

## High-Power 7 MHz Bandpass Filter

### *Introduction*

I began building my station's SO2R capability two years ago. In addition to the automatic-switching Hamation Bandpass filters on each radio, I have tuned coaxial stubs to reduce harmonics just prior to going to the antennas. This function is desirable in that while affording additional strong signal immunity, it also serves to reduce any harmonics emanating from each amplifier. Obviously, the stubs must operate near the 1,500 watt level.

There are several references<sup>i</sup> available which accurately point out the sensitivity of a stub implementation to its placement along the transmission line. In short, if the stub is attached at a high-impedance point on the line, it can offer, singly, around 25 dB of additional attenuation to the harmonic for which it is designed. This will deteriorate as the stub's placement is located at lower and lower impedance points along the transmission line.

I want to have immunity from stub placement on the line while also offering considerably more attenuation to all frequencies other than the desired pass frequency. Toward that end I designed and constructed a sixth order elliptic bandpass filter described herein.

### *Background on Design Process*

Today there are multiple, automated filter synthesis programs available. For my design I utilized ELSIE<sup>ii</sup> which is available "free" for filters up to 7<sup>th</sup> order. For higher order filters one must purchase a license for ~ \$100. ELSIE will synthesize Butterworth, Chebyshev, Elliptic, and Gaussian filters, in lowpass, highpass, or bandpass configurations. This design is a 6<sup>th</sup> order Cauer (elliptic) bandpass filter.

There are several commercially available filters like this filter, however they range in price from ~ \$300 (Amplifiers, Filters, Antennas in the UK) each to as much as \$500 (DX Engineering). This adds up quickly across six different HF amateur bands. This fact, plus the fact I enjoy designing and building filters, I elected to go the "homebrew" route.

When operating at the 1,500 watt level, simple calculations reveal very quickly the importance of minimizing loss. Only 0.3 dB insertion loss leads to 100 watts dissipated in the filter. This loss, and the accompanying heat, is our enemy. The heat, if allowed to grow too large, will skew the filter's passband, leading to more loss, and in a worst case, eventual destruction of the filter. From a conservative perspective, moderate heat will age the components as well, possibly leading to premature failure. These things need to be avoided, therefore I strived for minimum loss.

### *How to Attain Minimum Loss*

A number of elements enter into the loss mechanisms in any filter. Fundamentally, theory shows us that minimum loss is not always achieved by using the lowest filter order deemed sufficient for the application. This means more research on the part of the designer is required. The actual stopband width is crucial in that there is a "Q multiplying effect" which if left unattended, can drive component currents to excessively high levels. This design uses what I considered the largest practical passband width to reduce required element Qs. Additionally, the diameter<sup>iii</sup> of each inductor compared to the average inductor length was chosen to achieve theoretical Qs exceeding 400. This is a "must" for low insertion loss.

### *Other Philosophies in the Design*

Cost is important to me – this is my hobby. Doorknob and silver mica capacitors at the required voltage ratings are not cheap these days. And, more than likely, one must consider paralleling multiple, smaller value capacitors in order to achieve RF current spreading so as not to exceed the current capability of any one capacitor. This adds cost, possibly considerable cost. The route chosen here to drive down the cost of capacitors is to use MLCCs: multi-layer ceramic chip capacitors. More on the capacitor selections follows.

While I greatly preferred a professional looking PCB board for the filter, the overall dimensions of it are so great as to preclude obtaining a reasonable cost commercially produced board. Therefore, I etched my own board, using for the most part medium and large-point magic markers to layout the copper landscape desired. I wound each inductor before beginning the board layout, otherwise I would not have known the linear dimensions required to accommodate each coil.

Each inductor is wound with #12 polypermalzeze wire available through The RF Connection<sup>iv</sup>. In retrospect, #14 wire would have been sufficient for the lower current inductors.

Very integral to the overall design process is the continual assessment of the accompanying voltages and currents for each design. For a 1500 watt filter, these details cannot be left out. For each design considered, I modeled it in Simetrix, a SPICE type program. In so doing, I was able to assess both the voltage and current expected across/through each component when drive with 1,500 watts. This is

very important, as only by doing this analysis can one know where the marginal/stressing parts are in your filter design.

All traces on the PCB are around 0.25 inches in width. Even if this deviates the microstrip's impedance slightly from the desired 50 ohms, it is of paramount importance in order to not exceed the current density capabilities of the 1 oz. PCB used in this design.

