) whether there is room for the converter card. Also, it goes without saying that the radio should be in working condition. Do not expect miraculous sound from your radio. The sound quality will be limited by the host radio, not the FMC. Although you will be receiving an FM signal, on smaller cheaper radios FM stations may sound a lot like AM stations. Better radios (with larger, better speakers and careful design of the audio circuit) will be able to take advantage of the superior fidelity of the FMC.

Most post 1932 tube radios are good candidates. Suitable home radios include:

> The classical post-1935 AC-only tube radio uses the following tubes:
> 6A8 or 6K8 or 6SA7, 6K7 or 6SK7, 6Q7 or 6SQ7, 6V6 or 6F6 or 6K6, and 80 or 5Y4 or 5Y3 or 5Z3 or 5W4 or maybe 6X5. Other tubes are possible too. These sets are AC-only and have a large transformer that supplies the heaters in parallel.
>
> A more modern version uses 6BE6, 6BA6, 6AT6 or 6AV6, 6AQ5, and 6X4 or 5Y3.
>
> The classical All-American 5 (AA5) uses this tube line-up:
> 12SA7, 12SK7, 12SQ7, 35L6 or 50L6, 35Z5.
> These sets are “AC-DC” sets and run the heaters in series.
>
> The more modern version of the AA5 uses these tubes:
> 12BE6, 12BA6, 12AV6 or 12AT6, 50C5 or 50B5, 35W4.
>
> There are numerous variations on these themes, some with fewer or more tubes, some using other tubes such as the “Loktal” (7- and 14-) tubes, or some mixture between tubes. Some do not use a 6Q7/6SQ7 but rather use a dedicated diode such as the 6H6. Some use an older style of tubes with the larger bases (like 6A7, 6D6, 75, 42, 80) . Some more expensive radios may use many more tubes with high power push-pull outputs, tuning eyes, fancy IF strips. All of these are quite suitable for conversion.

12V tube car radios with negative chassis work well with the converter. (Positive chassis is not impossible to work with, but adds complications) Space tends to be at a premium in these radios.

6V tube car radios with negative chassis work, but a low-drop 5V regulator must be used. (Positive chassis is not impossible to work with, but adds complications)

European radios can be converted, and should offer no special challenges, but I have less experience with them.

Radios that present challenges:

Portable (Battery-only or battery/AC sets) tube radios are a challenge. The circuitry to feed the filaments from the AC mains, typically 7.5V, relies on the filaments consuming 50mA. The converter draws about 35mA, so the radio circuitry would need to be modified to accommodate the extra current. Portable radios that operate on 7.5V or 9V filament batteries can be converted. Portable radios that use 1.5V or 3V filament battery simply do not have enough voltage.

Radios that use 2.5V filament tubes (like 2A7, 57, 58 etc…), do not have enough voltage unless you use a voltage tripler to generate enough DC voltage to feed the regulators (about 6V with the LDO).

TRF (unless you make one of the amplifier stages oscillate) or regenerative radios cannot be converted.

Farm radios usually use a 1.5V or 2.0V filament supply inherently do not have enough voltage. However, if you are using your farm radio, you have probably procured an external power supply that may be capable of supplying 6V needed for the converter.

5. Making connections to your radio:

There are three documents on https://rabjohn.ca/gord/projects/fmconversion/ that describe in detail, how to connect to the 3 most common types of host radios: AC-DC "All American 5" (AA5) radios, AC radios, and car radios. These three documents will cover the majority of radios found in North America. I recommend that you check these documents out if your radio falls into one of these categories. The instructions below are more general and necessarily less detailed.

