MSK 007 Leapfrog Voltage-Controlled Filter

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Contents

General notes

This manual documents the MSK 007 Leapfrog VCF, which is a voltage-controlled filter module for use in a Eurorack modular synthesizer. It is a five-pole filter with a leapfrog topology, technically a species of state-variable filter, with volt/octave tracking; exponential and linear frequency modulation; and a built-in voltage-controlled amplifier which can be switched for use on the output or to control feedback. In the standard configuration (others may be possible as "mods"), the Leapfrog module implements a "musical near-elliptic" low-pass curve, with an extremely sharp cutoff and response peaks at frequencies harmonically related to the cutoff.

Specifications

The module's maximum current requirement in ordinary use is 70mA on the +12V supply and 65mA on the −12V supply. Unusual loads on the outputs, including directly-connected headphones or speakers and so-called "passive" modules, may cause the MSK 007 to draw more than this amount of current. It does not require +5V power.

The input impedance is nominally 100kΩ for all inputs, varying a little with control knob positions. The output impedance is very low, with current limited by a protection resistor inside an op amp's feedback loop. The output is DC coupled. Shorting any input or output to any fixed voltage at or between the power rails should be harmless to the module; patching the MSK 007's output into the output of some other module on the same power system should be harmless to the MSK 007, though doing that is not recommended because it is possible the other module may be harmed.

The design target was for a cutoff range from 10Hz to 10kHz, with oscillation at 0.733 times the cutoff frequency, and V/oct tracking to within ±5 cents across most if not all of that range. Those specifications are not guaranteed, however, and will depend on component quality, adjustments, and so on. The first production units tested were found to have slightly lower limits at both ends, something like 4Hz to 9kHz.

Tracking is temperature-compensated by an NTC thermistor at and near room temperature, but not as precisely nor over as wide a temperature range as one might want for a dedicated oscillator module. The exponential FM input is nominally also V/octave when set to maximum sensitivity (control knob fully clockwise), but it is not calibrated and will not be as accurately V/octave as the main V/octave input.

The VCA control voltage input, at maximum sensitivity (control knob fully clockwise) is linear with unity gain at roughly 4.8V, normalled to the equivalent of 5.1V (a little above unity, subject to attenuation) when there is no cable plugged in. The gain will increase linearly above unity with control voltages all the way up to the positive supply at 12V, and it is safe to use voltages as high as that, though no higher; but output level limiting, described below, means there may be significant distortion when using high control voltages. Negative control voltages cause the VCA to block signals entirely (zero gain), to the extent possible.

The filter is intended for use with typical Eurorack audio levels of ±5V (10V peak to peak) but can process considerably higher voltages with some distortion. The built-in VCA has soft limiting between 8V and 12V peak-to-peak (hard limiting at the top of that range), and that defines the expected maximum audio level under ordinary conditions. Under extreme conditions (VCA switched to feedback mode, external control voltage pushing it beyond unity, a hotter than Eurorack input audio signal, and a lot of distortion) I have been able to push my prototype unit to 17V peak-to-peak audio output. Such use is not damaging *to the MSK 007*; no warranties are made as to the possible effects on other equipment.

This filter is DC-coupled throughout, so it can be used on control voltages all the way down to zero frequency. The tolerances of the analog ICs used will result in some DC offset appearing on audio signals, and some feedthrough of control voltage. An effort has been made in the design to minimize these effects, but like any other DC-coupled active analog filter, the MSK 007 will still exhibit them to some degree.

The point of a low-pass filter is to remove part of the signal, and that implies there will be less signal on the output than on the input. An input signal at standard Eurorack level may have significantly less voltage after passing through the filter, depending on the spectrum and the cutoff frequency. This effect occurs with all low-pass filters, but it is stronger on the MSK 007 than on most others because of the MSK 007's unusually steep cutoff slope. The built-in VCA's ability to amplify beyond unity is intended to help compensate for this effect when desired; but in low-pass gate applications, the volume loss can be desirable.

This module (assuming a correct build using the recommended components) is protected against reverse power connection. It will not function with the power reversed, but will not suffer or cause any damage. Some other kinds of misconnection may possibly be dangerous to the module or the power supply.

Front panel controls and connections

Here's a summary of the items on the front panel of the module.

TUNING knobs two of them labelled "coarse" and "fine": these control the basic cutoff frequency of the module, which can be modified by input control voltages. The range of the coarse knob is about ten octaves, and that of the fine knob about half an octave.

VCA mode switch with settings of "FB" (to the left) and "OUT" (to the right). These control whether the built-in VCA controls feedback (in which case the module output comes directly from the filter core) or output (in which case there is no feedback). See Figure 1 for a block diagram. Note that the built-in VCA has a soft-clipping limiter built in, and will result in deliberate distortion when used at very high signal levels.

EXP FM knob and jack This input and attenuator knob add exponential FM to the filter cutoff frequency. Sensitivity is approximately 1V/octave with the knob at maximum. Input voltages of ±12V are safe to use, but may not extend the filter's frequencies past the range of the tuning knobs.

LIN FM knob and jack This input and attenuator knob add linear FM to the filter cutoff frequency. *This is an AC-coupled input and DC or very slow AC control voltages will have no effect.* Sensitivity with the knob at maximum is approximately ±100% of the centre frequency at ±5V input; it does not support through-zero modulation.

VCA knob and jack This input and attenuator knob control the built-in VCA, which in turn either controls feedback or output level depending on the VCA mode switch. The control voltage input is normalized to the equivalent of a little over 5V, and the VCA gives unity gain at about 4.8V. In feedback mode with no cable plugged in, the module will oscillate starting with the knob at about half to two thirds of its range. Note that *the module will produce no output* if the switch is set to "OUT" and the knob is set to minimum, nor if the switch is set to "OUT" and there is a cable plugged in with a zero control voltage or nothing plugged in at the other end. Voltages in the range ±12V are safe to use, but all negative voltages are equivalent to zero; voltages higher than 5V give greater than unity voltage gain, but at high signal levels will also result in increasing distortion.

IN jack This input is for audio input to the filter. It is intended for standard Eurorack signal levels of ±2.5V, but will accept up to ±12V (with distortion likely later in the chain).

1V/8ve jack This is a volt/octave pitch control voltage input. It should be reasonably accurate, and is temperature-compensated, though (as appropriate for a filter) it may be less accurate than the best dedicated VCOs.

OUT jack This is the audio output from the filter: either the filter core or the VCA depending on the setting of the VCA mode switch.

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;
- LaTeX for document compilation;

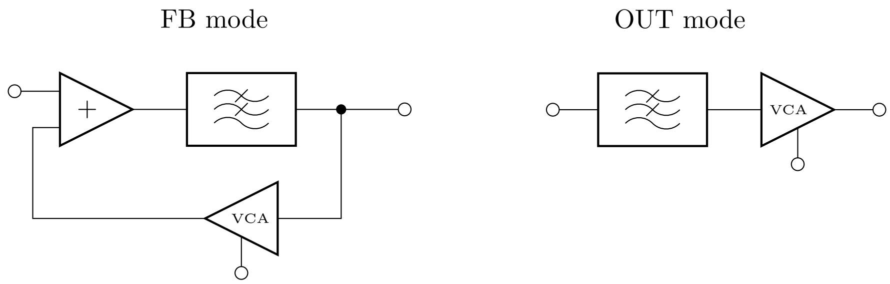


Figure 1: Simplified block diagram of the module, according to VCA mode

- LaTeX.mk (Danjean and Legrand, not to be confused with other similarly-named 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 kicad-symbols/ subdirectory contains my customised schematic symbol and PCB footprint libraries for Kicad. Kicad doesn't normally keep dependencies like symbols inside a project directory, so on my system, these files actually live in a central directory shared by many projects. As a result, upon unpacking the ZIP file you may need to do some reconfiguration of the library paths stored inside the project files, in order to allow the symbols and footprints to be found. Also, this directory will probably contain some extra bonus symbols and footprints not actually used by this project, because it's a copy of the directory shared with other projects.

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 three boards, each 3.90″×2.95″, or 99.06mm×74.93mm. They are intended to mount in a stack parallel to the Eurorack panel, held together with M3 machine screws and male-female hex standoff hardware. See Figure 2.

Component substitutions

Most of the components in the circuit are not really critical as to their identities. For panel components (the potentiometers, jack sockets, and DPDT toggle switch), my boards are designed around the components I prefer to use for quality reasons, including BI Tech conductive-plastic potentiometers and Lum-

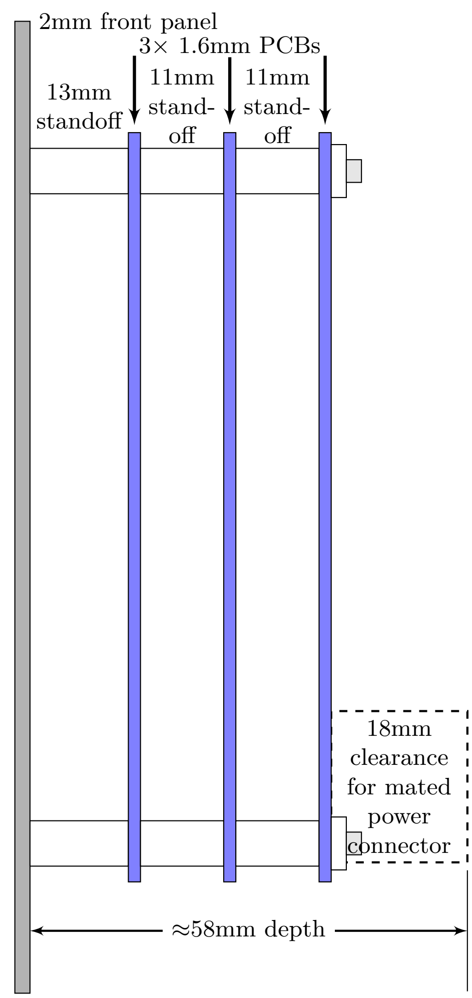


Figure 2: Assembled module, side view.

berg jack sockets. If you want to substitute cheap, lower-quality components in a home build, check the PCB design carefully to make sure it will still work with those components. The panel-to-board distance is also carefully chosen, and the recommended components just barely fit. Substituting through-panel components means you may need to take a close look at the physical design to be sure it will still work.

The integrator capacitors (C7, C8, C9, C20, and C21) are important. To achieve an accurate response curve, they ought to be 470pF ±1%, and for best audio quality and oscillation performance across the design range of frequencies, they ought to be at least good quality film or NP0 types. Whether people can really hear differences among capacitor types beyond their objectively-measurable specifications is a controversial subject. We can truthfully say that for best performance in this filter, the capacitors should have close tolerances and very little loss across the audio spectrum; going any further than that on capacitor selection *may* only be mumbo-jumbo.

North Coast Synthesis Ltd. ships polystyrene integration capacitors in our assembled MSK 007 modules and full kits. They are top quality, but expensive, and they require care during soldering. The PCB includes alternate through-hole pads for the integration capacitors at 0.2″ and 0.6″ spacing, and also surface-mount pads, to allow for multiple options of mounting whatever weird and wonderful capacitors home builders may wish to substitute. I used silver mica capacitors in my first prototype; they work quite well, but are even more expensive than the polystyrene capacitors, and they may have some loss issues at the lowest audio frequencies. Silver mica capacitors are more appropriately used in radio applications; I would not recommend them here because the less-expensive polystyrene units are really better. Good NP0 ceramic capacitors should work well in this filter, and they are cheaper, but I have not tested them, and it would probably be necessary to choose surface-mount versions in order to get the 1% tolerance. Glass capacitors, sometimes available as military surplus, possibly with hand-selection to get down to the right tolerance, would be fun to try.

I recommend two 2N5088 NPN transistors for the exponential converter (Q14 and Q15), as high-quality amplifier transistors likely to be decently matched without special selection. I use a third of this same type (Q12) as a voltage follower in the VCA control voltage processor, in order not to need yet another distinct component type on the BOM; but really, almost any typical NPN transistor would be fine for Q12, you could save a few cents by putting in a 2N3904 there, and you could probably get away with substituting the exponential transistors with cheaper general purpose types, too.

The Leapfrog VCF uses a lot of PNP discrete transistors in current-source roles. I originally designed it using BC557CG transistors in the current sources. Those were discontinued shortly before I took the design into commercial production, and I had to scramble to find a replacement on a short timeline. For the first few years of the module's lifetime as a commercial product, I used PN200A transistors. In 2021, those were also discontinued. As of this writing, I am preparing to switch to SS8550D transistors for the PNP current sources, and making a lifetime buy to reduce the risk of future discontinuations. The SS8550D transistors are a fair bit more expensive, and they may be overkill for this relatively undemanding application, but I wanted to make sure there was no quality compromise involved in making the change. Really, almost any generic silicon PNP junction transistor, preferably with high gain, should work.

With any transistor substitution, make sure the pinout is compatible. Also be aware that some transistors in TO-92 packages are commonly sold with "formed" leads, designed to plug into three holes side by side 0.1″ apart, and my boards are designed for use with unformed-lead TO-92 packages, the leads plugged into a triangular pattern for physical strength. It is annoying and requires some care to plug a formed-lead transistor into these boards; I make an effort to source transistors with unformed leads.

The NTC thermistor used in the control voltage processor (R71) ought to be Vishay type NTCLE203E3103FB0. If you cannot get this exact type, you face a choice of other options:

- Use some other NTC thermistor with a nominal 10kΩ resistance at room temperature, and hope its performance will be close enough;
- Use a plain metal film 10kΩ resistor with a very small temperature coefficient and forfeit temperature compensation;
- Use a +3350ppm/°C 22kΩ PTC "tempco" resistor instead of R75, a plain metal film resistor for R71, and rearrange the physical design to put R75 in contact with Q14 and Q15, or possibly make further changes to accomodate a different nominal value of "tempco" or reduce

the complexity of the resistor network; or

- Use some other NTC thermistor for R71 and redesign the circuit by choosing values for R67, R68, R72, and R77, to fit the temperature-to-gain function as well as possible to the known performance of silicon transistors.

Temperature compensation for a filter is usually not critical anyway, so it may not be a big problem if the performance of this part of the circuit is not the best possible.

Modification for ±15V power

The unmodified MSK 007 circuit should work acceptably with ±15V power, assuming an appropriate substitution or adapter for the Eurorack power connector itself, and that all components used are rated for the increased voltage. Most voltage-critical parts of the circuit are driven by an internal +9V bus, and the regulator for that has plenty of spare power capacity and should accept +15V input without needing any extra heat sinking. The DC offset trimmers will need to be adjusted for the voltage being used. They and the tuning knobs have range-setting resistors which are calculated for ±12V, and so will cover a wider range (possibly wider than is usable, in the case of the coarse tuning knob) unless the range resistors are changed. Recommended changes are as follows:

- R73 (range for coarse tuning knob): change from 240kΩ to 300kΩ
- R74 (range for fine tuning knob): change from 4.7MΩ to 5.6MΩ
- R87 (range for core offset trim): change from 390kΩ to 470kΩ.
- R90 (range for VCA offset trim): change from 1MΩ to 1.2MΩ.

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, including 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/. Your support of my business is what makes it possible for me to continue releasing module designs for free. Even if you only use the free plans and cannot buy the commercial products I sell, any assistance you can offer to increasing the profile of North Coast would be much appreciated. For instance, you might post photos of your completed DIY build on your social media. The latest version of this document and the associated source files can be found at the North Coast Web site.

Email should be sent to mskala@northcoastsynthesis.com.

Safety and other warnings

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 still 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.	
1	C29	22pF	radial ceramic, 0.2″ lead spacing
1	C25	100pF	radial ceramic, 0.2″ lead spacing
19	C1, C3–C6, C10, C12–C15, C17, C18, C22–C24, C26, C27, C30, C31	0.1μF	axial ceramic
1	C2	0.47μF	film, 0.2″ lead spacing
4	C11, C16, C19, C28	10μF	radial aluminum electrolytic, 0.1″ lead spacing
5	C7–C9, C20, C21	470pF 1%	precision integrator capacitor; see notes
2	D1, D3	1N4148	or 1N914; switching diode
2	D7, D9	1N5230B	4.7V Zener
2	D6, D8	1N5233B	6.0V Zener
2	D4, D5	1N5818	or SB130; Schottky rectifier
4	H13–H16		nut for M3 machine screw
8	H21–H28	M3x11	M3 male-female standoff, 11mm body length
4	H17–H20	M3x13	M3 male-female standoff, 13mm body length
8	H29–H36	M3x6	M3 machine screw, 6mm body length
4	H37–H40		nylon washer for M3 machine screw
6	J1–J6	1502 03	switched mono 3.5mm panel jack, Lumberg
4	J7–J10		female single-row socket, 10 pins at 0.1″
4	P26, P40, P42, P44		male single-row header, 10 pins at 0.1″
1	P24		male Eurorack power header, 2×5 pins at 0.1″
3	Q12, Q14, Q15	2N5088	NPN general purpose amplifier, TO-92 EBC
12	Q1–Q11, Q13	SS8550D	or PN200A; PNP high gain, TO-92 EBC
1	R43	200Ω	vertical multiturn, Bourns 3296Y/Vishay T93YB
1	R77	500Ω	horizontal multiturn, Bourns 3296P/Vishay T93Z
1	R34	1kΩ	vertical multiturn, Bourns 3296Y/Vishay T93YB
13	R16–R21, R45–R48, R52, R53, R80	1kΩ	
6	R7–R9, R26, R27, R38	2kΩ	vertical multiturn, Bourns 3296Y/Vishay T93YB
1	R54	2.4kΩ	
2	R72, R76	2.7kΩ	
1	R58	3.3kΩ	

Qty	Ref	Value/Part No.	
1	R3	3.6kΩ	
2	R40, R44	4.3kΩ	
7	R2, R4–R6, R24, R25, R60	5.6kΩ	
1	R23	6.2kΩ	
1	R1	6.8kΩ	
1	R22	7.5kΩ	
1	R49	8.2kΩ	
1	R82	10kΩ	
1	R67	11kΩ	
2	R35, R75	22kΩ	
1	R39	24kΩ	
1	R68	27kΩ	
1	R84	39kΩ	
1	R63	68kΩ	
2	R59, R61	91kΩ	
1	R89	100kΩ	horizontal multiturn, Bourns 3296P/Vishay T93Z
3	R30, R32, R50	100kΩ	vertical multiturn, Bourns 3296Y/Vishay T93YB
5	R56, R62, R69, R78, R81	100kΩ	vertical conductive plastic panel pot, BI Technologies P260T series, linear taper
8	R57, R64–R66, R70, R79, R83, R85	100kΩ	
11	R10–R15, R36, R37, R41, R42, R51	140kΩ	E48 value; use 130kΩ (second choice) or 150kΩ (third) if a more common value is desired
1	R55	150kΩ	
1	R73	240kΩ	
1	R87	390kΩ	
1	R88	680kΩ	
1	R33	820kΩ	
1	R31	910kΩ	
1	R90	1MΩ	
1	R74	4.7MΩ	
1	R71	10kΩ NTC	thermistor, Vishay NTCLE203E3103FB0
1	SW3	100DP1T1B1M2	E-Switch 100-series DPDT on-on toggle
1	U8	78L09	+9V regulator in TO-92 package
3	U1, U2, U6	LM13700	dual operational transconductance amp
5	U3–U5, U7, U10	TL074	quad JFET-input op amp
1	U9	TL431	2.495V reference in TO-92 package

Fixed resistors should be 1% metal film throughout. Capacitor values are not critical *except* the 470pF 1% integration capacitors (marked as such), which must be 1% or better tolerance and should have good loss and temperature characteristics. 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, DIP sockets, one nylon cable tie, PCBs, panel, knobs, Eurorack power cable, etc.

Building Board 3

The three circuit boards in the Leapfrog Filter are numbered from 1 (closest to panel) to 3 (furthest from panel), but I recommend building them in the opposite order, with board 3 first. One reason is so that if impatient, you can do the "pre-adjustment" (page 44) on Board 3 and see that something is working early in the game, before the other boards are built.

There are three header connectors on Board 3 which serve to link to Board 2. My recommendation is not to solder these in place until you build Board 2, because it is convenient to assemble the boards into a stack to hold the connectors in exactly the right places while soldering them. Accordingly, the soldering for these connectors is described in that chapter instead of here.

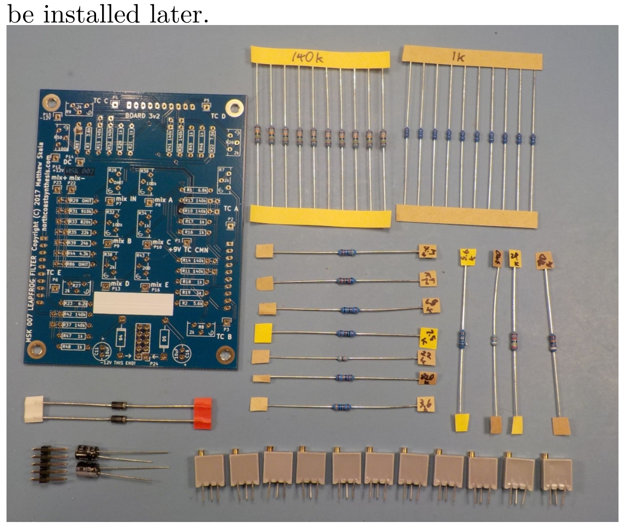
Note that although I'm describing a separate step for each component value, and that's how I built mine so as to have plenty of photo opportunities, if you are reasonably confident about your skills you may find it easier to populate all or most of the board (i.e. put the components in place) and then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

The first PCBs for Board 3 were labelled "BOARD 3v2" and had some minor differences in the silkscreen art, of which the most important was that R87's value was labelled "1M." That batch was mostly for prototyping, but there were a few left over which I will sell. In prototyping I determined that R87 ought to have the value 390kΩ instead (to allow a larger adjustment range for the core DC offset), so if you have a v2 board you should mount a 390kΩ resistor in this position regardless of the silkscreen label. Later versions ("v3" and any subsequent) will say "390k" here, and I'm putting stickers over the "1M" labels on the existing v2 boards that I sell to help remind DIY builders of the change. There is no electrical change in the board itself between v2 and v3; the updates are all to the silkscreen.

The Board 3 PCB is designed to support modifications. The resistor network on this board configures the filter core on Board 2 to produce the desired response curve, and by substituting other resistor values instead of the ones shown, you could build a different type of filter (highpass, bandpass, a different shape of lowpass, or whatever). A future version of this manual may include suggested modifications; until then, adventurous do-it-yourselfers can experiment with calculating their own using the procedure given starting on page 64. In order to support alternate curves, there are a few footprints (R28, R29, and R86) labelled "OMIT" on the PCB. These are not used, and you should just leave them empty, for the MSK 007's musical near-elliptic low-pass default response. Some modified curves might call for mounting components in these positions.

Preliminaries

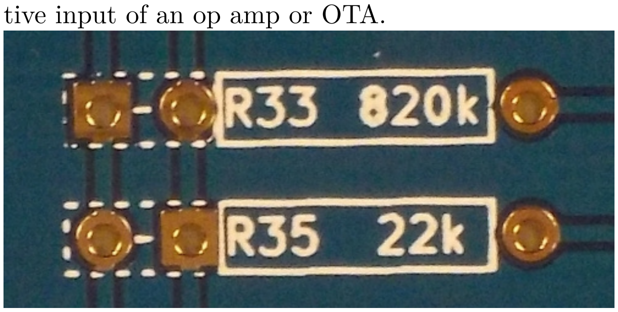
Count out the right number of everything according to the bill of materials. There is an abbreviated BOM for Board 3 in Table 2, excluding the headers that will be installed later.



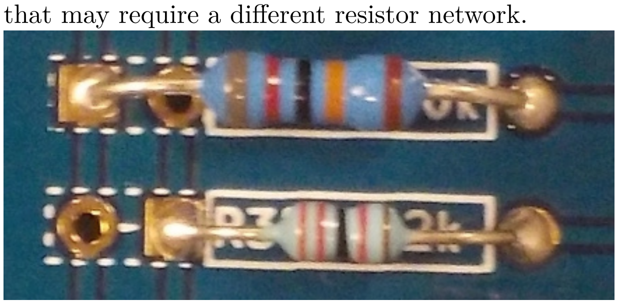
There are 11 multiturn trimmers to be installed on this board. Before installing them, use an ohmmeter to adjust each one to 50% of its range. Measure the resistance along the track, then measure the resistance from the wiper to one end and adjust to make the wiper half the total track resistance. This need not be exact, but it will help with adjustment later, by reducing issues with interaction among the different settings. With all trimmers pre-set to 50%, the module should basically work even if it is not at its best, whereas if many are installed at extreme values instead, then you may have trouble getting it up and running enough to adjust it more accurately.

Fixed resistors

In order to allow as many options as possible for modified filter curves using this same PCB design, many of the resistors on Board 3 have special three-pin footprints, as shown below. These are meant to offer the choice of connecting a signal to the positive or negative input of an op amp or OTA.



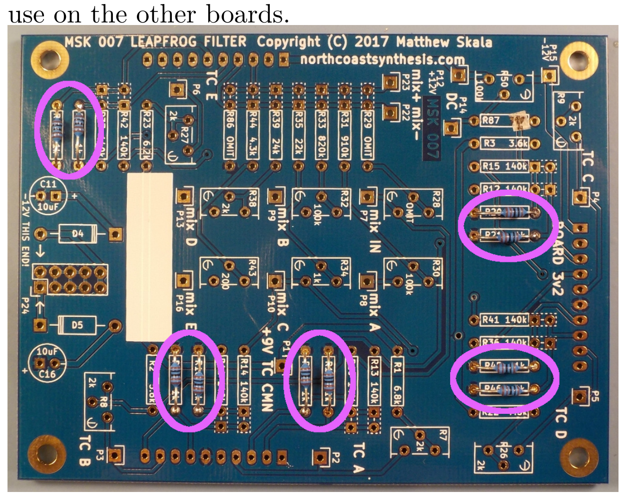
In each of these special footprints the resistor connects between the pad at right, and *one of* the two pads at left. The pad you should use for the default response curve is always the pad with the *square corners*, which may be the nearer or farther pad depending on the individual footprint. The other, circular, pad should not be used in a standard build but is reserved for possible use by some future modification that may require a different resistor network.



Throughout the installation of the fixed resistors on Board 3, check carefully against both the pad shapes on the board, and the photos in these instructions, to be sure you install each resistor into the correct pads. Getting any wrong will likely result in little or no response from the filter, or a highly distorted frequency response curve.

Resistors are never polarized. I like to install mine in a consistent direction for cosmetic reasons, but this is electrically unnecessary. In this module, metal film 1% resistors are recommended for all fixed-value resistors. These will usually have blue bodies and four colour bands designating the value, plus a fifth band for the tolerance, brown in the case of 1%. These are the resistors normally shipped in the North Coast kits, but we may occasionally ship better-tolerance resistors (such as 0.5%) 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 ten 1kΩ (brown-black-black-brown) resistors R16 through R21 and R45 through R48. These are parts of the voltage dividers that control input levels for the five integrators making up the filter core. A full MSK 007 kit should contain 13 of these resistors, so there should be three left over for use on the other boards.

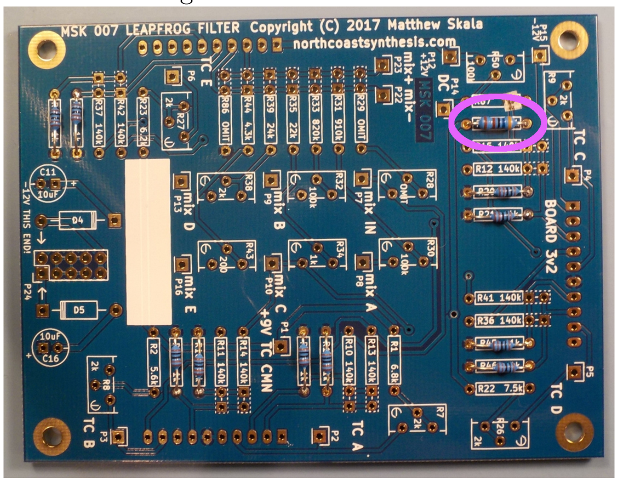


This table is not a substitute for the text instructions.

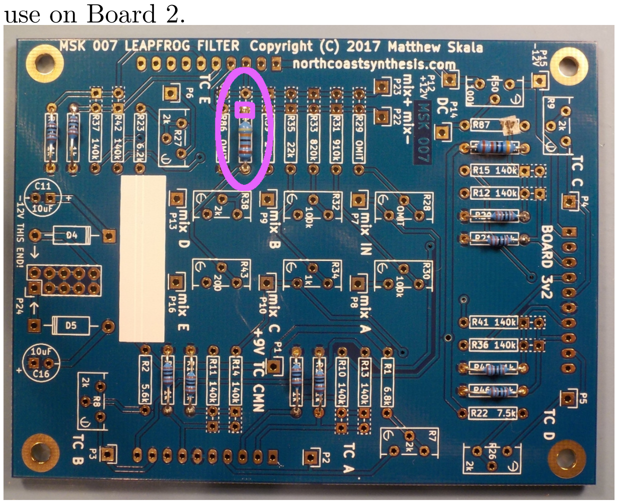
Qty	Ref	Value/Part No.	
2	C11, C16	10μF	radial aluminum electrolytic, 0.1″ lead spacing
2	D4, D5	1N5818	or SB130; Schottky rectifier
1	P24		male Eurorack power header, 2×5 pins at 0.1″
1	R43	200Ω	vertical multiturn, Bourns 3296Y/Vishay T93YB
1	R34	1kΩ	vertical multiturn, Bourns 3296Y/Vishay T93YB
10	R16–R21, R45–R48	1kΩ	
6	R7–R9, R26, R27, R38	2kΩ	vertical multiturn, Bourns 3296Y/Vishay T93YB
1	R3	3.6kΩ	
1	R44	4.3kΩ	
1	R2	5.6kΩ	
1	R23	6.2kΩ	
1	R1	6.8kΩ	
1	R22	7.5kΩ	
1	R35	22kΩ	
1	R39	24kΩ	
3	R30, R32, R50	100kΩ	vertical multiturn, Bourns 3296Y/Vishay T93YB
10	R10–R15, R36, R37, R41, R42	140kΩ	E48 value; use 130kΩ (second choice) or 150kΩ (third) if a more common value is desired
1	R87	390kΩ	
1	R33	820kΩ	
1	R31	910kΩ	

Table 2: Bill of Materials for Board 3.

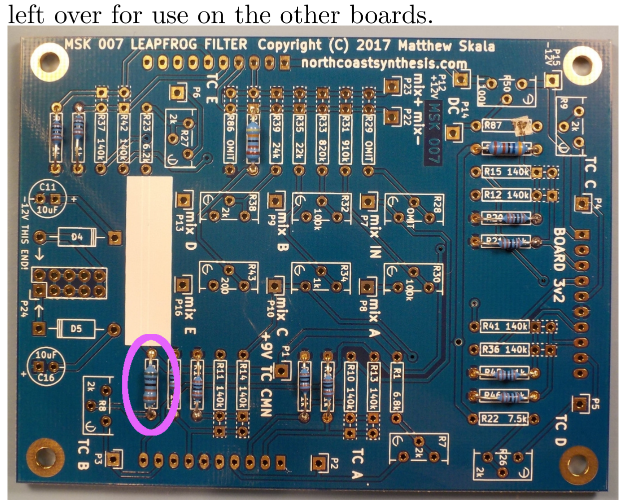
Install the 3.6kΩ (orange-blue-black-brown) resistor R3. This resistor controls the linearizing diode current for integrator C.



