High Performance Crystal Radios

Gord Rabjohn, Don Asquin. © 2008

Some men's mid-life crises involve abandoning serious endeavors and embracing toys; often toys with large engines and two seats. Our mid-life crisis has been almost the opposite; we have taken a childhood toy, the crystal radio, and attacked it with rigor and diligence only engineers could muster to bring it to new levels of performance.

Gord has been building crystal radios for almost 40 years, starting as a child living near Toronto. Toronto was especially challenging for first-time crystal radio builders because of the large number of high-power AM stations in the area. He was a few miles from the antenna of CHIN radio at the high end of the AM band, and this station obliterated every other station on a simple crystal set like the one shown in Figure 1. The two stations he most wanted were CFRB at 1010kHz and CHUM at 1050kHz, and their high power exasperated their close spacing. So, his conclusion, as a kid, was that crystal sets were just toys and incapable of "DX" (long distance) reception.

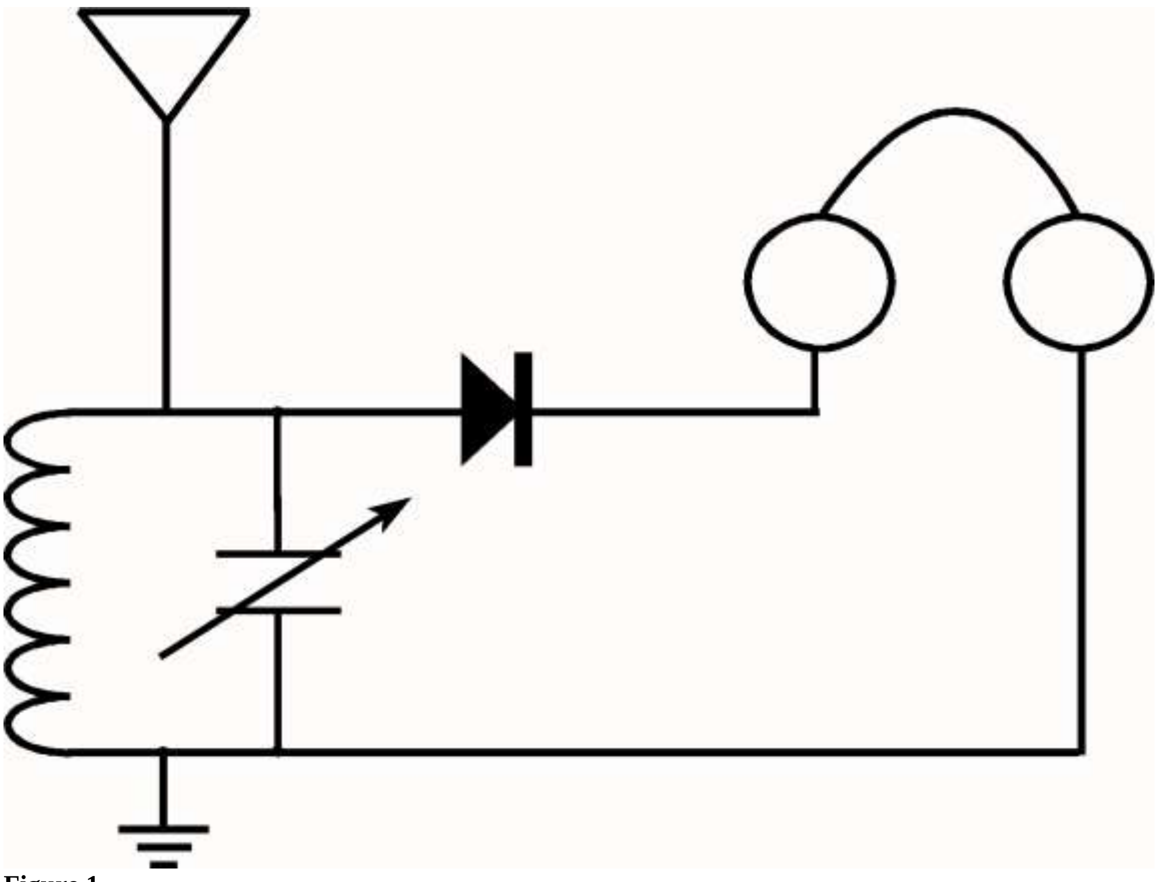

Figure 1

For Don, interest in radios also began with a crystal set, given not to him, but his older brother. After building the set, Don's brother wasn't interested anymore, but Don certainly was. The Eldon set pictured in Figure 2 (www.crystalradio.net) was a single tuned circuit with frequency adjustment provided by a slider on the coil. For Don in Calgary, CHQR 810 was his nemesis. This station overpowered every other station in Calgary, including CKXL, the much hoped for Rock & Roll station. However, the bug for radios had bitten, and over the years Don built other radios and eventually a large long wire antenna stretching from one corner of his parent's property to the other. Very popular in the community I'm sure!

Figure 2

Over the years, we had read frequent accounts of crystal sets picking up stations many hundreds or thousands of miles away. Either many people were lying, or we were doing something wrong. Eventually, Don cobbled together a two-circuit crystal set out of vintage 1920 components and amazingly DX from New York and Chicago started coming in. One night, a night Gord would not soon forget, Don demonstrated his radio to him, starting a sequence of events that might never end. We individually embarked on the search for our version of the perfect crystal set.

In reality, much of this exploration is rediscovering the knowledge of the 1910s and early 1920s, before vacuum tubes allowed designers to become sloppy. Even then, there were claims of DX performance with crystal sets. Unfortunately, the Eldon type kits of the 1960s and today have given crystal sets a bad name.

Today, there are perhaps thousands of interesting articles on the web and elsewhere on building crystal radios. Crystal set designers of today have taken what was learned in the 1920s and added some new technologies that have made crystal sets that surpass the performance of anything before. Currently, Mike Tuggle is one of the most successful crystal set designers. His set, the Lyonodyne-17 has heard stations in Cuba from his home location in Hawaii! (Fig 3,4)What can we possibly add that is new? Our goal is to share our experience about what is important. What are the critical elements that you need to get right to build a high-performance crystal set?

