

Voltage Controlled Oscillator (Excellent 1V/Octave Tracking)

Article by Ray Wilson

This is an intermediate to advanced project and I do not recommend it as a first project if you are just getting started in synths or electronics. Only the circuit and some explanation are shown here. A lot of project building, troubleshooting and electronics experience is assumed. Additionally, electronic equipment ownership (scope, meters, etc.) is taken for granted. If you are interested in building this project please read the entire page before ordering PC boards to ensure that the information provided is thorough enough for you to complete the project successfully.

CHANGE ADVISORY NOTE

There has been a board layout change to allow the board to accommodate either a pair of matched discrete transistors, or an 8 pin DIP package for SSM2210 or LM394 dual transistors or an 8 pin surface mount SOIC package for SSM2210 and SSM2212. You REALLY have to be a good at soldering to solder a SOIC package so please don't make this your maiden voyage just in case. I do it under a magnifier with a sharp chiseled soldering tip and thin rosin core solder. If you don't need a magnifier to solder SOICs then vision is your super power in case you hadn't discovered it yet. Additionally R11 changed from 20K to 100K trimmer potentiometer to aid in high frequency trimming.

Features

- Years of MFOS VCO improvements all rolled into this design.
- Good tracking over several octaves (**6 to 8**).
- Can be temperature compensated with a metal film 2K Ohm 1/4W +/-2% T.C. +3300 PPM tempco.
- Simultaneous Rectangle, Ramp, Triangle and Sine Outputs (Ramp core design)
- Designed for 1V/Octave control voltage
- 4 1V/Octave control voltage inputs.
- 1 Linear control voltage input.
- Hard sync input.
- Rectangle wave duty cycle adjustable between 10% and 90%
- Rectangle wave duty cycle voltage controllable
- Frequency range is from sub audible (approximately 0.1 hertz) to ultra-sonic 20kHz.
- Power supply can be +/-12 or +/-15 volts.



MP3 Samples

[Sine wave with sequencer and keyboard](#)

[Sine wave with sequencer and keyboard](#)

[Triangle wave with sequencer and keyboard](#)

[Ramp wave with sequencer and keyboard](#)

[Square/Pulse with sequencer and keyboard](#)

[Sync Effects](#)

[Frequency Range Demonstration](#)

[Modulation with keyboard and LFO](#)

[Messing about with ramp waves \(3 VCOs\)](#)

[Messing about with square waves \(3 VCOs\)](#)

[Messing about with the sequencer attached \(4 VCOs\)](#)

[Messing about with the sequencer attached \(4 VCOs\)](#)

Links to previous versions for reference

- [VCO200604REV01.html](#)
- [VCO200503REV01.html](#)
- [VCO20090724REV0.html](#)

Introduction

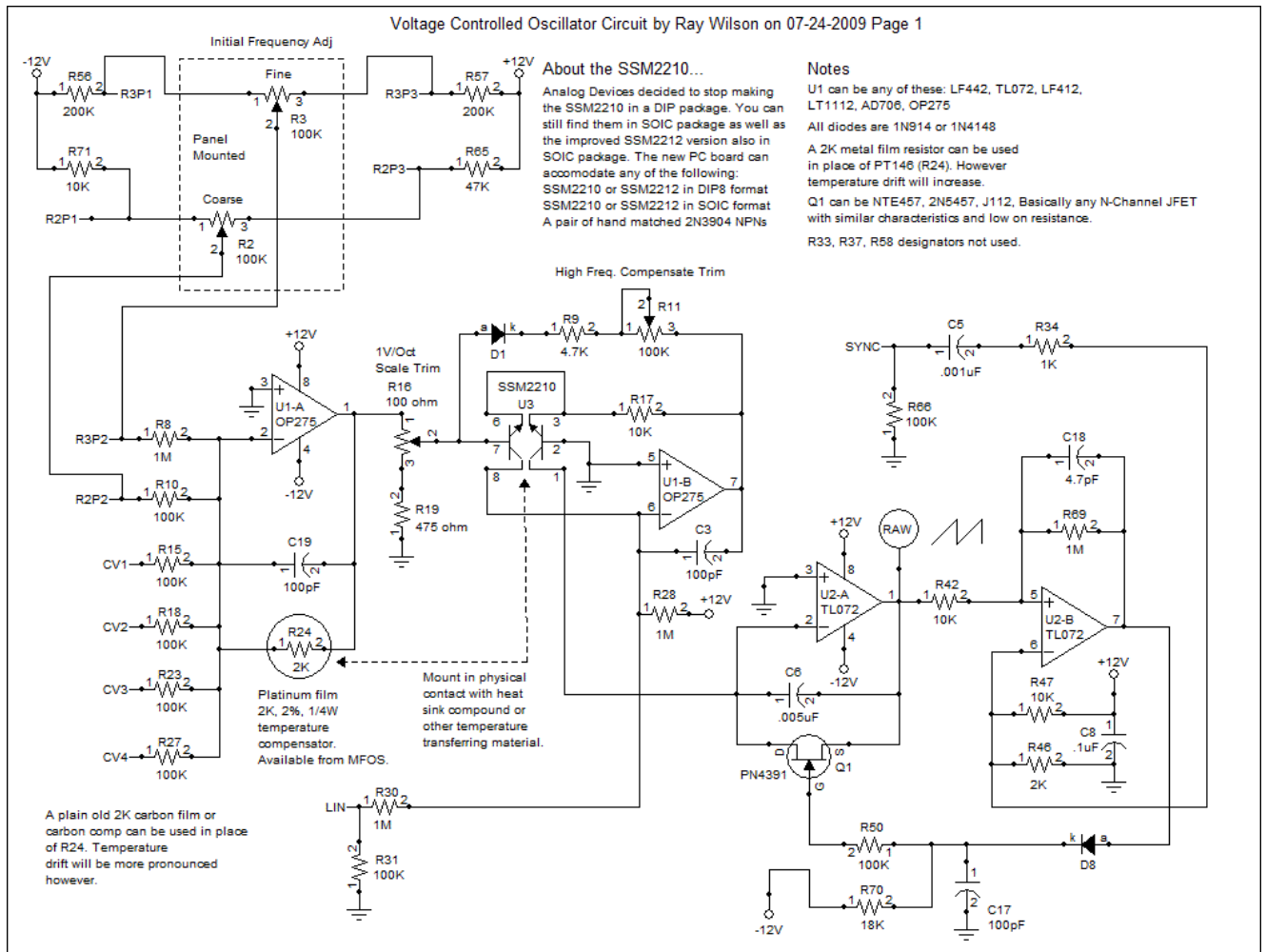
Oscillators are the main tone generating modules of your synthesizer. This oscillator produces sine, square, triangle and ramp waveforms and with careful adjustment tracks at 1V/octave over 6 to 8 octaves. The parts for it are easily obtained and not extremely expensive. The whole circuit is here so breadboard it and see if you like it. I like this oscillator but please recognize that it relies on a well matched pair of transistors. Its frequency range is from below audible to beyond audible. If this oscillator meets your needs I have high quality PC boards for sale for this design.

Voltage Controlled Oscillator Schematic Page 1 [PDF](#)

+/-15V Users Take Note

While helping diyer Doug Slocum improve the tracking on his MFOS VCOs I found a few things +/- 15V users should change.

- Change R46 to 1.54K metal film (1.5K carbon will be ok too). This sets the bias for the comparator since it changes at +/-15V. This corrects the whole rest of the waveform chain's amplitude.
- Change R10 to 150K and R65 to 43K this will give you a better range on the coarse freq control. Use metal film.
- Change R28 to 1.5M metal film. Changes the starting current of the expo convertor to 1uA.
- Use OP275 for U1. Its performance is superior to other op amps.
- Make sure and use a 100K multi-turn for the high frequency adjust.



