Evolution in Radio Design: building the next

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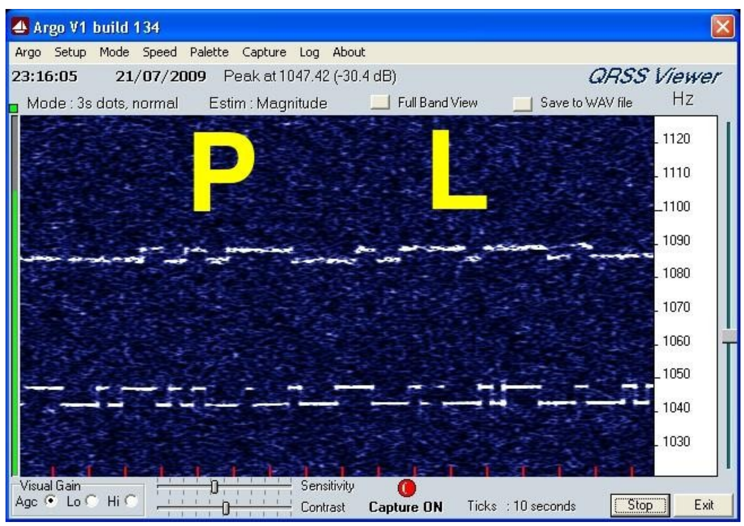
Introduction

I studied physics at university. I'm not an RF engineer, not an electronic engineer, not any kind of an engineer. Yet here I am, somehow ended up earning a living designing QRP Labs radio kits for QRP'ers. I've been thinking about all this lately. So in this seminar, I'm going to talk briefly about the QRP Labs story, from simple beginnings to significant complexity, one step at a time. Then some details about designing the next product in the QRP Labs lineup, with the simple aim: to create one of the greatest QRP transceivers in amateur radio history.

QRP Labs kits

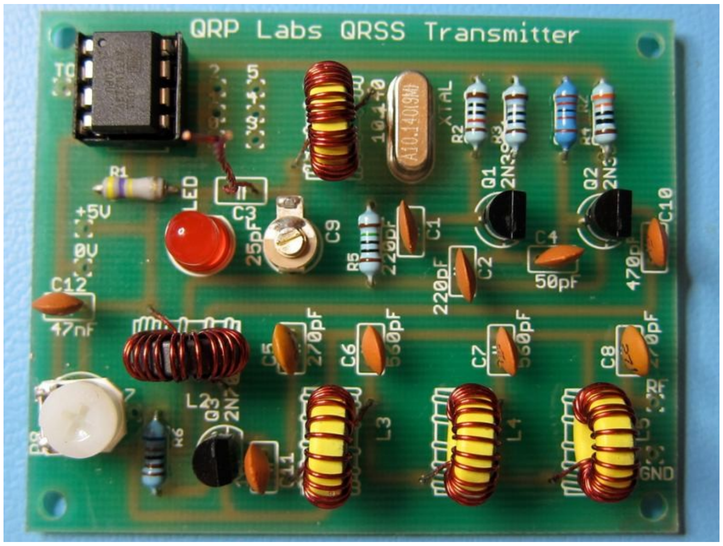
Back in May 2010, I presented a Dayton FDIM seminar for the first time, on the topic of QRSS (weak signal) modes. I excluded WSPR (Weak Signal Propagation Reporter) which was at that time still quite a new mode and was outside my personal experience.

The previous summer (July 2009) I had been on a two week vacation to Grenada, Caribbean. My wife and I aren't particularly quick at packing and it wasn't until 3am that we were finally finished, only two hours remained for sleeping before we had to get up and leave for the flight from London's Heathrow airport. Two hours? At that point – I just thought well, why bother to sleep at all, I'll build a QRSS beacon transmitter to take with me! I already had a 30m LPF from a former project, and some code on an ATtiny13 8-pin microcontroller to produce the letters "UPL" over and over in slow Morse. Two hours was enough to build a crystal oscillator, a 100mW amplifier, assemble it all in a tiny mint tin, test and adjust it, and have it ready with some antenna wire and a cellphone charger, in an ice cream box stuffed into the suitcase.



The screenshot (right) is a reception report by M0PUB on the opposite side of the Atlantic, showing the “PL” part of the “UPL” transmission. Weak Signal “ARGO” software (spectrum analysis) is used on a PC to display the transmission which can then be decoded visually. I used a 10.140 MHz crystal oscillator with a 5mm red LED used as a varactor diode to apply a small shift of a few Hz (typically 5 Hz) to the transmission on the Morse key-downs.

When I was invited to speak at Dayton FDIM 2010, my good friend Steve G0XAR and I had the idea that we could between us produce a QRSS kit to accompany the event. Back then there were no kits for QRSS modes at all. You either rolled your own or used a commercial transceiver. This was a first.

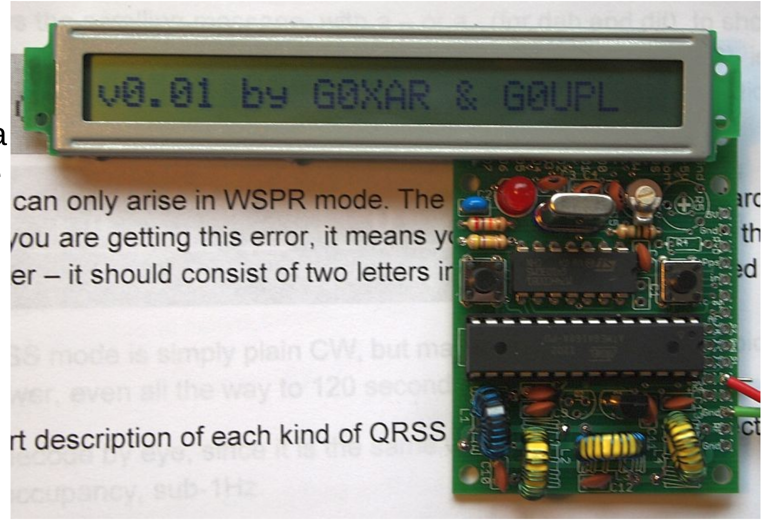


Using the proven Grenada QRSS design seemed a natural fit so that’s what we did. Steve handled the production (PCB, component procurement, kitting), while I did the design, firmware, documentation and support. We had no idea how to run a kit business, how to price a kit, anything. We decided to produce 100 and see what happened. The result was a long pile-up snaking around the FDIM conference hall on vendor’s evening, everyone seemed to want one of these little $15 kits! It took the whole evening for me to clear the pileup, each of the little ATtiny13 AVR chips had to be programmed specifically with a firmware version with the operator’s callsign programmed in.

A great success and we decided to keep producing them after the event. The first thing to go wrong was a little incident of cloning which was at the time quite annoying, but after a while being annoyed, I decided to put the energy instead into designing the NEXT QRP Labs kit. Following the don’t-get-mad-get-even ethos, the new kit would be so much better, and with only a modest price increase, that the cloners would need to give up. Which neatly solved that problem, as well as pushed QRP Labs forward.

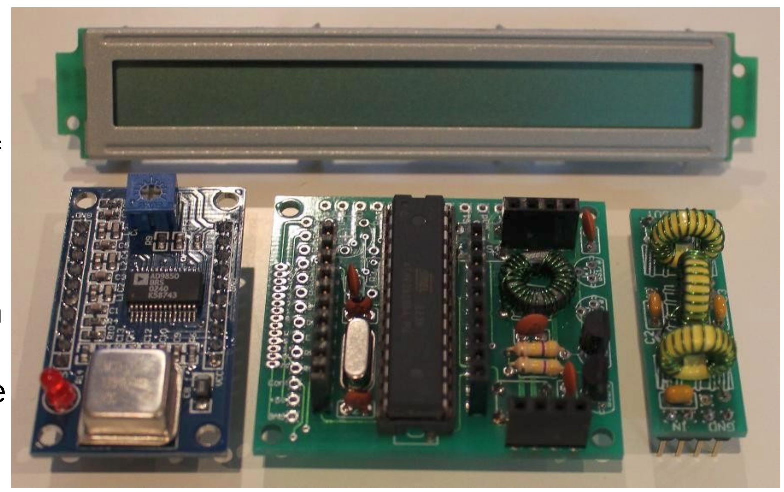
So begins a story of continuous evolution. Every QRP Labs kit was built on the lessons and elements of its predecessor(s). As my knowledge and experience grew, the complexity and quality of the kits grew with it, along with the worldwide popularity of these kits.

The “Ultimate QRSS/WSPR” kit used the same source code for its CW encoding as the first QRSS kit but added much much more. Now it was the first product ever to included WSPR in a standalone format, not requiring a PC to encode the WSPR tones. There were other modes too such as slow Hellshreiber. A higher quality double-sided, through-hole plated was easier to build and more durable. It had an LCD screen and two-button user interface so that the operator could configure it himself - no more need for individually compiled microcontroller programs! Plus a GPS interface for time and frequency discipline.



At the end of 2012 Steve G0XAR and I decided amicably to part ways on the QRP Labs project and a few months later I decided to relaunch it again on my own, with a new kit, the Ultimate2.

The Ultimate2 QRSS/WSPR kit was again a logical progression from the Ultimate (which became known then as U1). Much of the source code was the same. But now instead of the crystal oscillator, I used an AD9850 DDS module (the blue PCB on the left here). These were available for some years from China at very low prices – much less than the cost of an AD9850 DDS chip on its own from Digikey! I believe there was a batch of chips that became obsolete when ROHS (lead-free) regulations came in and ended up on the black market where they were made into these plug-in DDS boards.



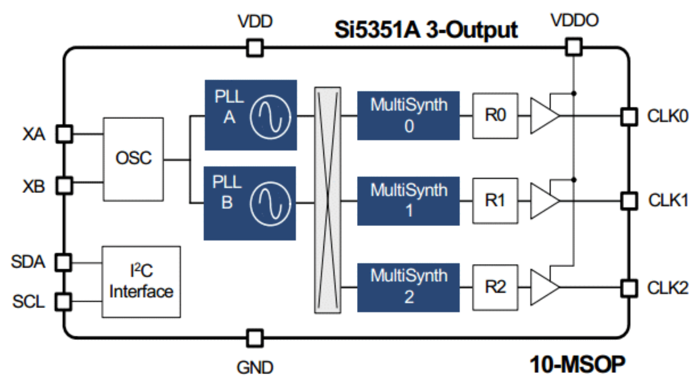
The other step forward was the use of the plug-in Low Pass Filter board. The frequency agility and precision provided by the DDS board, and the plug-in Low Pass Filter board, meant the Ultimate2 transmitter kit could be easily changed to another band. The U2 was also where I started my habit of stacking boards together using pin headers – the LPF and DDS boards plugged into the main board.

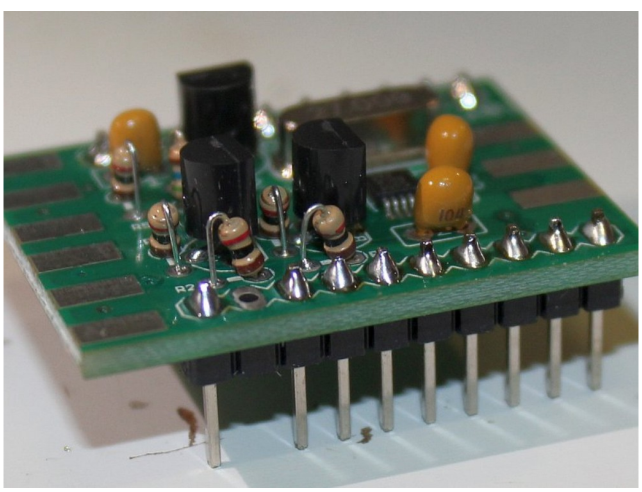
The Ultimate3 kit replaced the Ultimate2 less than a year later. The price of the attractive 16 x 2 blue backlit displays based on the HD44780 controller IC had come down so far that it wasn't much more expensive to upgrade to this nicer display instead of the surplus 24 x 1 LCD I'd used previously.

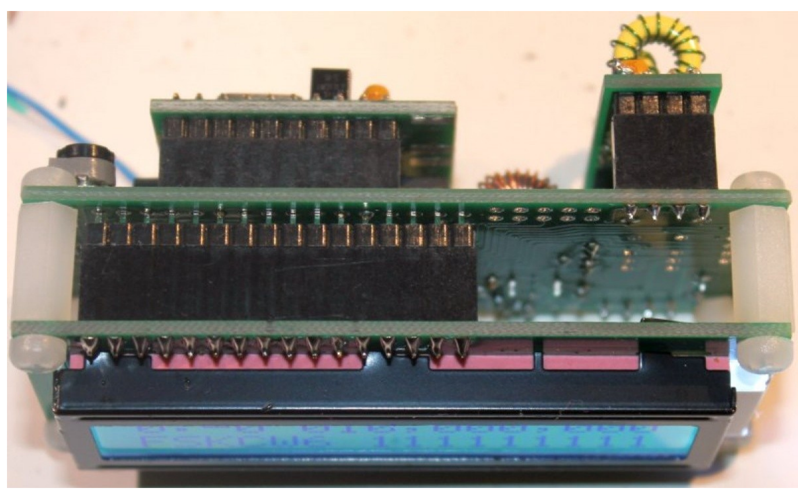
Again the U3 was based on the U2 kit. The big upgrade though was that since I could communicate with the 16 x 2 LCD module in 4-bit mode, freeing up a number of I/O lines from the microcontroller – that enabled me to add an optional 6-band relay kit with slots for plugging in more Low Pass Filter boards. The result was a 6-band weak signal modes QRSS/WSPR transmitter kit that provided a pile of functionality and fun.

Unfortunately by the end of 2014 the supply of black market AD9850 DDS modules had evidently started to dry up, no doubt me having gone through about 2,500 of them in the production of U3 kits didn't help. The price more than doubled and it got harder and harder to find them.

Luckily around the same time a new IC by SiLabs was just making its way into the amateur radio consciousness and I was tipped off by my friend Jan G0BBL. This little miracle, the Si5351A chip is a completely integrated Digital Phase Locked Loop (PLL) in a tiny 10-pin 3 x 3mm SMD package, programmed via an I2C serial bus, and featuring three outputs each of which are programmable to any desired frequency from 3.5 kHz to over 200 MHz. This chip quickly became vital, at the heart of many QRP Labs kits!



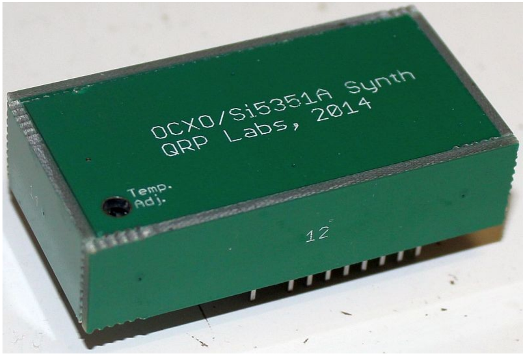




The Ultimate3S kit was a replacement for the Ultimate3, using an Si5351A chip designed onto a little daughterboard with a somewhat compatible pinout to the previous AD9850 DDS module so that it could even be used in the Ultimate3 board. The rest of the Ultimate3 was almost unchanged, and for a while the same firmware could be used on Ultimate3 and Ultimate3S, featuring automatically selected drivers for the AD9950 DDS and Si5351A chips as the RF synthesizer.

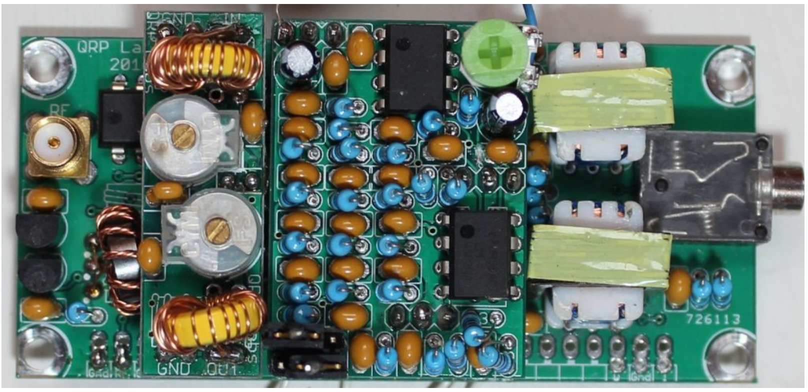
A whole ecosystem of compatible kits grew up around the Ultimate3S, which is still available today (2015 to 2023 and still going strong). Many of the boards are built on an 80 x 37mm PCB that is almost the same size as the popular 16 x 2 LCD module (which is 80 x 36mm).