And finally, as will be seen, each capacitor is realized by the paralleling of as many as 12 capacitors for current sharing. This drives layout considerations.

And finally, the reader should ask, "Why a 6<sup>th</sup> order filter instead of an odd-order?" For elliptic filters, even-orders produce output impedances different than 50 ohms. In this case the result was 48 ohms. The reason this was done here is that  $L_4$ - $C_4$  circulating currents in the 5<sup>th</sup> order design were ~ 25 amps compared to ~ 16 amps for the 6<sup>th</sup> order.

### **Physical Layout**

Illustrated to the right in Figure 1 is the PCB layout for the filter. It measures 3" x 11". The overall aluminum plate is 6" x 16". In retrospect, a smaller footprint is probably possible, although I wanted to ensure no diminishment of inductor Q by housing walls. A second auxiliary board is also used in order to mount the needed MLCCs for the last resonator. (This additional auxiliary board is not yet installed in Figure 1)

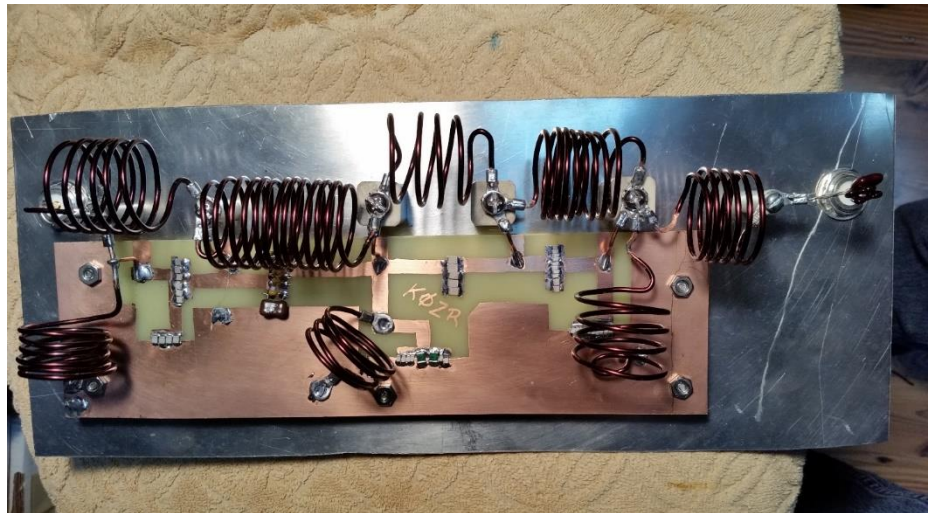


Figure 1 Construction of BPF on Aluminum Plate

## Details of the Design

**Topology**

- Capacitor-input lowpass
- Inductor-input lowpass
- Nodal capacitor-coupled bandpass
- Nodal inductor-coupled bandpass
- Shunt-input bandpass
- Series-input bandpass
- Mesh capacitor-coupled bandpass
- Cauer-only bandpass
- Capacitor-input highpass
- Inductor-input highpass
- Series-input bandstop
- Shunt-input bandstop

**Family**

- Butterworth
- Chebyshev
- Cauer
- Bessel
- Gaussian
- Gaussian to 12
- Constant-K
- M-derived