Page 1 shows the voltage to exponential current conversion and ramp generator circuitry. U1-A is the control voltage summer. Its output feeds the scale trimmer R16 whose wiper is connected to the base of the current reference NPN transistor in the feedback loop of U1-B. The CV summer (U1-A and associated components) with its 2K feedback resistor and 100K input resistors has a gain of $-1/50$ th or $-.02$. Its purpose is to accept control voltages fed to its inputs and scale them to 20mV per volt of input. The trimmer R16 permits adjustment to 18mV per volt which is what the base of the NPN in the SSM2210 at pins 8(c), 7(b) and 6(e) expects in order to convert the voltage in an exponential manner. Linear changes in voltage applied to the CV1 through CV4 inputs of U1-A are converted to exponential changes in current at the current sink (collector of NPN transistor at pins 1(c), 2(b) and 3(e) of the SSM2210 Super Matched NPN Pair IC). For each additional volt of CV there is a doubling of the current flowing into pin 1 of U3.

The high frequency compensation circuitry D1, R9 and R11 allow the output of U1-B to boost the current at the current sink at higher control voltage (and thus higher frequency) to make up for the finite time required to discharge the integration capacitor C6 during oscillation. There is some interaction between the scale trimmer and the high frequency compensation adjustment so expect to go back and forth a bit during calibration. I like to set R11 to minimum (wiper to pin 1) and first calibrate with just R16. I adjust R11 when I see the frequency start to go flat at higher (greater than 4kHz) frequencies.

The current flowing into pin 1 of U3 causes the integrator made up of U2-A and C6 to ramp from ground toward V+. The better the linearity of the op amp used for U2 the better the oscillator will track. The ramping voltage on the output U2-A is fed into the comparator made up of U2-B and associated components. As long as the ramping voltage is below the voltage on the non-inverting input of comparator U2-B (approximately 2V), U2-B's output stays at about -10.6 volts. When the ramp voltage gets to about 2.2 volts U2-B's output shoots from about -10.6V to about 8V and forward biases D8, charges C17 and turns on the PN4391 N channel JFET which resets the integrator (causes the

output of U2-A to return to ground). The reset takes about 1uS after which the output of U2-A again begins to ramp up linearly. The output of U2-B when U2-A's output exceeds 2.2V is a very brief pulse (ALWAYS use the x10 setting on your scope probe to observe it) that goes from -10.6V (op amp negative saturation voltage) to about 8V and then back to -V. It is about 3 uS in duration.

Thus the output of U2-A (point RAW) is a ramp wave that goes from ground to +2.2 volts. The ramp's frequency is determined by the current flowing into pin 1 of U3. Since the current doubles for every increase in 1V applied to the CV summer the frequency doubles in kind. When the current doubles the rate of the ramp generator doubles and thus the frequency of the ramp wave doubles.

This is the heart of the VCO (literally). Applying a control voltage to the LIN input causes a linear shift in frequency as this input affects the reference current in the exponentiator. Applying a square wave from another oscillator to the sync input causes the comparator to reset the integrator (on the rising edges of the square wave) which produces interesting timbres when the outputs of the oscillator providing the sync signal and the oscillator being synced are mixed. Panel mounted pots R2 and R3 provide the initial frequency (tuning) adjustment. Detailed calibration instructions are in a section below. R16 and R11 should definitely be multi-turn cermet type trim pots so you have fine resolution when adjusting the V/Oct scale and high frequency compensation.

These ideas were pioneered by the Alan Pearlmans, Bernie Hutchins, and Robert Moogs of the world I am merely a student of their landmark work.

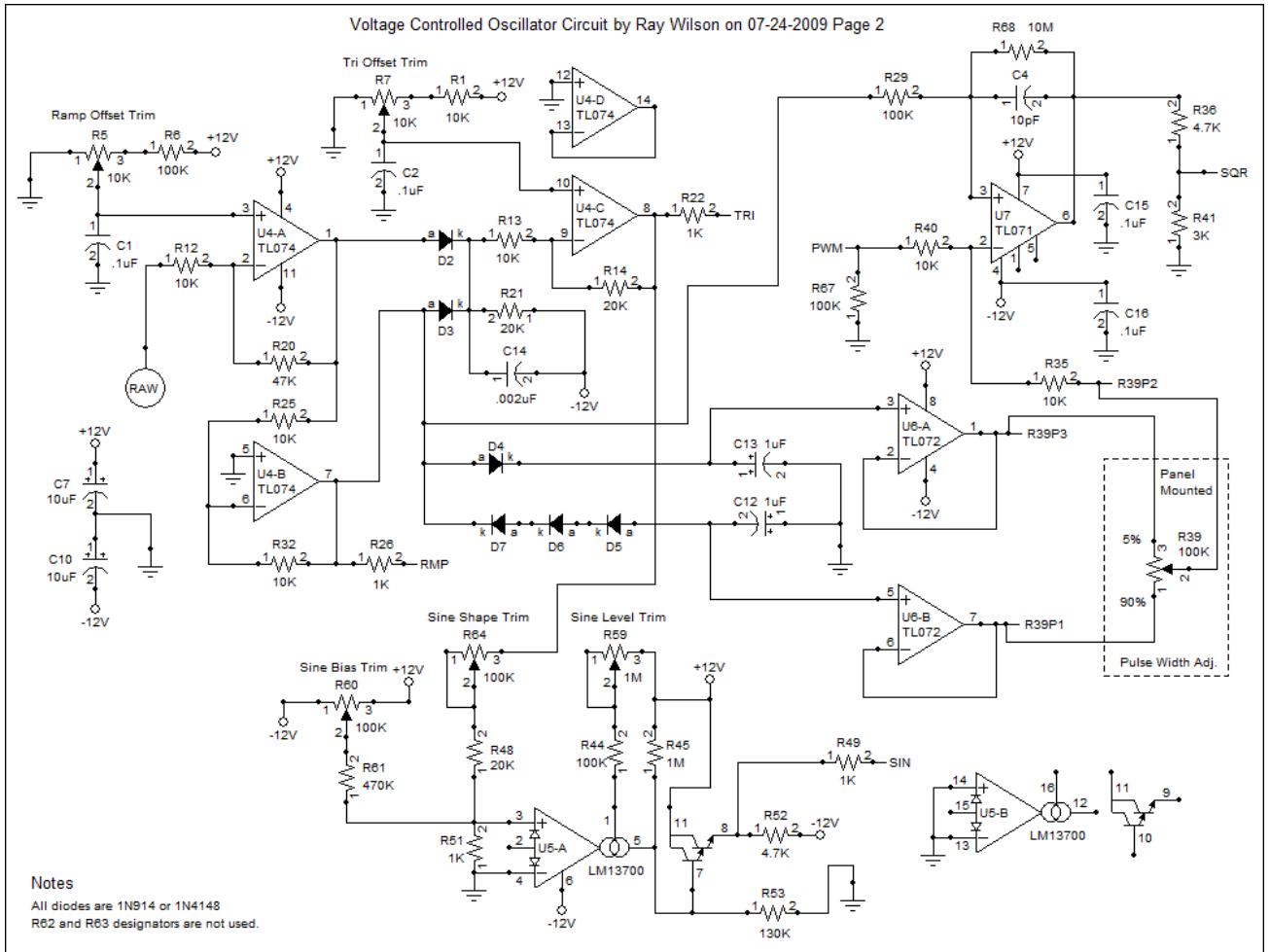
For best performance and least temperature drift use: 1% resistors throughout this portion of the circuitry, a metal film 2K Ohm 1/4W +/-2% T.C. +3300 PPM tempco for R24, and a silver mica or polystyrene capacitor for C6. If you use the tempco for R24 you need to put it in direct thermal contact with the matched transistor pair used in the linear voltage to exponential current convertor. The board is designed to accomodate a wide range of transistors from matched pairs in 8 pin pacackages to two separate transistors. You can substitute some of the parts as listed at the beginning of the parts list section below but the PN4391 and OP275 are highly recommended.