- Ultimate3S kit – the basic foundation kit, with its microcontroller, LCD module and plug-in Low Pass Filter and plug-in Si5351A Synthesizer
- Optional OCXO/Si5351A version of the synthesizer, a pin-compatible plug-in replacement featuring the only kit-built Oven Controlled Crystal Oscillator in the world, providing high frequency stability particularly useful on VHF bands (OCXO kit now retired)



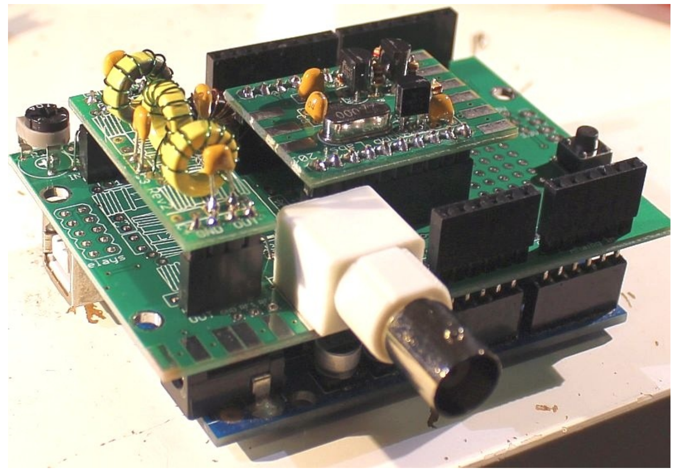
- 6-band relay-switched filter board (same 80 x 37mm PCB size)
- Low Pass Filter plug-in boards for every band from 2200m to 2m and 222 MHz
- Receiver board (same 80 x 37mm PCB size)
- Band Pass Filter plug-in boards for the receiver board – also compatible with the relay-switched filter board, and popular in people's own homebrew projects
- Polyphase SSB demodulation board plug-in for the receiver board
- 5W PA kit with raised cosine envelope shaping (same 80 x 37mm PCB size)
- GPS Receiver kits (QLG1, later replaced by QLG2)

The receiver board is of interest for its double-balanced Quadrature Sampling Detector (QSD, a.k.a. Tayloe Detector) which was used in later kits too, and was when I first used the low noise high performance LM4562 op-amp. The 5W PA and its voltage modulator that allowed the raised cosine RF envelope shaping is also worthy of note and remember it well for later in this article.



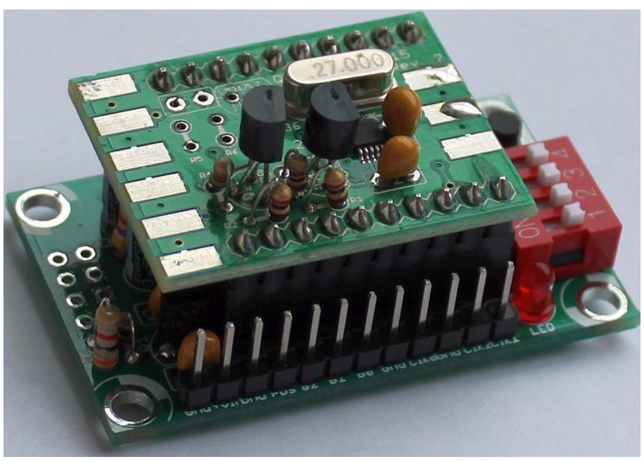
The Ultimate3S kit had required AC coupling of the synthesizer output to the PA, and a bias setting trimmer potentiometer. It left me at one point with a batch of Ultimate3 PCBs that I could no longer use as the AD9850 DDS modules had priced themselves out of range and availability, and the Si5351A chip had taken over in QRP Labs designs. The problem of what to do with the surplus U3 PCBs was solved by spinning off two new kits which used the exact same U3 PCB but with different firmware and plug-in options. One was a clock with optional GPS discipline and highly configurable display and alarm outputs; the other was a VFO/Signal Generator which could also be paired with the relay-switched filter board to produce a broadband sinewave output, again with optional GPS discipline. These two became quite popular in their own right.

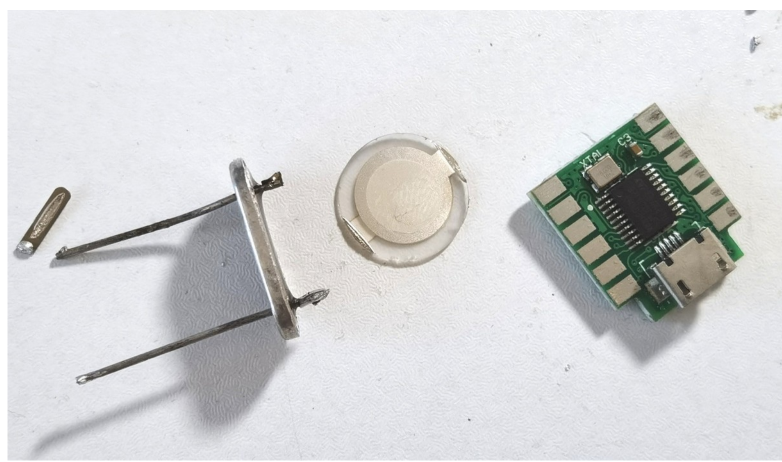
Another development was the Arduino shield kit – an answer to everyone who felt that the Ultimate1/2/3/3S firmware should be open source so they could write their own software, and who didn't know what had happened to me the last time I published the firmware (the first QRSS kit and its cloning event). The Arduino kit was compatible with most of the other kits in the Ultimate-related kit range, which could be plugged in and controlled as a complete system by your own code running on the Arduino.



2016: QRP Labs gets serious

In 2016 I left my 22-year career in investment bank IT to pursue QRP Labs activities full time. That year I produced a couple of new kits, starting with the 50-ohm Dummy load kit. The "ProgRock triple programmable crystal" kit was a microcontroller paired with the Si5351A Synth board, providing a non-volatile programmable configuration storage to set the Si5351A up with no programming needed. It could be used as three independent crystal-replacement outputs with 8 selectable banks of triplets of frequencies and optional GPS discipline. It was replaced in 2023 by ProgRock2, having a similar concept but tiny size, small enough to fit inside an HC6 crystal case, and with onboard micro-USB for programming via a PC terminal emulator.



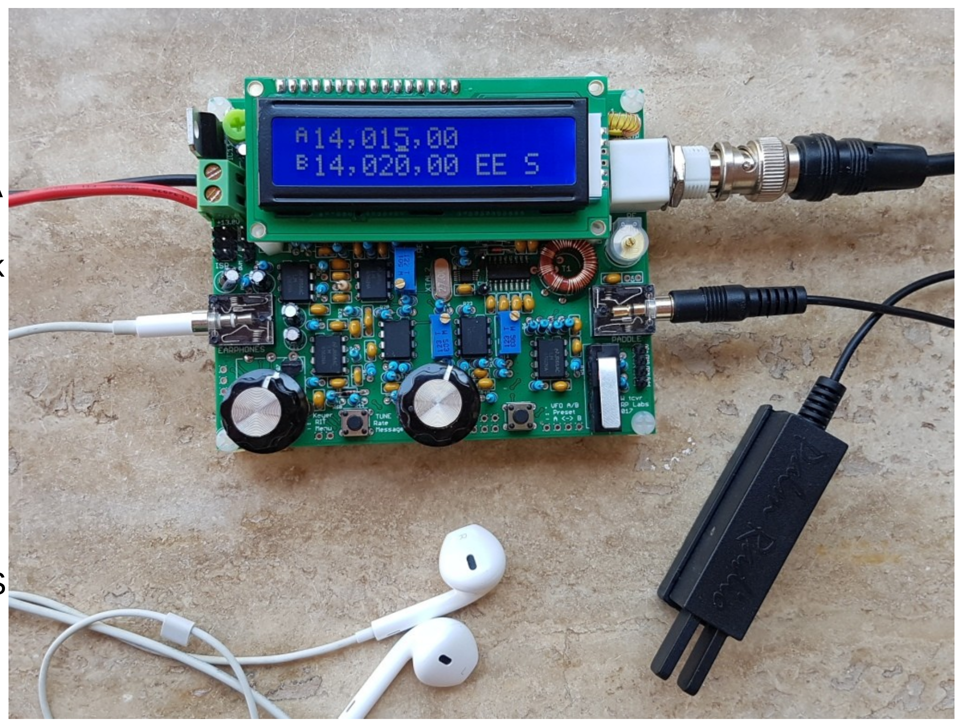


2016 was also the year the aforementioned 5W PA for the Ultimate3S was developed.

The QCX-series CW transceiver kits

Still, what had I been dreaming of for several years? Developing a complete CW transceiver kit. Indeed I almost had all the modules developed already. A VFO/Signal Generator, Transmitter, Receiver module, Polyphase single signal (SSB) demodulation, and a 5W PA with RF envelope shaping, Band Pass and Low Pass filters. All the elements of a radio transceiver. But what's wrong with this setup? It's modular. Modular sounds great, you can build and understand all these different modules, test them on their own, perhaps replace or substitute them. Fine for a homebrew project. Where it all falls apart for a kit producer is that if you just add up all those individual kit modules, plus some kind of motherboard where they will all be interconnected – you end up with a rather expensive CW transceiver. I came to the conclusion that modular should stay in homebrew projects. If you want to produce a high performance to cost ratio transceiver, you have to design it as a product in its own right.

The impetus for that came in February 2017 with a email from the RSGB (Radio Society of Great Britain), who were to be hosting the YOTA Summer Camp buildathon in the UK in August 2017. The email said they were looking for suggestions for a kit buildathon with a budget of £1,000 for 78 participants (around $1,250 at that time). That sounded like quite a good joke and after enjoying a good laughter break I deleted the email and got back to work. Yet my mind couldn't leave it alone. What really COULD you do for $16/participant? What if you made 500 kits, selling the remaining 422 at a profit to subsidize the 78? Before long it tied itself together with my CW transceiver dream and within a couple of hours I had gone looking for that deleted mail in the trash folder and replied to RSGB with my proposal for QCX, a 5W single-band CW transceiver, easy-to-build single board kit, feature-packed with high performance and low cost ($49).



QCX boasted an Si5351A-synthesized VFO, rotary encoder tuning, high performance QSD (Tayloe Detector) with unwanted sideband cancellation, Class-E PA stage for 5W output from three BS170 transistors with no heatsink necessary, Dual VFO RIT and Split operation, message and frequency memories, IAMBIC keyer, CW decoder, built-in test and alignment equipment and its own onboard microswitch Morse key. It even boasted a bonus feature, a WSPR beacon and GPS interface!

Several people have commented that it is a kind of modernized version of the Norcal 2030 transceiver; it does indeed share some similarities in concept: QSD and phasing method unwanted sideband cancellation; and the 90-degree phase shift circuit is the same as the NC2030. There are also a greater number of differences and improvements. NC2030 was an inspiration - but not the foundation - of QCX.

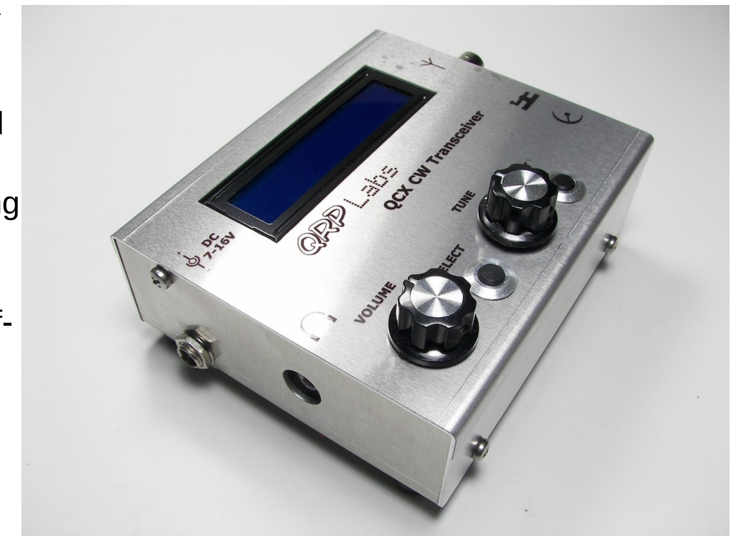
Continuing the theme of evolution of hardware and software modules – QCX re-used many earlier elements I had developed in the QRP Labs kit lineup:

- The 16 x 2 blue LCD and all the interface firmware for that.
- Double-balanced QSD from the Receiver module kit

- Low Pass Filter designs the same as the LPF kit
- Si5351A Synth and control code from the Ultimate3S kit
- CW encoding, WSPR and GPS discipline code from the Ultimate3S
- Button and rotary encoder, LCD menu system from VFO and Ultimate3S code

QCX was a great success; I managed to complete the kit development in time for the August YOTA summercamp event which reportedly went well; and when the kits were put on sale later in August the 400+ remaining kits sold out in just over 1 day. The next year was a flurry of trying to keep up with the huge demand for this CW transceiver kit which exceeded all expectations by orders of magnitude! To date around 20,000 QCX-series transceiver kits have been sold, in less than 6 years.

May early 2020 I was sufficiently annoyed by my own mechanical design failures on the QCX project that I decided to fix it. I had really been under time pressure and something had had to slip: that something was the mechanical aspect. Great for a low cost, single board transceiver design. But not easy if you wanted to put it in an enclosure: the LCD, gain control, rotary encoder, two buttons and microswitch along the front edge of the PCB all stood at different heights; with the connectors being on the left and right sides, combined to make it hard to fit the whole thing in an enclosure unless you mounted the controls, connectors and LCD off-board (which many people did). A German company (BaMaTech) produced a cleverly engineered solution to this problem, with shaft encoders and button extenders and a bent aluminium enclosure that fit the QCX without off-board wiring or any other modifications.



QCX+ was my solution, with a larger main PCB (easier to build, more space for modifications), two-PCB construction, with all connectors along the rear edge of the main PCB, and controls held on a front panel PCB. The extruded aluminium enclosure is robust and elegant, with plenty of space inside for user modifications. There's a Dev board kit which has a 0.1-inch matrix of through-hole plated holes, 12mm spacers to screw it to the main board, and pin header connections to strategic places on the main QCX+ circuit board. The firmware and schematic are the same as QCX, but the mechanical design is greatly improved.

No sooner had I launched this new improved QCX+ model, and announced the retirement of the original QCX which became known as QCX

Classic, than people started to complain that the new QCX+ is bigger and heavier, therefore less well suited to portable operations such as SOTA activations.

The QCX-mini was my answer to that, launched in December 2020. Again it's the same schematic (almost – there's an additional backlight switch controlled from a menu entry) and the same firmware. But a revised mechanical implementation with a very small, sturdy black extruded aluminium enclosure. The PCB is populated with many SMD parts pre-assembled by a PCB assembly facility. This makes the kit assembly parts count lower than a QCX+, but the smaller size does make for a more detailed finer assembly procedure.

QCX-mini has become very popular for portable operations and is available for any band from 160m to 17m (and with 15, 12 and 10m versions on request). Both QCX+ and QCX-mini are available in Assembled form for an additional fee.

Additional modules are available: a 25MHz 0.25ppm TCXO module which provides about a 100x factor improvement in frequency temperature stability compared to a basic quartz crystal; and an AGC module, correcting a feature which the QCX lacked and some operators felt was a necessity. These modules can be installed easily in both the QCX-mini and QCX+ transceivers.

I hope you can see the progression of software, hardware and design ideas that evolved through the QRP Labs kit range development. Each kit inherits ideas, circuit blocks and firmware code modules from its predecessors.

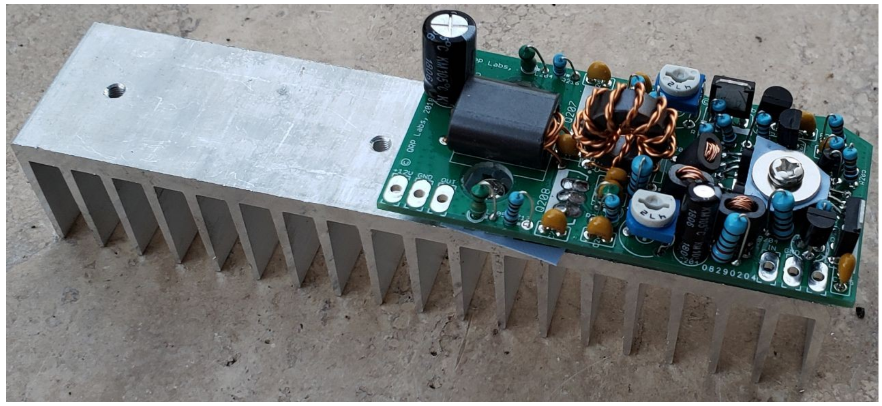
The QSX debacle

In 2018, buoyed by the blockbuster success of the QCX and feeling near invincible, I embarked on an ambitious all-band, all-mode project called QSX (QRP Labs Sideband Transceiver).

