The Tualatin QRP CW Transceiver

2007 FDIM Potluck Contest

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Overview

The Tualatin transceiver is a single-band superheterodyne QRP CW rig designed for the 2007 FDIM Potluck Contest. In keeping with my Oregon waterways naming scheme, I dubbed this transceiver "Tualatin," after the river which flows through the beautiful valley that I now live in.

The parts selection in the Potluck kit seemed to scream "transceiver", so it was natural to try to build one. My original design goal was to create a dual-band CW transceiver, however this turned out to be too ambitious. Once I managed to get my expectations under control, I found that the kit of parts provided a challenging but useful selection of components. I believe that the Tualatin has efficient use of the available components, given it's features.

Features and Specifications

General

- 40 Meter VFO-tuned CW transceiver, approximately 65 kHz coverage (7.000 MHz to 7.065 MHz)
- Full-QSK keying
- Solid-state T/R switching
- Clean sine wave sidetone
- VFO drift (after 10 minute warm up at 25°C): 70 Hz in 30 minutes

Receiver

- Single-conversion superheterodyne
- Two-pole crystal ladder IF filter, 250 Hz bandwidth
- Four-pole low-pass active audio filter
- Minimum Discernible Signal (MDS): -131 dBm
- RX Current (13.8 V, max AF/IF Gain): 230 mA

Transmitter

- Adjustable output power, approximately 5 W maximum at 13.8 V
- Maximum spurious output: -45 dBc
- TX Current (13.8 V, 4.5 W power out): 870 mA

Design Philosophy and Inspiration

The general design of the Tualatin, as well as many of the specific features, were derived from some well-known QRP rigs. The rig was perhaps most heavily influenced by the K8IQY 2n2/xx series of QRP transceivers. The original 2N2/40 was also designed for a building contest, which allowed me to study the design considerations and trade-offs which went into its construction.

Another project which had a large impact on the design of the Tualatin was the Nuts and Bolts radios designed by NB6M. These rigs were very well documented in a series of three articles printed in the now-defunct AMQRP Homebrewer magazine. The detailed design commentary in the articles gave me much insight into the important elements of successful transceiver design. Another benefit was the similarity of the Nuts and Bolts 40 to the final Tualatin design.

Underlying all of this great QRP design information is the book no homebrewer should be without, *Experimental Methods in RF Design* (*EMRFD*). When it came time to implement the ideas for the various circuits in the transceiver, this was the book that I turned to more than any other. The amount of practical RF circuit information in this book is incredible. For some classic, well-established circuitry, I also found myself turning to its predecessor, *Solid State Design for the Radio Amateur*. The design guidance from both of these books proved invaluable during development of the Tualatin.

The ability to model circuits, quickly change parameters, and view the effect on the circuit conditions was extremely important in the development of the Tualatin. I used what is perhaps the best free modeling tool available for amateur use, *LTSpice*. I doubt that I would have had the time to breadboard every circuit that I wanted to evaluate for the contest. By first modeling potential circuits in *LTSpice*, I was able to quickly adapt many existing circuit designs for use in the Tualatin transceiver.

The parts selection available to the contest participants seemed to mostly dictate the way in which a superheterodyne transceiver could be built. Just enough small-signal diodes were available for the construction of two mixers and a product detector (given you wanted to use diode mixers). The three 4.9152 MHz crystals ensured the selection of the intermediate frequency. One 2N5109 driver transistor and one 2SC2075 PA transistor were available to generate RF for the transmitter. Although there were considerable constraints on the parts available, I still felt that I had just enough latitude to make the design changes necessary to make a functional transceiver out of the parts given.

Receiver

The Tualatin receiver is derived from the classic single-conversion superhet topology which uses passive diode mixers and a crystal ladder filter for sharp IF selectivity. Although I stayed with a very conventional block diagram for the receiver, I did use some slightly unconventional circuits to compensate for the lack of certain components.