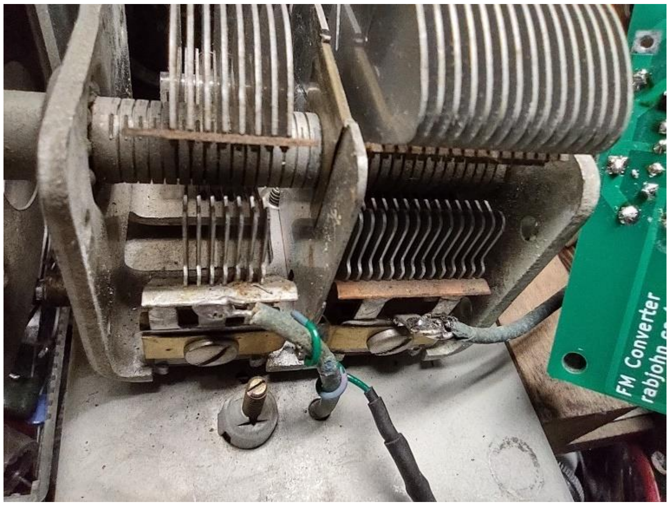
Three connections (local oscillator signal, audio output, power) plus ground must be made to the radio, generally made at the tube sockets. It is very easy to make these connections without any disassembly, modification, or soldering to the host radio by using socket adaptors.

5.1 The local oscillator

There are 2 ways to do get this signal: either use a capacitive link to the "LO" variable capacitor, or connect to a pin on the "Converter" tube.

The FMC's LO port is quite sensitive, so only a small LO signal is required, and this can be extracted with a capacitive link if your radio has a good healthy LO amplitude. An insulated wire wrapped around another wire may provide enough capacitance to extract the LO signal. The link can be made by wrapping insulated copper wire from the FMC LO port to the LO tuning capacitor in the host radio. Radios have dual (or more) tuning capacitors, and you must pick the right one. If they are of unequal size, then the smaller one is the one you want to couple to. If they are equal size, try this: Turn on the radio and tune to a station at the upper end of the AM band. Touch each variable capacitor terminal, one at a time, with an insulated screwdriver. Touching the LO side will make it sound like the radio is being tuned away. Touching the other (antenna) side will have a less dramatic effect, may even increase volume.

A short, shielded wire (short to reduce capacitive loading; strive for under 10cm) should be used between the tuning capacitor and the FMC. A solid insulated copper wire should be soldered to the center conductor of the shielded cable (or replace the original stranded center conductor with a solid, insulated one), and the outer shield is left unterminated. Insulate well with heat-shrink tubing. The insulted wire is wrapped around (3-4 turns should be enough) the wire connecting to the LO variable capacitor that was identified above. No "DC" electrical connection is required.



The LO signal may also be pulled directly from the “converter” tube, or the LO tube if it is a separate tube. This may be the easier technique if the tuning capacitor is difficult to access. This technique allows more signal to be coupled into the FMC, so suitable for radios with a weak LO. In principle, you could pull the signal from either the grid or the plate of the oscillator, but I have found that the grid (which is usually connected to the oscillator coil and tuning capacitor) is more sinusoidal; the plate can have significant harmonics that can fool the phase locked loop.

The best way to make this connection is through a tiny capacitor (say 5-10pF) mounted very close to the tube pin. This way, minimal capacitance will be added to the oscillator circuit. The capacitor is connected to the circuit board LO port with a short shielded cable (under 10cm long). A “socket adaptor” is recommended so no soldering is required on the host radio. For octal and “Standard” tubes, this is easily made with the male end taken from an old tube, and a matching tube socket on the female end. The pins are wired up 1 to 1. This gives you access to the nodes required. Miniature tube socket adaptors may take a little more creativity, but soldering rigid AWG18 wires to a miniature socket works.



Above: a socket adaptors. It plugs into the radio, and the tube plugs into it.

In radios that have a separate oscillator tube and mixer tube (radios that use a 6L7 mixer, or early radios that use some other tube (perhaps a 24)), it is best to find the associated local oscillator tube (which can be many different tube types) and tap the signal from its grid, or tap the LO tuning capacitor.

I do not include European tubes in this list, because I don't have much experience with them, however it should work just as well with them. European radios often used a separate triode oscillator in the same envelope as the mixer, and the LO can be pulled from the grid or plate of the triode. Pin 3 or a UCH42/ECH42, for example. I have seen examples where the tuned circuit is in the plate of the oscillator, so some experimentation may be necessary. Please let me know how it goes. I have received some feedback from Portugal that a grid connection seemed to work better than plate, even though the plate was coupled to the tuning capacitor.