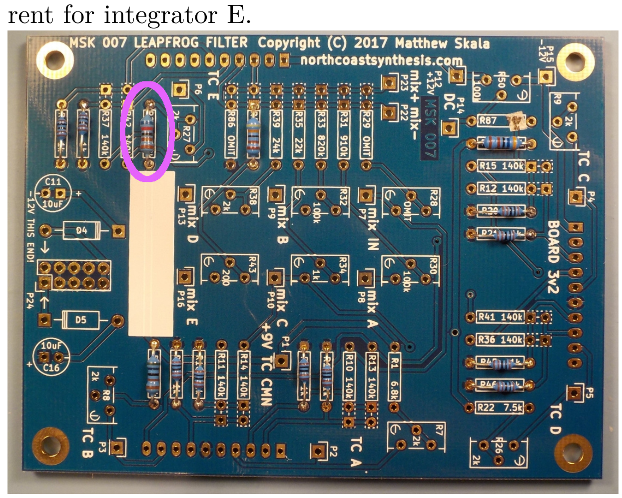
Install the 4.3kΩ (yellow-orange-black-brown) resistor R44. This resistor controls the proportion of integrator E in the output mix. Connect it to the nearer pad. A full MSK 007 kit should contain two of these resistors, so there should be one left over for use on Board 2.



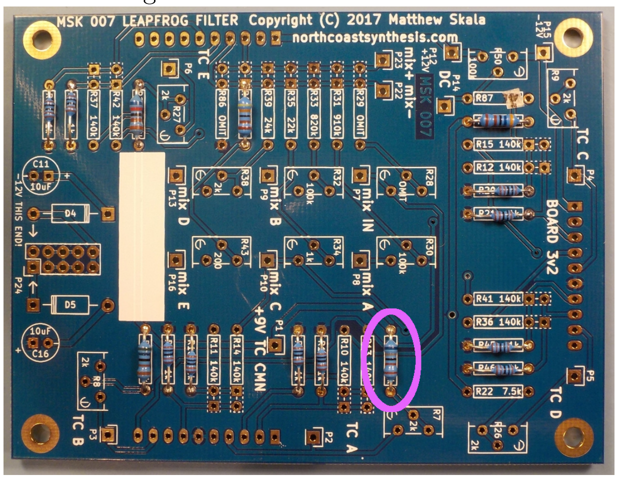
Install the 5.6kΩ (green-blue-black-brown) resistor R2. This resistor controls the linearizing diode current for integrator B. A full MSK 007 kit should contain seven of these resistors, so there should be six left over for use on the other boards.



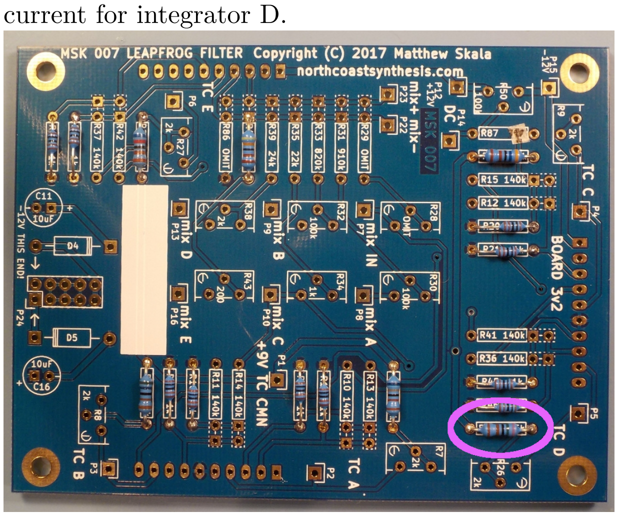
Install the 6.2kΩ (blue-red-black-brown) resistor R23. This resistor controls the linearizing diode current for integrator E.



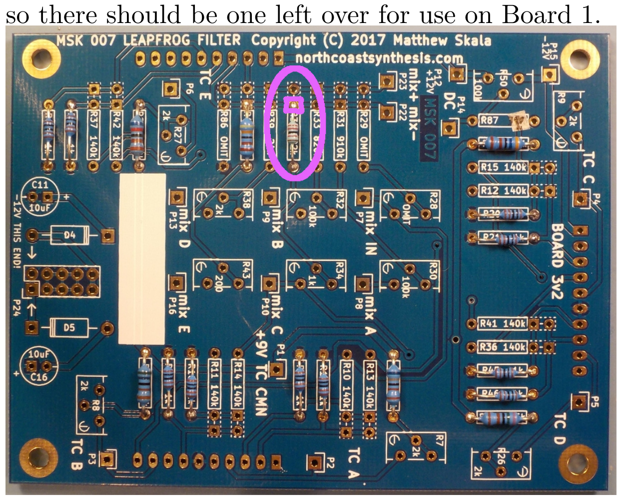
Install the 6.8kΩ (blue-grey-black-brown) resistor R1. This resistor controls the linearizing diode current for integrator A.



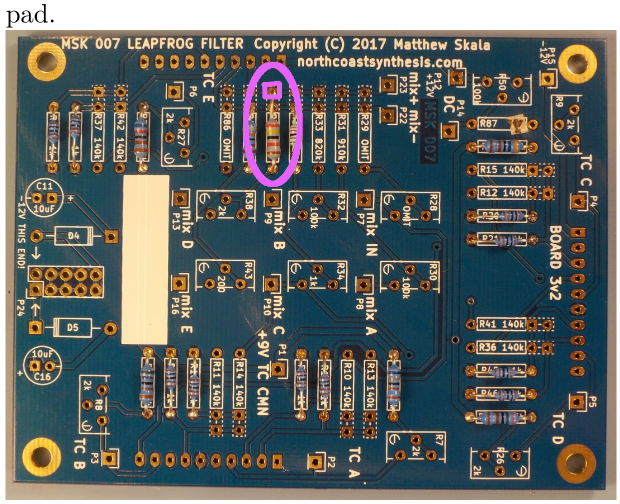
Install the 7.5kΩ (violet-green-black-brown) resistor R22. This resistor controls the linearizing diode current for integrator D.



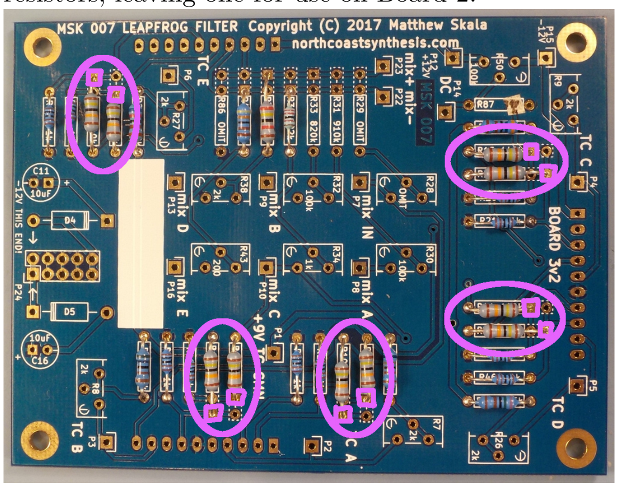
Install the 22kΩ (red-red-black-red) resistor R35. This resistor controls the proportion of integrator C in the output mix. Connect it to the nearer pad. A full MSK 007 kit should contain two of these resistors, so there should be one left over for use on Board 1.



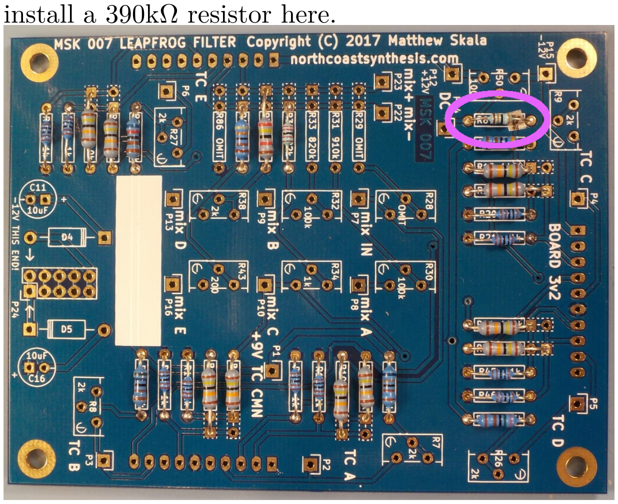
Install the 24kΩ (red-yellow-black-red) resistor R39. This resistor controls the proportion of integrator D in the output mix. Connect it to the farther pad.



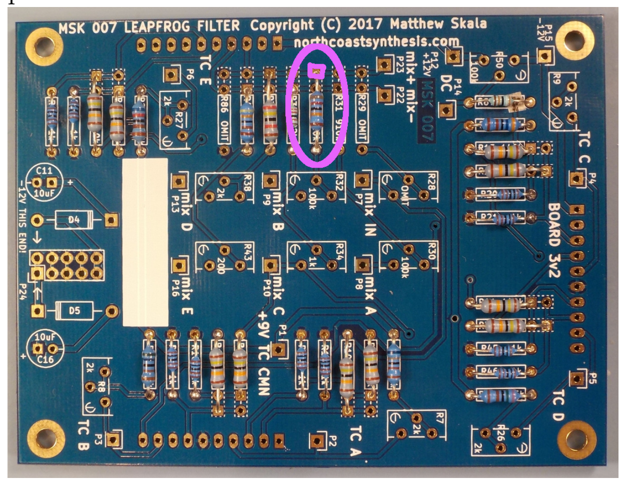
Install the ten 140kΩ (brown-yellow-black-orange) resistors R10 through R15, R36, R37, R41, and R42. These are parts of the voltage dividers that control input levels for the five integrators. The resistors are installed in five pairs, each with one connected to the nearer and one connected to the farther pad. Check the photo and the board pad shapes carefully. A full MSK 007 kit should contain 11 of these resistors, leaving one for use on Board 2.



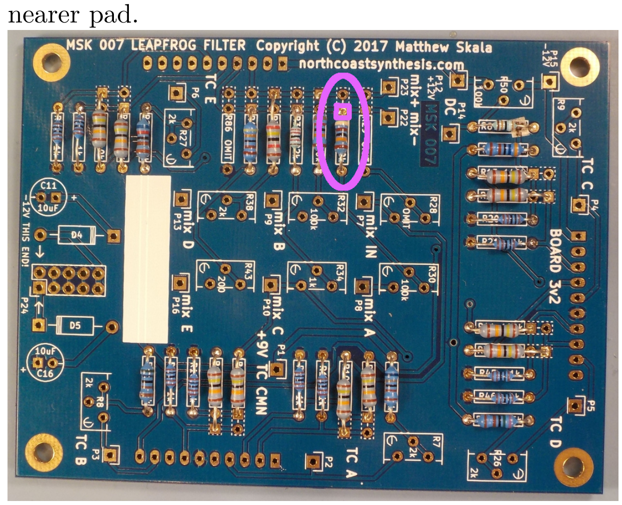
Install the 390kΩ (orange-white-black-orange) resistor R87. This resistor sets the adjustment range for the core DC offset trimmer. Note that if you have a v2 board (like the one in the photo) then the silkscreen for this resistor will read "1M" and possibly be covered by a bit of tape; nonetheless, you should install a 390kΩ resistor here.



Install the 820kΩ (grey-red-black-orange) resistor R33. This resistor controls the proportion of integrator B in the output mix. Connect it to the farther pad.

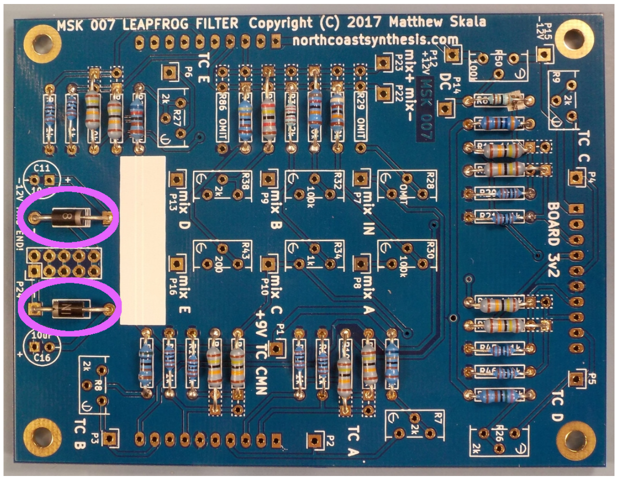


Install the 910kΩ (white-brown-black-orange) resistor R31. This resistor controls the proportion of integrator A in the output mix. Connect it to the nearer pad.



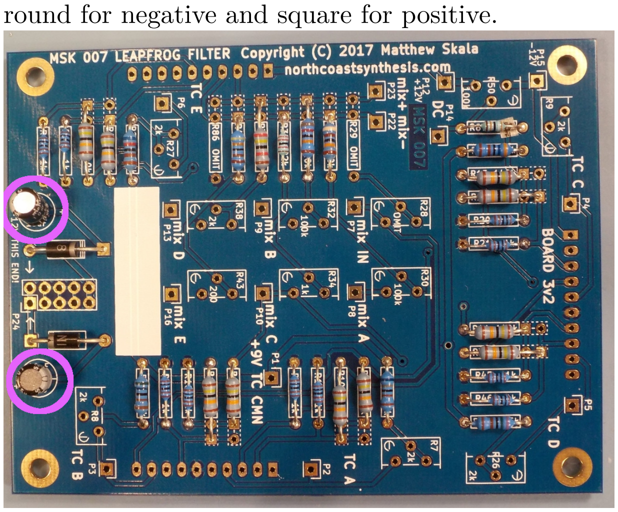
Semiconductors

Install the two Schottky diodes D4 and D5. These protect the module against reverse connection of the power supply. They are polarized and must be installed in the correct direction; otherwise they will prevent the module from operating. One end of each diode will be marked, usually with a stripe of grey paint around the black plastic body of the diode. That end is the cathode. The diode outline on the PCB silkscreen is marked with a similar stripe showing the direction of the cathode, and the solder pad for the cathode is square instead of round.



Electrolytic capacitors

Install the two 10μF electrolytic capacitors C11 and C16. These filter incoming power to prevent noise in the case power system from affecting the Leapfrog. They are polarized components, and may explode if connected backwards. As such, there are multiple clues to help you install them in the right direction. The negative leg of each capacitor will be marked in some way, usually with a printed stripe and minus signs on the plastic wrapping of the capacitor body. The negative leg of the capacitor will usually also be shorter, though that is less reliable than the body markings. On the PCB, the positive and negative pads are marked with positive and negative signs in the silkscreen, and the solder pads themselves are round for negative and square for positive.



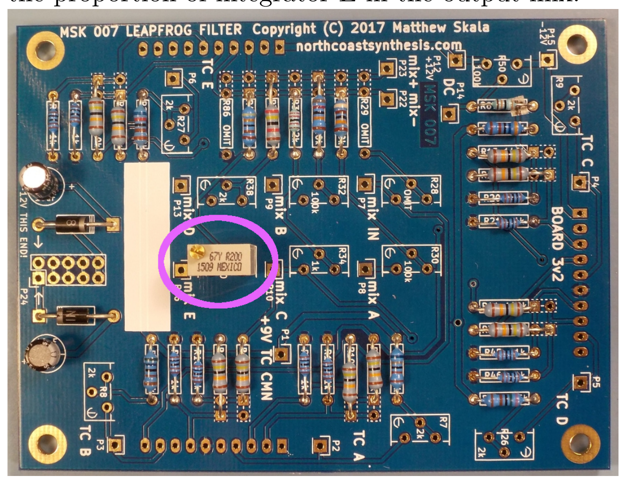
A full MSK 007 kit should contain four of these capacitors, leaving two for installation on Board 2.

Trimmer potentiometers

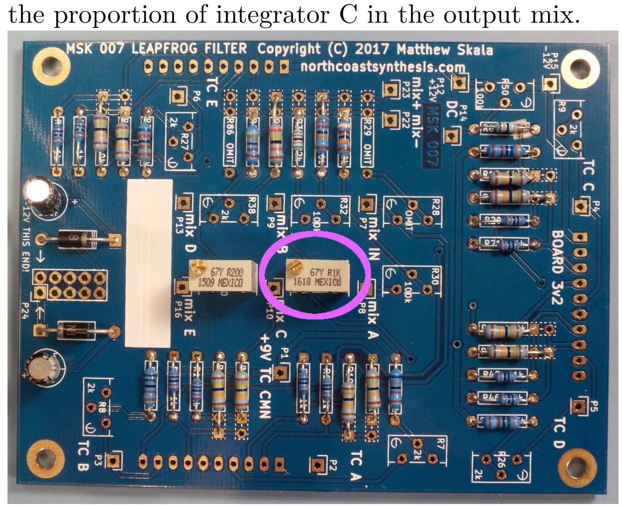
If you have not already set the trimmers to 50% of their full scale value as described under "Preliminaries" above, then do it now.

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.

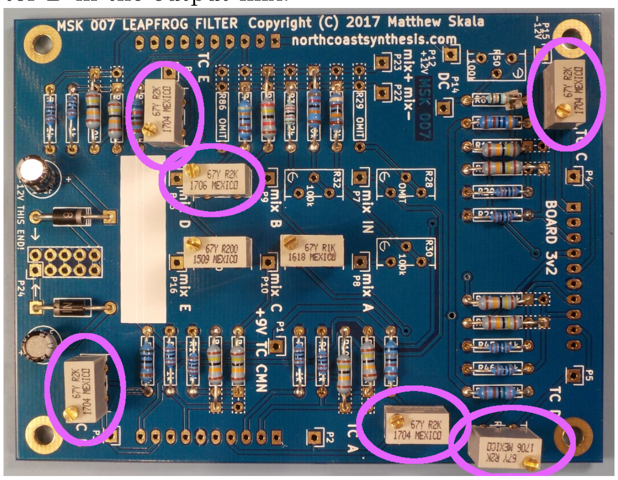
Install the 200Ω trimmer R43. This trimmer sets the proportion of integrator E in the output mix.



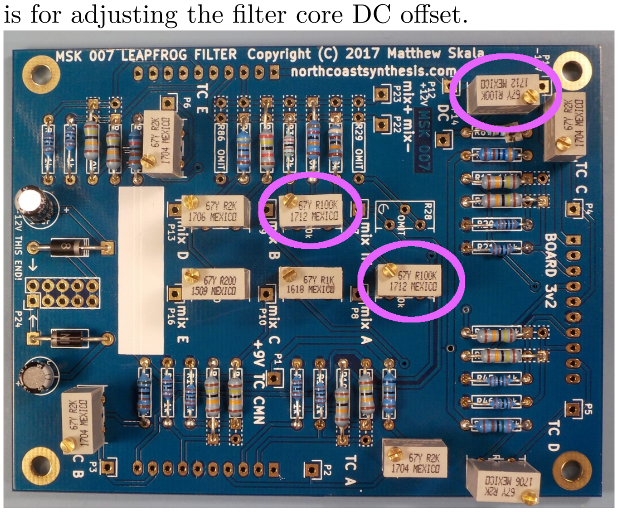
Install the 1kΩ trimmer R35. This trimmer sets the proportion of integrator C in the output mix.



Install the six 2kΩ trimmers R7 to R9, R26, R27, and R38. Most of these are for adjusting the diode currents, and indirectly the time constants, of the integrator stages; R38 sets the proportion of integrator D in the output mix.

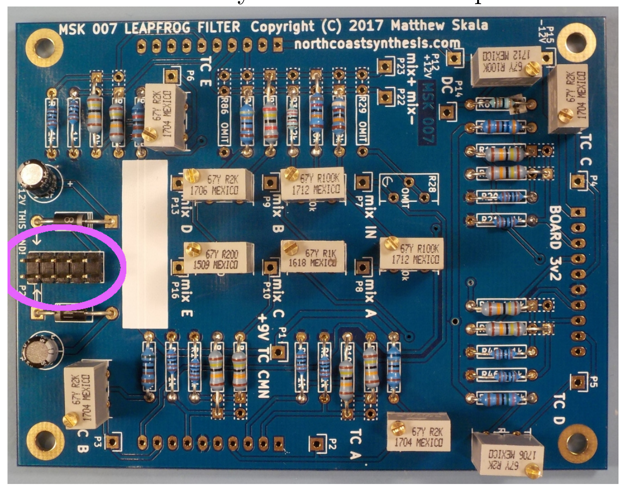


Install the three 100kΩ trimmers R30, R32, and R50. The first two of these set the output mix amounts for integrators A and B respectively; R50 is for adjusting the filter core DC offset.



Power header

Install the 10-pin dual-row Eurorack power header P24. 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, possibly with tape, 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 −12V power. For most modules including the MSK 007, the red stripe should be at the *bottom* when the module is mounted vertically in a case. On the MSK 007, the correct location of the −12V supply is also marked with the text "−12V THIS END!" and arrows on both sides of 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.

At this point you may, if you wish, do the pre-adjustment procedure described starting on page 44. Whether you do that now or leave it until the rest of the build is complete, in between completed boards is a good time to take a break.

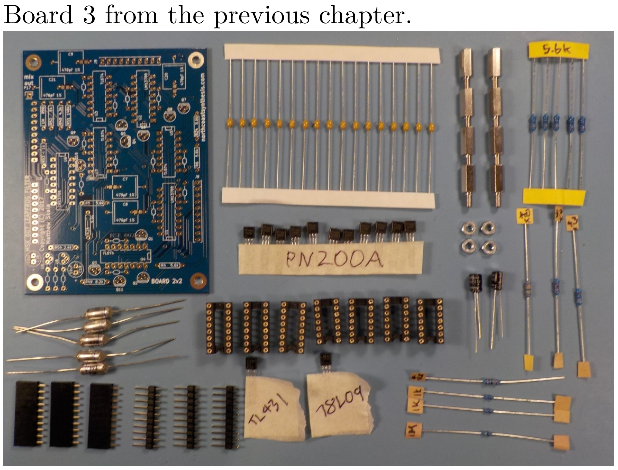
Building Board 2

There are a few header connectors which serve to link the boards together. My recommendation is to solder in the three links to Board 3 while working on Board 2, and accordingly, the partial Bill Of Materials in Table 3 includes these connectors. The link to Board 1 will be left for later.

Note that although I'm describing a separate step for each component value, and that's how I built mine 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.

Preliminaries

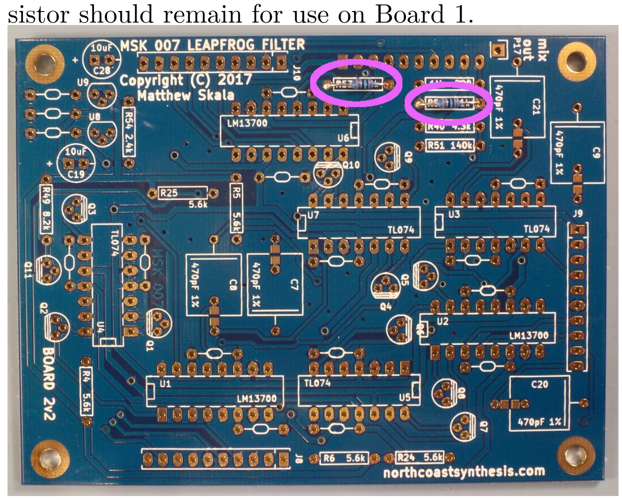
Count out the right number of everything according to the bill of materials. There is an abbreviated BOM for Board 2 alone in Table 3, including some hardware that will be useful for this part of the build but overlaps with the requirements for other boards. In addition to these things you will need your assembled Board 3 from the previous chapter.



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, metal film 1% resistors are recommended for all fixed-value resistors. These will usually have blue bodies and four colour bands designating the value, plus a fifth band for the tolerance, brown in the case of 1%. These are the resistors normally shipped in the North Coast kits, but we may occasionally ship better-tolerance resistors (such as 0.5%) 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 two 1kΩ (brown-black-black-brown) resistors R52 and R53. These are input resistors for the OTA in the VCA section. After installing them, and the ten 1kΩ resistors on Board 3, one more 1kΩ resistor should remain for use on Board 1.

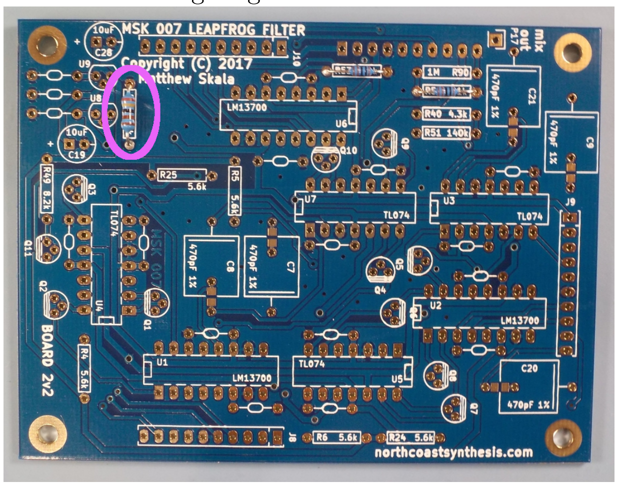


This table is not a substitute for the text instructions.

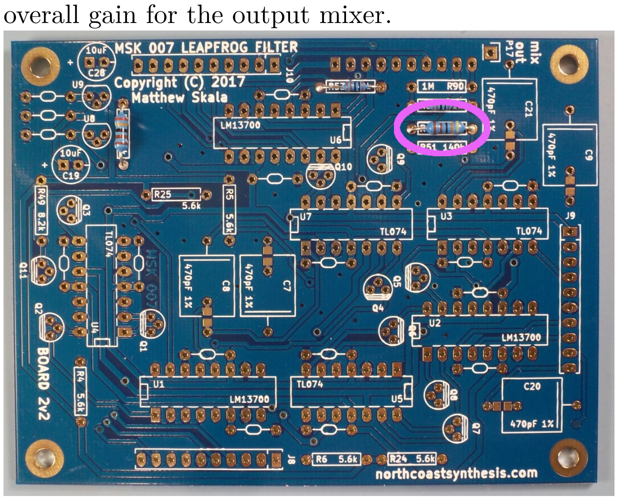
Qty	Ref	Value/Part No.	
17	C1, C3–C6, C10, C12–C15, C17, C18, C22–C24, C26, C27	$0.1\mu F$	axial ceramic
2	C19, C28	$10\mu F$	radial aluminum electrolytic, 0.1″ lead spacing
5	C7–C9, C20, C21	470pF 1%	precision integrator capacitor; see notes
4	H13–H16		nut for M3 machine screw
8	H21–H28	M3x11	M3 male-female standoff, 11mm body length
3	J8–J10		female single-row socket, 10 pins at 0.1″
3	P40, P42, P44		male single-row header, 10 pins at 0.1″
11	Q1–Q11	SS8550D	or PN200A; PNP high gain, TO-92 EBC
2	R52, R53	1kΩ	
1	R54	2.4kΩ	
1	R40	4.3kΩ	
5	R4–R6, R24, R25	5.6kΩ	
1	R49	8.2kΩ	
1	R51	140kΩ	E48 value; use 130kΩ (second choice) or 150kΩ (third) if a more common value is desired
1	R90	1MΩ	
1	U8	78L09	+9V regulator in TO-92 package
1	U9	TL431	2.495V reference in TO-92 package
4	U3–U5, U7		14-pin DIP socket
3	U1, U2, U6		16-pin DIP socket

Table 3: Bill of Materials for Board 2.

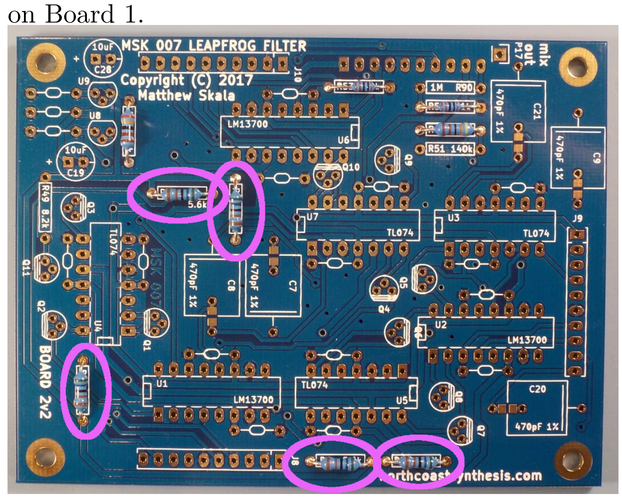
Install the 2.4kΩ (red-yellow-black-brown) resistor R54. This resistor provides a minimum load for the TL431 voltage regulator.



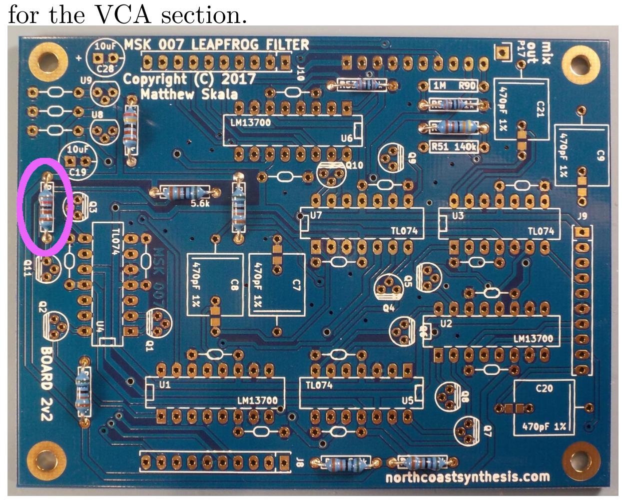
Install the 4.3kΩ (yellow-orange-black-brown) resistor R40. This is the feedback resistor that sets overall gain for the output mixer.



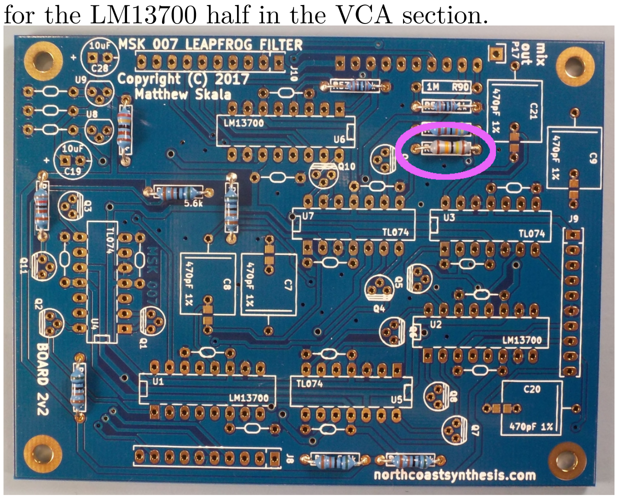
Install the five 5.6kΩ (green-blue-black-brown) resistors R4 to R6, R24, and R25. These are references for the control current generators, one per integrator. One more 5.6kΩ resistor should remain for use on Board 1.



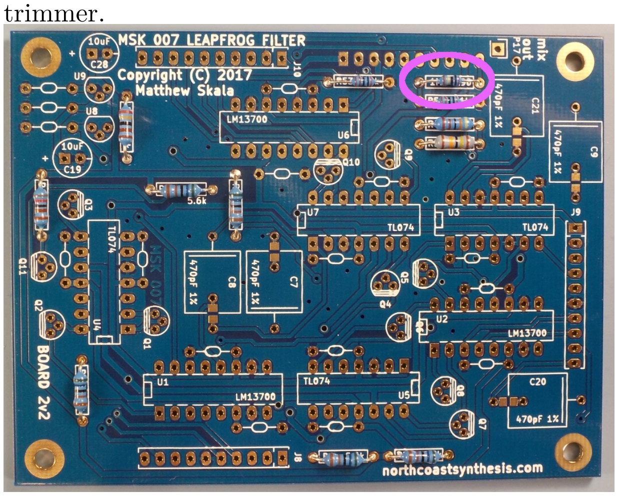
Install the 8.2kΩ (grey-red-black-brown) resistor R49. This resistor sets the linearizing diode current for the VCA section.