The front end consists of a 7 MHz double-tuned circuit bandpass filter directly connected to a single-balanced diode mixer. The *Double Tuned Circuit* program provided with *EMRFD* enabled me to quickly design the bandpass filter with a 50 Ω end termination and 250 kHz bandwidth. A single-balanced diode mixer was chosen over a double-balanced mixer because of the limited amount of ferrite cores available for use. A very simple diplexer was placed on the RF and IF ports of the mixer in order to try to terminate them correctly. This diplexer is far from ideal, but was a design compromise I had to make to conserve parts.

Following the mixer is perhaps the most important amplifier in the whole receiver chain. In order to preserve a high dynamic range, there needs to be a large amount of standing current in this amplifier. Normally, a transistor capable of handling such a high current would be used in this amp. Because the only transistors available with this current capacity were already reserved for the transmitter, a different approach was necessary. *EMRFD* has a general purpose receiver front end with an IF amplifier which fit the bill perfectly (Fig. 6.69). Two 2N3904 transistors are used in parallel, set so that there is about 20 mA of standing current in each device.

The post-mixer IF amplifier was designed to be terminated in 220 Ω, to match the impedance of the two-pole crystal ladder filter. A 6 dB, 220 Ω resistive pad was placed between the post-mixer amplifier and the crystal filter to ensure a very good return loss. Since the Tualatin was designed from the start to be a CW-only rig, I decided to use a 250 Hz filter bandwidth. Once again, the software provided with *EMRFD* allowed me to quickly design and prototype the filter. In this case I used *XLAD*, along with *GPLA* to design the filter to my desired specifications. Illustration 1 shows the results of my sweep of the filter, which proves that software does a pretty good job for little effort.

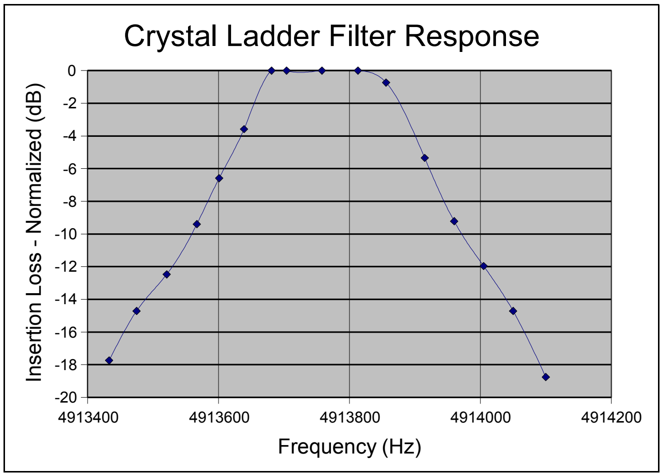

Illustration 1: Crystal Ladder Filter Response

Attached to the output of the crystal filter is a typical broadband feedback amplifier, which is in place to compensate for losses in the filter. This amplifier is terminated with a 4 dB, 50 Ω resistive pad to help the input return loss, so that the crystal filter sees a good load at all frequencies. The 4 dB attenuation was chosen mainly because it was close to the value that I wanted, and I had the small value resistors on-hand to implement it.

The final IF amplifier in the receiver is a design provided in *EMRFD* in Figure 6.41. The unique feature of this particular amplifier is its IF gain control. A potentiometer provides a variable amount of current to a forward-biased diode in the emitter degeneration leg of the amplifier.

Next in the receiver chain is the product detector, followed by the audio circuits. The product detector is similar to the mixer on the front end, but only has two diodes instead of four. This creates a bit more unbalance at each port, but didn't seem to make much difference in practice. Since only one 4.9152 MHz crystal was left over after building the crystal ladder filter, the BFO and Carrier Oscillator functions had to be combined. While this is a little different than the usual superhet receiver, it is not very difficult to get around this limitation. Normally, the transmit offset would be realized by shifting the carrier oscillator frequency the desired amount from the BFO. In this case, I had to incorporate the transmit offset into the VFO during keydown, much like you would see in a direct conversion transceiver. The BFO/carrier oscillator signal is shared by using a 3 dB hybrid splitter to present a 50 Ω port to each mixer.

