Automatic Antenna Tuner for HAM Radio Application

Motivation

I spent a whole group of money on a log periodic antenna which according to its specification, was to have a maximum VSWR of 2:1 over a bandwidth of 4 MHz through 30 MHz, and no more than 3:1 over the bandwidth of 3 MHz through 4 MHz. Even after two visits from the manufacturer to “fix” the antenna, it is nowhere close to meeting specifications, so I now need an antenna tuner. The main attraction of the log periodic in the first place was to avoid the necessity of an antenna tuner.

Getting Started

I have four Collins 208U-10K 10,000 Watt HF linear amplifiers that I have been cribbing parts from for various projects and sales. Each of these linears has two variable pancake inductors, and two variable vacuum capacitors with the servo assemblies to drive them, making perfect parts for use in an automatic antenna tuner for HF. There are also some high power Jennings vacuum relays I could use for directing RF through various paths, or switching components in the tuning network as required. I am using the smaller loading inductor with a range of 0.3 uH through 18 uH, and one of the vacuum variables with a range of 16 pF through 1500 pF along with all the servo motor drives, gear trains, and position potentiometers. I have these mounted on a heavy aluminum rectangular plate along with the vacuum relay for transmit/receive, a vacuum relay to bypass the matching network, and another vacuum relay to switch the vacuum variable from the input side to the output side of the series pancake inductor, depending on whether the antenna presents a |Z| of less than or greater than 50 Ohms.

Design Methodology

The plan was to use a homemade Vector Network Analyzer (VNA) to measure the antenna’s complex impedance at the chosen operating frequency, then calculate the L network parameters to transform that measured impedance to (50, +j0) Ohms for the transmitter’s liking.

Upon selecting a frequency to transmit on, the exciter will generate a 30dBm carrier at that frequency which is sent to the VNA, and on to the antenna tuner which is in bypass mode. A microprocessor which is driving the whole affair, then measures the antenna’s complex impedance at the chosen frequency, computes the network parameters for the L-Network, adjusts the variable inductor, variable capacitor, and shunt capacitor switch for either the input or output configuration, and finally takes the tuner out of bypass mode. A final VNA measurement with the tuner tuned, and in the path, then verifies the correct tuning, and if any touchup is required, makes it happen.

The original homemade VNA consisted of a Tandem Match Dual-Directional Coupler with a 33 dB coupling factor. Following the Forward and Reflected ports are a 23 dB attenuator, and several Analog Devices log power-to-voltage converters. Off of the Forward port and the Reflected port, were two AD8362 devices measuring absolute power, and two AD8302s, both off the Reflected port, with the reference inputs connected to a zero-degree reference signal at the requisite frequency, and the other AD8302 with its reference at a 90 degree shifted identical frequency. The reason for two AD8302s is that the included phase detector cannot discriminate between a positive phase shift, and a negative phase shift. By using a 90 degree reference along with the zero-degree reference, it is easy to determine in which of the 4 quadrants the phase shift really lays. I had also planned to use the outputs from the AD8362s to compute an SWR even though the station 1500 Watt linear amplifier already contains an

SWR meter. By doing that independent SWR measurement, I could include the reading on a web page, also generated by the microprocessor running the whole show.

Unfortunately, the above scenario only partially worked. The first problem was with the tandem dual directional coupler. I used FT-87A-43C toroids for both the current and voltage transformers. With 1 cm of cross-sectional area, and a minimum frequency of 1.5 MHz, the voltage core started to saturate with only 20 Watts of RF. I had 33 turns on the primary, and a 1 turn secondary terminated with 50 Ohms. I calculate that the saturation flux density with only 20 Watts of RF is orders of magnitude lower than the saturation flux density of Mix 43 ferrite, so why does it go into saturation? There is a remote possibility that there is some DC from the exciter, and I have not looked into that, because there are other problems…