5.2 The Audio

In general, the audio is injected at the detector, though if the radio has a phono input, that may be another option. Detector diodes in tubes tend to come in pairs, and either or both diodes could be used as the detector, and the other diode could be open or shorted or used elsewhere. You will need to determine which diode to use, either by consulting the schematic, or looking under the chassis, or simple trial and error.

This connection should be made with grounded shielded cable to avoid hum pick-up. The shield of the shielded cable can connect to ground at the socket as well. Note that the chassis of an AC-DC receiver may not be at ground! The cathode of the audio triode is almost always at ground. A socket adaptor is a good way to do this (and to extract the power, too).

Ideally, the diode should be disconnected. The audio will be fed into the socket pin that the detector diode was disconnected from (which usually connects to the last IF transformer). If the negative voltage generator is not available (e.g. in installations where the converter board is supplied with DC, such as car radios), the tube detector diode must be disconnected. Failure to do so will slightly increase the amount of audio distortion, and very strong AM stations may break through.

Radios with a switched "Phono Input" can receive audio through that connection. But beware, radios like this sometimes remove power from the RF section and might disconnect the coils when the radio is switched to "phono" mode, so tuning could be impossible. If the connections are maintained, then you may be able to turn your radio into a true AM-FM radio.

I have less experience with European radios, however they should work just fine. Often, the diode is included in with the IF amplifier which should cause no difficulty.

If you do not have enough head room for a tube adaptor, you can try connecting directly to the tube pins (wrap a solid wire around the tube's pin) or using a solid-state tube replacement.

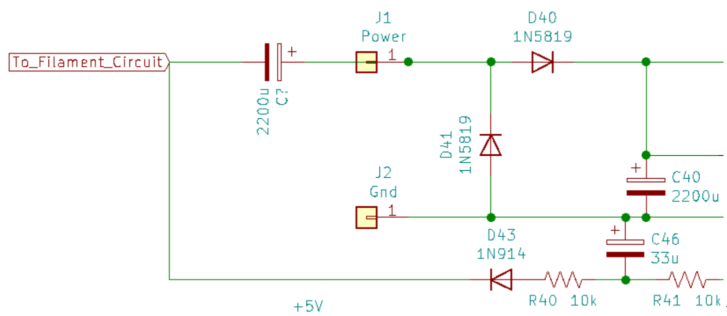
5.3 Power

The circuit draws about 35mA, and needs a minimum of 6VAC or 8VDC. If you use lower voltages, make sure you are using a Schottky diode for D40, and a low drop-out regulator for U40. Internally, the PLL needs 5V regulated. If only lower voltages are available, then a voltage doubler or tripler can be used in an AC set. Extracting the power can be done several different ways, depending on the voltages available and whether the tube heaters are in series or in parallel.

AC Sets (parallel heaters)

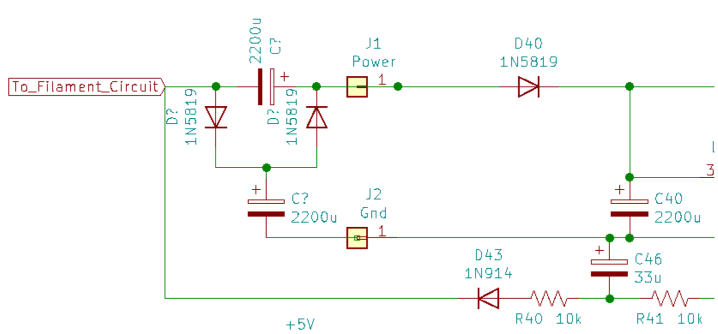
AC sets (sets with a power transformer) have all the heaters in parallel. The power for the converter board may be extracted from any of the filament pins (other than the rectifier! Please not the rectifier!). Note that one filament pin will usually be grounded and the other will have (usually) 6VAC on it, and the live pin must be determined by looking under the chassis or using a voltmeter. Connect the powered filament pin to the power pad on the FMC board, and a ground pin to the ground pad on the circuit board. D41 and D42 are not required. In the rare cases where 12V tubes with parallel filaments are used with AC on the filaments, please make sure capacitor C40, C46, C47, and C48 (if used) are rated at 20V or more.