Approx. Current Consumption	
+12V	28mA
-12V	26mA

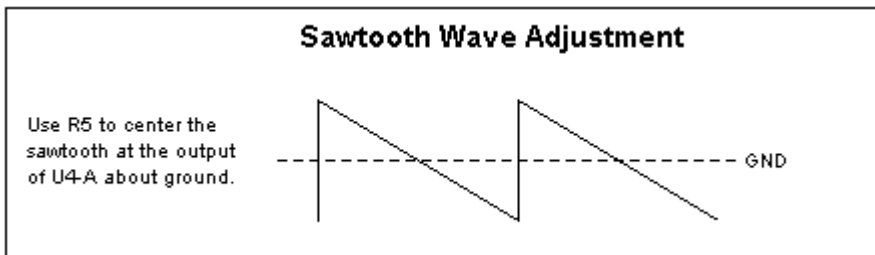
Assume slightly higher for +/-15V

Wider Pulsewidth Adjustment Range

While putting together a few oscillators recently I changed R68 to 1M and got a much wider range of pulsewidth adjustment. However, in the extreme settings (all the way up or all the way down) it could cause the pulse wave to cease output. I don't mind this as it lets me set very narrow pulse widths.

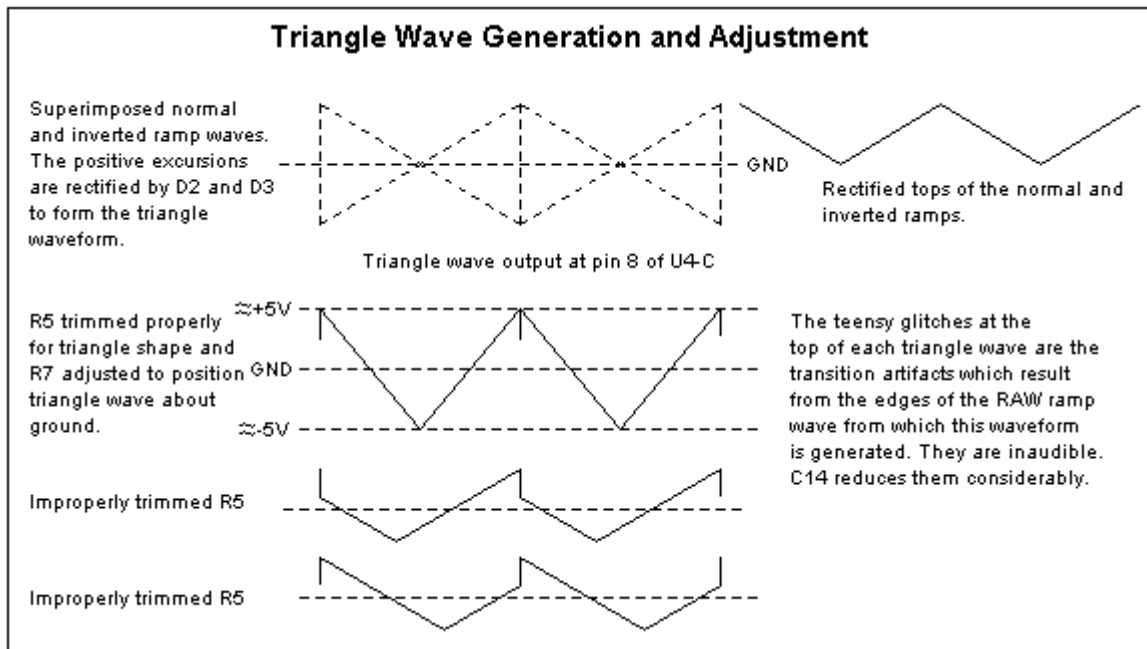


Page two shows the circuitry that converts the raw ramp wave into ramp, triangle, sine, and rectangle waveforms. RAW is applied to inverting buffer U4-A where gain and offset are applied to the signal. The original 2.2 volt signal is boosted to about 10 volts P-to-P. Adjust R5 so that the sawtooth waveform at pin 1 of U4-A oscillates evenly about ground.

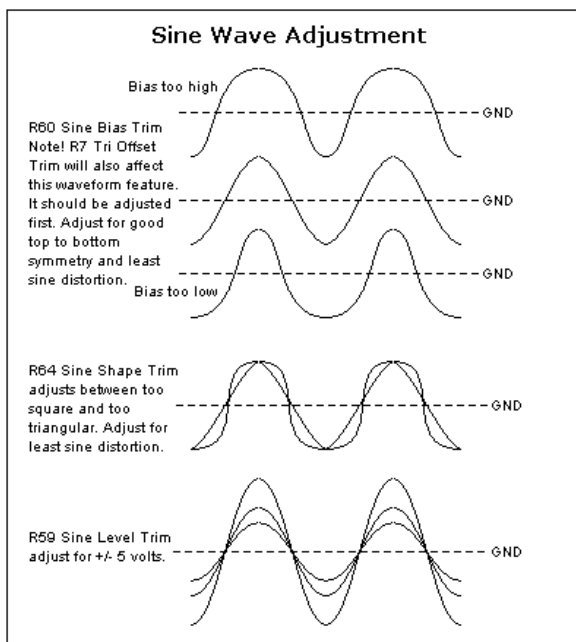


U4-A's output is fed to inverting unity gain buffer U4-B. The positive excursions of the outputs of U4-A and U4-B are rectified by D2 and D3 and dropped across R21 (20K resistor to -12V) and fed to U4-C inverting buffer with a gain of 2. This results in a triangular waveform at the output of U4-C after the Saw Offset and Tri Offset trims have been properly adjusted. As explained in the drawing this design produces inaudible glitches at the time the integrator is reset by the comparator. This is because

of the finite fall time of the integrator's output. Even though the integrator's fall time is about 1 uS the output of U4-A after inversion and gain takes about 3 uS (due to slew rate limiting of the op amp) to go from low to high (remember its inverted). U4-B takes about 3 uS to go low (its the original with x2 gain, again due to slew rate limitations). Thus a glitch of about 6 uS takes place at the peak of the triangle wave. This glitch is so fast that in practice it contains no audible information. C14 reduces the amplitude of the glitch by filtering the majority of it to -V.



The triangle waveform is fed into the circuit which uses the U5 (LM13700 or equivalent) to apply non-linear distortion which effectively approximates a sine wave. R60 (Sine Bias Trim), R64 (Sine Shape Trim), and R59 (Sine Level Trim) are all used to get the best sine shape possible. The figure below illustrates the effects of these pots on the waveform. Shaping circuits are never perfect and in the end if you achieve 1% distortion figure you will be very happy. If you don't have a distortion analyzer use your scope and your ears to determine the best sine shape. It is interesting to adjust the waveform to where you believe it sounds best and then tweak a little. You will be surprised to see how little distortion it takes to start adding overtones to the fundamental frequency. Adjust until you hear the purest tone with the least overtones. Listen while sweeping the frequency with the coarse adjust knob as well. Again, try to achieve the purest tone throughout the oscillators musical range.