A single-band version of the QSX was built by the YOTA 2018 summercamp participants in S.Africa in August 2018, though had hardware issues rendering it incomplete and inoperable.

The existence of the project became known, with no attempt by me to maintain any degree of secrecy. I thought within a few months I would be able to complete the QSX project! How wrong I was!

The only module of QSX launched so far, was the 10W Linear to be used as the power amplifier for QSX. It uses a pair of inexpensive IRF510 MOSFETs with a BS170 push-pull driver for a total 26dB gain, flat +/-1dB from 160m to 10m, and seemingly virtually indestructible (overload, over voltage, shorts, open-circuits, SWR mismatches etc).



My only relief was that, other than taking orders for the 10W Linear, I had not been unreasonably bold (a.k.a. foolish) enough to take QSX pre-orders. Elecraft did take pre-orders a few months later with the K4 launch at Dayton in May 2019, which also slipped beyond delivery estimates. Yes, the Covid19 pandemic and correlated component shortages is a factor. But there was also, in my case at least, the heady dreamy over-optimism caused by the success of QCX, the under-estimating of the magnitude of the project, and the sheer number of new elements to the QSX compared to earlier kits in the QRP Labs range.

As deadlines slipped and pressures mounted, the public knowledge of the project caused suggestions to flow in too, which is also known as “feature creep” - enlarging the project further. Pressure and creativity are enemies of each other and before long, I felt somewhat burned out on the project.

Eventually I realized that such negativity could get mentally damaging and it would be much better to put it to one side and not force anything; so I allowed myself to work on other projects such as:

- U4B balloon tracker
- 50W Power Amplifier for the QCX-series
- QDX (more on this in a moment)
- QCX+ and QCX-mini evolutions of the QCX transceiver

It was far more productive, mentally positive, and profitable to allow these distractions to intervene, than to get bogged down in artistic blockages on QSX. And in many ways, as I will mention later, each of these developments has in itself been a step (or few) closer to the QSX. When the time is right, one day a pleasant surprise will await – QSX will be ready and on sale.

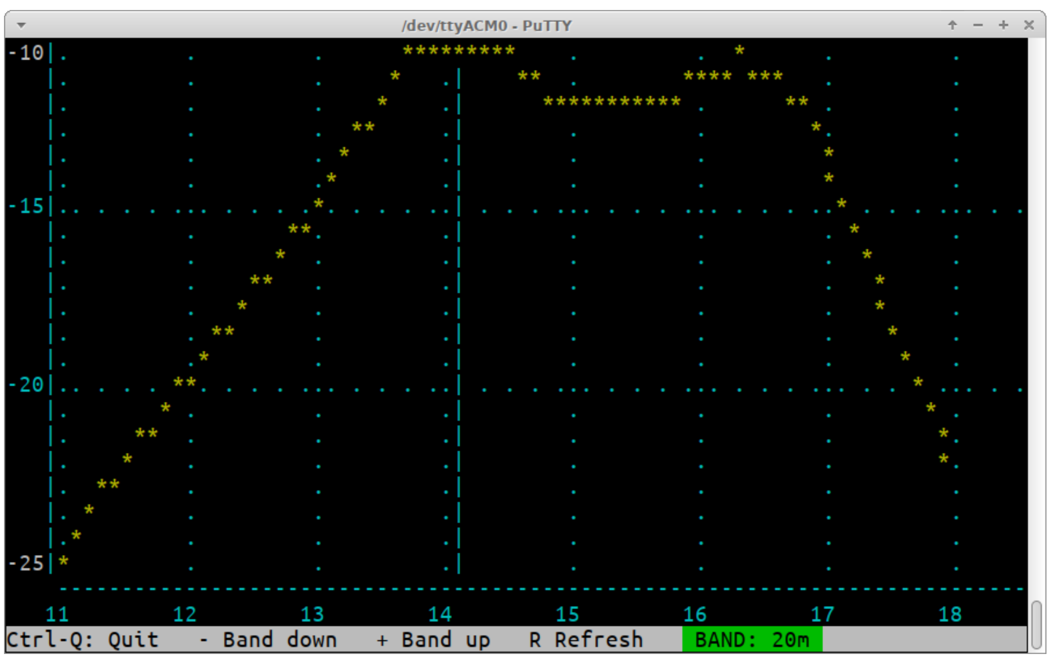
QDX, the 5-band Digital modes transceiver

The next blockbuster success kit for QRP Labs has been the QDX (QRP Labs Digital Transceiver). A project that began in late 2019, inspired by the lackluster performance and feature set, yet immodest pricing, of several digi mode kits aimed at FT8, the most popular digi mode today.

QDX is an innocent-looking little black box measuring just 3.5 x 2.5 x 1 inches, launched in October 2021 (yes it too, took almost 2 years of development!).

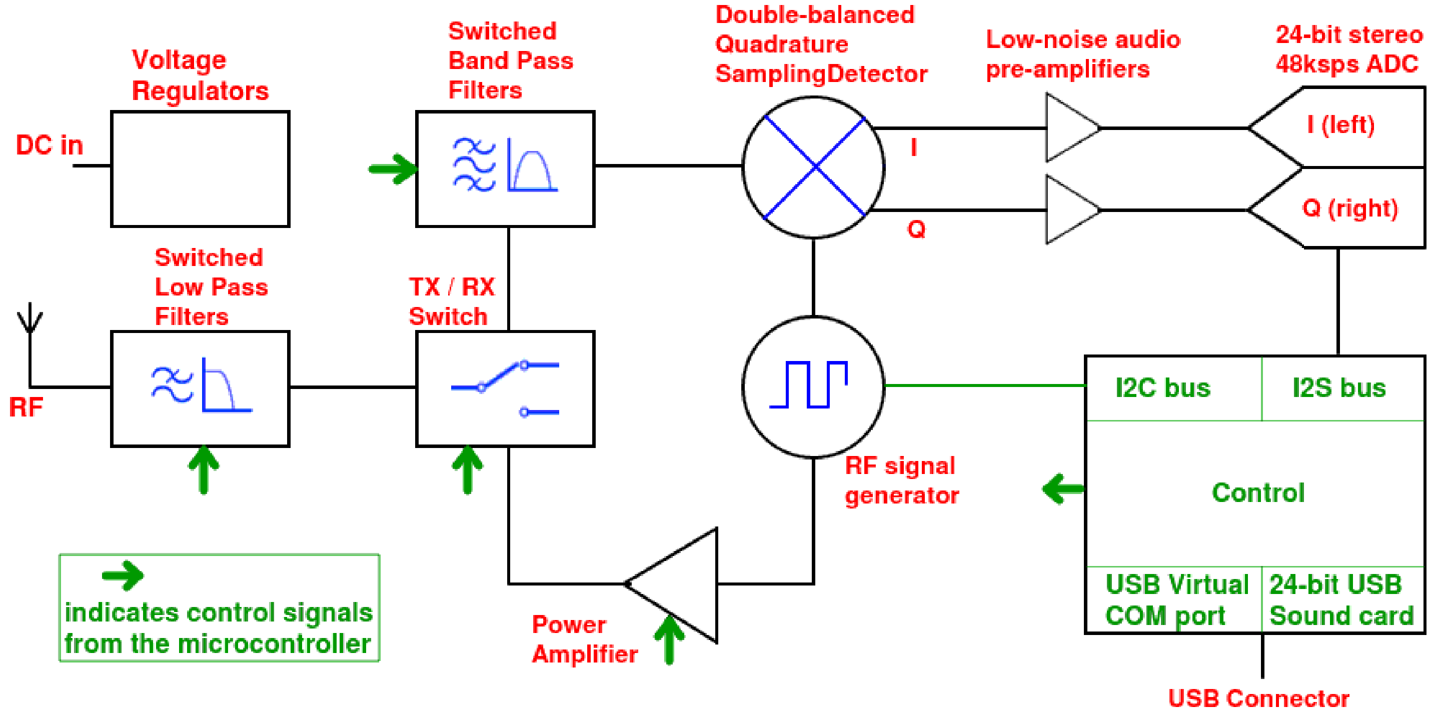
QDX is a very high performance embedded SDR receiver based on the popular down-converting I-Q method SDR using a 24-bit 48ksps stereo ADC chip. The transmitter is an unusual Class-D push-pull amplifier developed for this transceiver with PIN diode switched low pass filters. The TCXO and Si5351A are familiar from the QCX-series and earlier products. The transmitter takes the novel approach of measuring audio frequency from the PC (WSJT-X software encoding the audio tones etc) and synthesizing the required RF frequency directly. It results in a significant complexity reduction as well as improvements in performance – unwanted sideband, residual carrier and IP3 intermodulation characteristics that exist in SSB transceivers simply are totally absent in QDX because it generates its single RF output directly. This simplicity and excellent performance do come at a price – multi-tone and phase shift modes can't be transmitted. Given that most digital operation is now on FT8 and some other WSJT-X modes which are all Frequency Shift Keyed (FSK) modes, this is not a too bad compromise.

Additionally QDX includes a virtual 24-bit USB sound card for lossless, distortion-free, hum-less audio transfer to and from the PC; and a virtual COM serial port for CAT control so WSJT-X or whatever other digital modes software you are using, can easily change frequency and handle the Rx/Tx changeover etc.



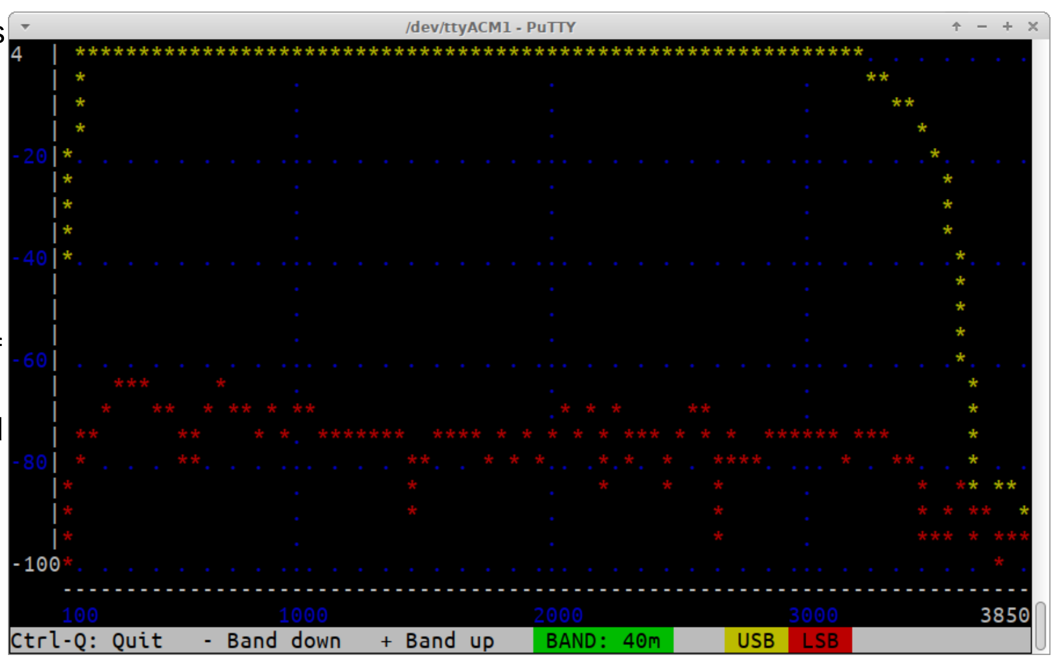
QDX includes a single status LED but is otherwise a "headless" transceiver controlled by the host PC; though it does have a suite of terminal emulator applications that let you experiment with and apply different configurations, sweep RF filters and measure image rejection, among other things.

QDX uses a 32-bit ARM microcontroller from the STM32 series, a Cortex M4 cored CPU with onboard DSP and floating point units. This implements the SDR, controls the entire circuit, and implements the USB interfaces to the host PC.

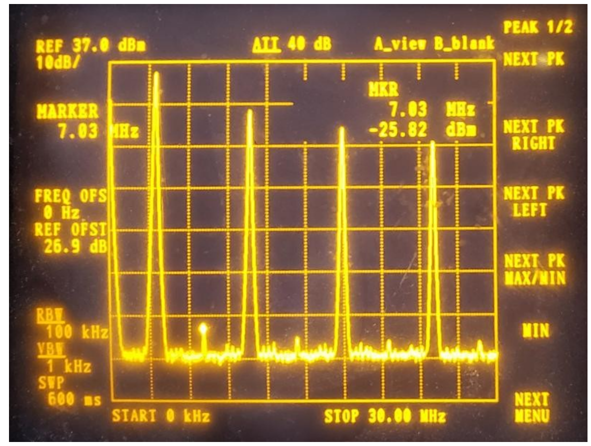


The receiver part of the design block diagram is a classic down-converting I-Q receiver, as used in many transceivers including the Elecraft KX2 and KX3. The performance of this receiver is determined largely by the dynamic range of the ADC and the noise floor (voltage input noise) of the op-amps used in the pre-amplifiers straight after the detector.

After the ADC chip provides sampling to the digital realm, the microcontroller implements a superhet receiver with 12kHz IF and a sharp audio filter bandwidth covering 150-3200Hz. QDX can even, use the third clock output of the Si5351A to inject a test signal into its own input and measure its own audio passband characteristic, using the provided terminal application tools.



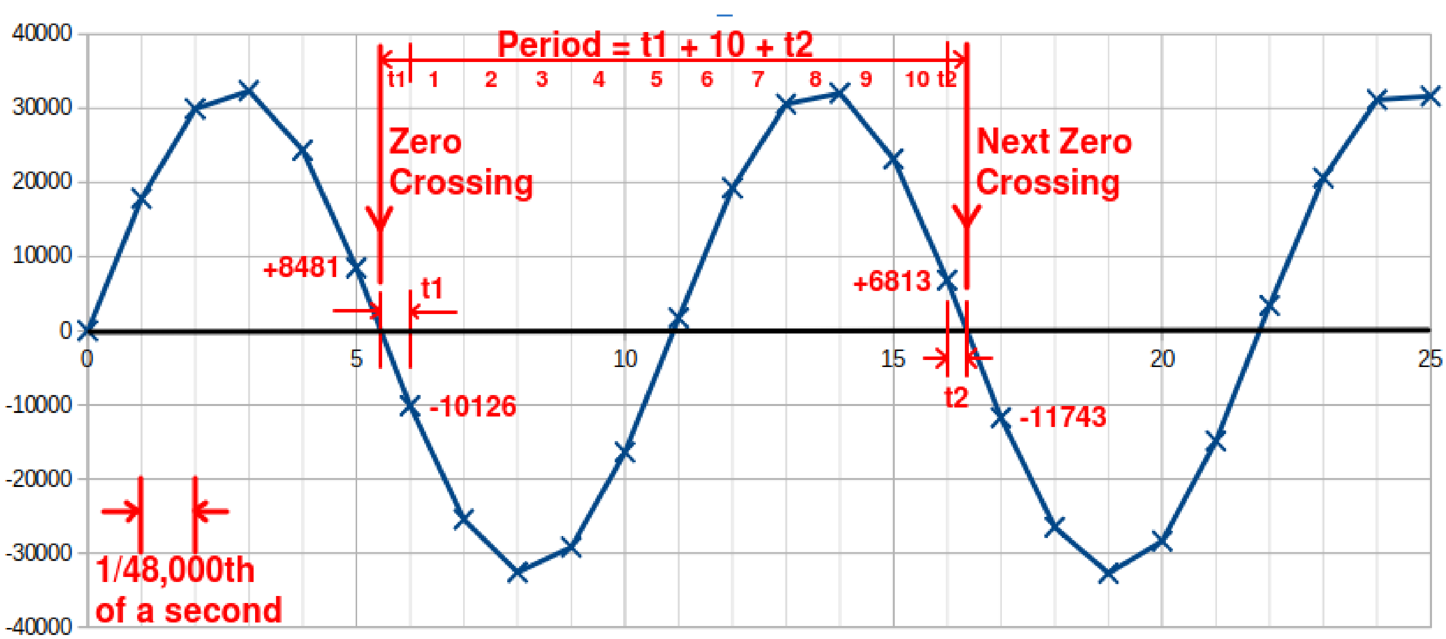
The design of these filters is eased by the fact that a push-pull amplifier cancels its own even harmonics to a large extent – this greatly reduces the burden on the Low Pass Filter to clean up the harmonic content of the output, and allows simpler filters which can in some cases, be used on more than one band.