See normalized values

Manual entry

**Cauer even terms**

- Best selectivity
- Equal terms

**Cauer BPF topology**

- Normal
- Zig-zag

**Bandwidth (Hz) (Fc)**

4M

**Center frequency (Fo)**

7.2M

**Order (N) [21 max]**

6

**Input termination (Rs)**

50

**Passband ripple (Ap)**

0.00107

VSWR: 1.0319    Return: -36.085 dB

**LP prototype**

**Stopband width (Fs)**

7.3976M

**Stopband depth (As)**

50

**Dimensions**

cm

in

Add title to printout

Add info to Elsie file

Entry assistance

Figure 2 The "Design" Window Within ELSIE

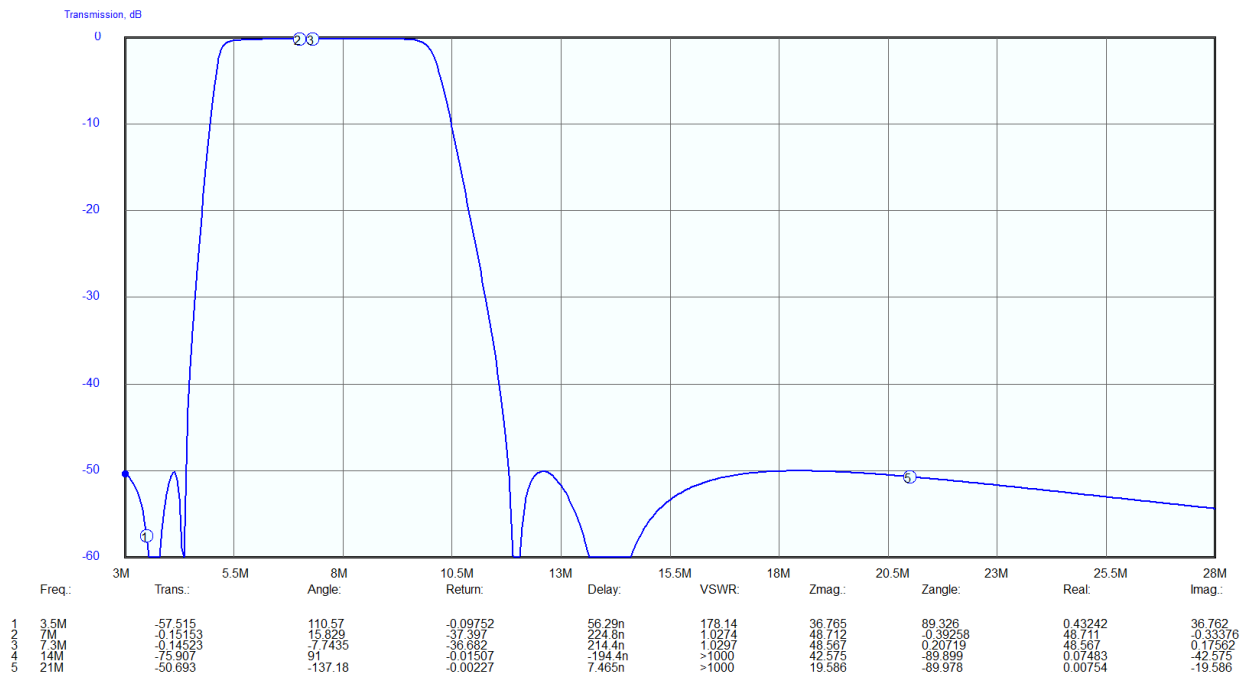
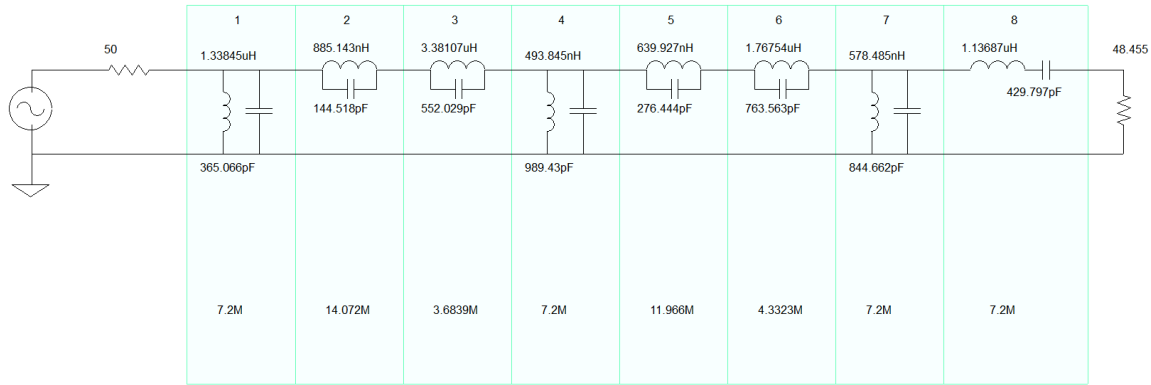


Figure 3 Passband and Stopband Response – Directly from ELSIE



Design data:  
 Bandwidth: 4M  
 Center: 7.2M  
 Family: Cauer  
 Passband ripple: .00107  
 Cauer LP stopband freq: 7.3976M  
 Cauer LP stopband depth: 50

