

# **MSK 015 Quad Voltage-Controlled Amplifier**

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Documentation for the MSK 015  
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## General notes

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This manual documents the MSK 014 Quad Voltage-Controlled Amplifier, which is a module for use in a Eurorack modular synthesizer. This module contains four identical channels. Each is a two-quadrant voltage multiplier or VCA (Voltage Controlled Amplifier), which allows a signal to pass through to the output in varying amounts depending on the values of two control voltage (CV) inputs. There are normalised connections between the inputs, and some additional mixing outputs that provide the sums and differences between channel outputs.

By careful use of the connections between channels it is possible to realize other functions beyond those of a basic VCA, such as crossfading and four-quadrant voltage multiplication (“ring modulation”). Be sure to read the chapter on patch ideas, starting on page 7 in this manual, for hints on how to combine the channels.

### Front panel controls and connections

The front panel of the Quad VCA is shown in Figure 1. It is divided into four sections for the four channels, which are referred to as channels A, B, C, and D, left to right.

**Inputs** Each channel has three inputs: an audio or signal input (second row, labelled “IN”); a positive or non-inverting CV input (top row, labelled “+”); and a negative or inverting CV input (third row, labelled “-”). Positive voltage on the non-inverting input tends to make more signal pass through the VCA. Positive voltage on the inverting input tends to make less signal pass through the VCA. See the detailed descriptions below for exactly how these inputs operate.

The signal inputs are normalised from left to right and top to bottom as shown by the black lines connecting the jack sockets. If you do not insert a plug in the IN socket for channel B, it will take its signal input from the input of channel A. Channel C will similarly take input from B, and D from C, if these channels are not given input of their own. So a single cable inserted in channel A’s input can drive all four

channels if no other input cables are inserted.

There is similar normalising all the way across for the positive CVs, but the normalising for the negative CVs is a little more complicated: the channel A and C negative CVs, if no plug is inserted, will take normalised input from the same channel’s positive CV, but the channel B and D negative CVs will take normalised input from the previous channel’s negative CV. This pattern of default connections is intended to make some common multi-channel patches easier.

**Attenuators and offsets** Each channel also has three knobs: from top to bottom, they are an attenuator for the positive CV, an attenuator for the negative CV, and an offset knob. The attenuators control the sensitivity of the channel to the corresponding voltage, from zero at full counterclockwise (control voltage will have no effect) to maximum at full clockwise (control voltage will have maximum effect). These are *attenuators*, not “attenu-verters,” meaning that they start at zero and go in one direction. To get an inverted effect from a CV, plug it into the other input.

The offset knob for each channel is slightly bipolar: its range of adjustment is from about  $-0.6\text{V}$  to  $+5.0\text{V}$ , with the zero point not quite at the counterclockwise extreme of the knob’s rotation, for reasons discussed in more detail in a separate section below. Turning this knob up can be useful to allow signal through without a CV, using the module as a basic manual attenuator or mixer; or in combination with the negative CV input to achieve special effects.

**Outputs** Each channel has its own per-channel output, labelled “A,” “B,” “C,” or “D” and located immediately below the column of knobs for the channel. There are also sum and difference outputs for the pairs of channels on either side of the module: “A+B,” “A-B,” “C+D,” and “C-D.” These simply add or subtract the voltages sent to the per-channel outputs.

Finally, the “ALL” output carries the sum of all four per-channel outputs.

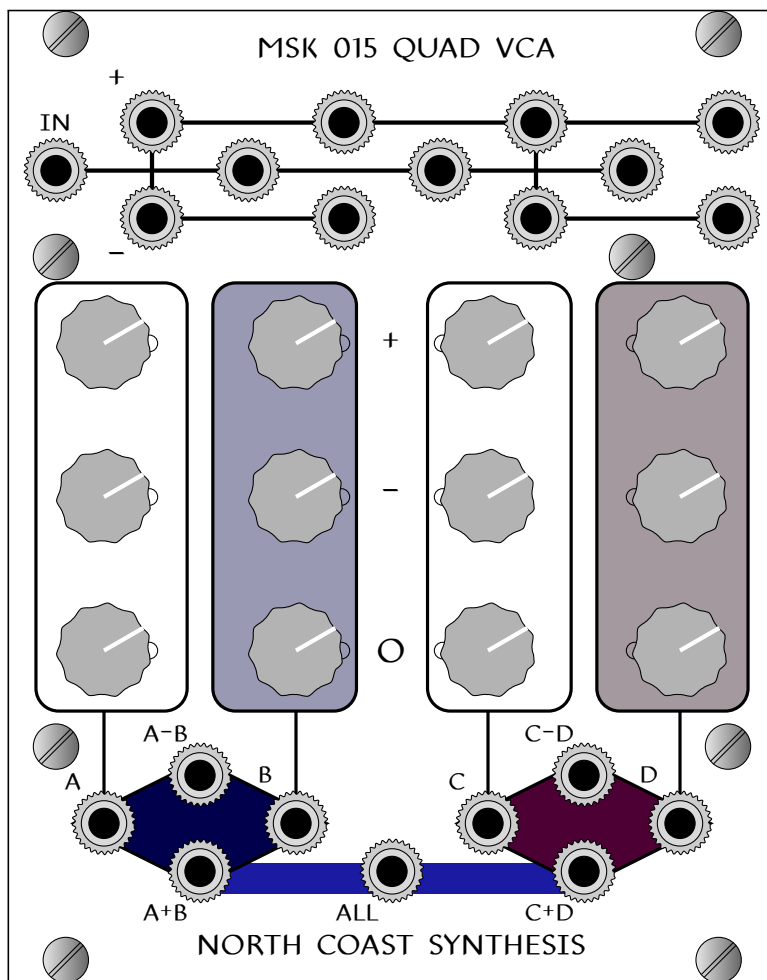


Figure 1: Module front panel.

## Module function in linear mode

It's useful to describe each channel's behaviour in terms of an *effective control voltage*, which is defined as:

- the non-inverting CV input (top row of jack sockets), attenuated from zero to full strength by the channel's "+" knob;
- minus the inverting CV input (third row of jack sockets, below the main inputs), attenuated from zero to full strength by the channel's "-" knob;
- plus the setting of the channel's "O" knob (for "offset"), which is a voltage ranging from  $-0.6\text{V}$  to  $+5.0\text{V}$ .

There is a DIP switch on the back of the module for choosing *linear* or *exponential* mode for each channel. Exponential mode is described in a separate section below; this section and most patches assume linear mode.

When the effective control voltage is zero or negative, the channel lets through no signal from input to output, to the extent reasonably possible. For positive effective control voltages up to about  $+8\text{V}$ , the channel lets through more and more signal as the effective control voltage increases, in proportion to the effective control voltage. At  $+5\text{V}$  it achieves unity gain: output level the same as input level. It should remain linear from  $+5\text{V}$  to  $+8\text{V}$  effective control voltage, reaching a gain of 1.6 (voltage) or approximately 4dB (power) at  $+8\text{V}$ . For effective control voltages beyond  $+8\text{V}$ , the gain may increase a little further still, but it will no longer increase linearly.

The  $+5\text{V}$  level above is quite accurate, for both the knob range and the input voltage response. This voltage is trimmed during module construction. So if you turn the offset knob fully clockwise with zero CV inputs, the channel will have unity gain, passing the input through to the output with the level unchanged. Offset at zero (which means almost but *not* fully counterclockwise), CV knobs fully clockwise, and either non-inverting CV at  $+5\text{V}$  or inverting CV at  $-5\text{V}$  (the other at zero), will also give unity gain.

## The offset knob and "bleed"

The offset knob's voltage when fully counterclockwise is not zero but about  $-0.6\text{V}$ . Briefly, that is intended to prevent "bleed."

In more detail: users often complain of VCA modules not completely turning off when given what the users believe is zero CV. Perceived "bleed" through

a VCA does not always really originate in the VCA module, and it cannot always be prevented by the VCA module, but to the extent reasonably possible, the MSK 015 is designed to help eliminate "bleed."

Modules that generate or process control voltages often introduce small offsets, so a CV that was meant to be zero may not really be exactly zero when presented to the VCA. Typical Eurorack wiring practices can also create a skew in the zero-voltage reference levels between different modules in a rack, so that the same voltage that seems to be zero at one module may not be measured as zero by another module with a different reference. Then a linear VCA seeing a small positive CV may correctly allow through a small amount of signal.

Without trying to assign blame, having the offset knob start at a small negative voltage means you can adjust the point where the VCA will turn on so that the VCA will be solidly turned off when you want it to be turned off. However, having the offset range start below zero creates some responsibility for the user to adjust the offset for exactly the desired effect.

If you turn the offset knob all the way counterclockwise, then for small positive CVs like  $+0.1\text{V}$  on the non-inverting input, the effective control voltage will still be below zero and the channel will not turn on. The CV input jack will have to reach about  $+0.6\text{V}$  before signal starts to pass. Then the ends of decay tails, or very quiet dynamics, may be lost. To make the VCA start to turn on closer to zero, you must turn the offset knob up a little, so the VCA turns on at exactly the voltage you want. Unless you are compensating for a significant input offset introduced by some other module, you will probably find the best zero setting to be about 10% up from the bottom of the knob's range.

There is no perfect compromise possible here. If the module always turned on at exactly zero, then offsets in the input would be likely to create "bleed." But if it always required a significant positive voltage to turn on, then linear gain behaviour near zero would be difficult to achieve. The MSK 015 gives the user a choice, but requires the user to make the choice, adjusting the knob while listening to the output for best results.

It is the offset knob alone that can go a little bit below zero. The other two knobs per channel have their zero points at the fully-counterclockwise positions and cannot usefully be set to negative values. Also, this entire discussion refers to offsets in the control voltages, not any offset that might exist in the

audio input.

When users have problems with “bleed” in synthesizer racks it is also possible that the undesired signal may not be passing through the VCA at all; and then stopping it at the VCA does not help much. For example, depending on the way your power is wired it is possible that an oscillator may be putting some fraction of its signal onto the power lines, and then a sensitive amplifier may pick up the oscillator signal through the power lines even without any signal passing through the VCA. That is a common problem often misdiagnosed as related to the VCA. One useful test is to set up a patch where “bleed” is perceptible, and then unplug the signal cables to the VCA. If you can still hear the undesired signal despite no connection to the VCA, then the signal couldn’t be passing through the cables you just removed, and it must be on some other path.

## Exponential mode

The DIP switch on the back of the module selects, for each of the four channels (“A B C D”), whether the channel will operate in linear mode (“LIN”) or exponential mode (“EXP”). Although doing this has not caused damage in my testing, I do not recommend switching the mode switches while the module is powered up.

Exponential mode is an optional extra that most users will seldom require. It was easy to add to the circuit at low cost, and it seemed like it might add some value and flexibility to the module, but it is not the main intended mode of operation. The MSK 015 in exponential mode will not compete with a dedicated exponential VCA. It did not seem appropriate to disrupt other parts of the design (for instance, by making the front panel bigger to add more controls) in order to make exponential mode more full-featured. Some of the more complicated patches designed for linear mode, such as ring modulation and cross-fading, will not work well when the channels are in exponential mode.

In exponential mode the VCA’s gain is set by the effective control voltage (defined the same as in linear mode) with a sensitivity of about 12dB/V, and unity gain at effective control voltage approximately +4.4V. With the offset knob turned fully counter-clockwise and no inverting CV input, this means the VCA in exponential mode will give unity gain at about +5.0V on the non-inverting CV input with that input’s knob at maximum. Maximum gain achievable is about 2 (voltage) or +6dB (power), at about +5.5V

control voltage input under these conditions.

Exponential VCAs theoretically never shut off completely, and the minimum possible gain for the MSK 015 when in exponential mode is limited by a voltage-protection diode in the input circuit to about -70dB at about -1.4V effective control voltage.

All the gain specifications in exponential mode are approximate and may vary with temperature, or between individual AS3360 chips. Linear mode will be less temperature sensitive.

## Input and output specifications

The nominal input impedance is 100k $\Omega$  for each audio input and a minimum of 73k $\Omega$  (depending on knob position and whether it is an inverting or non-inverting input) for each control voltage input. It is possible for a single inserted cable to drive more than one input in parallel through the normalling. In the worst case of that, the apparent input impedance could be as low as 25k $\Omega$  for audio (four inputs) or 10k $\Omega$  for CVs (eight inputs); but those values would seldom occur in real use.

All outputs use in-the-loop 1k $\Omega$  current-limiting resistors, giving them effectively zero output impedance in normal use but limiting the current in case of short circuit.

Although intended primarily for audio signals, the signal path in this module is DC coupled and should pass Eurorack control voltages without trouble. Intended frequency range is DC to 20kHz, though it will probably be usable at higher frequencies with only a moderate roll-off.

It should not cause damage to apply any voltage between the power supply rails ( $\pm 12V$  when powered on) to any input or output of this module, at least briefly. Long-term short circuits of outputs directly to power supply rails could overheat the output resistors and eventually make them fail. Patching MSK 015 outputs to outputs of other modules is not recommended, to avoid any small risk of damaging the other module and because such patches are unlikely to have any useful effect.

Although it will not be damaged by  $\pm 12V$ , this module is intended to work with voltages in a  $\pm 5V$  range on the audio inputs and  $\pm 8V$  on all outputs. It can probably be pushed a little further, but outside those ranges first distortion and then hard clipping will set in. Control voltages individually may usefully cover the full  $\pm 12V$  range, but depending on the channel mode, knob settings, and the other CVs, not every such voltage will really be useful, because of

the mode-dependent limits on *effective control voltage* described in earlier sections.

Note the voltage limits apply to outputs as well as inputs. For instance, if you set all channels to unity gain and apply +5V to all the signal inputs, then you will get +5V on all the per-channel outputs. The “ALL” output in principle should be the sum of the four per-channel outputs; but that would be +20V, which is not realistically possible with a  $\pm 12\text{V}$  power supply, and in fact the measured voltage on “ALL” under such conditions would probably be about +11V.

The maximum current demand expected for this module in normal operation is 55mA from the +12V supply and 50mA from the -12V supply. Placing an unusually heavy load on the outputs (for instance, with so-called passive modules or output-to-output patching) can increase the power supply current beyond those levels.

## Source package

A ZIP archive containing source code for this document and for the module itself, including things like machine-readable CAD files, is available from the Web site at <https://northcoastsynthesis.com/>. Be aware that actually building from source requires some manual steps; Makefiles for GNU Make are provided, but you may need to manually generate PDFs from the CAD files for inclusion in the document, make Gerbers from the PCB design, manually edit the .csv bill of materials files if you change the bill of materials, and so on.

Recommended software for use with the source code includes:

- GNU Make;
- $\text{\LaTeX}$  for document compilation;
- LaTeX.mk (Danjean and Legrand, not to be confused with other similarly-named  $\text{\LaTeX}$ -automation tools);
- Circuit\_macros (for in-document schematic diagrams);
- Kicad (electronic design automation);
- Qcad (2D drafting); and
- Perl (for the BOM-generating script).

The package is covered by the GNU GPL, version 3, a copy of which is included in the file COPYING.

## PCBs and physical design

The enclosed PCB design is for two boards, each  $3.90'' \times 4.30''$  or  $99.06\text{mm} \times 109.22\text{mm}$ . The two boards are intended to mount in a stack parallel to

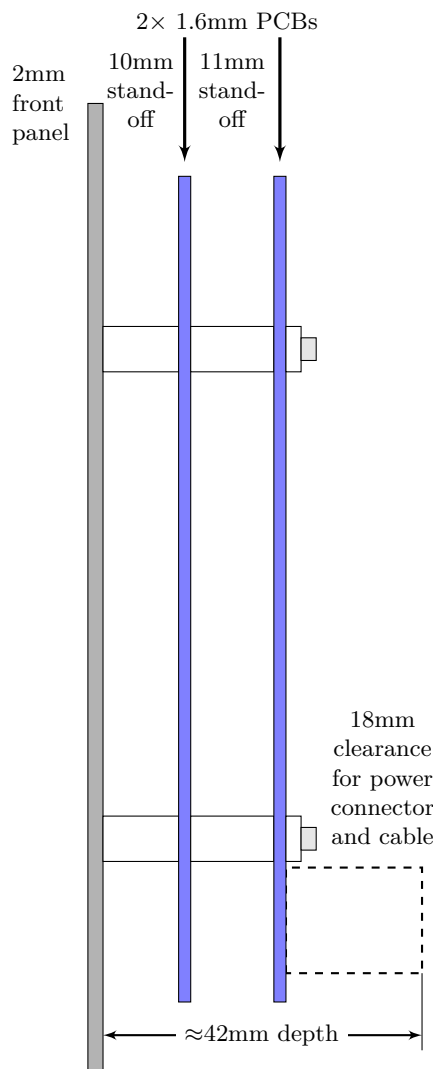


Figure 2: Assembled module, side view.

the Eurorack panel, held together with M3 machine screws and male-female hex standoff hardware. See Figure 2. Including 18mm of clearance for the power connector and cable, the module should fit in 42mm of depth measured from the back of the front panel.

## Use and contact information

This module design is released under the GNU GPL, version 3, a copy of which is in the source code package in the file named COPYING. One important consequence of the license is that if you distribute the design to others – for instance, as a built hardware device – then you are obligated to make the source code available to them at no additional charge, in-

cluding any modifications you may have made to the original design. Source code for a hardware device includes without limitation such things as the machine-readable, human-editable CAD files for the circuit boards and panels. You also are not permitted to limit others' freedoms to redistribute the design and make further modifications of their own.

I sell this and other modules, both as fully assembled products and do-it-yourself kits, from my Web storefront at <http://northcoastsynthesis.com/>. The latest version of this document and the associated source files can be found at that Web site while it remains open.

Your support of my business is what makes it possible for me to continue releasing module designs. As of the release of the Quad VCA, I am in danger of going out of business. Sales dropped sharply in 2022, and unless I receive a lot more orders for modules and kits in 2023, this may be the last module design from North Coast Synthesis.

Email should be sent to  
[mskala@northcoastsynthesis.com](mailto:mskala@northcoastsynthesis.com).

## Safety and other warnings

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Ask an adult to help you.

North Coast Synthesis Ltd. does not offer warranties or technical support on anything we did not build and sell. That applies both to modules built by you or others from the kits we sell, and to fully-assembled modules that might be built by others using our plans. Especially note that because we publish detailed plans and we permit third parties to build and sell modules using our plans subject to the relevant license terms, it is reasonable to expect that there will be modules on the new and used markets closely resembling ours but not built and sold by us. We may be able to help in authenticating a module of unknown provenance; contact us if you have questions of this nature.

For new modules purchased through a reseller, warranty and technical support issues should be taken to the reseller *first*. Resellers buy modules from North Coast at a significant discount, allowing them to resell the modules at a profit, and part of the way they earn that is by taking responsibility for supporting their own customers.

We also sell our products to hobbyists who enjoy tinkering with and customizing electronic equipment. Modules like ours, even if originally built by us, may be quite likely to contain third-party “mods,” added or deleted features, or otherwise differ from the standard specifications of our assembled modules when new. Be aware of this possibility when you buy a used module.

Soldering irons are very hot.

Solder splashes and cut-off bits of component leads can fly a greater distance and are harder to clean up than you might expect. Spread out some newspapers or similar to catch them, and wear eye protection.

Lead solder is toxic, as are some fluxes used with lead-free solder. Do not eat, drink, smoke, pick your nose, or engage in sexual activity while using solder, and wash your hands when you are done using it.

Solder flux fumes are toxic, *especially* from lead-free solder because of its higher working temperature. Use appropriate ventilation.

Some lead-free solder alloys produce joints that look “cold” (i.e. defective) even when they are correctly made. This effect can be especially distressing to those of us who learned soldering with lead solder and then switched to lead-free. Learn the behaviour of whatever alloy you are using, and then trust your skills.

Water-soluble solder flux must be washed off promptly (within less than an hour of application) because if left in place it will corrode the metal. Solder with water-soluble flux should not be used with stranded wire because it is nearly impossible to remove from between the strands.

Residue from traditional rosin-based solder flux can result in undesired leakage currents that may affect high-impedance circuits. This module does not use any extremely high impedances, but small leakage currents could possibly reduce its accuracy. If your soldering leaves a lot of such residue then it might be advisable to clean that off.

Voltage and current levels in some synthesizer circuits may be dangerous.

Do not attempt to make solder flow through the board and form fillets on both sides of every joint. Some soldering tutorials claim that that is desirable or even mandatory, it does look nicer, and it may happen naturally when the conditions are good and the leads happen to be small in relation to the holes. But with large wire leads that just fit in the holes, when the holes are connected to the ground plane (even through thermal reliefs), on some harder-to-wet lead finishes, with lead-free solder, and so on, you may only end up dumping excessive heat into the joint and damaging the components while you fuss over perfect fillets. A well-made solder joint that just covers the pad and makes good contact to the lead on one side of the board, is good enough.

Building your own electronic equipment is seldom cheaper than buying equivalent commercial products, due to commercial economies of scale from which you as small-scale home builder cannot benefit. If you think getting into DIY construction is a way to save money, you will probably be disappointed.

## Bill of materials

This table is not a substitute for the text instructions.

Qty	Ref	Value/Part No.	
9	C1, C2, C10–C12, C14, C24–C26	100pF	radial ceramic, 0.2" lead spacing
2	C8, C22	4700pF	film, 0.2" lead spacing
14	C3–C7, C9, C15, C18–C21, C23, C27, C28	0.1μF	axial ceramic
3	C13, C16, C17	10μF	radial aluminum electrolytic, 0.1" lead spacing
4	D3, D4, D7, D8	1N5818	or SB130; Schottky rectifier
4	D1, D2, D5, D6	1N5230B	4.7V Zener
4	H1–H4		nut for M3 machine screw
4	H9–H12	M3x11	M3 male-female standoff, 11mm body length
4	H17–H20	M3x10	M3 male-female standoff, 10mm body length
4	H21–H24	M3x6	M3 machine screw, 6mm body length
21	J1–J21	1502 03	switched mono 3.5mm panel jack, Lumberg
3	J22–J24		female single-row socket, 10 pins at 0.1"
1	P3		male Eurorack power header, 2 × 5 pins at 0.1"
3	P4–P6		male single-row header, 10 pins at 0.1"
9	R18, R19, R51, R56, R57, R71, R101, R104, R105	1kΩ	
4	R37, R41, R89, R93	1.2kΩ	
5	R33, R34, R53, R85, R86	1.8kΩ	
4	R29, R30, R81, R82	3kΩ	
4	R44, R45, R96, R97	3.6kΩ	
5	R47, R49, R50, R99, R100	10kΩ	horizontal single turn, Vishay T73YP or similar
1	R8	12kΩ	
5	R42, R43, R58, R94, R95	15kΩ	
20	R1–R3, R13, R35, R36, R38–R40, R46, R60–R62, R67, R87, R88, R90–R92, R98	27kΩ	
4	R54, R55, R102, R103	30kΩ	
5	R4–R7, R14	36kΩ	
2	R48, R52	47kΩ	
4	R106–R109	62kΩ	



Qty	Ref	Value/Part No.	
12	R9, R11, R12, R15–R17, R63, R65, R66, R68–R70	100k $\Omega$	vertical conductive plastic panel pot, BI Technologies P0915N series, linear taper
4	R27, R28, R79, R80	100k $\Omega$	
4	R31, R32, R83, R84	150k $\Omega$	
17	R10, R20–R26, R59, R64, R72–R78	270k $\Omega$	
1	S1	206–124	4-position SPDT DIP switch (CTS)
4	U1–U4	TL074	quad JFET-input op amp
2	U5, U6	AS3360	dual audio VCA (ALFA)
1	U7	LF353	dual JFET-input op amp
1	U8	TL431	2.495V reference in TO-92 package

Fixed resistors should be 1% metal film throughout. RoHS-certified zinc-plated steel hardware is recommended, not stainless steel because of galvanic-corrosion incompatibility with aluminum parts.