The next problem has to do with the generation of the 90 degree phase shifted reference used on the second AD8302 to determine the proper quadrant of the real phase shift. The circuit has a 10 pF capacitor on the input RF, in series with a 10 Ohm, 2 Watt carbon composition resistor to ground. The center of this network was one input to the AD8302. Using the following formula to find the phase shift:

$$Phase\ Shift = \arctan(\frac{X_c}{R})$$

With a capacitor of 10 pF, and a 10 Ohm resistor, the phase shift should be 88+ degrees. I measured as little as 22 degrees, and only under a few cases was able to see near 90 degrees as expected. At least the phase shift was leading the zero degree input reference, so I could determine the correct quadrant for the measurement, but here is the rub: when the measured phase is near zero degrees, or near ±180 degrees, the phase detector in the AD8302 goes non-linear and the accuracy of the AD8302 falls down. The plan was to use the 90 degree shifted phase to get into the linear portion of the ASD8302's curve for a more accurate measurement, but if I couldn't trust the 90 degree phase shifted value, then I had to rely on the zero degree reference's value, and as I mentioned, that was not accurate at the ends of the AD8302's measurement curve. I believe that the poor 90 degree phase measurement from the AD8302 might be due to a low amplitude signal on the phase detector inputs. Anyway, rather than fiddle with the levels, I decided that was the final nail in the coffin of my original design.

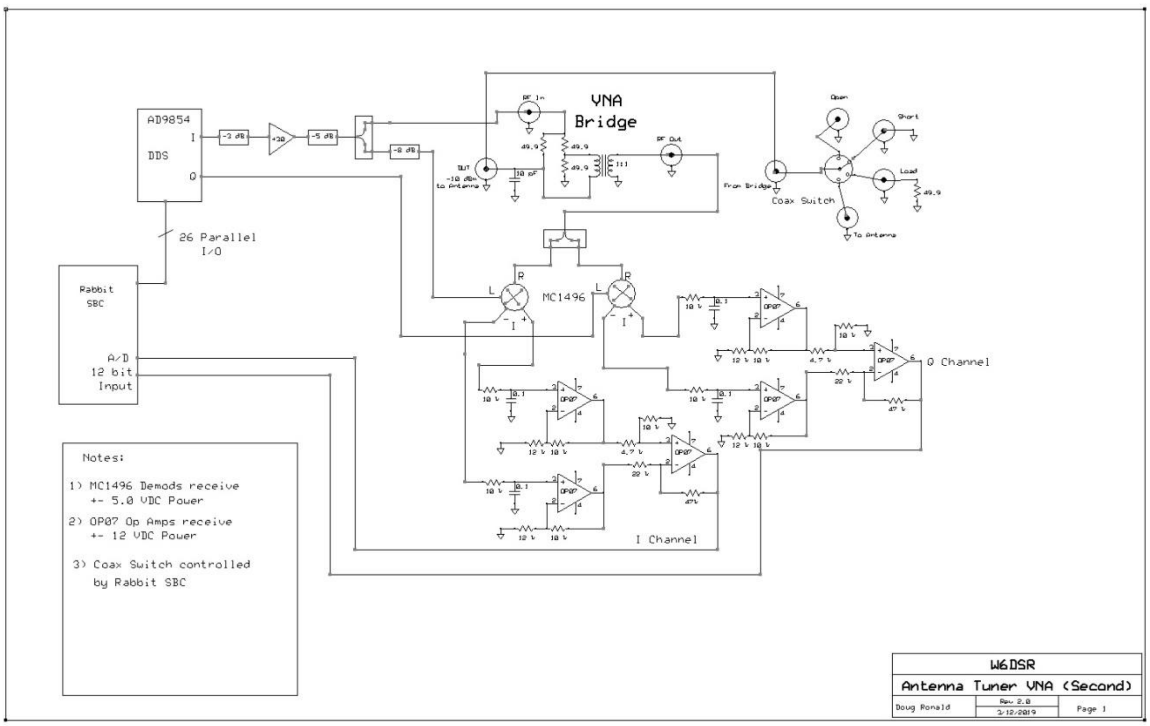
There is a Chinese company selling on eBay, various RF boards which appear to be knockoffs of Analog Devices' evaluation boards for really reasonable prices. I bought one with an AD9854 DDS chip for around $50 with SMA connectors and a power regulator on board. In small volume from Mouser, the chip is about $38, so this board seemed reasonable even if the chip is a counterfeit.

The board arrived with zero documentation, and nothing found online, except for other hobbyists complaining about the same thing, so I hooked up power (after translating the Chinese indicating it needed 7 VDC to operate), and a 26 wire parallel interface to a Rabbit microprocessor SBC with plenty of parallel digital I/O ports. The board designer hard-wired the serial enable line to the parallel mode of communication, so it was obvious I needed the parallel mode to talk to the 9854. Also, the silkscreen has English symbols for the 26 pin parallel header connector, so I knew where the RD, and WR signals needed to be.