Q values:  
 Inductors: 300  
 Capacitors: 10000

Maximum / minimum ratios:  
 Capacitors: 6.8464  
 Inductors: 6.8464

Unbalanced preview  
 Normal - unbalanced  
 Balanced - A  
 Balanced - B

Artwork only

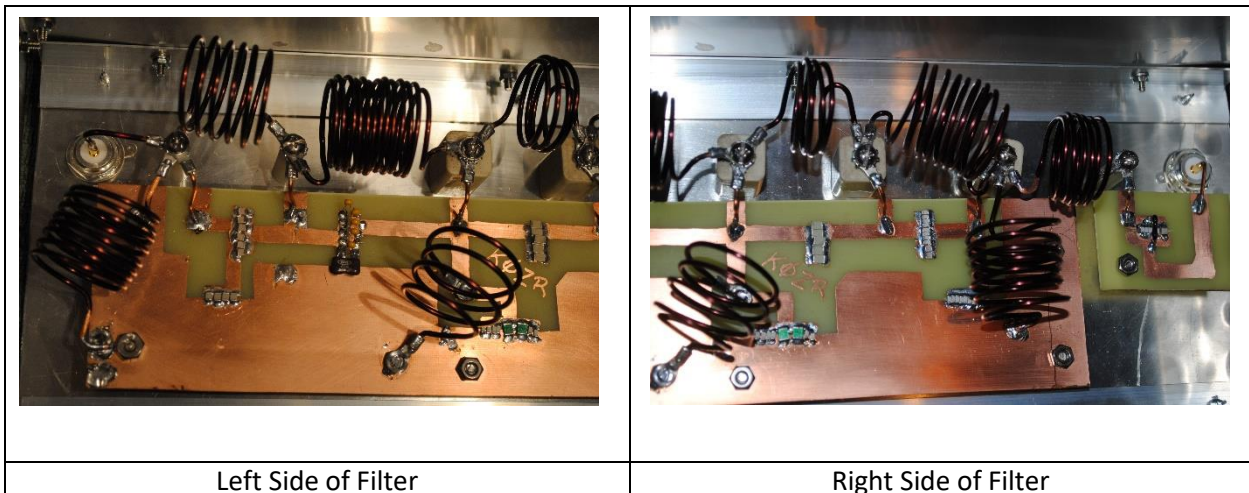
Figure 4 Schematic of 6th Order BPF – Directly from ELSIE (Note each resonator’s tuned frequency)

Proceeding left-to-right in the schematic above, the associated currents for resonators 1-8 are the following, determined from Simetrix, at 1500 W input. All voltages were less than 500 V.

Comp	Amps	Comp	Amps
L1	6.4	L5	12.5
C1	6.4	C5	4.6
L2	10.8	L6	4.9
C2	3.0	C6	12.7
L3	3.0	L7	14.7
C3	10.9	C7	14.5
L4	17.35	L8	7.8
C4	17.3	C8	7.8

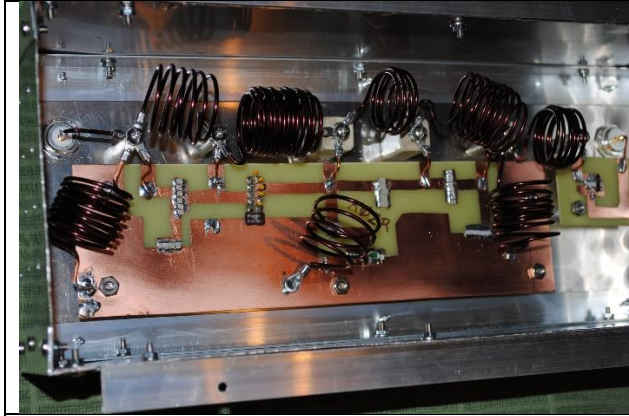
Figure 5 Table of Component Currents at 1,500 W