Some AC radios use a center-tapped winding for the filaments, which means that only 3.15VAC (half of the 6.3VAC) is available, and this voltage is not sufficient with a simple half wave rectifier. In cases like this, a voltage doubler configuration using Schottky barrier diodes (such as 1N5817 - 1N5819) must be used. Not too difficult, requires an additional diode (at D41, on the board), and an external electrolytic cap. If the negative bias circuit is used, C48 must be connected back to the filament.



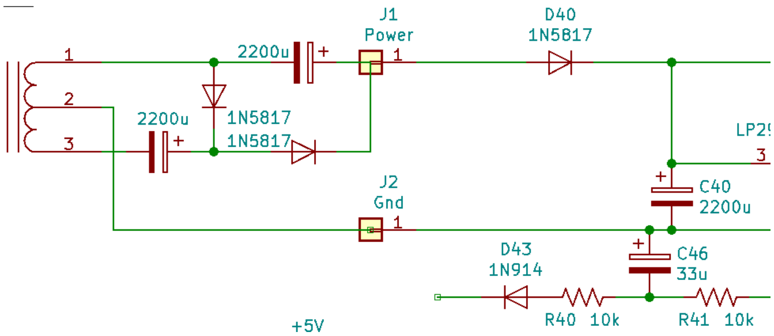
←Doubler

Radios that use tubes with 2.5V filaments actually require a tripler to generate enough voltage. This required 2 additional capacitors and 2 additional diodes.



← Tripler for 2.5V heater tubes

If you have a radio with 2.5V filaments and a center-tapped filament transformer, there is still an option. By using both sides of the centre-tapped filament supply, you can get a tripler to generate enough voltage. 2 additional capacitors and 2 additional diodes. If you need the negative supply, it will need a similar treatment.



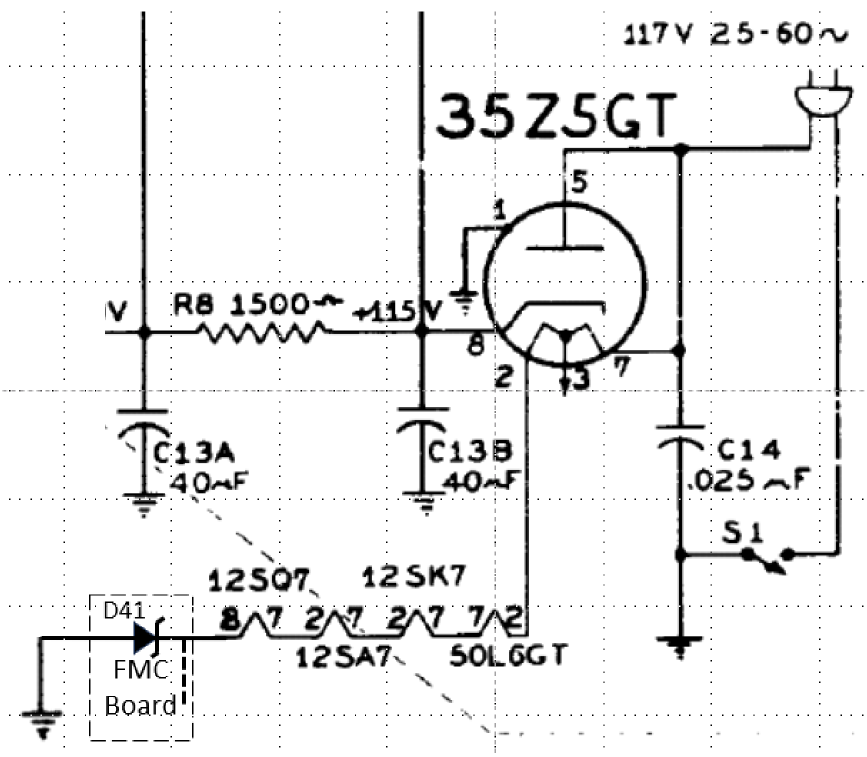
←Fancy tripler, for radios with a center tapped 2.5V filament transformer (the transformer at the left is the radio's power transformer).