When the AD9854's master reset is asserted, the device configures itself to a default group of settings. By experimenting, and reading the Analog Devices' documentation, I was able to configure the board to output an I and Q sine signal. With the SBC, I can control the amplitudes of both the I and Q sines independently, plus set a common frequency. With this DDS, I now had a source of excitation I signal, and an absolutely rock-solid 90 degree Q signal for the homemade VNA.

Instead of using my homemade dual-directional coupler which started to saturate way below designed power levels anyway, I decided to use a MiniCircuits directional coupler with better specs than my unit, and stick with low power to tune the antenna. The model number is a PDC-20-3+ which is a 20 dB coupler. I use two of them back-to-back in order to measure the forward power, and the reverse power since these are not dual-directional couplers.

So, the final lineup of my VNA is an AD9854 supplying a reference frequency and the quadrature complement as the signal source. The I component is amplified to 20 dBm and fed to the two couplers in cascade, the output of which goes to the antenna. The 20 dB forward coupled port goes to an AD8362 to measure the forward power, and the reverse port goes to another AD8362 to measure reverse power. Also, from the reverse port are two AD8302s with one AD8302 having its reference from the I AD9854 DDS sine, and the other AD8302 having its reference from the DDS Q output.



The software resident in the Rabbit SBC controls everything. When it receives a command from the PC to perform an auto tune, it is given the frequency of pending operation, and told to report when it has completed tuning. The firmware then programs the DDS to that frequency, and sets the I & Q amplitudes to yield 20 dBm at the antenna port. Not shown on the diagram above, but part of the system, is a set of switches, both high-power and low-power, to direct RF to various places as required. At this juncture, the “Antenna” port on the diagram is directed to a multi-pole coaxial switch. The SBC commands the switch first to an open load, then a short, then a 50 Ohm load, and finally to the antenna for a reactance measurement.

Input to the software are four measurements for each setting of the coaxial switch: Forward Power, Reflected Power, Reflected Reference Phase, and Reflected Quadrature Phase. The shorted load should place a reading on a Smith Chart at the left edge and on the center real axis. This is (0.0, j0.0), but the actual reading may have both an amplitude and phase offset. The opposite load of infinity should place the reading on the right edge of the Smith Chart on the real axis, but there may be an offset here too. The 50 Ohm load should be a point right in the center of the Smith Chart. Phase-wise, all three points are on the same line, but will have a phase rotation due to various factors. Initially, the software corrects for the amplitude errors by scaling both the left point and the right point of the Smith Chart amplitudes to make them fall on the edge of the circle. Phase-wise, the entire line is rotated to make it align with the real axis on the chart. The de-rotation correction and the amplitude corrections are applied to all further readings.

There are three error terms that are correctable. There is the coupler's directivity error, the source signal generator's mismatch error, and the various magnitude plus phase tracking errors. The math for these corrections was derived by the creators of the TAPR VNA device sold several years ago, but no longer supported because of a lack of software support in light of numerous changes in Windows. Those folks derived their methods from a Microwave Engineering Textbook by David Pozar in his chapter 4 on Network Analyzers. I won't restate it here, but their excellent article documenting the VNA is available from the Jul/Aug 2004 QEX magazine.

The final result from the VNA portion of this antenna tuner is a complex impedance of the antenna at the chosen frequency. These data are then used with the math supplied by David Birnbaum via his article "Direct Calculation of Antenna Tuner Losses in the Nov/Dec 2018 issue of QEX, to calculate the parameters of an L-Network. Depending on the real value of the impedance, being either less than Z_0 or greater than Z_0, the shunt variable capacitor is either switched to the output or input side of the series variable inductor.

After much experimenting with this incarnation of my VNA, I found that the accuracy of the measurements was severely lacking. Most of the error was in the phase component of the measurement, and I believe this is because of the AD8302 phase detector's non-linearity, especially around the 0 degree and 180 degree areas. The above referenced QEX article explains all the computations those authors had to come up with in order to obtain respectable readings. I decided again to scrap this incarnation of my VNA because I was not willing to repeat those calculations, especially since I only had a small SBC to work with, and not a full-blown Windows desktop computer.