Install the 140kΩ (brown-yellow-black-orange) resistor R51. This is part of the input voltage divider for the LM13700 half in the VCA section.



Install the 1MΩ (brown-black-black-yellow) resistor R90. This controls the range for the VCA offset trimmer.



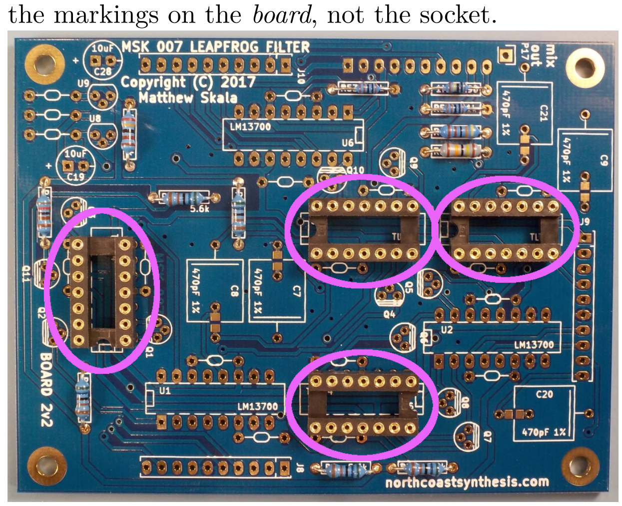
DIP sockets

Install the four 14-pin DIP sockets for the TL074 quad op amp chips U3 to U5 and U7. These amplifiers are used for multiple purposes throughout the filter core. One more 14-pin DIP socket should remain for use on Board 1.

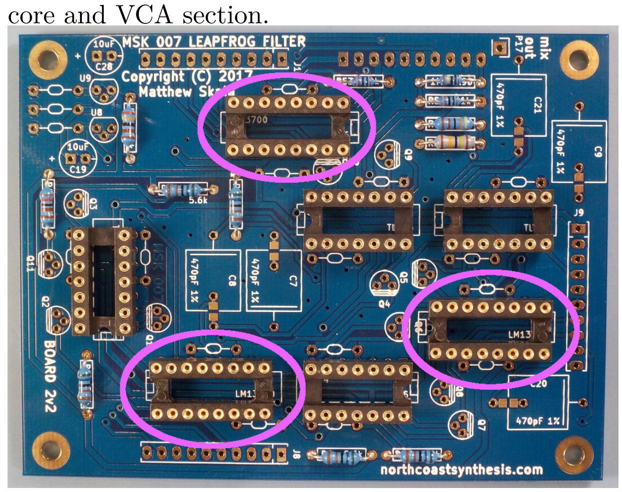
The sockets themselves do not care which direction you install them, but it is critically important that the chips installed in the sockets should be installed in the right direction. To help with that, the sockets will probably be marked with notches at one end (indicating the end where Pin 1 and Pin 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, 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 when you insert the chip to insert it so the chip matches the markings on the *board*, not the socket.

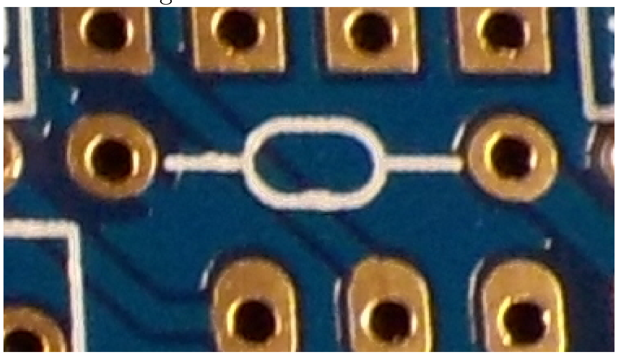


Install the three 16-pin DIP sockets for the LM13700 dual operational transconductance amplifier chips U1, U2, and U6. These current-controlled amplifiers provide variable amplification for the filter core and VCA section.

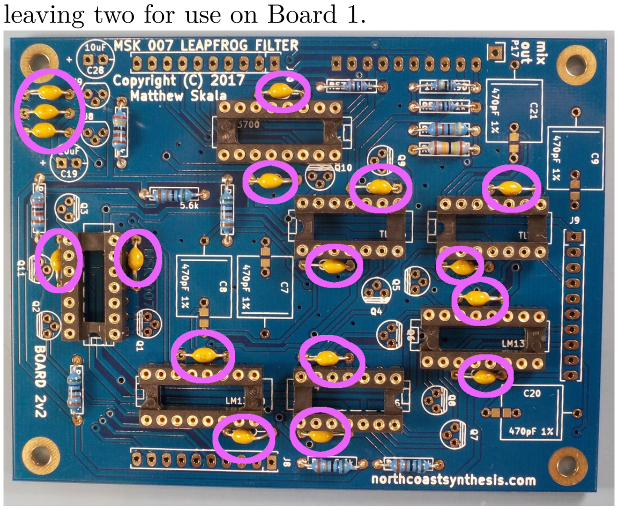


Decoupling capacitors

The 17 axial ceramic 0.1μF decoupling capacitors are shown on the board by a special symbol without their reference designators.



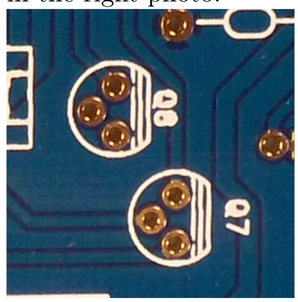
Install these capacitors where the symbol appears. They are not polarized and may be installed in either orientation. Most of these capacitors act as filters for the power supplies to the amplifier chips, reducing any coupling of high-frequency noise between them and the rest of the synthesizer. Three perform a similar function for the voltage regulators. A full MSK 007 kit should contain 19 of these capacitors, leaving two for use on Board 1.

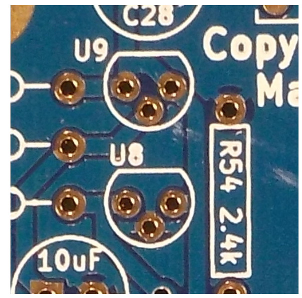


TO-92 semiconductors

The MSK 007 contains four different types of components packaged in TO-92 packages, of which three types are used on Board 2. Each such component looks like a little black pill of epoxy plastic with one flat side and three metal legs; they can be distinguished by etched or printed numbers on the flat side, and it is important to sort them carefully and install only the proper component type in each footprint.

There is not enough space on the boards to print a part number for every TO-92 component, but there are two different silkscreen symbols used to help with recognition. The PNP transistors, which are the most numerous type in this project, are shown on the board with extra silkscreen lines along the flat edge, as in the left photo. All other TO-92 components (78L09, TL431, and 2N5088 which is not used on Board 2) are shown by a plain outline without extra lines, as in the right photo.

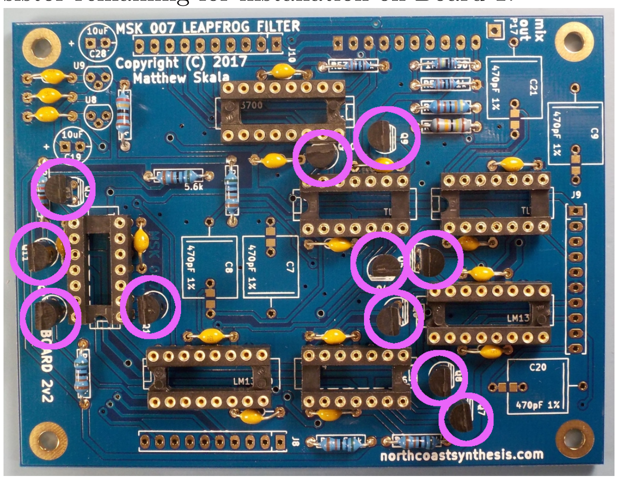




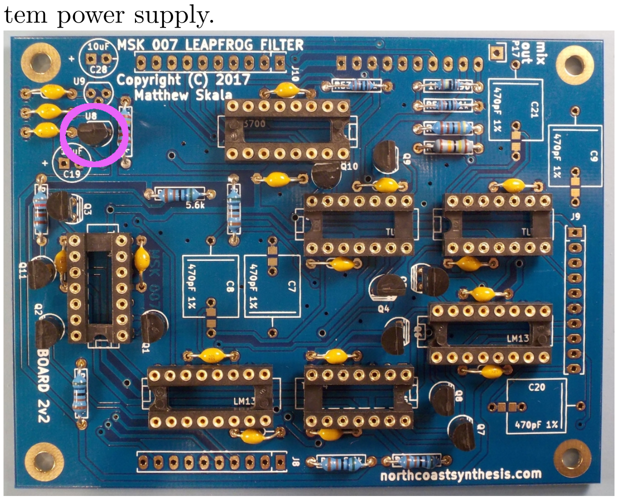
All TO-92 components in this project are polarized and must be installed in the correct orientation to work; that orientation is shown by the silkscreen symbols. Install each component so that its fully flat side points in the same direction as the flat side shown on the silkscreen. The three legs of 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.

The solder pads for TO-92 components are smaller and closer together than for any other through-hole components in the project, and the components themselves tend to be relatively heat-sensitive. Solder them carefully, avoiding creating any solder bridges between adjacent pads. Do not use excessive time and heat trying to get the solder to flow through the board and fillet on both sides, especially not on pads connected to the ground plane; two-sided fillets may happen naturally, but it is enough for solder to completely cover the pad on one side.

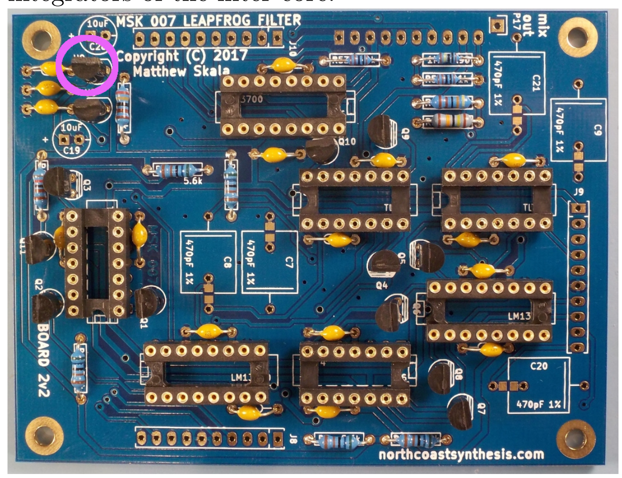
Install the eleven PNP transistors, type SS8550D or PN200A with references Q1 through Q11. These are all used as current sources for biasing the LM13700 chips. There should be one more PNP transistor remaining for installation on Board 1.



Install the 78L09 voltage regulator IC, U8. Be sure not to confuse it with the nearby symbol for the other voltage IC. This regulator controls an internal voltage bus from which all the control currents are drawn, helping to isolate the filter core from the system power supply.

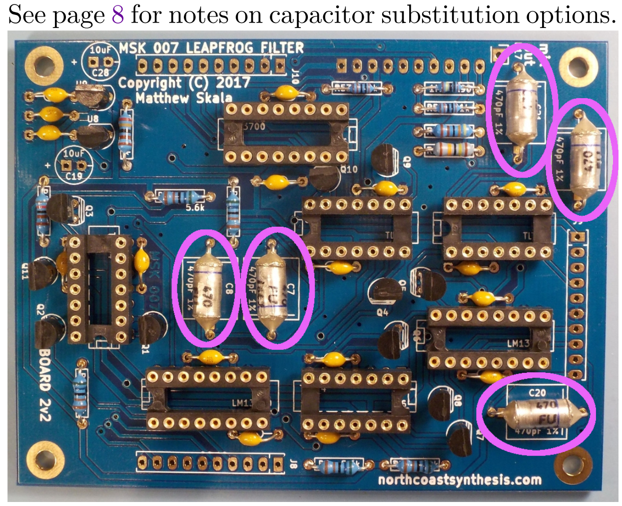


Install the TL431 voltage reference IC, U9. This IC controls another internal voltage bus, nominally +6.5V but really defined by its difference from the +9V bus. The difference between the two busses is used as a reference for the voltage-to-current converters that mirror the module tuning to control the five integrators of the filter core.



Integrator capacitors

Install the five integrator capacitors C7, C8, C9, C20, and C21. These store voltages that directly represent the "state variables" by which the filter calculates its response. Each footprint has extra holes and pads to allow options for mounting a through-hole capacitor with 0.2″ or 0.6″ lead spacing, or a surface-mount chip of reasonable size. The polystyrene capacitors recommended as defaults and included in North Coast kits should be mounted in the 0.6″ holes. See page 8 for notes on capacitor substitution options.

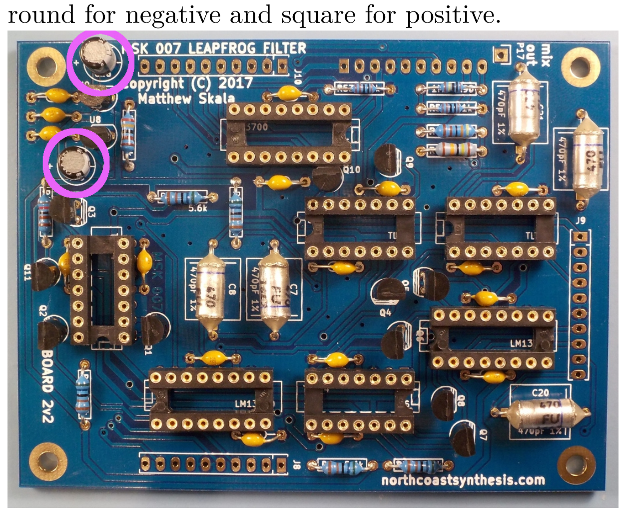


The polystyrene capacitors are expensive and delicate. Do not overheat them while soldering; do not use extra time and heat trying to get the solder to go through the board and fillet on both sides. You may wish to use a clip-on heat sink on the component side of the board while soldering, to reduce the exposure of the capacitor body to the soldering heat. Devices made specifically for this purpose are available from the same suppliers as other soldering accessories, but it also works to simply clip on the kind of alligator clip used for electronic testing.

Although these capacitors are not polarized as such, and polarized capacitors should not be substituted here, axial film capacitors do usually have a marking at one end (often a dark stripe) which indicates the end connected to the outermost foil wrap. It's better for that end to be connected to ground potential. If your capacitors have such a marking, install them so that the marking matches the similar marking on the PCB footprint, to reduce the voltage between the outside of the capacitor and the nearby ground plane. In this particular circuit, this measure is unlikely to make any real difference, but given that you have a choice about which way to install the components, it makes sense to do it right.

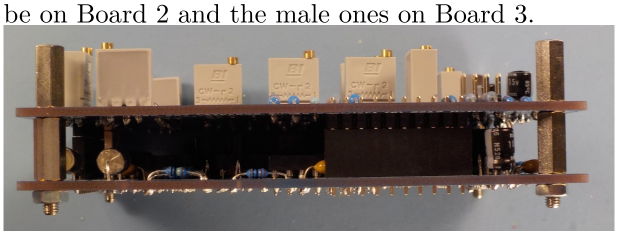
Electrolytic capacitors

Install the two 10μF electrolytic capacitors C19 and C28. These filter the 9V and 6.5V reference voltages and ensure stability of the regulators that control those busses. They are polarized components, and may explode if connected backwards. As such, there are multiple clues to help you install them in the right direction. The negative leg of each capacitor will be marked in some way, usually with a printed stripe and minus signs on the plastic wrapping of the capacitor body. The negative leg of the capacitor will usually also be shorter, though that is less reliable than the body markings. On the PCB, the positive and negative pads are marked with positive and negative signs in the silkscreen, and the solder pads themselves are round for negative and square for positive.

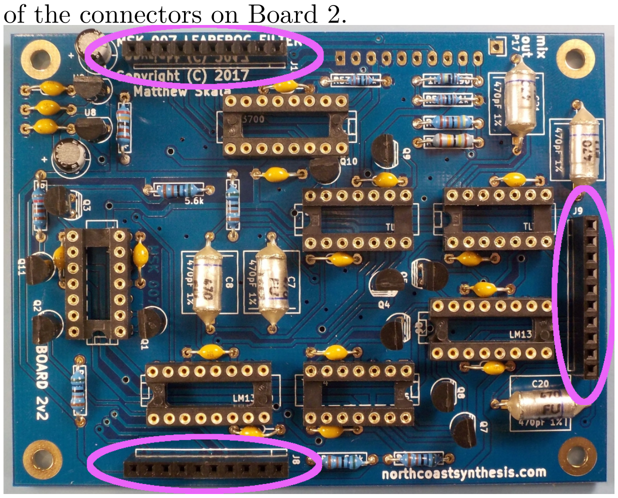


Connection to Board 3

Mate the 10×1 header connectors J8, J9, J10, P40, P42, and P44 into pairs and assemble Boards 2 and 3 with the three pairs of connectors sandwiched between them as shown. The female connectors should be on Board 2 and the male ones on Board 3.



Use four 11mm standoffs to separate the boards. The hex nuts and additional 11mm standoffs are listed on the BOM for temporary use in making this assembly; I suggest using standoffs for this because they are easier to assemble by hand for a temporary assembly than machine screws, and 11mm in particular to reduce the possibility for confusing the different sizes in the kit. For reference, here are the positions of the connectors on Board 2.



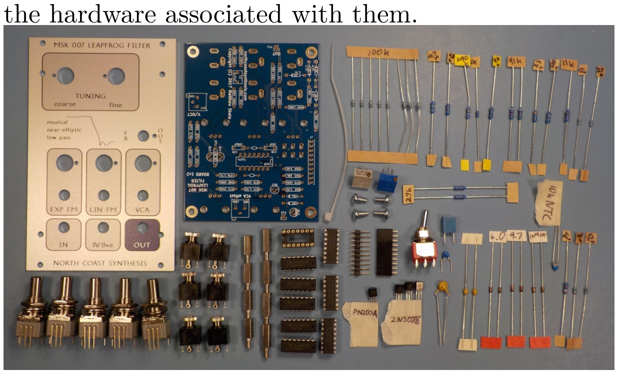
Solder the connectors and then unscrew the temporary assembly and carefully separate the boards. You have finished Board 2, except for the connection to Board 1 which will be made later. In between completed boards is a good time to take a break.

Building Board 1

Board 1 has components on both sides, which makes the order of assembly important; installing the wrong components first may make it difficult to safely maneuver the soldering iron to install later components without damaging the already-installed components. This chapter also includes instructions on installing the connector on Board 2 that links it to Board 1.

Preliminaries

Count out the right number of everything according to the bill of materials. There is an abbreviated BOM for Board 1, and the final assembly steps, in Table 4. In addition to these things you will need your assembled Boards 2 and 3 from the previous chapters, and the hardware associated with them.



There are two multiturn trimmers to be installed on this board. Before installing them, use an ohmmeter to adjust each one to 50% of its range. Measure the resistance along the track, then measure the resistance from the wiper to one end and adjust to make the wiper half the total track resistance. This need not be exact, but it will help with adjustment later, by reducing issues with interaction among the different settings. With all trimmers pre-set to 50%, the module should basically work even if it is not at its best, whereas if many are installed at extreme values instead, then you may have trouble getting it up and running enough to adjust it more accurately.

Some notes on knobs

The first batch of knobs I ordered for North Coast products turned out to have serious quality problems, specifically with the setscrews that hold the knobs onto the potentiometer shafts. Some of the screws had marginal threads that would strip when the screw was tightened, and I ended up having to do a bunch of extra testing and ship extra knobs to some customers to replace any that might fail. Later batches have also had issues, although they're under better control now because the bad first batch served as a warning to step up the testing procedures. Starting with kits prepared in August 2019, I switched to blue knobs with 100% testing; in September 2020, I switched to a new manufacturer, and knobs that are a slightly darker shade of blue. Although all the knobs I ship in kits now have been tested and passed at least twice, and should be fine to use, I am also shipping spare setscrews in any kits with knobs from batches where a signficant number of knobs failed testing.

Here are some things to be aware of as a kit builder.

- Some photos in these instructions were taken with the older grey knobs, and some dealers may still have kits containing grey knobs in their stock, but newer kits will have blue knobs.
- Do not overtighten the setscrews when attaching the knobs! The screw should be tight enough to hold the knob onto the shaft, but there's no advantage to making it tighter than that, and overtightening may risk destroying the screw thread or damaging the drive slot.
- If, despite my efforts to make sure no bad screws get sent to customers, you still get a bad screw that cannot be tightened and no spare for it, then please contact me.
- If you want to source an exact replacement for the setscrew, it should be an M3×3mm flat-tip slotted setscrew, which is also sometimes called a "grub screw," made of RoHS-compliant brass (possibly by exemption). Stainless steel is fine too, and I may sometimes ship stainless steel screws instead of brass if I can find a reliable source for them; plain steel should not be used here for galvanic corrosion reasons. Hex-socket screws are fine if you have the driver for them,

This table is not a substitute for the text instructions.

Qty	Ref	Value/Part No.	
1	C29	22pF	radial ceramic, 0.2″ lead spacing
1	C25	100pF	radial ceramic, 0.2″ lead spacing
2	C30, C31	0.1μF	axial ceramic
1	C2	0.47μF	film, 0.2″ lead spacing
2	D1, D3	1N4148	or 1N914; switching diode
2	D7, D9	1N5230B	4.7V Zener
2	D6, D8	1N5233B	6.0V Zener
4	H17–H20	M3x13	M3 male-female standoff, 13mm body length
4	H29–H32	M3x6	M3 machine screw, 6mm body length
6	J1–J6	1502 03	switched mono 3.5mm panel jack, Lumberg
1	J7		female single-row socket, 10 pins at 0.1″
1	P26		male single-row header, 10 pins at 0.1″
3	Q12, Q14, Q15	2N5088	NPN general purpose amplifier, TO-92 EBC
1	Q13	SS8550D	or PN200A; PNP high gain, TO-92 EBC
1	R77	500Ω	horizontal multiturn, Bourns 3296P/Vishay T93Z
1	R80	1kΩ	
2	R72, R76	2.7kΩ	
1	R58	3.3kΩ	
1	R60	5.6kΩ	
1	R82	10kΩ	
1	R67	11kΩ	
1	R75	22kΩ	
1	R68	27kΩ	
1	R84	39kΩ	
1	R63	68kΩ	
2	R59, R61	91kΩ	
1	R89	100kΩ	horizontal multiturn, Bourns 3296P/Vishay T93Z
5	R56, R62, R69, R78, R81	100kΩ	vertical conductive plastic panel pot, BI Technologies P260T series, linear taper
8	R57, R64–R66, R70, R79, R83, R85	100kΩ	
1	R55	150kΩ	
1	R73	240kΩ	
1	R88	680kΩ	
1	R74	4.7MΩ	
1	R71	10kΩ NTC	thermistor, Vishay NTCLE203E3103FB0
1	SW3	100DP1T1B1M2	E-Switch 100-series DPDT on-on toggle
3	U1, U2, U6	LM13700	dual operational transconductance amp
5	U3–U5, U7, U10	TL074	quad JFET-input op amp
1	U10		14-pin DIP socket

Table 4: Bill of Materials for Board 1. Also needed: knobs, a cable tie, and module-to-rack mounting hardware.

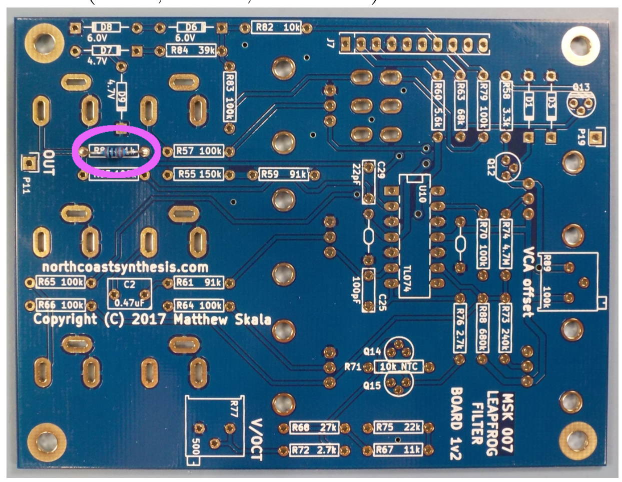
but I don't ship those because I'm not sure all DIY builders do have the right driver.

- Because it's a standard M3 thread, in a pinch it's possible to substitute a plain M3 machine screw such as are commonly used with Eurorack cases, although one of those would obviously look less nice.

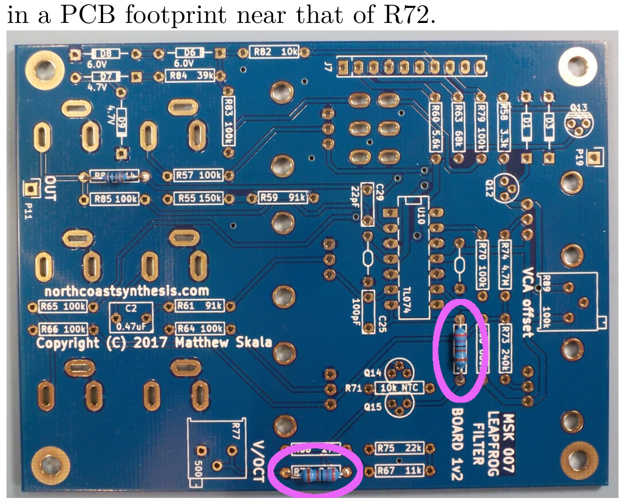
Fixed resistors

Resistors are never polarized. I like to install mine in a consistent direction for cosmetic reasons, but this is electrically unnecessary. In this module, metal film 1% resistors are recommended for all fixed-value resistors. These will usually have blue bodies and four colour bands designating the value, plus a fifth band for the tolerance, brown in the case of 1%. These are the resistors normally shipped in the North Coast kits, but we may occasionally ship better-tolerance resistors (such as 0.5%) 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.

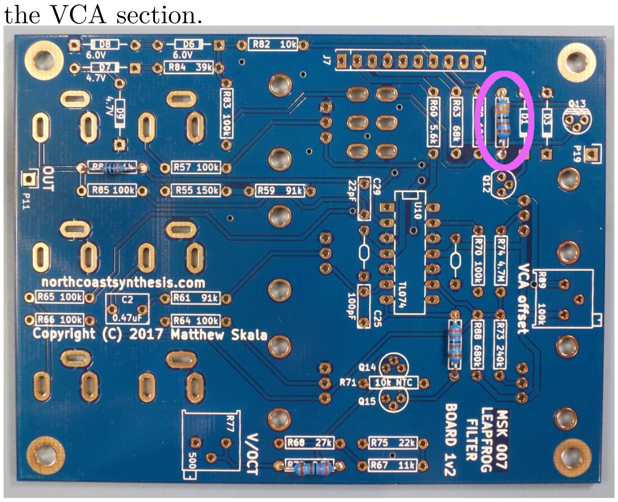
Install the 1kΩ (brown-black-black-brown) resistor R80. This resistor limits the current that can flow on the module output, as well as separating the output driver op amp and its stability capacitor from any destabilizing capacitance that may be attached to the output (for instance, from a long patch cable). Do not confuse it with the other power-of-ten resistor values (10kΩ, 100kΩ, and 1MΩ).



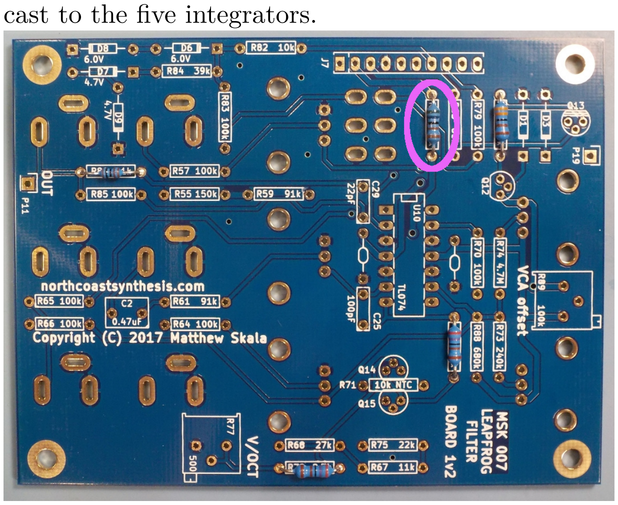
Install the two 2.7kΩ (red-violet-black-brown) resistors R72 and R76. These resistors are used in the exponential converter, R72 as part of the network that scales the control voltage and R76 to control voltage and current at the output of the servo op amp. Do not confuse them with the 27kΩ resistor, which has a similar colour code and is to be mounted in a PCB footprint near that of R72.



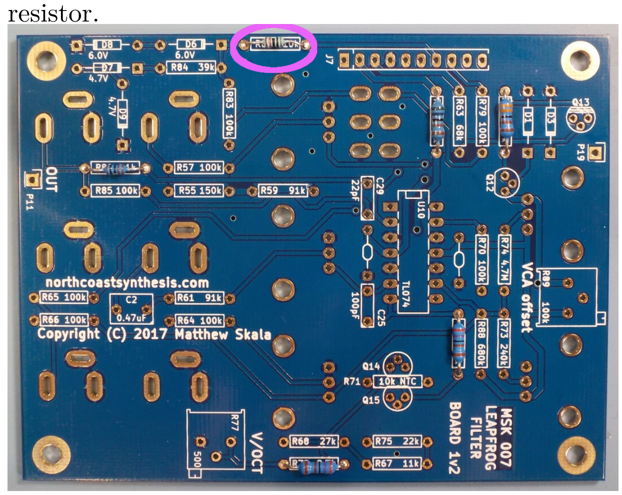
Install the 3.3kΩ (orange-orange-black-brown) resistor R58. This resistor is used in the linear voltage-to-current converter that provides control current to the VCA section.



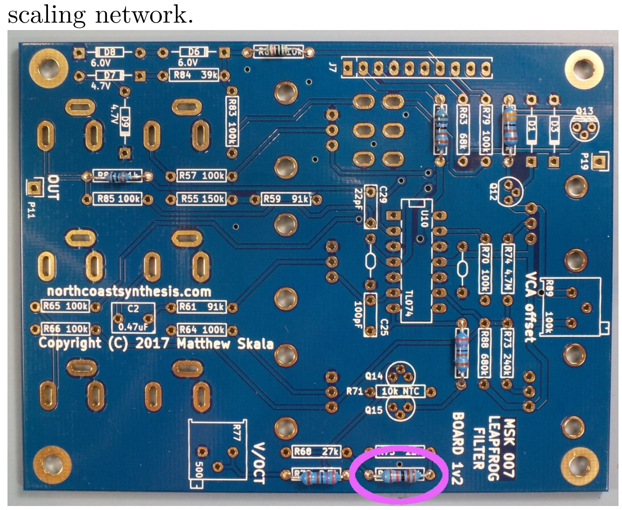
Install the 5.6kΩ (green-blue-black-brown) resistor R60. This resistor converts the exponential converter's output current back to a voltage for broadcast to the five integrators.