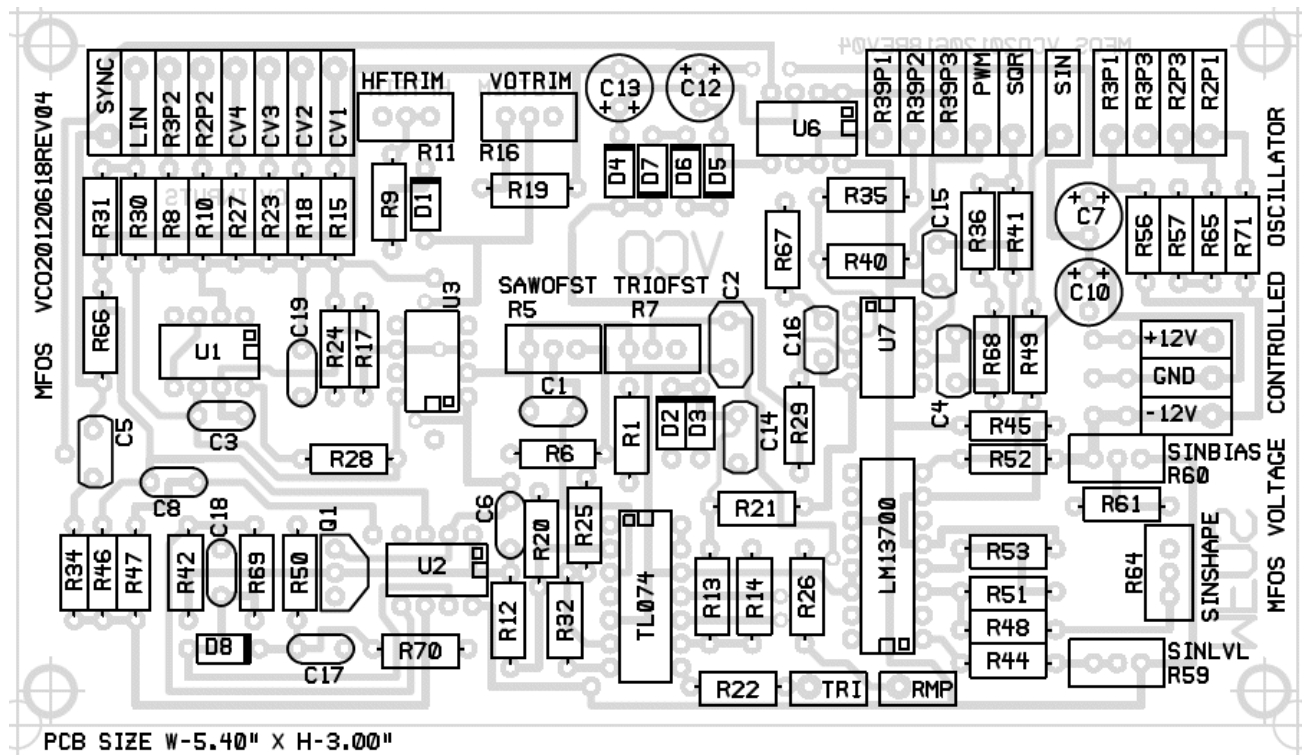
In order to provide bias levels for the rectangle wave comparator I use the ramp wave which appears at the output of U4-B. Note that the positive excursions forward bias D4 and charge C13. The negative excursions forward bias D7, D6 and D5 and charge C12 negatively. We end up with ramp positive peak minus one diode drop on C13 and ramp negative peak - 3 diode drops on C12. We buffer these voltages with U6-A and U6-B respectively and apply them to the ends of R39 panel mounted Pulse Width Adjustment pot. The wiper of R39 provides continuous adjustment between these two voltages and is connected to the inverting input of U7 (which is used as a comparator). When the voltage of the ramp waveform applied to the non-inverting input via R29 goes above the threshold set by the pot the output of U7 goes high. When the voltage of the ramp waveform applied to the non-inverting input via R29 goes below the threshold set by the pot the output of U7 goes low. Thus you have pulse width adjustment of between approximately 10% to 90% duty cycle for the rectangle wave's output. Voltage applied to the PWM input changes the threshold and thus provides a means to "voltage control" the pulse width.

Voltage Controlled Oscillator Scale Calibration

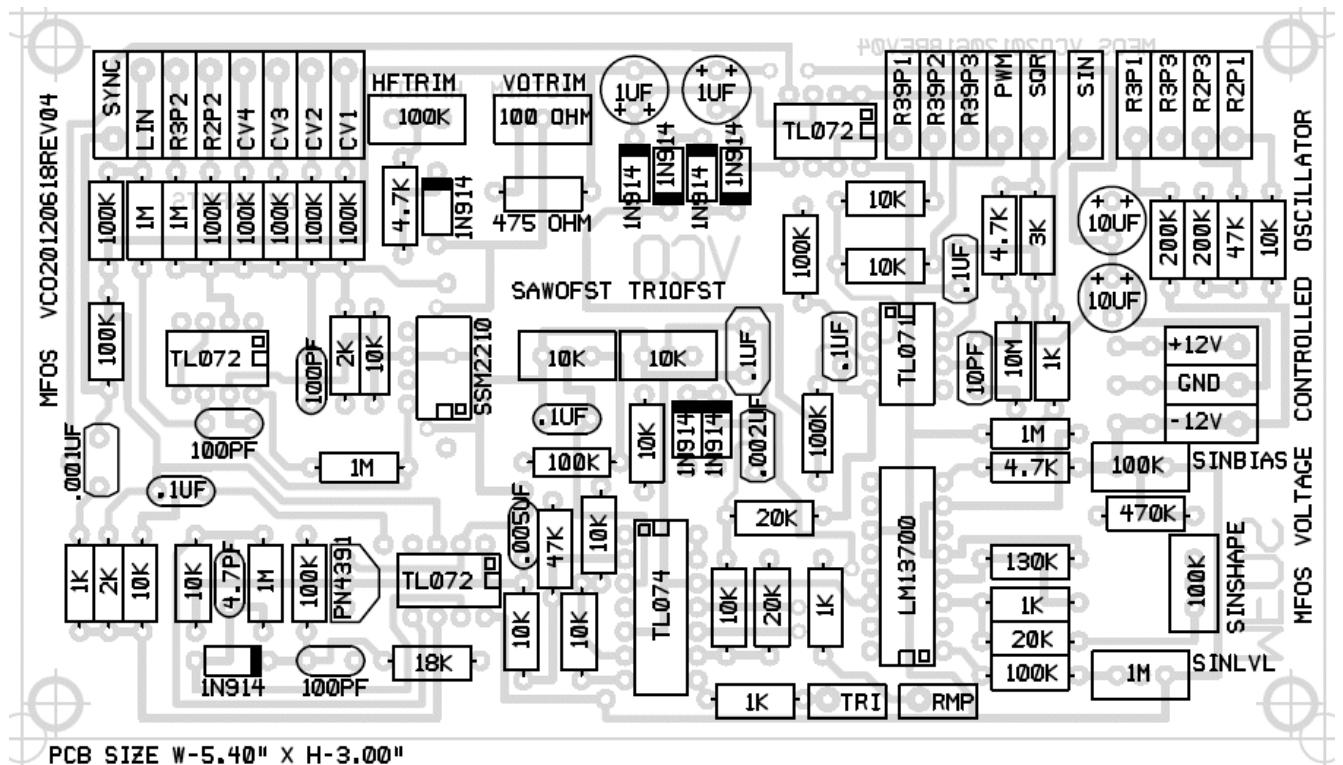
After getting the waveforms adjusted properly you need to set the oscillator scale factor and high frequency compensation trim pots. You will need a stable adjustable voltage source that can provide 0 through 10 volts, an accurate DVM, and a frequency counter. You can use an oscilloscope instead of the frequency counter but the frequency counter is more accurate. Without a frequency counter or scope you will need to use your ears. The following process is iterative and can be tedious. If you have a keyboard controller or MIDI to CV convertor that puts out 1V/octave I find it is easier to simply play octaves on the keyboard and trim the scale factor and high frequency compensator until I get the correct 1V/octave response.