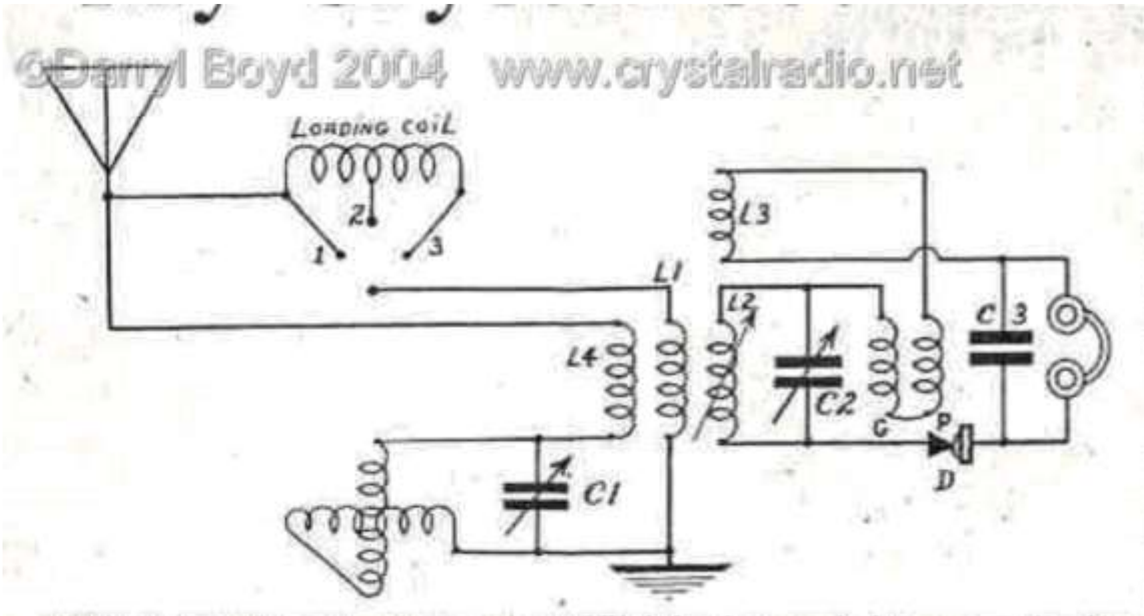

Figure 3

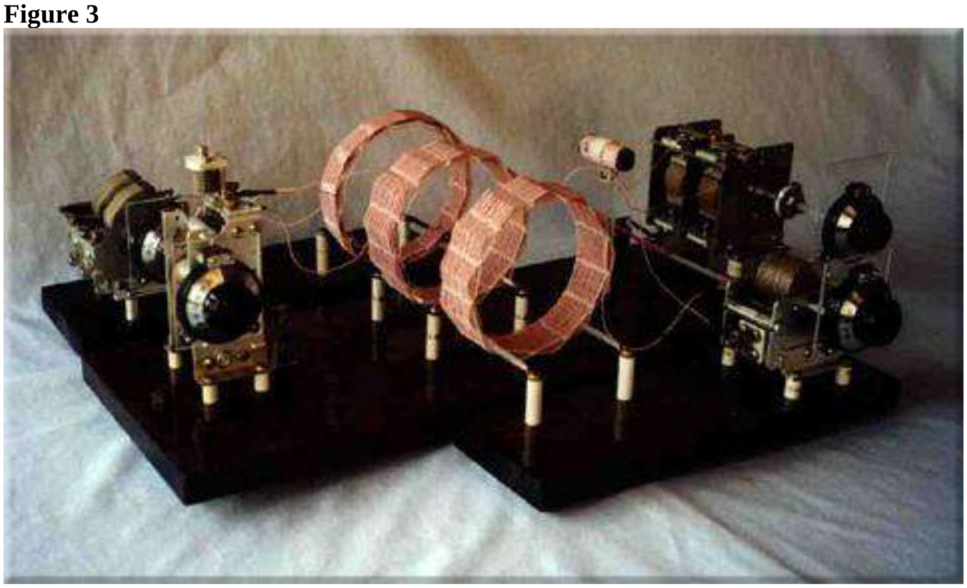
Figure 4

Most of the stations you will be tuning into are 50,000 Watt "clear channel" stations. (A clear channel station is a high power American station that shares its frequency with very few other stations) A good list can be found at http://www.northpine.com/broadcast/50kwam.html. Think of this as your life list, just like birdwatchers use. A good catch, but not unusual, with a crystal set is 1000 km (Chicago is about 1000km from Ottawa). By the time this wave has reached your crystal radio it has undergone about 127dB of attenuation so there is under 10 nanoWatts to work with!

You can divide a crystal set into 4 basic elements: the antenna (and ground) system, the tuner, the detector (the crystal), and the headphones. To get a good DX crystal set, you need to get all 4 elements right.

The Antenna

It's probably obvious to anyone interested in this article that a long antenna is essential to successful long-distance reception. Volumes have been written about antenna design, however most theory is on directional, multiple element antennas. One fundamental rule in antenna design is that antenna gain can come only through increased directionality (which, if you think about a transmitting antenna, makes sense: squirt your power in one direction only, and that direction appears to get more power. Receive antennas follow exactly the same laws) Directionality is usually achieved by manipulating the phase of a signal in multiple radiators. To achieve the needed phase shifts, antennas must physically large, at least a quarter wavelength, generally more. The wavelength of the AM band is so long (1MHz is 0.3km) that most of us don't have enough real estate to achieve any significant gain.