Design Number 3

Okay, onward-and-upward as they say, to VNA number three. This time I am using a bridge detector, rather than a coupler. After winding a simple TLT with a 1:1 ratio, and testing the bridge with my oscilloscope, this version looked really promising. Initially I was going to use a pair of Mini-Circuits SRA-1 mixers to convert the bridge's RF output to DC with the DDS's I and Q signals as LO, but the SRA-1 requires +7 dBm of LO to switch the diodes, and this meant I would have to amplify both the I and Q channels of the AD9854 DDS to those levels, so I decided to use a 4096 synchronous modulator/demodulator for the down-conversion.

Below is a high-level schematic of this VNA. Again the Rabbit SBC is in control, setting the DDS's frequency, plus the I and Q power levels. Each MC1496 mixer outputs a DC signal, the I channel the real portion, and the Q channel the imaginary portion. Those outputs are a differential voltage, and the following OP07 op-amps first low pass the outputs to eliminate any influence from the sum signal of the mixer's output, buffer the differential output from the MC1496s, and then combine the differential voltages into a single ended voltage for reading by the A/D converter on the Rabbit SBC board. The following equation explains what the two voltages represent:

$$V_{DC-0} = |G_{Det}||V_{RF}|\cos(\emptyset_{RF} + \theta_{Det}) + \, V_{Offset-0}$$

$$V_{DC-90} = |G_{Det}||V_{RF}|\cos(\emptyset_{RF} + \theta_{Det}) + \, V_{Offset-90}$$

The offsets of the two orthogonal channels of the MC1496s are measured with no RF present. I turn off the RF by commanding the AD9854 DDS to have zero output on the I channel and the Q channel. The two offsets measured are then subtracted from all subsequent measurements of the I and Q channels to yield these results:

$$V_{DC-0} = |G_{Det}||V_{RF}|\cos(\emptyset_{RF} + \theta_{Det})$$

$$V_{DC-90} = |G_{Det}||V_{RF}|\cos(\emptyset_{RF} + \theta_{Det})$$

$|G_{Det}|$ is the 1496 detector's gain.

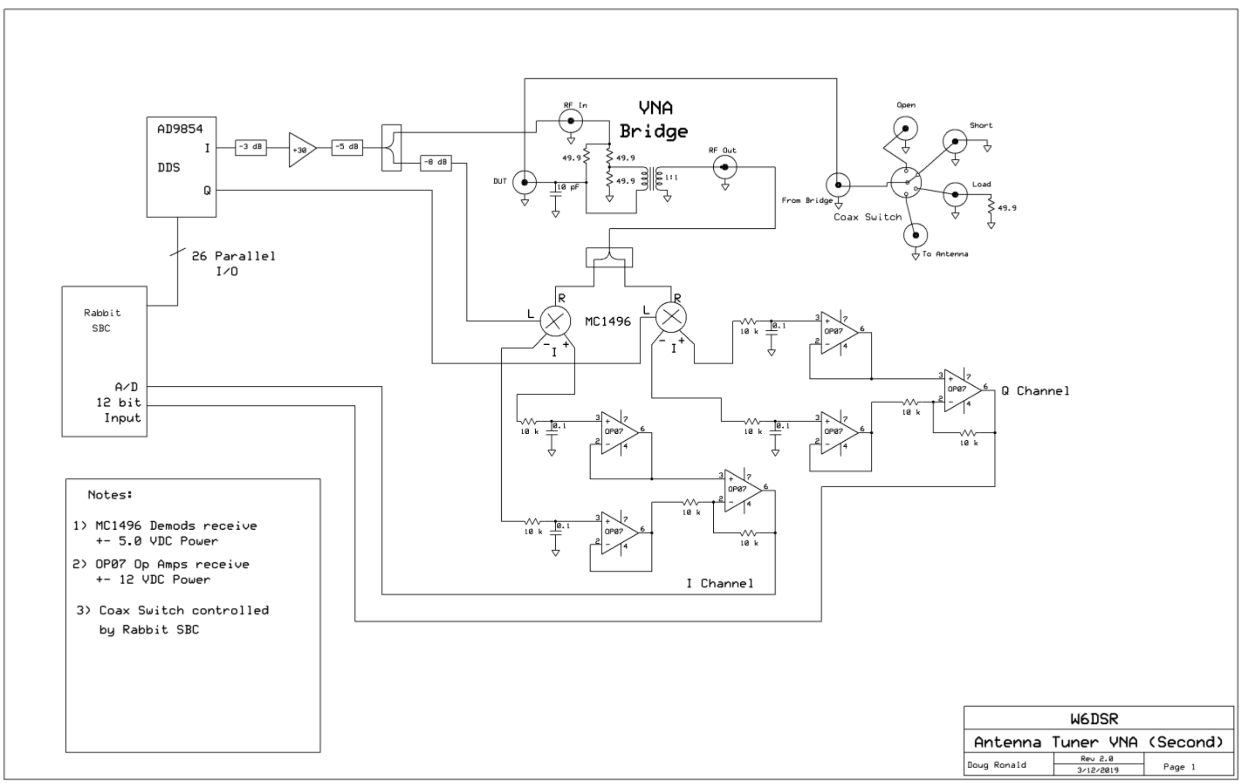
$|V_{RF}|$ is the voltage at the bridge's input.