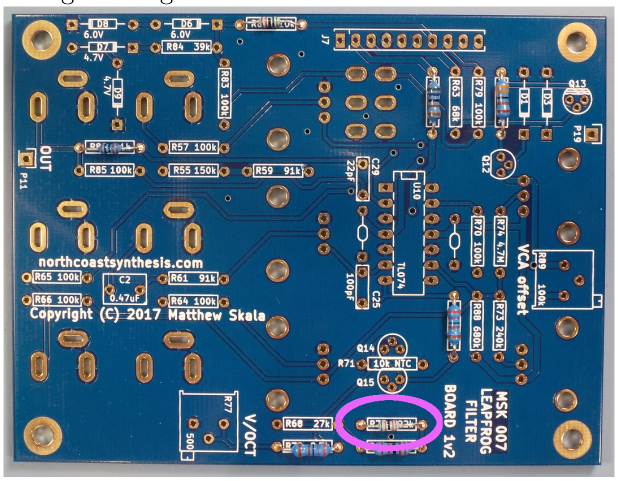
Install the 10kΩ (brown-black-black-red) resistor R82. This resistor sets the maximum attenuation of the VCA soft-clipping section. Do not confuse it with the other power-of-ten resistor values, nor the 11kΩ resistor.



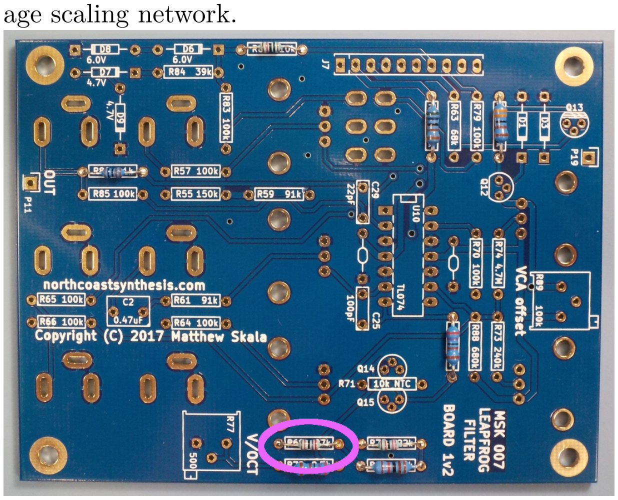
Install the 11kΩ (brown-brown-black-red) resistor R67. This resistor is part of the pitch control voltage scaling network.



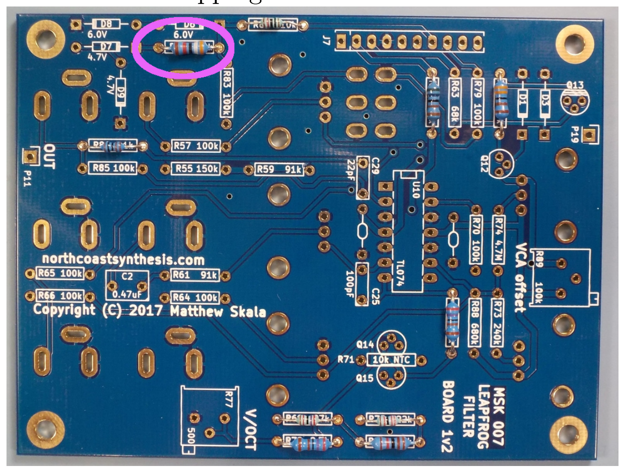
Install the 22kΩ (red-red-black-red) resistor R75. This resistor sets the gain of the op amp in the control voltage scaling network.



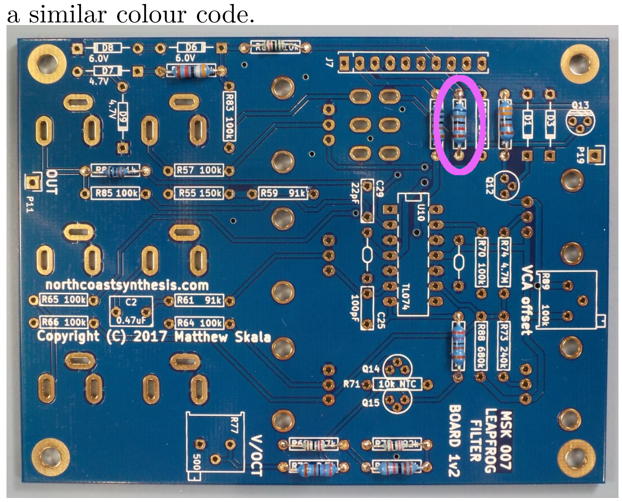
Install the 27kΩ (red-violet-black-red) resistor R68. This resistor is another part of the control voltage scaling network.



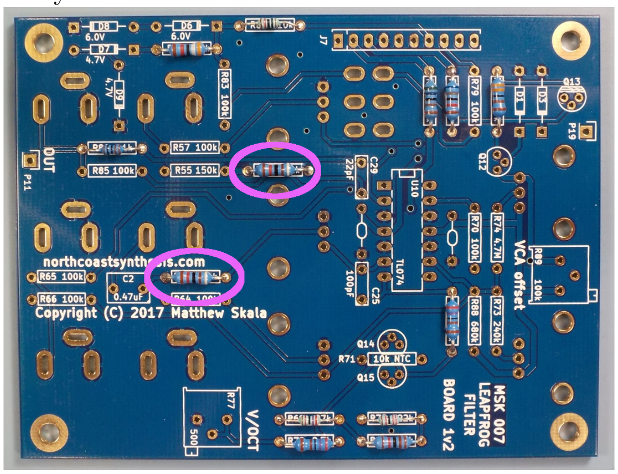
Install the 39kΩ (orange-white-black-red) resistor R84. This resistor sets the mid-level attenuation of the VCA soft-clipping circuit.



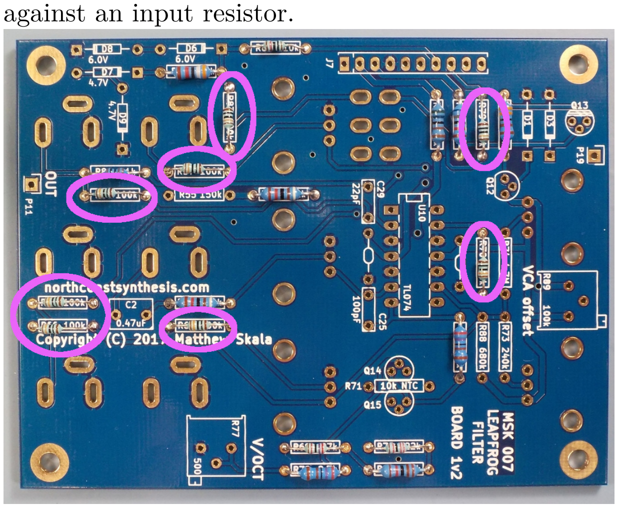
Install the 68kΩ (blue-grey-black-red) resistor R63. This resistor pulls down the base of the transistor Q13 to bring the VCA's zero-gain point near 0V. Do not confuse it with the 680kΩ resistor, which has a similar colour code.



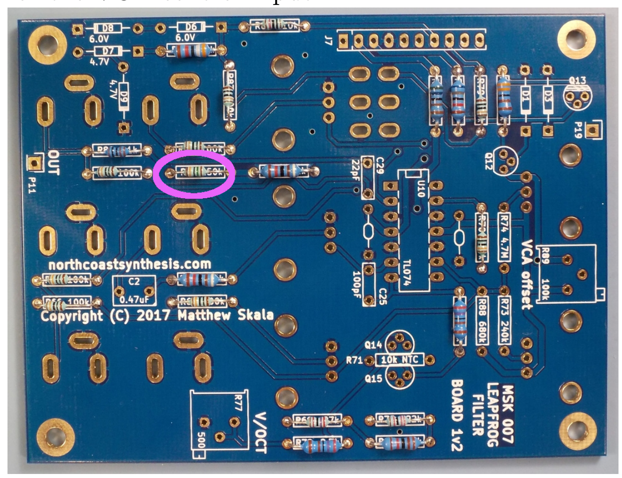
Install the two 91kΩ (white-brown-black-red) resistors R59 and R61. These two resistors set the reference current for the exponential converter, and the maximum sensitivity of the linear FM input, respectively.



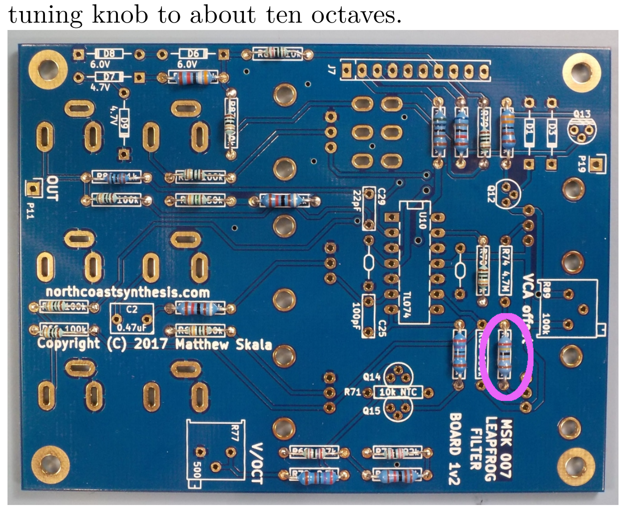
Install the eight 100kΩ (brown-black-black-orange) resistors R57, R64 through R66, R70, R79, R83, and R85. These resistors are used in multiple places throughout the input and output circuits to either set input impedances to Eurorack standard, or set op amp gain to negative unity by balancing against an input resistor.



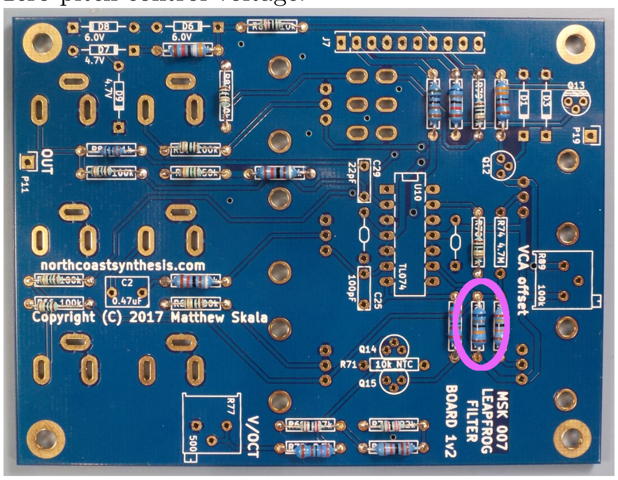
Install the 150kΩ (brown-green-black-orange) resistor R55. This resistor sets the DC normalization for the VCA control input.



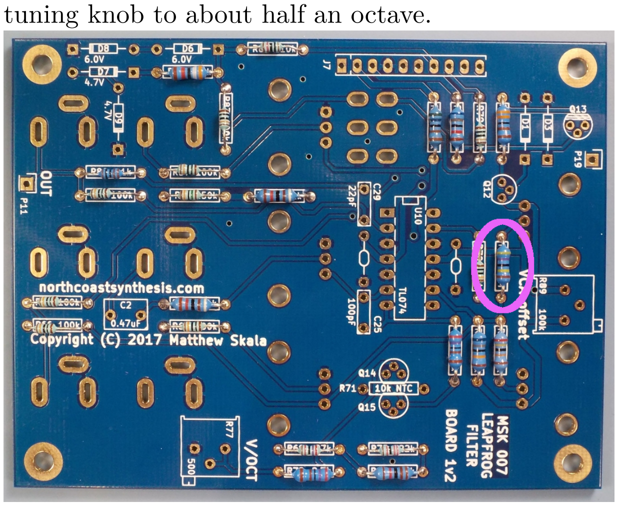
Install the 240kΩ (red-yellow-black-orange) resistor R73. This resistor sets the range of the coarse tuning knob to about ten octaves.



Install the 680kΩ (blue-grey-black-orange) resistor R88. This resistor sets the overall offset of the tuning knobs, for a non-guaranteed design target of approximately 10Hz to 10kHz cutoff frequency with zero pitch control voltage.



Install the 4.7MΩ (yellow-violet-black-yellow) resistor R74. This resistor sets the range of the fine tuning knob to about half an octave.



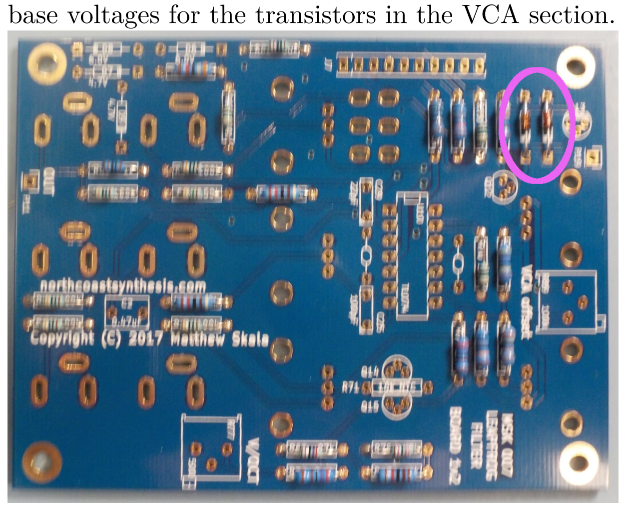
Diodes

There are six diodes to be mounted on Board 1: two each of 1N4148 or 1N914 switching diodes; 1N5230B 4.7V Zener diodes; and 1N5223B 6.0V Zener diodes. They all look like pretty much identical orange-pink glass beads, and it is important not to confuse them. Their bodies will be marked with type numbers in very small print, and they should be labelled in a kit, but if you are in any doubt, test them for breakdown voltage.

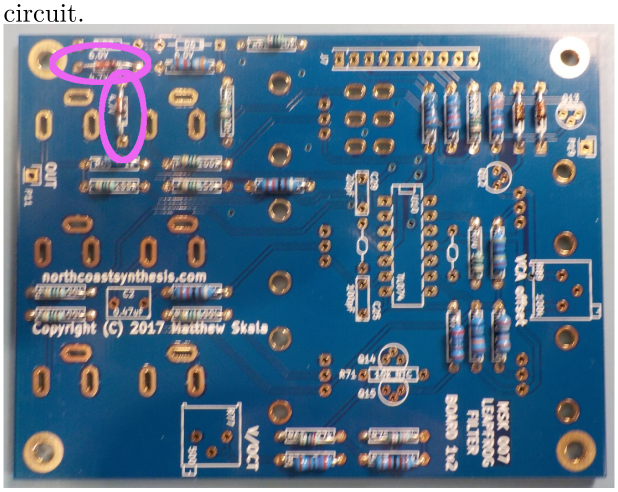
To do a breakdown voltage test: use clip leads or a breadboard to connect the diode under test in series with a small resistor (anything from 1kΩ to 10kΩ) reverse biased across a 12V power supply. That is, the power supply positive connects to one end of the resistor, the other end of the resistor connects to the cathode (striped end) of the diode, and the anode (other end) of the diode connects to the power supply negative. Then measure the voltage across the diode. It should be close to the specified Zener voltage of 4.7V or 6.0V if you are testing a Zener diode, and equal to the power supply voltage if you are testing one of the switching diodes. From that it should be possible to determine which diodes are which. If the measured value is less than 1V, then you most likely have the diode backwards and are measuring its *forward* voltage, which will be about the same for all three of these diode types and is not a useful way to distinguish them.

All these diodes are polarized components and it is important to install them right way round. Each diode has a black 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.

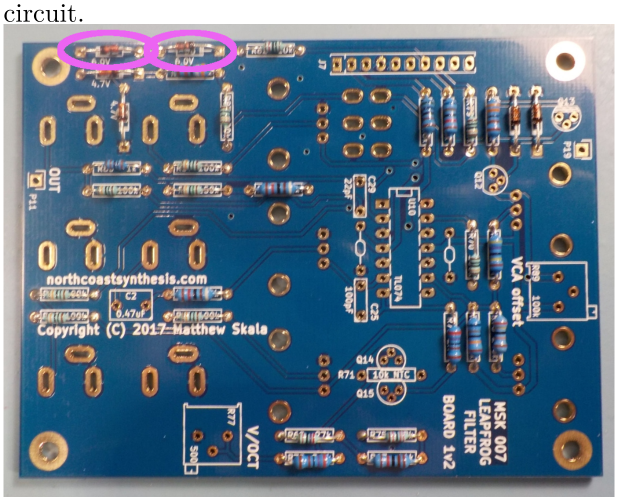
Install the two 1N4148 or 1N914 switching diodes D1 and D3. These are used to control the minimum base voltages for the transistors in the VCA section.



Install the two 1N5230B Zener diodes D7 and D9. Their breakdown voltage of 4.7V is marked on the silkscreen as an additional guide to where they go. These set the lower voltage level for the soft-clipping circuit.

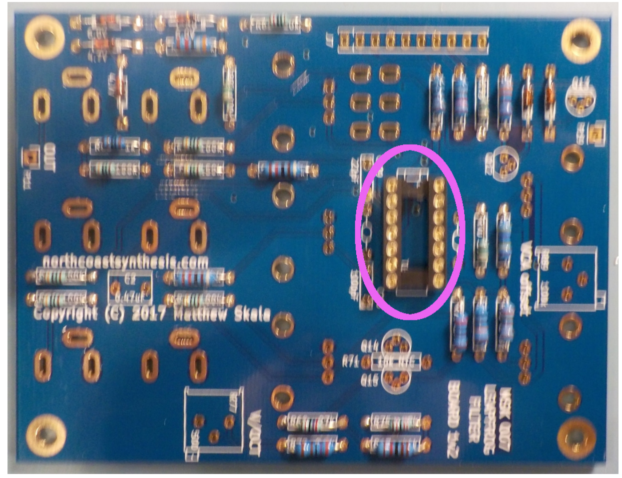


Install the two 1N5233B Zener diodes D6 and D8. Their breakdown voltage of 6.0V is marked on the silkscreen as an additional guide to where they go. These set the higher voltage level for the soft-clipping circuit.



DIP sockets

Install the 14-pin DIP socket for the TL074 quad op amp chip U10. The amplifiers in this chip are used in the exponential converter and as buffers between the filter core and the outside world. See page 24 for notes regarding orientation of the socket, procedure for soldering it flat to the board, and so on.

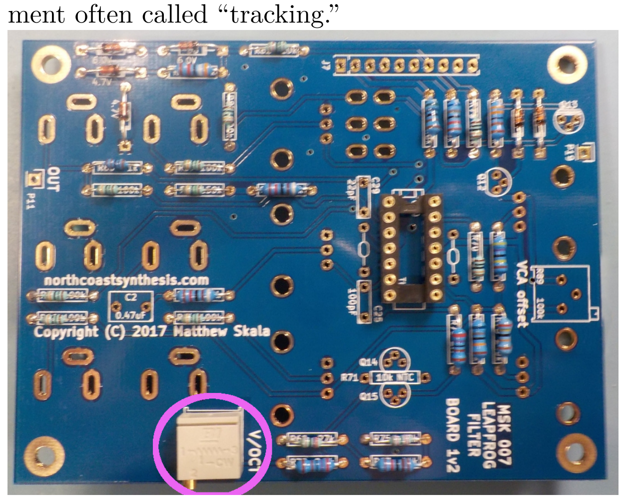


Trimmer potentiometers

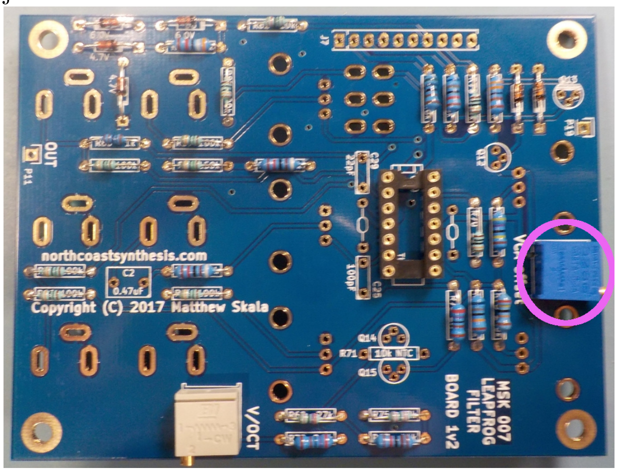
If you have not already set the trimmers to 50% of their full scale value as described under "Preliminaries" above, then do it now.

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.

Install the 500Ω trimmer R77. This trimmer sets the scale factor for the V/octave pitch CV, an adjustment often called "tracking."



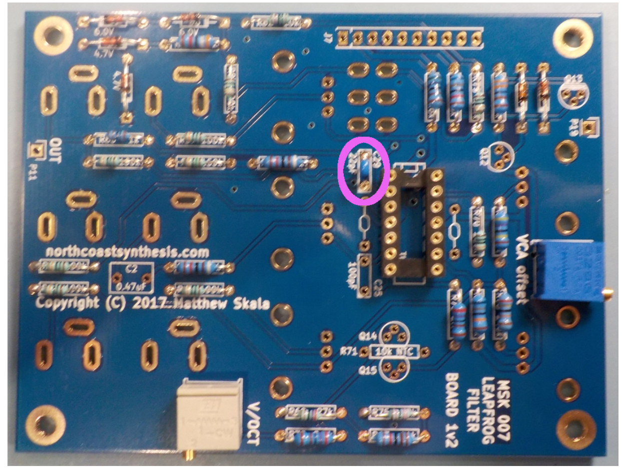
Install the 100kΩ trimmer R89. This trimmer adjusts the DC offset in the VCA section.



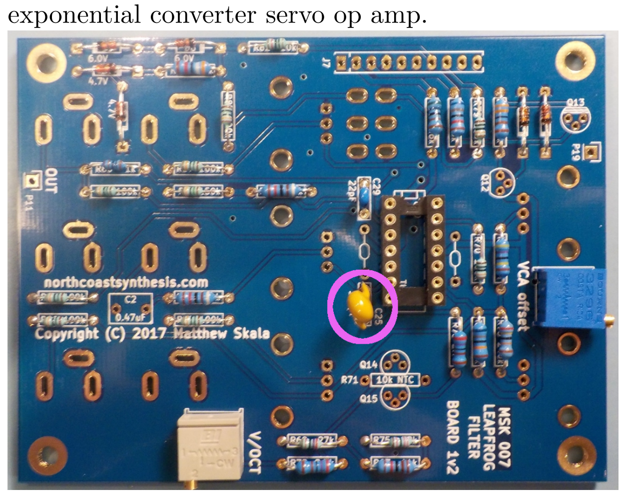
Capacitors

Small-valued ceramic capacitors are usually labelled with numbers in a pattern similar to the resistor colour code: two digits for the main value, followed by a third digit that says how many zeroes to append to get the value in picofarads. Thus the 22pF capacitor may be labelled "220" and the 100pF capacitor "101." Other markings on the capacitor body may indicate tolerance, voltage rating, dielectric type, and so on. The 0.1μF decoupling capacitors will probably have very abbreviated markings, but if they are labelled on the three-digit system the code would be "104" for 0.1μF = 100000pF (10 followed by 4 additional zeroes); and the box-type 0.47μF film capacitor will likely be marked with its value in microfarads using μ instead of the decimal point, thus "μ47." None of the capacitors to be installed on this board are polarized.

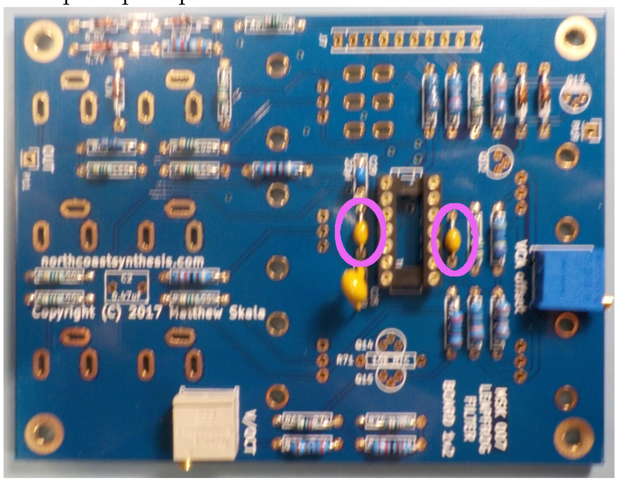
Install the 22pF ceramic capacitor C29. This capacitor prevents high-frequency oscillation of the output driver op amp.



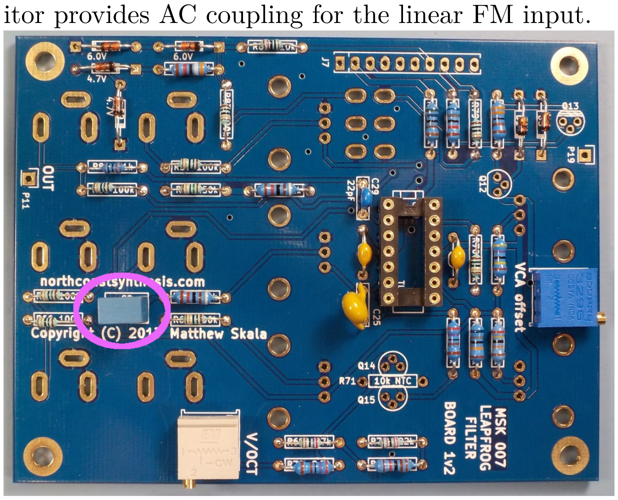
Install the 100pF ceramic capacitor C25. This capacitor prevents high-frequency oscillation of the exponential converter servo op amp.



Install the two 0.1μF decoupling capacitors. As described on page 25, they are shown on the board silkscreen by a special symbol without values or reference designators. They filter the power supplies for the op amp chip.



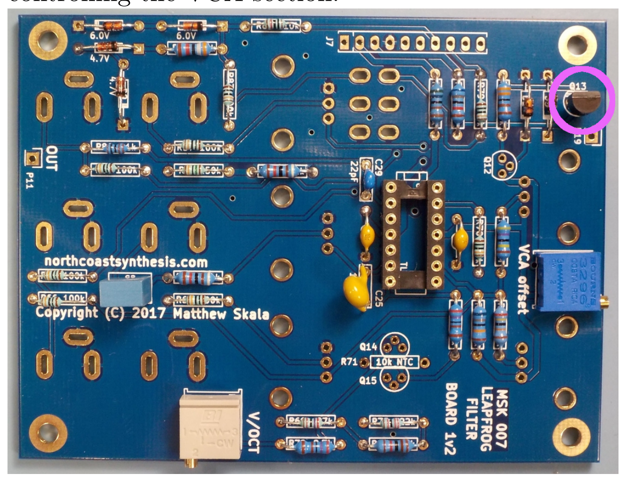
Install the 0.47μF film capacitor C2. This capacitor provides AC coupling for the linear FM input.



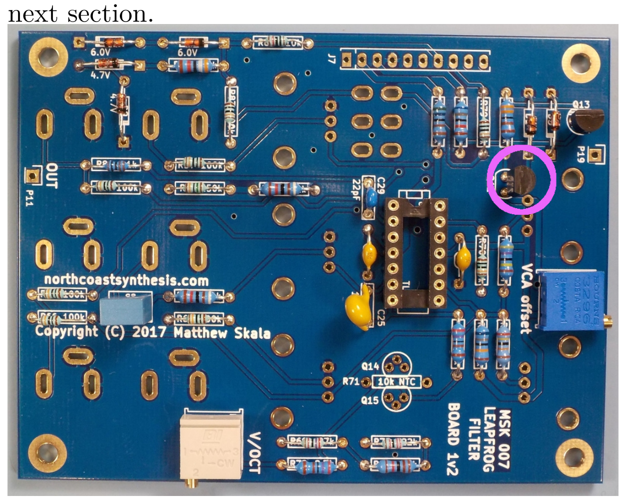
TO-92 semiconductors

See page 25 for general instructions regarding TO-92 semiconductors and the board symbols used for them.

Install the PNP transistor Q13, type SS8550D or PN200A. This transistor acts as a current source for controlling the VCA section.



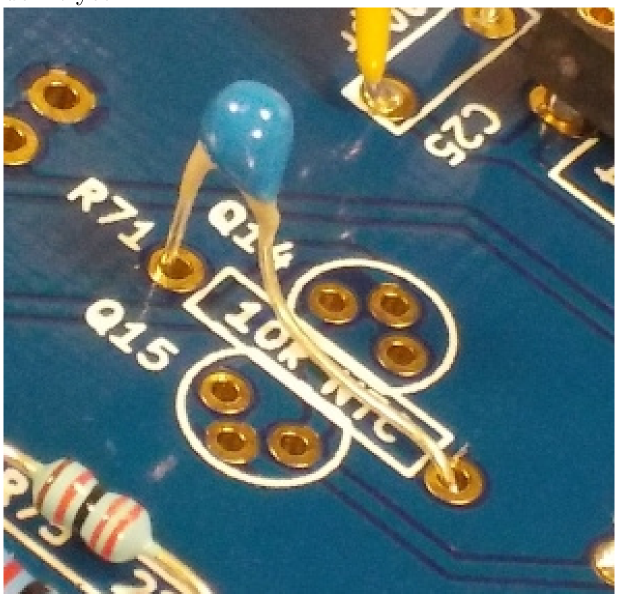
Install the 2N5088 NPN amplifier transistor Q12. This transistor acts as an emitter follower to translate the input control voltage to a current for Q13. There are two more 2N5088 transistors to be installed in the next section.



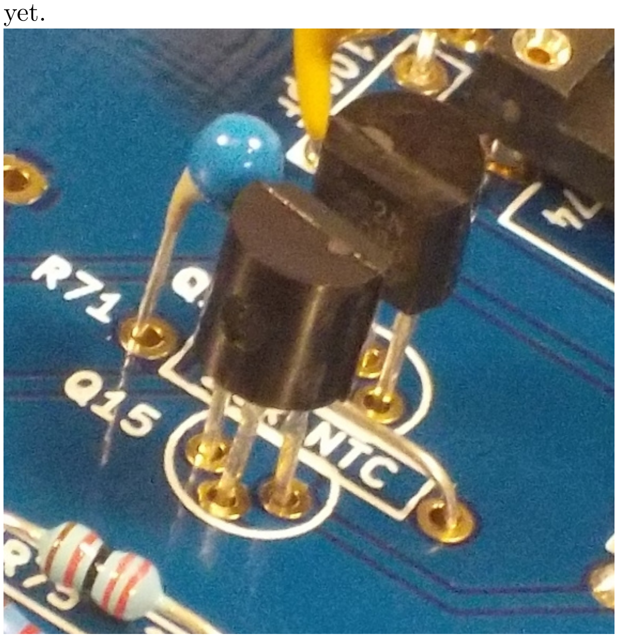
Exponential converter cluster

In order to reduce the temperature dependence of the exponential converter as far as possible, is is important that the two transistors Q14 and Q15, and the thermistor (temperature-sensitive resistor) R71, should all be kept at the same temperature. This is accomplished by mounting them all in contact with each other and tightening a nylon cable tie around them to keep them pressed together. Constructing this cluster of components is a little tricky and annoying; follow the directions carefully.

Bend the thermistor legs as shown: one leg straight down, the other down about 3mm, then to the side, then down again, to fit the R71 footprint. Place the thermistor in its footprint, but do not solder it yet.

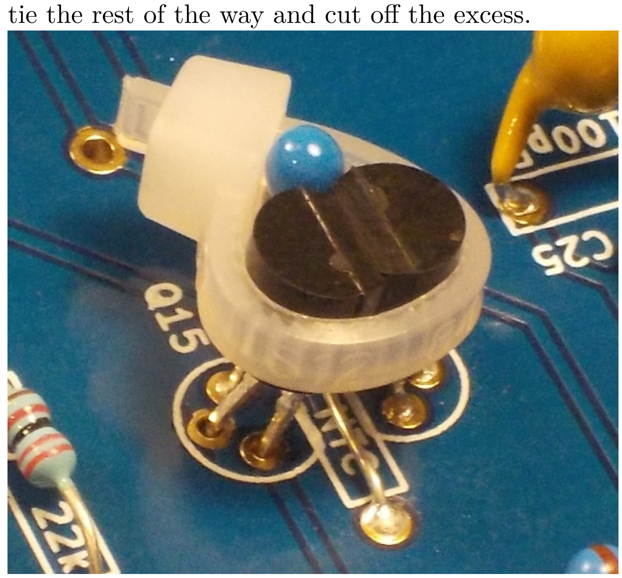


Insert the two 2N5088 transistors Q14 and Q15 in the board, face to face as shown. Do not solder them yet.