- Adjust the waveforms properly as described above.
 - Connect the square wave output to your frequency counter.
 - (Optional) Connect the sine wave output to an amplifier to listen as you go.
 - Adjust R11 so that you have the most resistance between its pin 2 and pin 3 and thus the least high frequency pitch correction. We will adjust this later as necessary.
 - Apply an adjustable voltage source to one of the 1V/Oct CV inputs.
 - **ITERATION POINT A**
 - Set the adjustable voltage source connected to the 1V/Oct CV input up to 0.000 volts.
 - Adjust R2 and R3 so that the oscillator frequency is 100 Hz.
 - Set the adjustable voltage source connected to the 1V/Oct CV input up to 3.000 volts.
 - Observe the new frequency (which should be 800 Hz).
 - If the observed frequency is 800 hz continue to "ITERATION POINT B"
 - If the observed frequency is higher adjust R16 (Scale Adjust Trimmer) to cause the frequency to go higher. If the observed frequency is lower adjust R16 (Scale Adjust Trimmer) to cause the frequency to go lower. Repeat from "ITERATION POINT A"
 - **ITERATION POINT B**
 - Set the adjustable voltage source connected to the 1V/Oct CV input up to 3.000 volts.
 - Adjust R2 and R3 so that the oscillator frequency is 800 Hz.
 - Set the adjustable voltage source connected to the 1V/Oct CV input up to 6.000 volts.
 - Observe the new frequency (which should be 6400 Hz).
 - If the observed frequency is 6400 hz continue to "CALIBRATION COMPLETE"
 - If the observed frequency is flat adjust R11 to cause the frequency to go to 6400 Hz.
 - **CALIBRATION COMPLETE**
-

Voltage Controlled Oscillator Component Designator View



Voltage Controlled Oscillator Component Value View



Voltage Controlled Oscillator Detailing Placement and Orientation of SOIC Dual Transistor Chip

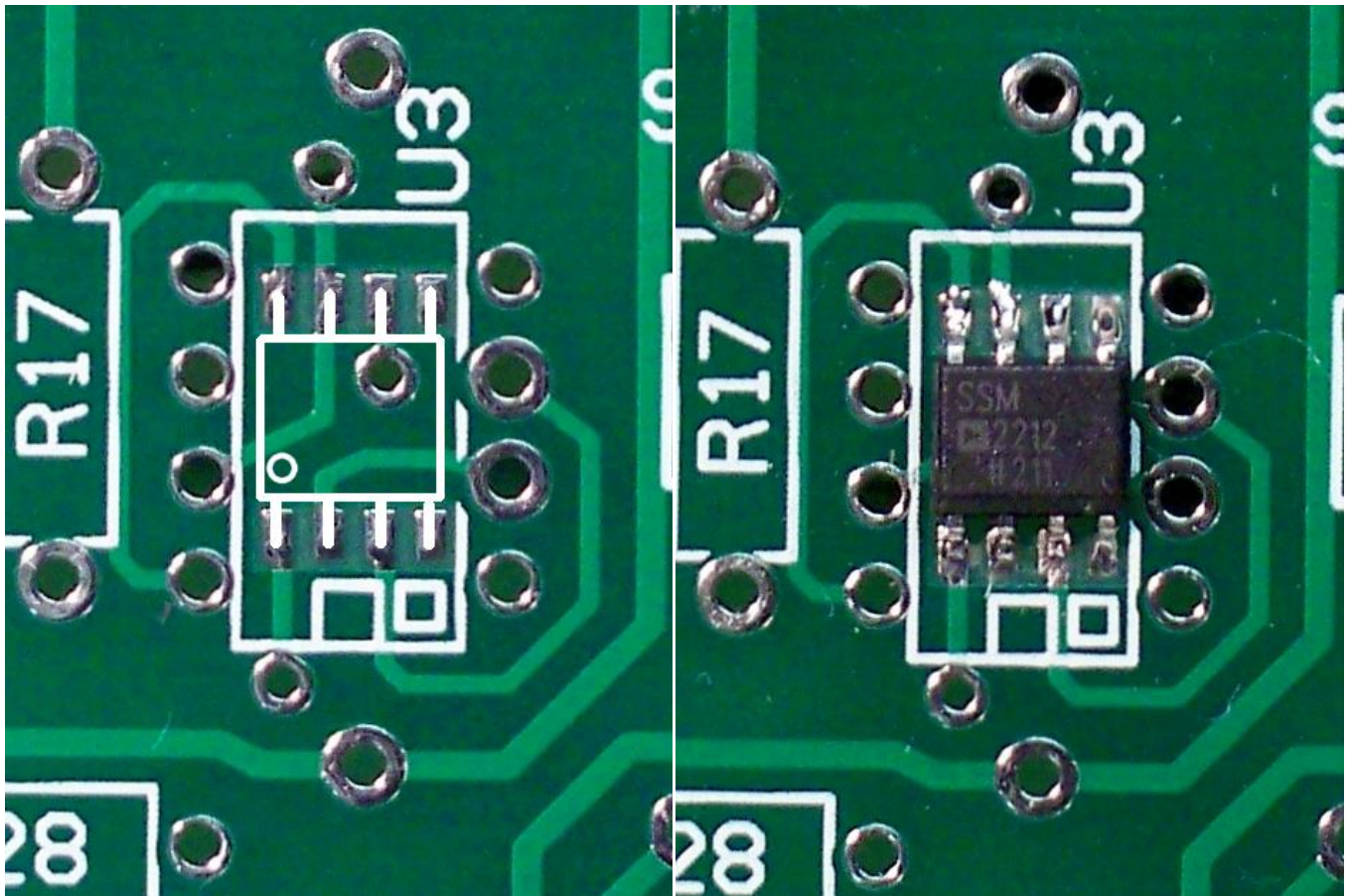
A SOIC style package can be used for the dual transistor chip on the new VCO board layout. Soldering a SOIC chip is DIFFICULT and it is VERY easy to bridge the pads. Use a fine tipped soldering iron (I prefer a fine chisel point) and very thin solder and very little of it.

Here are some YouTubes that give some tips on soldering surface mount components. Glean what you can and remember that the drag soldering technique relies on having first applied flux as shown in the vids. You can definitely solder the part with your regular small tipped soldering iron but as they show first tack two opposite corner legs down. Take your time, use a magnifier, use VERY LITTLE solder, and have your desolder braid handy for removing any excess.

- [Norman Mier of BEST, Inc.](#)
- [SMT Hand Soldering - Surface Mount SOIC IC](#)
- [Professional Hand Soldering \(Basic to Advance\) - Surface Mount, Through-Hole, Wires & Terminals](#)

This is how to orient the SOIC package. There is no legend on the PC board for it.

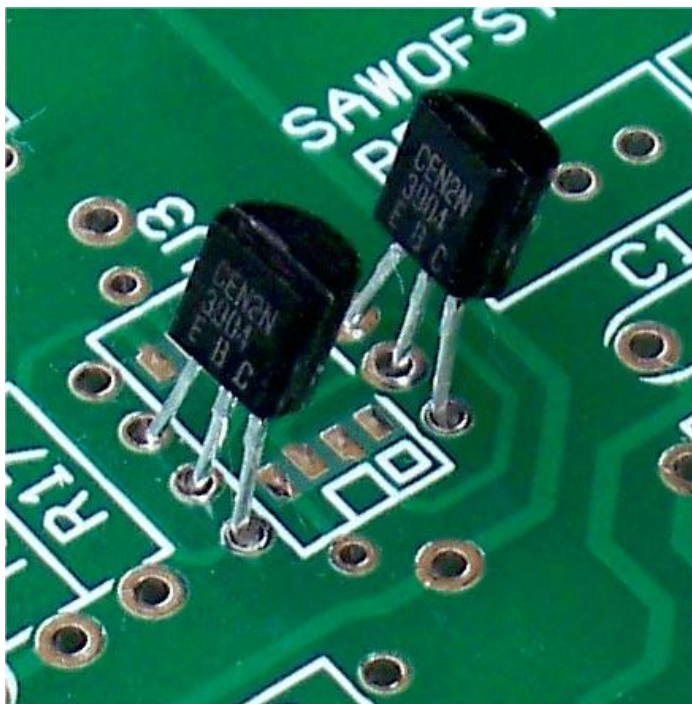
This is after soldering (I could have used less solder). I had to wick away some solder when I bridged two adjacent pads.