Also needed: solder and related supplies, PCBs, panel, knobs, Eurorack power cable, etc.

## Building Board 2

The recommended order for building this module is to assemble Board 2, the one further from the front panel, first. That will make it easier to get all the physical positioning right for the components that bridge between the boards or pass through the panel.

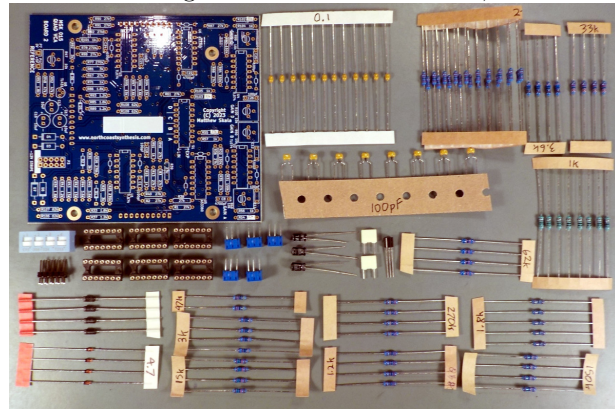
Note that although I'm describing a separate step for each component value, and that's how I built my prototype so as to have plenty of photo opportunities, if you are reasonably confident about your skills you may find it easier to populate all or most of the board (i.e. put the components in place) and then solder them in a single step. Except where noted, the order in which you add components does not matter much.

### Version 1 boards

The first batch of MSK 015 boards had the value for R54, R55, R102, and R103 indicated as 27k $\Omega$  on the silkscreen; it was subsequently changed to 30k $\Omega$  so that the trimmer adjustment range would better cover the range of gain variation in AS3360 chips. If you have a board from this first batch, it should come with stickers showing the new value, but even if a sticker is missing, be sure to install 30k $\Omega$  resistors in these four footprints.

### Preliminaries

Count out the right number of everything according to the bill of materials. There is an abbreviated BOM for Board 2, excluding a few items that will be added when combining this board with Board 1, in Table 2.

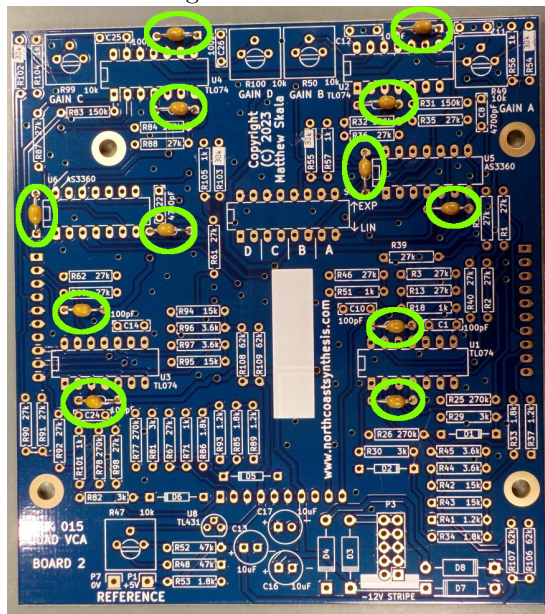


### Decoupling capacitors

The 12 axial ceramic 0.1 $\mu$ F decoupling capacitors, C3–C7, C9, C15, C18–C21, and C23, are shown on the board by a special symbol without their reference designators.



Install these capacitors where the symbol appears. They are not polarized and may be installed in either orientation. These capacitors act as filters for the power supplies to the integrated circuits. An MSK 015 kit should include 14 of these capacitors; save the remaining two for use on Board 1.



This table is not a substitute for the text instructions.

Qty	Ref	Value/Part No.	
8	C1, C10–C12, C14, C24–C26	100pF	radial ceramic, 0.2" lead spacing
2	C8, C22	4700pF	film, 0.2" lead spacing
12	C3–C7, C9, C15, C18–C21, C23	0.1 $\mu$ F	axial ceramic
3	C13, C16, C17	10 $\mu$ F	radial aluminum electrolytic, 0.1" lead spacing
4	D3, D4, D7, D8	1N5818	or SB130; Schottky rectifier
4	D1, D2, D5, D6	1N5230B	4.7V Zener
1	P3		male Eurorack power header, 2 $\times$ 5 pins at 0.1"
8	R18, R51, R56, R57, R71, R101, R104, R105	1k $\Omega$	
4	R37, R41, R89, R93	1.2k $\Omega$	
5	R33, R34, R53, R85, R86	1.8k $\Omega$	
4	R29, R30, R81, R82	3k $\Omega$	
4	R44, R45, R96, R97	3.6k $\Omega$	
5	R47, R49, R50, R99, R100	10k $\Omega$	horizontal single turn, Vishay T73YP or similar
4	R42, R43, R94, R95	15k $\Omega$	
20	R1–R3, R13, R35, R36, R38–R40, R46, R60–R62, R67, R87, R88, R90–R92, R98	27k $\Omega$	
4	R54, R55, R102, R103	30k $\Omega$	
2	R48, R52	47k $\Omega$	
4	R106–R109	62k $\Omega$	
4	R31, R32, R83, R84	150k $\Omega$	
4	R25, R26, R77, R78	270k $\Omega$	
1	S1	206–124	4-position SPDT DIP switch (CTS)
1	U8	TL431	2.495V reference in TO-92 package
6	U1–U6		14-pin DIP socket

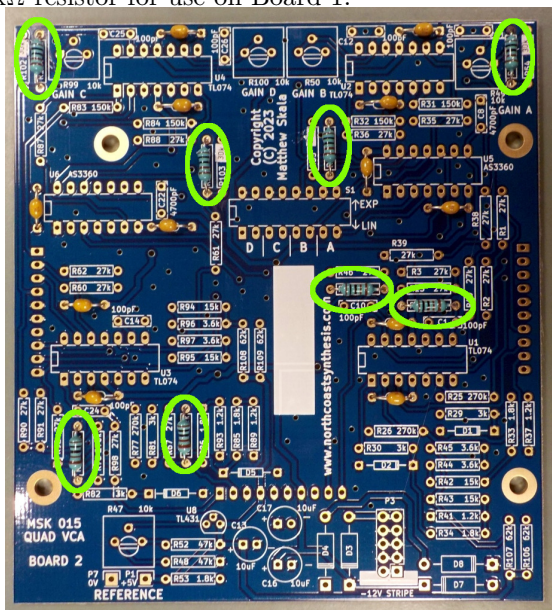
Table 2: Bill of Materials for assembling Board 2 – excluding a few that are better added later, during the Board 1 build. Also needed is the PCB itself.



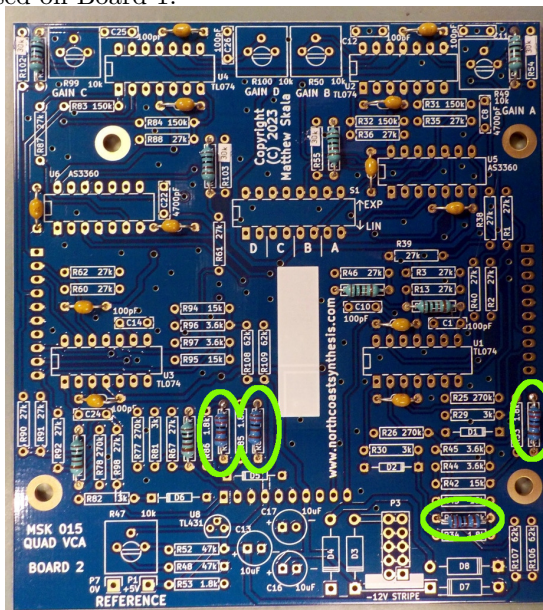
## Fixed resistors

Resistors are never polarized. I like to install mine in a consistent direction for cosmetic reasons, but this is electrically unnecessary. In this module, the fixed resistors are metal film 1% type. They usually have blue bodies and four colour bands designating the value, plus a fifth band for the tolerance. The tolerance band is brown for 1%, but note that we may occasionally ship better-tolerance resistors in the kits than the specifications require, if we are able to source them at a good price. Accordingly, I mention only the four value band colours for this type of resistor; if you are using resistors with other codes, you are responsible for knowing them. Note that colour codes on metal film 1% resistors are often ambiguous (reading from one end or the other end may give two different values, both plausible) and some of the colours are hard to distinguish anyway. If in doubt, always measure with an ohmmeter before soldering the resistor in place.

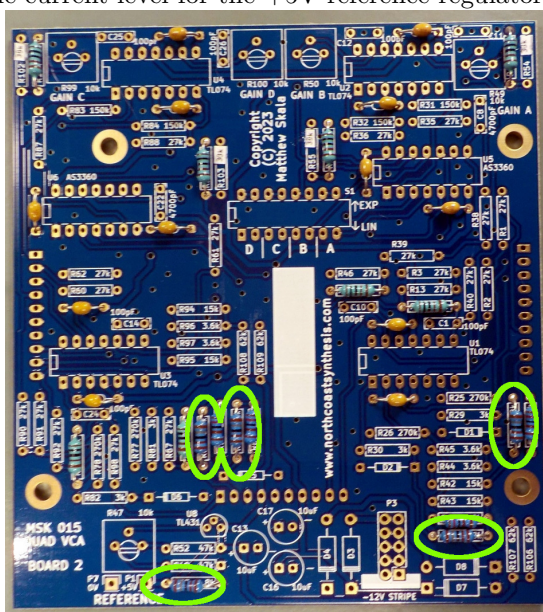
Install the eight 1k $\Omega$  (brown-black-black-brown) resistors R18, R51, R56, R57, R71, R101, R104, and R105. These are output protection resistors: they limit current through the output jacks to a safe level, and prevent capacitive cables from making the amplifiers unstable. Do not confuse these with the other power-of-ten value 100k $\Omega$ , which has a similar colour code. An MSK 015 kit should also contain a ninth 1k $\Omega$  resistor for use on Board 1.



Install the four 1.2k $\Omega$  (brown-red-black-brown) resistors R37, R41, R89, and R93. These are used in the resistor networks that scale control voltages to the range required by the AS3360 VCA chips. Do not confuse these resistors with the 12k $\Omega$  resistors to be used on Board 1.

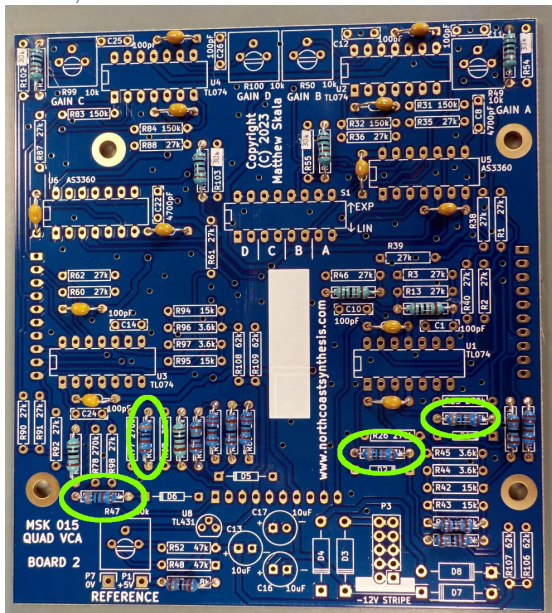


Install the five 1.8k $\Omega$  (brown-grey-black-brown) resistors R33, R34, R53, R85, and R86. Most of these are used in the control voltage scaling networks (one per channel), but R53 is a ballast resistor that sets the current level for the +5V reference regulator.

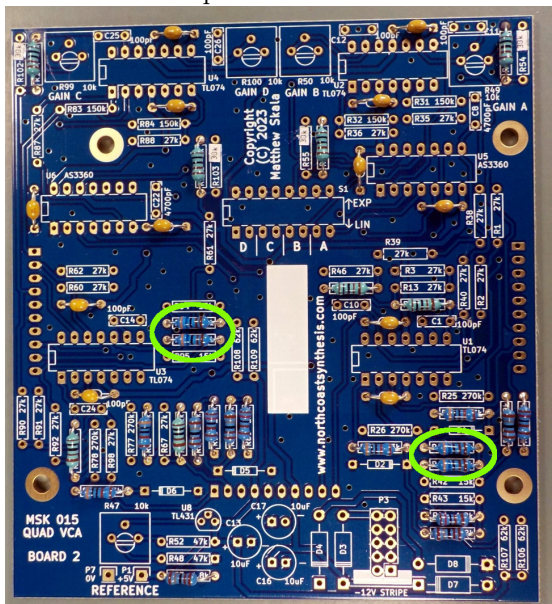




Install the four 3k $\Omega$  (orange-black-black-brown) resistors R29, R30, R81, and R82. These are used at the inputs of the control voltage scaling networks, to limit the maximum current through the protective diodes there. Do not confuse these with the 30k $\Omega$  resistors, which have a similar colour code.

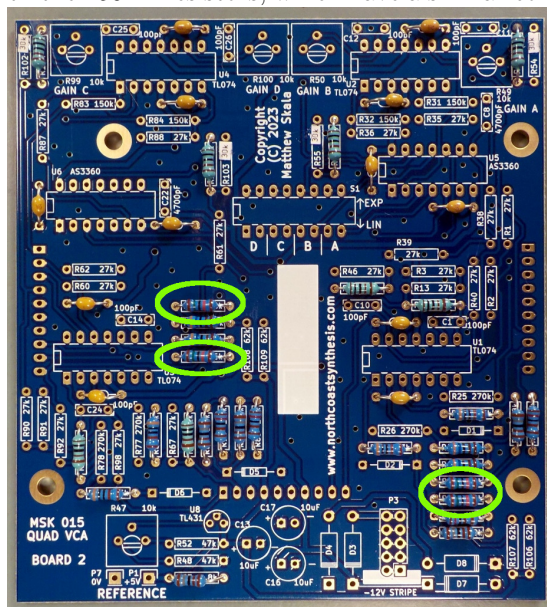


Install the four 3.6k $\Omega$  (orange-blue-black-brown) resistors R44, R45, R96, and R97. These are used in the control voltage scaling networks, specifically to set the offset for exponential mode.

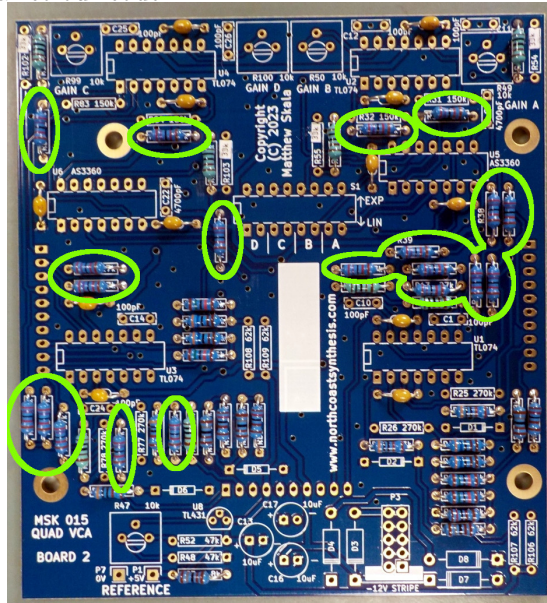


Install the four 15k $\Omega$  (brown-green-black-red) resistors R42, R43, R94, and R95. These are also used

in the control voltage scaling networks, specifically to set the CV sensitivity in exponential mode. A full kit should contain five 15k $\Omega$  resistors, with the last one reserved for use on Board 1. Do not confuse these with the 150k $\Omega$  resistors, which have a similar colour.

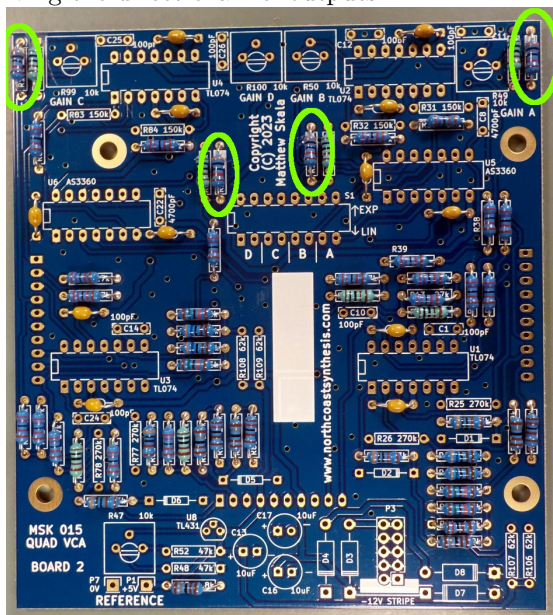


Install the 27k $\Omega$  (red-violet-black-red) resistors. There are 20 of them: R1–R3, R13, R35, R36, R38–R40, R46, R60–R62, R67, R87, R88, R90–R92, R98. These serve as feedback and gain-setting input resistors for the VCA channels and the op amps driving the sum and difference outputs. Do not confuse these resistors with the 270k $\Omega$  resistors, which have a similar colour code.

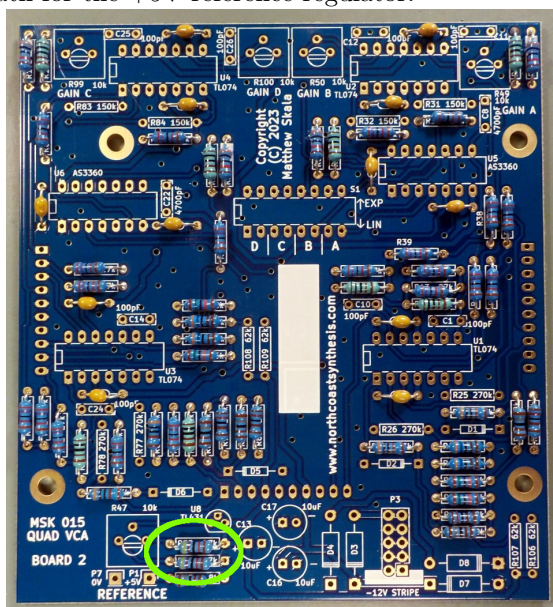




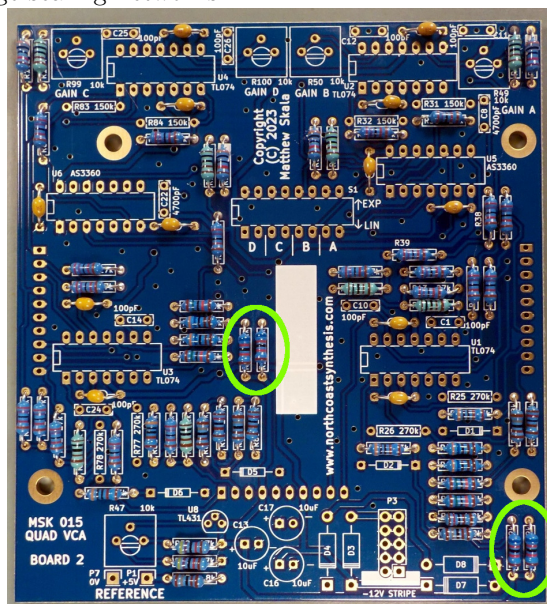
Install the four 30k $\Omega$  (orange-black-black-red) resistors R54, R55, R102, and R103. On version 1 boards these footprints should be marked with stickers. These are feedback resistors for the op amps driving the direct channel outputs.



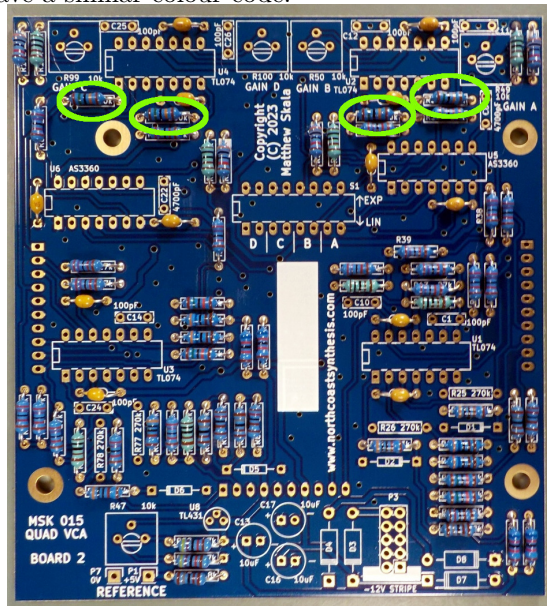
Install the two 47k $\Omega$  (yellow-violet-black-red) resistors R48 and R52. These form part of the feedback path for the +5V reference regulator.



Install the four 62k $\Omega$  (blue-red-black-red) resistors R106–R109. These are used in the control voltage scaling networks.

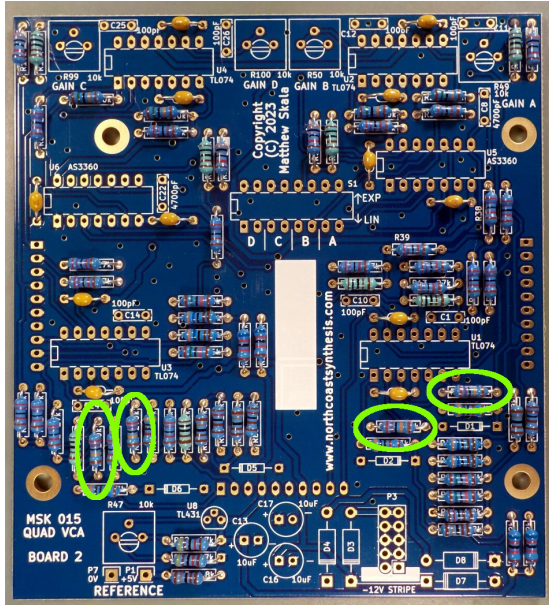


Install the four 150k $\Omega$  (black-green-black-orange) resistors R31, R32, R83, and R84. These are feedback resistors for the audio input buffers. Do not confuse them with the 15k $\Omega$  resistors already installed, which have a similar colour code.





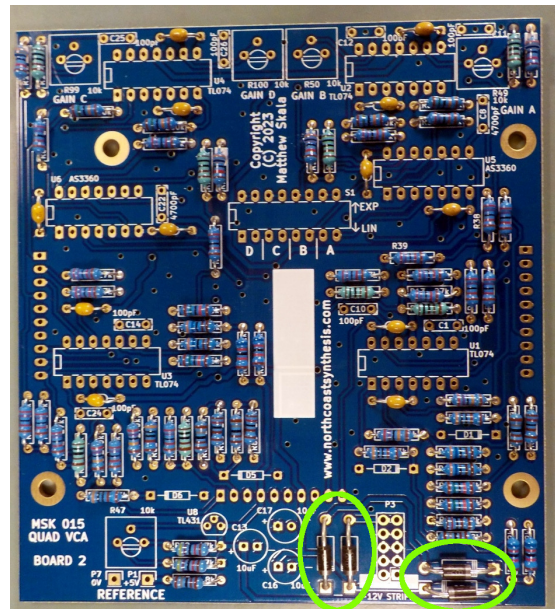
Install the four 270k $\Omega$  (red-violet-black-orange) resistors R25, R26, R77, and R78. These are feedback resistors for the control voltage input buffer/mixer op amps. Do not confuse these resistors with the 27k $\Omega$  resistors already installed, which have a similar colour code. A full MSK 015 kit should contain 17 270k $\Omega$  resistors; the 13 resistors not used here are for Board 1.