The AF signal from the product detector is then processed by an active low-pass filter. The type of design used here is normally used with op-amps, but I was able to find design information for a discrete transistor version in *Solid State Design for the Radio Amateur*. The filter has a cutoff frequency of approximately 900 Hz and a roll-off rate of 40 dB/decade. In retrospect, this filter probably isn't necessary in this receiver, but it was one of the first circuit blocks I built and I didn't feel like taking it out.

The final stage of the receiver is the mute circuit, followed by a preamp and a class-AB audio amplifier. There is nothing special about the mute circuit used here; it's the standard JFET type seen in many other QRP designs. The final AF amplifier consists of a class-A preamplifier stage followed by a class-AB amplifier. This stage is a modification of a design posted by W8DIZ on his Potluck Circuit Repository. The advantage of using this type of amplifier is the elimination of the need for a audio transformer on the output. A low impedance load can be driven directly from this amplifier. The trade off is a slight amount of crossover distortion, but proper biasing of the transistors will minimize that.

Transmitter

Design of the transmitter portion of the Tualatin was a bit easier and more straightforward, but provided larger challenges in the implementation. The transmitted signal begins with the single-balanced diode transmit mixer. This mixer is similar to the other mixers in the transceiver. However, a 3 dB, 50 Ω resistive pad is used instead of a diplexer to terminate the output.

The output of the mixer has many spurious and image products which need to be eliminated before any further amplification. Another 7 MHz bandpass filter was designed to accomplish this task. Normally, I would have merely duplicated the bandpass filter in the front end of the receiver, but there were not enough trimmer capacitors left to do that. Fortunately, I still had two identical 10 μH trimmer inductors available, so I went back to the *EMRFD* software to design a new filter around these components.

Next, two nearly identical feedback amplifiers follow up the bandpass filter. These broadband amplifiers are used to compensate for the losses in the bandpass filter and amplify the signal to an appropriate level for the transmitter driver stage. The total gain of these two cascaded stages is approximately 35 dB. A potentiometer voltage divider was placed on the output of the stage to allow the RF drive level to be varied.

By the time that I started building the transmitter amplifiers, I was running out of FT37-43 toroid cores. Included in the kit were two BN-43-2403 and one BN-43-302 ferrite binocular cores. I had never used binocular cores before, but given my parts shortage, I was forced to for this radio. I found that it was very easy to make a broadband bifilar transformer with a binocular core; perhaps easier than using a toroid. I would highly recommend that any homebrewers who haven't yet used binocular cores give them a try in their next project.

At the output of the transmitter amplifiers, the transmitted signal is at a maximum power of about +10 dBm. The transmitter driver which follows is another broadband class-A design, using a 2N5109. This stage gives about 15 dB of gain, which provides a maximum power of approximately +25 dBm (about 320 mW) to the power amplifier. Broadband class-A amplifiers were chosen for each stage in order to maximize the stability and reduce the amount of tweaking needed.

The power amplifier used in the Tualatin is a very typical class-C circuit seen in many other CW rigs. A broadband bifilar transformer is used on the input to change the 50 Ω input impedance down to 12.5 Ω for a better match to the transistor input impedance. An L-network was used on the collector output to transform the 50 Ω load to 18 Ω for the transistor. The collector load was derived using the classic formula

$$R_L = \frac{{V_{CC}}^2}{2P_O}$$

where the desired power output was 4 W.