Voltage Controlled Oscillator Detailing Placement and Orientation of Matched Pair of Discrete 2N3904 NPN Transistors

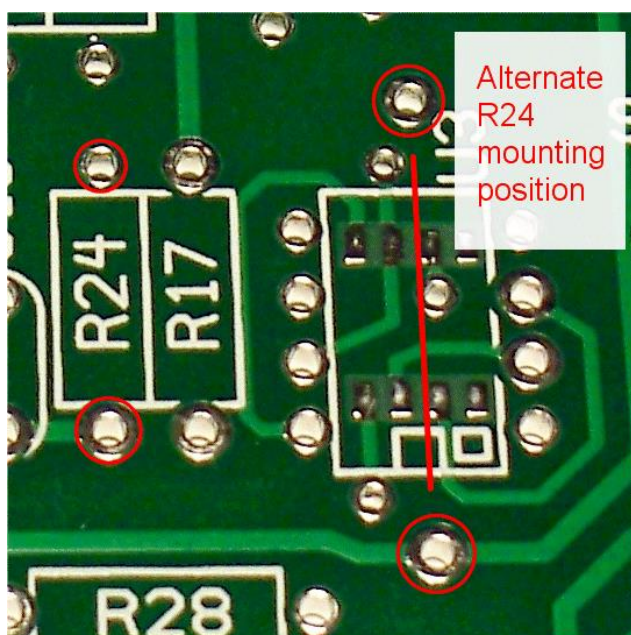
Two matched 2N3904 transistors can be used on the board for the linear voltage to exponential current convertor.

[MFOS sells a package with two matched transistors and a temperature compensator.](#)



!!! IMPORTANT !!!

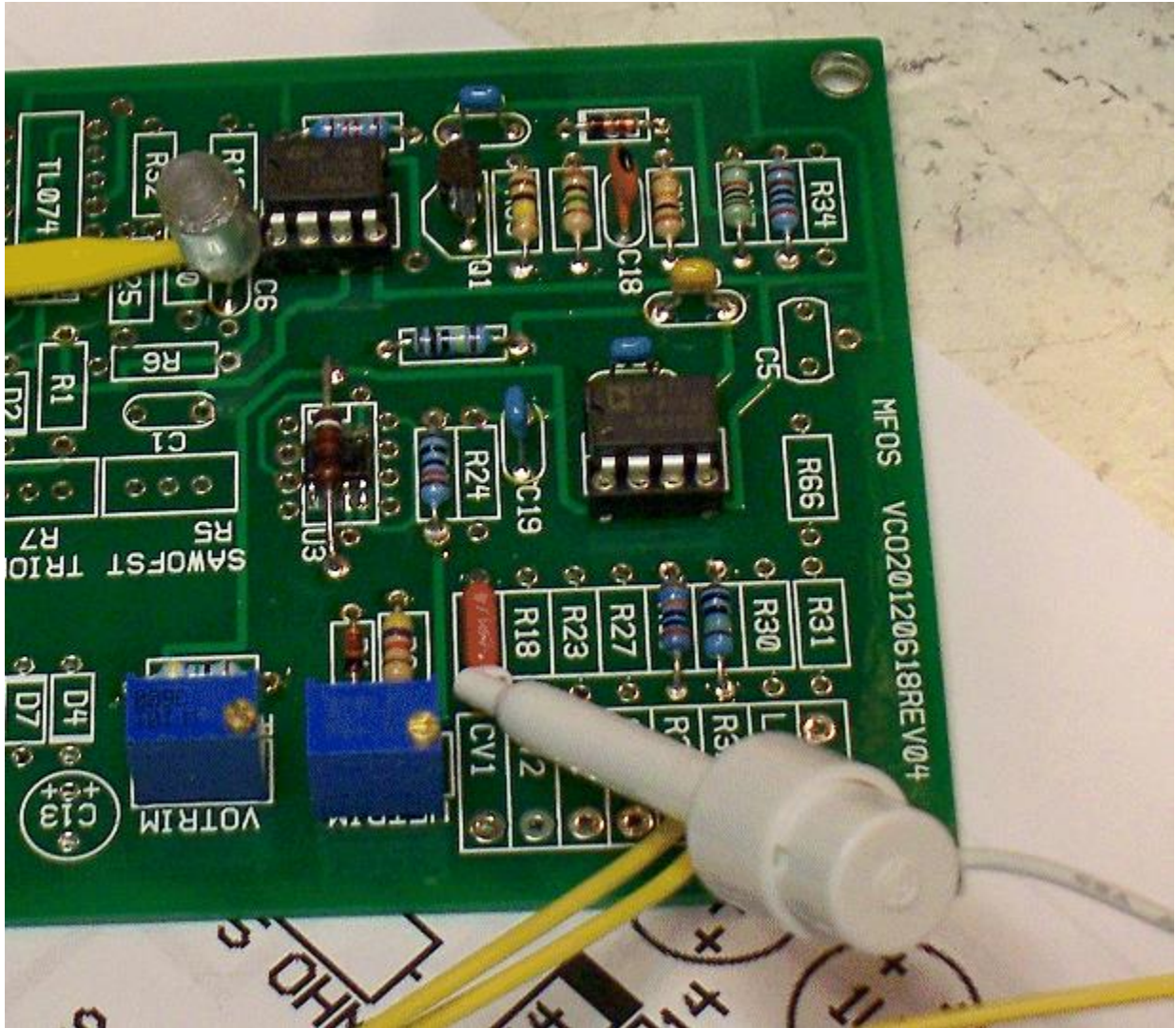
Notice that there is a legend for R24 but there are also two alternate mounting holes on the board specifically for mounting a metal film 2K Ohm 1/4W +/-2% T.C. +3300 PPM tempco as R24 so that it is in thermal contact with U3 (or matched discrete transistor pair). Use thermal grease or epoxy to make the thermal contact. The tempco can go above a dual transistor package or between 2 discrete transistors. I find I am able to make a breeze shield using a large heat shrinkable tube placed over the transistors and tempco. Don't overdo the heat or you may cause the shrink tube to crack due to the uneven shape of the transistors and tempco together.



If you mount the 2K +3300 tempco in the alternate location for R24 (in contact with the expo transistors) DO NOT install a 2K resistor in the location of the R24 legend. The 2K +3300 tempco is used instead of carbon or metal film resistor R24 and connects to the same points on the PC board.

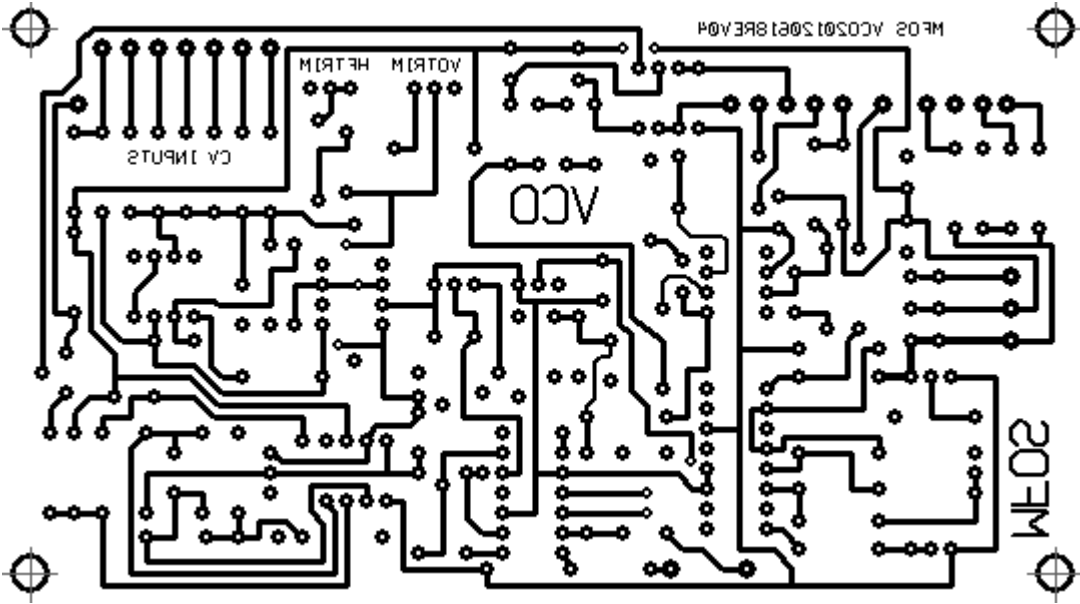
I tested the VCO's front end after the PCB change to allow use of a SOIC package for U3. It's all go flight! That's a 2K platinum film tempco across the SOIC chip.