This makes antenna design rules very easy: Make your antenna as long and high as possible, and keep losses low. Keep losses low by using thick wire (Gord discovered that #30 magnet wire is useless), good ceramic insulators, and avoiding proximity to lossy material like wood. You will discover that a long antenna will offer a better impedance to a crystal radio making it easier to match.

As kids, both Gord and Don had long wire antennas mounted in their attics. These delivered fair performance, but the close proximity to wood, and the layer of snow in winter made them under-perform. Get your antenna outside and make it as high and long as possible.

The ground provides the completion of the current path for the radio signals. You can always attach a wire to a cold-water pipe, but the best ground remains a copper plated rod pounded into the ground. Home Depot sells these rods for grounding electrical systems. One of these will provide a great ground. If installed near a water tap, the ground can be kept moist and conductive.

A lightning arrester is a safety device that in the event of a lightning strike or near-strike will short the charge to ground rather than through the house. Commercial units can sometimes be found at OVRC auctions, and there are plans on the web for home-made units. They consist of two conductors with a gap between them. One end is connected to the antenna, the other to the ground. The idea is that under normal operation the radio signals don't jump the gap but travel straight into your radio. When lightning is nearby or strikes, the huge voltage will cause an arc across the gap and travel into the ground. Do they work? We hope so!

The Tuner

The function of the tuner is to match the radiation resistance of the antenna to the impedance of the detector, and to provide selectivity; that is some means of separating stations from one-another. Fortunately, these two functions are quite complimentary.

The traditional tuner that most first-time crystal radio builders use is a single parallel L-C combination (as seen in Figure 1). This configuration, by itself, does not offer enough degrees of freedom. When the circuit is resonant, it does no impedance transformation; that is, an ideal parallel L-C circuit looks like an open circuit at resonance. At a frequency just below the natural resonance, the tuned circuit is inductive and if the circuit is tuned correctly, there will be enough inductance to cancel the capacitance presented by a typical antenna. This leaves the radiation resistance of the antenna, which is a poor match to the detector (that is, the resistance of the source does not match the resistance of the load, resulting in a loss of transferred power).

What is needed is two degrees of freedom that can be used to optimize the antenna radiation resistance to match to the detector and at the same time allow station tuning. The solution commonly used, and has been used since the birth of radio, is the loose coupler. The loose coupler is simply two coils (each generally resonated with a capacitor) lightly coupled to each other. One coil is connected to the antenna, the other is connected to the detector.

The loose coupler may seem a mystery. Why would you ever want to *reduce* the coupling between the antenna and the detector; wouldn't that reduce energy transfer? It turns out that mathematically, the variable coupling (mutual inductance) gives that extra degree of freedom to allow the cancellation of the reactive part of the antenna resistance *and* the correct transformation of the antenna resistance. Interestingly, the optimum coupling is usually quite loose with the coils spaced some distance apart.

There is an optimum amount of coupling between the coils. Too much coupling (the overcoupled case) causes a wide, double peaked response. (this will be familiar to anyone experienced in tuning FM IF strips) Too little coupling indeed prevents adequate energy transfer. Just the right coupling (termed critical coupling) gives optimal energy transfer (no loss if the coils are ideal), and narrow bandwidth.

Figure 5 shows a graph of the response of a loose coupler for different coupling coefficients (k). It was derived assuming a 100kOhm detector load, 100uH coils, driven from a 1000pF antenna with 1.0ohm real part. Note that k=0.0039 means that less than 0.4% of the magnetic field from one coil couples to the other.