The 2SC2075 transistor used in the PA is actually able to give about 5 W maximum output with an input of 320 mW. During the development of the Tualatin, I managed to drag my oscilloscope probe against the 2SC2075 heatsink, which shorted the collector to ground and destroyed the transistor. While I was waiting for the replacement, I scrounged up a 2SC1969 that I had left over from an old project. Interestingly enough, I was able to get nearly 8 W of power from this transistor using the same drive level.

A 40 meter low-pass filter terminates the transmitter chain to reduce spurious products and produce a clean sine wave output from the class-C power amplifier. Illustration 2 shows transmitter waveform when set for nearly full power into a 50 Ω dummy load. The signal observed on my Tektronix TDS1012 oscilloscope was very clean and stable.

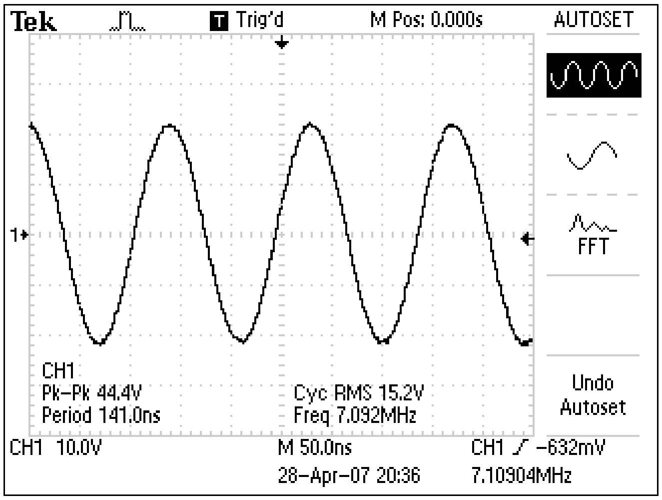

Illustration 2: Transmitter Output Waveform

The TDS1012 also has the ability to display a FFT plot of a signal, which was very useful for measuring the spurious output of the transmitter. Illustration 3 shows that the highest spurious product is more than 45 dB below the carrier.

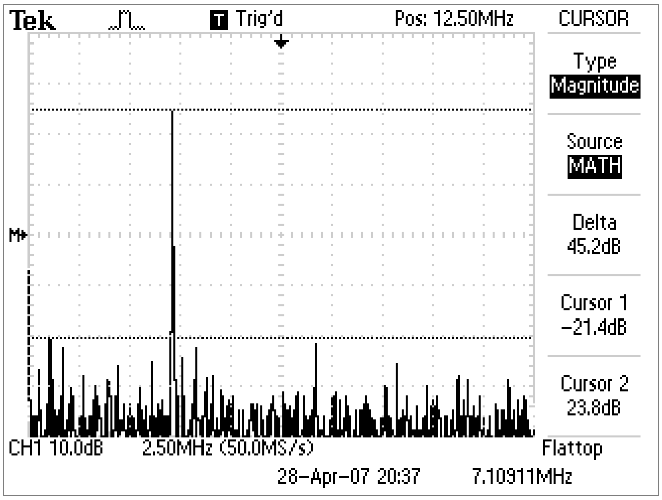

Illustration 3: Spurious Products

VFO

The Tualatin VFO is based on a typical Hartley oscillator configuration. Although an air variable capacitor is the best tuning element to use in a VFO, I didn't have a good variable capacitor on hand. I also wanted a large range of frequency coverage, but did not have the necessary vernier drive for an air variable capacitor. I decided to go with a varicap tuned VFO using a 10-turn potentiometer. The problem with using varicaps as the main tuning element in VFOs is their tendency to drift quite a bit if not properly temperature compensated. Very fortunately, there were a couple of factors which helped me with the situation. The first was the inclusion of one type-7 toroid core in the kit. I'm sure this was no accident, as type-7 has a very good temperature coefficient. The other factor was the inclusion of N150 capacitors. These allowed me to compensate for the positive temperature coefficient of the other components in the VFO tank. Using a bit of experimentation, I was able to compensate the VFO to drift approximately 70 Hz in 30 minutes after a 10 minute warm up. Illustration 4 shows a plot of the VFO drift measured at 25°C.