C48 (into the negative voltage supply) must be connected back to the node with most AC voltage swing. If there is inadequate negative voltage, there are still options. Make sure the detector diode tube is disconnected. The IF amplifier and RF amplifier (if present) tubes can be removed in a set with filaments wired in parallel. This will allow the set to run a little cooler, eliminates the possibility of AM stations breaking through, and may give more room to manoeuvre in compact sets. Shorting the antenna terminals will also help prevent AM breakthrough.

AC/DC sets (series heaters)

In series heater AC-DC sets, the power must be extracted in series with the heaters. It is essential that a 8.2V, 5W Zener diode be populated at D41 on the board. (Failure to do this will destroy the board!)

You must locate the tube that is at the "ground end" of the heater string. This will almost always be the detector + first audio tube. One end of the filament will go to ground (generally not the chassis ground, rather will be connected to the cathode of the triode). This ground-end of the filament is opened (with the socket adaptor), and connected to the power port of the board.



← an example of an AC-DC set.

AC/DC radios all offer another challenge: safety. Even without the FMC, they can present a shock hazard because much of the radio circuitry is connected directly to the line cord. When connected properly, the FMC is tied to one side of the AC power line. To be safe, this board should be situated (possibly enclosed) within the radio so that it cannot be accidentally touched.

12V car radios

The challenge with car radios is finding a place for the circuit board inside the radio; it may be impossible, so mounting the board outside may be the only option. 12V negative ground car radios that use 12V (filament) tubes are quite easy to connect to. Follow instructions in section 3.1 . If the radio uses a vibrator to generate high voltage, there may be some interference from the vibrator. Additional shielding or decoupling may be necessary. If the radio uses 12V low plate voltage tubes (quite common in the late 1950's and early 1960's), no difficulty should be encountered. Note that these radios often use permeability tuning, but that should cause no difficulty. 12V positive ground radios will be more challenging, and I will not go into the difficulties likely to be encountered.

6V car radios

6V negative ground car radios can be used, but the board must be modified. Diode D40 is shorted (D41 and D42 are not used). And the 5V regulator must be a Low Dropout Regulator.

6V positive ground car radios present a problem, because the audio signal is referenced to the noisy negative supply. Attempt this only if you are an expert!

Portable (battery) radios and farm radios

Portable radios are challenging because they operate at such low voltages. Portable radios that can also run from AC often use 7.5V batteries for the filament, and this voltage will supply the FMC nicely when operating from a battery. (But, who has 7.5V batteries these days?) However, when running from AC, the filament voltage is generated by a (hot) series resistor. The FMC takes too much current to simply connect it, so the resistor would need to be reduced, and possibly the rectifier would need to be enlarged. Probably easier to use a battery (a 9V battery is suitable) to power the FMC.

Portable battery-only radios (this includes farm radios) usually employ low voltage (1.5 or 2V) batteries for the filament. The only option here is to use a separate supply (a 9V battery does nicely) for the FM converter. Farm radios are usually used with external power supplies these days, and the FMC may be able to get power from this.

The FMC can be used with a transistor radio, as long as 6V or more is available, however finding the LO tap-off point may take some experimentation.