$\emptyset_{RF}$ is the phase of the voltage at the bridge's input.

θ_{Det} is the phase constant associated with the 1496 detector's gain.

I initially used the results from these readings to compute the S_{11} magnitude and phase using atan2() and sqrt(I*I + Q*Q), and was really surprised at the accurate results – finally!

From the Pozar book, referenced above, I decided to do a full Short, Open, Load (SOL) calibration, just to improve on the already encouraging results from the bridge VNA detector.



Again from David Pozar's book, and from the QEX magazine article:

E_d is a directivity error from crosstalk and leakage in the bridge plus impedance mismatches between the VNA's bridge and the antenna port.

E_s is the error from the source's impedance being slightly different than the VNA bridge's input.

E_t represents tracking errors between the magnitude and phase of the interconnect cables, connectors, and the measuring circuits, mostly the 1496 demodulators themselves.

In the following equations, the superscript of “a” means the actual values, and the superscript of “m” means the measured values.

$$S_{11}^{a} = \frac{S_{11}^{m} - E_d}{E_s(S_{11}^{m} - E_d) + E_t}$$

Where:

$$E_d = S_{11,load}^{m}$$

$$E_s = \frac{2S_{11,load}^{m} - (S_{11,short}^{m} + S_{11,open}^{m})}{S_{11,short}^{m} - S_{11,open}^{m}}$$

$$E_t = \frac{2(S_{11,open}^{m} + S_{11,load}^{m})(S_{11,short}^{m} + S_{11,load}^{m})}{S_{11,short}^{m} - S_{11,open}^{m}}$$

All the S_{11} values are complex numbers derived from the measured analog DC voltages measured from the outputs of the summing op-amps by the following:

$$Phase = atan2(Q_{volts}, I_{volts})$$

$$Magnitude = sqrt(I_{volts}^{2} + Q_{volts}^{2})$$

$$S_{11}real = Magnitude \times \cos(Phase)$$

$$S_{11}imag = Magnitude \times \sin(Phase)$$

The software, all in the C language, sets the coaxial rotary switch first to the open port, and makes a measurement of the I and Q channels at the operating frequency. It then rotates the switch to the short position, and makes another measurement. Next a rotation to the 50 Ohm terminator port, with the requisite measurement, and finally directs the coaxial switch to the antenna’s port.

All of the above SOL corrections are applied to the final reading from the antenna’s impedance, and the parameters of the L network to bring the antenna’s impedance to (50, +j0) are computed.

I was amazed at the accuracy of this “roll-my-own” VNA! Using my HP-8753D Network Analyzer as a reference, I measured 50 Ohm loads, an open and shorted 3 dB attenuator, an open and shorted 8 dB attenuator, a complex load of an inductor, and a complex load of a capacitor. The non-reactive components were within 1% of the HP’s readings, and the complex loads were within 3%. Of course this VNA could be a very practical instrument, save for all the software required to display the results, a non-trivial pursuit, so I’ll be happy with this VNA simply reading the antenna’s impedance.

I’ve decided to change the operational philosophy for how to tune the L-network after finding that the vacuum relays have a small closed-circuit resistance. I could probably reduce the measured 4 Ohms by passing a current through the relays to clean the contacts, but I can eliminate a relay completely by doing a pre-pass calibration over the entire 3 – 30 MHz range. My software will allow a pre-pass calibration for the entire range, a band-only range, or a user given range. Since I only presently have one antenna, and in the future can’t anticipate more than about three antennas, I can do a frequency sweep of the entire 3 – 30 MHz range and store the complex impedance of the antenna on an SD card resident in the Rabbit SBC. The software will pick a start frequency, measure the complex impedance using the VNA, and then increment the frequency by a kHz-or so. If the impedance does not change by much, the software will discard this measurement, and proceed on to the next increment. If there is a substantial change, I shall divide the increment by half, and measure again until a small delta is observed. Stored will be the frequency, and complex impedance for that increment. Since the frequencies are expected to increment in a non-linear way, I'll compose a hash table of the frequencies with their storage position in the linear array of complex impedances. That should vastly improve the retrieval speed when a new frequency has been chosen to transmit on.