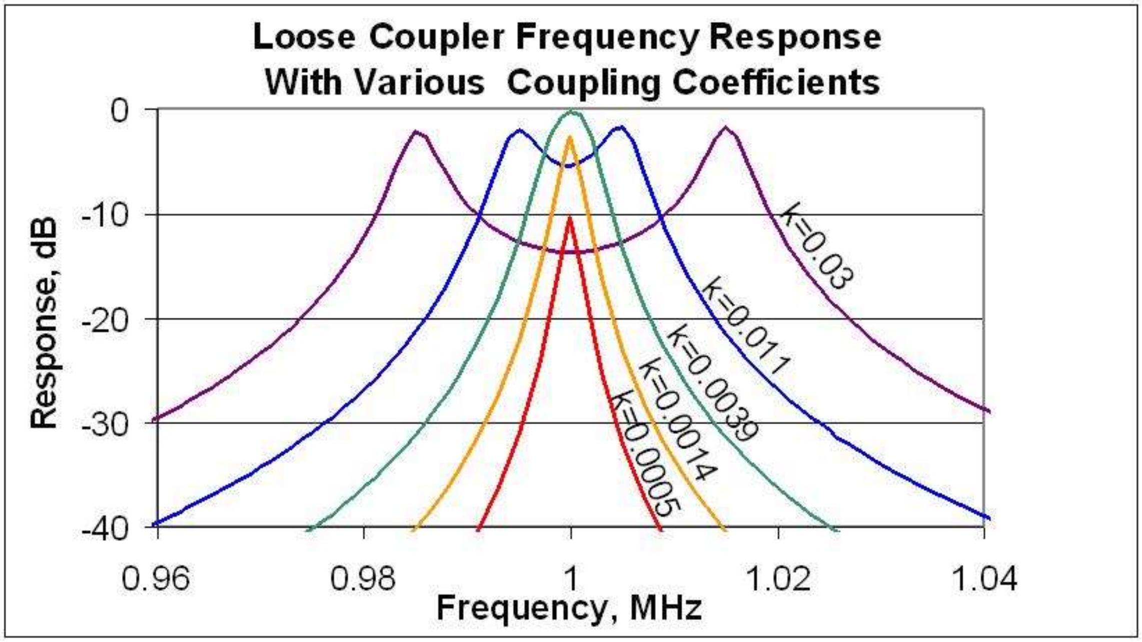

Figure 5

We all know that the inductors in a loose coupler should have as high a "Q" (Quality) as possible. "Q" can be defined many ways, which are equivalent, and give different insights. For an inductor, "Q" is the ratio of the energy stored (in the magnetic field) to the energy lost (through resistive and magnetic losses). Clearly, this tells us that a high "Q" coil will lose less energy, a good thing in a crystal radio. If you model a real inductor as an ideal inductor with a series resistance, "Q" is the ratio of the inductive reactance of the ideal inductor to the resistance. We all knew this: don't wind a coil with Nichrome wire. Another definition of "Q", for a tuned circuit is the ratio of the center frequency to the bandwidth. Clearly this last definition also tells us that we need a high "Q" to achieve selectivity. Unloaded "Q" refers to the "Q" of an inductor by itself. The loaded "Q" refers to the "Q" of an inductor including the losses imposed by the circuit it is used in. Loaded "Q" is only defined for an inductor when it is connected or coupled to another circuit. Loaded "Q" is always lower than unloaded "Q".

While magnetic cores of ferrite or powdered iron increase the inductance achievable per turn of wire, thereby making small coils possible, the very best coils still seem to be air-core based. A straight solenoid wound coil is a good start, but the proximity of the turns to each other cause current crowding in the cross-sectional area of the wire and additional stray capacitance. The magnetic coupling between adjacent wires causes a build-up of current on the close surfaces of parallel wires, and therefore higher losses. This is related to skin effect. Coils with spaces between turns will have better "Q". Basket style coils (reminiscent of a wicker basket) are popular because the configuration avoids parallel adjacent lines, reducing capacitance and current crowding. Spider-web style coils are also popular. These coil configurations reduce both the self capacitance, and the current crowding.