5.4 Examples

A Viking (Electrohome) 5-tube AC set

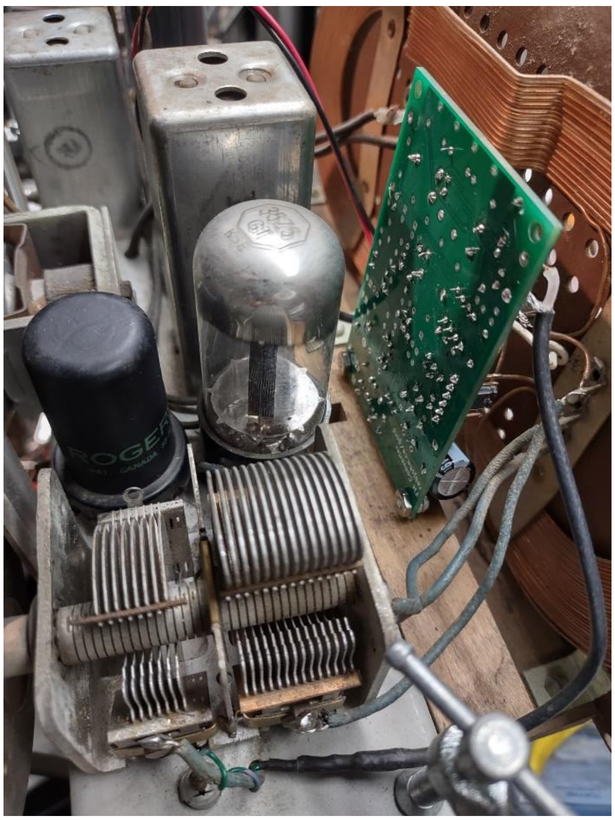
This is a very standard AC-only 2-band radio from about 1946. It uses these tubes: 6SA7, 6SK7, 6SQ7, 6F6GT, and 5Y4G. It has a phonograph input, but switching to phono also kills the bias to the 6SA7, so this cannot be used as an audio input. The FMC is held in place by screwing it to the antenna/ground terminals of the host radio. The LO is extracted by wrapping an insulated wire (the orange wire) to a terminal on the oscillator variable capacitor. In this case, socket adaptors were not used; the power and audio were connected to the radio by wrapping a wire around the appropriate tube pin. This particular FMC uses the Si4836 tuner and the 74HCT9046 PLL. Diodes D41 and D42 were not needed. It does use the negative bias generator to kill the IF gain and reverse bias the detector diode. The pictures show V1 of the FMC.

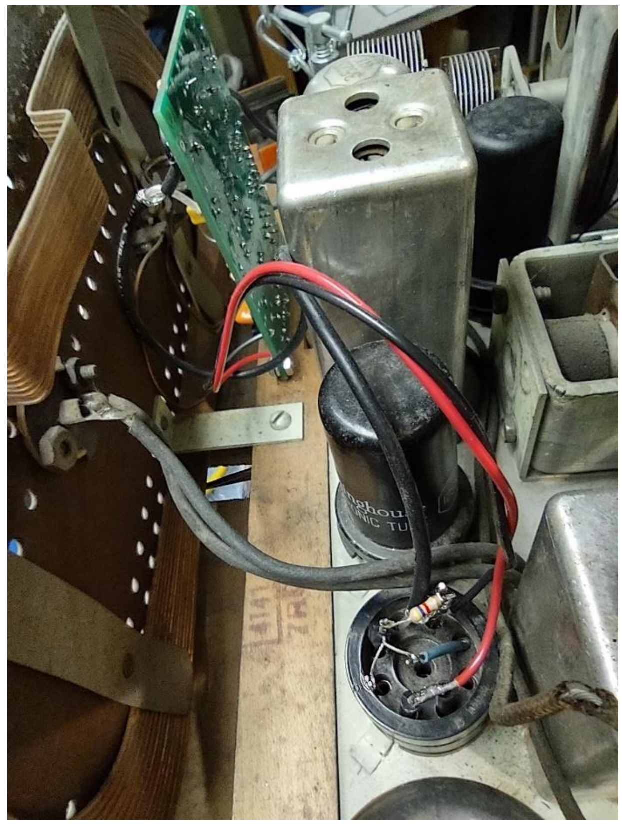

YELLOW
GREEN
RED
BLACK

The RCA “Little Master” AC-DC set

The little master is a very typical AC-DC set using a 12SA7, 12SK7, 12SQ7, 50L6GT, and a 35Z5GT. It has a phono input on the back, but there is no switch for it, so it is not terribly useful. LO was extracted by wrapping the insulated LO input to the variable capacitor terminal. DC was extracted with a 8.2V Zener diode in series with heater chain. I did this one a little differently: The 12SQ7 triode was replaced with a high voltage, low current D-mode MOSFET, the Supertex/Microchip LND150 (with a source resistor to set current). The Zener diode replaced the 12SQ7 filament. The detector diodes of the 12SQ7 were not needed, of course. Please contact me if this implementation is of interest and I can provide more details.