I had developed the use of ordinary 1N4007 diodes as PIN diodes (for RF switching) in the QCX-series 50W Power Amplifier transmit/receive switches and furthered that work here in the QDX design. These diodes are used for switching in one of three different Low Pass Filters on the board. A PIN diode is in the "on" state when it is forward biased by a sufficiently large current (30mA in QDX) and "off" when it is reverse biased by a sufficiently large voltage. In QDX this voltage is derived by a rectifier/doubler which acts on the output of the power amplifier stage.

Another important evolution in the QDX design came with the Rev 4 PCB, a year or so after the QDX launch, with a switched mode DC-DC voltage converter to provide forward bias current for the PIN diodes on transmit, much more efficiently than the former resistors to +12V supply. The switching converter was implemented in discrete components not a "real" SMPS IC, with the control loop and PWM generated by the QDX microcontroller. This improvement to the QDX design reduced the heat generation by three quarters of a watt during transmit!

On transmit the QDX measures the audio frequency by calculating the precise interval between interpolated zero crossings, a highly accurate and quick measurement on a single audio cycle, made possible by the use of the USB Sound card which provides loss-less distortion-free audio samples straight from WSJT-X.



QDX has become a very popular member of the QRP Labs kit family and is now our best-selling kit. Just like the QCX-mini and QCX+, we offer it as assembled/tested/adjusted too for an additional fee.

Challenges

No story involving the last few years would be complete without a little sob story on the topic of challenges faced. As well as sharing-is-caring therapy, actually challenges overcome are a lesson and inspiration. Remember, what doesn't kill us makes us stronger.

The first challenge I want to talk about is deciding to leave your stable lifetime corporate career and do something as crazy as trying to start a radio kit business. This requires a lot of careful thought, as well as a sensible XYL to discuss it with, provide the voice of reason, good risk reduction strategies and much-needed support. Leaving a corporate environment would not be for everyone. Aside from the obvious risks of losing your job or your mind (whichever comes first), corporate employment does provide a certain level of security. Generally you have a boss, who tells you what to do, and that happens within the framework of the company overall which provides all the support functions you would need. As long as you do the job, don't do it too well, nor too badly, everything will generally proceed quite smoothly and a paycheck will arrive in your bank account monthly. Of course all the money you help make, is for someone else. That's the deal. Now on the other hand, branch out on your own: now you have no boss guiding you, no framework, no support structure. You keep the money, but now live and die by your own sword. It's not bad vs good, it's just different and you have to be sure it's for you; even if it is, it's still a tremendous adjustment that shouldn't be taken lightly.

Now working from a home office is a whole new set of challenges, as well as moving country (Japan to Turkey, in our case). A home office is a wondrous thing with a rather short commute time. On the other hand, maintaining focus becomes a challenge, getting serious work done without interruption becomes a much harder to reach goal. Particularly when your task is such complex design work, where concentration is crucial.

The success of the QCX brought a sudden sharp increase in the volume of orders, which was a really big shock to deal with. Of course, it's a nice problem to have, but it's still a problem that has to be dealt with and solved. In our case it meant moving the operations from Japan (where I had two Japanese helpers working part-time evenings to ship QRP Labs kits) to Turkey where I could expand more easily. So now you have employees, all too short a time after you left corporate management…

Technical challenges are a whole subject of their own that could be their own entire seminar topic. It cannot be over-emphasized, how many unexpected things will jump out and bite your posterior at the worst possible moments. Analog electronics, particularly RF electronics, is really black magic. When you're learning it as you go, even more so.

As the Covid pandemic hit, numerous additional challenges came with it. Home-schooled kids. Which also coincided with a new baby in the family. Whoever heard of Zoom previously? Now couldn't live without it. Or hate fixing it, more. Lockdowns made it hard to have employees on site.

The global semiconductor crisis came at the same time as the Covid pandemic and brought many of its own new challenges. Debate rages over whether Covid caused it or triggered it or whatever. Either way, components got suddenly rather hard to find. You went from a situation where ordering whatever you need used to consist of click click, go to Digikey, Mouser etc website, choose the parts you need, pay by credit card.. and be sure to have them delivered a few days later in Hong Kong for board assembly – with never the concept that Digikey might be out of stock of anything – to suddenly being in a situation where almost everything you want, is out of stock and has a 1+ year lead time. Which in most cases, simply means neither Digikey nor the manufacturer have any idea how long the lead time will be. New suppliers had to be found and with that came the problem of fake components or under-specification components. In many cases substitutions had to be made, which bring their own surprises and validation work. Ouch!

All the while – the demand for QRP Labs kits kept growing and growing, so does the team size, and so manufacturing has to continue somehow, to keep up with the demand. We were fortunate to be small enough to be nimble about suppliers, components, substitutions and design changes, to be able to largely continue the entire kit range without major interruptions. The largest interruption was a few months for the differential amplifier design for QDX to suit the new PCM1804 ADC with its differential input.

Stepping stones to QSX?

As I mentioned earlier, QSX has not yet seen the light of day, to the disappointment of many. But at the same time, many elements of QSX have been developed and proven. Several smart observers have commented on this. Each of these brings closer the final day when QSX is ready at last.

Perhaps the first area to mention is enclosures. Starting with the 50W PA kit enclosure, whose extrusions were used also in both the QCX-mini and QDX kits (with different lengths cut and front and rear panel designs) and continuing with the QCX+ enclosure design – I developed mechanical design skills and techniques, supplier and fabrication sources, that will make the final enclosure for QSX much easier to design and produce professionally.

Band switching and transmit/receive switching is one thing that had been a problem in QSX. But mastering 1N4007 diode transmit/receive switching in the 50W PA, and the Low Pass Filter switching in QDX, as well as the simpler LPF designs in QDX, are all elements that are required for QSX.

Not everyone knows that the source code for QDX was originally based on QSX. So now, some QSX source code (the embedded SDR and DSP filtering) is already perfected and released into the world in the form of the QDX kit.

The QLG2, QDX, ProgRock2 and U4B kits are all based on the STM32 microcontroller series and all include a firmware update procedure, where the kit appears to a host PC as a USB Flash drive. Updating the firmware is a simple matter of copying in the new firmware file into this USB memory drive. This was a crucial requirement for QSX which was the first time I used STM32 microcontrollers. So these intervening kits have perfected this USB bootloader (firmware update procedure) and lots of experience and code has been developed on the STM32 series. All great progress for the QSX transceiver.

The terminal applications in QDX and U4B will also be used in QSX. It was always my intention to develop a scripting language for QSX so that user functionality could be developed by the users to tailor it to their own specifications. The U4B balloon tracker includes this BASIC programming language which is directly applicable to QSX.

Evolution, not big bang!

I hope you can see the way the QRP Labs kit range evolved over the years since the humble beginnings in May 2010. How each kit uses concepts, ideas, circuit blocks, mechanical designs, and firmware code modules developed for the earlier kits.

QSX was a too ambitious, too large step. I now realize that evolving gradually step by step, and keeping my big mouth shut, would have been a much better, less stressful, more efficient strategy. The famous QCX monoband analog CW transceiver didn't come about, big bang style, in 2010. It came at the end of a string of predecessor kits, building on their successes.

Building the next: QMX

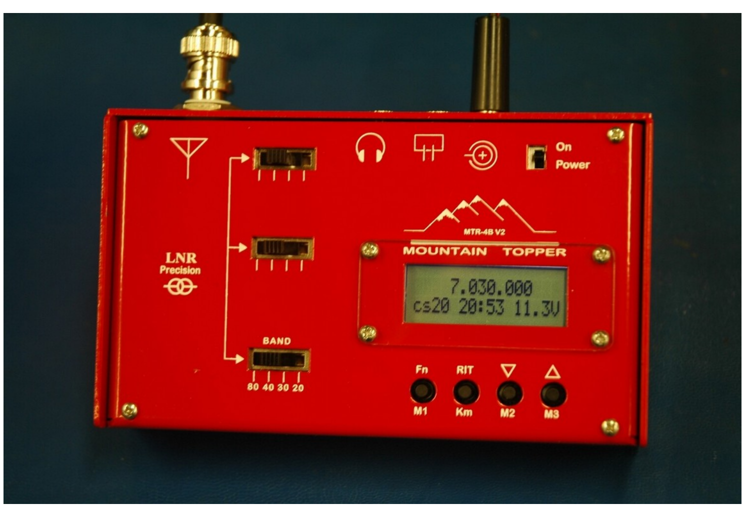
Now we come to the design of what might become, perhaps, the final step on the way to the QSX. And along the way, perhaps become one of the greatest portable QRP rigs yet seen.

QMX. The M is for Marriage. Magnificent. Merger. Marvelous, many things like that. It's what you get when you marry the mechanical and conceptual design of QCX-mini, with the SDR, multi-band digital implementation of QDX. Simply: QDX + QCX-mini = QMX.

This part of the story details some of the design decisions in the development of QMX.

Why QMX?

Because it provides another stepping stone on the way to QSX. It seems a logical progression. And because there's a need for a high performance, inexpensive, small. portable multi-band, multi-mode transceiver. Many people have things like an Elecraft KX3, Yaesu FT817 etc. But if you take this with you into the wild, if it gets stolen, broken, damaged somehow, that's quite a hole in your pocket. Some people prefer something less expensive for their portable operations. The popular LNR Precision mountain toppers are one option but $370 is hardly all that inexpensive, and it's limited to CW only. Performance isn't stellar, band switching is clumsy and the design is a bit cheesy in my opinion. The uSDX series fit the "inexpensive" requirement but you suffer a not inconsiderable performance penalty, in addition to the 3D printed plastic enclosure which doesn't shout "quality" at you. Neither have big-easy-to-read-outdoors displays either. (Photos from the respective websites).



Lots of people have asked me for a multi-band QCX CW transceiver. But it's inherently difficult to change this mono-band design into a multi-band transceiver. The Class-E output stage isn't easily mutli-band-able as it is a tuned resonant load circuit by definition. There certainly isn't space in a QCX-mini for band switching. The firmware of the ATmega328 chip already fills up the 32K Flash memory space of the processor chip entirely. Switching to a higher AVR chip is possible but this would mean a SMD package, which makes plugging in a firmware chip to upgrade the firmware impossible; so it means a lot of new development for a bootloader to allow firmware updates. There are a host of issues with trying to multi-band a QCX – the Low Pass Filters, Band Pass Filters, and Class-E resonant load circuits are all band-dependent and in need of switching.

Lots of other people asked if QDX (5-band Digi modes transceiver) can do CW, or could be made to do CW. The reason QDX can't do CW is that a design choice (for simplicity and low cost) was to not include any RF envelope shaping. That is (reasonably) fine for digi modes where you have an FSK signal and the only sharp on/off RF carrier transition is at the beginning and end of the transmission where it is relatively harmless. But if If you transmit CW - which is inherently an on/off keyed mode - without envelope shaping, you generate wideband clicks that will annoy people on nearby frequencies, even if you are only using 5 watts QRP. So you need envelope shaping for CW. It could be implemented in QDX without too much trouble. But you'd still need to type your CW message on a PC and have the PC send it to QDX as audio. The majority of CW operators will want the full CW experience, keying properly on a straight key or paddle. So why not do it properly? Hence QMX.

Features

I'd like to incorporate all the standalone user interface features of QCX-mini (no host computer necessary), with all the embedded SDR, DSP filtering and digital features of QDX, available to an optional host computer if required.

I'd also like to include several stretch goals, including the potential of SSB (more on that later). Some of the stretch goals are so so stretchy I won't even dare mention them right now.

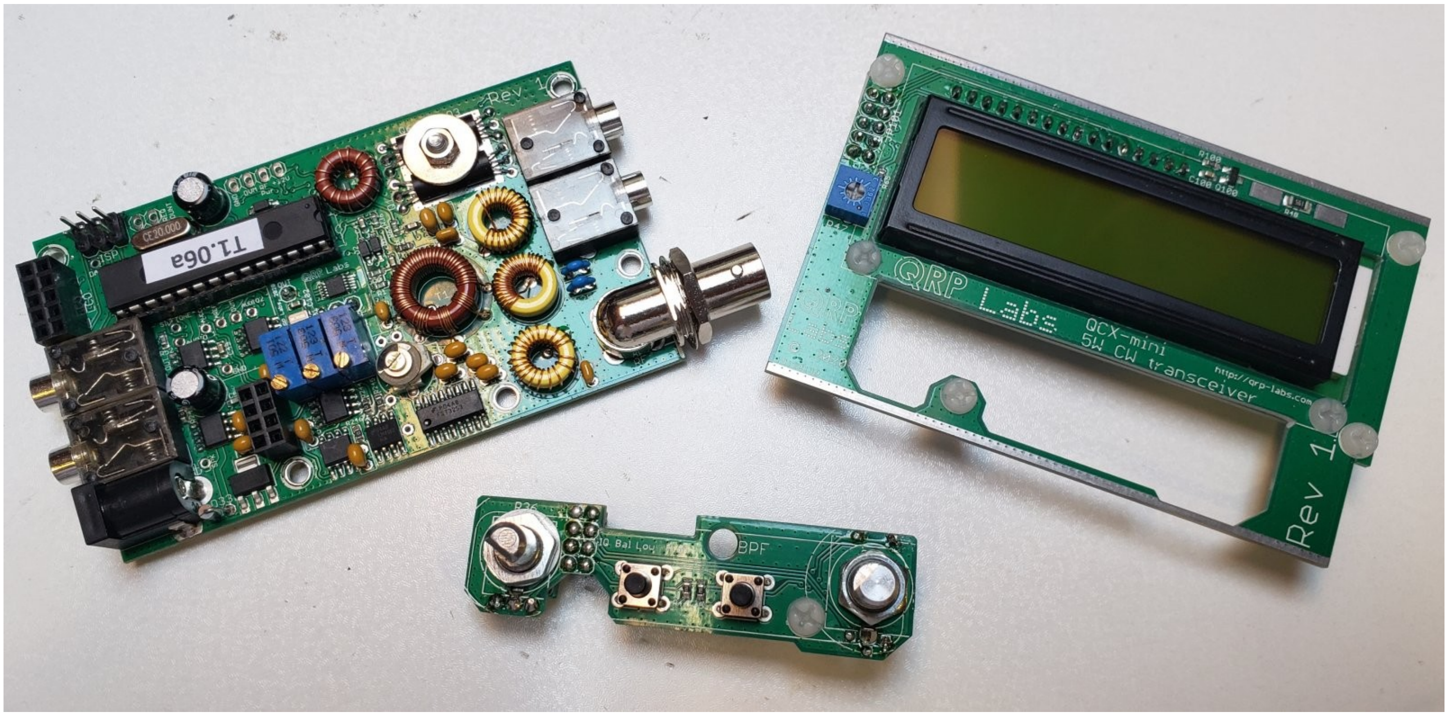
Low receive current is a parameter many people have their eye on for portable operation. DSP means a powerful CPU and that gobbles power. It's an area where an analog design has an advantage. Because of this I'd like to include switched mode DC-DC converters for the internal power supply rails for 3.3V and 5V supplies, so as to make the power supplies as efficient as possible. Yet these switching converters mustn't create RF noise that interferes with the performance of the receiver.

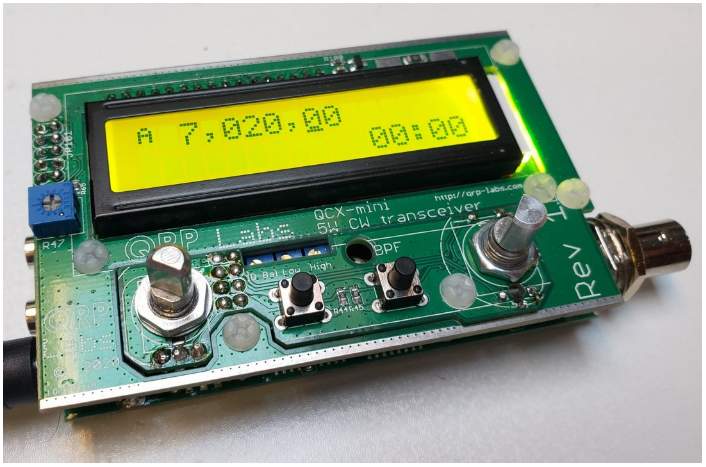
A new feature I want to include, is inline SWR metering. It's another oft-received request, particularly for portable operations where the QMX will often be used, and antennas are likely to be more variable than at a fixed home location. A criticism of QDX and QCX-mini could be the vulnerability and lack of protection against bad SWR situations. So let's try and address that here from the outset, by including SWR measurement and metering, even protection features in the firmware.