## Diodes and DIP sockets

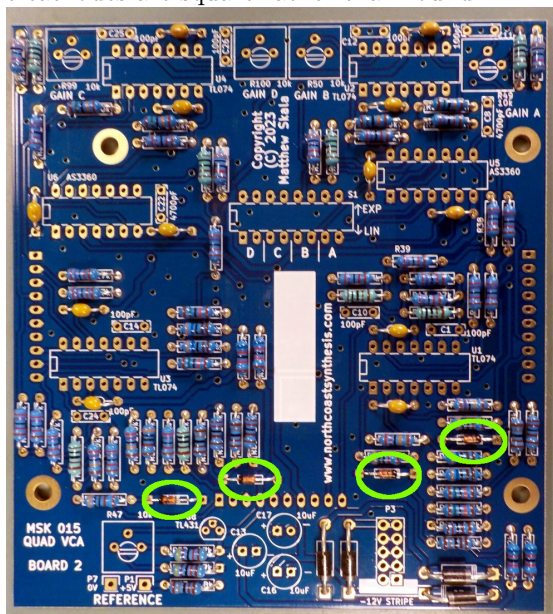
Install the four 1N5818 or SBA130 Schottky rectifier diodes D3, D4, D7 and D8. These are for protection from reverse voltage, which could occur through misconnection of the power cable, or the combination of shrouded headers and an improperly wired cable; and from missing rail conditions, which could occur during startup, in a power supply malfunction, or if another module triggers part of the power supply to shut off.

The diodes are polarized and it is important to install them in the right direction. Each diode is packaged inside a black or dark grey plastic slug with a white or light grey stripe at one end; that end is the *cathode*. The silkscreen markings on the board have a corresponding stripe and the diodes should be installed with their stripes matching the markings on the board. The solder pads for the cathodes are also square instead of round. Installing these backwards means they will have the opposite of the intended protective effect.

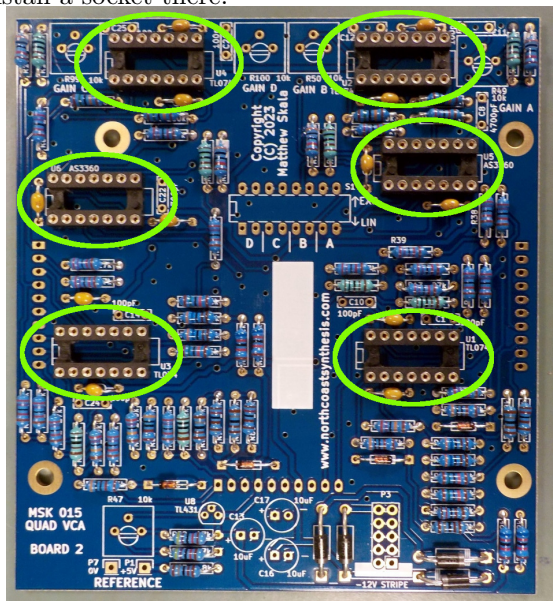


Install the four 4.7V Zener diodes (type 1N5230B) D1, D2, D5, and D6. These are packaged in small orange-pink glass beads, much smaller than the Schottky diode packages. Their function is to limit the control voltage applied to the VCA chips to a safe range. The Zener diodes will have black stripes at one end, indicating the cathode, and as with the Schottky diodes, they are polarized and it is important to install them the right way around. The silkscreen markings on the board have stripes at one end showing the cathode orientation, and the solder pads for

the cathodes are square rather than round.



Install the six 14-pin DIP sockets for the ICs U1–U6, which are general-purpose op amp chips (U1–U4) and the audio VCA chips (U5 and U6). Note that there is a seventh DIP footprint on the board which is a 16-pin footprint for the DIP switch S1; do not install a socket there.



DIP sockets themselves do not care which direction you install them, but it is critically important that the chips installed in the sockets should be installed in the right direction. To help with that, the sockets will probably be marked with notches at one end (indicating the end where Pin 1 and Pin 14 are located) and you should install the sockets so that the notched ends match the notches shown on the PCB silkscreen. The solder pad for Pin 1 is also distinguished by being rectangular instead of rounded.

Installing DIP sockets without having them tilted at a funny angle can be tricky. I recommend inserting the socket in the board, taping it in place on the component side with vinyl electrical tape or sticking it there with a small blob of putty at each end, then soldering one pin on one corner and checking that the socket is snug against the board before soldering the other pins. That way, if you accidentally solder the first pin with the socket tilted, it will be easier to correct (only one pin to desolder instead of all of them).

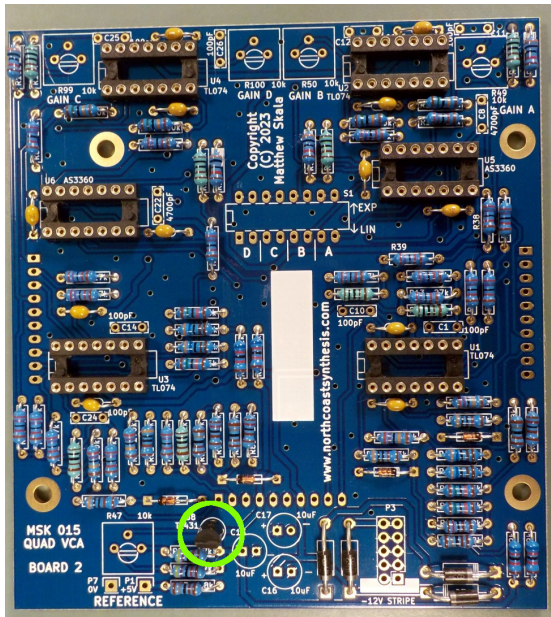
If you somehow manage to solder an entire socket in backwards, don't try to desolder it to turn it around. Just leave it as it is and remember that when you insert the chip, you must insert it so the chip matches the markings on the *board*, not the turned-around socket.

## TL431 voltage reference

The only component with a TO-92 package in the MSK 015 build is the TL431 voltage reference U8, which creates the +5V reference voltage for gain control. It is polarized and must be installed in the correct orientation to work; that orientation is shown by the silkscreen symbol. Install the component so that its flat side points in the same direction as the flat side shown on the silkscreen.

The three legs of the component must be carefully bent into the same triangular pattern (left and right forward, middle backward) as the holes on the board, and then the component pressed into place. There should be a gap of about three millimetres between the board and the component body; do not attempt to seat the component flush on the board because of the risk of breaking off the legs where they enter the body.

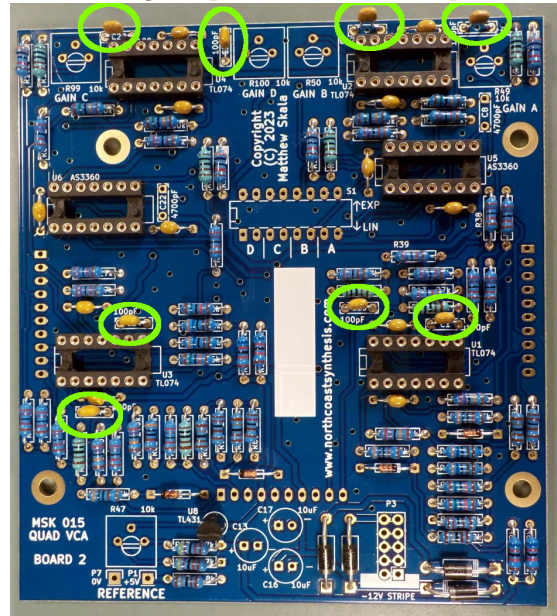




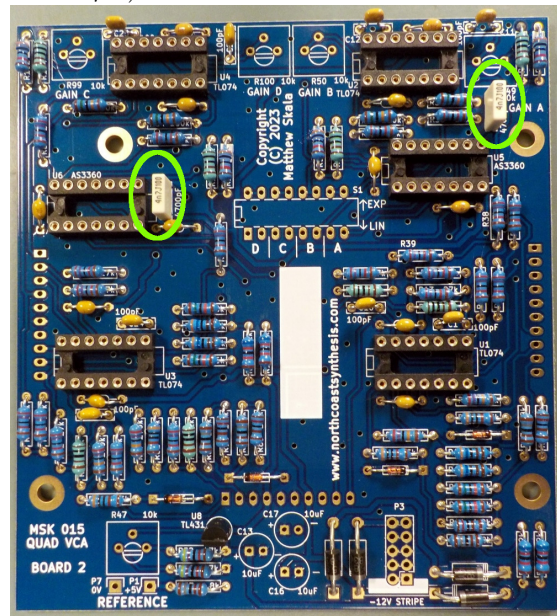
## More capacitors

Install the eight 100pF ceramic capacitors C1, C10–C12, C14, and C24–C26. These are compensation capacitors used to ensure stability on op amps that have outputs exposed to the outside world. They are unpolarized and may be installed in either orientation. Note that these capacitors may come in a number of colours (most often yellow or blue), not necessarily matching the photo. The capacitors are likely to be marked “101” for the digits 10 followed by one more 0, that is 100, number of picofarads (much like the resistor code). There should be one 100pF capacitor left over to install on Board 1.

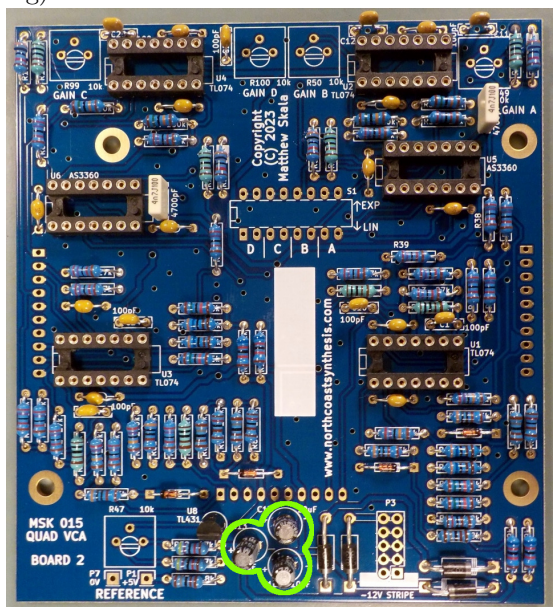
Be careful not to install 100pF capacitors in the similar-looking footprints labelled “4700pF.”



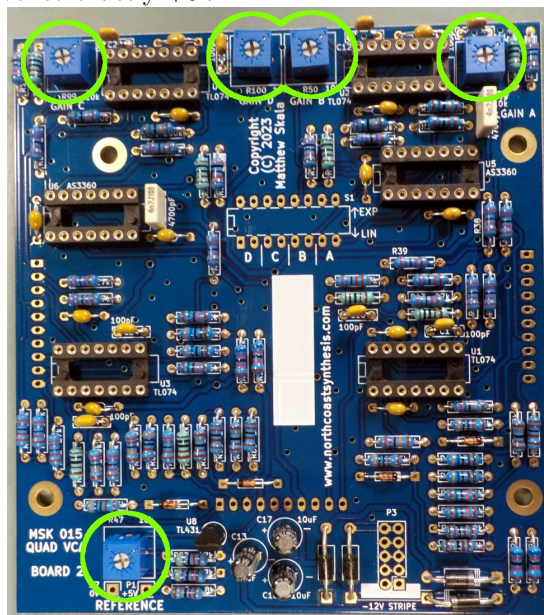
Install the two 4700pF film capacitors C8 and C22. These are special decoupling capacitors required by the VCA chips’ built-in voltage references. They are unpolarized and may be installed in either direction. The markings on film capacitors, and the colour of their plastic bodies, vary depending on the manufacturer and model. These ones might be marked “472” (for 47 followed by two zeros number of picofarads), “4n7” (for 4.7nF), or even “0.0047” (value in  $\mu\text{F}$ ).



Install the three  $10\mu\text{F}$  electrolytic capacitors C13, C16, and C17, which filter the power supply for the module as a whole and the +5V reference voltage. These are polarized components and they may explode if installed backwards. Each one will be marked on its casing with a stripe and minus signs to indicate the negative lead; the positive lead will probably also be longer. These clues should be matched with the markings on the PCB: plus and minus symbols in the silkscreen and a square solder pad for the positive (long) lead.



Install the five  $10\text{k}\Omega$  single-turn trimmers R47, R49, R50, R99, and R100. Four of these set the output gain (referenced to +5V control voltage in linear mode) for the four VCA channels. The remaining trimmer, R47, is for trimming that +5V reference level to exactly +5V.



## Trimmer potentiometers

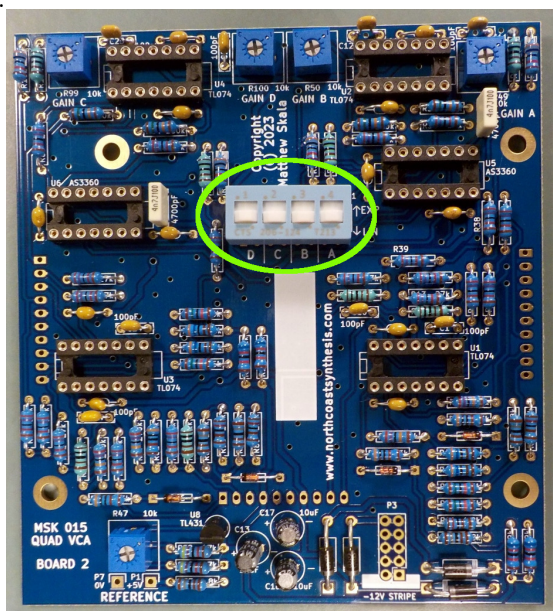
Trimmers usually are not washable, so if you plan to clean your boards by full immersion in water or other solvent, your last chance is now; future cleaning will have to be done with a brush and some care to avoid letting liquid seep into the trimmers. Even now you should take some care with the DIP sockets, because although they are in principle washable, solvent can carry flux residue into the sockets and form a varnish-like layer if not carefully rinsed away.

Trimmers are not exactly polarized, but the three legs of each trimmer serve different functions and need to be connected to the right holes. The physical arrangement of the legs and corresponding holes should make it impossible to install the trimmers wrong way round.



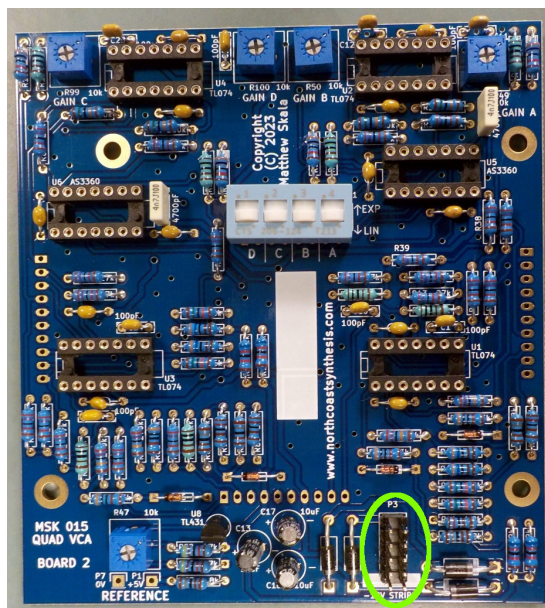
## DIP switch

The four-position SPDT DIP switch S1 mounts to a 16-pin DIP footprint in the middle of the board. It has a top and bottom direction defined by the writing on the top of the switch, and I recommend installing it so that the writing will be right-side-up with respect to the top and bottom of the board. However, its electrical connections are in fact symmetrical in a way that would make it operate identically even if installed upside-down. Much of the same general advice that applies to DIP sockets, in the section on those above, also applies to this switch: secure it to the board with tape or putty first, then solder one corner or two opposing corners, then check that it is not at an angle, before proceeding. That way, if there were a problem, you would have less work to do fixing it.



## Eurorack power connector

Install the 10-pin dual-row Eurorack power header P3. It is not polarized in the horizontal plane. However, if it has shorter legs on one side, then those are the ones that should go through the PCB (leaving the longer legs sticking up to mate with the connector on the power cable), and if it has tin plating on one end of the pins and gold on the other, then the tin side should be the one soldered through the board. Secure the header carefully to the board with tape or putty before soldering it. It is easy to accidentally solder it at an angle, which is a difficult error to fix and may cause trouble when you later attach the power cable.



Note that Eurorack power connections are polarized even if the connectors are not. The cables are usually grey ribbon type with a red stripe along one side indicating pin 1, which carries  $-12\text{V}$  power. For most modules including the MSK 015, the red stripe should be at the *bottom* when the module is mounted vertically in a case. On the MSK 015, the correct location of the  $-12\text{V}$  supply is also marked with the text “ $-12\text{V}$  STRIPE” and a white stripe in the PCB silkscreen. This module is also protected (by the Schottky diodes you just installed) from damage in case of a reversed power connection; if you connect the power backwards and nothing else is wrong, then the module will not power up but will be fine once you connect the power correctly. However, many other modules are not so protected, and it is dangerous to get into the habit of depending on protection diodes. Destroying a module by connecting power backwards is almost a rite of passage for Eurorack users.

A little more assembly is required for Board 2, namely installing the pin headers for connecting to Board 1, and inserting the DIP ICs in their sockets, but it is more convenient to do those steps later as part of the Board 1 and final assembly.

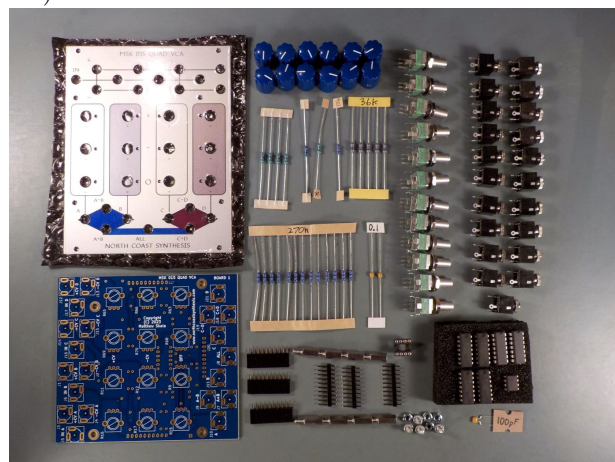
In between completed boards is a good time to take a break.

# Building Board 1

Board 1 has components on both sides, and for best results, it is important to install them in the right order. Build Board 2 first, and see the general comments in the Board 2 chapter about how to approach the task.

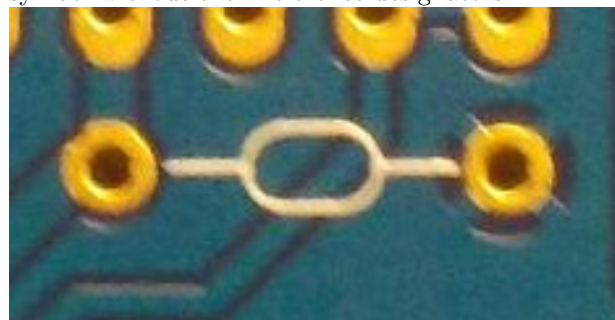
## Preliminaries

Count out the right number of everything according to the bill of materials. There is an abbreviated BOM for the items needed in this chapter (including the connection to Board 2 and final assembly of the module) in Table 3.

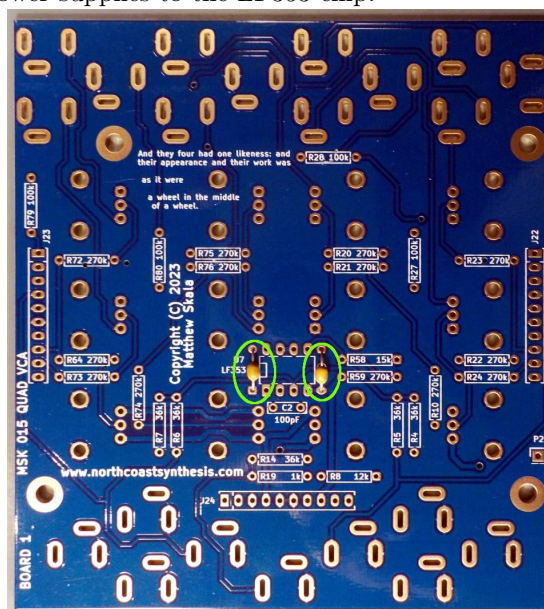


## Decoupling capacitors

The two axial ceramic  $0.1\mu\text{F}$  decoupling capacitors C27 and C28 are shown on the board by a special symbol without their reference designators.



Install these capacitors where the symbol appears. They are not polarized and may be installed in either orientation. These capacitors act as filters for the power supplies to the LF353 chip.



## Fixed resistors

Resistors are never polarized. I like to install mine in a consistent direction for cosmetic reasons, but this is electrically unnecessary. In this module, the fixed resistors are metal film 1% type. They usually have blue bodies and four colour bands designating the value, plus a fifth band for the tolerance. The tolerance band is brown for 1%, but note that we may ship better-tolerance resistors in the kits than the specifications require, if we are able to source them at a good price. Accordingly, I mention only the four value band colours for this type of resistor; if you are using resistors with other codes, you are responsible for knowing them. Note that colour codes on metal film 1% resistors are often ambiguous (reading from one end or the other end may give two different values, both plausible) and some of the colours are hard to distinguish. If in doubt, always measure with an ohmmeter before soldering the resistor in place.

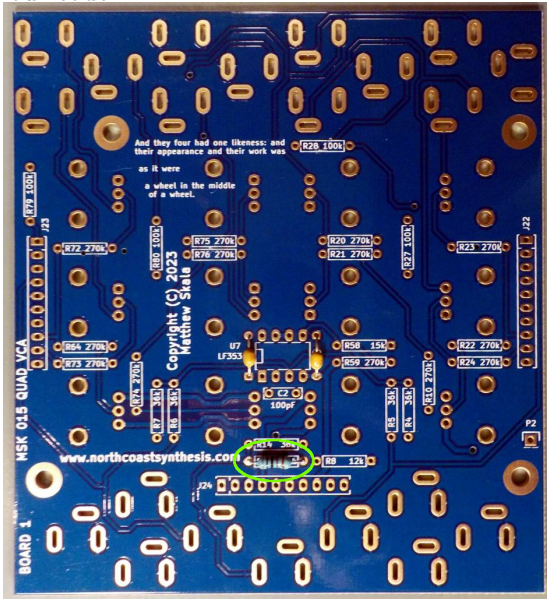
This table is not a substitute for the text instructions.
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Qty	Ref	Value/Part No.	
1	C2	100pF	radial ceramic, 0.2" lead spacing
2	C27, C28	0.1 $\mu$ F	axial ceramic
4	H1–H4		nut for M3 machine screw
4	H9–H12	M3x11	M3 male-female standoff, 11mm body length
4	H17–H20	M3x10	M3 male-female standoff, 10mm body length
4	H21–H24	M3x6	M3 machine screw, 6mm body length
21	J1–J21	1502 03	switched mono 3.5mm panel jack, Lumberg
3	J22–J24		female single-row socket, 10 pins at 0.1"
3	P4–P6		male single-row header, 10 pins at 0.1"
1	R19	1k $\Omega$	
1	R8	12k $\Omega$	
1	R58	15k $\Omega$	
5	R4–R7, R14	36k $\Omega$	
12	R9, R11, R12, R15–R17, R63, R65, R66, R68–R70	100k $\Omega$	vertical conductive plastic panel pot, BI Technologies P0915N series, linear taper
4	R27, R28, R79, R80	100k $\Omega$	
13	R10, R20–R24, R59, R64, R72–R76	270k $\Omega$	
4	U1–U4	TL074	quad JFET-input op amp
2	U5, U6	AS3360	dual audio VCA (ALFA)
1	U7	LF353	dual JFET-input op amp
1	U7		8-pin DIP socket

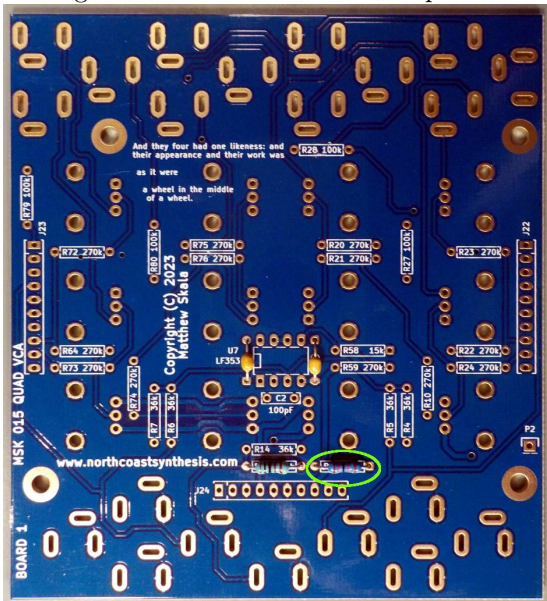
Table 3: Bill of Materials for Board 1 and the final assembly of the module. Also needed: the PCB itself, the aluminum front panel, knobs, the assembled Board 2, and panel-to-rack mounting hardware.