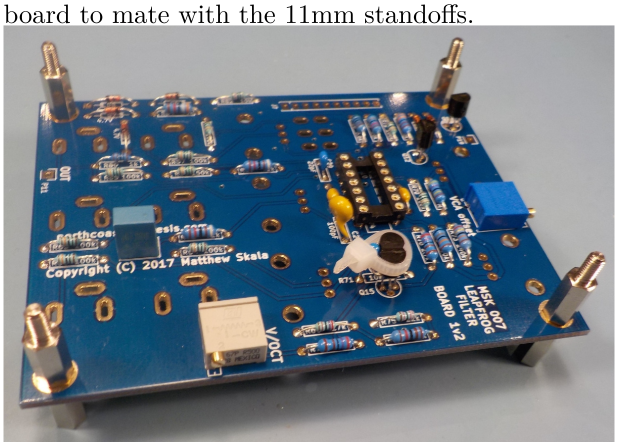
Put a nylon cable tie around the three components and tighten it far enough to hold them loosely together. Concentrate in particular on having the two transistors meet as cleanly face to face as possible. Do not overtighten the cable tie or cut it off yet. This is probably the hardest step, and North Coast kits include a spare cable tie for use in case you ruin one. Be aware that the components should not stick out any further above the board than is normal for other TO-92 components; if you seat the transistors too high up, at the full length of their legs, you may exceed the 11mm of clearance between this board and Board 2 above it.

Solder the components. Then tighten the cable tie the rest of the way and cut off the excess.

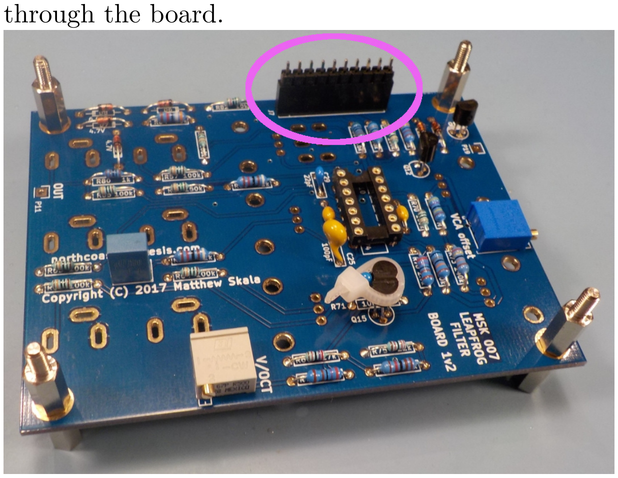


Board to board connectors

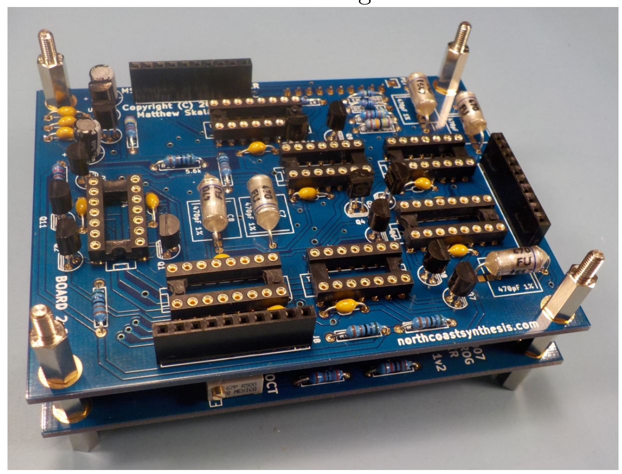
Screw one 13mm and one 11mm standoff into each of the four mounting holes in Board 1, as shown. The shorter (11mm) standoff should be on the top, the same side as the components already installed, with the male-threaded ends sticking up. These standoffs will separate Board 1 from Board 2 in the final module. The longer (13mm) standoffs should be on the bottom, with their male ends passing through the board to mate with the 11mm standoffs.



Mate the 10×1 header connectors J7 and P26 and place them (do not solder yet) in the J7 footprint on Board 1 with the legs of the female connector J7 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 P26 going through the P26 footprint, and fasten it with the remaining four 11mm standoffs.



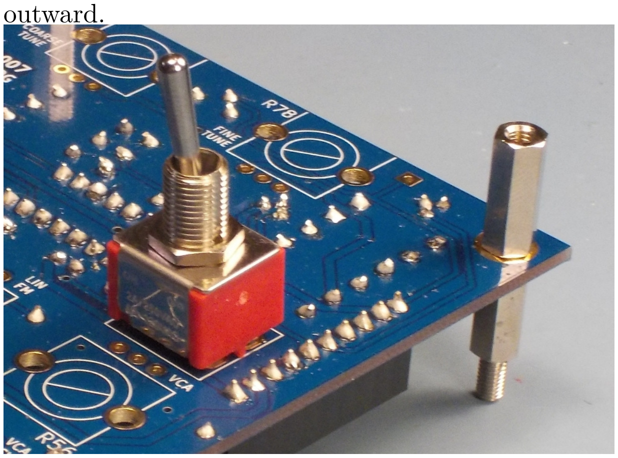
Solder J7 and P26 in place on the two boards. Then remove Board 2 and the four standoffs holding it in place, but keep the standoffs that go through the holes in Board 1.

Panel components

Flip Board 1 over; you will now be installing the components that go between it and the panel. The exact details of how the pieces fit together are important and may not be obvious; see the exploded assembly diagram on page 77, which may clarify things.

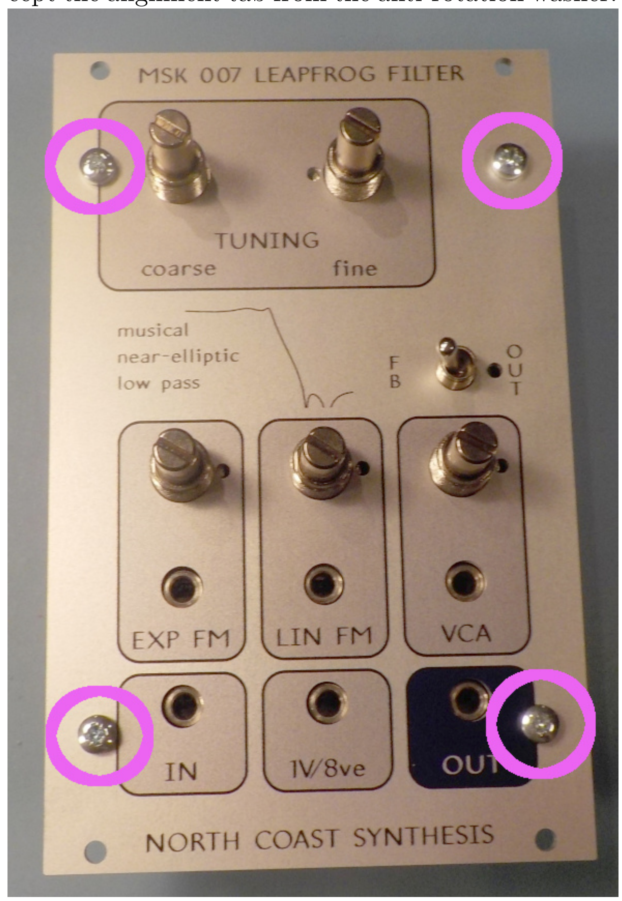
The toggle switch SW3 is for switching the VCA section between providing feedback and controlling the output. It has a body just a little shorter than will fit well into the 13mm space between Board 1 and the panel. This space is forced to be 13mm to accommodate the potentiometer bodies. The switch comes with two nuts and only needs one for fastening on the front of the panel. We use the second one as a spacer behind the panel to hold the switch body far enough back that its legs will go through the holes in the board. Remove and save the hardware from the switch bushing, then screw on one of the nuts all the way down to the bottom of the bushing.

The switch's electrical connections are symmetrical, but it has a slot or keyway in its bushing, used to hold the special anti-rotation washer in place. This keyway must face toward the outer edge of the board in order for the anti-rotation washer to be able to connect the switch properly with a matching small hole in the panel. Place (do not solder yet) the switch in its footprint on Board 1, with the keyway facing outward.



Place (do not solder yet) the five panel control potentiometers R56, R62, R69, R78, and R81 in their footprints on the board. These provide manual control of the module's functions. Place (do not solder yet) the six phone jack sockets J1 through J6 in their footprints. These are for patching signals to and from other modules. All these components should only be able to fit into the board in one way.

Line up the panel on top of the asembly and fasten it in place by driving the four machine screws through their corresponding holes into the 13mm standoffs. Double check that the keyway on the switch bushing is facing the small hole near the switch which will accept the alignment tab from the anti-rotation washer.



Install all the hardware for the panel components. In the case of the switch, the sequence is first (nearest the panel) the anti-rotation washer, with one of its tabs fitting into the keyway on the bushing and the other sticking into the small panel hole provided for this purpose; then the toothed lock-washer (sharper side of the teeth facing up to engage with the nut, if there's a noticeable difference between the two sides); and finally the nut. In the case of the potentiometers, the sequence is first (nearest the panel) the conical spring washer, high side in the middle and low side around the outside; then the toothed lock-washer; then the nut.

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. You may need to tilt the assembly and jiggle it a bit to get the jack sockets to fall into the right alignment with their bushings poking through the panel. On the other side, when correctly installed their solder legs (and those of the switch) will just barely pass through the circuit board.

Do not overtighten any of this hardware, and be careful, if you are using wrenches or pliers, to avoid scratching the panel. Wrapping the tool jaws with tape may help.

Solder the panel components. It can be tricky to do the joints where a component leg just barely passes through the board, but if you take it slow and make sure that the PCB hole is filled with solder and the whole joint is liquid before you remove the heat, then you can be reasonably sure that you have wetted the leg and made a good electrical connection. It may help to use a larger-than-usual soldering iron tip if you have one.

Final assembly

Attach the knobs to the potentiometers. Twist each shaft to its limits in each direction to ascertain how the slot in the shaft corresponds to where you want the knob pointer, then slide the knob onto the shaft in the correct orientation and tighten the setscrew with a small flat screwdriver. See the comments at the start of this chapter about knobs, and be sure not to overtighten the setscrews when attaching them.

Insert a TL047 chip in the U10 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.

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. Attach Board 2, carefully fitting its header plug into the header socket on Board 1 and the male ends of the standoffs through the corresponding holes in Board 2. Screw on the remaining 11mm standoffs to hold it in place.

Insert the remaining four TL074 chips and the three LM13700 chips in their corresponding sockets. See the notes above on inserting DIP chips in general, and pay special attention to the directional markings on the board silkscreen and the notches in the sockets to make sure you have them installed in the right directions.

If you have not yet done the "pre-adjustment" described in the next chapter, do it now, before assembling Board 3 with the rest of the module. But assuming that is complete, add Board 3 to the assembly, fitting its three male header connectors into the header sockets on Board 2, and screw on the four hex nuts to hold it in place. Be careful with your nutdriver, pliers, or other tools not to damage other components near the nuts on Board 3. If using a nutdriver, socket wrench, or similar, be careful not to overtighten the nuts: some tools make it easy to apply more torque than the threads can sustain.

There is a rectangular white area on Board 3 reserved for adding a serial number, signature, quality control marking, or similar. Use a fine-tipped permanent marker to write whatever you want there.

Your module is complete.

Pre-adjustment

To complete the preadjustment process you will need an ohmmeter; a tool (probably a small slotted screwdriver) to adjust the trimmers; and your completed Board 3. A Eurorack power supply and voltmeter are optional.

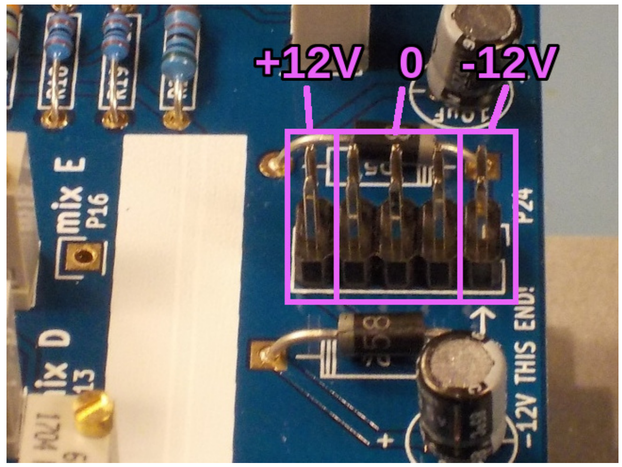
Note this procedure is to be done on Board 3 *disconnected* from any other boards; the measurements will not be correct if it is attached to the other boards. Figure 3 shows the silkscreen art for Board 3, which may help to locate the trimmers and test points. Version 3 of the art is shown; if you have one of the earlier Version 2 boards, all the trimmers and test points are in the same places, but there are minor differences in some of the label positions.

Throughout these instructions, calculated target values for the measurements are given to more precision than it is usually practical to measure or adjust. Just round them off to the appropriate level for what your test equipment can do.

Short-circuit test

This check will be done again on the entire module during the regular adjustment phase, but it's worth doing it right at the start on Board 3 alone to help narrow down any problems you might discover.

The two pins on the Eurorack power connector nearest the edge of Board 3 (at the bottom when the module is mounted upright in a case) are for the −12V connection. That is the end where the red stripe on the cable would normally connect. The two pins at the other end of the connector (furthest from the edge of the board) are for +12V power. All six pins in the middle are for 0V (ground).



Check for shorts between the three power connections, testing each pair in both directions (six tests in all). Ideally, you should use an ohmmeter's "diode test" range for this, and it should read infinite in the reverse direction (positive lead to −12V and negative lead to each of the other two, as well as positive lead to ground and negative to +12V) and greater than 1V in the forward direction (reverse those three tests). If any of these six measurements is less than 100Ω or 1V, then something is wrong with the build and you should troubleshoot it before applying power.

Integrator time constants

Each of the five integrator stages has a time constant controlled primarily by a trimmer. At this point we set these roughly by setting the resistances to values that would be correct if all other components in the circuit had their design values; in the later, more precise adjustment step, the values may be modified to compensate for variations in those other components.

Measure the resistance between P1 "+9V TC CMN" (that is, "time constant common"; the test point is connected to what will be the internal +9V supply when the module is fully assembled) and P2 "TC A" and adjust R7 to bring this resistance to 7.9856kΩ.

Measure the resistance between P1 "+9V TC CMN" and P3 "TC B" and adjust R8 to bring this

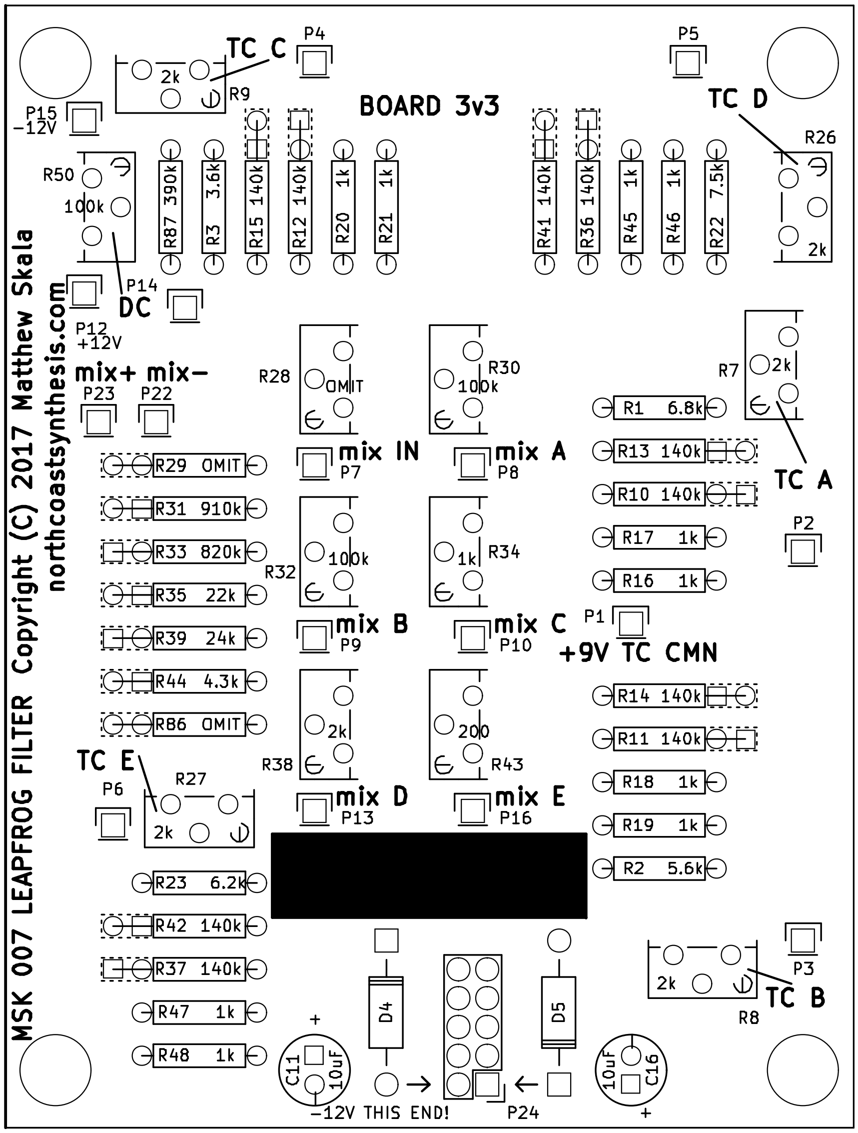


Figure 3: Board 3 silkscreen art

resistance to 6.8820kΩ.

Measure the resistance between P1 "+9V TC CMN" and P4 "TC C" and adjust R9 to bring this resistance to 4.4816kΩ.

Measure the resistance between P1 "+9V TC CMN" and P5 "TC D" and adjust R26 to bring this resistance to 8.1997kΩ.

Measure the resistance between P1 "+9V TC CMN" and P6 "TC E" and adjust R27 to bring this resistance to 7.4310kΩ.

Output mix

The output of the filter is a carefully chosen fixed mixture of the output signals from the five integrator stages. There is an interaction between the R43 and R34 adjustments, hence their repetition in these instructions; the stated sequence should minimize any problems caused by interaction.

Measure the resistance between P22 "mix −" and P16 "mix E" and adjust R43 to bring this resistance to 4.2802kΩ.

Measure the resistance between P23 "mix +" and P13 "mix D" and adjust R38 to bring this resistance to 25.144kΩ.

Measure the resistance between P22 "mix −" and P10 "mix C" and adjust R34 to bring this resistance to 19.3130kΩ.

Measure the resistance between P23 "mix +" and P9 "mix B" and adjust R32 to bring this resistance to 890.04kΩ.

Measure the resistance between P22 "mix −" and P8 "mix A" and adjust R30 to bring this resistance to 961.04kΩ.

Measure the resistance between P22 "mix −" and P16 "mix E" a second time; it should be near 4.2802kΩ. If necessary, adjust R43 to make it exactly 4.2802kΩ.

Measure the resistance between P22 "mix −" and P10 "mix C" a second time; it should be near 19.3130kΩ. If necessary, adjust R34 to make it exactly 19.3130kΩ.

Note the footprint labelled R28, corresponding to the test point P7 "mix IN," is meant for reusing this board design with other filter curves; in the standard lowpass configuration there is no trimmer there and no adjustment needed.

DC offset trim

The DC offset trimmer R50 should be set to its midpoint for now; it will be adjusted up or down to compensate offset in the OTA chips later. If you followed the build instructions carefully, then you will have set it to its midpoint before installing it and no further adjustment is needed at this point.

Otherwise, connect the board to a Eurorack power supply, and confirm that +12V appears on test point P12 and -12V on P15, relative to any convenient grounded point on the board (such as the mounting hole nearby) and to within the voltage tolerance of your power supply. Measure the voltage on P14 labelled "DC" and adjust R50 to bring the measured voltage to zero.

Alternate procedure: instead of connecting the board to a power supply, you can measure the resistances among P14, P12 (labelled +12V), and P15 (labelled −12V). The wiper of the 100kΩ trimmer is connected to P14 and the two ends of the track are connected to P12 and P15, so with no power applied to the board, you can adjust for equal resistances (of 50kΩ subject to tolerance) between P12 and P14 and between P14 and P15.

Adjustment

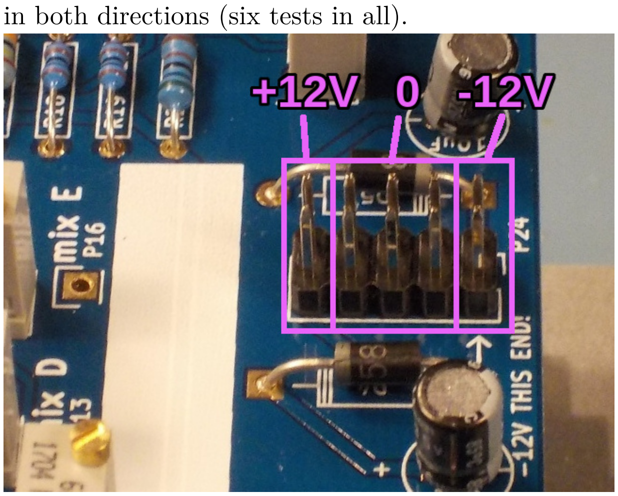
A properly built module will probably sound okay if you skip some or all of these final adjustment steps (for instance, because of not having the right test equipment), but to really operate at its intended level of performance, the module should be adjusted carefully to compensate for the natural variations in the components.

Do the pre-adjustment in the previous chapter on Board 3 first.

For the steps in this chapter, you will need (in addition to specific items mentioned in the individual steps) a multimeter, a tool such as a small screwdriver for adjusting trimmers, a Eurorack power supply, and your complete, fully assembled, MSK 007 Leapfrog Filter module.

Short-circuit test

Without power applied to the module, check for shorts between the three power connections on the Board 3 Eurorack power connector, testing each pair in both directions (six tests in all).



Ideally, you should use an ohmmeter's "diode test" range for this, and it should read infinite in the reverse direction (positive lead to −12V and negative lead to each of the other two, as well as positive lead to ground and negative to +12V) and greater than 1V in the forward direction (reverse those three tests). If any of these six measurements is less than 1kΩ or 1V, then something is wrong with the build and you should troubleshoot it before applying power.

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.

Optional: Plug the module into a Eurorack power supply *backwards*, see that nothing bad happens, and congratulate yourself on having assembled the reverse-connection protective circuit properly. Reconnect it right way round before proceeding to the next step.

DC offsets

For this step you will need the capability to measure DC voltages, including the DC component of an audio-rate signal. If you are using a voltmeter, make sure it will not be confused by a signal that includes both AC and DC. If you are using an oscilloscope, make sure it is set to DC-coupled input.

The MSK 007 is a DC-coupled filter and in principle, DC applied to the input can pass all the way through to the output. That can be advantageous in some patches where you may want to pass a control voltage or envelope through the filter. However, it has the disadvantage that offsets created by the normal tolerances of the amplifier chips can add up (especially around the multiple feedback loops).

Including a trimmer for every possible offset-introducing component would be prohibitively expensive and complicated. Instead, the MSK 007 has two: R50 on Board 3, which trims offset in the filter core, and R89 on Board 1, which trims offset in the VCA circuit. The following adjustment procedure is a trade-off intended to reduce offset as much as possible under common operating conditions. Some DC offset will still remain at the edges of the normal operating range (for instance, very high or low cut-off frequencies).

Disconnect all cables from the filter. Apply power. Set coarse and fine tuning to their midpoints, exponential and linear FM to zero, VCA mode to feedback (toggle switch left), and VCA amount to minimum.

You should have set R50 on Board 3 and R89 on Board 1 to their midpoints before installing them (or R50 during pre-adjustment), but if not: measure the voltage at P14 "DC" (on Board 3 near R50) and adjust R50 to bring this voltage to zero; and measure the voltage at P19 (on the upper edge of Board 1 near R89) and adjust R89 to bring this voltage to zero.

Measure the output voltage of the module, either by plugging into the output jack or at P11 on the bottom edge of Board 1 (which is directly connected to the output jack). It should be a pure DC voltage. Adjust R50 on Board 3 to bring this voltage to zero.

Turn the VCA amount knob up to maximum. The module should start to oscillate, probably at a frequency of about 200Hz (wide tolerance on frequency) and with voltage at least 4V peak to peak. Measure the *DC offset* of the AC output voltage and adjust R89 on Board 1 to bring the offset to zero.

Switch the VCA mode to output (toggle switch right) and measure the DC output voltage. Adjust it with R89 on Board 1 *halfway* from wherever it currently is, to zero.

Optional: integrator phase shifts

If you did the pre-adjustment carefully, your module will probably already give something very close to the designed response curve. One significant advantage of the leapfrog topology is that it is especially tolerant to inaccuracies in component values: the curve will not change much with small misadjustments. However, the pre-adjustment procedure only takes into account the tolerance variation of the components on Board 3. There are some components on Board 2 (particularly the integration capacitors and the control current distribution system) which also affect filter performance, and so to really adjust everything as well as possible, it is necessary to do a final adjustment of five integrator phase shifts on the fully assembled module.

In my experiments on prototype modules, doing the full adjustment procedure seems to provide a very small improvement in stopband attenuation, but makes very little difference to the main filter curve. And the phase shift adjustment has the disadvantage of being time-consuming and annoying. The five trimmers all mutually interact and the phase shifts one must measure to get them set right, are not easy to measure accurately. There is the danger that if you do it and screw it up, you may end up with a worse filter than if you had just stopped at the pre-adjustment. So for do-it-yourselfers I am describing this procedure as "optional." You can do it if you want to; in theory, it makes things better; but it is quite likely that you won't be able to hear or even measure a difference between doing it and not doing it. If you do mess things up with a bad full-adjustment procedure, it is not a big problem. You can always separate Board 3 from the rest of the module and re-do the pre-adjustment alone to go back to that level of performance.

For this step you will need the capability to tune the module to self-oscillation at 740Hz or the F♯ one and a half octaves above middle C (either by measuring its output frequency directly, or by tuning to zero-beat against a known source of this frequency); to generate a clean sine wave at this same frequency; and to measure the phase or timing difference between two such sine waves. A two-trace digital oscilloscope will probably do most of the measuring functions conveniently, and a computer can act as a signal generator. Alternatively, a modular synthesizer VCO with a sine output will work as the signal generator if you have some way to tune it, and a dual-trace analog oscilloscope can be used for the phase measurements with some care. It may also be possible to use software on a computer, with the two signals fed in as left and right stereo channels to the audio interface, to do the phase measurements. Details of how to use different kinds of test equipment are not covered here; this description just gives the needed adjustment targets assuming you know how to use your equipment.

Disconnect any input or modulation signals and apply power to the filter. Set coarse and fine tuning to their midpoints, exponential and linear FM to zero, VCA mode to feedback, and VCA amount to maximum. Monitor the output; the module should produce a sine wave in the range of a few hundred Hz.

Tune the module with the coarse and fine tuning, and reduce the VCA amount, until it oscillates at the F♯ one and a half octaves above middle C (12-EDO concert pitch); that is theoretically 739.9888Hz, but it is probably best to aim for exactly 740Hz. Measure the frequency with the VCA amount just high enough to keep the oscillation stable. *From this point on, to the end of the phase-shift adjustment, don't touch the tuning knobs.*

Note that it may be difficult to make some of these adjustments precisely. I give the target values down to hundredths of a degree of phase, but (especially for the phase shifts on integrators B and A, the last ones to be adjusted, which seem especially finicky) it may not be possible to really adjust them within better than one or two whole degrees. Just do the best you can. The closer these adjustments are to perfection, the better the module will comply with its theoretical response curve; but even significant errors in the adjustment will only degrade performance a little bit.

Note that there will be moderate differences in amplitude (up to a factor of two in voltage) among the signals measured in the next few steps, and some may have noticeable DC offsets. That is normal; the important differences to measure are in their phases. However, be on the lookout for clipping indicated by flat tops or bottoms on the waveforms. If you see that, your input reference waveform level is too high and it may be rendering the measurements inaccurate. Turn it down.

Turn the VCA amount down to zero. The module will stop oscillating; but leave the VCA mode switch set to feedback mode. Feed a pure sine wave of the same reference frequency, 739.9888Hz or 740Hz, into the input, preferably with an amplitude of about 5V peak to peak. I use a Hikari Sine oscillator patched through an attenuator.

In the following steps, be careful to adjust the right trimmers. The phase measurements are taken at test points near the centre of the board, labelled "mix A," "mix B," and so on; but the trimmers to adjust are the time constant trimmers, nearer the edges and labelled "TC A," "TC B," and so on, not the mix trimmers nearest the test points. The mix trimmers were set in the pre-adjustment step and if you change them, you will need to separate the boards again to take the necessary measurements for returning them to the correct positions. Throughout the phase shift adjustments, if adjusting a trimmer seems to have no effect on the measurement you are taking, *stop* and make sure you are turning the correct trimmer. Some of them are more sensitive than others, but every one should make some measureable difference.

If during the following steps you find there is not enough adjustment range on a trimmer to hit the desired measurement, then leave it at the end of its range nearest the desired setting, and if necessary go around the six adjustments steps again until you come back to it. The interactions between the adjustments mean that on the next visit it will probably not be pushed to an extreme. If that doesn't seem to work, it may be necessary to re-tune the module to oscillate at the reference frequency, and then try again. If even *that* doesn't allow the trimmers to be adjusted to their desired settings, then there may be a build error and you should troubleshoot for things like solder bridges.

Measure the phase difference between the signals at P16, labelled "mix E" on the back of the module, and P13, labelled "mix D." Adjust R27, labelled "TC E," so that the P16 "mix E" signal leads the P13 "mix D" signal by 45.59° or 171.15μs; your equipment may instead display this as a lag of 314.40° or 1180.19μs.

Measure the phase difference between the signals at P13, labelled "mix D" on the back of the module, and P10, labelled "mix C." Adjust R26, labelled "TC D," so that the P13 "mix D" signal leads the P10 "mix C" signal by 40.98° or 153.84μs; your equipment may instead display this as a lag of 319.02° or 1197.54μs.

Measure the phase difference between the signals at P10, labelled "mix C" on the back of the module, and P9, labelled "mix B." Adjust R9, labelled "TC C," so that the P10 "mix C" signal leads the P9 "mix B" signal by 30.36° or 113.96μs; your equipment may instead display this as a lag of 329.64° or 1237.40μs.

Measure the phase difference between the signals at P9, labelled "mix B" on the back of the module, and P8, labelled "mix A." Adjust R8, labelled "TC B," so that the P9 "mix B" signal leads the P8 "mix A" signal by 48.68° or 182.75μs; your equipment may instead display this as a lag of 311.32° or 1168.63μs.

Measure the phase difference between the signals at P8, labelled "mix A" on the back of the module, and P7, labelled "mix IN." Adjust R7, labelled "TC A," so that the P8 "mix A" signal leads the P7 "mix IN" signal by 14.40° or 54.04μs; your equipment may instead display this as a lag of 345.60° or 1297.31μs.

Repeat the above steps a second time, starting from the measurement of the lag between P16 "mix E" and P13 "mix D."

These measurements are summarized in Table 5.