Now it's on to the next phase (pun) of the project, which is to develop the 2-phase servos to drive the series inductor, and shunt capacitor to their proper correction values.

My servo motors take 115 VAC 60 Hz on the stator, and a 28 VAC, 60 Hz 90 degree shifted voltage on the rotor. The amplitude of the rotor signal determines the torque on the motor's shaft, and whether the 90 degree phase is leading or lagging the stator's phase, determines the direction of rotation. To obtain the leading or lagging 90 degree shifted voltages for the rotor, I use a simple 6.3 VAC center tapped small filament transformer with two RC phase shift networks to generate the in –phase, and quadrature-phase signals.

Each servo gear train has a 25 turn potentiometer which yields a linear resistance with inductance variation reading. Using the pot as a voltage divider with a reference voltage on the top end of the pot, I get a voltage proportional to the inductance setting of the servo. The same type of pot is on the capacitor's gear train, so I get a proportional voltage to the capacitance setting from that servo. I am using the servo amplifiers from the original Collins transmitter which need 28 VDC for power and a 90 degree shifted 60 Hz voltage proportional to the speed desired for the requisite servo motor, with the phase of the 90 degree shift either leading or lagging depending on the direction of rotation desired.

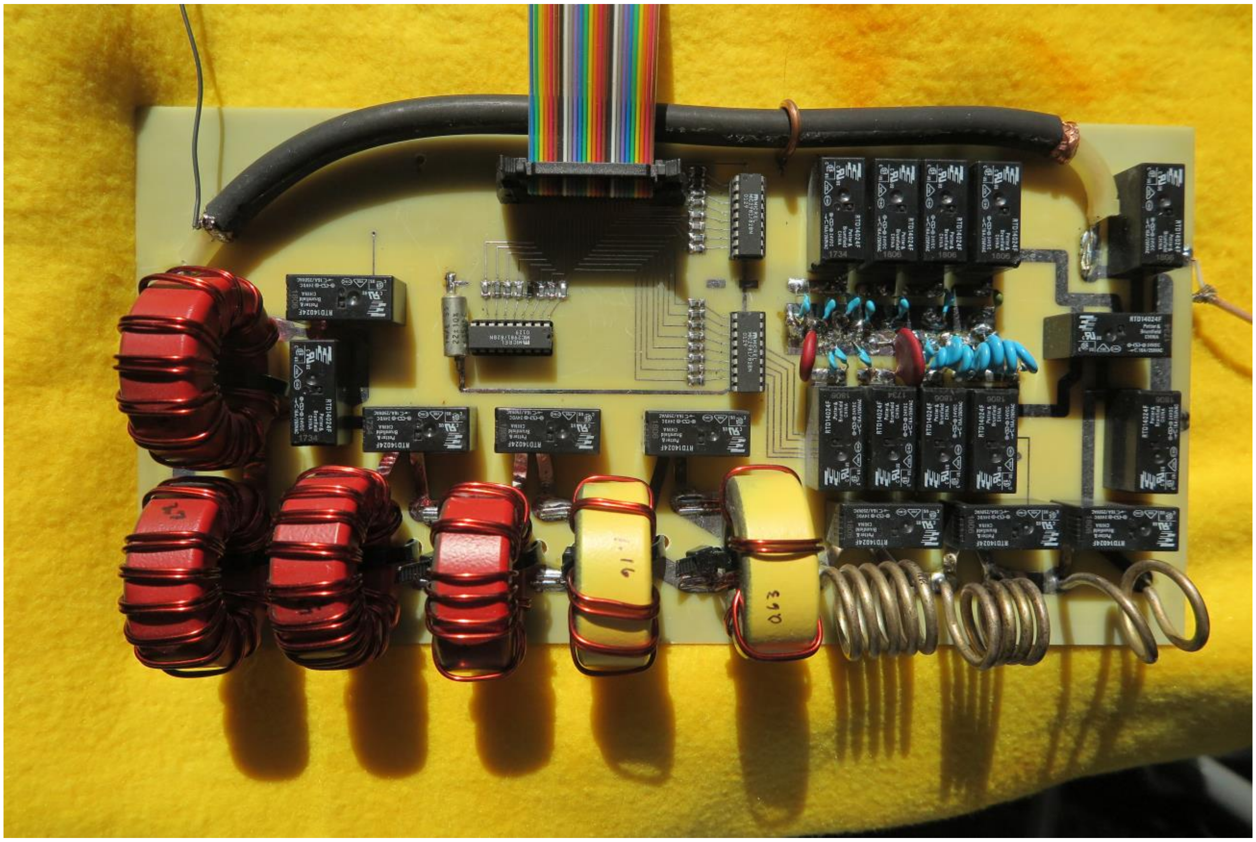
After putting all this together, and testing the tuning using a dipole antenna resonant on 40 meters, I find the tuning to be unacceptably slow. It all works as designed, but waiting 20 seconds for the servos to adjust the inductor and capacitor is just too long, so on to design number four…

