

## Low-pass Filter Design Part 2

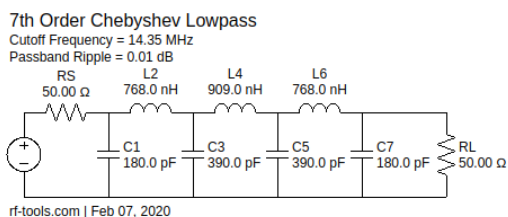
In part 1, a new list of W3NQN filters (one for each Ham band) was selected from the original list of 30 filters. In part 2, these filters are further analyzed, and a design tool is used to develop a worst-case filter design.

### Online Filter Design Tool

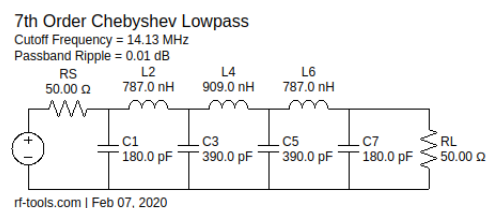
The article by W3NQN referenced a BASIC program, which was used to calculate his 7-element filter values. I tried to find this program or a similar program to calculate the best filter values myself. I found this tool (<https://rf-tools.com/lc-filter/>) on the Internet. Three additional online tools were available on the Internet, but they all produced the same results, so I continued with my first selection for the next part of my analysis.

Using the rf-tools online tool, the Chebyshev 7-element low-pass filter with 0.01 dB passband ripple (which should give a maximum VSWR of 1.1:1) and 50 ohms input / output impedance was selected. Standard component values (5% for capacitors and 1% for inductors) were selected. The more precise 1% inductor values were used to calculate the number of turns for the toroids. Because the original problem was low output power on the 20 meter band, the evaluation was conducted for this band.

The first specified cutoff frequency was 14.350 MHz (the top of the 20 meter band). The results can be seen in the figure below. F-30dB is approximately 22.44 MHz, well below the 2<sup>nd</sup> harmonic of 28 MHz. Interestingly, the capacitors are the same value as the current QCX low pass filter, and the inductors are nearly the same value.

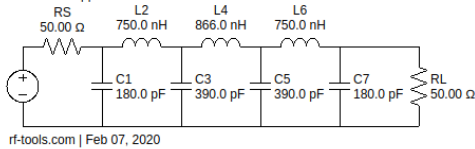


The second specified cutoff frequency was 14.130 MHz, below the middle of the 20 meter band. F-30dB is approximately 21.29 MHz, well below the 2<sup>nd</sup> harmonic of 28 MHz, and the capacitors are the same value as the current QCX low pass filter.



Finally, the third specified cutoff frequency was 14.830 MHz, well above the 20 meter band. F-30dB is approximately 22.78 MHz, still well below the 2<sup>nd</sup> harmonic of 28 MHz, and the capacitors are the same value as the current QCX low pass filter.

7th Order Chebyshev Lowpass  
 Cutoff Frequency = 14.83 MHz  
 Passband Ripple = 0.01 dB



Actually, I identified 14.13 MHz and 14.83 MHz through trial and error. I wanted to find the highest and lowest cutoff frequencies that would require the same components, including the same number of turns on the toroids. I used this tool (<http://toroids.info/T37-6.php>) to calculate the turns. The list below shows the component values and turns for the 3 frequencies.

F-co	14.13 MHz	Turns	14.35 MHz	Turns	14.83 MHz	Turns
C1, 7	180 pF		180 pF		180 pF	
C3, 5	390 pF		390 pF		390 pF	
L2, 6	0.787 uH	16.2	0.768 uH	16.0	0.750 uH	15.8
L4	0.909 uH	17.4	0.909 uH	17.4	0.866 uH	17.0

As can be seen from this example, without considering component tolerances, the same components define a filter with a cutoff frequency anywhere from 14.13 MHz (inside the 20 meter band) to 14.83 MHz, a 600 kHz spread. Adding component tolerances of 5%, the span between standard capacitor values, and the span between inductor values with the same number of turns can easily increase this spread to more than 1 MHz and account for the QCX-20 low output power. Therefore, a worst-case design of the low pass filters seems appropriate.

### Worst-case Design

The easiest approach to a worst-case design would be to use software that can calculate standard capacitor values and toroid turns versus cutoff frequency, simplifying the trial and error process. Therefore, I returned to the four online filter tools that all produced the same results. Choosing the HTML/JavaScript source code that was easiest to follow/understand, I rewrote the JavaScript in C. This C program was easier to expand and adjust to meet the additional needed parameters. When exact component values were selected for each online tool, all online tools and my C program produced the exact same results, suggesting that they all use the same calculations.