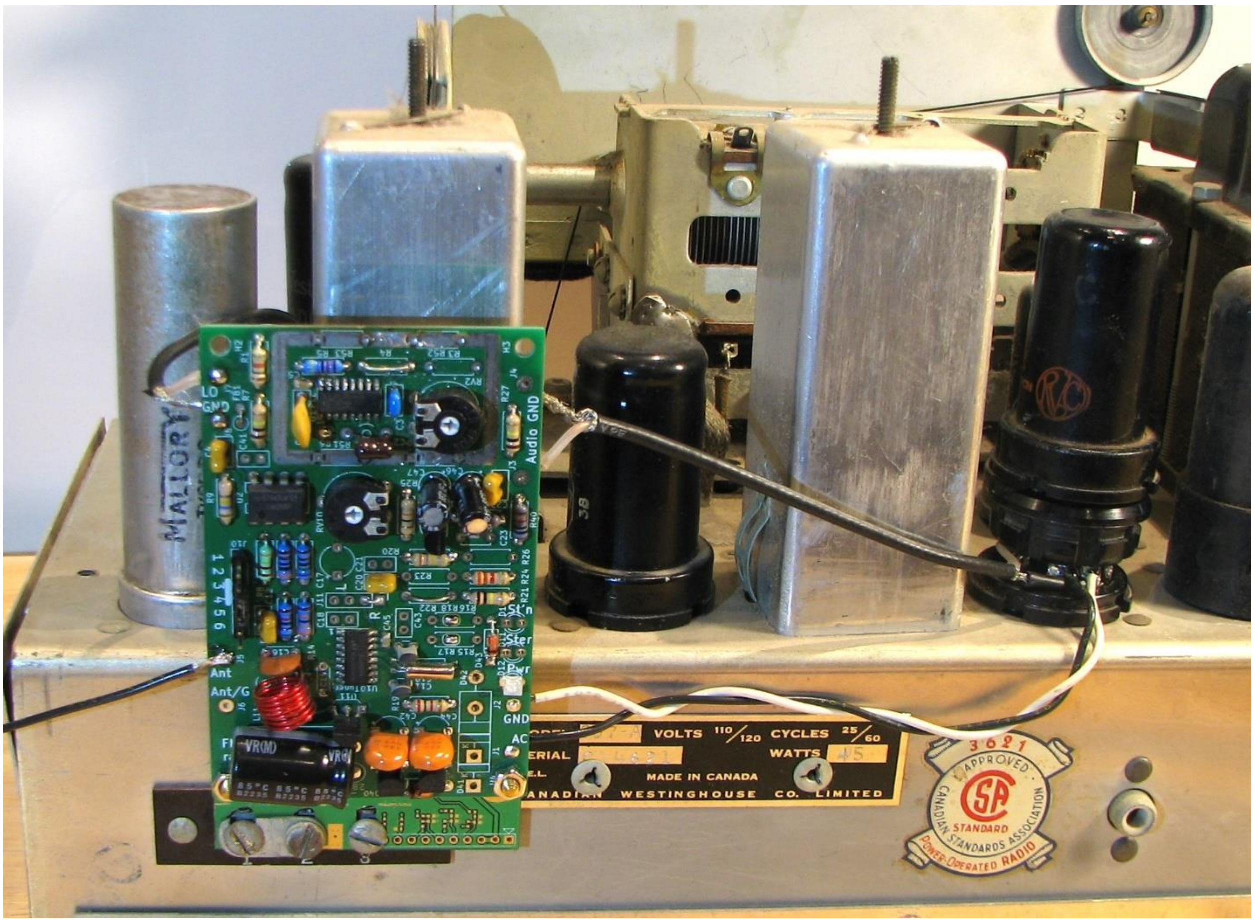
The board is mounted on the wood support at the back of the radio with 2 eye hooks.