**Miscellaneous Assembly Pictures**

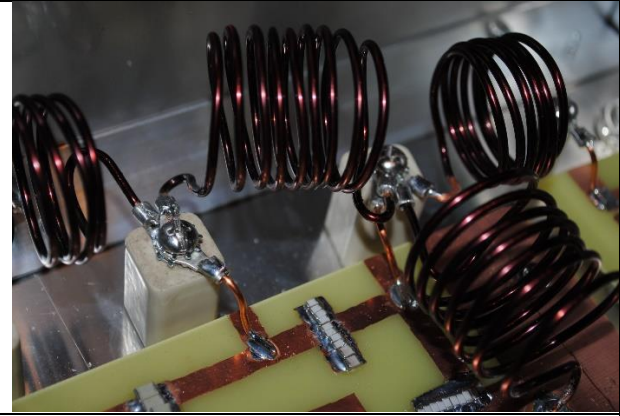


Left Side of Filter

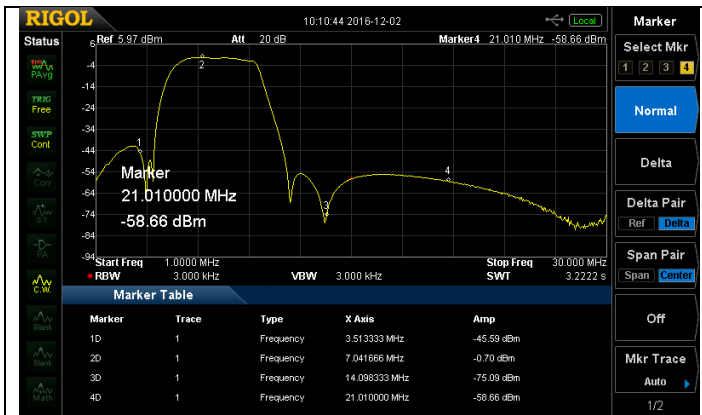
Right Side of Filter



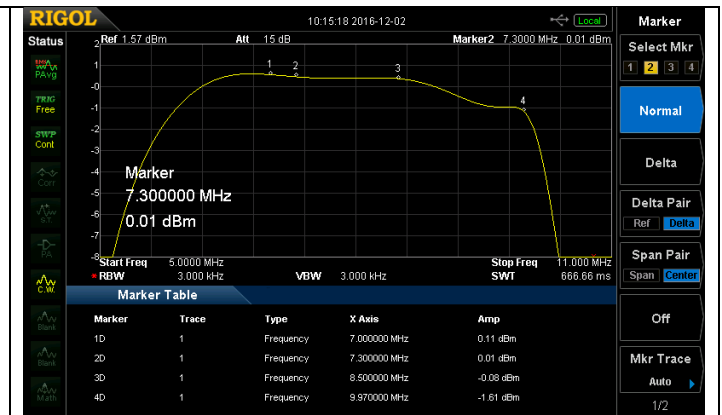
Full Filter Assembly “in its box”



Close-Up of Inductor Standoffs and MLCCs



Full Frequency Sweep



Close-Up of 7 MHz Passband

Note the insertion loss in the left figure specifies 0.70 dB. This is considerably above the  $\sim 0.2$  dB true insertion loss just due to resolution on the full-scale plot.

### Tuning Up the Filter

This filter is actually reasonably straight forward to tune up given its topology. Noting Figure 4, each resonator has a “self-resonant frequency” listed. In the process of constructing the filter, I had beginning turns numbers for each inductor, determined through use of the web-based inductance calculator referenced in the end notes. I constructed a small PC board on which I mounted each inductor, one at a time, and resonated it with a fixed capacitance. I would adjust the inductor until the resonant frequency was what it should be for the amount of capacitance used; in my case 138 pF. This was very effective in getting a good starting point for each resonator.

After complete assembly, those parallel resonators that created “zeros in transmission”, specifically 14.072, 3.6839, 11.966, and 4.332 MHz, I adjusted each respective inductor to attain the deep notches seen in the overall transmission display. These were resonators 2,3,6, and 7. Once this was accomplished I began iterating back and forth with the resonators to be tuned to 7.2 MHz, striving to get the return loss I wished across the 40m band. The return loss is greater than 25 dB across the 40m band. While at times I had the return loss even better, the overall shape of the filter was not as “pretty”, so I went for “pretty” and said 25 dB return loss is good enough!

## Miscellaneous

Trials runs with the filter began with 500 W, then proceeded to ~ 1200 W. Operating for ~ 10 minutes with 1,200 W yielded a temperature rise in the C<sub>4</sub> capacitors of only around 5 degrees as registered on an IR gun temperature sensor. I operated the 2016 CQWW with the filter in place and had no problems whatsoever. A check of the passband after the contest for signs of possible stress or over-heating revealed all was well, and the passband remained unchanged.

One aspect of this project is selection of the MLCCs. While one can do this manually, it is much less time consuming, and probably accurate, to get some computer help. Therefore, I surveyed what MLCCs with breakdown voltages above 1 KV were available from Mouser. I inserted this information in a "list" within a Python script and let it do its work. One instructs the program regarding total current through the capacitors (obtained using Simetrix), maximum current through a single capacitor, and the total capacitance required. The Python script then works with the available values to select those combinations of capacitors which can be considered. In making these selections, you don't want the different capacitors to be too different in value, otherwise the current distribution across the capacitor bank will be skewed, with some getting more current than desired.