I'd like to take several more steps toward QSX too, as mentioned earlier, and this will influence the design process, particularly on the software side of the design.

Mechanical design

The QCX-mini is a quite nice mechanical design which I'm rather proud of. The enclosure is extruded aluminium, 3.7" wide by 2.5" deep and 1.0" high (plus control knobs). Inside is a display board which slides into the rails in the walls of the enclosure extrusion; the main board plugs onto that from behind and is slightly smaller so doesn't use the enclosure rails. There is a small plug-in board holding the gain control and buttons, that breaks out of the LCD cut-out of the display board. It all fits together and is bolted using some nylon spacers and nylon screws. The aluminium end plates (left and right) are screwed in their corners, to holes in the aluminium extrusions. No other mounting screws are required, to hold the QCX-mini boards to their enclosure. The 16 x 2 yellow/green LCD is dated (OK very dated, HD44780 displays go back to the mid 80's) but still ideal for a portable rig for many reasons: sunlight readable, big, easy to read characters, low cost, and low current consumption (under 1mA when the backlight is off). This picture shows the QCX-mini boards:





Here's how the boards stack up (right).

QMX has a lot more components to squeeze inside. But for reasons of pride and challenge, I don't accept making the enclosure larger. So that'll be a significant design challenge. I want to keep the enclosure visually almost identical to QCX-mini.

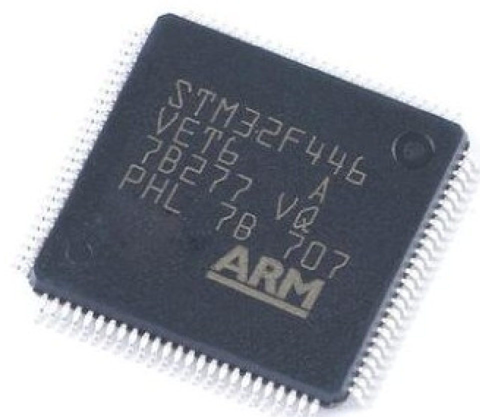
So QMX has the same connectors on left and right, as the QCX-mini. DC power, audio out, and paddle input on the left. RF (BNC), PTT output, and serial on the right. But the QCX-mini "serial" is a 38,400 baud serial connection on a 3.5mm stereo jack. Whereas for QMX we need a USB connector for the USB 48ksps stereo 24-bit sound card and the Virtual COM Serial ports.

Which USB connector? Well USB-micro? I'm sorry, yuck. It's flimsy in my experience. Who had an Android phone in the USB-micro days, and after a while the cable connection got intermittent? Or worse, the problem was on the phone side, much harder to deal with than a new cable. I used USB-micro on the first batch of U4B trackers and there were connection problems; I have to use it on the ProgRock2 module which is tiny by design, but at least the USB connection is likely temporary. But I'd prefer NOT to use it here in a design which is to be used portable and needs to be robust. USB-mini was nice, but never as common. USB-B (full size USB) as often used on printers, is robust, hardly ever fails, and is what I love to use in QDX. But – it's big, it's TOO big, it won't fit on the QMX PCB in the available height under the LCD module. So we're left with USB-C, the modern popular implementation of USB which can deliver power at lots of different voltages, can be plugged in either way, and is hopefully mechanically more robust than USB-micro was. In QMX we won't use the power delivery funkiness, we'll just stick to plain old USB connections. Furthermore, to reduce the risk of connection problems in the field – and since this is a critical component - we'll choose a high quality USB-C connector from Digikey, having through-hole pin connections rather than SMD.

Other than the change in the host computer connector, to USB-C, and the labeling on the front panel, the rest of QMX will look very similar to the QCX-mini and be difficult to tell apart. QCX-mini is a well-loved, insanely cute transceiver implementation so it makes all the sense in the world to re-use the mechanical design here; and a nice challenge to try not to increase its size (such as, make the enclosure wider).

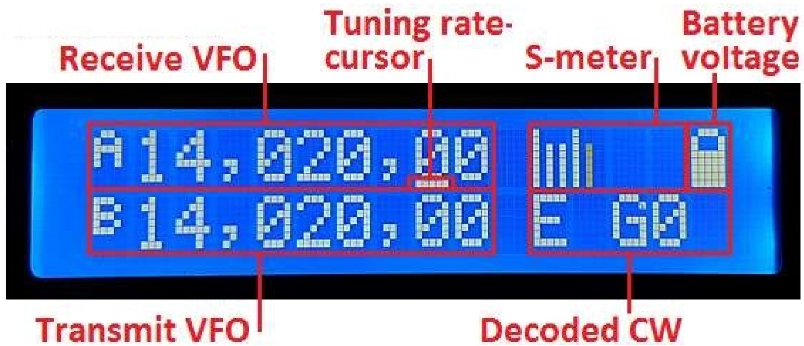
Microcontroller

We will of course, in keeping with the step-by-step evolutionary approach, stick with the STM32 series. QDX has a 64-pin microcontroller. For QMX, we want to incorporate more features, more I/O is needed, and more peripherals, more Flash and RAM, as I will have a number of things I want to try out on the step by step path to the QSX all-mode all-band 10W HF transceiver. Hence QMX needs a step up in the processor family, to a 100-pin microcontroller, probably the STM32F446VET6. Not entirely coincidentally, you will note that STM32F446 is the same family member used in the QSX so far (YOTA 2018 builds).



User Interface

The QCX two-button and rotary encoder interface is intuitive and we have 6 years of dealing with it; it itself evolved from the earlier menu and control systems used on the Ultimate-series beacon kits described earlier, and the VFO/SigGen kit (rotary encoder handling code). So let's build on the same user interface used in the QCX, which



uses the same 16 x 2 LCD. The same menu system can be used, of course with modifications for the enhanced functionality in QMX.

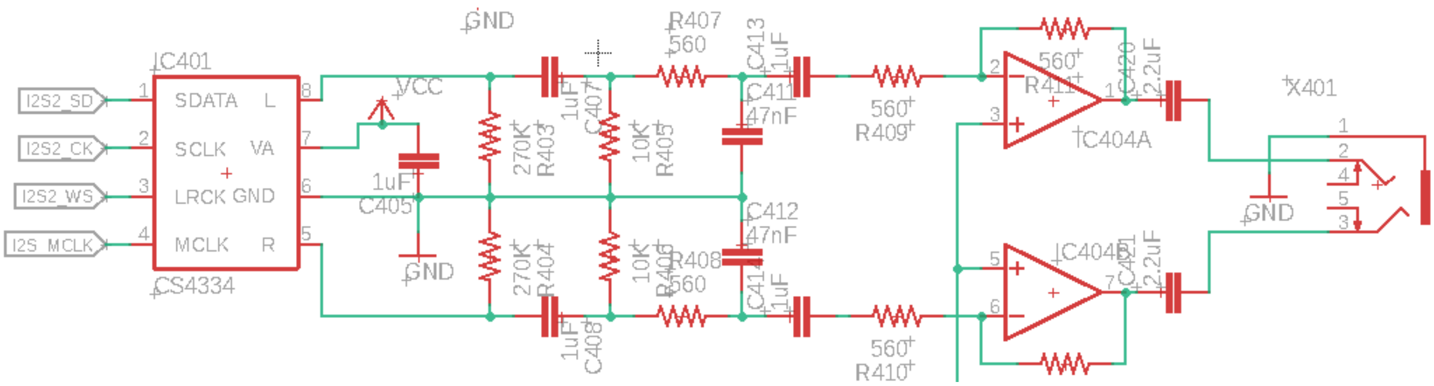
People are familiar with the QCX-series user interface. Many QMX owner operators will be previous QCX-series owner operators. This is another reason for keeping the user interface similar.

A third, more pragmatic reason, is not re-designing a whole new user interface! The whole 2023 theme for me is about re-use, step by step evolution.

So that's it – let's keep the user interface as similar as possible to the QCX-series and in particular, the QCX-mini!

The exception is the gain control. QCX, being an analog design, has a potentiometer as the gain control. QMX is a digital design, the internal electronic design of QMX is much closer to QDX than QCX. So why make an analog audio output stage with an analog potentiometer like the old days? Furthermore, people may not know: the analog potentiometers used in QCX-mini and in QCX+, are custom-components custom-manufactured for QRP Labs. It's always cheaper, faster, and less vulnerable to supply chain issues, when you can source off-the-shelf standard components rather than use specially manufactured custom ones.

So for QMX the audio output is a 24-bit stereo DAC, this gives sufficient dynamic range to implement the audio output level control entirely digitally (also just like in QSX – spot a pattern here?). A rotary encoder can therefore be used, just as in the right hand knob of QCX-mini. This additionally gives us one more button for free, which we can use for things such as, ah, I don't know, well, changing the mode, band, and a soft power switch!



The audio output uses the same I2S 24-bit DAC chip, CS4334, as the QSX design. There are no accidents. The left and right channels separately drive two halves on an op-amp that drives the earphones. Keeping the channels separate will in future, allow things like gain adjustment to balance left and right channels for people with hearing defects, or in future, binaural reception.

Transceiver design

The design of the actual transceiver closely mirrors the QDX 5-band Digi modes transceiver with a few additions. What we are basically doing is taking a QDX, adding RF envelope shaping, a user interface and a couple of other new things, and putting it into a QCX-mini enclosure.

The design closely follows the block diagram for QDX shown previously. I don't intend to cover the entire QDX design in great detail, which was the topic of last year's seminar and is documented extensively elsewhere. I'll summarize it then let's talk about what's new in QMX.

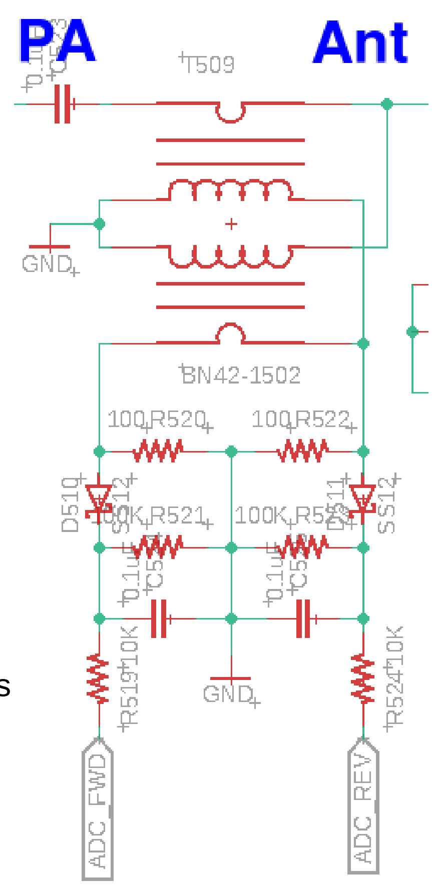
The receiver has a double balanced Quadrature Sampling Detector (QSD, a.k.a. Tayloe detector) converting RF to I and Q baseband signals. These are amplified, sampled at 48ksps by a 24-bit ADC chip with very high performance, and the rest of the demodulation is done digitally in an embedded SDR on a 32-bit STM32F4 ARM processor, that implements a superhet receiver with 12kHz Intermediate Frequency. Ahead of the QSD is a simple series resonant tuned circuit as band pass filter, with capacitors and inductor taps selected by a CMOS switch under processor control. The transmit/receive switch can be simple and the Low Pass Filtering is shared between transmitter and receiver sections.

The transmitter uses a push-pull power amplifier with two BS170's on each side. This has the advantage of very low even-order harmonic content, simplifying the LPF design. There are three LPFs, each of which contains two toroidal inductors and four NP0 capacitors. These LPFs are PIN diode switched under control of the processor to select the band.

The synthesized oscillator is our good old friend, the Si5351A; which in the transmit mode outputs 180-degree out of phase signals, and during receive provides quadrature output suitable for driving the QSD directly with no need for the old divide-by-4 circuit. This was a trick I developed in 2017 for the QCX, it reduces parts count and has high performance.

Several key differences between QDX and QMX need discussion in greater detail:

- User interface (LCD, buttons and connectors discussed already)
- SWR measurement
- RF envelope shaping
- Power supplies



SWR measurement

A very standard SWR bridge is used, which samples forward and reverse power. It remains always inline between the PA and Antenna. The output voltages are measured by microcontroller ADC inputs.

This circuit or variants of it are seen in many transceivers and standalone power meters.

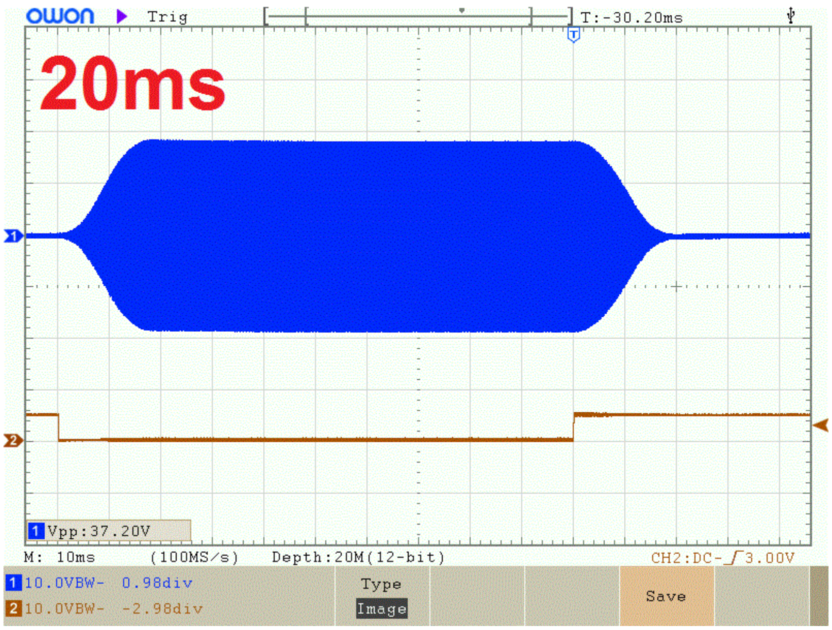
Note that the two transformers are often implemented on ferrite toroids such as FT50-43 toroids. Here we use a more compact method, a binocular core. The two transformers are each wound in the two separate holes. As far as the binocular core is concerned, what happens on one side is electrically invisible from what happens on the other. So the use of a single binocular core instead of two toroids is a parts count reduction benefit and also in our case, crucially, helps reduce the space required, which in QMX Is at a premium.

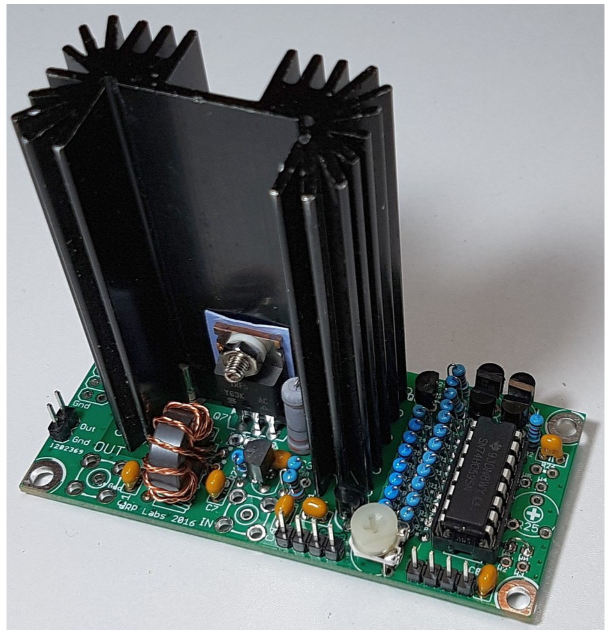
RF Envelope shaping

The QCX CW transceiver design uses a simple PNP transistor to provide a kind of trapezoidal approximation leading and trailing edge shaping. It's not an ideal raised cosine shape, but it's close enough to provide very good no-click performance.

A problem is that the rise and fall times are heavily influenced by variations in component tolerance, particularly the hFE parameter of the PNP transistor, and these can be highly variable even between devices in the same batch. We aim for a 5ms rise and fall time, but the actual variation from one QCX to another is quite considerable. It would also be nice if the rise/fall times could be adjusted depending on the operators' preference, or automatically depending on keying speed, etc. For the SSB stretch goal, it would be excellent to have fine control over the envelope shaping (effectively, amplitude modulation). More on this later.

So for QMX I've gone back to the design developed together with Alan G8LCO for the 5W PA kit designed for the Ultimate3/3S QRSS/WSPR kits.