Optional cross-checks: Measure the phase difference between the module input and module output. They should be close to 180° apart. Disconnect the input and turn the VCA amount back up until the module oscillates. It should still be close to 740Hz. There is no specific guidance on *how* close these mea-

trimmer	measure	target	
TC E	MIX E–MIX D	45.59°	314.40°
TC D	MIX D–MIX C	40.98°	319.02°
TC C	MIX C–MIX B	30.36°	329.64°
TC B	MIX B–MIX A	48.68°	311.32°
TC A	MIX A–MIX IN	14.40°	345.60°

Table 5: Measurement targets for time constant adjustment

surements should be to their targets.

Tracking (with automated test)

"Tracking" refers to the slope of the V/octave control voltage response. It should be exactly 1.0V/octave. The trimmer R77, located on Board 1, adjusts this response.

The best way to adjust this setting, if you have the equipment and skills, is by hooking up the module to a computer that can send it control voltages, measure the output frequency in self-oscillation, and compute an estimate of the current V/octave ratio, which allows realtime feedback as you adjust the trimmer. I provide a piece of software in the file `voct-0.1.tar.gz` to support this process.

The software is written for the Linux ALSA MIDI and PCM drivers, and it includes hardcoded assumptions about things like device numbers. *You need C programming skills to use this software. I will not provide support on it.* If you cannot modify the software as needed to suit your installation, then I recommend using the manual tracking procedure in the next section instead.

Read the C source code and make any appropriate changes for your installation. Compile it. Connect your MIDI-to-CV interface to the V/oct input on the MSK 007, and connect the MSK 007's audio output to your computer's audio input. Remove any other cables from the MSK 007, set the VCS mode to feedback, the VCA amount high enough for reliable oscillation, and exponential and linear FM to zero. Optionally (requires other appropriate software, not included), send MIDI note 69 to the MIDI interface and adjust the tuning of the MSK 007 to make it oscillate at 440Hz; otherwise set the coarse tuning to about 10 o'clock and the fine to its midpoint. Adjut the sensitivity of the audio input to bring the Leapfrog's signal to about 50% of full scale. Run the `vcoslope` software.

The vcoslope program sends random MIDI notes, makes brief recordings of the oscillator output, and attempts to fit an exponential function (using linear regression) to the note/frequency data in the last N notes, for several different values of N. From that it can determine the current sensitivity of the V/octave input. Using multiple frequencies to test like this gives better accuracy than would be the attainable with just testing at two frequencies (as in the standard manual procedure). Using notes in random order is preferable to testing them in an increasing or decreasing sequence, because of self-heating effects in the exponential converter. The program tries multiple sample sizes (the most recent 10, 32, 100, and 316 points) to allow both quick feedback on any trim changes, and accurate results over longer periods.

It will start producing lines of output, one every few seconds. Each line starts with a decimal sequence number (1, 2, 3, . . .) and the MIDI note number that was sent. The next two columns are the measured frequency in Hertz, and the number of octaves plus or minus that is relative to the 440Hz reference pitch. Then come up to four columns of V/octave estimates: the first determined from the last 10 notes tested, the second from the last 32 notes, then 100 notes, then 316 notes. These columns each show up only once there have been the requisite number of notes, so at first there will be no such column, then the first one will appear on the tenth note, then the second at note 32, and so on.

Let the program run for at least 10 or 20 notes so you can get some idea of the module's current V/octave response. Then try adjusting R77 one turn clockwise. Watch for another 10 lines of output. The 10-note V/oct estimate should start to move, then settle in on a new value. From there you should be able to estimate how far (how many turns) and in which direction you need to adjust R77 to bring the response to 1.000V/oct. Try to do that. As you get in closer, the natural noise in the V/oct numbers may become significant in relation to the sizes of adjustment you are making. In that case, switch to one of the slower-updating columns to get a more stable reading (larger sample size). You will need to wait longer between adjustments for those columns to reach full precision. Continue until you have the module performing as accurately as you want, or until you run out of patience.

Tracking (by hand)

This simpler tracking procedure does not require computer skills, only the ability to send reproducible control voltages of 0V and 1V to the filter and test the resulting frequencies. It is somewhat less accurate because it tests only two frequencies instead of averaging over many, but it is similar to the way people commonly adjust VCOs, which have much more demanding accuracy requirements than most VCFs.

A North Coast Synthesis MSK 008 Octave Switch, assuming it has itself been properly adjusted, makes an ideal voltage source for the following procedure.

Hook up your control voltage source to the filter's V/oct input, set up your equipment as necessary to test the frequency of the audio output, disconnect any modulation signals, and power up the filter. Set the VCA mode to feedback, VCA amount to just enough to get a stable oscillation, and set both modulation controls to zero.

Send a 0V control voltage to the filter. Tune it with the coarse and fine tuning knobs to an oscillation frequency of 440Hz (or any arbitrary frequency of your choice, but this one is convenient).

Without changing the tuning knob settings, send a 1V control voltage to the filter. Adjust R77, not the tuning knobs, to bring the oscillation frequency to 880Hz (or twice the initial frequency if you are using something other than 440Hz).

Send a 0V control voltage and test the output frequency; is it 440Hz or your chosen other reference frequency? If not, adjust the tuning knobs to make it so. Repeat these two steps, of alternately adjusting for the low frequency with 0V and the tuning knobs, and the high frequency with 1V and the trimmer potentiometer, until both readings are reliably what they should be without seeming to need further adjustment.

For even better accuracy: use two control voltages more than 1V apart, and a correspondingly wider frequency range. For instance, an MSK 008 octave switch can conveniently generate +1V and −1V, which could be used with reference frequencies of 880Hz and 220Hz to set tracking over two octaves instead of just one.

Patch ideas

Here's a basic subtractive synthesis patch: pitch CV from the MIDI interface connects to the V/octave inputs on a sawtooth oscillator and the MSK 007, while the gate CV drives and ADSR envelope which controls the built-in VCA on the MSK 007 (VCA mode switch set to "output").

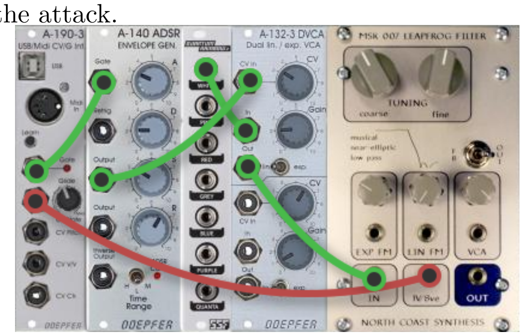
In a more elaborate subtractive synthesis patch, two ADSR envelopes drive the amplitude and filter cutoff separately, with an external VCA which frees the MSK 007's built-in VCA to provide feedback.

Deluxe subtractive synthesis patch demonstrating the use of the MSK 007 with other North Coast Synthesis modules: the pitch CV goes through an MSK 008 Octave Switch (normalled to both channels) to provide separate manual octave switching up and down for the VCO and the filter. A sine wave from the MSK 010 controls linear frequency modulation of the filter cutoff for a unique effect.

The MSK 007 can be a minimal synth voice all by itself, using the gate input to control the VCA in feedback mode to switch oscillation on and off. A MIDI interface is shown, but any CV-gate controller would work.

An envelope generator set up to create a spike (fast attack and decay, zero sustain level) can "ping" the filter when fed into the audio input. Set the VCA to feedback mode and adjust the level to the point where it almost, but not quite, sustains oscillation.

Pinging with a noise burst instead of just a voltage spike produces a different sound with some extra grit in the attack.



The MSK 007 can take inputs all the way down to DC, so with the cutoff frequency very low (at or near its minimum) it can process control voltages as an unusual kind of slew rate limiter, with a bit of bounce or overshoot on rapidly-changing inputs (especially in feedback mode). The gain through the filter is not easy to adjust to precisely unity, so you might not want to use this for critical melodic material; but with a square wave LFO input, as shown, it puts an interesting twist on the control waveform for generating a drone texture.

Doepfer's A-188-1 bucket brigade module does not include an output filter, so at low clock rates the clock will be audible unless you filter it out externally. The MSK 007 is especially well-suited for that because of its low cutoff. With the MSK 007 tuned to cut off at the Nyquist frequency (half the BBD's clock frequency), it will cleanly eliminate both clock and alias signals.

Spectral inversion is another use for a sharp low-pass filter. Tune the sine wave VCO (here used as a *local oscillator*) to generate a carrier a little above the highest frequency in the input. Ring-modulate (four-quadrant multiply) the input with the carrier. That produces two frequency bands: upper sideband consisting of the input shifted up by the carrier frequency, and lower sideband consisting of all the input frequencies subtracted from the carrier frequency. The MSK 007 removes the upper sideband and any carrier feedthrough.

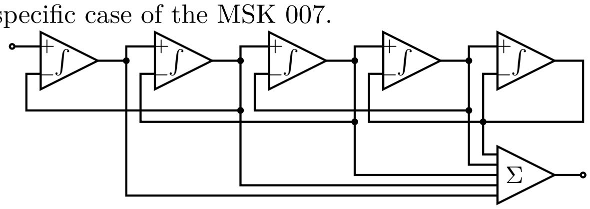
Spectral inversion is an interesting effect in itself, but you can also use two copies of this patch (two MSK 007 modules, two oscillators, and two channels of four-quadrant multiplication) with slightly different carrier frequencies, to serve as a frequency shifter.

Circuit explanation

The MSK 007 Leapfrog Filter is a complicated circuit, and really understanding how it works requires going quite deeply into the theory of differential equations, complex variables, and so on. I'm not going to go that far. This chapter presents *three* intuitive descriptions (take your pick!) of what goes on in a leapfrog filter in general, attempting to use no more than basic calculus; as well as a practical summary of how the MSK 007 in particular realizes the leapfrog design. For more background, read some standard textbooks on filter design, differential equations, and complex variables; there are also some references footnoted at appropriate points in this explanation.

Core topology

The MSK 007's fifth-order leapfrog filter core consists of five active integrators, each of which integrates the difference between the outputs of the next and previous integrator in the sequence. There is special handling at the ends: the first one uses the filter input as its otherwise-nonexistent "previous" neighbour, and the last one uses its own output as its otherwise-nonexistent "next" neighbour. Then there is also an output mixer that combines the outputs of all five integrators in a fixed proportion. In principle, the circuit input could also be included as an input to the output mixer, but in fact that is not done in the specific case of the MSK 007.



Keep this topology of the core in mind while reading the next sections, which attempt to justify *why* it is a useful way to build a filter core.

Calculus intuition

This intuitive explanation is for readers with a more mathematical inclination; read the "analog electronics" section below if you find that approach easier to understand. Note that here I'm going for easy understandability, not rigour.

Suppose we want to build a filter that has a specific response to input described by a differential equation, like this:

$$Ax^{(\mathrm{v})} + By^{(\mathrm{v})} + Cy^{(\mathrm{iv})} + Dy''' + Ey'' + Fy' + Gy = 0\,. \tag{1}$$

The variables x and y represent the input and output, respectively. Both of those are functions of time ($x(t)$ and $y(t)$), and the primes and Roman numerals represent taking multiple derivatives of them with respect to time. In words, (1) says that some linear combination of the fifth derivative of the input $x^{(\mathrm{v})}$, and of all derivatives of the output from y up to $y^{(\mathrm{v})}$, adds up to zero.

Exactly *why* it makes sense to describe a filter's response that way, and how we choose the coefficients A through G (all of which are constant real numbers) to make the filter sound the way we want it to, are beyond the scope of this explanation. In very rough terms, we'll just say that filters do tend to be well-described by this kind of equation—it's a natural way to describe what a filter does—and having seven different coefficients to choose means we have a lot of opportunities to tailor the filter to respond in a way we want. So with that in mind, just assume we have somehow chosen coefficients for the differential equation such that a filter behaving according to that equation would be a filter we would like to build. Now how can we build one?

First, it's more convenient to build electronic integrators than differentiators, so let's take the integral of the differential equation, five times, so there are no primes left. I'll just write integral signs instead of spelling out limits, constants, and the fact that all of these are integrals over time:

$$\begin{aligned} Ax + By + C\int y + D\iint y + E\iiint y \\ + F\iiiint y + G\int\!\!\iiiint y = 0\,. \end{aligned} \tag{2}$$

At this point we could actually turn it into a circuit. Starting with the signal y coming from some-where, we'd chain together five integrators to compute each multiple integral up to $\iiiint\!\!\int$. Given x and all the integrals, what is left is just a single linear equation with only one unknown, y; so we can build a constant-ratio linear mixer that actually computes the value of y to satisfy (2). That value of y is the circuit output, and it also loops back to supply the value of y to the input of the integrator chain. The feedback allows the circuit to solve the equation.

What I've just described is (one form of) a classical state-variable filter with five state variables. Note that what people usually call a "state-variable filter" in synthesizers is specifically a two-pole version with some tricks to allow it to have multiple useful outputs. This five-pole state-variable filter is a little different, but both are examples of the general state-variable technique.

There are some problems with actually building a multi-pole state variable filter that way, however, notably that it's necessary to get the coefficients exactly right or else the final output will be far from its correct value. By means of Laplace transforms and algebra, it is possible to rearrange our equation into a system of equations in new variables v_1, v_2, v_3, v_4, v_5 such that it has the same solution as (1) but a different form:

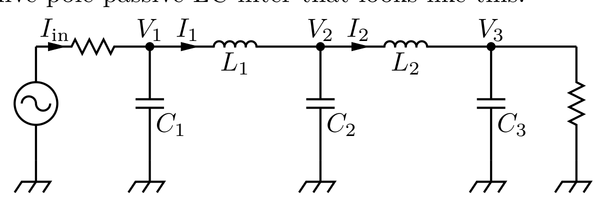
$$
\begin{aligned}
v_1 &= H \int (x - v_2) \\
v_2 &= I \int (v_1 - v_3) \\
v_3 &= J \int (v_2 - v_4) \\
v_4 &= K \int (v_3 - v_5) \\
v_5 &= L \int (v_4 - v_5) \\
y &= Mx + Nv_1 + Pv_2 + Qv_3 + Rv_4 + Sv_5 \,.
\end{aligned}
\tag{3}
$$

One way of thinking of this is that it comes down to putting a matrix into tridiagonal form. Choosing values for the coefficients H through S is complicated, but only a matter of arithmetic using formulas that have been published in the academic literature.* Every one of those equations is something we can easily calculate with an analog computer: just a scaled integral of the difference between two other signals for v_1 through v_5, or a linear mixture of signals for y at the end. There are still five integrations being performed, but with multiple feedback conenctions among them instead of just one master feedback connection from the end back to the start. The circuit solves the system of equations (3), which has the same solution as (1) and (2), so it also functions as a filter with the desired response.

The important difference is that expressing the filter response in the form (3) is more *numerically stable*. Small errors in the coefficients don't have as much effect on the final output as would be the case with the classical state-variable form. As a rough intuition, that is because any feedback tends to cancel out errors, but here an error in one integrator's output loops back to its input after passing through at most one other integrator, whereas in the classical design it would go around the entire cycle through all the other integrators, causing more damage. So it is more likely that if we build a machine according to (3), it will actually work to compute the response we want.

Analog electronics intuition

If you're more comfortable thinking about components than differential equations, this section may interest you. Suppose we want to build a traditional five-pole passive LC filter that looks like this:



The component values would probably come from using a table of prototype filters; that method and the math that goes into making the lookup tables are beyond the scope of the current discussion.

We probably wouldn't actually build a filter using real capacitors and inductors like that, especially not at audio frequencies, because inductors suck. They do not behave much like the mathematical model of what an inductor is supposed to do, and so the filter will not really work well. Even if we tried, the necessary component values for audio frequencies would probably lead to our needing inductors that are too physically large to be practical. Passive LC filters like the above are sometimes used in radio applications, where the component values are more reasonable and it's possible to make inductors that work acceptably, but for audio it's much more common to do what we're about to: build an analog computer that *sim-*

*Yichuang Sun, 2006, Synthesis of Leap-Frog Multiple Loop Feedback OTA-C Filters, IEEE Transactions on Circuits and Systems, Part 2: Express Briefs, 53, 9.

ulates the passive LC circuit as if it were built with ideal instead of real-life components.

Now, looking at the circuit diagram, let's assume all the impedance matching has been magically done for us, so that the input looks to the source as if it were a pure resistance. The resistors shown on the diagram just represent perfectly matched impedances; let's pretend they are each 1Ω, which conveniently makes voltage and current through each one equal. We can describe the input signal then equivalently as a voltage or a current; for convenience, use the current I_{in}. To understand the operation of this circuit we need to be able to calculate the final output voltage V_3, and it'll help to compute all the other voltages and currents in between the input and output.

Current feeding through the input resistor splits into current through L_1, named I_1, and current through C_1, which doesn't have a name but by Kirchoff's Current Law must be equal to $I_{\text{in}} - I_1$. A capacitor's voltage is just the integral of the current through it, scaled to the inverse of the capacitance, so we have:

$$V_1 = \frac{1}{C_1} \int (I_{\text{in}} - I_1) \, .$$

Note that we can decide that equation is true, even though we haven't actually calculated the value of I_1 yet.

Computing the current I_1 through L_1 is next. The current through an inductor is just the integral of the voltage applied to it—apply a fixed voltage for a period of time and the current increases linearly. So we can write:

$$I_1 = \frac{1}{L_1} \int (V_1 - V_2) \, .$$

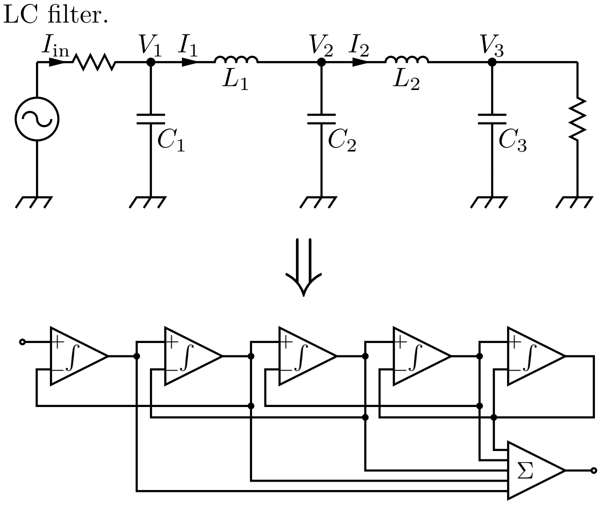
The same considerations give expressions for V_2 and I_2:

$$V_2 = \frac{1}{C_2} \int (I_1 - I_2)$$
$$I_2 = \frac{1}{L_2} \int (V_2 - V_3) \, .$$

The expression for the final voltage V_3 is a little special because we need to use the current exiting through the output resistor. There is no label for that on the diagram, but remember we assumed the output resistor is 1Ω, so this mystery current is actually equal to V_3. Then we get this expression for V_3, which is the output voltage (and current):

$$V_3 = \frac{1}{C_3} \int (I_2 - V_3) \, .$$

Now look what we've done: we have a set of formulas that describes the behaviour of the passive LC ladder filter, where each formula is a scaled integral of the difference between the values of the next and previous formulae, with some special handling at the ends. Except for different names on the variables and constants, these integrals look just like the ones in (3). We can build a simple electronic circuit—an analog computer–that calculates the value of each of the five formulas as a voltage. The circuit looks like an integrator with a differential input and a fixed, carefully chosen time constant representing the inverse of the component value for the corresponding inductor or capacitor. Each integrator output voltage represents either the voltage across a capacitor, or the current through an inductor, in the simulation of the passive LC filter.



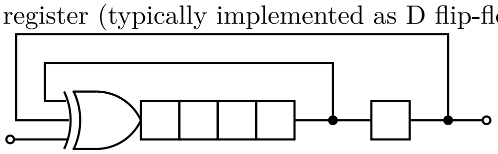
I have pulled a bit of a fast one on you here by not mentioning the output mixer, nor the fact that passive LC filters are not necessarily simple ladders like the one shown. In fact, the MSK 007 in its standard configuration simulates something close to an *elliptic* filter (the name comes from *elliptic integrals* used in designing the response curve, though it's also the case that the poles of the transfer function are located on an ellipse), and in a passive LC elliptic filter, some of the rungs are tank circuits (an inductor and capacitor in parallel) instead of just being single components. Both the more complicated filter topology and the output mixer are related to the fact that the response curve has what are called *transmission zeroes*—points of theoretically infinite attenuation—at certain frequencies.

We could use substantially the technique above to simulate the more complicated passive LC elliptic filter, but it would require more integrators and more complicated connections between them, and it would lose much of the elegance of the all-in-a-row leapfrog design. Instead, it turns out that it's possible to use math on the original filter response function to eliminate the extra components. Instead of building or simulating the more complicated elliptic-filter ladder, we build a simple ladder of only single inductors or capacitors, then tap out several signals from it at different points, combine them in a fixed proportion, and the resulting responses cancel out in a way that leaves the desired response.

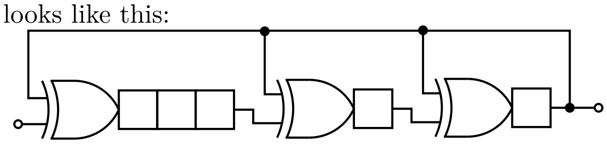
Implementing the output-mixing scheme would be difficult to do with a passive filter built of real inductors and capacitors, because some of the signals we need will be currents and others voltages, and there's danger of disrupting the signals when we tap them out of the circuit unless we're very careful about impedances. But since we're simulating it anyway, all the signals appear as voltages at the outputs of op amps (thus, buffered to low impedance), and so we can freely take as many outputs as we want from different parts of the core. Then the output mixer combines them in a carefully chosen fixed proportion, and the signal from it represents the signal that would have come out of the passive LC filter if built with ideal components. We can even cheat a little and add some gain to the output mixer to eliminate the insertion loss of the equivalent passive circuit.

Digital electronics intuition

This is a wacky idea, but I think it's really cool and maybe you will, too. Consider a linear feedback shift register (LFSR), often used as a pseudo-random number generator. In the "Fibonacci form" it looks like this, where the little squares represent single bits of shift register (typically implemented as D flip-flops):



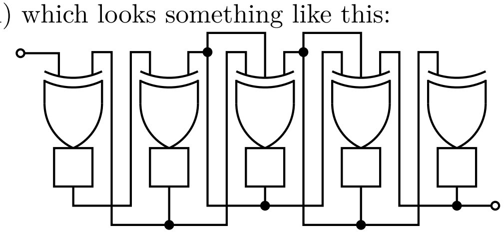
And in the "Galois form," which looks different but is in some sense mathematically equivalent, it looks like this:



The usual analysis is that this circuit computes division of polynomials with coefficients in $GF(2)$ (that is, the only numbers allowed are 1 and 0, with $1 + 1 = 0$ so that addition and subtraction are the same and correspond to XOR). In the Galois LFSR, we have one-bit registers each of which computes the difference between the previous clock cycle's value of the register immediately on the left, and optionally the last register on the right (with input coming in to the left of the leftmost register). Its response is described by an expression something like this:

$$\frac{1}{x^5 + x^4 + 1} \,.$$

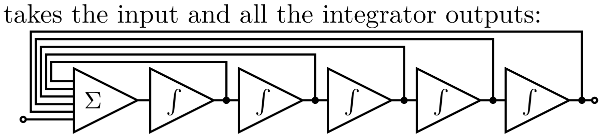
But LFSRs are not the only way to do polynomial division. You can also build a "cellular automaton," (CA) which looks something like this:



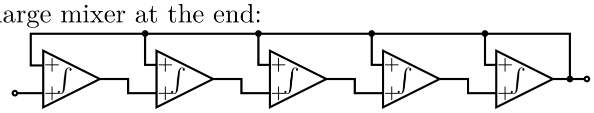
Each one-bit register computes (using the previous cycle's values) the XOR, which is also the arithmetic subtraction, of its two neighbours, and optionally itself. We feed input into one end and take output from the other. And the discrete mathematicians have shown an equivalence between LFSRs and CAs, so that for any polynomial, instead of building an LFSR, you could instead build a CA with some pattern of cells that do or don't include themselves in the XOR, to divide by the same polynomial.

Note I have not worked through the tap-location math in these examples and I do not promise that all my diagrams correspond to the same polynomial, nor that it's the one for which I gave the formula; the point is only that each such circuit divides by *some* $GF(2)$ polynomial.

Now consider a classical state-variable filter, which is a chain of integrators fed by a mixer that takes the input and all the integrator outputs:



There is an equivalent form where the mixing is done at each integrator stage, instead of in a single large mixer at the end:

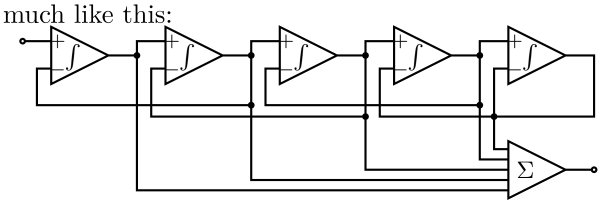


The response of either of these is described, in terms of its Laplace transform, as an expression something like this:

$$\frac{1}{As^5 + Bs^4 + Cs^3 + Ds^2 + Es + 1}\,.$$

Notice the similarity of the circuits. The first state-variable filter looks like a Fibonacci LFSR, the second looks like a Galois LFSR, and all four circuits perform the basic function of *dividing by a polynomial*. Exactly what it means to divide by a polynomial is different between the LFSRs and the state-variable filters, and I'm waving my hands around a lot of mathematical details, but it sure looks like we can say that in some sense a state-variable filter is really an analog LFSR.

So what happens if we take a step in the direction that goes from LFSRs to CAs, but we start from classical state-variable filters instead? The CA is a row of one-bit registers each taking the difference between its two neighbours' outputs as the main input. If we change each register to an integrator, keeping the same pattern of connections, we get something much like this:



That's a leapfrog filter. Leapfrog filters are to classical state-variable filters as CAs are to LFSRs.

Integrator circuit

Figure 4 shows the schematic for one of the five integrators in the core. The others are substantially the same, with some differences in the resistor values for the linearizing diode current source. Integrator C also has a potentiometer that adds or removes some extra current from the OTA positive input, for offset nulling.

This section's basic function is to integrate the difference between two input voltages, multiplied by a global control voltage (applied to all the integrators) and divided by a local time constant. One half of an LM13700 (U1A) does the subtraction, multiplication, and division. It needs its input at a very low level for low distortion, so the input voltages (nominally 10V peak to peak) go through 141:1 voltage dividers to bring them down to about 71mV peak to peak. Note the dotted lines on the schematic; the PCB design offers a choice of pads so that R10 and R13 can each be connected to either input of the operational transconductance amplifier. Normally, R13 would connect to the positive and R10 to the negative input, providing an inversion (compare to the assignment of positive and negative in the earlier explanations of the filter core) which will cancel out the inversion of the integrator.

The LM13700 takes two control signals, both of which must be provided as currents flowing into a pin held near some fixed voltage (either the negative supply, or ground). Both currents come from op amp/PNP transistor sources, which generate currents proportional to the difference between an input *voltage* and the +9V supply. For the linearizing diode current, into pin 2, the "control voltage" is actually a constant, the signal called VREF6.5. It is really only approximately 6.5V; its actual definition is one TL431 reference voltage (should be close to 2.495V) less than the +9V supply (which is regulated by a 78L09 and may be only approximately 9V). The point is that the current source, U4A and Q1, generate a stable constant current with a value controlled by the sum of R1 and R7. That is trimmed during adjustment to set the constant coefficient for this integrator stage. Other integrators will have different resistances and therefore different diode currents, but using this scheme to generate the diode currents ensures that the ratios among the different integrator time constants will remain stable and can be trimmed precisely.

The second control signal, into pin 1, comes from a similar op amp and PNP transistor arrangement, but here it is controlled by the global signal CVLIN, which is linear in the module's cutoff frequency, equal to the +9V supply at 0Hz and decreasing (nominally) 0.560V/kHz. The source that generates this control voltage cannot go below ground, so the module's global cutoff frequency is limited to about 16kHz. The current source for the integrator sources (to within the limits of its components) the current that would flow through the 5.6kΩ resistor R4 if it were connected between +9V and CVLIN, therefore 100μA per kHz. However, the current comes from the +9V supply and the op amp; it does not load up the CVLIN line, which drives only the high-impedance input of the TL074 op amp.

With the two voltage and two current inputs, U1A generates a current output on pin 5. That is connected directly to the virtual ground on pin 6 of U4B, the integrator. Its output drives the other side of C7, the integrator capacitor, to whatever voltage is needed to keep the virtual ground at ground potential; thus except for the tiny bias current of the

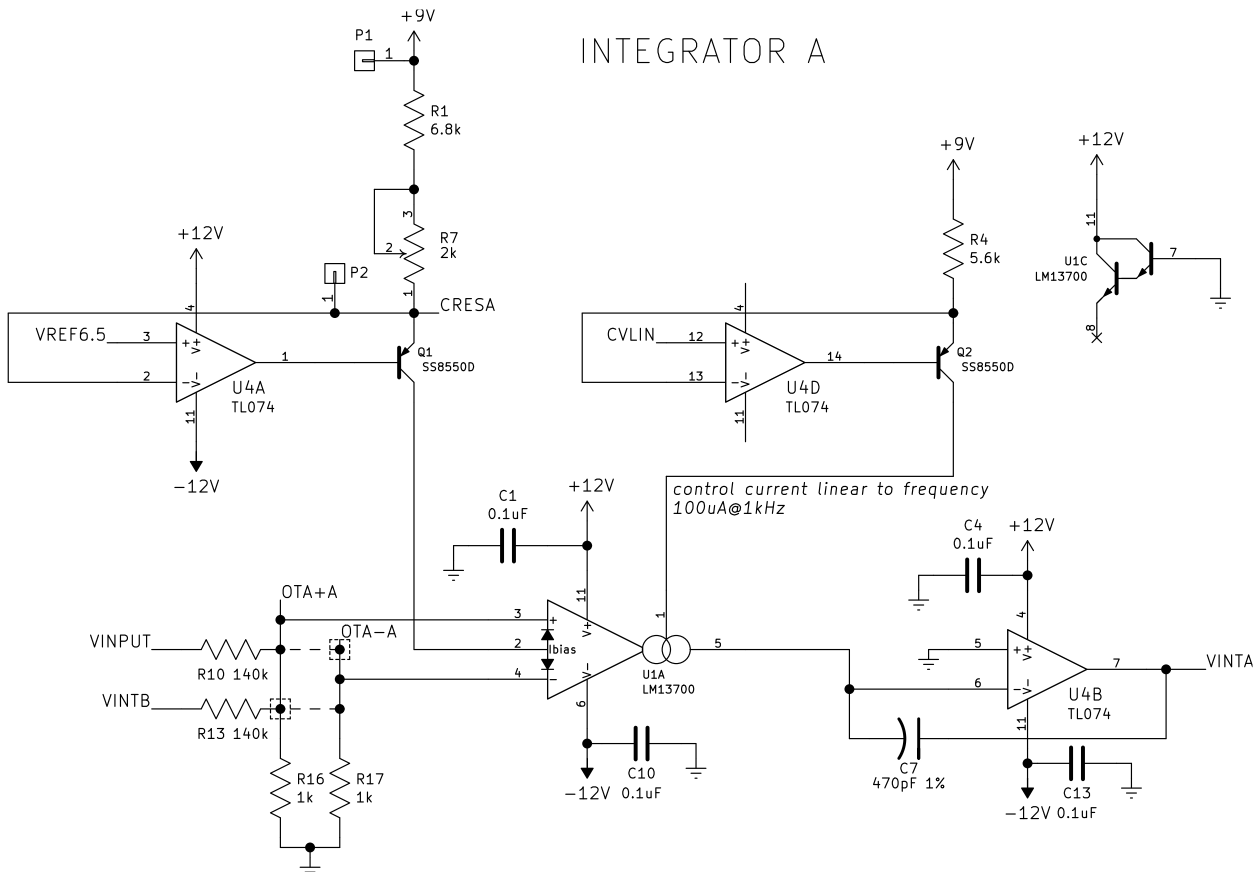


Figure 4: One integrator in the filter core.