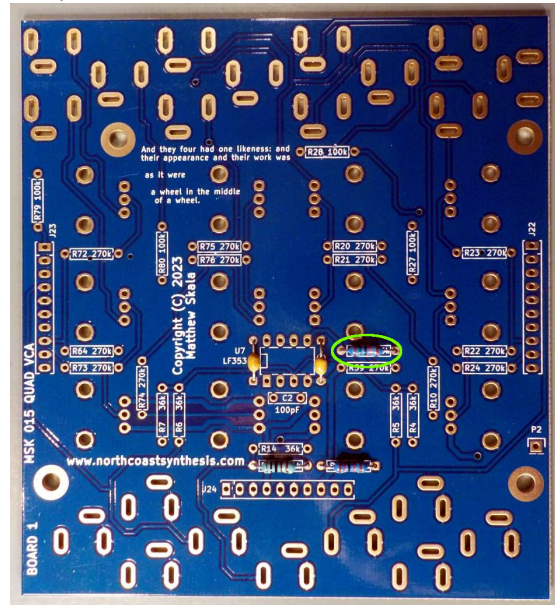
Install the 1k $\Omega$  (brown-black-black-brown) resistor R19. This is an output protection resistor for the “master sum” output. Do not confuse it with the other power-of-ten value 100k $\Omega$ , which has a similar colour code.



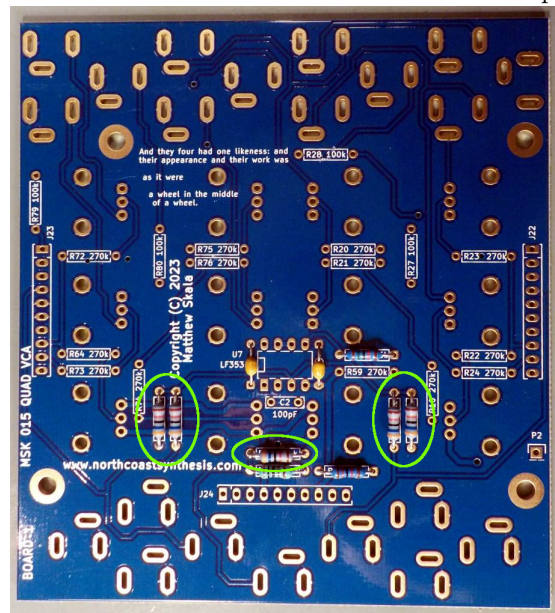
Install the 12k $\Omega$  (brown-red-black-red) resistor R8. This is part of the feedback voltage divider that sets the gain for the “master sum” output.



Install the 15k $\Omega$  (brown-green-black-red) resistor R58. This is part of the voltage divider that sets the value of -VL0, the small negative reference voltage used by the offset knobs.

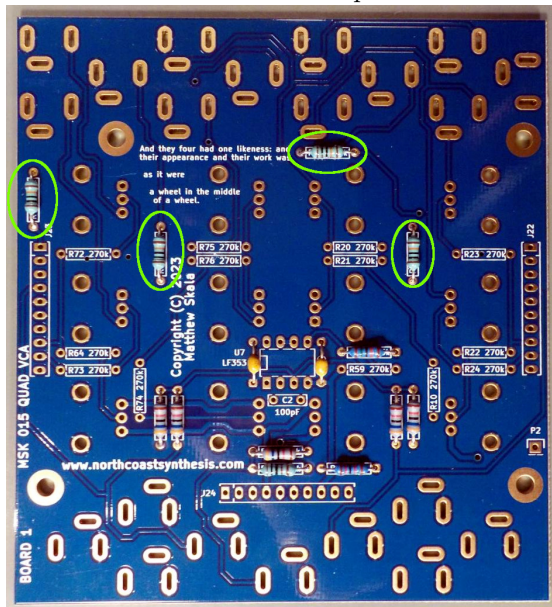


Install the five 36k $\Omega$  (orange-blue-black-red) resistors R4 to R7 and R14. These are gain-setting input and feedback resistors for the “master sum” output.

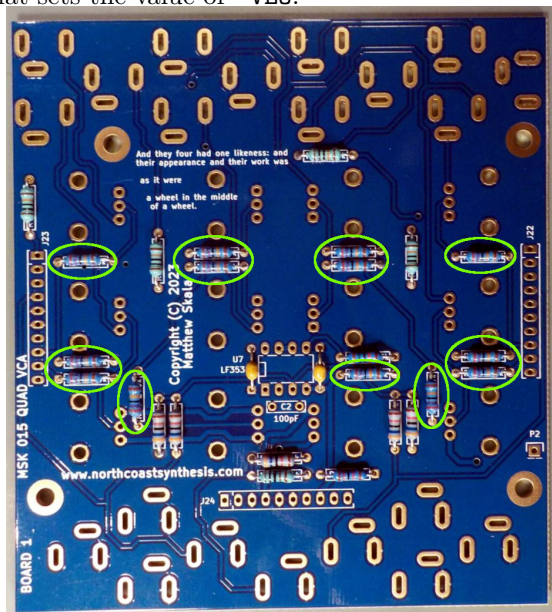




Install the four 100k $\Omega$  (brown-black-black-orange) resistors R27, R28, R79, and R80. These set the input impedance, and convert voltages to currents, for the four channels of audio input.

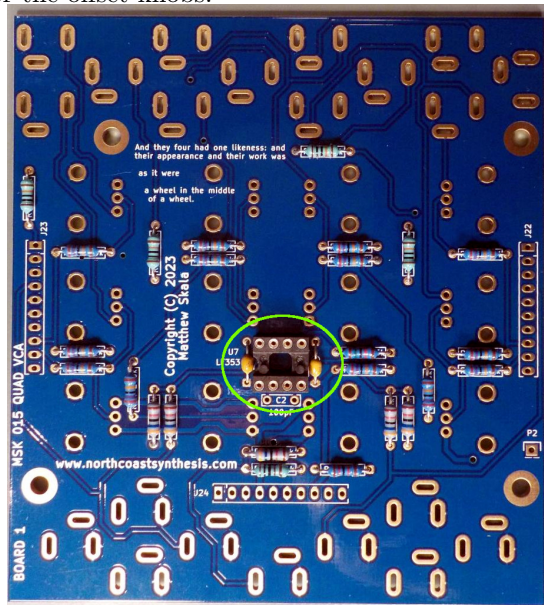


Install the thirteen 270k $\Omega$  (red-violet-black-red) resistors R10, R20 to R24, R59, R64, and R72 to R76. Most of these are input resistors for the op amps that mix control voltages from the knobs and external inputs. The resistor R59 is part of the voltage divider that sets the value of  $-V_{LO}$ .



## DIP socket

Install the 8-pin DIP socket for the LF353 dual operational amplifier U7. The amplifiers in this chip generate the “master sum” output and buffer  $-V_{LO}$  for the offset knobs.



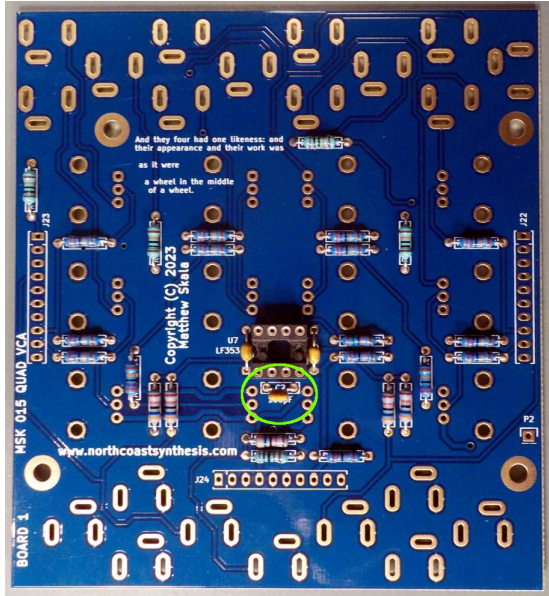
Recall from the Board 2 build that DIP sockets themselves do not care which direction you install them, but it is critically important that the chip installed in the socket should be installed in the right direction. To help with that, the socket will probably be marked with a notch at one end (indicating the end where Pin 1 and Pin 8 are located) and you should install the socket so that the notched end matches the notch shown on the PCB silkscreen. The solder pad for Pin 1 is also distinguished by being rectangular instead of rounded.

Installing DIP sockets without having them tilted at a funny angle can be tricky. I recommend inserting the socket in the board, taping it in place on the component side with vinyl electrical tape or sticking it there with a small blob of putty at each end, then soldering one pin on one corner and checking that the socket is snug against the board before soldering the other pins. That way, if you accidentally solder the first pin with the socket tilted, it will be easier to correct (only one pin to desolder instead of all of them).

## Stability capacitor

Install the 100pF ceramic capacitor C2. This capacitor is intended to ensure stability of the “master sum” amplifier if a capacitive load like a long cable is con-

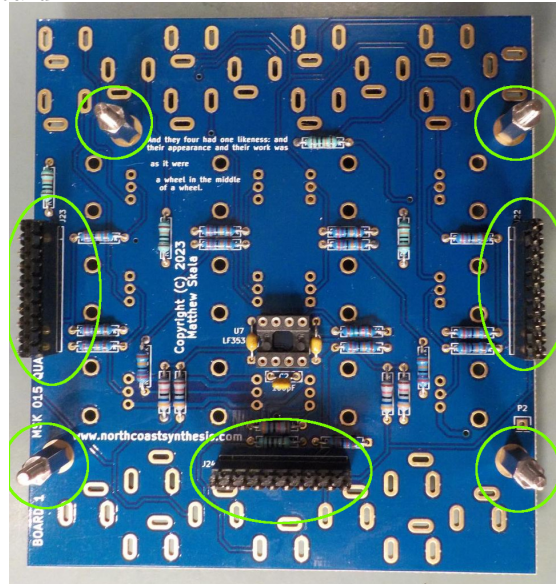
nected to the output. It is unpolarized and may be installed in either direction. The capacitor will likely be marked “101” for the digits 1 and 0 followed by 1 more zero, thus 100, number of picofarads.



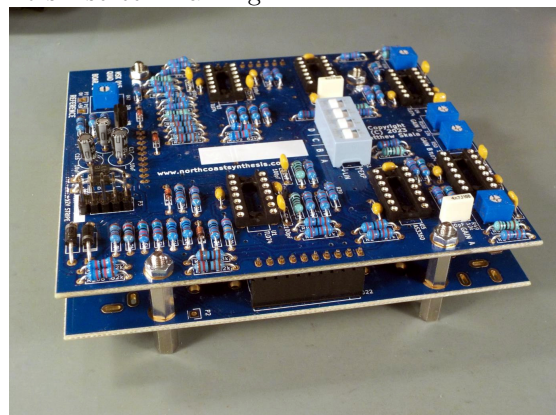
## Board to board connectors

Fasten the four 10mm standoffs on the back of Board 1; that is the side opposite the components already installed. The male ends of the 10mm standoffs should pass through the mounting holes in the board and mate with the female ends of the 11mm standoffs on the front or component side of the board. Be careful to get right which standoffs are the shorter ones (10mm) and which are the longer ones (11mm).

Mate the three pairs of 10×1 header connectors J22–J24 and P4–P6 and place them (do not solder yet) in the J22–J24 footprints on Board 1 with the legs of the female connectors going through the board.



Place your completed Board 2 from the previous chapter on top of the assembly, component side up with the legs of P4–P6 going through the footprints on the back of the board, and fasten the board to the 11mm standoffs with the four hex nuts. The resulting temporary assembly should be as shown in the photo. The asymmetric locations of the holes for the standoffs should make incorrect assembly difficult, but also note that for every connector, there is a silkscreen marking, and the connector itself goes on the side of the board with the corresponding silkscreen marking. You will be soldering it on the other side, where there is no silkscreen marking.





## Panel components

Remove any hardware such as nuts and washers that may be supplied pre-threaded onto the panel components and set all that stuff aside before proceeding.

Install all the hardware for the panel components. The potentiometers will each have one washer and one hex nut; the washer goes on first, nearest the panel. In the case of the jack sockets, the knurled nuts provided for these will have screwdriver slots on one side, and those should face the outside with the smoother side facing the panel.

Then solder all the panel components. Some of joints are large and will require a lot of both heat and solder. You will probably find it helpful to switch to a larger soldering iron tip at this stage, and possibly add extra flux. Nonetheless, try to avoid using more heat than necessary, especially on the jack sockets, because overheating them can warp the plastic and

interfere with the proper functioning of the switching contacts.

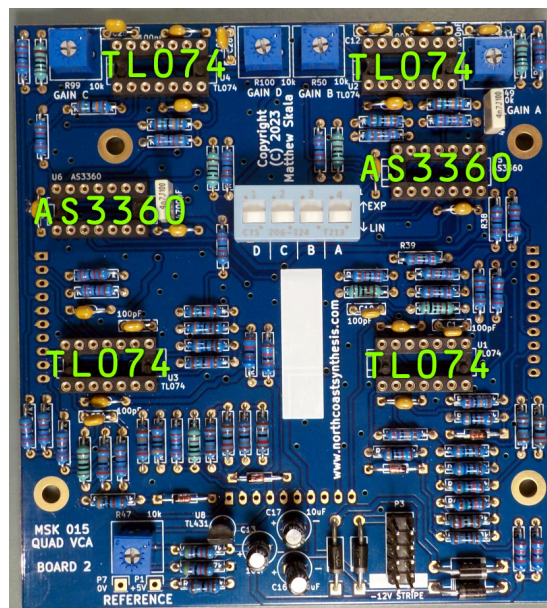
## Final assembly

Insert the LF353 chip U7 in its socket on Board 1. Be careful to insert it right way round: the end with Pin 1 will be marked by an indentation at one corner or a notch in the end and this end of the chip should be inserted to match the notch in the socket and on the board silkscreen and the rectangular Pin 1 solder pad. The Pin 1 end of the chip is at the bottom when the module is inserted in a rack.

Also be careful that all the legs of the chip go into the corresponding holes in the socket. These chips, when brand new, usually have their legs splayed outward a little bit (a measure intended to help them fit snugly into circuit boards when used without a socket) and you must gently bend the legs inward in order to fit them in the sockets. If you apply pressure to a chip prematurely, without all the legs properly fitting into the holes, it is easy to have the legs fold up or even break off.

It should not be necessary to remove the panel from Board 1 again. Just attach Board 2, carefully fitting its header plugs into the header sockets on Board 1 and the male ends of the standoffs through the corresponding holes in Board 2. Then use the hex nuts to fasten Board 2 in place.

Insert the TL074 and AS3360 chips in their sockets on Board 2. Be careful to insert them right way round, with the Pin 1 markings on the chips matching those on the board. Also, be careful not to confuse these chips with each other. They are both 14-pin DIPs and could physically fit in the same sockets, but will be damaged if swapped around. There is a label reading “TL074” or “AS3360” in the silkscreen near each socket.



As with the chips on Board 1, be careful all the legs are in the holes of the socket before you press each chip down, lest you fold up the delicate legs. Also be careful not to confuse which chip goes in which socket.

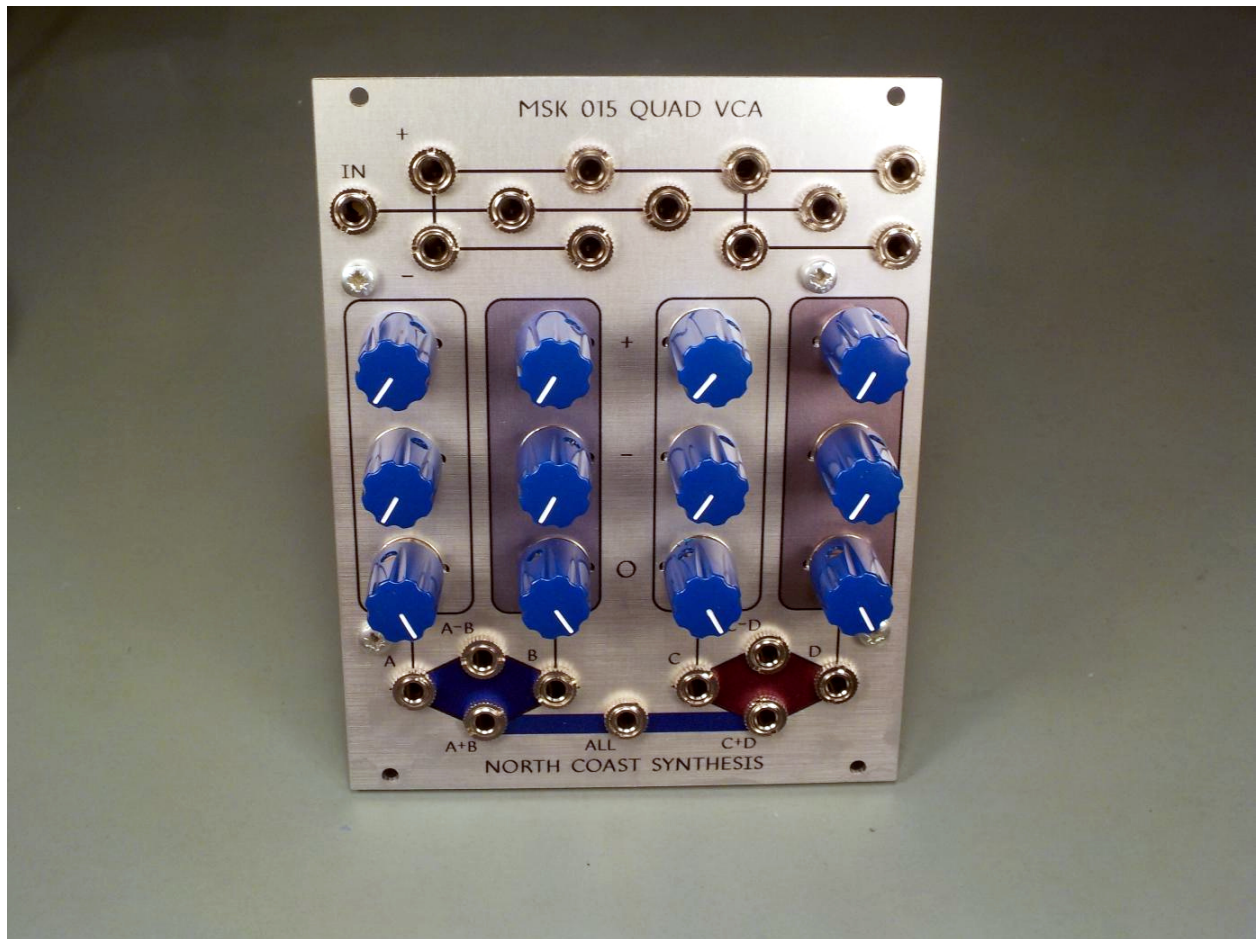
Add the knobs. Be careful not to overtighten the setscrews. They are deliberately made of relatively soft metal to grip well on the shafts, but that makes their threads easy to strip.

There is a rectangular white area on Board 2 reserved for adding a serial number, signature, quality control marking, or similar. Use a fine-tipped permanent marker to write whatever you want there. Isopropyl alcohol will probably dissolve marker ink, so do this step after any board-cleaning.



Your module is complete.





## Adjustment and testing

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This section describes how to adjust the five trimmers on the back of the Quad VCA for accurate unity gain at +5V control input and when the offset knobs are turned to maximum. There are also some suggestions here on how to troubleshoot build issues.

A multimeter and a voltage source are recommended for basic debugging and adjustment.

### Short-circuit test

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With no power applied to the module, check for short circuits between the three power connections on the Board 2 Eurorack power connector. The two pins at the bottom, marked with a white stripe on the circuit board, are for  $-12\text{V}$ . The next three pairs are for  $0\text{V}$ ; and the two pins at the top are for  $+12\text{V}$ . Check between each combination of these three voltages, in both directions (six tests in all). Ideally, you should use a multimeter's "diode test" range for this; if yours has no such range, use a low resistance-measuring setting. It should read infinite in the reverse direction (positive lead to  $-12\text{V}$  and negative lead to each of the other two, as well as positive lead to ground and negative to  $+12\text{V}$ ) and greater than  $1\text{V}$  or  $1\text{k}\Omega$  in the forward direction (reverse those three tests). If any of these six measurements is less than  $1\text{k}\Omega$  or  $1\text{V}$ , then something is wrong with the build, most likely a blob of solder shorting between two connections, and you should troubleshoot that before applying power.

*Optional:* Although we test all cables before we sell them, bad cables have been known to exist, so it might be worth plugging the Eurorack power cable into the module and repeating these continuity tests across the cable's corresponding contacts (using bits of narrow-gauge wire to get into the contacts on the cable if necessary) to make sure there are no shorts in the cable crimping. Doing this *with the cable connected to the module* makes it easier to avoid mistakes, because the module itself will short together all wires that carry equal potential, making it easier to be sure of testing the relevant adjacent-wire pairs in the cable.

Plug the module into a Eurorack power supply and make sure neither it nor the power supply emits

smoke, overheats, makes any unusual noises, or smells bad. If any of those things happen, turn off the power immediately, and troubleshoot the problem before proceeding.

### Adjusting the +5V reference voltage

---

With the module powered up, measure the DC voltage between test points P7 and P1, which are located on the back of the module at the bottom left and labelled "REFERENCE." This voltage should have an adjustment range of about  $4.3\text{V}$  to  $5.5\text{V}$ . Adjust the trimmer R47, located immediately above these test points, to bring the voltage as close as possible to exactly  $5\text{V}$ . Within a few millivolts is good enough.

Adjust this reference voltage first, before doing the channel gain adjustment below.

### Adjusting channel gain

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The basic goal of this adjustment is that when a channel is set up for unity gain, either by turning the offset knob fully clockwise or by giving it a control voltage of  $+5\text{V}$ , the channel should have exactly unity gain. We will achieve that by configuring the channel for unity gain, giving it some input, and then adjusting the channel until the output matches the input.

You have a choice about whether to use a DC or AC input for this adjustment. It is probably easier to use DC, and in particular, it may be easier to measure DC voltages accurately; however, AC is probably a closer match to the audio signals the module will often handle in practice, and measuring an AC waveform allows a purer measurement of gain alone without including offset. I normally use  $5\text{V}$  DC for adjusting factory-assembled modules.

Be sure you have done the reference voltage adjustment, described above, before this one. Set all channels to linear mode (DIP switch levers downward). Turn all four offset knobs fully clockwise and all other knobs fully counterclockwise. Apply power and remove any other cables from the module.

Choose what you will use as a reference signal. Ideal choices would be a DC voltage of about  $5\text{V}$  or an audio-frequency AC signal of about  $\pm 5\text{V}$  (that is,

10V peak to peak), but there is a lot of flexibility here.

Patch your reference signal into the signal input of channel A (leftmost channel) on the MSK 015. The normalling connections mean that this will actually apply the signal to all four channels. Measure the voltage of the reference signal.