Design Number 4

Well, I see the commercial automatic antenna tuners are mostly using fixed inductors, fixed capacitors, and small relays to switch the required L-network to match the antenna's impedance to 50 Ohms. I had considered this methodology at the get-go, but have been leery of the voltage and current capacity of the small relays. Upon further investigation, I see they are using regular 60 Hz AC type relays with in one example I looked at, 12 Amp / 250 VAC contacts. Okay, so for my 4th and final iteration, I am going that route with 16 Amp / 250 VAC contacts in a small form factor 24 VDC coil configuration. I really don't need to hot-switch anything, but I am still going to use the Jennings vacuum relays I have on hand for the antenna tuner bypass, and transmit/receive relays because of the vastly better isolation, high current/high voltage capacity, and they look cool.

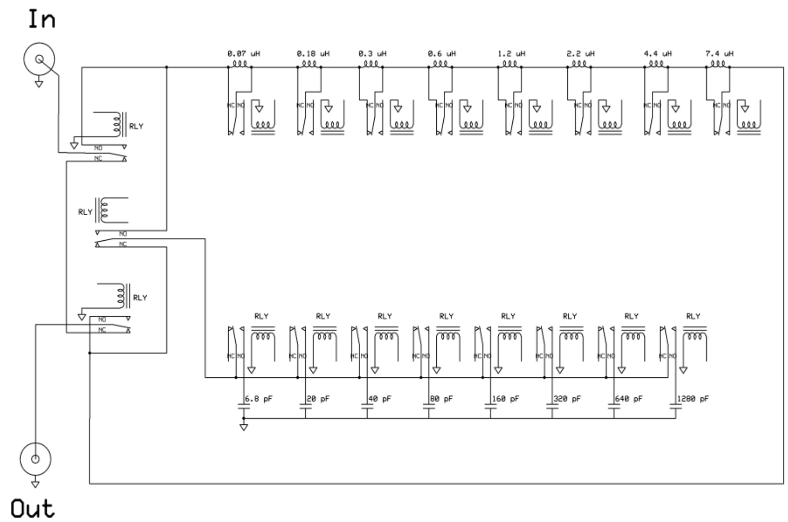
The inductors will be in a 1, 2, 4, 8… sequence starting with 70 nH at the low end. I'll keep the same 1, 2, 4, 8… sequence with the fixed capacitors, starting at 6.8 pF, and on up. My LPDA antenna's impedance is fairly well bounded, so I don't need compensation for an SWR of 10:1 or anywhere near that kind of mismatch, so I can get away with 8 switched inductors and 8 switched capacitors in the L-network.

The following image is the finished PC board. The two inductors on the left are in series which is why you see nine inductors. The capacitors are all 2 kV RF devices, and the relays are all 250 VAC, 16 ARMS (at 60 Hz) devices.



The integrated circuits are relay drivers with 24 VDC as the supply, and standard TTL levels which come in through the ribbon cable as switching lines. The TTL lines are low-pass filtered to try and keep the healthy amounts of RF floating around on the board from affecting the switching circuits.

The air-core inductors are all silver plated copper tube stock which I excised from a high-power transmitter. All the inductors were tuned with an HP-4275 LCZ meter. I used a lot of copper on the PC board both top and bottom, for the current carrying conductors. The chunk of RG-8 coax is the return from the last series inductor back to the bypass relay.



Cognitive Tools		
Automatic Antenna Tuner		
W6DSR	Rev 1.0 2/1/2020	L-Network