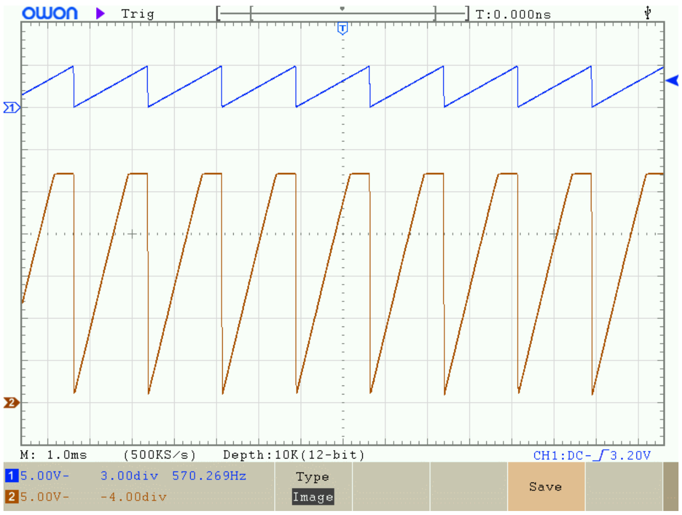
The circuit may be considered as a variable voltage regulator whose output voltage is set by a control voltage which may be provided from a Digital to Analog Converter (DAC) under microcontroller control. In our QMX case now, the chosen STM32 microcontroller has its own fast accurate internal 12-bit DACs so this is even easier.

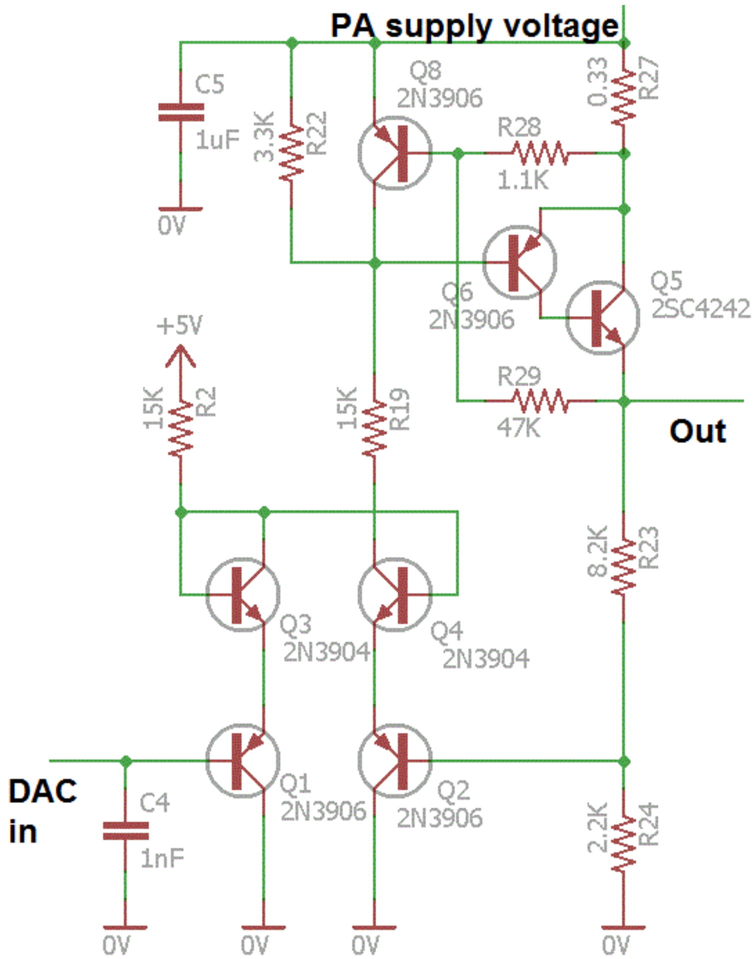
You might even consider this as a sort of power operational amplifier! The schematic fragment reproduced below is taken from the 5W PA manual. In QMX the same layout is used but of course the transistors are replaced by appropriate miniature SMD ones.

The voltage at the DAC control input will be in the range 0-3.3V, in 4096 little steps (12-bit). The output voltage is simply this control voltage multiplied by the ratio created by the potential divider R23/R24.

In testing of the 5W PA this circuit was found to be very linear, and fast-operating.

In this 'scope screenshot the triangular waveform ramp frequency is 570 Hz. The control voltage ramp is shown at the top trace (blue) and the output voltage is the bottom trace (brown).





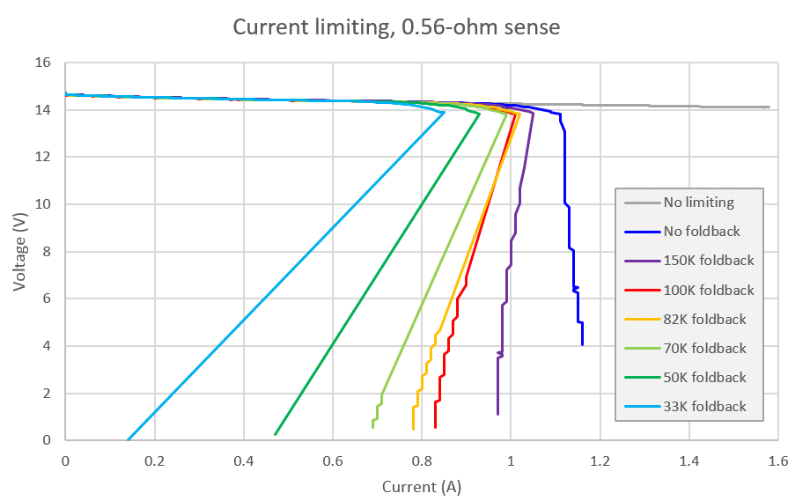
This circuit will hopefully be plenty fast and accurate enough in this application too.

The 'scope screenshot also shows what happens if the "gain" (R23/R24 potential divider ratio) is too high – just like any op-amp, the output is limited to the supply rail voltage. So it's necessary to take care, particularly when the supply voltage to the transceiver can itself have a variable range. But the microcontroller in QMX can also measure that supply voltage so will be able to predict what the maximum DAC control voltage can be for any given supply voltage to avoid clipping.

An additional benefit of this shaping circuit is the foldback current limiting feature. In the event of a current threshold being breached, the circuit automatically and immediately shuts down.

So if there was a short circuit, or even a too high current condition caused by a bad SWR mismatch, the PA would automatically shut down to avoid the high current condition.

This is quite a useful additional feature to avoid PA damage in abusive situations!



Power supplies

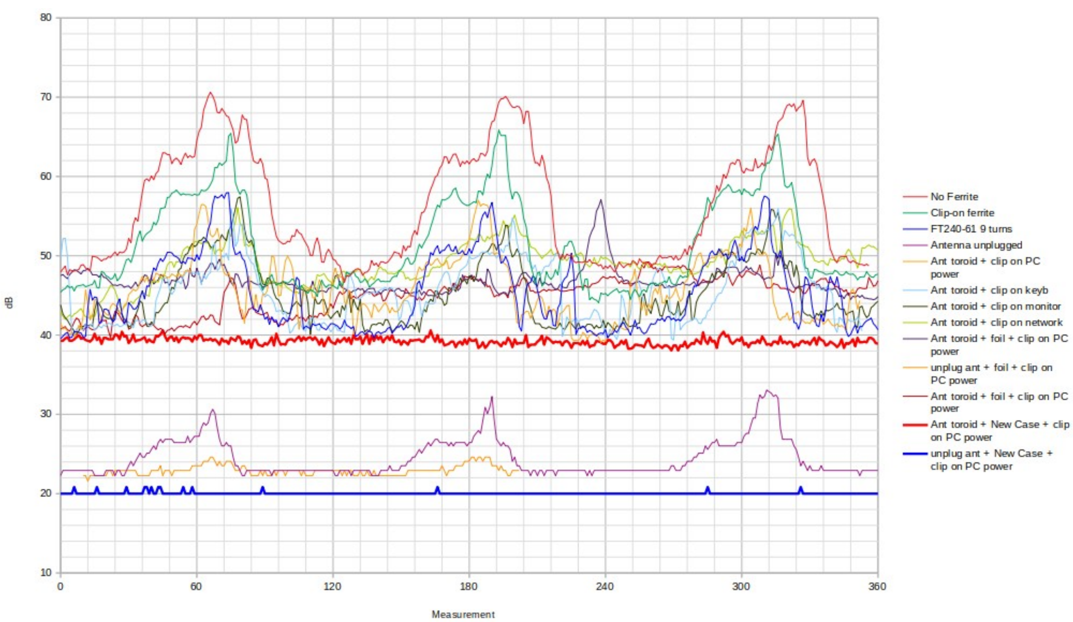
This is a really key problem area. You can insult the poor strong signal intermodulation performance of a cold-war era SA602 superhet receiver design such as used in the Mountain Topper radios (for example) as much as you like. But people will always pop up, and rightly so, to tell you: “ah yes, but it has very low receive current consumption! When I’m on top of a mountain, it’s more important to me that the rig doesn’t drain my battery quickly, rather than the finer details of its dynamic range!”. Yes!

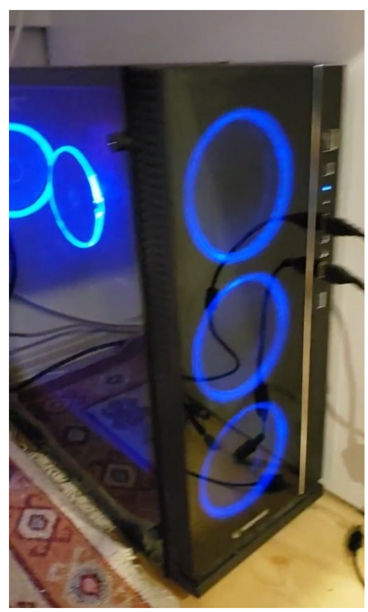
Unfortunately low receive current is the enemy of a high performance embedded SDR receiver architecture. The Si5351A synthesizer by itself consumes 25-30mA of current. The microcontroller running at 72MHz (QDX) or more, sucks current quite thirstily too. High performance and low noise is correlated to higher current consumption in operational amplifiers – and we must have four high performance low noise operational amplifiers in the pre-amplifiers to the ADC on the I and Q baseband channels, since this critical point determines the sensitivity and dynamic range of the whole radio. The ADC chip takes quite some current too. To put some ballpark figures on this, QDX consumes around 150mA on receive. On QMX we add the audio output and LCD module (with disable-able backlight). Current consumption can only go in one direction.

We need both 3.3V and 5V supplies, as well as a transmit-only forward bias current supply for the PIN diodes. If the total current draw on these supplies is somewhere in the range 150-200mA, then at 12V supply to the radio, the receive current draw will also be the same – IF we are using linear voltage regulators.

It’s a whole other story if we are using switched mode voltage regulators (DC to DC converters)! Now we have a much higher conversion efficiency, we don’t waste so much energy as heat. If the current consumption on a 3.3V bus for example is 100mA, then if the converter was 100% efficient, at 12V supply the current consumption would be only 27.5mA. Quite a significant improvement! In practice we never achieve 100% conversion efficiency of course, but the improvements are still major and worthwhile.

Having decided we need switched mode voltage regulators, the next issue we are faced with is NOISE. Switching regulators have a reputation for being RF noise generators!





Here's an example of switching mode regulator noise. This graph was a record of me a couple of years ago, trying various tests to improve my station receiver (QCX) performance in the face of interference from my new PC's switched mode power supply. It turns out to be hard to buy a PC these days that doesn't come in an enclosure with at least one tempered glass wall, and full of all kinds of pointless coloured LED lighting. Faraday would be turning in his grave. You can see on the graph, the huge noise peaks which come and go every couple of minutes as the noise drifts past the operating frequency (horizontal axis is time in seconds).

All the details are a long story in their own right. To summarize, I had to search for an "all-metal" case; which when it arrived, turned out to have a plastic front. My Mother-in-law had recently donated an old cable TV tuner box whose steel lid could be cut to size and inserted inside the plastic front of the new PC. That got me a Faraday cage. Part of the problem was also common mode feedline current on the antenna coax (also another whole topic), the solution to that was 10 turns of RG58 coax around an FT240-43 ferrite. With all these measures in place, the noise from the PC power supply noise went from 30+ dB over the antenna band noise, to completely undetectable.

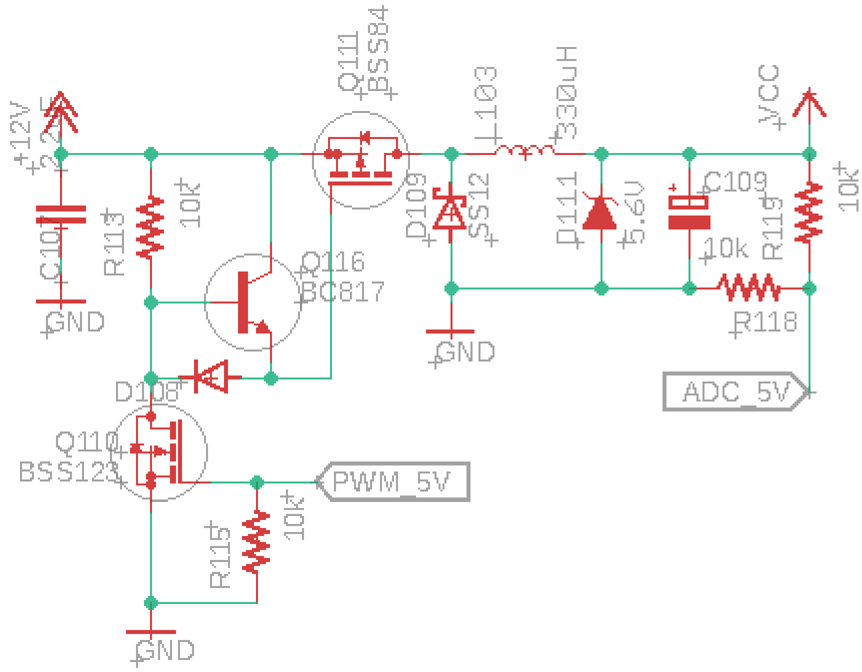
The trouble with switched mode power supplies is that the current is in principle switched hard on/off, typically at 50kHz or more. After this switching comes an inductor and capacitor smoothing circuit whose effect is to average out the spikes to give you your desired output voltage; a control circuit manages the necessary pulse width modulation (PWM) and/or frequency control to regulate the output voltage to the correct target voltage.

The hard switching generates harmonics well up into the RF spectrum. One problem is that of course these supplies are supposed to be as cheap and nasty as possible, who cares about radio frequency interference. They typically use simple resistor-capacitor oscillators which are drifty and have very bad phase noise performance. Therefore you usually get a band of noise which drifts up and down; on HF it sounds like a horrible raspy S9+ noise that is several kHz wide, drifts up and down slowly, and if you tune up and down the band, appears to repeat itself every 50kHz or so.

My idea with QMX is to design switching converters which solve these problems as follows:

1. Produce the PWM frequency from the microcontroller, so it is crystal referenced (good narrow low phase noise performance) – any interference should be constrained to a narrow band or birdie.
2. Control the frequency at which the switching occurs; the microcontroller knows what frequency the radio is operating on and should be able to predict where the harmonics will land; it can therefore make adjustments to the switching frequency in order to move the inevitable birdies away to a harmless place far from the operating frequency.
3. Put the DC converters on their own separate PCBs to try and shield the rest of the circuit. OK part of the reason for this is also that the main PCB is full…

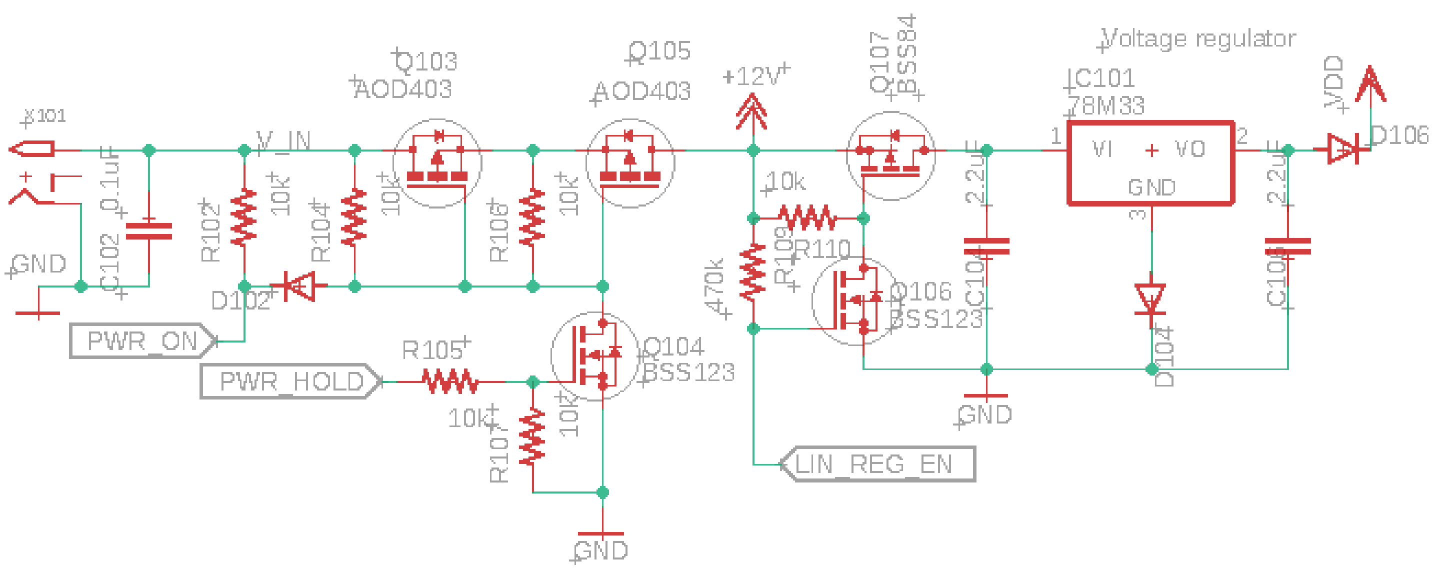
The circuit fragment shown here is the 5V regulator. The circuit is the same as the one I developed for the PIN diode forward bias current in the QDX PCB Rev 4, that provided a great improvement in efficiency and removed three quarters of a watt of unnecessary heat generation from the enclosure during transmit.