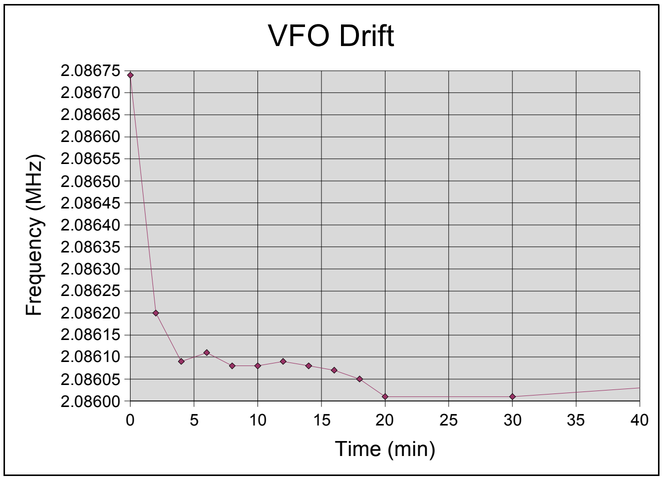

Illustration 4: VFO Drift Characteristics

Integration

The integration of the Tualatin was perhaps the trickiest portion of the build and design. It's relatively easy to get an individual circuit block up and running, but getting a collection of those circuits to work together as a whole introduces many factors which are hard to foresee. Things such are circuit layout and proper bypassing start to become very important when placing all of the circuits into one small area.

Building the receiver portion of the Tualatin was fairly trouble free. I started with the final audio amplifier and worked my way backwards from there. By injecting an appropriate signal into the portion of the completed receiver chain, performance was easily verified at each step.

When the transmitter chain was built, more problems started to creep into the integrated radio. Perhaps the most significant problem was unwanted RF feeding back into circuits where it should not be. After the initial build of the transmitter up to the driver stage, the transmitted signal was very noisy and erratic. Quite a bit of unscientific poking around showed me that RF was interfering with the transmit bandpass filter. A bit more investigation indicated that the proximity of the bandpass filter to the driver amplifier was causing RF to feedback into the variable inductor cans in the filter. I believe that this would not have been as problematic if I has used toroids, since their magnetic fields are almost completely self-contained. Placing shielding between the offending stages greatly helped the instability, but did not get rid of it entirely.

More study of the receiver circuitry showed that some of the audio stages were not properly bypassed for RF. After strategically placing some 68 nF capacitors in the right areas, the transmitter instability was cured. Unfortunately, the problem reoccurred after the power amplifier stage was built. The power output would sometimes be a full 5 W, then after slightly moving the circuit board would be nearly zero. Other times, the power output would much higher than 5 W, but at a subharmonic frequency. More troubleshooting revealed that the placement of the transmitter amplifier V_{CC} supply leads was the contributing factor to this instability. During the build, this wire was not dressed on the board correctly. Instead, it arced across the top of the circuit, picking up stray RF. Rerouting the supply leads down to the copper clad resolved this nasty problem.

One more major problem ended up plaguing the transceiver during final integration. On transmit, the mute circuit did not seem to eliminate a loud thump on keydown and keyup. Permanently enabling the mute circuit did not help to reduce this thump at all, indicating that the mute was not the problem. Many hours of troubleshooting finally pointed me to the cause of the thumps. A very large, low frequency (400 Hz) damped wave was being generated in the receiver at keydown and keyup. When this impulse reached the final audio amplifier, it was nearly 4 V peak-to-peak. I never managed to find the root cause of this wave, but I did find a way to nearly eliminate it. By providing a circuit to turn off power to the IF amplifiers during transmit, the offending signal was greatly attenuated. There is still a slight artifact of this thump, but it is not loud enough to be a major problem.