If possible, you should measure the input voltage *under load*, that is, while it is patched into the module; you might do this by using a passive or unbuffered multiple to split the signal. Don't use a buffered multiple, which might not accurately reflect the load on one of its outputs to another. By measuring under load, you are measuring the voltage actually applied to the module's input impedance, which (if your reference signal is coming from something like another synthesizer module) might differ from the open-circuit voltage that would be measured with no load except the voltmeter.

Measure the output voltage of channel A and adjust the trimmer R49, at the upper right on the back of the module and labelled "GAIN A," to bring the output voltage of channel A as close as possible to your measurement of the reference signal.

Similarly, measure the output voltages of the other three channels and adjust their gain trimmers (lined up along the upper edge of the back of the module) to bring each output voltage as close as possible to the voltage you measured for the reference signal. Pay attention to the labels on the trimmers. They are in A-B-D-C order, not matching the order of the four channels across the front panel.

## Troubleshooting

If the module does not perform as it should, some kind of debugging or troubleshooting may be necessary. It would require several books to convey all the skills and knowledge useful in troubleshooting even a simple electronic circuit like this one, but here are some possible symptoms and some suggestions on diagnosis and treatment.

In general, the first order of business in debugging is to narrow down the set of things that could be wrong. Think about the different sections of the module: reference voltage generator, CV processors, VCAs as such, output mixers. It is possible for more than one thing to be wrong at once, but usually, any single problem will affect only one section of the module, so the important question is, which section.

If you can determine which of the major sections is at fault, try to narrow it down further: does the

problem affect just one output? Just one input? Is it limited to a specific feature of the module? The more narrow a description you can find, the fewer places you will need to look to find what is wrong.

The most common problems I see in my own builds are solder bridges, and issues with insertion of DIP ICs (such as leads folded up under the chip). In builds I did not do myself, as well as those issues, another common issue is that the builder tried to source their own parts instead of buying a kit, they made substitutions, and the substitute parts do not really work. I make no money when people download and use the plans without buying my products. As well as helping me to earn a living and continue releasing new module designs, buying a kit means you will actually get the right parts.

Many problems can be diagnosed just by looking closely at your work, preferably with at least one night's sleep between when you assembled the module and when you examine it. Look for bad solder joints that fail to connect; solder bridges between nearby connections; components missing; components exchanged (especially resistors with similar colour codes, such as 1k $\Omega$  swapped with 10k $\Omega$ ); polarized components such as diodes mounted backwards; and so on. In practice, only the soldering issues are really common. Most builders are quite careful about the other points on the list and don't make such mistakes often, but it is worth checking for these kinds of assembly mistakes once you have narrowed down the part of the circuit where the problem may be occurring.

General tips for debugging DIP ICs: make sure, for each IC, that

- it really is the type of IC it's supposed to be, not something else (beware of cheap ICs you buy from Chinese sellers on eBay and AliExpress, especially if they are offering unusually good prices on expensive chips);
- it is plugged in snugly;
- all the legs of the chip go nicely into the corresponding holes in the socket, with none bent outside or folded up under the chip;
- it is plugged in *at all*;
- it is plugged in the right way around, with the Pin 1 indentation or notch matching the clues on the board (if this is wrong, the chip is probably destroyed and will need to be replaced);
- there are no solder bridges on the chip socket, unsoldered pins, debris clogging the socket holes, or similar; and

- its decoupling capacitors (the small ceramic ones) are installed and there is nothing wrong with their solder joints.

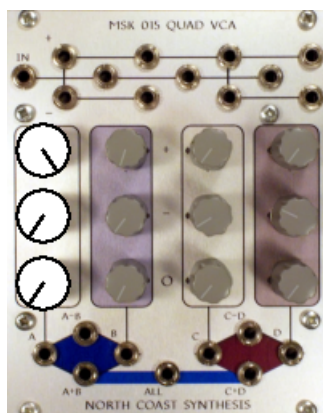
You can try swapping a suspect chip with another one of the same type from elsewhere in the module and see if that causes the problem to change; if so, it's likely that one of the two you swapped was bad. However, beginners are often too quick to suspect defective or damaged ICs, which are an uncommon source of problems. I prefer not to replace components, especially not if they are expensive, hard to find, or if replacing them would involve a lot of desoldering, unless and until I'm sure I know what is wrong. It is disappointing to go through the work of replacing something only to find that it didn't help after all; and instead of doing experimental component replacements to learn more about a problem, it is usually easier and just as informative to poke around with a multimeter.

No signal coming out of one jack, or no response to input on one jack: first make sure that a signal or a response is expected based on the other settings of the module. If so, then a missing signal or response suggests a bad jack. Try wiggling the plug in the jack, and try inserting it and removing it slowly, watching the response. If it works with the plug inserted just partially, but not when fully inserted, that suggests a damaged jack.

## Patch ideas

The MSK 015 Quad VCA can perform many different functions depending on how it is patched and how the front-panel knobs are set. Here are some ideas; you will no doubt think of your own, too.

In order to make the knob positions clearer I have overlaid graphics on the panel photos, showing the approximate positions of the indicator lines on the knobs for the channel or channels involved in the patch.

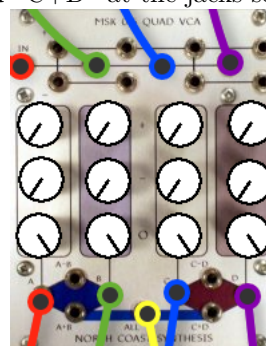


In many cases you will want to turn each knob fully clockwise or fully counterclockwise, as implied by the diagrams; but with the offset knobs in particular (bottom row) the knob range goes a little below zero, and in patches like the ring modulation patch, you may get the cleanest sound by turning a “counterclockwise” knob not *quite* to the bottom of its range, that is, almost but not all the way fully counterclockwise. In all patches it’s best to experiment to see what gives the most pleasing sound.

### Attenuator/mixer

With no CV input, each channel functions as a manual attenuator controlled by the offset knobs. Audio input to each channel, per-channel outputs for single-channel attenuation. Adjust the offset knobs as desired for the amount of signal to let through each channel; unity gain when fully clockwise. Mix of all four channels at the “ALL” output, sub-mix outputs

of “A+B” and “C+D” at the jacks so labelled.



### Basic VCA

Each channel can function as a basic linear VCA. With the positive CV knob turned fully clockwise, unity gain is at +5V of CV input and the response is appropriate for an 0–8V nominal envelope generator like the MSK 012 (shown). Adjust the offset knob to control “bleed” and make sure the response at low control voltages is exactly as you want it.

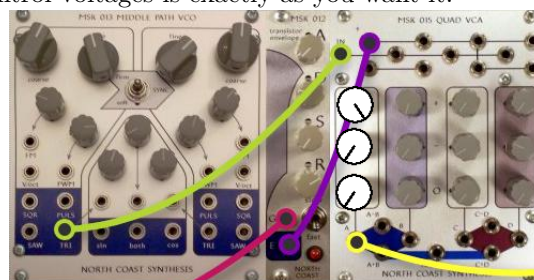


Figure 2 shows a fancier and more complete patch, where two channels of the MSK 015 work with a dual oscillator, four envelope generators, two filters, an LFO module, and the MSK 014 Gracious Host for control, to make a complete synthesizer with two independent voices and individual amplitude and filter envelopes. As shown the filters are non-tracking (like an acoustic instrument’s body response) but for a more synthetic sound, you could also mult the pitch control voltages to the filters to make them track more or less with the oscillator pitch.



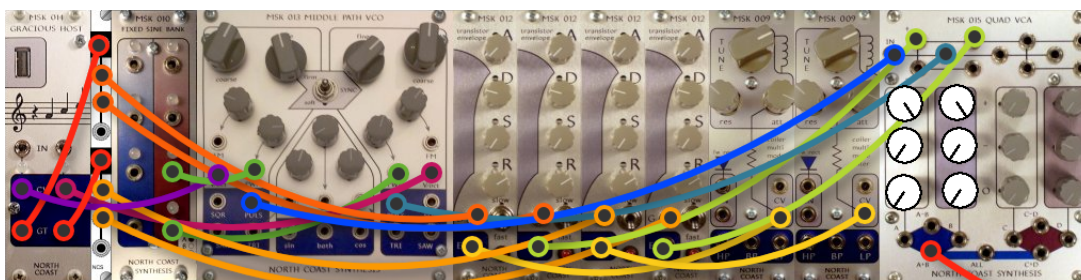
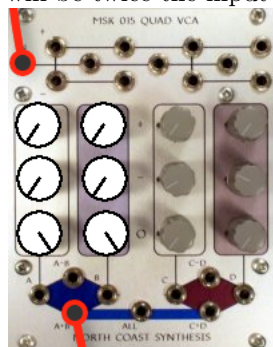


Figure 2: A complete two-voice synthesizer.

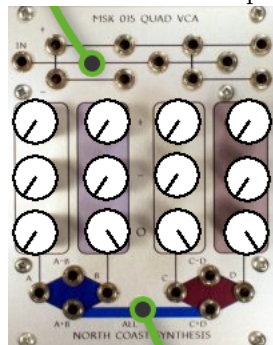
## Fixed voltage gains

I don't encourage synthesizer players to think too hard about voltages while playing; the goal should be to make it sound good rather than to count volts. Nonetheless, it's sometimes useful to multiply a voltage by a chosen small integer, and the MSK 015's trimmed unity gain makes that easy.

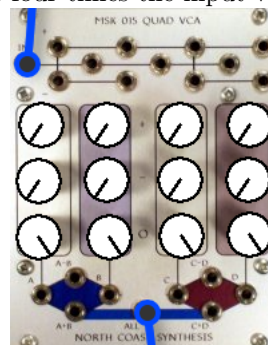
To multiply voltage by two (+6dB): patch the input to the lefthand channel of a pair (A or C), set that and the next channel to unity gain, and then A+B or C+D will be twice the input voltage.



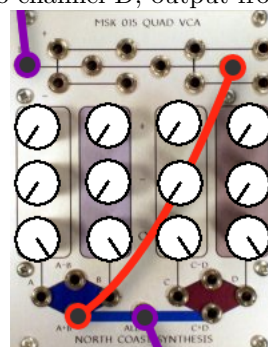
To multiply by three (+9.5dB): leave channel A unused. Patch input into channel B, set B, C, and D to unity gain, and use the ALL output.



To multiply by four (+12dB): you could do it by using the "double voltage" patch twice, but in theory you get a more accurate multiplication by four if you just use all four channels in parallel. Patch into channel A input, it normals across to all four channels, and when they are set to unity gain the ALL output will be four times the input voltage.



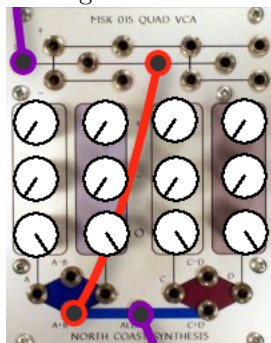
To multiply by five (+14dB): this modifies the times-four patch by replacing channel D with the double voltage from the A+B output. Input to channel A, A+B to channel D, output from ALL.



To multiply by six (+15.5dB): very similar to the times-five patch, but the A+B self-patch moves back to channel C so we are adding one, one, two, and two times the input voltage for a total of six. This is a lot of amplification and it's not clear when you would need so much, but it might make sense if you



are trying to improvise a guitar-pedal to Eurorack interface or something.



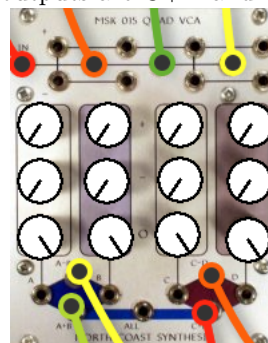
Inverting voltage, or multiplying by a negative number: this is possible by careful use of the A–B and C–D outputs but I will leave it for readers to figure out for themselves. As for non-integer multiplication, that is certainly possible by tweaking the offset knobs to non-maximum settings. It is basically the same thing as attenuation. But the module has no calibrated scale for measuring non-integer gains, so you will need to either adjust for best sound or with some other measuring device to achieve precisely planned amounts of attenuation.

## Mid-side encoding and decoding

Mid-side encoding is a way of using mono effects, filters, and so on to manipulate stereo signals. The idea is to convert (“encode”) the left and right channels into their sum (“mid”), which is basically what you would hear listening to that stereo signal on mono equipment, and their difference (“side”), which represents the extra information that makes the signal stereo. You process the mid and side signals however you want. What you do to the mid will end up affecting the overall sound while probably not changing the stereo image much, whereas what you do to the side will change the stereo image and not much else. Then you recombine these split signals to recover a left and right channel for the output.

The MSK 015 can do mid-side encoding and decoding just by setting each channel to unity gain and using the pairwise sum and difference outputs. With left and right to channels A and B, the A+B output is “mid,” and the A–B output is “side.”

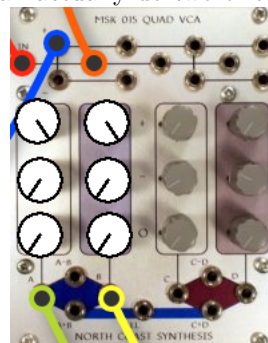
After processing these signals, patch mid into the channel C input, side into channel D, and then the left and right outputs are C+D and C–D.



With the channels set to unity as described, the mid-side encoding and decoding process will have an overall gain of +6dB: the final left and right channels will be at twice the input voltages. Many mid-side encoders and decoders work that way, and it has the advantage of using the precisely adjusted unity gain feature of the MSK 015 so that the signal will be well-balanced without careful adjustment. If you would prefer unity overall gain for the mid-side encoding and decoding, then you can turn down the offset knobs to reduce the gain as desired, but doing that may require some care to get the overall balance right. The theoretically optimal gain per channel to achieve unity overall would be 0.707, meaning the offset knobs at about 75% of their maximum range.

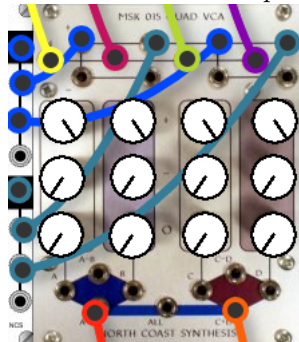
## Stereo VCA

A “stereo VCA” is just two VCAs with a shared CV connection, and the MSK 015 can do that just by plugging the CV into channel A or C and then using that and the next channel through the normalising. The module can actually do two of these at once.



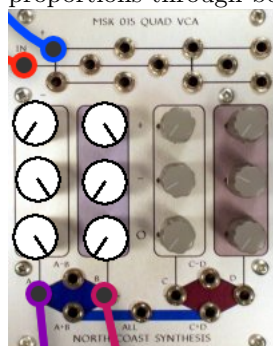
You can also use the mix outputs to combine the output of the two “stereo VCAs,” but doing that requires a little bit of trickery with a multiple or stacking cables, to apply the two control voltages to the

four channels in a pattern other than the way the normally connections work. Left channel for the first stereo signal to channel A, left of second signal to channel B, right channels of the two stereo signals to channels C and D, then first CV to channels A and C, second CV to channels B and D, and the stereo output comes from the A+B and C+D outputs.



### Voltage-controlled pan

This patch sends a signal to one of two outputs depending on the value of a control voltage. Audio to channel A input (normalling sends it to channel B also), and control voltage to channel A positive CV (normalling sends it to the other CV inputs of channels A and B). The knob settings activate channel B's positive and channel A's negative CV, with maximum offset on channel A. The result is that at zero CV input, the signal goes straight through channel A (because of the offset) and not through channel B at all (because no CV). At +5V CV input, the situation is reversed: the inverted CV cancels the offset on channel A and the positive CV allows the signal through channel B. At voltages in between, the signal goes out in varying proportions through both channels.



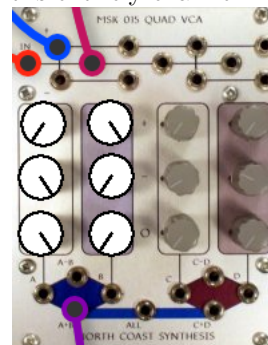
This patch as shown pans hard left at 0V input and hard right at +5V input. If you instead turn both offset knobs to the same value (which might be maximum or somewhat lower), then you will get centred output at 0V input and can pan left and right with

bipolar control voltages. However, then you may need to experiment with the offset levels to get a pleasing effect, bearing in mind that the VCA channels can only go a certain amount above unity gain.

Two VC pans can be combined to mix together much as in the “two stereo VCAs and mix” patch, with the channels interleaved and the control voltages milted. The details will be left to the reader.

### Voltage-controlled crossfade

This is nearly the same patch as the VC pan, but it takes two inputs to one output (using the A+B sum output) instead of one input to two outputs. At 0V control voltage input the output consists entirely of the input to channel A, whereas at +5V control voltage input it is entirely channel B.

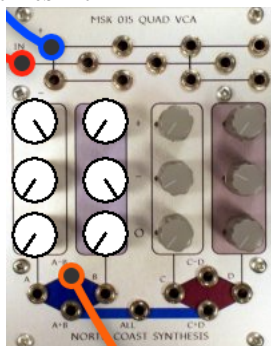


You can probably figure out how to combine the “pan” and “crossfade” patches for voltage-controlled “balance” on a stereo signal.

### Four-quadrant multiplier (“ring mod”)

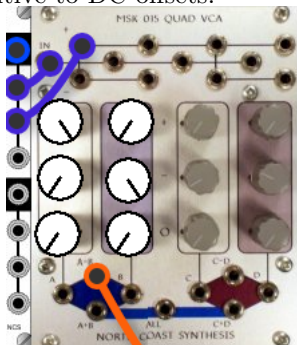
I prefer to call this patch a four-quadrant multiplier and reserve the term “ring modulator” for modulators that actually use a diode ring; but it produces the same effect that is commonly called ring modulation. The concept is that two channels each handle two quadrants of multiplication: when the modulator is positive channel A is active, and when the modulator is negative channel B is active. Each channel is zero when not activated by the control voltage; so subtracting them gives the desired four-quadrant multiplication.

Carrier to channel A audio input, modulator to channel A positive CV input; both are normalised across to channel B as well. Positive CV is turned up on channel A, negative on channel B, offsets are zero, output comes from A-B.



Because of the anti-bleed feature of the VCA offset knobs, if you turn those two knobs all the way counterclockwise then there will be a small range of near-zero modulator voltages where neither channel will turn on, resulting in some crossover distortion of the modulator signal. Real ring modulators have that too, because of the forward voltages of the ring diodes, so it may be desirable if you want to closely emulate a real ring modulator; but if you want a smoother sound, you may find it by turning the offset knobs up a little, not quite fully counterclockwise, adjusting it by ear for the most pleasing output spectrum.

If you four-quadrant multiply a signal with itself, you get an octave fuzz effect similar but not identical to full-wave rectification. That can be interesting on guitar-ish kinds of sounds. You also get a DC offset, so the resulting signal should probably go through something AC-coupled (like the AC output of an MSK 011 mixer) before being used in modules that are sensitive to DC offsets.



## Quadrature madness

Remember the formula for multiplying two complex numbers in Cartesian form?\*

$$(a + bj)(c + dj) = (ac - bd) + (ad + bc)j$$

The interesting thing there is the real part of the result:  $ac - bd$ . That is the difference of two multiplications, and a function we can (almost) compute with the MSK 015.

Why you would want to do so, is because of frequency shifting. Some frequency shifters (in particular, the Bode design) work by converting signals into pairs of voltages that can be thought of as representing real and imaginary parts, and then doing complex-number multiplication. An ordinary four-quadrant voltage multiplier, treating the voltages as real numbers, gives you sum and difference frequencies, but if you extend it to work on complex numbers, you can get *only* sum or *only* difference frequencies in the output. Do it between an input signal and a sine wave representing the desired amount of shift, and you have the classic frequency shift effect. That's why two four-quadrant multipliers plus a mixer that combines their outputs, is a common set of features to include in one module: it's exactly what you need at the end of a chain of modules for frequency shifting.

Really doing a proper frequency shift effect requires what are called *analytic* signals, that is, where each frequency component is split into two voltages that have the relationship of the sine and cosine functions. Such signals are relatively easy to generate when they are pure sine waves, but not with any other waveshapes. The imaginary part is not just the real part waveform shifted by  $90^\circ$  of the entire waveform; each sine component needs to be shifted by  $90^\circ$  individually, which usually gives the imaginary part a totally different overall waveform. Most of the work in building a Bode frequency shifter ends up going toward doing the shift properly at different frequencies to create an analytic signal from the audio input.

The MSK 013 Middle Path VCO does not generate a true analytic signal, but it does have two outputs labelled “sin” and “cos” that are *kind of sort of like* an analytic signal. This patch works by pretending that's what they are, processing them as if to do a frequency shift. I call it the quadrature madness patch. Because the Middle Path outputs are not really analytic signals (except in a few special cases)

\*You should. It will be on the quiz.

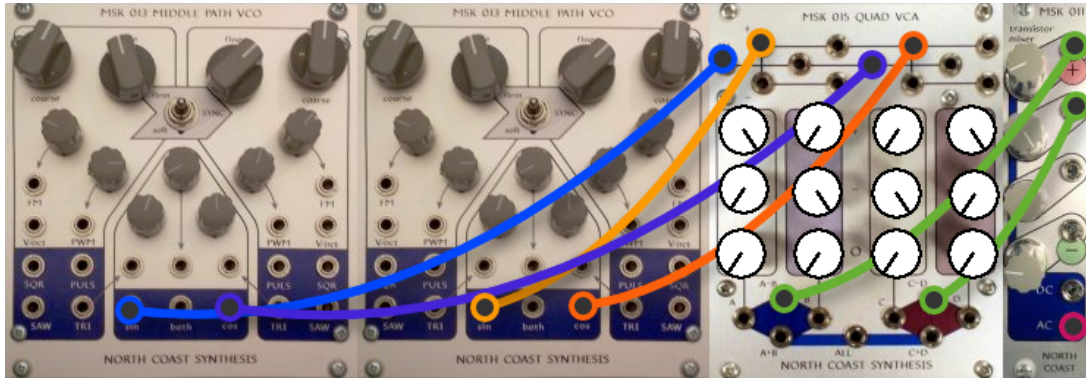


Figure 3: Quadrature madness.

the result is not really a frequency shift; but it's still an interesting sound, especially for drones, combining both harmonic and inharmonic elements.

If you don't have two Middle Path VCOs, you can use any two sources of signals that have some kind of sine/cosine or  $90^\circ$  phase relationship, and the results will probably be interesting even if not identical to mine.

The patch is in Figure 3. Channels A and B, and channels C and D, of the Quad VCA are configured as two four-quadrant multipliers with the four-quadrant multiplier patch. The positive and negative CV knobs are reversed for the second pair of channels in order to have the effect of inverting that multiplier's output. Then the two multiplier outputs, which appear at the Quad VCA's A-B and C-D jacks, are combined with an external mixer – in this case a North Coast Synthesis MSK 011, though really any basic mixer would do.

Using the ALL output on the Quad VCA would not work to do the mixing because it doesn't invert the audio on channels B and D; the output on that jack is also interesting but incorporates a lot of distortion (from the implied full-wave rectification of both modulators) and it's not the intended effect.

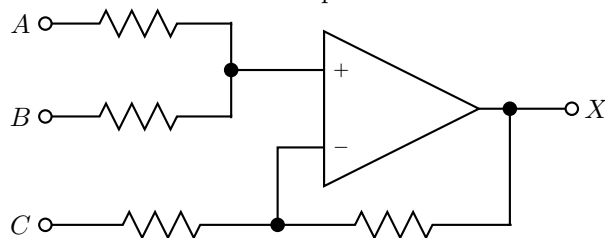


## Circuit explanation

The MSK 015 Quad VCA is made up of a few simple kinds of sections, most of which are used multiple times to build up the four-channel VCA. This chapter describes each section; for the bigger picture of how they connect to each other, see the schematic diagram near the end of the manual. It is assumed you are already familiar with the module's overall function as described in the "General notes" chapter.