There's a P-channel MOSFET which is switched by a PWM signal from the microcontroller. The microcontroller also monitors the output voltage using an ADC input, and has a control loop implemented in firmware. NPN transistor Q116 provides an improvement in efficiency by ensuring a fast discharge of the Q111 gate charge, in other words a quick turn-off. More details are in the QDX manual. Note that here I also added a 5.6V zener diode as protection at the output. Because who wouldn't be nervous that something somehow could go wrong and pffff all the 5V circuits would be fried by too high supply voltage?

Very similar discrete component buck converter circuits are used for the 3.3V rail and the PIN diode forward bias current (as on QDX).

On the 3.3V line there's a little complication. The microcontroller is the control loop for the three buck converters. But the microcontroller needs 3.3V to operate. How can it get 3.3V to operate its control loop, if the voltage regulator which supplies it, is itself controlled by the microcontroller? It's a classic chicken and egg situation.

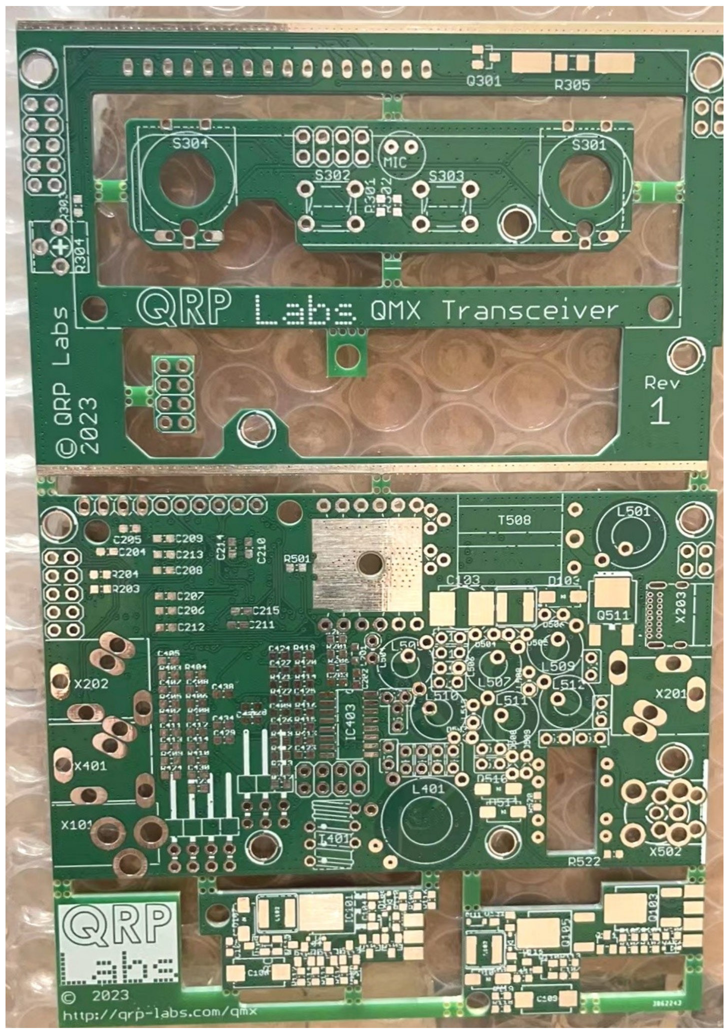


The solution is to include a 78M33 linear voltage regulator. At power up, the Q106 and Q107 switching circuits will ensure that the 78M33 linear voltage regulator is active. Then the microcontroller can boot up and sort itself out, and when it feels ready it can switch over to the efficient buck regulator by pulling the LIN_REG_EN signal low.

The circuit above also does much more than this, because it has an AOD403 as reverse polarity voltage protection, and also a soft power switch, that is connected to the button of the left rotary encoder. This effectively gives QMX an On/Off power switch so that it may be permanently connected to batteries for example. Press the button to switch on QMX. Once done, the microcontroller applies a 3.3V logic “high” signal at PWR_HOLD which keeps the power switched on though the button is released (and the button may then be used normally for other purposes). When the QMX is switched off, then it releases PWR_HOLD and the P-Channel MOSFET switches off, cutting power to the circuit. An additional advantage of this is that QMX is able to save its state (operating frequency, volume, mode, etc) before shutting down – so that when you next power up, it comes on in exactly the same state you left it.

PCB Design

The QCX-mini enclosure is really tiny. Quite a bit of board area is consumed by the connectors. Smaller connectors could be found, such as for the 3.5mm connectors… but these work and we have long experience with them (QCX, QCX+, QCX-mini) – any change is risk. A smaller connector might have shorter life or reliability issues; who knows until you have thousands of radios out in the field and the problems start!



Making the enclosure larger would solve a lot of my headaches but I had already set my challenge and there it is. QMX has to fit the QCX-mini enclosure, period.

The photo shows the prototype PCB.

There is naturally some similarity to QCX-mini. QCX-mini has two PCBs, a main PCB and a display PCB; the display PCB further pops out a small board which holds the buttons and controls, and a couple of tiny spacing boards to get the height of the control board correct.

For QMX it was all done on one single board, sized 3.6 x 5.5 inches. This contains snap-off boards, so it all breaks apart into:

- Display board (top)
- Main board (bottom)
- Controls board
- Two small power supply boards
- Spacer boards for the control board mounting

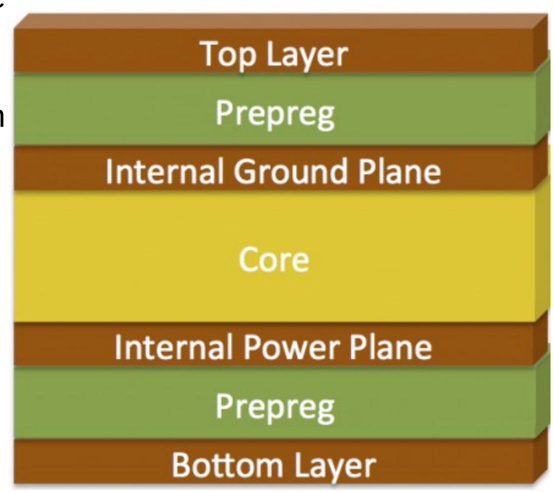
The five boards all have connections to the main PCB using inexpensive pin header connectors.

The big problem I had was that the large number of necessary SMD components, which must be on both sides of the main PCB, meant that there was simply not enough space to route the necessary interconnection signals between them on the top and bottom layers. Let alone provide any remnants of a nice groundplane to look after the noise performance. For the switched mode buck regulator boards, for reasons of available space, I had to have components only on the top side; and for wishing to avoid noise interference, I wanted the bottom side of those boards to be only groundplane. So again had nowhere to route traces.

Accordingly I had to resign myself to designing my first ever, multi-layer board, which sounded very scary indeed. But in the end it's not so difficult, and in many ways is actually easier than struggling with so many signals and maintaining ground plane integrity on a normal 2-layer board (top and bottom copper). There are YouTube videos and websites. These days all the information in the world is instantly at your fingertips and you can learn anything you need to know.

Some people might not like the idea of a multi-layer board. Some want to see every trace. Well OK I'll give you a large diagram so you can see where all the traces go. Others worry: how will they repair a broken trace that's inaccessible inside the board? I'm sorry, you won't. I'd like to ask, how are you planning to damage that internal trace hidden inside, in the first place? "Well what if I drill into it?"… WHY would you want to drill into a PCB, specifically a multi-layer PCB… OK if you do, all bets are off.

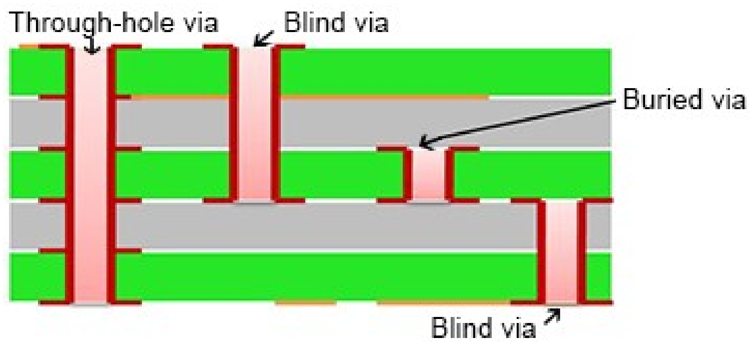
One interesting YouTube video talked about the mistake of the most common 4-layer board stack-up which has signals on the top and bottom layers, a ground plane on one inside layer and a supply plane on another. It was very well explained. A "via" is a plated hole drilled through the board to transition or connect a signal from the top layer to the bottom layer. The video pointed out that a return current flows on the ground plane under any signal. At the point the signal transitions through the board from the top side to the bottom side, the ground plane return current now has to flow on the supply voltage plane (which is also assumed to be RF ground). The problem is that now you have two unconnected return ground return signals, moving away from that layer transitioning via, and you just created a little dipole antenna which can radiate any signal on the trace, or indeed pick up noise. To solve that, you need to arrange a low impedance connection between the two grounds (in this case, ground plane and power supply plane).



The video explained that the only way to do this, because they are at different DC potentials, is now to put a capacitor between them. Yes the layers themselves act like a capacitor but it's not a particularly large, useful or low impedance one. So you would ideally now need a capacitor next to every via transitioning signal from one layer to another. Of course this capacitor has to sit on one layer or the other, and have its own via connecting one side to the opposite layer. Nothing is as good or low impedance as a simple via connecting the two ground planes. So the best thing to do is forget about the power supply plane, and make both internal planes ground. The video pointed out that even an 8 mil trace can handle over an amp of current – so massive thick traces or power planes aren't necessary for current handling purposes in most applications (unless you're designing some kind of industrial high power electronics for example).

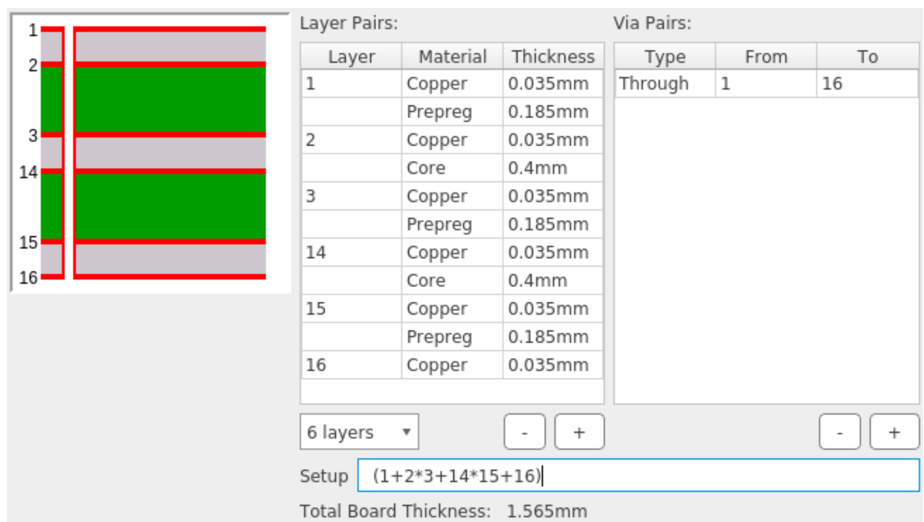
I was all ready to start designing my 4-layer board, having two ground planes in the middle, but I realized that even 4 layers wasn't going to be enough, if I wanted to have good ground planes everywhere. Which I do – because it's quite important on a board which mixes high performance sensitive analog electronics with potentially noisy digital electronics like a fast microcontroller.

I even got fancy and included lots of blind vias. Blind and buried vias are ones that don't go all the way through the PCB (see diagram). A blind via starts or finishes at one surface of the PCB and goes part way through only; a buried via exists only on the inside.



They're useful because if you're stuck in a tight spot to route a signal, and you can't put a via in right there because there's an SMD component on the bottom side of the PCB under that location, for example – you can still connect a signal on the top layer of the PCB to an inside layer, by using a blind via. It doesn't go all the way though and contact with the SMD component on the bottom side. They're also useful when it comes to more groundplane stitching because again, you can do it underneath SMD components.

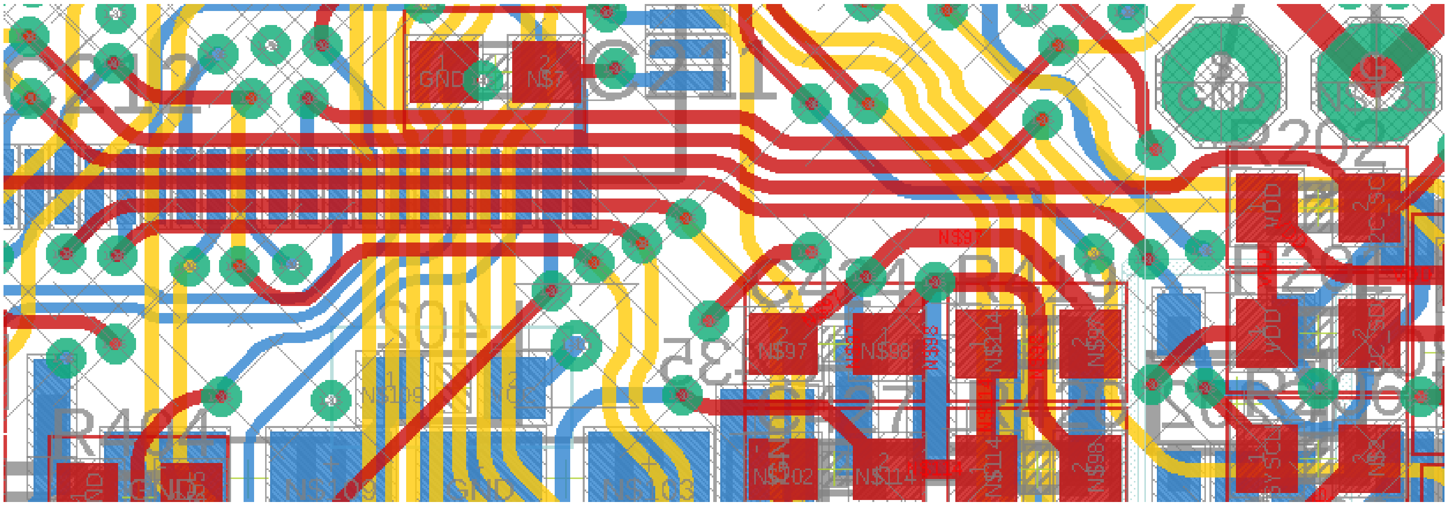
The image shows how the layers stack up in Eagle CAD which I use for all my PCB design. It uses 6 of Eagle's available 16 layers.



1: Top layer (SMD components)
2: Strictly groundplane only
3: Signal interconnect
4: Mostly power connections
5: Strictly groundplane only
6: Bottom layer (SMD components)

I kept two layers for purely ground plane, with no exceptions. Layer 4 has mainly power connections with a few signal interconnects where I could not manage it any other way; but mostly ground plane.