The best wire for high “Q” coils is Litz wire. Litz is derived from the German word “Litzendraht” meaning woven wire. Litz wire consists of many strands of parallel connected, individually insulated wire woven together in a regular pattern such that each wire alternates evenly between the middle and the outside of the bundle. This forces each wire to carry about the same current, thereby minimizing skin effect (the tendency for current to flow along the outside surface of a wire), and loss. If you are going for the ultimate “Q”, the right Litz wire is a must. The holy grail of Litz wire is made up of 420 to 660 individual strands of 46 AWG wire all twisted together to make a 16-18 AWG wire. The main manufacturer of Litz wire is New England Electric Wire Corporation. (See www.neewc.com). With patience, Don has found Litz wire at Toronto surplus stores and even Cohen’s in Ottawa. Verify that the wire is solder-strippable; removing high temperature insulation from hundreds of strands requires caustic chemicals.

Both Gord and Don used Litz wire in a basket weave pattern to achieve high Q in their crystal sets. A “Q” of over 500 (1MHz value) should be achievable. Always endeavor to achieve the highest “Q”; there is no “point of diminishing returns” when it comes to coils used in crystal sets. (Because you can couple a higher Q coil more lightly and achieve similar energy transfer and better selectivity)

A good spreadsheet type application for predicting coil inductance and LC tank tuning range is called “Dr. Coyle” available.
http://www.crystalradio.net/professorcoyle/index.shtml

The Detector

Much has been written about the relative merits of different detectors. There are many that believe a silicon medium barrier Schottky gives the best performance. (low barrier Schottky diodes are not considered optimum) Our experience is that it is hard to beat a good germanium diode. Germanium is good because its barrier height (turn-on voltage) is lower than silicon, and a germanium diode is truly a point-contact diode (not P-N diode), so has low charge storage (and therefore fast switching times). They are specified with very low capacitance, less than 1pF. The main complaint about 1N34A diodes is that they tend to have high and highly variable leakage and as we want the detector to work at a high impedance, a small amount of leakage is noticeable. The best solution here is to try several, doing A-B comparisons, and select the best germanium diode in your drawer. 1N34A’s are the most popular, but any germanium diode (1N60, 1N270, 0A47, etc) is worth a try. The standard silicon junction diodes (like the 1N914 or 1N4148) have higher capacitance, and higher turn-on voltage, so are almost useless as crystal radio detectors.

Gord has tried forward biasing diodes with little success. The theory is that if a diode is forward biased slightly, less signal voltage will be required to turn them fully on, and therefore sensitivity will be enhanced. He has not found this to be the case. Our recommendation is to simply stick with a germanium diode such as the 1N34A diode.

Ben Tongue’s web site (of Blonder-Tongue fame, www.bentongue.com) contains several detailed papers on detector optimization and inductor coupling. They make good reading if you want to go further. Another interesting site in Germany is: http://www.oldradioworld.de/gollum/ . There are several construction articles and ideas regarding diode comparison on this site, all completely bilingual in English and German.

It is useful to have an R-C network in series with the diode. This network generates a DC potential on strong signal levels that lowers distortion on local stations, almost like an AGC.

The key to any detector is getting the voltage into it as high as possible. (The reason for this is that at low signal levels, diodes are "Square Law" devices, that is, the output voltage is the square of the input voltage. Clearly, then, doubling the input voltage more than doubles output voltage, so efficiency increases at high signal levels) So, for a given input power, high voltage implies a low current (Power equals Voltage multiplied by Current (P=IV)), and therefore a high impedance (Voltage equals Current multiplied by Resistance (V=IR)). Therefore, a detector will tend to work best when used at a high impedance, somewhere around 100 kOhms. The output impedance of a diode detector is directly related to its load, so it is important that the headphone load on the detector is kept very high.

No headphone offers an adequately high impedance to a detector. However, there are "Microphone transformers" available that offer a 100 ohm primary (which the headphone is connected to) transformed up to a huge 100 kOhm secondary (which is connected to the detector). Both Don and Gord use a UTC model C2080 and Stanley/UTC TF-1A-10-YY microphone transformers, which have an inductance of over 1000H on the 100 kOhm winding. These are available from Fair Radio Sales www.fairradio.com . Gord has tried audio line matching transformers cascaded with the 100K transformer, but see little improvement. Don has used two microphone transformers in various parallel and series combinations, with some improvement. Other transformers to consider include tube audio output transformers, TV vertical output transformers and audio line matching transformers; but none match the "Microphone Transformers".