### Op amp adder/subtractor

Much of the circuitry of the MSK 015 consists of close variations of this simple op amp circuit. It is modified somewhat in each place it is used, but it is worth studying the basic circuit in an idealized form before looking at the modifications in real use. All four resistors are assumed to be equal.



The first thing to know in analyzing this circuit is that a voltage divider with equal resistances computes the average of the two ends at its centre; so the op amp's positive input voltage is  $(A + B)/2$  and its negative input voltage is  $(C + X)/2$ . The op amp will, to the extent it can, increase or decrease its output voltage to make its inputs equal; so, assuming the voltages are such that the op amp can achieve this, we will have  $(A + B)/2 = (C + X)/2$ . Then simple algebra gives the following equation, which describes the purpose of the circuit.

$$X = A + B - C$$

This basic circuit just adds two voltages, and subtracts a third, presenting the result at its output. Apart from the algebraic description above, you can convince yourself with an intuitive argument based on calculus: suppose you increase the voltage at *A* a little bit, say 0.1V. That will raise the op amp pos-

itive input by half as much (0.05V) because of the voltage divider driving the positive input. Then the negative input will be less than the positive input, so the op amp will increase its output voltage until the inputs are equal again. In order to do that, it must raise the negative input 0.05V, which means raising the output 0.1V because it is going through a divide-by-two voltage divider. The change in circuit input *A* is reflected by an equal change in the output *X*. Similarly, changes in *B* appear equally at the output, but changes in *C* are reversed.

There are four copies of this basic adder/subtractor circuit used for the CV inputs of the MSK 015. The one for channel B is shown in Figure 4. Here the resistor value is chosen to be 270k $\Omega$  to keep the input impedance reasonably high. In the worst case, which is the negative CV input with the pot turned to maximum sensitivity, the input impedance is 270k $\Omega$  in parallel with 100k $\Omega$ , or about 73k $\Omega$ ; but because normalising allows a single patch cable to drive multiple inputs, the worst-case impedance presented to a cable could be as low as about 9.8k $\Omega$ . That is still high enough to be reasonable for Eurorack. I have not added a compensation capacitor because the output of this section is only driving the well-behaved input of the CV-scaling resistor network; there is no real danger of instability from an unpredictable load here.

Four more copies of the basic adder/subtractor are used for the *A+B*, *A-B*, *C+D*, and *C-D* outputs; the first two of those are shown in Figure 5 and the others are closely similar. In each case one of the three inputs of the section is connected directly to 0V to give just an addition, or just a subtraction, as the overall function. These sections are driven by the low-impedance buffers of the per-channel outputs, so they don't need a high input impedance, and the resistor value 27k $\Omega$  was chosen as a reasonable compromise between noise and power consumption.

These sections drive connections to the outside world, where the user might patch in something badly behaved (like a long cable with significant capacitance of its own), so they feature 100pF compensation ca-

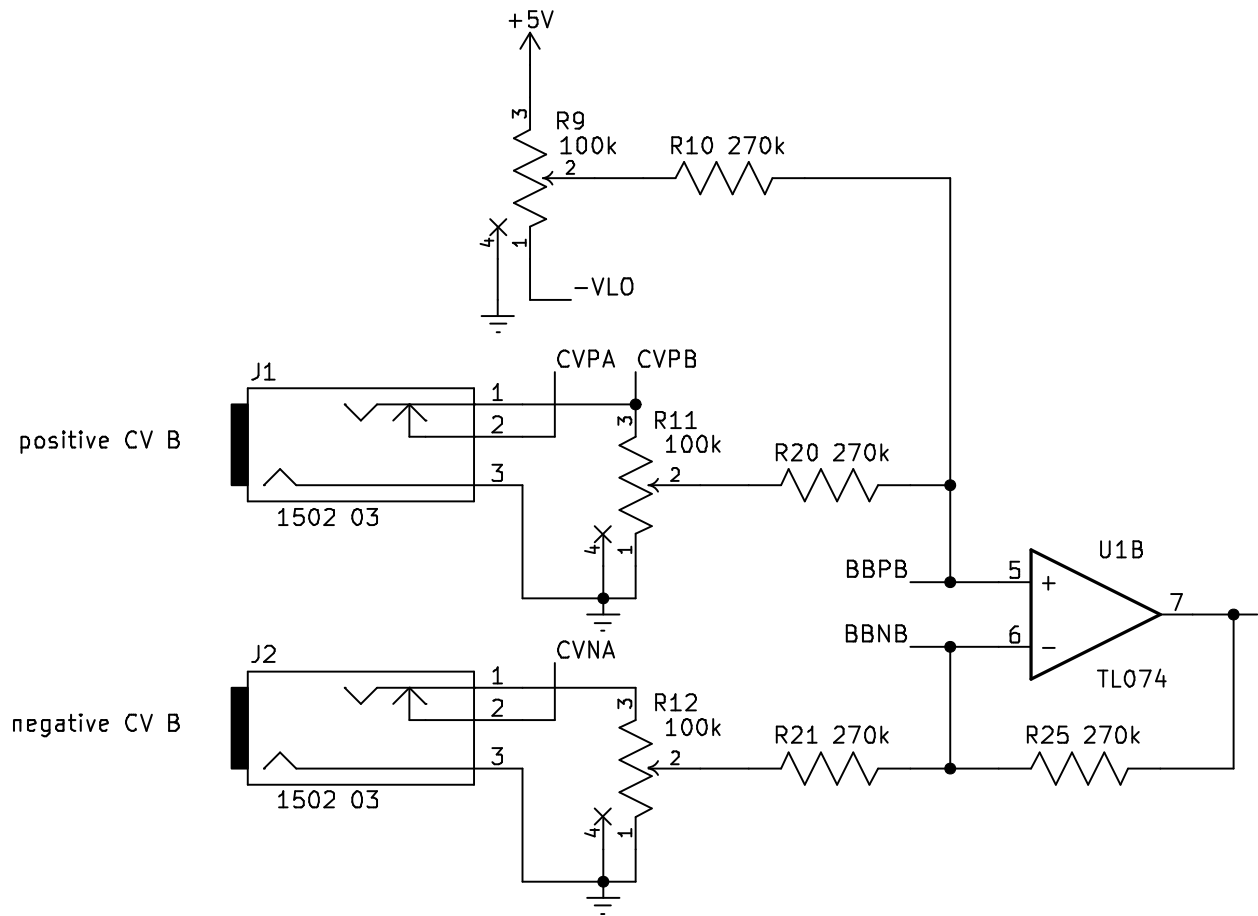


Figure 4: Control voltage input processing.

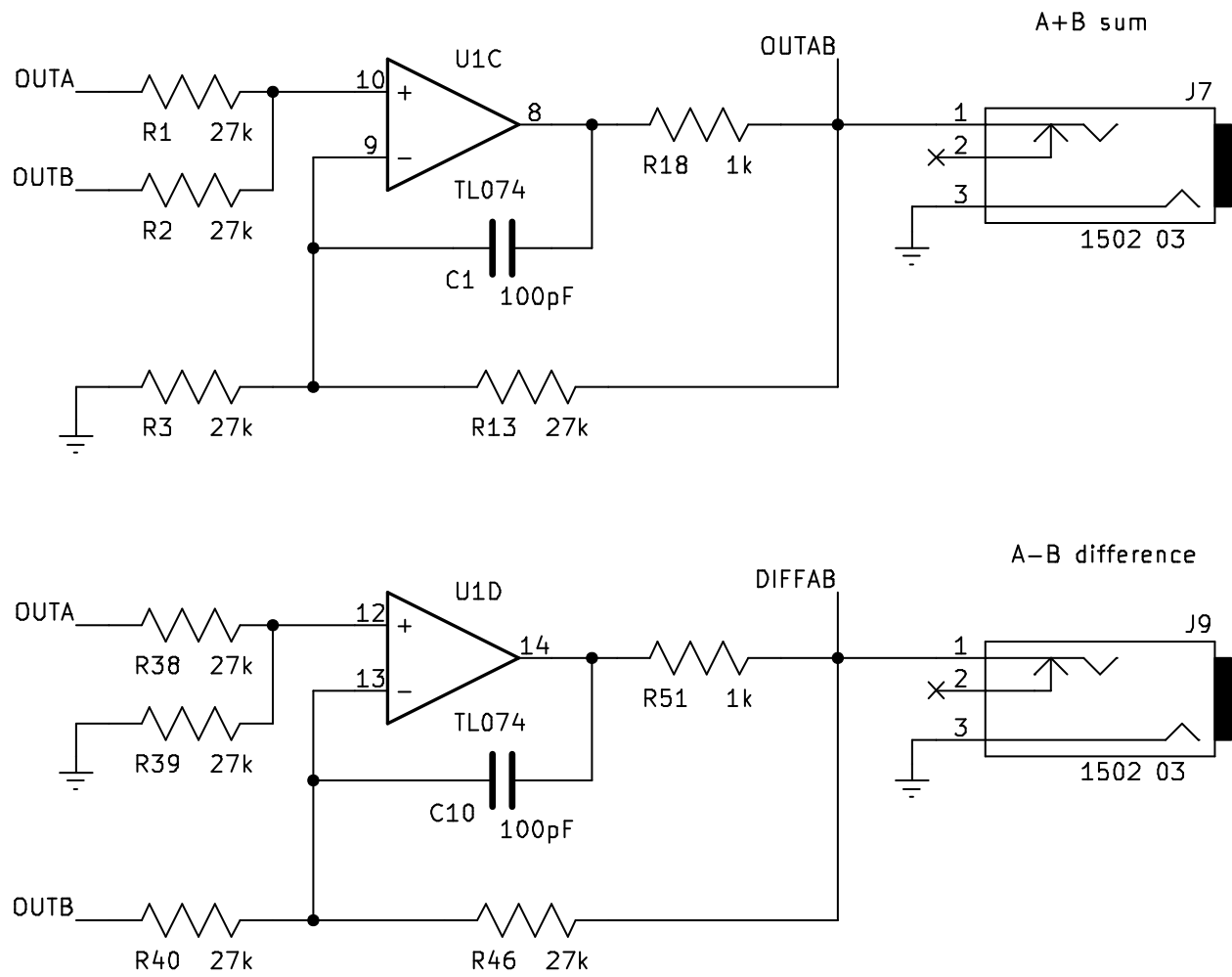


Figure 5: Add and subtract outputs.

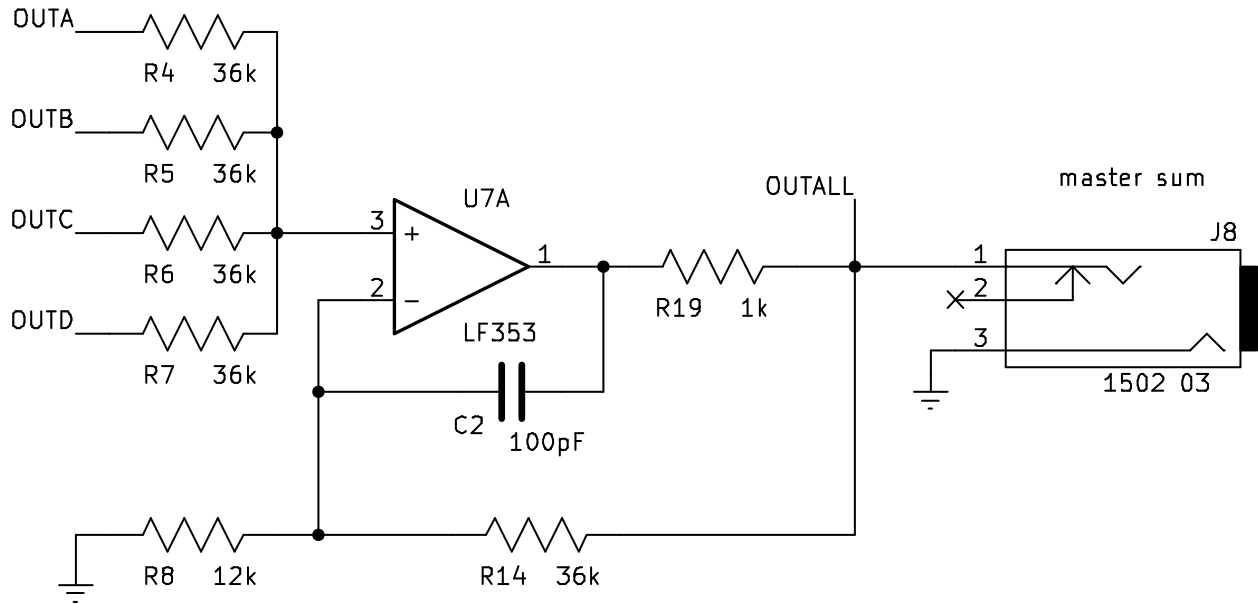


Figure 6: Master sum output.

capitors bypassing the feedback networks to ensure stability, and series  $1k\Omega$  resistors to limit short-circuit current and also help with stability. The capacitors kill the gain at higher-than-audio frequencies, so parasitic oscillations cannot be maintained. The  $1k\Omega$  resistors mean that the literal output pins of the op amps will need to go to slightly higher voltages than the analysis suggests, but defining the circuit output voltage  $X$  as the voltage at the output jack, the analysis remains valid.

The master sum output, shown in Figure 6, is a similar circuit designed to add four inputs instead of two. Here the averaging network of four  $36k\Omega$  resistors keeps the positive input voltage of the op amp at  $(A + B + C + D)/4$ . The negative input is a  $36k\Omega$  to  $12k\Omega$  voltage divider, so if the circuit output is  $X$  then the negative op amp input is  $X/4$ . The op amp adjusts its output to keep the inputs equal, so we have  $(A + B + C + D)/4 = X/4$  and  $X = A + B + C + D$ .

## VCA channels

The VCAs as such are based on the AS3360 chip and their design follows from the chip's needs and interfacing it to Eurorack conventions. Let's start by talking about the AS3360 chip and its unique requirements, which determine the design of the circuit surrounding it. This is a modern product of ALFA RPAR in Latvia, intended to functionally replace the

1980s-era Curtis CEM3360 dual VCA. It was selected for this module as an interesting chip with the desired performance while being reasonably priced and available in a through-hole package. Each chip supports two channels, so there are two chips in the four-channel VCA.

The AS3360 is a voltage-controlled amplifier with current input and output. That is, instead of applying a varying voltage to the signal input, the chip holds its input at a fixed voltage near  $0V$  and you apply a varying current. Then a current comes out the output of the chip, which ideally is to be held near  $0V$  by external circuitry. The maximum signal current for the input and output is specified as "typically"  $\pm 400\mu A$ , though it may give lower distortion with a little less signal. In order to interface this chip to the voltage-based signalling of Eurorack, we need to convert voltage to current for the input and current back to voltage for the output.

At maximum gain, the current at the output of the AS3360 is basically equal to the current at the input. But depending on the control voltage, it might pass through less current, down to a minimum of basically zero current coming out the output. Controlling the amount of gain is a little complicated. The way it works is that the AS3360 tells you the reference level: pin 8 is an *output* of the chip that says the control voltage the chip will interpret as maximum



gain. If you put that voltage on the exponential CV input (pin 3 or 12), then the output current will be basically equal to the input current. If you give it a lower control voltage, there will be less gain, with the gain decreasing by about 1dB for every 3mV the control voltage is less than the reference voltage.

The reference voltage is about 1.8V, so if you give the AS3360 a control voltage of 300mV less than that, or about 1.5V, then the gain will be about -100dB, which is about as low as it can meaningfully go given the noise floor. But you can't just feed in 1.8V for maximum gain and 1.5V for minimum gain! The reference voltage is only approximately 1.8V. It can change with temperature and from one individual chip to the next, so you have to really use the reference-voltage output and shift your control voltage in relation to that.

Both to help with handling the reference voltage, and because many applications need a linear instead of exponential response, the AS3360 also includes a logarithmic converter for each channel, which calculates the proper exponential control voltage based on a linear-response input. Instead of giving the chip an exponential control voltage directly, you can feed a linear control voltage in the range 0V to about 1.7V into pin 5 or 10, and then the output on pin 4 or 11 will be the right exponential control voltage to give the AS3360 for the desired amount of gain, including the proper reference offset. Ideally, the linear voltage input should perhaps also be scaled to the reference voltage, but that is less critical than in the case of the exponential control voltage. Since the logarithmic converters are built on the same chip as the amplifiers, using them gives decent temperature compensation more or less for free.

The MSK 015 module is intended to be able to produce above-unity voltage gain (unity at 5V linear CV input but additional gain up to at least 8V CV), and to offer both linear and exponential control as selectable options. With those features in mind, the following are approximate design targets for the driver and interfacing circuits.

- Translate  $\pm 5V$  signal voltage input to  $\pm 300\mu A$  current.
- Translate  $\pm 300\mu A$  signal current output to  $\pm 8V$  voltage.
- Scale 0–8V linear CV to 0–1.7V for the AS3360 logarithmic converters.
- Allow trimming of the overall gain to make the unity gain at +5V accurate.
- Scale exponential CV to 1.5–1.8V for AS3360

direct exponential CV, such that at 5V module CV input the overall gain will be unity; but that “1.8V” must shift with the reference output, so the range is really  $(V_{ref} - 300mV)$  to  $V_{ref}$ .

- Limit the voltages and currents so that damaging out-of-range voltages and currents cannot be applied to the AS3360 even if the user applies unexpected voltages to the module inputs.

The voltage/current and gain trimming functions are handled by the input and output amplifiers, one channel of which are shown in Figure 7. Control voltage handling is discussed in the next section and not shown in this partial schematic. Do note the 4700pF capacitor C8, which decouples the 1.8V (nominal) reference voltage output. This is specified (as “5nF,” essentially the same value) in the AS3360 data sheet, and it was clear in my breadboard testing that leaving it out causes the AS3360 to misbehave in strange, hard-to-debug, ways.

The input amplifier U2B is a basic inverting type. The input resistor R27 sets the input impedance to the Eurorack target of 100k $\Omega$ . The feedback resistor R31, with a value of 150k $\Omega$ , makes the overall gain -1.5. At  $\pm 5V$  signal input, the op amp output will cover  $\pm 7.5V$ , which it can definitely do; but the op amp's output cannot go beyond its power supply voltages of  $\pm 12V$ , and that prevents the circuit from being able to apply excessive current to the AS3360 input.

The resistor R35, with a value of 27k $\Omega$ , translates the voltage from U2B into a current for the AS3360. Applying Ohm's Law,  $7.5V/27k\Omega$  gives a nominal input current of  $\pm 278\mu A$ , comfortably within  $\pm 300\mu A$  range that the data sheet promises all AS3360 chips can handle. The AS3360 data sheet does not specify an absolute maximum rating (i.e. an “exceed this and you damage the chip” limit) for input current, but it specifies that some chips can handle  $\pm 500\mu A$  in normal operation. That seems a reasonable safety limit. The op amps can probably drive their outputs to about  $\pm 10V$ , certainly no further than  $\pm 12V$ , and those translate to  $\pm 370\mu A$  (within the “typical” input current specification) and  $\pm 444\mu A$  (within the “maximum” input current specification).

On the output side, the current coming out of the AS3360 chip is, at maximum gain, basically equal to the current on the input. We want that to translate to a voltage gain that can be adjusted to exactly 1.6. The current to voltage converter, with an inversion to undo the inversion of the input amplifier, looks like another inverting op amp circuit missing its input

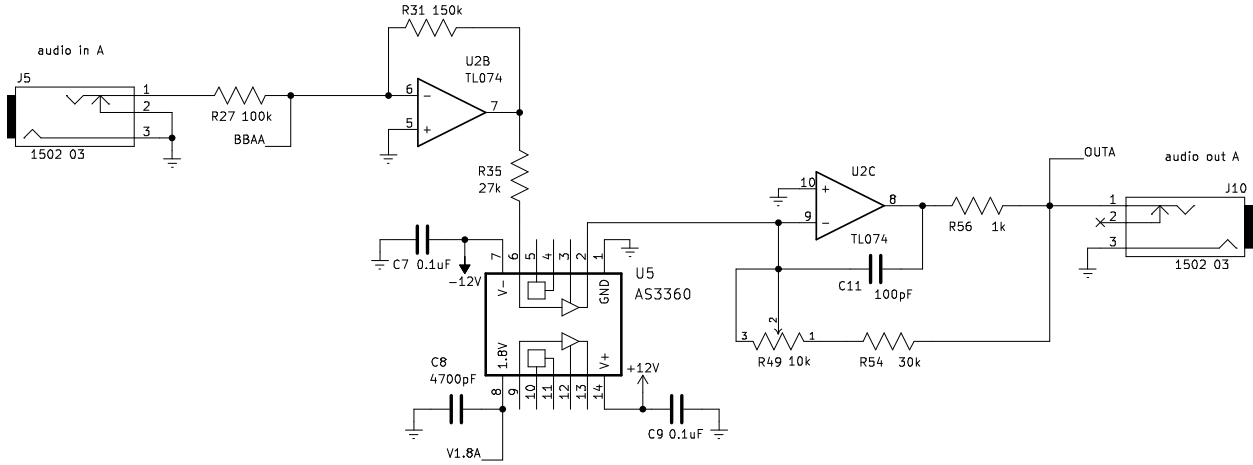


Figure 7: Main signal path for channel A.

resistor. Bearing in mind that the input amplifier had a gain of magnitude 1.5 and fed a  $27\text{k}\Omega$  resistor to convert to current, to get the overall voltage gain to 1.6 we need the feedback resistance of U2C to be a little more than  $27\text{k}\Omega$ , to bring the output voltage to a little more than what was originally applied to the  $27\text{k}\Omega$  input resistor.

The feedback resistance is made up of a  $30\text{k}\Omega$  fixed resistor plus the variable resistance of a  $10\text{k}\Omega$  potentiometer, so it can be adjusted to the right value. Assuming the AS3360 to have unity gain, the target for the total value would be  $28.8\text{k}\Omega$ . Really, the control voltage scaling network puts the AS3360's gain at a little less than unity with  $+8\text{V}$  linear control voltage input, so the target resistance is close to  $35\text{k}\Omega$ , the centre of the trimming range, with adjustment room on either side for accommodating the range of variation among AS3360 chips. Getting this adjustment range right was a development challenge; further notes on that in a later section.

Like the other output-jack drivers, the per-channel output amplifiers have  $1\text{k}\Omega$  in-the-loop resistors for current limiting and stability, and  $100\text{pF}$  capacitors to ensure stability.

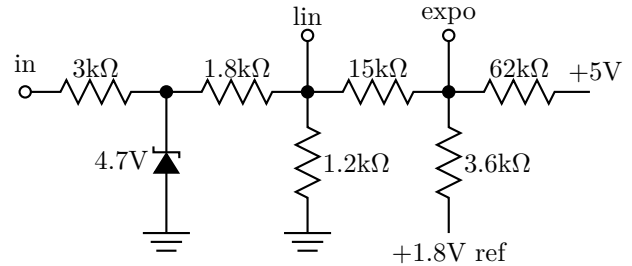
## Control voltage scaling

The *effective control voltage* as described in the “General notes” chapter is computed explicitly for each channel by an add/subtract section like that of Figure 4. This voltage is nominally in the range  $0\text{V}$  to  $+8\text{V}$ . It passes through a network of resistors, with a limiting Zener diode, to create two control voltages for the AS3360 chip: a linear voltage, ranging

from about  $0\text{V}$  to  $1.7\text{V}$ , and an exponential voltage, ranging from about  $1.5\text{V}$  to  $1.8\text{V}$ . The linear voltage is applied to the chip's logarithmic converter, generating an equivalent exponential voltage; then the SPDT DIP switch is used to select which exponential voltage will really be used.