For those not familiar with MLCCs, some further comments. Little information can be found, at frequency, for the current handling capability of MLCCs. ATC MLCCs, which are very costly, come with this information but few other manufacturers provide this. The current capacity comes down to what is the ESR – equivalent series resistance – of the MLCC. It is this resistance, acting with the RF current which will generate heat and potentially destroy/short the capacitor. So, to the extent possible, choose low ESR MLCCs, larger packages to help with heat dissipation, and in my case I tried to keep the RF current to 1.5 amps or less per MLCC.

Enter Total Capacitance : 350  
Requested Maximum Current Capacity = 12  
Minimum # of Capacitors to use is 8.0

#	C1	#	C2	Cap Range	Tot Cap
1	33.0	7	47.0	14.0	362.0
2	33.0	6	47.0	14.0	348.0
3	33.0	5	47.0	14.0	334.0
2	39.0	6	47.0	8.0	360.0
3	39.0	5	47.0	8.0	352.0
4	39.0	4	47.0	8.0	344.0
5	39.0	3	47.0	8.0	336.0
5	39.0	3	56.0	17.0	363.0
6	39.0	2	56.0	17.0	346.0
5	47.0	3	33.0	14.0	334.0
6	47.0	2	33.0	14.0	348.0
7	47.0	1	33.0	14.0	362.0
3	47.0	5	39.0	8.0	336.0
4	47.0	4	39.0	8.0	344.0
5	47.0	3	39.0	8.0	352.0
6	47.0	2	39.0	8.0	360.0
2	56.0	6	39.0	17.0	346.0
3	56.0	5	39.0	17.0	363.0

## Python Script

```
# Script to Optimize Capacitor Selection for Filter Designs
# Jeff Crawford December 1, 2016
# K0ZR
#
import math

CapList = [10, 12, 15, 18, 20, 22, 27, 30, 33, 39, 47, 56, 68, 82, 100, 110, 120, 150, 160, 180, 220, 240, 270, 300]

Ia = input('Enter Total Current, A: ')
Imax = input('Maximum Current in Each Capacitor, A: ')
Ctotal = input('Enter Total Capacitance : ')
CapN = math.ceil( Ia*1.0/Imax)

M = len(CapList) # Maximum number of capacitors in list to choose from

# Capacitors considered are from 2 below to 2 above an 'index' into the capacitor list
# This is done for reasons of maintaining reasonably equal current sharing across the CapN number of capacitors
# If the range of capacitors gets too extreme, current division will not be as needed and some capacitor's current
# capacity could still be exceeded.

print 'Requested Maximum Current Capacity = ' + str(Ia)
print 'Minimum # of Capacitors to use is ' + str(math.ceil(CapN))
print ""

selects = [] # Initialize Candidates to Zero Selections
print ' # C1 # C2 Cap Range Tot Cap'
for index in range(2, len(CapList)-2):
    offset = -2
    while offset <= 2:
        C1 = CapList[index]
        C2 = CapList[index+offset]
        for k in range(int(CapN)):
            h = CapN - k
            calcc = k*C1 + h*C2
            if (calcc > 0.95*Ctotal) and (calcc < 1.05*Ctotal) and (C1!=C2):
                string1 = str(k) + ' of ' + str(C1) + 'pF and ' + str(h)
                string2 = ' of ' + str(C2) + 'pF' + ' Tot Cap = ' + str(k*C1+h*C2)
                string3 = ' Cap Diff = ' + str(math.fabs(C1-C2))
                print "{0:4} {1:7.1f} {2:8} {3:10.1f} {4:12.1f} {5:12.1f}".format(k, C1,int(h), C2, math.fabs(C1-C2), calcc)

        offset = offset + 1
```

<sup>i</sup> "Managing Interstation Interference", Revised Second Edition, W2VJN, George Cutsogeorge, 2009

<sup>ii</sup> ELSIE, Tonnes Software, tonnessoftware.com/elsiedownload.html

<sup>iii</sup> Single-Layer Helical Round Wire Coil Inductor Calculator, <http://hamwaves.com/antennas/inductance.html>

<sup>iv</sup> RF Connection, email: [rfc@therfc.com](mailto:rfc@therfc.com), website: therfc.com

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