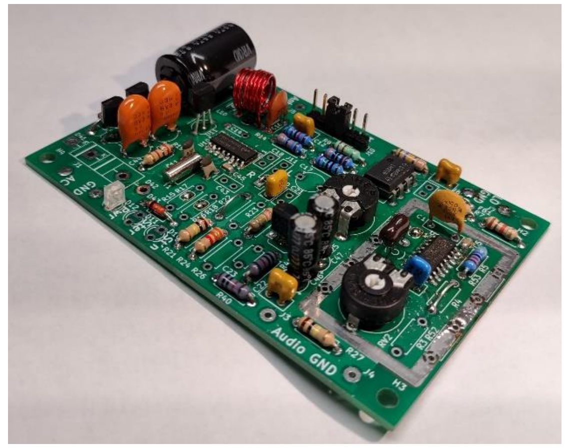
Westinghouse 697A AC set

This is a late 1940's AC-only AM-SW 3-band radio. It uses these tubes: 6SA7, 6SK7, 6SQ7, 6J5, 6F6G, and 5Y4G. The FMC is held in place by screwing it to the antenna/ground terminals of the host radio. The LO is extracted with a socket adaptor (hidden from view) that includes a 5pF capacitor. The power and audio were connected to the radio with the socket adaptor clearly visible in the picture. This particular FMC uses the Si4825 tuner and the 74HCT9046 PLL. Diodes D41 and D42 were not needed. It does use the negative bias generator (D43 etc) to kill the IF gain and reverse bias the detector diode. The pictures show V1 of the FMC.



I have tested the FMC on a Delco 12V "Hybrid" (circa 1960) car radio, a GE H53 radio (turning it into an AM/SW radio, see the document "AM-SW_Converter"), a Stewart-Warner "Little Colonel", and others have tried it on Zenith and even a European radio.

6. Specifications



I/O:

- Antenna (2 wire balanced or 1 wire single-ended).
- LO (Local Oscillator) input from host radio.
- Audio output to host radio.
- Power from host radio.
- Common ground.

Power Supply:

- Current draw ~36mA DC.
- Voltage required:
  >8VDC (negative ground) or >5.6VAC (50/60Hz). Use a voltage doubler or tripler for lower voltages.
  >5.6VDC (with low-drop regulator and D40 removed).
  Maximum voltage 30VDC or 20VAC. Increase voltage rating of C40, C46, C47 above 15VDC/10VAC.

FM:

- Covers FM band: 87-108MHz (75us deemphasis). Other bands possible by modifying R13/R14 (eg: 86.5-109MHz or 76-90MHz or 64-87MHz).
- Sensitivity: ~4uV (Si4825) or ~2.2uV (Si4836) (from data sheet).
- Antenna Input: Balanced or single-ended, isolated from the rest of the radio.
- Audio Output: ~1V p-p with a standard FM station into a high impedance load. Output impedance 10k.
- Frequency Response: 30Hz – 15kHz.
- Distortion: 0.1% typical (from data sheet, I cannot confirm).
- Either mono output or (with Si4836) R or L channel of a stereo output.

Local Oscillator (LO) Interface:

- LO frequency: 0.5MHz-2MHz (1MHz to 2MHz is typical). Suitable for a “Broadcast Band” or “MW” receiver with an IF of 175-500kHz. It will lock up to over 15MHz (with modified C2).
- Minimum swing (using a 9046 PLL): ~10mV RMS (measured at LO input at board with a 50 ohm RF source). Most LOs have >20X this, so only very light coupling is needed.

Size:

- 5.5cm X 8.5cm X 1.5cm. Mounting holes (for 4-40 or M3 screws) on 4.85cm X 7.85cm centres.
- 2-layer 0.062” thick board with plated-through holes.