Next, the selection of standard value capacitors and the turns on toroids of a given  $A_L$  was added to the program. The list of standard value capacitors was derived from TDK and Vishay data sheets for C0G/NP0 capacitors. However, using standard values creates problems. First, the capacitors typically have a tolerance of +/- 5%, and the standard values are 18 – 25% apart from each other, depending on the value. Second, the powder iron cores typically have a tolerance of +/- 5%, and the inductance values are 8 – 15% apart from each other, depending on the number of turns. That means that the capacitor and inductor values can be as much as 15% above or below the value calculated for a particular filter.

The problem is how to make the selection of the capacitors and turns. This is the approach taken in my program. In each calculation, the difference between the closest lower capacitor/inductor value and the next higher value is calculated, and the difference is divided by the by the closest lower value. Instead of

following the usual rounding rules of rounding up at 0.5, the program rounds up at 0.9, emphasizing the lower values more heavily.

The argument for this approach is as follows. Selecting a value that may be too high will reduce the frequency of the low-pass filter and may cause attenuation in the pass-band. However, selecting a value that is too low will increase the F-30dB, which is usually well below the 2<sup>nd</sup> harmonic, and not cause a problem.

The next step was to calculate the capacitor and inductor values for a filter for each Ham band and compare the values to the associated W3NQN filter. Using my program, I calculated the standard capacitor values and exact inductor values, so the values could be directly compared to the W3NQN filter values. The frequency of the top of each band was used for the specified cutoff frequency. The spreadsheet below shows the comparison. The component designators are from the previous schematic (same as the W3NQN article).

Cutoff Frequency is Band Top Frequency								
Band	C1.7 pF		C3.5 pF		L2.6 uH		L4 uH	
	PRGRM	W3NQN	PRGRM	W3NQN	PRGRM	W3NQN	PRGRM	W3NQN
160	1200	1000	2700	2400	5.540	4.863	6.498	5.880
80	560	560	1200	1300	2.770	2.624	3.249	3.135
40	330	270	680	680	1.518	1.380	1.780	1.698
30	220	180	470	470	1.092	0.952	1.280	1.188
20	150	150	390	360	0.772	0.729	0.906	0.882
17	120	110	270	270	0.610	0.548	0.715	0.668
15	120	82	220	220	0.517	0.444	0.606	0.561
12	100	82	220	200	0.443	0.406	0.520	0.493
10	82	62	180	160	0.373	0.324	0.438	0.403

In each case, the program generated capacitor values are the same or higher than the W3NQN values, and the program generated inductor values are all higher than the W3NQN values. This makes sense because some padding is needed between the top of the band and the specified cutoff frequency to allow for tolerances and stray capacitance and inductance. Not knowing how much padding W3NQN allowed, I increased the cutoff frequencies until I could more closely duplicate W3NQN's results.