Conclusion

It was a great thrill to finally get the Tualatin completed and put on the air. I made quite a few checks of the transmitter signal quality, stability, and frequency before attempting to make my first QSO with the rig. When the time came to finally attempt the first contact, I didn't wait for it to go into its cabinet, in case there were some final bugs to work out. Not to mention that any homebrewer with his salt has to have at least one QSO with the rig splayed out across his bench, with clip leads tangled everywhere.

Illustration 5: First QSO

After a lot of tweaking and troubleshooting, it was a welcome relief to finally be able to try for my first QSO with the Tualatin. My antenna for this try was a 40-foot longwire shot out the second-story window to a tree, along with a counterpoise draped down the side of the house. Calling CQ for about an hour yielded no results, which got me to worrying if the rig was working correctly. I put the Tualatin back on the dummy load and double checked my power output, my transmit offset, and that I was listening to the correct sideband. Satisfied that everything was working correctly, I started tuning the band for a CQ to answer. This time I found NY6P calling CQ at a speed I could copy, so I gave him a call. My heart leaped as I heard him come back with my callsign. The QSO was a bit rough from bad QSB and my nervous fist, but my 5 W made it about 1000 miles. Not too bad given the circumstances!

To complete the Tualatin, it needed to go into a cabinet. The circuit board just barely ended up fitting into a Ten-Tec TG-38 enclosure with a bit of trimming. I built the VFO on a separate board and did not have room to place it side-by-side with the main board. It ended up on a pair of standoffs above the active audio filter, as seen in Illustration 6. This arrangement worked out well, as it gives me access to the trimmer cap on the VFO for adjustments. I also intend to add RIT to the VFO at some point (there's a nice empty spot for it visible in Illustration 6), so I will be able to place the new components without having to take the board out.

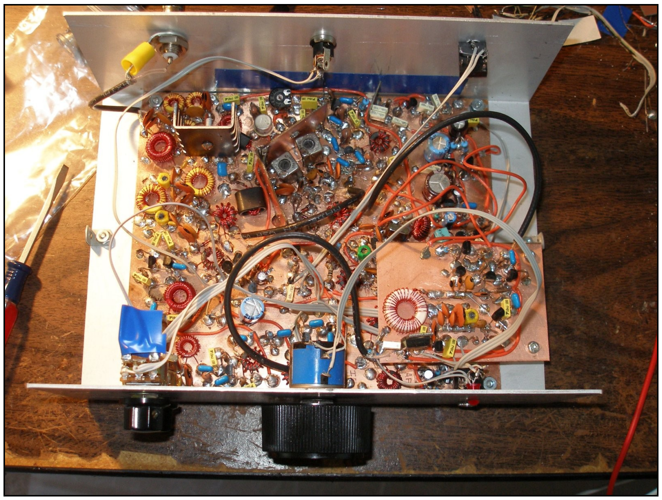

Illustration 6: Tualatin Inside View

I have been pleased with the performance of the Tualatin overall. The receiver is sensitive and the filtering isn't bad for a two-pole filter. The only time it really gets into trouble is with the kilowatt guys trying to bust DX pileups. Cranking the IF gain all the way down will take care of that, but AGC would have been a nice addition. The transmitter is clean and stable, and the VFO drift is decent for a varactor tuned circuit. A RIT circuit was designed, but I wasn't able to include it because I couldn't acquire a center-detent pot in time.

There are still two moderate problems that I would have like to have resolved, but ran out of time to. The first is the remnants of the keying thump mentioned earlier. While the thump is not very offensive, it is still there during keying. It doesn't ruin the use of the rig, but operation would be nicer without it. The other problem is a loud birdie around 7.020 MHz. I haven't yet traced the root cause of this signal, but I suspect better internal shielding would have prevented it.