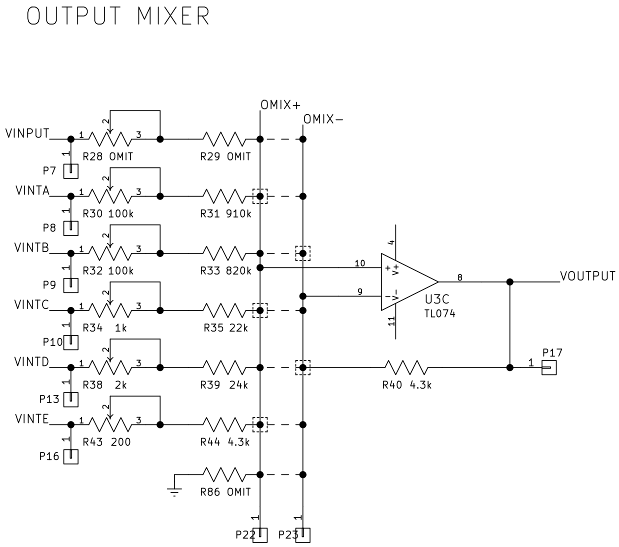


Figure 5: The output mixer.

JFET-input op amp, the current output from U1A directly charges and discharges C7, providing a clean integrated voltage at the output of U4B.

The only remaining significant item in the integrator section is U1C, which is one of the buffers built into the LM13700. It is hooked up to do nothing; using U4B for the integrator (and output buffer) renders the LM13700's built-in buffer superfluous.

Output mixer

Figure 5 shows the schematic for the output mixer, which combines the integrator signals to generate the filter core output. It is a standard op amp sum/difference circuit, computing a linear combination of the integrator outputs. Each one has a trimmer for fine adjustment of its coefficient in the sum. Note that here, too, the dotted lines indicate alternate pads on the PCB, allowing this board to be used to realize other response curves by substituting component values and connections. There are also footprints provided (R28, R29, and R86) for components not needed in the standard build, but which might possibly be used by other response curves.

Control voltage processing

Figure 6 shows the schematic for the control voltage processing section. This is a fairly conventional design. There are several exponentially-scaled inputs that all feed into the summing node of the first op amp U10C: V/octave input through J3 and R66; exponential FM through J4, R64, and R69; coarse and fine tuning from the panel pots R81 and R78 and the scaling resistors R74 and R74; and a constant offset controlled by R88.

Note that the exponential FM input is really just a second V/octave input with an attenuation pot to allow it to be less sensitive than V/octave. However, because R64 and R66 might not match perfectly, the maximum-sensitivity setting on this input may not be perfectly exactly 1V/octave.

With both of the tuning panel pots seeing a 24V range, using 240kΩ to scale the coarse knob means it will have a range of ten octaves, and using 4.7MΩ on the fine tuning knob gives it a range of about half an octave.

The 680kΩ offset resistor R88 was chosen by experiment with the prototype. It keeps the tuning knob range roughly where we want it; in particular, it prevents the highest knob settings from hitting the hard limit on control current.

All these exponential control signals go through U10C, which is a standard inverting amplifier with a negative sub-unity gain. Its output responds at -220mV/octave. Then R67, R68, R71, R72, and R77 are a temperature-compensated voltage divider which reduces the control signal further to about -18mV/octave, with the same temperature coefficient as a silicon transistor (at least, as long as the ambient temperature is roughly in the 15° to 30° range). That scaled and temperature-compensated exponential control signal is applied to Q14.

What follows is a fairly standard two-transistor exponential current sink. The op amp U10B maintains a virtual ground on its negative input, pin 6. To do that, it must keep a constant current of 99μA flowing through Q14. The emitter of Q14 is therefore at its base voltage, minus whatever base-to-emitter voltage it takes to make such a transistor pass 99μA.

Suppose the control voltage applied to the base of Q14 were zero. Then Q14 and Q15 would see the same base-to-emitter voltage and each pass 99μA. CVLIN would then have a voltage 0.554V less than the +9V supply, the op amps in the integrator control current sources would copy that voltage across their own 5.6kΩ resistors, and the control currents would all be 99μA, making the module's nominal cutoff frequency 990Hz.

If the control voltages going into U10C are such as to drive the frequency up an octave (1V added to the V/octave input, or equivalent changes to the tuning knobs and FM input) then the base of Q14

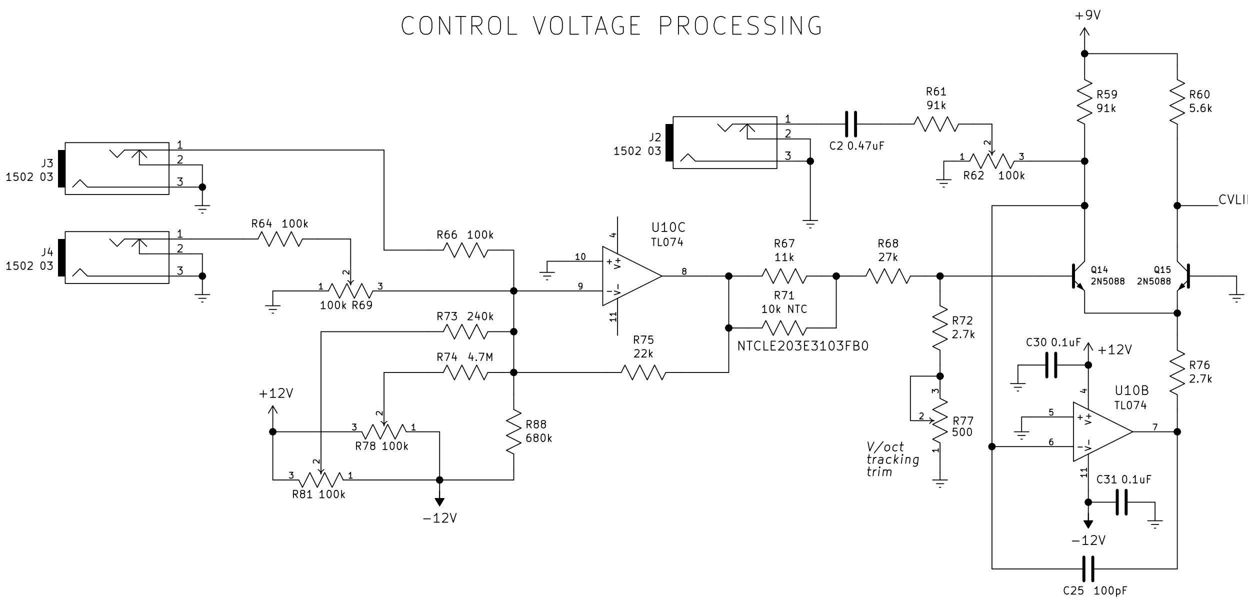


Figure 6: Control voltage processing.

will be driven down a temperature-adjusted 18mV. The op amp U10B pulls down its emitter accordingly. Then the base-to-emitter voltage of Q15, whose base is held constant at 0V, is increasing by 18mV, which by the nature of NPN transistors means its current must double. Thus, the tuning goes up an octave. The same thing happens in reverse if the base of Q14 goes up 18mV; then the current through Q15 is cut in half and the module tunes down an octave.

The resistor R76 is chosen to keep the output voltage of U10B in a comfortable range; higher resistance is better for stability, but we don't want the op amp output to go too close to the rails in normal operation. Here, it will be at about −5.3V (1.6mA for Q15 and 0.1mA for Q14 going through the 2.7kΩ resistor, plus about 0.7V for Q15's base-to-emitter drop) when the control current hits its limit.

The capacitor value for C25 was chosen after taking some careful scope measurements on a prototype of the circuit. The thing is that op amps like the TL074 are designed to guarantee stability when used at gains of at least unity. They are used with feedback loops typically composed of resistors, which invariably have some insertion loss. Insertion loss in the feedback loop is equivalent to gain in the overall op amp circuit, and improves stability. Even an inverting op amp circuit like that around U10C which may appear to have sub-unity gain has a greater than unity "noise gain" because of the loss in the feedback loop, and it is unconditionally stable. But in the case of U10B, we have Q14 in the feedback loop of the op amp functioning as a common-base amplifier from the op amp's point of view, and the gain of that amplifier will drive the op amp into instability unless we do something about it. Including C25 kills the loop gain at ultrasonic frequencies (starting from about 100kHz) and prevents the op amp from going into parasitic oscillation in the low megahertz range.

About the current limit: note that CVLIN cannot go much below 0V because the transistor will saturate and prevent its collector from going much below its base. That limits the current through R60, which is mirrored as the control current to all the LM13700s, to about 1.6mA, safely below their upper limit of 2.0mA. Attempts to drive the module to higher frequencies with higher control voltages will cause U10B to drive Q15 into saturation and suck increasing amounts of current through its base, but the power supply rails and R76 prevent that from being more than about 2 or 3mA, which is safely within the transistor's capabilities.

Linear FM is applied through J2, AC-coupled through C2 and attenuated by R62. Whatever current we add or remove through this jack will be added to or removed from the reference current passing through Q14; since the control currents to the LM13700s all consist of this reference current multiplied by the value set by the exponential control voltages, changing the reference current has the effect of scaling the module's master frequency. This is not through-zero linear FM; the lowest possible frequency is zero.

VCA and feedback

Figure 7 shows the schematic for the VCA and feedback subsystem. The VCA is a fairly standard LM13700 circuit using the one leftover amplifier (three chips, six amplifiers, five needed for the filter core). As with the core VCAs, the LM13700's built-in buffer is connected to do nothing.

Since accuracy is less critical at this point than in the core, we use just a single transistor (Q11) as the source for the linearizing diode current instead of a full op-amp-based precision current source. The current is fixed at about 230μA.

The control voltage drives Q12, which is configured as an emitter follower, to generate a current through R58 that will control the amplifier's gain linearly. The diode D1 is to protect the transistor against negative input voltages, and the resistor network allows the attenuation knob to work and makes the normalized input voltage when no cable is plugged in be equivalent to about 5V (it is actually 9V, but with a high impedance that drops it down to 5V).

D3 and R63 hold the base of Q13 at one diode drop below ground, so its emitter is roughly at ground; since Q12's emitter is one diode drop below its base, the overall voltage across R58 ends up being one diode drop less than the unipolar control voltage. At that level of approximation, it would seem the VCA cuts out when the input voltage goes below about 0.6V. In fact, this effect is not sharp, because the "diode drop" from emitter to base of these transistors is smaller when the current is very near zero; the VCA will start to pass signal at a small fraction of a volt, but then enter into its main linear behaviour at about 0.6V. Part of the rationale for this design is that we want to make sure it will fully "close" at zero input; VCAs which pass some signal with zero control voltage get a lot of complaints from users, and such behaviour would be especially annoying in the case of this filter, with its attempt at a brick-wall frequency response.

The VCA output goes through a Zener-diode clipping circuit that provides two levels of clipping, soft at about ±5.3V (4.7V Zener voltage from 0.6V for the other, forward-biased, diode) and hard at about ±6.6V. This is meant to provide both a clean gain roll-off when the module is used as an oscillator, and some "warmth" and reasonable limits on output level in filter mode when the built-in VCA is used. The sharp response cutoff makes output level especially unpredictable for this filter compared to other common synth filters.

The mode switch SW3 selects how the VCA will be connected. It can be in the output path, in which case the input buffer takes its input only from the module input jack J5, and the output buffer takes its input from the VCA. The other setting uses the VCA for feedback. Then the VCA output goes to the input buffer, and the output buffer is driven directly by the filter core's output mixer.

The input buffer is a very much standard negative-unity-gain inverting amplifier. It provides a well-behaved impedance to the outside world, sums the input signal with any feedback from the VCA when in feedback mode, and provides the 180° phase shift needed to support oscillation. The output buffer is a similar circuit adapted for driving a cable and another module's input: it has an in-the-loop current limiting resistor to protect against short circuit, and a 22pF capacitor for phase compensation.

Power inlet and reference generator

Figure 8 shows the schematic for the power- and voltage-handling circuitry.

Power from the Eurorack power connector P24 goes through two Schottky diodes for reverse-connection protection, and is filtered by a pair of 10μF capacitors before going to power all parts of the module. Control currents are all sourced out of a local +9V supply regulated by a 78L09 chip, both to keep them as clean as possible and so that op amp outputs can comfortably approach this supply voltage. There is also a reference voltage called VREF6.5, which is defined to be one TL431 drop (of 2.495V) less than the +9V supply. The constant difference between VREF6.5 and +9V is used as a reference by the constant-current sources for LM13700 linearizing-diode currents; they drive resistors to voltage drops matching this difference.

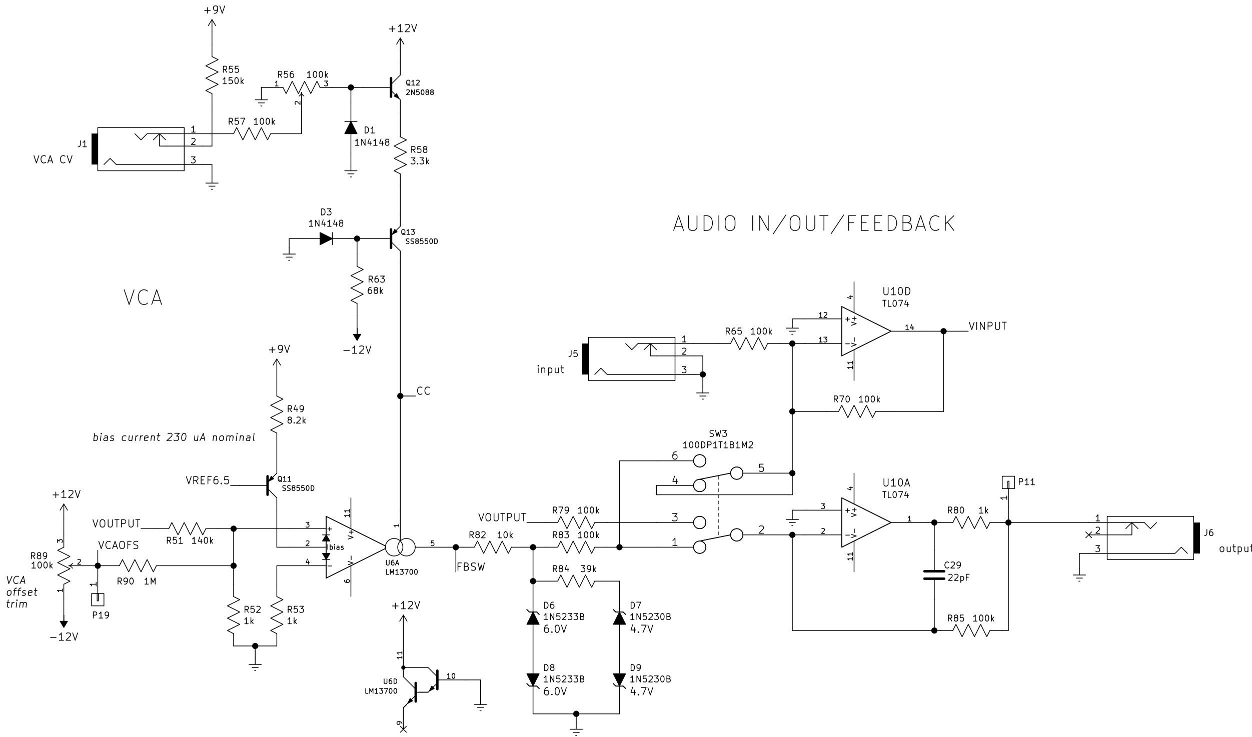


Figure 7: VCA and feedback.

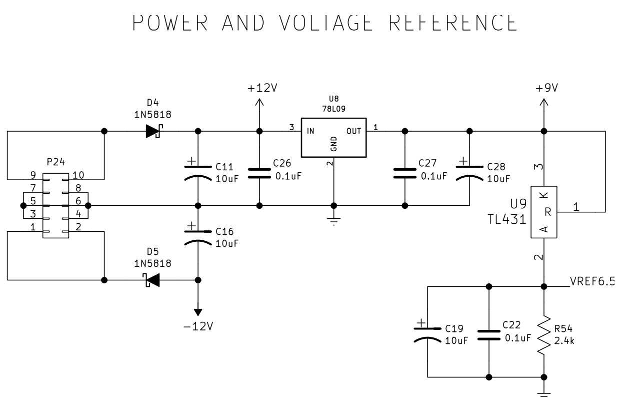


Figure 8: Power handling and reference voltage section

Filter curve calculations

This chapter goes through the calculations for choosing the component values and calibration data for the MSK 007's Musical Near-Elliptic (MNE) Lowpass response curve, which is the first and default response for the filter and corresponds to the silkscreened markings on the circuit boards. Understanding these calculations is not necessary for building or using the filter; they are provided for reference, education, and to support designing other response curves in the future. Calculations are usually given using as many decimal places as the input values allow, up to a maximum of eight, even though the actual hardware cannot be built to such precision.

Transfer function

The poles and zeroes were chosen by starting with those of an elliptic filter that would have low and high cutoff frequencies 1 and 2.3 respectively, with 3dB of passband ripple and a stopband attenuation of 70dB; observing that it has response peaks near frequencies $\frac{2}{3}$ and 1 and nulls near 2 and 3, which are in nice harmonic relations to each other; and then manually choosing the poles and zeroes to make those relations near-exact. The resulting selections of poles and zeroes are as shown in Figure 9.

The Bode plot is in Figure 10, with a curve showing the phase and some notable points marked. Note that the frequency at which the module will oscillate (with an inverting amplifier providing just enough feedback) is the one where 180° phase shift occurs, namely 0.7300 on the normalized scale of the plot. The highest-frequency peak at normalized frequency 1 is basically the cutoff of the lowpass action, and is at 1.3699 of the oscillation frequency.

The transfer function $H(s)$ is as shown in Figure 10. Normalizing to make the constant terms 1 (that is, dividing the numerator and denominator each by their constant terms, 36 and 0.12376413 respectively) gives the normalized transfer function $\hat{H}(s)$, also shown in the figure.

Poles: $-0.239,\ -0.178 \pm 0.680j,\ -0.060 \pm 1.022j$

Zeroes: $\pm 2j,\ \pm 3j$

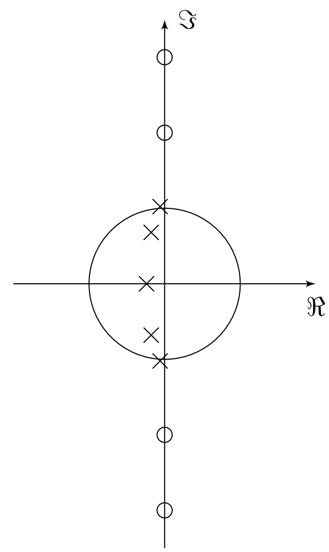
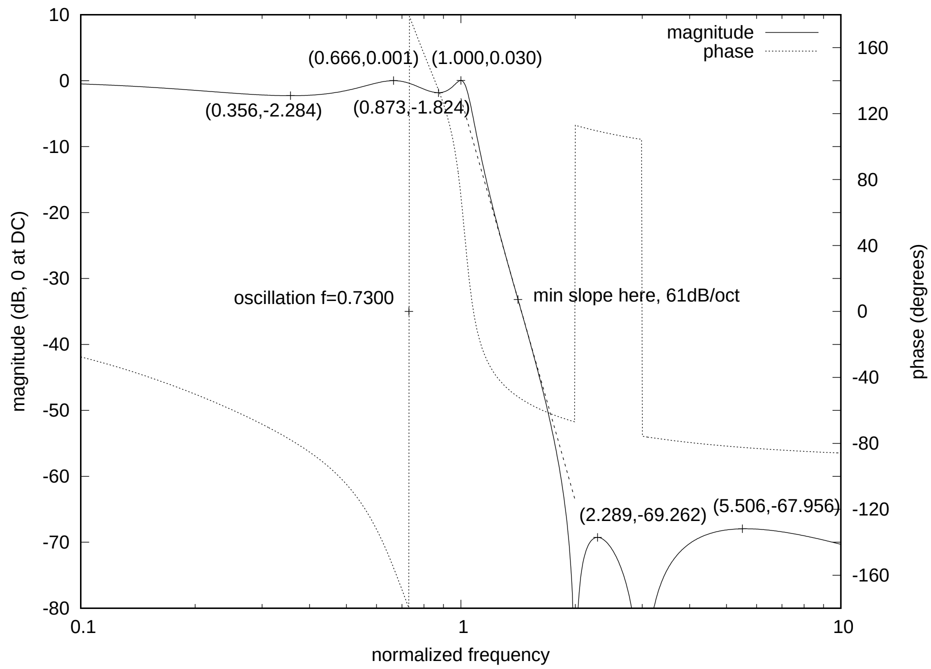


Figure 9: Poles and zeroes of the filter response



$$H(s) = \frac{(s^2+4)(s^2+9)}{(s+0.239)(s^2+0.356s+0.494084)(s^2+0.120s+1.048084)}$$
$$= \frac{s^4+13s^2+36}{s^5+0.715s^4+1.69865s^3+0.8112s^2+0.62119s+0.12376413}$$
$$\hat{H}(s) = \frac{0.02777778s^4+0.36111111s^2+1}{8.07988550s^5+5.77711814s^4+13.72489751s^3+6.55440312s^2+5.01914408s+1}$$

Figure 10: Bode plot and formulas for the filter response

Leapfrog design procedure

Now we follow the procedure of Sun* for a fifth-order output summer type leapfrog filter. In his notation, the coefficients of the transfer function are:

$$A_5 = 0 \quad A_4 = 0.02777778 \quad A_3 = 0$$
$$A_2 = 0.36111111 \quad A_1 = 0 \quad A_0 = 1$$
$$B_5 = 8.07988550 \quad B_4 = 5.77711814$$
$$B_3 = 13.72489751 \quad B_2 = 6.55440312$$
$$B_1 = 5.01914408 \quad B_0 = 1\,.$$

First we compute the rates for the integrators (design formulas from Sun's equation display (25), for a fifth-order transfer function). The units of measure (not shown) are technically seconds; the numbers represent the time required for the integrator to charge from zero to its input voltage if presented with a constant input voltage, when the filter is tuned to the normalized frequency 1 radian per second.

$$\begin{aligned}
\tau_5 &= \frac{B_5}{B_4} \\
&= 1.39860140 \\
\tau_4 &= \frac{B_4}{B_3 - B_2\tau_5} \\
&= 1.26747916 \\
\tau_3 &= \frac{B_3 - B_2\tau_5}{B_2 - (B_1 - \tau_5)\tau_4} \\
&= 2.31905231 \\
\tau_2 &= \frac{B_2 - (B_1 - \tau_5)\tau_4}{B_1 - \tau_3 - \tau_5} \\
&= 1.51017355 \\
\tau_1 &= B_1 - \tau_3 - \tau_5 \\
&= 1.30146660
\end{aligned}$$

Next we compute the weights for the output mixer ("output summer type" fifth order topology, design formulas from Sun's equation display (48)). These are unitless numbers, representing the proportion of each integrator's output that should be included in the sum for the global output. Note the last one forces them to sum to A_0, which (because of the normalization) is 1.

$$\begin{aligned}
\alpha_0 &= \frac{A_5}{B_5} \\
&= 0 \\
\alpha_1 &= \frac{A_4 - \alpha_0 B_4}{\tau_2\tau_3\tau_4\tau_5} \\
&= 0.00447430 \\
\alpha_2 &= \frac{A_3 - \alpha_0 B_3 - \alpha_1\tau_2\tau_3\tau_4}{\tau_3\tau_4\tau_5} \\
&= -0.00483124 \\
\alpha_3 &= \frac{A_2 - \alpha_0 B_2 - \alpha_1(\tau_2\tau_3 + \tau_2\tau_5 + \tau 4\tau_5) - \alpha_2\tau_3\tau_4}{\tau_4\tau_5} \\
&= 0.19307299 \\
\alpha_4 &= \frac{A_1 - \alpha_0 B_1 - \alpha_1(\tau_2 + \tau_4) - \alpha_2(\tau_3 + \tau_5) - \alpha_3\tau_4}{\tau_5} \\
&= -0.17101598 \\
\alpha_5 &= A_0 - (\alpha_0 + \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4) \\
&= 0.97829992
\end{aligned}$$

Integrator component values

The integrators in the MSK 007 have rates determined by a global frequency-control current I_{ABC} derived from the module-input control voltages and copied to all integrators; a diode-biasing current I_{D} local to a single integrator and actually determined by a programming resistance R (made up of a fixed resistor and a trimmer in series); resistor dividers on the positive and negative voltage inputs; and an integration capacitor C. After setting most of the other values from circuit-design requirements, we will choose the value of R to realize a given τ.

For the initial calculation: assume the module's operating frequency f is 10kHz, corresponding to $I_{\mathrm{ABC}} = 1$mA. With a 1V input, we want the output capacitor to charge at a rate $\partial V/\partial t = 2\pi f/\tau\mathrm{V} = 62.831853\mathrm{kV/s}$. Choosing a 470pF capacitor for now (a decision which originated in working backwards from reasonable scales for the final component values), we want the OTA to produce an output current I_{O} of $62.831853/\tau(\mathrm{kV/s}) \cdot 470pF = \tau 29.53097091\mu\mathrm{A}$.

We assume the input of the LM13700 consumes half of the current from the 1V input, and has infinite impedance. These assumptions, although false, have only a multiplicative-constant effect (so that the ratios will end up right); we can scale the capacitors using experimental data later to take up any slack, if necessary.

The 1V input is looking into a 141kΩ impedance

*Yichuang Sun, 2006, Synthesis of Leap-Frog Multiple Loop Feedback OTA-C Filters, IEEE Transactions on Circuits and Systems, Part 2: Express Briefs, 53, 9.

and generates a current of 7.09219858μA; half of that is the LM13700 input current $I_\mathrm{S} = 3.54609929\mu$A. Then from the formula in the LM13700 datasheet, solving for I_D,

$$I_\mathrm{O} = I_\mathrm{S}\left(\frac{2I_\mathrm{ABC}}{I_\mathrm{D}}\right)$$
$$I_\mathrm{D} = \tau 240.16137504\mu\mathrm{A}\,.$$

This current comes from imposing 2.496V (the TL0431 reference voltage) across the programming resistor R; so the resistance to produce this is $2.496\mathrm{V}/\tau 240.16137504u\mathrm{A} = 10.39301178\mathrm{k}\Omega/\tau$. We apply that formula to each of the programming resistances for the five dividers:

$$\begin{aligned}
\mathrm{R1} + \mathrm{R7} &= 10.39301178\mathrm{k}\Omega/1.30146660\\
&= 7.98561544\mathrm{k}\Omega\\
\mathrm{R2} + \mathrm{R8} &= 10.39301178\mathrm{k}\Omega/1.51017355\\
&= 6.88199831\mathrm{k}\Omega\\
\mathrm{R3} + \mathrm{R9} &= 10.39301178\mathrm{k}\Omega/2.31905231\\
&= 4.48157712\mathrm{k}\Omega\\
\mathrm{R22} + \mathrm{R26} &= 10.39301178\mathrm{k}\Omega/1.26747916\\
&= 8.19974963\mathrm{k}\Omega\\
\mathrm{R23} + \mathrm{R27} &= 10.39301178\mathrm{k}\Omega/1.39860140\\
&= 7.43100342\mathrm{k}\Omega\,.
\end{aligned}$$

Note we want to keep the programming current in the range of a few hundred μA. Texas Instruments recommends using as much as possible given gain constraints and what the chip can handle, to keep distortion low, with 1mA as a default target; but other experimenters have reported that 1mA is too much and causes other distortion, and 500μA works better. Here we have about a 2:1 range between the largest and smallest τ values, so it's possible to use the same capacitor values in all integrators and have all the programming currents in the desired range. The programming currents here are from about 304μA to 557μA, by Ohm's law on the above resistances and 2.496V. If there were a wider range of τ values, we might want to use unequal capacitors to bring the programming currents closer together.

Mixer resistor values

Now we follow the procedure described in several sources, including Sheingold[†] and Ardizzoni[‡] to choose resistor values for an op amp summer circuit. The op amp output voltage (`VOUTPUT` from U3C on the schematic) is supposed to be a weighted sum of the integrator voltages, where the weights are the α coefficients from the leapfrog design procedure. Some of them are negative; and in principle `VINPUT` could be included in the sum too, but for this particular curve, because $\alpha_0 = 0$, it will not be included and we can leave out the components R28 and R29 which would set its value.

We compute the sums of the positive and negative coefficients, as described by Sheingold.

$$\begin{aligned}
\Sigma_\mathrm{a} &= \sum_{\alpha_i>0}\alpha_i\\
&= 0.00447430 + 0.19307299 + 0.97829992\\
&= 1.17584721\\
\Sigma_\mathrm{b} &= \sum_{\alpha_i<0}-\alpha_i\\
&= 0.00483124 + 0.17101598\\
&= 0.17584722
\end{aligned}$$

Because the α values always add up to 1 in the leapfrog design procedure, the discriminant Δ will necessarily be 0; with the numerical values above it comes out to 0.00000001 due to rounding, but we will treat it as 0, which means that the resistor to ground R86 will not be needed. It is included in the schematic and PCB for extra flexibility, should someone want to change the design to have non-unity total gain through the mixer.

There are different ways to select the feedback resistance R_F. Sheingold suggests choosing a minimum impedance to appear at either op amp input and choosing the feedback resistance to achieve that. I instead worked from the constraint of not wanting the maximum input resistor value to be any more than 1MΩ, which means R_F can be at most 1MΩ times the absolute value of the smallest α (not counting the zero input coefficient α_0; in effect we are assuming we allow *infinite* resistors, just no finite ones greater than 1MΩ):

$$\begin{aligned}
R_\mathrm{F} &\le 1\mathrm{M}\Omega\cdot\min\{|\alpha|\}\\
&\le 4.47\mathrm{k}\Omega\,.
\end{aligned}$$

[†] Dan Sheingold, Analog Dialogue Vol. 10, No. 1 (1976), "Simple Rules for Choosing Resistor Values in Adder-Subtractor Circuits"

[‡] `http://electronicdesign.com/ideas-design/efficiently-design-op-amp-summer-circuit`

The next smaller E24 standard value is 4.3kΩ; we use that for R40. Resistance values for the inputs (each of which is the sum of a fixed resistor and a trimmer) follow by dividing the feedback resistor by the absolute value of each α:

$$\begin{aligned}
\mathrm{R30} + \mathrm{R31} &= R_{\mathrm{F}}/|\alpha_1| \\
&= 961.0437\mathrm{k}\Omega \\
\mathrm{R32} + \mathrm{R33} &= R_{\mathrm{F}}/|\alpha_2| \\
&= 890.0415\mathrm{k}\Omega \\
\mathrm{R34} + \mathrm{R35} &= R_{\mathrm{F}}/|\alpha_3| \\
&= 22.2714\mathrm{k}\Omega \\
\mathrm{R38} + \mathrm{R39} &= R_{\mathrm{F}}/|\alpha_4| \\
&= 25.1438\mathrm{k}\Omega \\
\mathrm{R43} + \mathrm{R44} &= R_{\mathrm{F}}/|\alpha_5| \\
&= 4.3954\mathrm{k}\Omega
\end{aligned}$$

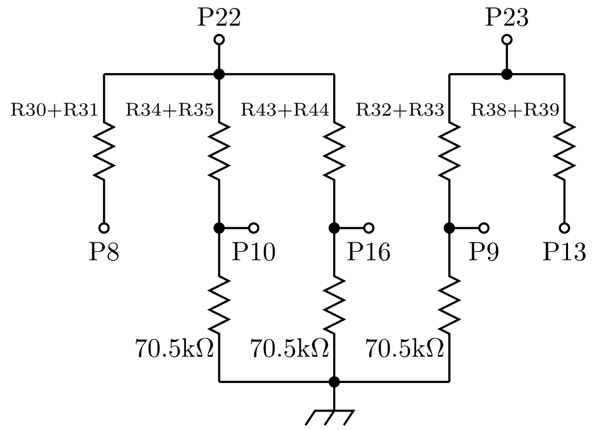
The breakdown of specific values for the fixed resistors and trimmers follows by choosing standard values to give adjustment ranges of between about ±2% and ±5% around the nominal totals. The fixed resistors corresponding to negative α values need to be connected (using the optional pads on the board) to the op amp negative input; those are R33 and R39. The other three go to the positive input.