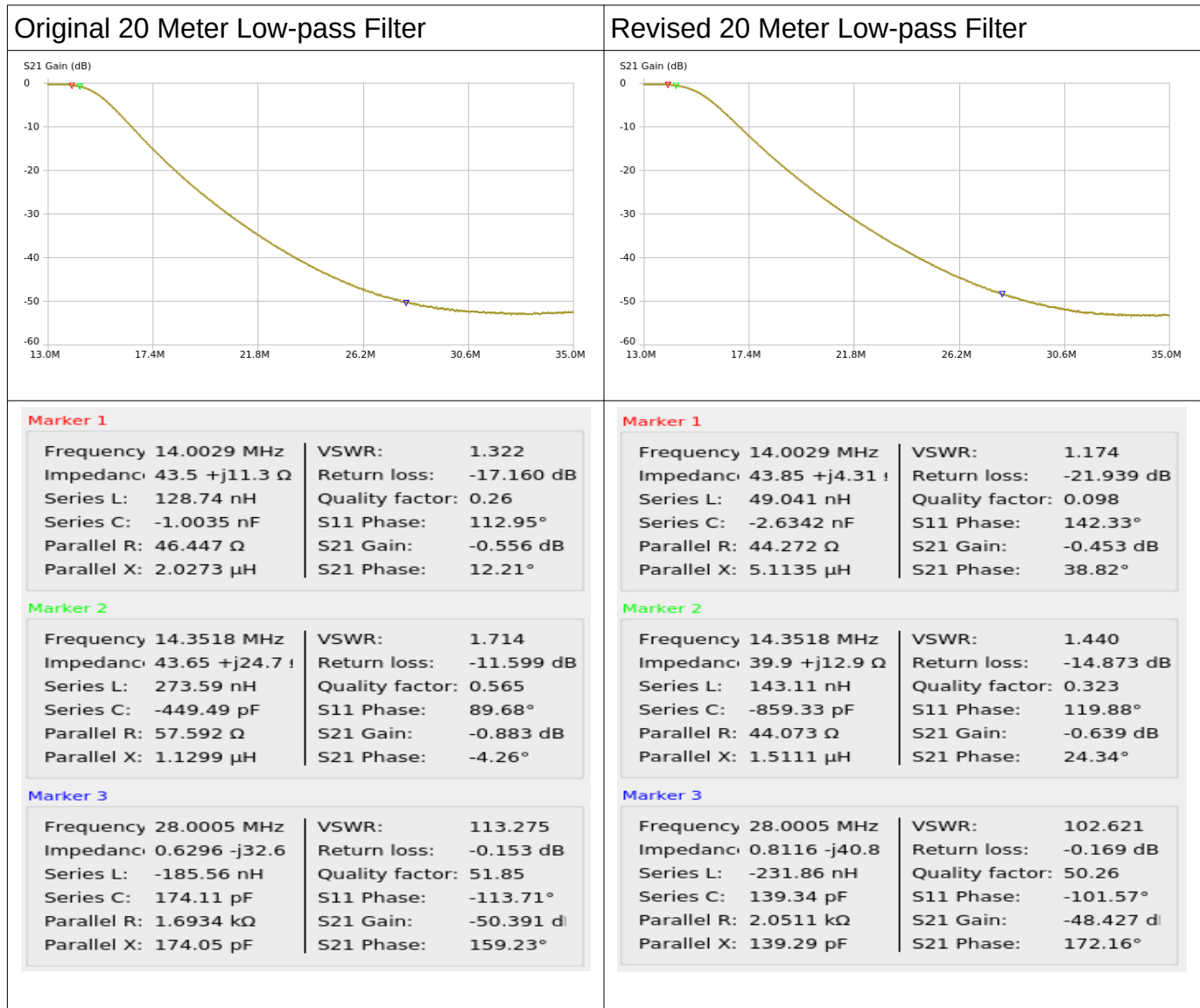
Cutoff Frequency Increased by 7%								
Band	C1.7 pF		C3.5 pF		L2.6 uH		L4 uH	
	PRGRM	W3NQN	PRGRM	W3NQN	PRGRM	W3NQN	PRGRM	W3NQN
160	1200	1000	2200	2400	5.178	4.863	6.073	5.880
80	560	560	1200	1300	2.589	2.624	3.036	3.135
40	330	270	680	680	1.419	1.380	1.664	1.698
30	220	180	470	470	1.020	0.952	1.197	1.188
20	150	150	330	360	0.722	0.729	0.846	0.882
17	120	110	270	270	0.570	0.548	0.669	0.668
15	100	82	220	220	0.483	0.444	0.566	0.561
12	82	82	180	200	0.414	0.406	0.486	0.493
10	68	62	150	160	0.349	0.324	0.409	0.403

With 7% padding, the values average about 3% higher than the W3NQN values. Most of the higher values are C1 and C7. The other values vary around the W3NQN values.

### 20 Meter Low-pass Filter Testing

I tested the original and revised low-pass filter values for 20 meters with a nanoVNA. The components were soldered to a piece of double-sided PCB, and the nanoVNA plotted the S21 gain. The results (below)

do not show a significant difference. The difference in attenuation at the top of the 20 meter band is only 0.244 dB, which would reduce the power by about 5%. The difference for my QCX-20 was 1W (2.5W for the original vs 3.5W for the revised) or about 30%.



Another factor that may contribute to the lower output power in the QCX is the operation of the class-E power amplifier. This class of amplifier depends on a resonant circuit to develop the output sine wave because the power transistor operates as a switch, not a linear amplifier. Using the QCX component designators, the resonant circuit is comprised of the inductance of L4 and the output capacitance of Q1-3 in parallel with C30. However, C27 (the first capacitor of the low-pass filter) is also effectively in parallel because C29 is much larger than C27. Therefore, the resonant frequency may shift with changes to the low-pass filter capacitors, causing a change in output power.

## Some Observations

First, it appears that in his article “A short guide to harmonic filter for QRP transmitter output,” G3RJV did not select the most appropriate W3NQN filters for each Ham band. Unfortunately, these values may have been applied to numerous Ham projects over the years.

Second, I noted in part 1 that the QCX-40 specified 21 turns for L1 and L3, where the calculation suggest 22 turns would normally be specified. I noticed a similar situation for all of the low-pass filter inductors in the 50W Amp for 20 and 40 meters. It is likely that testing indicated that a lower number of turns for these inductors improved performance.

Finally, the original list of 30 filters in W3NQN’s 1983/84 article appear to be appropriate, if properly selected. However, it should be noted that W3NQN wrote a more recent article “Second-Harmonic-Optimized Low-Pass Filters,” in the February 1999 issue of QST. In this article, W3NQN describes an 8-element filter that he calls a Chebyshev with Added Zero (CWAZ) filter, designed by W4ENE (WB6BLD). This improved filter provides greater attenuation of the 2<sup>nd</sup> harmonic. The article includes a schematic and component values for the 160 through 10 meter bands. In addition, “The ARRL Handbook” includes a schematic and component values for another W4ENE low-pass filter design, using seven elements.