The experience of designing and building the Tualatin has been the most rewarding thing I have ever done in amateur radio. I would like to thank QRP ARCI and the Flying Pigs QRP club for sponsoring such a fun competition. I also owe a debt of gratitude to all those on qrp-l.org who helped me with technical questions and provided feedback on my design.

Bill of Materials

C1, C8, C63, C67	56
C2, C9, C18, C21, C89, C93, C103	220
C3, C7, C101	45 var
C4, C6, C20, C117	150
C5	6.8
C10, C91, C95, C119	68
C11, C19, C22	270
C12, C17, C23, C25, C27, C28, C30, C31, C32, C33, C34, C51, C70, C71, C73, C75, C76, C80, C83, C86, C96, C111, C112, C113, C120	100n
C13, C14, C15, C16, C24, C26, C29, C69, C72, C74, C77, C78, C79, C81, C82, C84, C97, C124	10n
C35, C52 , C122	10u
C36, C37, C38, C39, C40, C41, C42, C43, C44, C47, C49, C55, C56, C57, C58, C59, C60, C98, C121	68n
C45, C46	1u
C48, C123	22u
C50	330u
C53, C54	220u
C61, C68, C88, C110	43
C62, C87	680
C64, C66, C100, C102	10
C65	1.5
C85, C90, C94	180
C92	1n
C99, C115, C116	100
C104	150
C105, C106, C107	82
C108	33
C109	4.7
C114	65 var
C118	35 var
C125	470u
D1, D2, D3, D7, D8, D11, D12, D13, D14, D15, D16, D18, D19	1N4148
D5, D6, D9, D10, D20	1N4007
D17	MVAM109
D21	Red LED
J1	PHONES
J2	BNC
J3	+13.8v
J4	KEY
L1, L2	2.1u T50-2 21T
L3	844n T37-2 15T
L4	8.6u T50-2 42T
L5	3u T37-2 27T
L6	235u FT37-43 28T
L7, L8	10uH trim
L9	4.1u T37-2 32T
L10	588n T37-6 14T
L11	10u T50-2 45T
L12, L13	1u T37-6 18T
L14	7.5u T68-7 38T
L15	50u FT37-61 31T
L16	20u FT37-61 20T
Q1, Q2, Q3, Q4, Q5, Q6, Q7, Q8, Q9, Q11, Q12, Q14, Q15, Q16, Q19, Q20, Q22, Q23, Q24, Q25, Q26, Q27	2N3904
Q10, Q21	J310
Q13, Q28	2N3906
Q17	2N5109
Q18	2SC2075
R1, R12, R61, R66, R78, R88	1.27k
R2	680
R3, R20, R22, R46, R109	1k
R4, R6, R58	61.9
R5, R16, R18, R64, R101	10
R7, R9, R47	75
R8, R13, R56, R59	301
R10, R37, R52, R55, R93, R105	5.49k
R11, R62, R67, R73	2.21k
R14, R26	178
R15, R50, R51, R71	0.5
R17, R85, R99	100
R19, R27, R28, R29, R31, R32, R33, R35, R38, R45, R53, R87, R94	3k
R21	220
R23	10k pot
R24, R36	48.7k
R25, R82	110k
R30, R34, R54, R69, R70	620
R39, R48, R49, R68, R74, R89, R90, R91	698
R40	10k log pot
R41, R43	26.7k
R42, R84	1.62M
R44, R96, R103, R104, R106, R108	23.2k
R57	25.5
R60, R65, R92	931
R63	340
R72	500 trim pot
R75	34
R76, R100, R102	38.3
R77	10k 10-turn
R79	49.9k
R80, R81, R86, R97, R107	11k
R83	15k
R95	499
R98	47
S1	SPST
T1, T4, T5	FT37-43 10T trifilar
T2, T3, T6, T10	FT37-43 10T bifilar
T7, T8	BN-43-2402 4T bifilar
T9	BN-43-302 5T bifilar
VR1	78M08
X1, X2, X3	4.9152 MHz