Mixer pre-adjustment targets

Most adjustments for the module are done by setting the trimmers in the resistor network on Board 3. The recommended procedure is to first "pre-adjust" Board 3 by itself, to bring the resistors to the values they ought to have if the other boards behaved exactly according to the nominal design values; then connect Board 3 to the other two boards and do any further adjustments needed to account for imperfect component values on the other boards (for instance, the tolerance of the integrator capacitors).

For the integrator programming resistances, the pre-adjustment is easy because disconnecting the boards allows a direct ohmeter reading of each programming resistance. For the output mixer, however, things are more complicated because some of the resistances that need to be adjusted are permanently connected with other things and cannot be measured in isolation.

With Board 3 separated from the others, the relevant portion of the resistor network is as shown in this simplified schematic:



There is also a connection to the power supplies through R87, but its effect is negligible. The signals `VINTA` and `VINTD` are deliberately assigned to two of the inter-board pins each, with the connections to the mixer joined to the OTA input voltage dividers only through traces on Board 2; these connections are broken when the boards are disconnected. These two signals were chosen for this purpose in an effort to maximize the sensitivity of the remaining indirect measurements while economizing on inter-board pins, which are in short supply. An earlier draft design used an elaborate arrangement of DIP switches on Board 3 to allow isolating the signals, but (given how well the module performed in breadboard testing even when very inaccurately adjusted) such complexity seemed unnecessary.

From the diagram, we can measure R30+R31 directly by testing resistance between test points P8 and P22; R32+R33 between P9 and P23; and R38+R39 between P13 and P22. That leaves R34+R35 and R43+R44 not directly accessible.

If we measure between P10 and P22, we see R34+R35 in parallel with a series combination of 70.5kΩ, 70.5kΩ, and 4.3954kΩ. The target measurable value for adjusting R34 is given by $22.2714\mathrm{k}\Omega \| (70.5\mathrm{k}\Omega + 70.5\mathrm{k}\Omega + 4.3954\mathrm{k}\Omega = 19.3130\mathrm{k}\Omega$.

If we measure between P16 and P22, we see R43+R44 in parallel with a series combination of 70.5kΩ, 70.5kΩ, and 22.2714kΩ. The target measurable value for adjusting R43 is given by $22.2714\mathrm{k}\Omega \| (70.5\mathrm{k}\Omega + 70.5\mathrm{k}\Omega + 22.2714\mathrm{k}\Omega = 4.2802\mathrm{k}\Omega$.

Precise adjustment targets

The precise adjustment procedure, with all three boards joined, starts by tuning the module to oscillate at a specified frequency, then turning down the feedback, feeding it the same frequency as input, and adjusting the integrator time constants to get the right phase shift through each integrator. The reason to adjust with an external signal rather than while the filter is self-oscillating is that during self-oscillation, the phase shift adjustments interact with the resonant frequency in a way that is difficult to control.

The reference frequency ought to be one we can conveniently measure, and around the typical setting of the module in actual use. Guessing that a cut-off frequency of 1kHz is typical, it corresponds to an oscillation frequency of 730Hz, and the closest musical note (concert pitch 12-EDO) is F♯ an augmented eleventh, or one and a half octaves, above middle C; that is 739.9888Hz. That's a convenient reference point. Users can call it 740Hz if they wish. One period of this frequency is 1351.3757μs.

The behaviour of the filter, given a sine wave at some fixed frequency, can be described by a set of simultaneous equations over the complex numbers. Where V_I and B_O are the input and output voltages respectively, and the integrator outputs are V_A, V_B, V_C, V_D, V_E, with f a variable representing the frequency scaling, we have

$$\begin{aligned}
V_\mathrm{A} &= (V_\mathrm{I} - V_\mathrm{B})fj/\tau_1 \\
V_\mathrm{B} &= (V_\mathrm{A} - V_\mathrm{C})fj/\tau_2 \\
V_\mathrm{C} &= (V_\mathrm{B} - V_\mathrm{D})fj/\tau_3 \\
V_\mathrm{D} &= (V_\mathrm{C} - V_\mathrm{E})fj/\tau_4 \\
V_\mathrm{E} &= (V_\mathrm{D} - V_\mathrm{E})fj/\tau_5 \\
V_\mathrm{O} &= \alpha_0 V_\mathrm{I} + \alpha_1 V\mathrm{A} + \alpha_2 V\mathrm{B} + \alpha_3 V\mathrm{C} \\
&\qquad + \alpha_4 V\mathrm{D} + \alpha_5 V\mathrm{E}\,.
\end{aligned}$$

We can find the oscillation frequency by fixing $V_\mathrm{I} = -V_\mathrm{O}$ (180° phase shift), and the response to other signals (of each integrator, not only the overall output response) by setting other values of V_I and looking at the resulting values of the variables. However, instead of solving these equations explicitly, I used the Qucs circuit simulator with voltage-controlled current sources feeding into ideal capacitors to simulate the integrators, referencing everything to 1Hz. An integrator with a time constant of τ would be simulated by a $(1/\tau)$A/V voltage-controlled current source feeding a $(1/2\pi)$F capacitor. I also added more voltage-to-current converters with rates equal to the α values, all feeding into a common summing node with a current probe to compute the response at the output (technically, it becomes I_O instead of V_O).

Assume the earlier computation of the oscillation frequency as 0.7300 of the cutoff frequency (which came from using Gnuplot to measure off the input-to-output transfer-function phase chart) was correct. Giving the simulated circuit a sine wave input of 0.7300Hz and 1V allows computing the complex amplitudes that should be observed in the oscillating filter. In magnitude and phase form, they are:

$$\begin{aligned}
V_\mathrm{A} &= 1.42150457\mathrm{V} \ @ -14.3969145^\circ \\
V_\mathrm{B} &= 1.46708733\mathrm{V} \ @ -63.0804611^\circ \\
V_\mathrm{C} &= 1.08763802\mathrm{V} \ @ -93.4388609^\circ \\
V_\mathrm{D} &= 1.67693332\mathrm{V} \ @ -134.421988^\circ \\
V_\mathrm{E} &= 1.17339866\mathrm{V} \ @ \quad 179.983267^\circ \\
I_\mathrm{O} &= 0.956850634\mathrm{V}@ \quad 179.983267^\circ
\end{aligned}$$

The closeness of the I_O phase to 180° gives some idea of the amount of precision we can really expect from this calculation. Taking differences of the phases in degrees, and multiplying by the period of the 739.9888Hz oscillation frequency (which is 1351.3757μs/360°), we get the following phase and time difference targets. For a perfectly adjusted module oscillating at 739.99888Hz:

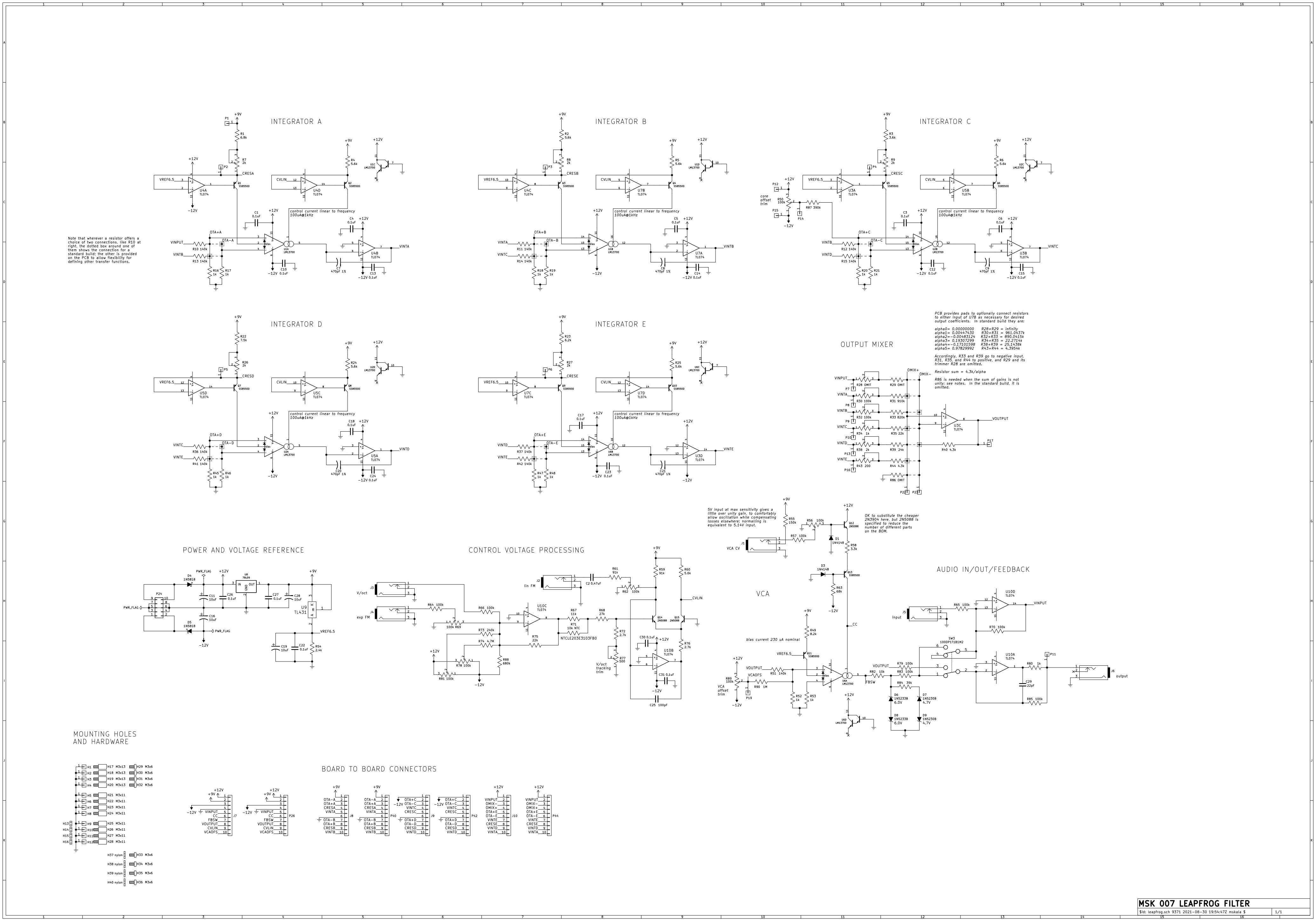
- the integrator A output should lead the core input by 14.3969145° or 54.04344558μs;
- the integrator B output should lead the integrator A output by 48.6835466° or 182.74933851μs;
- the integrator C output should lead the integrator B output by 30.3583998° or 113.96001050μs;
- the integrator D output should lead the integrator C output by 40.9831271° or 153.84333909μs;
- the integrator E output should lead the integrator D output by 45.594745° or 171.15452900μs; and
- the integrator E output and mixer output should be perfectly in phase.

Note the core input and mixer output are not the same as the module overall input and output; there are inverting buffers between the core and the outside world at both ends, and in feedback mode, the core output goes through the input buffer, which supplies the remaining 180° of phase shift.

Mechanical drawings

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 giving locations for components on the boards, both the board-to-board connectors and the components mounted on Board 1 that penetrate the front panel;
- 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.



INTEGRATOR A
INTEGRATOR B
INTEGRATOR C
INTEGRATOR D
INTEGRATOR E
control current linear to frequency
100uA@1kHz
Note that wherever a resistor offers a choice of two connections, like R10 at right, the dotted box around one of them shows the connection for a standard build; the other is provided on the PCB to allow flexibility for defining other transfer functions.
core offset trim
OUTPUT MIXER
PCB provides pads to optionally connect resistors to either input of U7B as necessary for desired output coefficients. In standard build they are:
alpha0= 0.00000000 R28+R29 = infinity
alpha1= 0.00447430 R30+R31 = 961.0437k
alpha2=-0.00483124 R32+R33 = 890.0415k
alpha3= 0.19307299 R34+R35 = 22.2714k
alpha4=-0.17101598 R38+R39 = 25.1438k
alpha5= 0.97829992 R43+R44 = 4.3954k
Accordingly, R33 and R39 go to negative input, R31, R35, and R44 to positive, and R29 and its trimmer R28 are omitted.
Resistor sum = 4.3k/alpha
R86 is needed when the sum of gains is not unity; see notes. In the standard build, it is omitted.
5V input at max sensitivity gives a little over unity gain, to comfortably allow oscillation while compensating losses elsewhere; normalling is equivalent to 5.14V input.
OK to substitute the cheaper 2N3904 here, but 2N5088 is specified to reduce the number of different parts on the BOM.
VCA CV
POWER AND VOLTAGE REFERENCE
CONTROL VOLTAGE PROCESSING
V/oct
exp FM
lin FM
V/oct tracking trim
VCA
bias current 230 uA nominal
VCA offset trim
AUDIO IN/OUT/FEEDBACK
Input
output
MOUNTING HOLES AND HARDWARE
BOARD TO BOARD CONNECTORS
MSK 007 LEAPFROG FILTER
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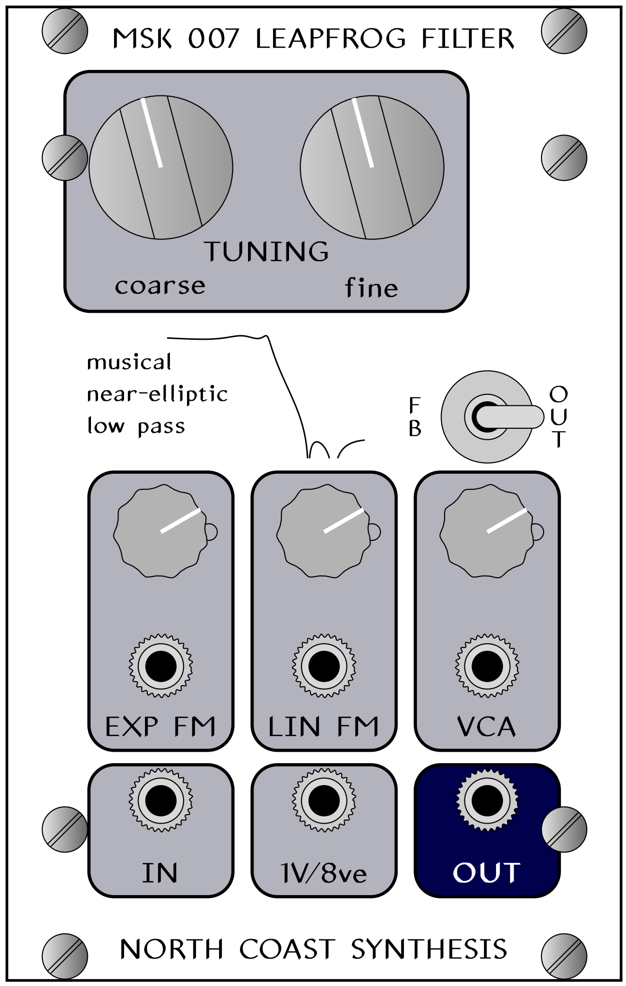
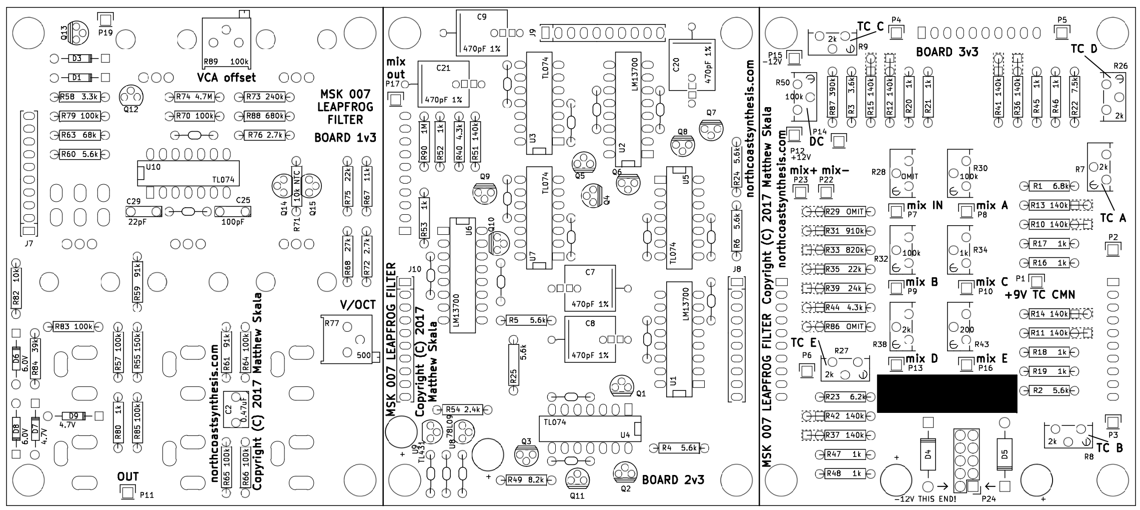
1/1


MSK 007 LEAPFROG FILTER
TUNING
coarse
fine
musical
near-elliptic
low pass
FB
OUT
EXP FM
LIN FM
VCA
IN
1V/8ve
OUT
NORTH COAST SYNTHESIS



MSK 007 LEAPFROG FILTER

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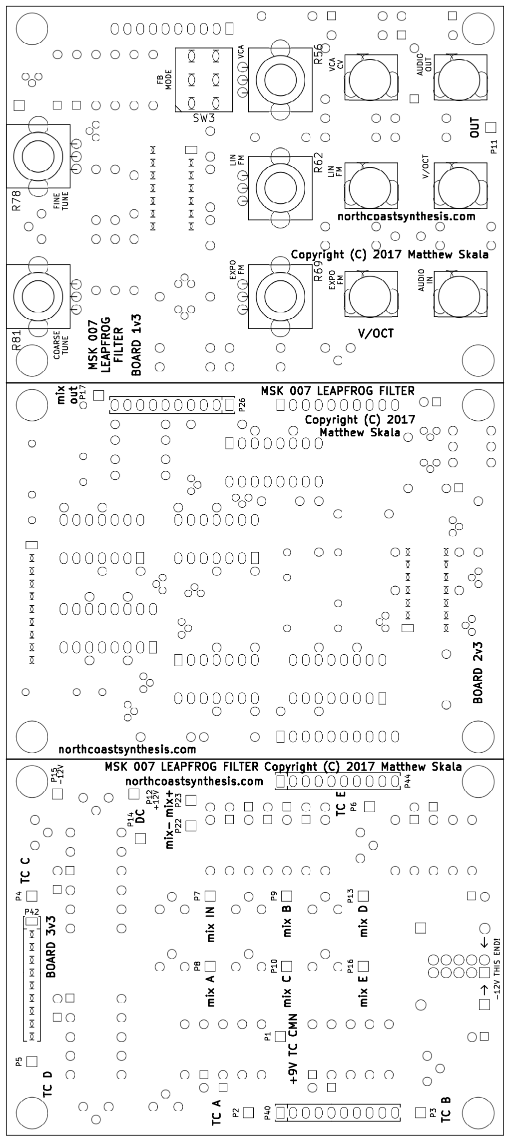
1/3



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1/3

BOARD TO PANEL HOLES

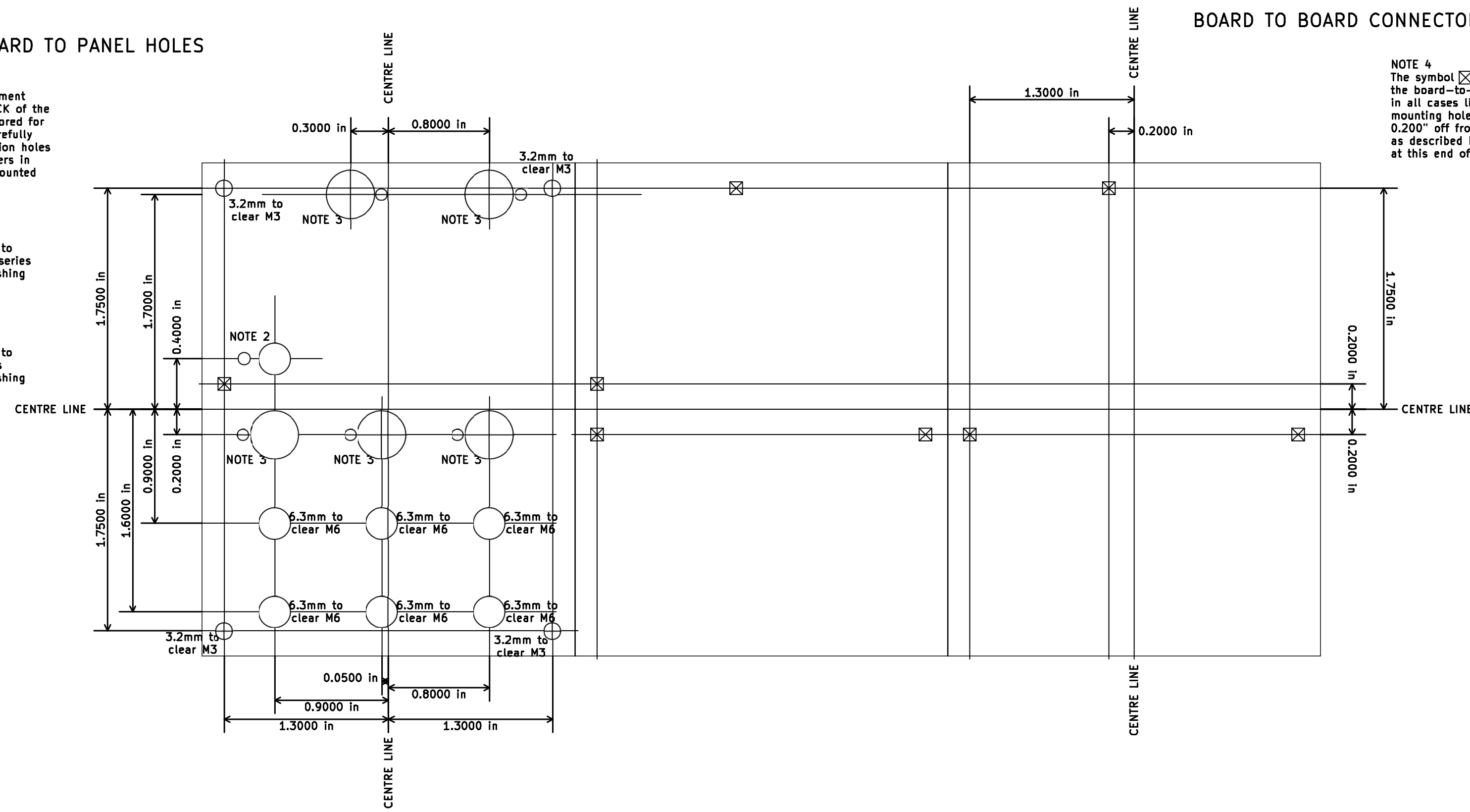
NOTE 1
This panel hole arrangement is as seen from the BACK of the panel and must be mirrored for a front view! Check carefully which side the antirotation holes are on; the potentiometers in particular are not all mounted in the same orientation.

NOTE 2
6.35mm hole on centre +2.38mm hole 6.10mm to side per E–Switch 100 series data sheet for 1/4" bushing and locking ring

NOTE 3
9.70mm hole on centre +2.20mm hole 6.35mm to side per BI Technologies data sheet for 3/8" bushing P260T potentiometers IN FIVE PLACES

BOARD TO BOARD CONNECTORS

NOTE 4
The symbol ☒ marks pin 1 of the board–to–board connectors, in all cases lined up with the mounting holes and pin 1 0.200" off from a centre line, as described by the dimensions at this end of the drawing.



MSK 007 LEAPFROG FILTER

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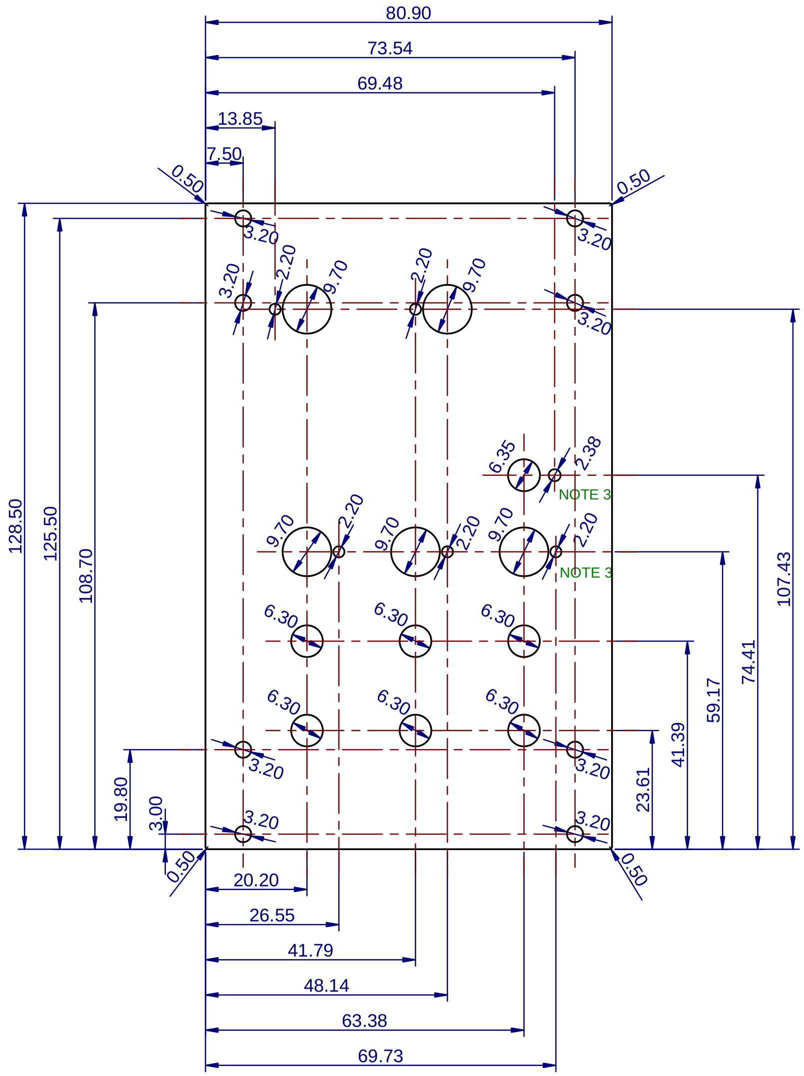
1/2



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 80.90mm, per Doepfer spec for a 16HP Eurorack synthesizer module.

3: These two holes have differing horizontal position, 69.48mm for the 2.38mm hole and 69.73mm for the 2.20mm hole.

MSK 007 Leapfrog Filter panel mechanical	
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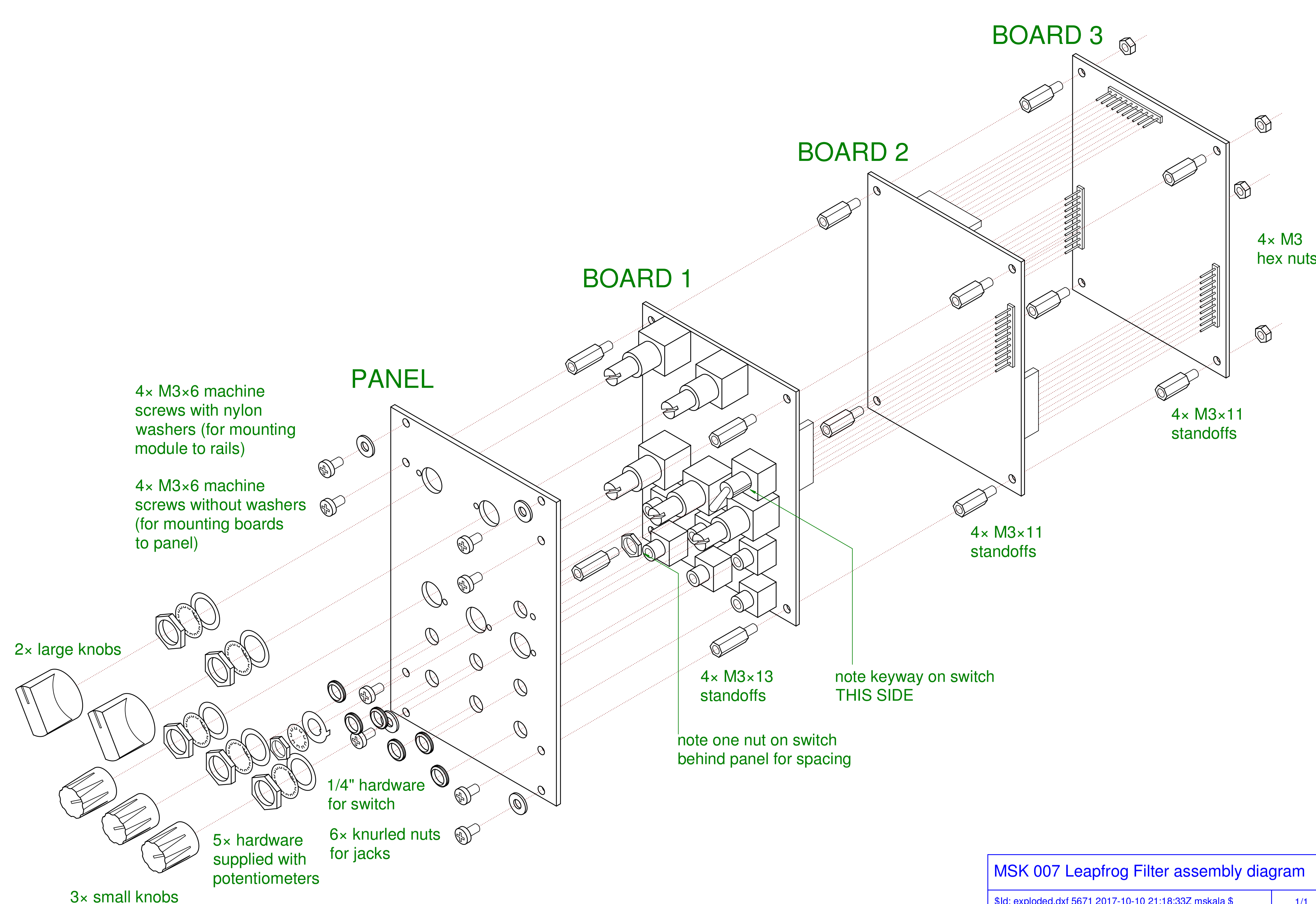

MSK 007 Leapfrog Filter assembly diagram

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