[MFOS sells a package with two matched transistors and a temperature compensator.](#)

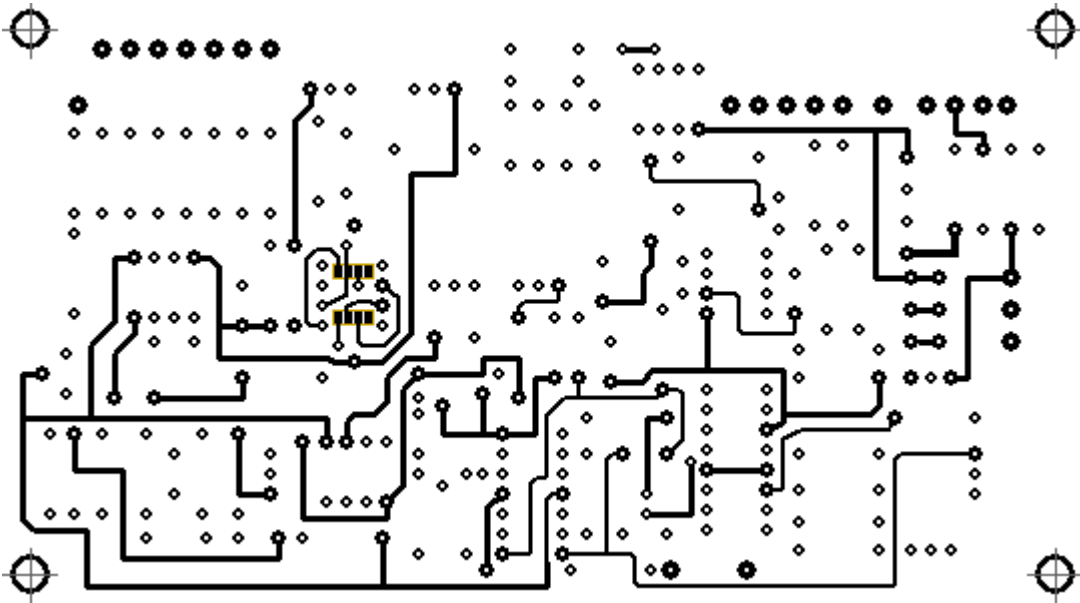


Voltage Controlled Oscillator PCB Layouts

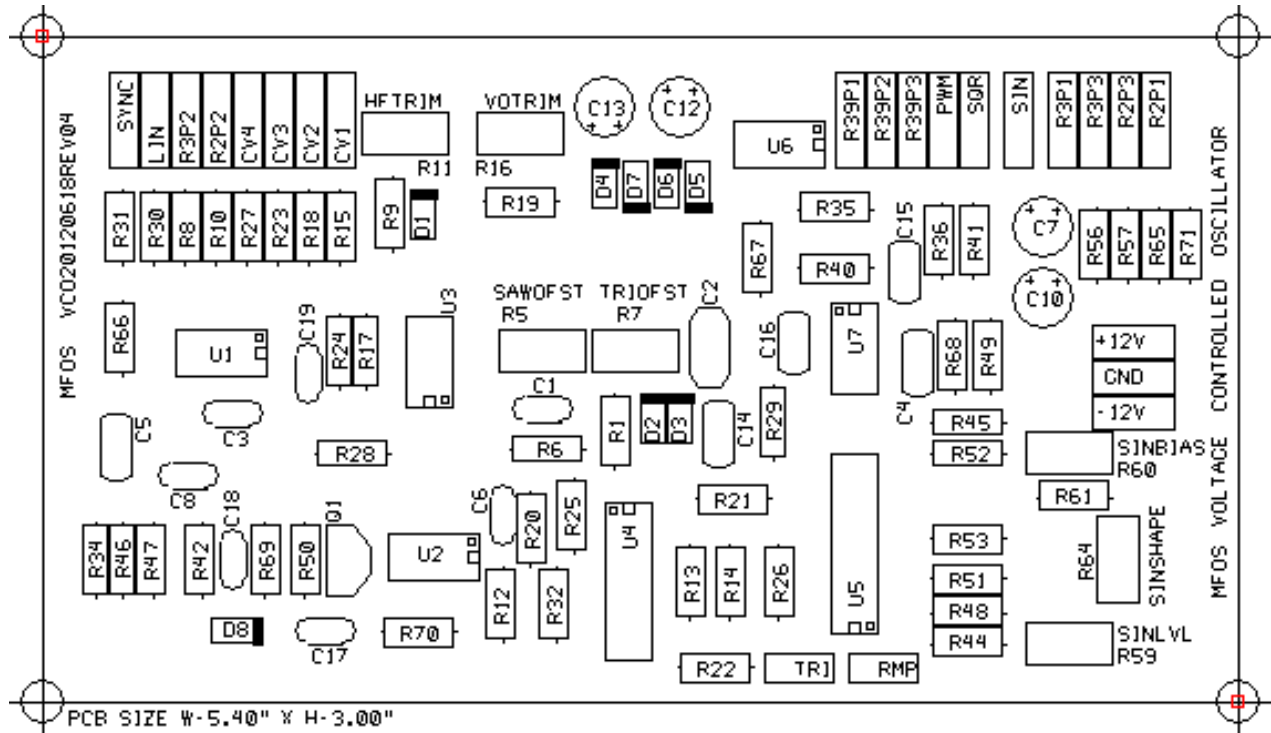
Voltage Controlled Oscillator PCB Bottom Copper (Parts Side View Shown)



Voltage Controlled Oscillator PCB Top Copper (Parts Side View Shown)



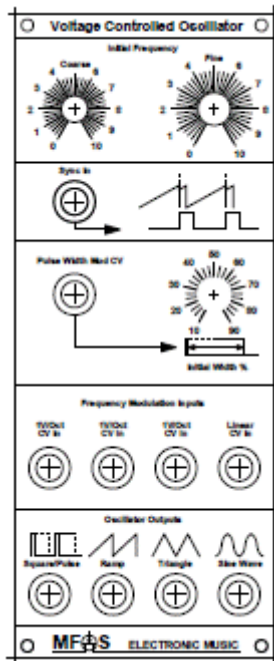
Voltage Controlled Oscillator PCB Silk Screen(Parts Side View Shown)



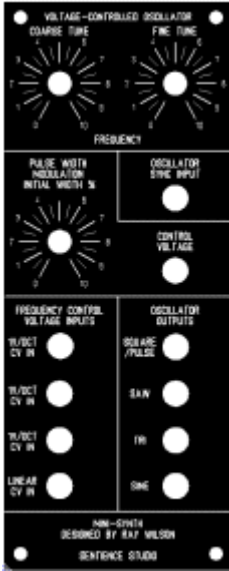
Voltage Controlled Oscillator Front Panel Drawings and Wiring

Voltage Controlled Oscillator Front Panel [PDF](#)

[This overlay fits the UNIVERSAL panels specified on this page.](#)



Dave Kronmeyer took the time to make a nice Front Panel Express design and share it with all of us. If you use it make sure you take into account any differences related to the wiring diagram.



David Kronmeyer did a nice Front Panel Express layout.