On all 6 layers, any unused areas are copper-pour groundplane. There are vias stitching the groundplanes together as close as possible to every signal via, and at intervals of not more than 0.1-inches in any open areas. Stitching groundplanes together is important. It ensures ground return currents always have the best possible lowest impedance path to "ground", minimizing the opportunity for noise-pickup ground loops. Since the inside of the PCB could also be considered a microwave cavity, by stitching together the groundplane frequently you break up the cavities into much smaller ones, which have far higher resonant frequency where they will be less and less troublesome.



The first nasty surprise came when I ordered 5 (minimum order quantity) prototype PCBs. $117 (23.something each), quite a jump from the usual few dollars per PCB we'd expect, even for a larger PCB like this one! Wow, making it 6-layer really bites. Hopefully when it comes to volume production, the price comes down a lot.

Not long after I'd got over that and paid… I had an email from the PCB manufacturer, oh, after the PCB audit we now have to tell you, the actual cost is going to be $1,519! To say I fell off my chair would be an understatement. For five boards! It turned out that blind and buried vias make things more expensive. A lot more expensive. So you think you're clever with all those blind and buried vias only to discover ooops, manufacturing those is not so easy nor inexpensive.

Back to the drawing board – I spent another few days repairing my 6-layer PCB layout to remove all the blind and buried vias!

6-layers is really not as hard as it seems and I really think I spent less time on the QMX layout than I did on the QCX-mini.

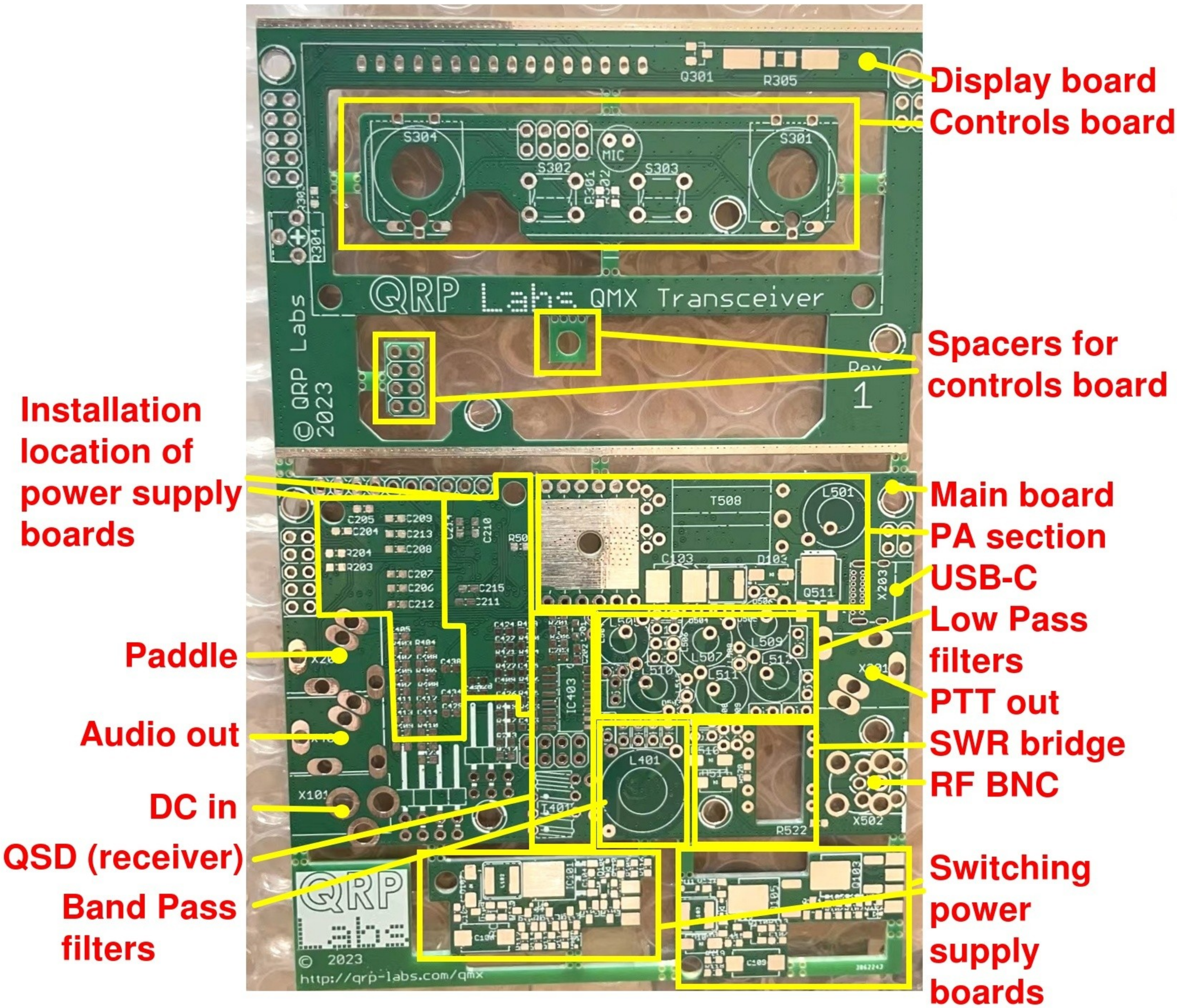
Physical layout – squeezing it all in

Getting all the required components to fit inside such a small enclosure was a major challenge. I used SMD components wherever possible. But that still leaves the larger components, like the connectors, toroids, controls, LCD.

There wasn't enough board area to fit all the SMD components so I had to design two little plug-in boards for the buck converter switching regulators, 3.3V and 5V. The PIN diode forward bias converter is on the main PCB near the output transformer.

The vertical space between the bottom surface of the LCD PCB and the top surface of the main PCB is 11mm. However the LCD module PCB itself deletes 1.6mm of that and there are further protrusions such as the epoxy blobs containing the LCD module IC's and the metal tabs which tighten the LCD module sandwich together. So it's necessary to design the component layout with all this in mind, so that nothing gets in the way of anything else!

- The position of connectors on the left and right main board edges is pretty much the same as for QCX-mini, except for the new USB-C connector for serial data. Which also makes space for four more pin header connections between main and LCD board.
- The controls board pin header connections were moved to make space for the pin header connectors under it on the main board, for the plug-in buck converter boards.
- Almost all the toroids have to lie down flat on the board! The only exception to this was the FT37-43 trifilar transmission line transformer which is part of the double balanced QSD in the receiver circuit – there's space for that standing up under the middle of the controls PCB.
- Smaller T30-6 toroids are used for the Low Pass Filter inductors, so that there is (hopefully) enough space to squeeze in the diodes, radial chokes and NP0 capacitors of the LPF and switching circuits!
- All the IC's under the position of the switching power supply plug-in boards are restricted to being on the lower side of the PCB, with only resistors and capacitors on the top side – because these are very low profile, less than 1mm high.
- The switching power supply plug-in boards only have components on the top side. Low profile tantalum capacitors had to be used instead of electrolytics, just because electrolytic capacitors are too tall to fit!
- For the SWR bridge, I believe based on my analysis a smaller binocular toroid can be used than the BN43-202 in the output transformer – I chose a BN43-1502 for this. It's the same cross-section as the BN43-202 but half the length.
- Even so – that smaller BN43-1502 in no way fits in the available height between the bottom of the rotary encoder on the controls board, and the main PCB top surface. Due to this, I had to cut out a rectangle which you can see at the bottom right of the main board, for the binocular core to sit in.



Stretch goals: SSB

SSB is the only stretch goal I'm going to talk about. The others are my secret, for now.

SSB capability is not only important for the sake of being able to transmit actual SSB, but also because some digital modes such as PSK31 or WinLink which involve either phase shift modulation or multiple concurrent tones, don't work on QDX with its non-linear exciter and power amplifier. The use of the push-pull switching amplifier in QDX and its unique method of audio frequency measurement and direct synthesis of the RF has plenty of advantages as discussed earlier, not least of which is the great circuit simplification of not needing a SSB exciter, and linear driver and power amplifier, all of which would make a design more complex.

SSB reception is no issue, and QDX does that already, indeed, very well… many people have commented that the QDX receiver outperforms their Yaesu, Kenwood, Icom etc. The problem area is SSB transmission.

The uSDX tranceiver project originally was based on the QCX Classic, with some hardware modifications and a totally new firmware written by Guido PE1NNZ on the ATmega328 microcontroller chip. Later, Manuel DL2MAN did a lot of work on improving the Class-E power amplifier and producing a slick implementation no longer based on the QCX. There are now several Far East uSDX productions and an “official” uSDX implementation called (tr)uSDX which is approved and supported by PE1NNZ and DL2MAN.

The uSDX transceiver uses the existing QSD baseband I & Q signals of the QCX receiver section, and implements an SDR on that low resource microcontroller chip sampling the I and Q channels with the 10-bit multiplexed ADC of the ATmega328. It uses PWM for its audio output.

On transmit, uSDX implements a version of Class-E Envelope Restoration (EER). The SSB signal is split into Phase and Amplitude components, which can then be transmitted using the radio’s Class-E power amplifier. The phase component modulation is implemented by rapid frequency change transmissions to the Si5351A which are equivalent to phase modulating the oscillator signal to the power amplifier. The amplitude component was originally implemented on uSDX by a PWM signal connected to the RF envelope shaping circuit. However the current designs use a DC blocking capacitor between the logic gate driver circuit, and the gate of the PA MOSFETs, then apply a variable DC bias to the MOSFET gates. The DC bias is derived from a PWM output of the processor.

Overall uSDX is a very clever design, and it is amazing that a multi-band multi-mode radio transceiver can be designed around such limited hardware! But it is not, in my view, a sufficiently high performance transceiver.

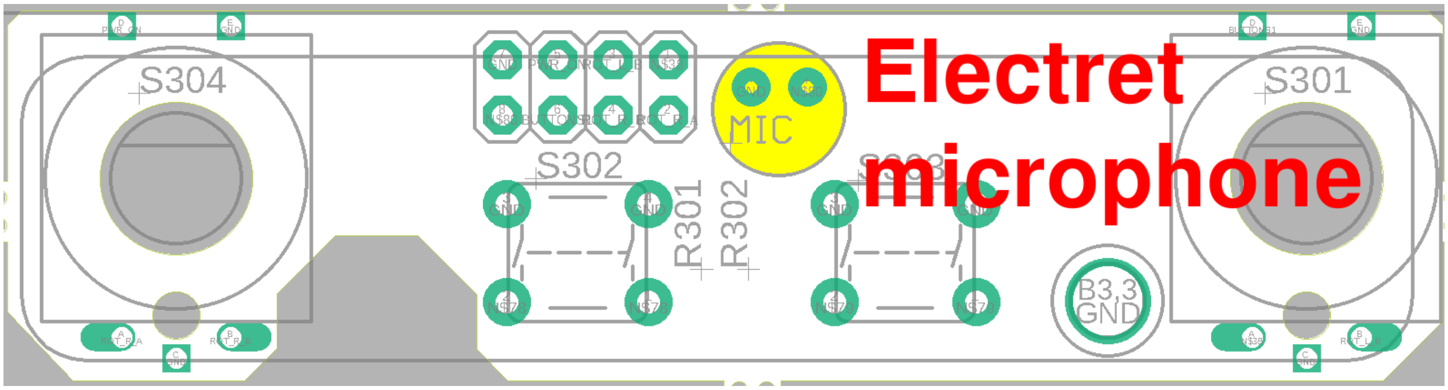
On receive, the performance is quite severely (in my view) limited by the hardware constraints. Dynamic range of an ADC is determined by the number of bits, at a rate of 6dB per bit. This is a theoretical maximum, the actual delivered performance is always worse than 6dB multiplied by the ADC bit depth, because it is also determined by the noise floor of the ADC chip being used. Furthermore, uSDX manages all that DSP on a dated 8-bit microcontroller running at 20MHz.

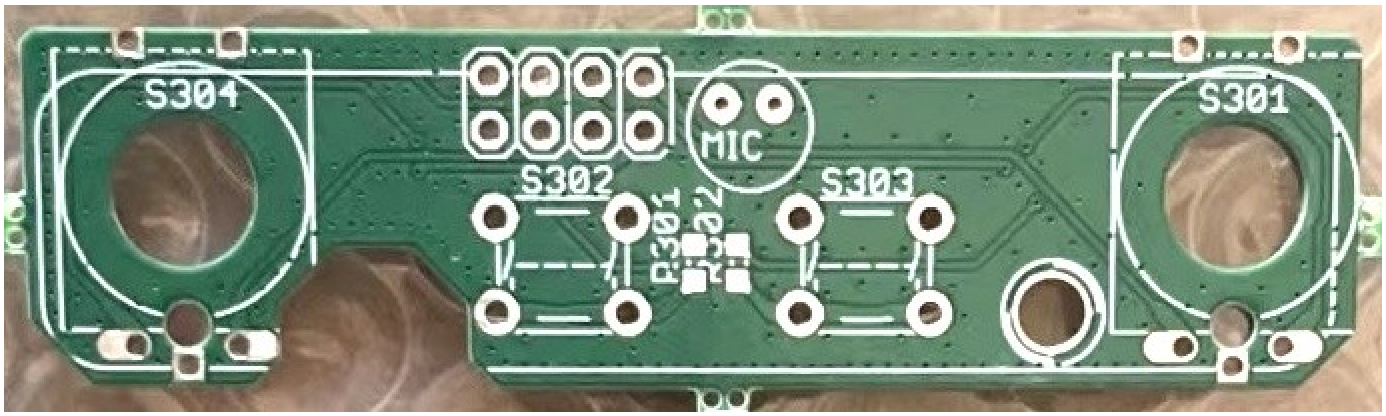
On transmit, the limitations of modulating amplitude by a low resolution processor PWM output, and the small control range (I measure 10dB or so) of amplitude control afforded by the DC bias at the BS170 MOSFET gates, along with its non-linearity and again the severe limitations imposed by such a low end (by modern standards) 8-bit 20MHz microcontroller, all combine to impact on the quality of transmit signal it can produce.

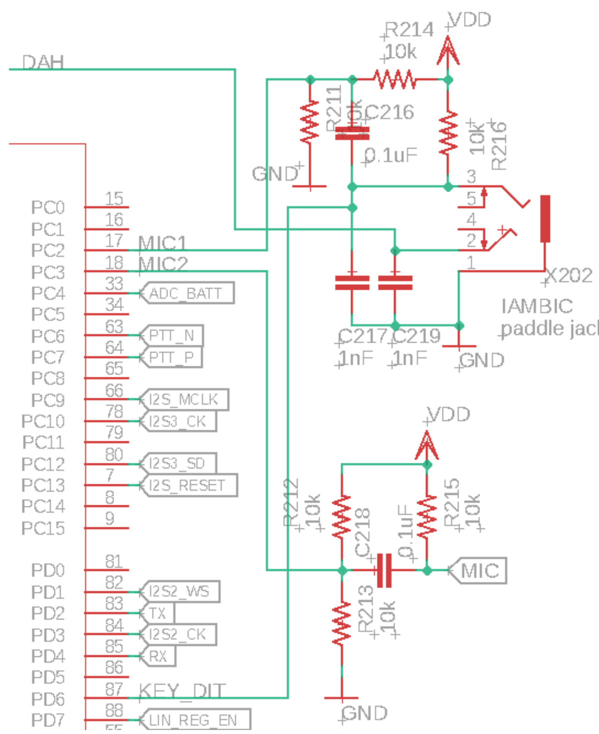
QMX, on the other hand, has several advantages:

- Fast 180MHz 32-bit ARM Cortex M4 microcontroller with DSP and Floating Point units
- High performance 48ksps 24-bit stereo ADC on receive, which results in a truly excellent performance SSB receiver (already in production in QDX for 18 months) – and should provide much improved performance on transmit
- 12-bit DAC controlled AM power modulator

This is why the little control PCB of the QMX design has space for a small electret microphone!







Two ADC inputs to the microcontroller are connected to the internal microphone connection to the controls board, as well as to the IAMBIC Paddle jack – which can then be used to plug in an external microphone and PTT switch if desired.

Only time and testing will reveal whether the stretch goal of including SSB transmission is feasible or not. I suspect it will be; but whether or not it works well enough (good enough performance) to own up to on the official list of supported modes and features, that's the real question.

Conclusion

I hope this article has been interesting and that you can understand a bit more about the evolution of QRP Labs kits; and I hope the new QMX design sounds as exciting to you as it does to me! I think it's a rig full of potential for further development, as well as an amazing combination of performance and features in a small package at such a low price. And most importantly of all: being one more stepping stone on the path of QRP Labs kit evolution! More: http://qrp-labs.com/qmx

73, Happy homebrewing and happy QRP!