As an added wrinkle, the high end of the exponential voltage range output from the network must be the voltage from the AS3360 reference generator, not just a fixed  $1.8\text{V}$  from some other source, in order for the temperature compensation to work. We have  $+5\text{V}$  and nominal  $-0.6\text{V}$  references generated elsewhere in the module, and must trust our global  $0\text{V}$  plane as it's the reference for everything, but we don't want to trust any other voltage sources (in particular, not the  $\pm 12\text{V}$  supply rails) because they may be noisy or inaccurate.

The network looks like this. There is one such network for each channel in the module.



First, the Zener diode serves to limit the voltages to a safe range. When the voltage at its cathode (the pointy end of the diode symbol) approaches  $+4.7\text{V}$ , it starts to conduct in breakdown mode, preventing the voltage from going any higher. Similarly, when

the cathode voltage approaches  $-0.6\text{V}$  the diode is forward biased and starts to conduct, preventing the voltage from going any lower. The surrounding resistors limit the current to safe levels in these cases. So we can analyze the rest of the circuit on the assumption that the range of voltages possible at the Zener cathode is  $-0.6\text{V}$  to  $+4.7\text{V}$ . Even if the user manages to drive the effective control voltage (the op amp output which drives the node labelled “in”) to an excessive voltage in either direction, the rest of the network cannot see a voltage at the Zener cathode outside this range.

We can estimate the range of effective control voltages that correspond to the limits, by observing that the  $15\text{k}\Omega$  resistor is a lot bigger than the  $1.8\text{k}\Omega$  and  $1.2\text{k}\Omega$  resistors nearby. It will not have much influence on the circuitry to its left. We can analyze the voltage across the Zener diode as if the  $15\text{k}\Omega$  resistor were not there, and get a reasonably accurate answer. In that case, the diode connects to the centre of a voltage divider with  $3\text{k}\Omega$  on either side, and the diode sees exactly half the input voltage.

Then the range of effective control voltages from  $-1.2\text{V}$  to  $+9.4\text{V}$  corresponds to what the voltage-limiting Zener diode will allow. Effective control voltages outside that range are clipped. Zener diodes, because of their historical use as power supply regulators, tend to be specified for breakdown voltage at a relatively high current level; in the case of this 1N5230B diode, the  $4.7\text{V}$  breakdown voltage is specified at  $20\text{mA}$  current, much more than we are using here. It will really start to pass some smaller but significant reverse current at just a little over  $4.0\text{V}$  across the diode. As a result, the clipping is soft at the high end of the range; but we can still say that there will be very little clipping observed at  $+8\text{V}$  on the input, which is the top of the range we really want to support. Within  $0\text{V}$  to  $+8\text{V}$  on the input, the diode does not conduct to any significant degree in either direction compared to the low impedance of the surrounding components, and we can pretend the diode is not present.

With both the diode and the  $15\text{k}\Omega$  resistor removed from the circuit, we can analyze the response from the input to the output labelled “lin” as a simple voltage divider, with  $1.2\text{k}\Omega$  on the bottom and  $4.8\text{k}\Omega$  on the top. It maps the  $0\text{--}8\text{V}$  input range to  $0\text{--}1.6\text{V}$ , about right for driving the AS3360’s logarithmic converter, which starts to clip a little below the  $1.8\text{V}$  reference voltage. When we consider the effect of the  $15\text{k}\Omega$  resistor too, it shifts the range up to more like

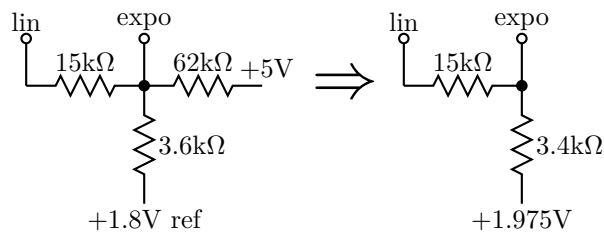
$0.1\text{--}1.7\text{V}$ , which is a better fit.

To achieve zero gain in linear mode the effective control voltage needs to go a little below zero, to bring the linear output right down to zero, but the small negative minimum voltage of the offset knob means it can be adjusted to make that happen with zero control voltage input at the front-panel jacks. And the resulting need to make the range between zero and unity gain slightly more than  $5\text{V}$ , is compensated by adding a little more gain to the output amplifier, as discussed in the previous section.

If the input goes high enough to drive the Zener into full conduction ( $+9.4\text{V}$  input or higher), the linear control voltage output ends up at about  $1.88\text{V}$ , at which point the AS3360 is clipping (no further gain available beyond about  $1.7\text{V}$ ) but the voltage is still small enough not to exceed the absolute maximum limits and damage the chip; similarly in the other direction with negative input voltage, where it gives zero rather than negative gain, but no damage.

The  $3.6\text{k}\Omega$ ,  $15\text{k}\Omega$ , and  $62\text{k}\Omega$  resistors form a three-way weighted averaging circuit that generates an exponential control voltage suitable for driving the AS3360 exponential input directly when linear control is not desired. We already have the input control voltage translated to a range of about  $0.1\text{--}1.7\text{V}$ . We want to scale and shift that to a range of about  $1.5\text{--}1.8\text{V}$  for the chip.

A voltage divider with a ratio of about 5.4 could do the scaling, but to get the shift into the proper range, the voltage on the far side of the divider would have to be a little higher than  $1.8$ , close to  $2.0\text{V}$ . We have no such reference voltage directly available, so we make it up by constructing a second voltage divider between the  $+5\text{V}$  and  $+1.8\text{V}$  references. The divider formed by the  $62\text{k}\Omega$  and  $3.6\text{k}\Omega$  resistors is Thévenin equivalent to a  $1.975\text{V}$  (nominal) voltage source with  $3.4\text{k}\Omega$  impedance. That forms one side of the voltage divider with the  $15\text{k}\Omega$  resistor as the other side, to give the desired range of voltages on the “exp” output. Since the  $1.8\text{V}$  reference from the chip is by far the largest contributor to this voltage, the temperature compensation (tracking of the chip’s changing reference voltage) should work more or less as desired.



## Notes on the design process

The scaling network is crucial, and although I have described how it works, it's not at all obvious where the design came from, and in particular how the resistor values were chosen. Some parts of the analysis are rather vague, and involve approximations like leaving out parts of the circuit that have small effect and then saying "it'll be close enough" or "that'll be compensated for, somewhere else."

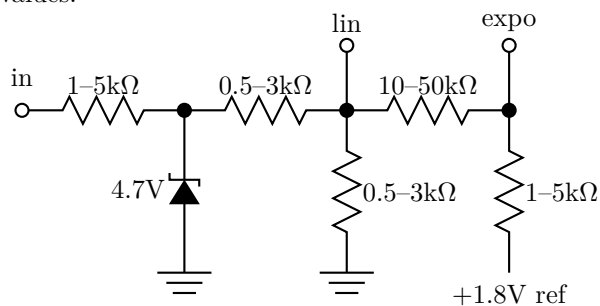
In fact, the explanation reflects how the design process worked. It was not a straightforward progression from start to finish. I started with an idea of the topology I wanted, and calculated component value targets by hand based on a preliminary analysis, including a couple of rounds of doing the calculation wrong and having to think harder. Then I refined the targets with a computer search over nearby standard resistor values and then some simulation; actually built a version of the circuit on stripboard to test how the real AS3360 chips would behave; found the response wasn't exactly what I wanted, and went back and made some changes, including small changes to the original topology.

The initial concept for the design was that I knew I had three voltage ranges to deal with: the 0–8V nominal range of the effective control voltage, the 0–1.6V nominal range of the linear control voltage for the AS3360, and the 1.5–1.8V nominal range of the exponential control voltage. There is another range hidden before any of those: the  $\pm 12$ V range of voltages that could theoretically come from the op amp and has to be limited to 0–8V equivalent.

Since each voltage range is smaller than the last, it made sense to build a cascade of voltage dividers: first something to limit  $\pm 12$ V to a range that will be equivalent to 0–8V, then something to gear that down to the range of the chip's linear input, then something to gear that further down to the range of the exponential input. The impedance levels of these voltage dividers should generally increase down the line, so that each one will not load down the previous one too much.

It made sense to limit the voltage with a Zener diode to ground, which would give the right shape to the allowed range (up to a certain amount from ground, down to not much below ground). I routinely stock a lot of 4.7V Zeners because they are used in my other designs, so it would be nice to use them instead of some new value; and given that about 4.0V is the highest voltage we can put across such a diode before it starts to conduct, and 8.0V was the top of the range I'd like to pass through the limiter unmolested, it made sense to use a 1:1 voltage divider with the Zener right in the middle. Then trading off between not too much current when in full clipping, versus keeping the impedance low to drive the rest of the circuit, meant that resistance value on either side should be in the low single digits of k $\Omega$ . The linear output is just tapped down to an appropriate point on the lower leg of the divider, splitting it into two resistors.

That thinking gave me the basic topology from the input to the linear output: series resistor, Zener to ground, another series resistor, another resistor to ground. It also gave me the idea that the first resistor should be equal to the sum of the next two, and they should all be in the few-kiloohm range. From there, I initially thought I could get away with just two more resistors, forming a voltage divider from the linear to the exponential voltage with the +1.8 reference on the other end, to do the scaling and shifting for the exponential output. The design at this point was just a topology and orders of magnitude for the resistor values.



I wrote a Prolog program to calculate the linear and exponential voltages depending on the input voltage and the resistor values, and added a lot of constraints, like the minimum and maximum amounts of current to draw at different voltages, acceptable impedance levels for the outputs, being able to hit specific targets at different points in the input range, and so on. I had it search over different combinations of standard resistor values and find ones that would meet all the criteria. I also experimented by hand

in a circuit simulator with some of the combinations that came out of Prolog.

When I thought I had a design that would work, I tried actually building it on stripboard and seeing how it performed. What I found was that it wasn't really satisfactory: not enough gain in exponential mode. Exponential mode was always going to be something of a compromise, because of the desire for wide dynamic range combined with reaching unity gain at a convenient voltage.

I had decided to aim for the same spec as the Doepfer A-132-4 exponential VCA, which is nominally 12dB/V and unity gain at +5V. That means the attenuation at 0V is only -60dB, but it seems a reasonable compromise. I think most people who use exponential VCAs in synthesizer patches are not primarily using them for completely shutting off signals anyway.

With that in mind, the performance of my stripboard build was not good enough. It was attenuating a fair bit at +5V CV, and getting unity gain required a high enough input voltage that I was running into the diode clipping limit.

I ended up making a topology change, adding a third resistor to pull the exponential output to a higher voltage. The new resistor going to +5V is the one eventually chosen to be 62k $\Omega$ . The topology change meant another round of Prolog optimization, simulation, and also experiments with modifying the stripboard build, until I had values for all the resistors in the network that seemed to give acceptable performance.

That is why the analysis is presented as a just so story. Now that I have the resistor values I can explain what they do, but the values were not directly chosen by following that analysis. Rather, I arrived at them by estimating about how big they should be, running a computer optimization to suggest standard values that might work, and then testing and tweaking on simulated and physical versions of the circuit.

## Chip gain variation

Each individual AS3360 chip, and actually each of the two channels in each AS3360 chip, has its own amount of gain. The data sheet describes the maximum current gain as ranging from a minimum of 0.9 to a maximum of 1.1, or  $\pm 10\%$ . Consistent gain at +5V effective control voltage is meant to be a feature of this module, so each channel has a trimmer\*

\*Not a bushing-less panel pot of the kind sometimes incorrectly called a "trimmer"; these ones are the real thing.

for adjusting the channel gain, and the idea is that after building the module, these can be adjusted to compensate for the variation between chips.

The trimmer provides a variable resistance of 0-10k $\Omega$  which goes in series with a fixed resistor to provide the feedback resistance in the output amplifier of each channel. The gain is proportional to that feedback resistance as well as the gain of the AS3360, so with a relatively low-gain chip the trimmer will be adjusted to high resistance and with a relatively high-gain chip the trimmer will be adjusted to low resistance. The range of resistances available needs to line up with the range of gains among AS3360s.

When I started developing this module I did some testing of different AS3360 chips and decided that based on the gains I'd observed, I calculated that it would make sense to have the feedback resistance be 27k $\Omega$  plus the 10k $\Omega$  trimmer. The calculation was based on my actual measurement of the real chips with the input voltages they would get in the finished module; because the +5V control voltage input target is not actually the maximum gain the chip can produce, and maximum possible gain is a less important parameter of the module, I was *not* calculating from the data sheet values.

Using 27k $\Omega$  was especially convenient because I already had a lot of 27k $\Omega$  resistors in the design, and it worked with all the chips I tested, and in the prototypes I built. So I had the first production batch of boards made with the label "27k" on the silkscreen for those resistors, wrote up the build manual for that value, and so on.

After building the first batch of production assembled modules, I started adjusting them, and I found halfway into the batch that there were a couple of modules where I couldn't adjust them to unity gain at +5V. I turned the trimmer all the way up and it wasn't enough. That was kind of a disaster: it meant I had a design I was about to push out the door that I couldn't be sure would always work. It meant almost a month's delay in releasing the module.

If it were just a matter of a few chips having less gain than I expected, then as far as assembled modules were concerned, I could just call those chips "defective," toss them out, and select higher-gain chips. But if I had actually misunderstood the range of variation that might exist among normal non-defective AS3360 chips, then I wouldn't want to be throwing out a significant fraction of my stock just because I'd designed the trimmer adjustment range wrong. And it would be a bigger problem for kit builders who

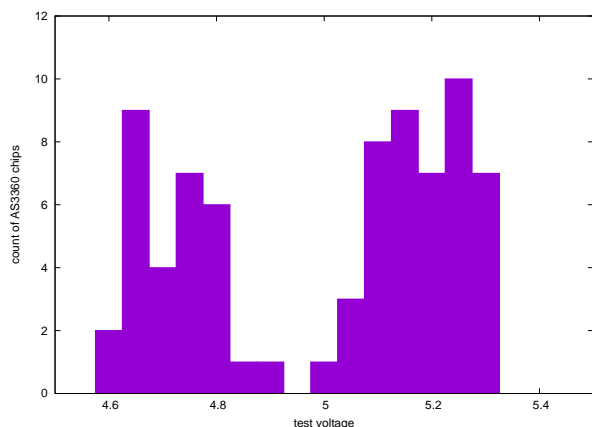


Figure 8: Results of AS3360 gain test.

might get an AS3360 that didn't work and not have a supply of others on the shelf that they could swap in to replace it.

So the most important thing to do was to figure out the nature of the problem: did I have a few bad chips, or had I somehow misunderstood the range of gain values that might occur among normal non-defective AS3360 chips?

I didn't want to be swapping chips in and out of a normally built MSK 015 module; the DIP sockets I normally use are not really designed for repeated swapping and I'd end up with damage to both the chips and the sockets. Instead I built a special-purpose testing device on a piece of stripboard with a ZIF socket (designed for repeated chip-swapping without damage). It would power up the chip under conditions similar to the conditions in an MSK 015 at unity gain, and then produce an output voltage proportional to the chip's gain (average across the two channels) which I could then read with a voltmeter.

I tested all the AS3360 chips I had handy that weren't already built into modules, a total of 75 of them, and Figure 8 shows a histogram of the results. The "test voltage" is proportional to the chip's gain at a given input control voltage. What we can see in this histogram is that it's a bimodal distribution: there are basically two populations of AS3360 chips, high-gain ones and low-gain ones.

The range in gain from the top to bottom of the distribution is a little narrower than the data sheet's  $\pm 10\%$ , so I think the chips are behaving according to specification and none of them are defective. For whatever reason, all the chips I initially tested happened to be in the "high-gain" group, so I chose my

27k $\Omega$  resistor value to comfortably cover all of that group, and I ended up with an adjustment range that would not cover the lowest of the low-gain chips.

It took some more trial and error to get it right. My first calculation suggested I could change the 27k $\Omega$  resistors to 33k $\Omega$ , and on doing that in one of my prototypes, I found that it did indeed cover all the low-gain chips correctly, but then I had the opposite problem: for some high-gain chips I could not trim the gain low enough. The compromise value of 30k $\Omega$  seems to work well with all the chips I have, including a bit of extra safety margin at both sides.

That is why the first batch of kits come with correction labels glued to the boards, and the first batch of assembled modules may actually contain other values than 30k $\Omega$  for these resistors. Maybe I can call that first batch a rare collector's edition. The new value was a last-minute design change to make sure all AS3360 chips would work in the module. I tested what I thought were enough individual chips before doing the original design, to be sure I understood the range of variation, but my sample evidently wasn't large enough. I think part of the issue was that the gain of the chips was not randomly distributed. Often five or ten consecutive chips in a packaging rail will be all high-gain or all low-gain, so my risk of getting all my sample from the same group (as evidently happened) was higher than naive probability would suggest. One lesson learned is that I should be careful to select a really random sample, instead of just pouring consecutive components out of the package.

It's an interesting question why the chips have this bimodal gain distribution. Maybe when they're manufactured, individual manufacturing batches tend to have narrower gain distribution but there's a wider variation from one batch to another, so my stock actually came from two different manufacturing batches and I'm seeing the separation between those in my own testing. Another possibility is that freshly-manufactured AS3360 chips actually have a more conventional bell-curve distribution of gain, but then ALFA RPAR pick out the ones near the centre to package as the more expensive and more tightly-controlled AS3360A version, so the ones sold as "AS3360" end up being the ones with gain further away from the centre. I think that's a less likely explanation because the AS3360A is actually specified for just as wide a range of gains as the AS3360; but it is more tightly-controlled on some other parameters, which might correlate with near-centre gain.

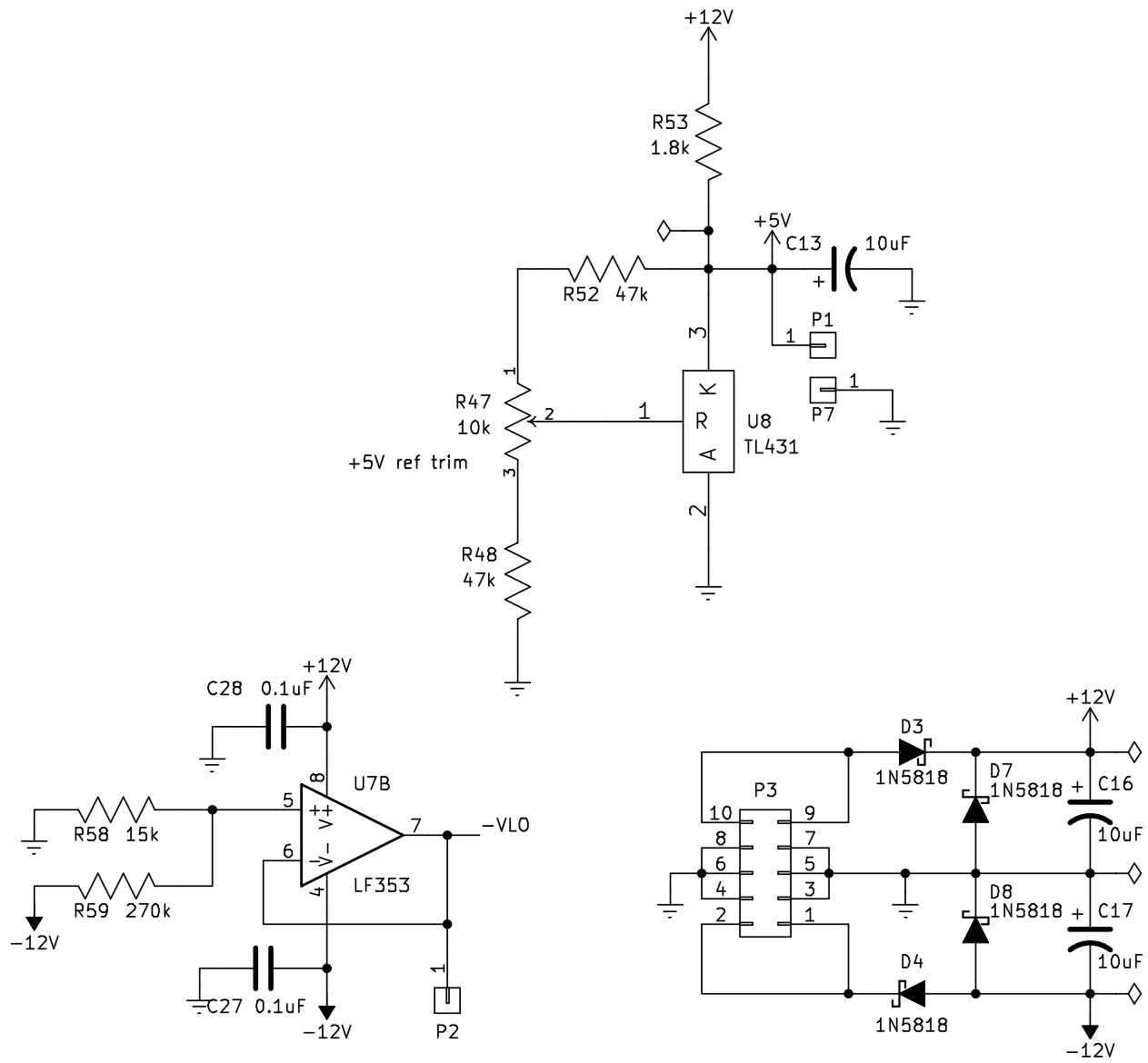


Figure 9: Power and reference voltage generation.



## Power and reference voltages

Figure 9 shows the circuits which generate power and reference voltages for the module. The  $\pm 12\text{V}$  power rails are protected from reversal by series Schottky diodes, and there are  $10\mu\text{F}$  electrolytic capacitors on them to help reduce conducted noise from the power supply. Both those are fairly standard. In this module I have also added another pair of diodes in parallel across the power supply lines to help protect against missing-rail conditions.

Sometimes if a Eurorack power supply is overloaded or fails, or briefly during startup, it may be the case that one of the  $\pm 12\text{V}$  rails is powered up while the other one is not. That is called a *missing rail* condition. Op amp circuits, and a lot of the analog electronics in a synthesizer in general, tend to draw their power between the  $+12\text{V}$  and  $-12\text{V}$  supplies, using the  $0\text{V}$  only as a voltage reference. So if there is nothing driving the  $-12\text{V}$  rail, while the power supply supplies power between  $+12\text{V}$  and  $0\text{V}$ , then it is possible that all the circuits trying to draw current from  $+12\text{V}$  and return it through  $-12\text{V}$ , will actually raise what should be the  $-12\text{V}$  line to a positive voltage like  $+3\text{V}$  relative to the  $0\text{V}$  line. Any circuits that do happen to draw their power between  $0\text{V}$  and  $-12\text{V}$ , will then see a reversed power supply.

Typical op amp circuits do not draw their power between  $0\text{V}$  and  $-12\text{V}$ , and are not importantly affected by a brief missing-rail condition. But the original SSM2164 VCA chip and some (not all) of its subsequent clones were notorious for sensitivity to this circumstance. They could be destroyed almost instantly by a power supply that did not always bring up the  $-12\text{V}$  rail simultaneously with the  $+12\text{V}$  rail. Adding a diode between  $-12\text{V}$  and  $0\text{V}$ , so that the  $-12\text{V}$  rail cannot become more positive than one diode drop above  $0\text{V}$ , has become a standard practice in 2164-based circuits.

I have not heard reports of the AS3360 being sensitive to the missing-rail issue in the same way as some versions of the 2164. But given that it does have a  $0\text{V}$  power connection (unlike an op amp), and is a VCA chip, it seems reasonable to take the precaution of adding protective diodes against missing-rail conditions.