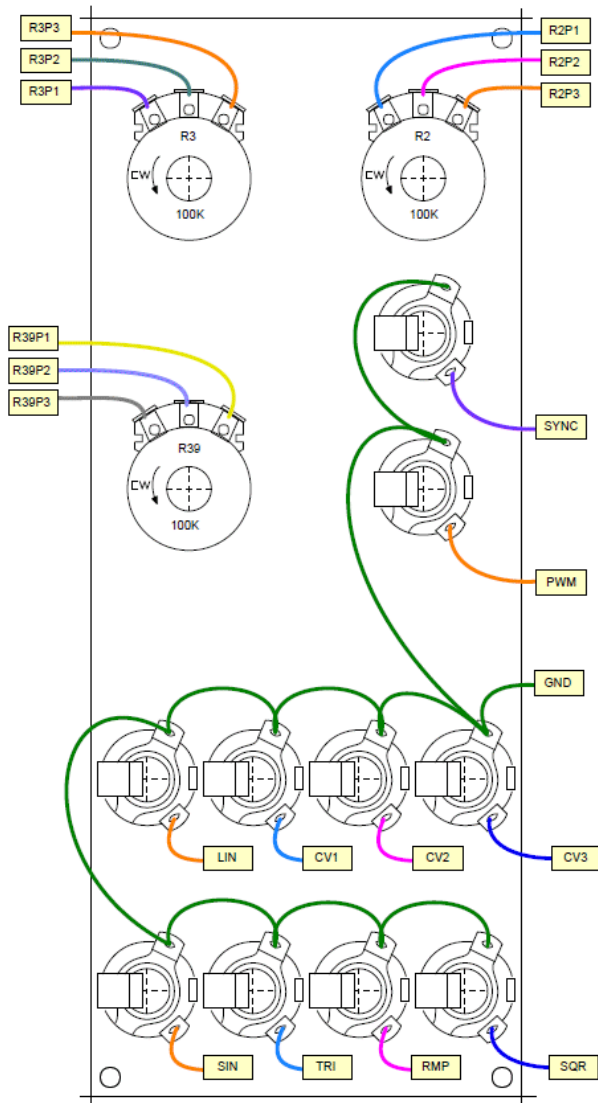
[Visit Front Panel Express](#)

Click the image to download the .FPD File.

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 .FPD File (Front Panel
 Express) File

Voltage Controlled Oscillator Back Panel [PDF](#)

Voltage Controlled Oscillator
 Rear View Panel Wiring



Voltage Controlled Oscillator Project Parts List

Order enough DIP sockets for ALL chips. Sockets are your friends!

Capacitor voltage rating should be 25V or greater for all capacitors.

Non-electrolytic capacitors can be film or ceramic type.

The integrator cap (C6 .005uF) needs to be temperature stable so buy silvered mica, polystyrene or polycarbonate.

Substitutions

OP275 - LT1112, AD706, LF442, TL072

AD SSM-2210 - LM394 DIP or Two matched transistors (specs similar to 2N3904)

R24 (metal film 2K Ohm 1/4W +/-2% T.C. +3300 PPM tempco) - 2K Carbon Comp Resistor (provides no temperature compensation)

LM13700 - LM13600, NE5517, AU5517, NTE870, NJM13600D

TL074 - Any quad JFET op amp

PN4391 - 2N5457, J210, NTE457

PN4391 can be replaced with 2N5457 N-Channel JFET

The PN4391 and 2N5457 N-Channel JFETs went out of production in 2012 so here are some sources for the NTE457, PN4391 and 2N5457 all of which are good replacements.

- [Allied Electronics NTE457 \(direct replacement for 2N5457\)](#)
- [Mouser Electronics NTE457 \(direct replacement for 2N5457\)](#)
- [Wholesale Electronics Inc. NTE457 \(direct replacement for 2N5457\)](#)
- [Parts Express. NTE457 \(direct replacement for 2N5457\)](#)
- [online components.com NTE457 \(direct replacement for 2N5457\)](#)

MFOS sells a pack of 5 brand new Fairchild 2N5457 N-Channel JFETs and a pack of 5 brand new Fairchild PN4391 N-Channel JFETs

- [MFOS 2N5457 pack of 5](#)
- [MFOS PN4391 pack of 5](#)

SSM2210 can be replaced with a matched pair of 2N3904 transistors.

Use a matched pair of 2N3904 NPN transistors or SOIC SSM2212 in place of the SSM2210 if you can't find it in a SOIC or DIP package

Resistor Types & Tolerances

I suggest using 1% metal film for all resistors shown on page 1 of the schematic. Using 1% metal film for all resistors shown on page 2 of the schematic except for R68 (10M) and R22, R26, R34, R49, R51 (1Ks) will give greater uniformity of operation among multiple VCOs and better temperature tolerance but 5% carbon film resistors can be used as well.

Qty.	Description	Value	Designators
1	LM13700 Dual gm OpAmp <i>See notes above for subs.</i>	LM13700	U5
1	OP275 Dual BiFET Op Amp <i>See notes above for subs.</i>	OP275	U1
1	SSM2210 Matched NPN Pair <i>See notes above for subs.</i>	SSM2210	U3

1	TL071 Op Amp	TL071	U7
2	TL072 Dual Op Amp	TL072	U2, U6
1	TL074 Quad Op Amp	TL074	U4
1	PN4391 N Channel JFET <i>See notes above for subs.</i>	PN4391	Q1
8	High Speed Switching Diode	1N914	D1, D2, D3, D4, D5, D6, D7, D8
3	Linear Taper Potentiometer	100K	R2, R3, R39
2	Metal Film 1/4 Watt 1% Resistor	2K	R24, R46
2	Metal Film 1/4 Watt 1% Resistor	47K	R20, R65
1	Metal Film 1/4 Watt 1% Resistor	475 ohm	R19
1	Metal Film 1/4 Watt 1% Resistor	470K	R61
3	Metal Film 1/4 Watt 1% Resistor	4.7K	R9, R36, R52
1	Metal Film 1/4 Watt 1% Resistor	3K	R41
12	Metal Film 1/4 Watt 1% Resistor	100K	R6, R10, R15, R18, R23, R27, R29, R31, R44, R50, R66, R67
11	Metal Film 1/4 Watt 1% Resistor	10K	R1, R12, R13, R17, R25, R32, R35, R40, R42, R47, R71
1	Carbon Film 1/4 Watt 5% Resistor	10M	R68
1	Metal Film 1/4 Watt 1% Resistor	130K	R53
1	Metal Film 1/4 Watt 1% Resistor	18K	R70
5	Carbon Film 1/4 Watt 5% Resistor	1K	R22, R26, R34, R49, R51
5	Metal Film 1/4 Watt 1% Resistor	1M	R8, R28, R30, R45, R69
2	Metal Film 1/4 Watt 1% Resistor	200K	R56, R57
3	Metal Film 1/4 Watt 1% Resistor	20K	R14, R21, R48
1	Top Adjust Multi-Turn Trim Pot	100 ohm	R16
3	Top Adjust Multi-Turn Trim Pot	100K	R11, R60, R64
2	Top Adjust Multi-Turn Trim Pot	10K	R5, R7
1	Top Adjust Multi-Turn Trim Pot	1M	R59
1	Ceramic Capacitor	10pF	C4

3	Ceramic Capacitor	100pF	C3, C17, C19
5	Ceramic Capacitor	.1uF	C1, C2, C8, C15, C16
1	Ceramic Capacitor	.002uF	C14
1	Ceramic Capacitor	4.7pF	C18
1	Ceramic Capacitor	.001uF	C5
2	Electrolytic Capacitor	10uF 25V	C7, C10
1	Silvered Mica, Polycarbonate or Polystyrene Cap	.005uF	C6
2	Tantalum Capacitor	1uF 25V	C12, C13

Miscellaneous

- (1) 4" x 10" 1/16" thick Aluminum plate for mounting the pots and switches.
- Unit is typically mounted in a synth case with other synth modules.
- Assorted hardware 1" 6-32 nuts and bolts, 1/2" #8 wood screws, etc
- Knobs for potentiometers, wire, solder and typical assorted electronics hand tools.
- Digital Volt Meter and a Signal Tracer or oscilloscope for testing.