The  $+5\text{V}$  reference is used by the front-panel offset pots and the control voltage scaling circuit. It is a standard TL431 regulator with a trim pot for setting the output voltage to exactly  $+5\text{V}$ , and test points for measuring that. The capacitor on the output is larger than necessary for smoothing the voltage

(which should be clean coming out of the regulator anyway) but helps guarantee stability.

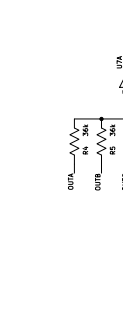
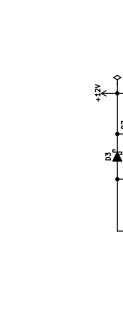
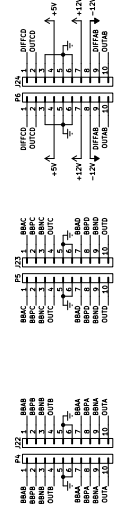
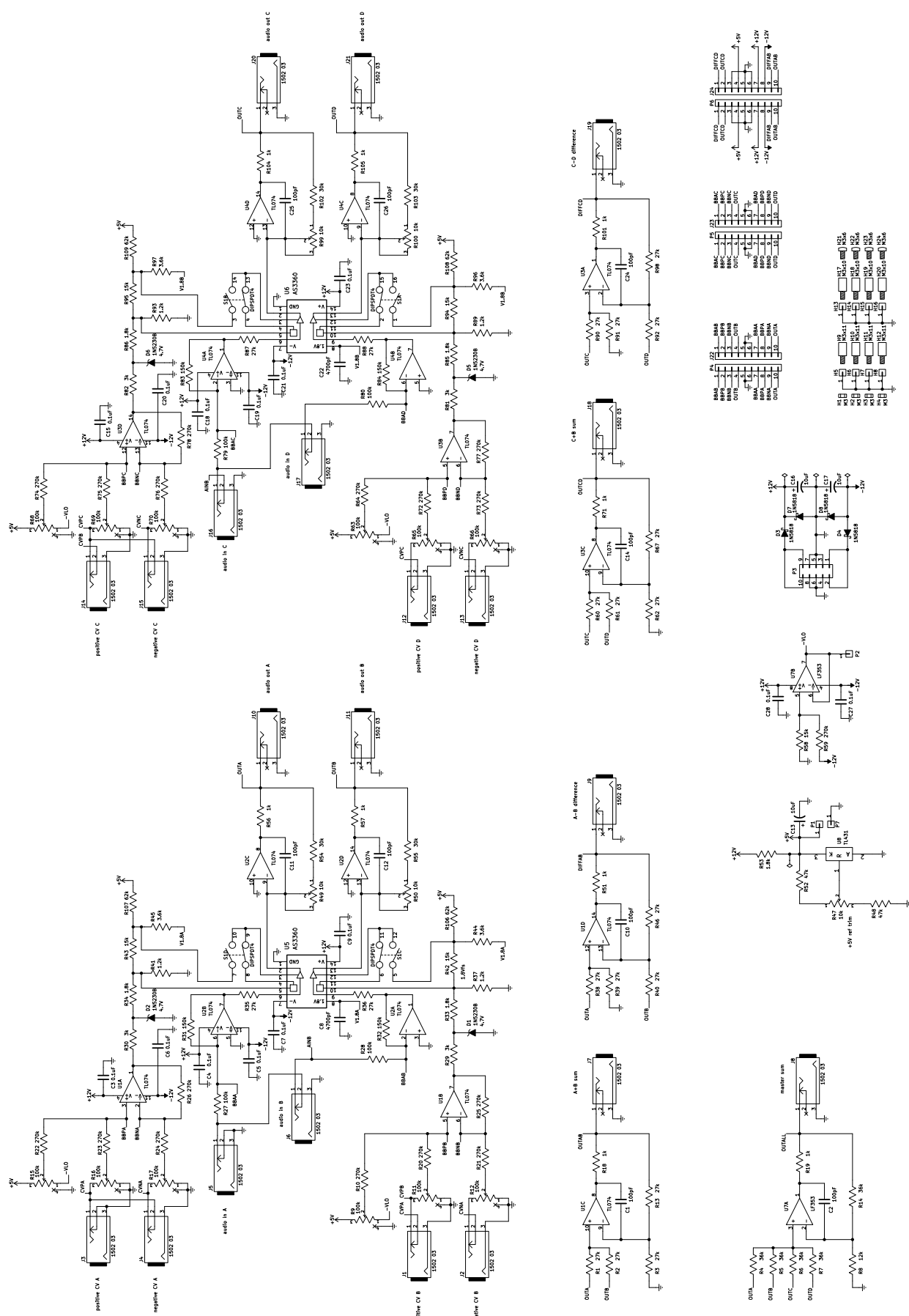
The front panel offset pots also require a small negative voltage, so that they can be adjusted to compensate for small offsets in the control voltage inputs (the “anti-bleed” feature). This voltage, called  $-VLO$  on the schematic, does not need to be particularly exact or clean, so it is generated by just taking a voltage division from the negative power supply and buffering it with an op amp.

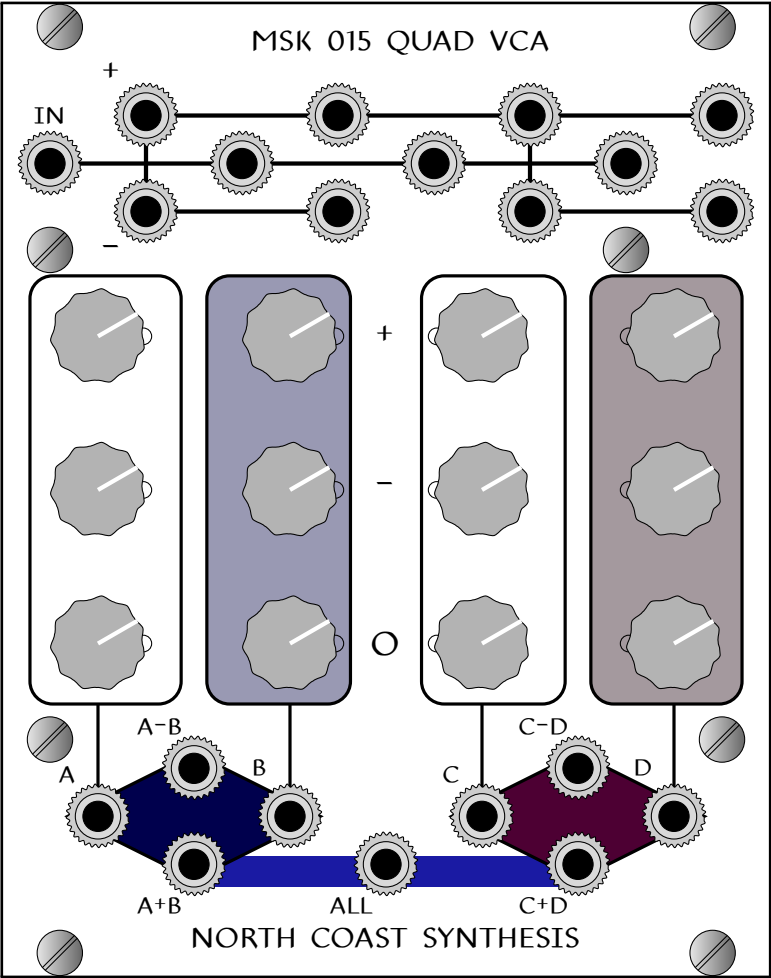
## Mechanical drawings

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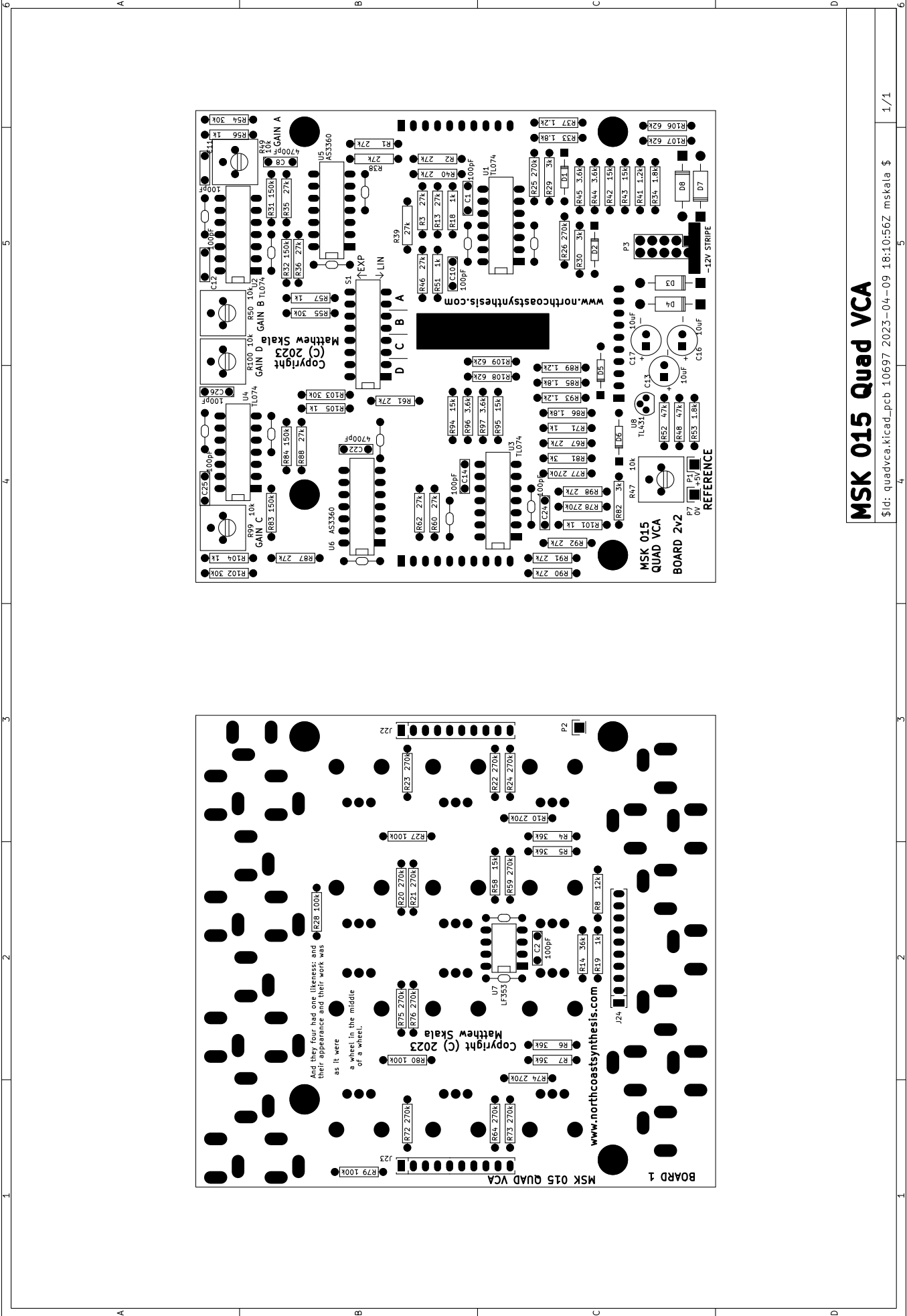
On the following pages you will find:

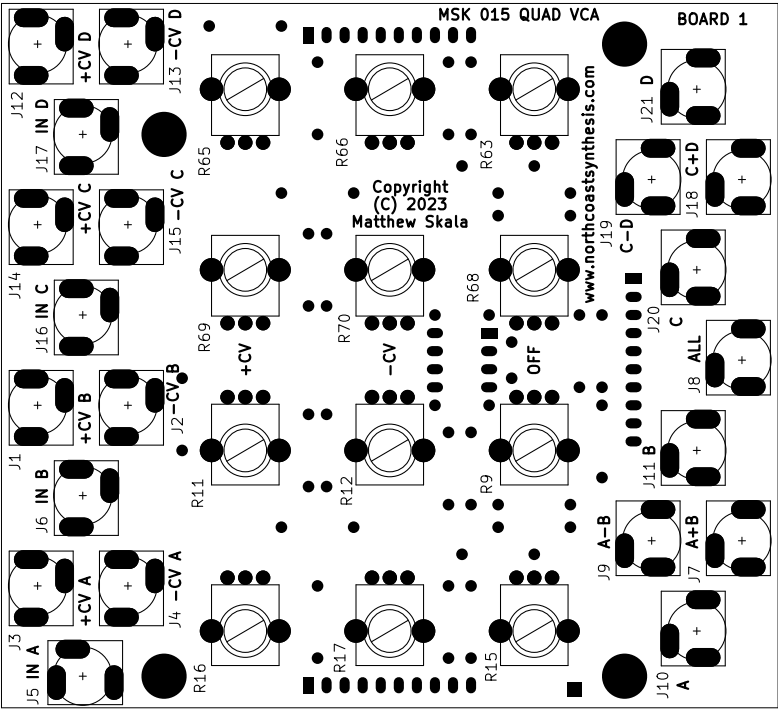
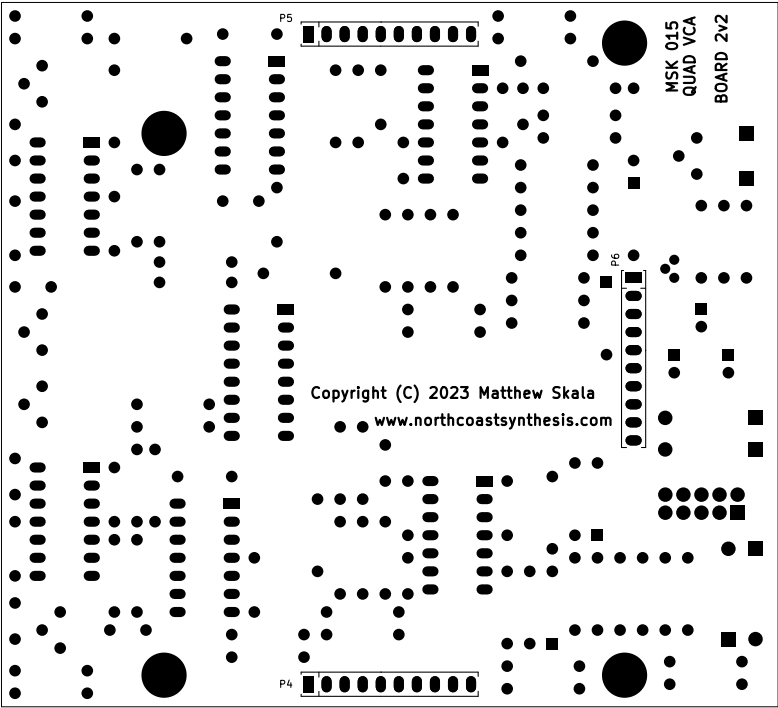
- the schematic diagram for the module;
- a mock-up of what the completed module looks like from the front panel;
- the top-side silk screen art showing component placement;
- the bottom-side silk screen art showing component placement (*note this drawing is mirrored, and shows what you actually see looking at the board, not the X-ray view used in other Kicad output*);
- a drawing of the front panel, with the hole locations and other information for manufacturing it; and
- an exploded isometric drawing showing how the boards and hardware fit together.





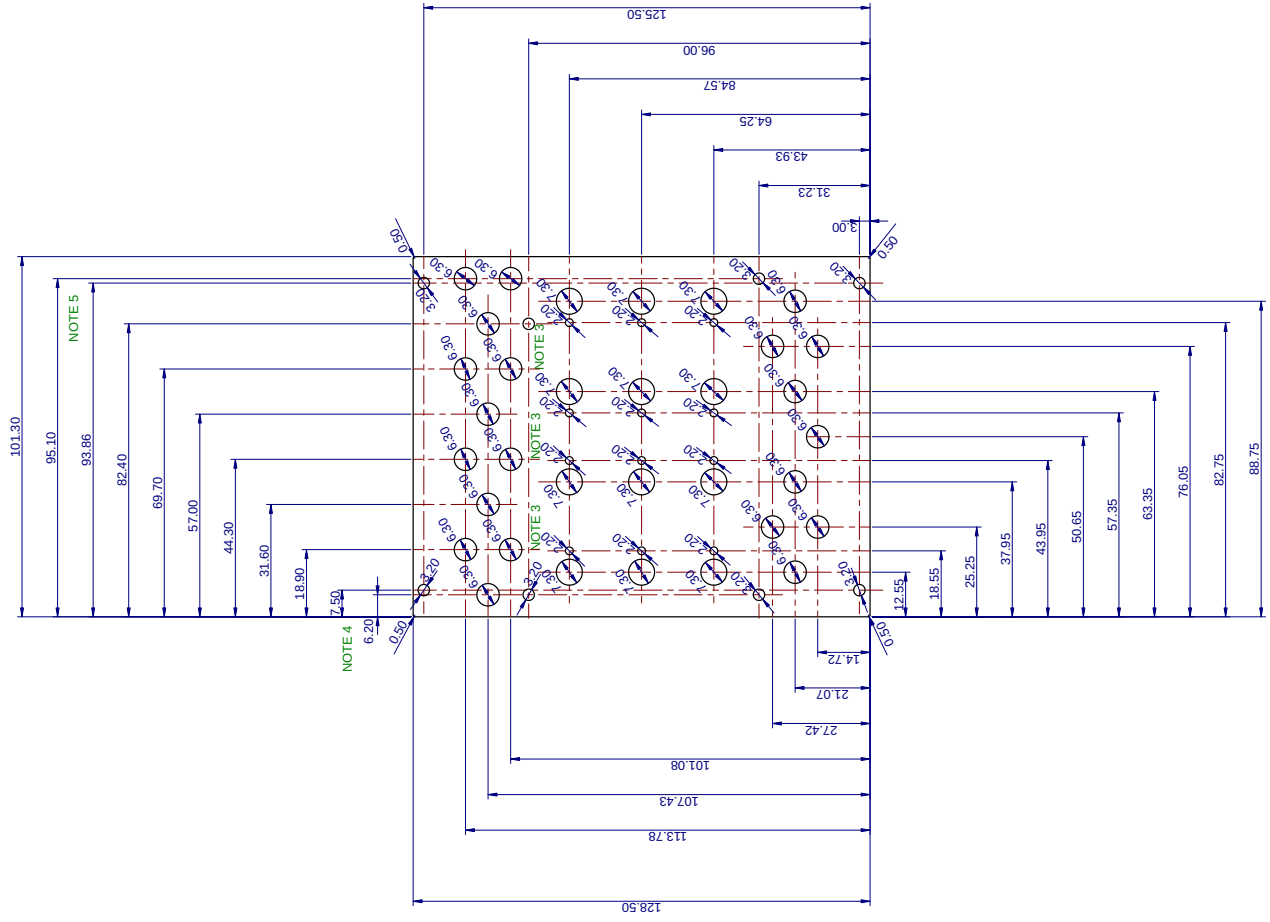






## MSK 015 Quad VCA

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## MSK 015 Quad VCA

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## NOTES

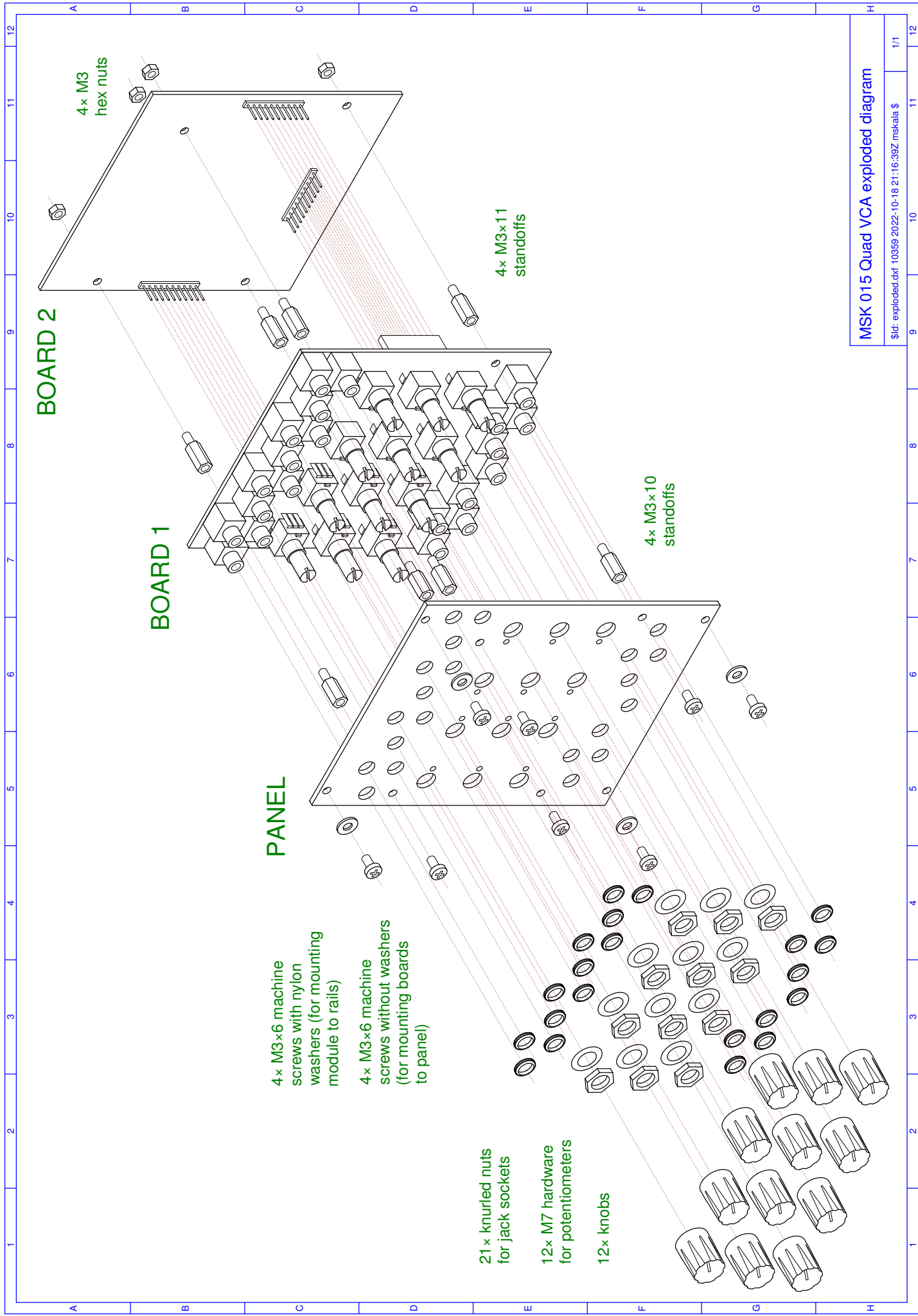
1: All dimensions are millimetres with tolerance +/- 0.10mm.  
Do not scale off drawing.

2: Material is aluminum, 2.00mm thick. Overall dimensions are 128.50mm by 101.30mm, interpolated from Doefer spec for a 20HP Eurorack synthesizer module.

3: Do not confuse similar horizontal positions. The twelve 2.20mm holes are centred 18.55mm, 43.95mm, 57.35mm, and 82.75mm from the left edge, in all cases 6.00mm from the corresponding 7.30mm holes nearby. The six 6.30mm holes at the top are centred 18.90mm, 44.30mm, 57.00mm, and 82.40mm from the left edge.

4: Do not confuse similar horizontal positions. The two 3.20mm holes at top and bottom are centred 7.50mm from the left edge. The other two 3.20mm holes, and the 6.30mm hole, are centred 6.20mm from the left edge.

5: Do not confuse similar horizontal positions. The two 3.20mm holes at top and bottom are centred 93.86mm from the left edge. The other 3.20mm hole, and the two 6.30mm holes, are centred 95.10mm from the left edge.



MSK 015 Quad VCA exploded diagram