The Audio Transducer

The best transducers (headphones) for crystal radio operation are "Sound Powered" headphones or "Deck Talkers". These headphones were developed in WWII for the navy to allow communications between the observers and gunners without the need for any electricity. They are so sensitive that the change in air pressure from the talkers voice in the microphone is sufficient to drive the headphones of the listener. An elaborate mechanism (usually a balanced armature system) gives the sound powered headphones their sensitivity. The best is probably RCA's "Big Cans", however there are many different versions of sound powered headphones available with widely different characteristics. Note that the microphone and earpiece in the deck-talkers use the same transducer. Deck-talkers have usually had a hard life and the transducers are sometimes corroded or misaligned, so buy several and pick the best pieces. The armature mechanism of a deck-talker is shown in Figure 6. The best source of information on sound powered headphones is at Darryl Boyd's website, www.crystalradio.net. The impedance of sound powered headphones is typically under 1000 ohms, much too low for direct use in a crystal set. However, the microphone transformers mentioned earlier are excellent choices for matching the impedance of the diode to the headphones.

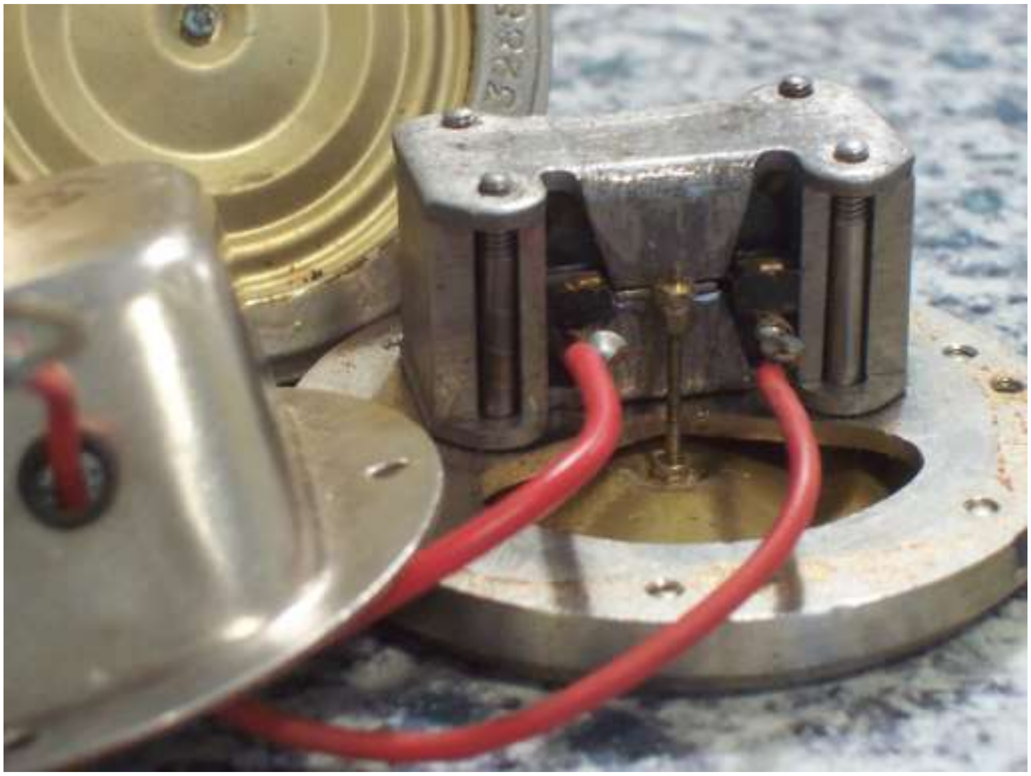

Figure 6

Crystal earplugs work, but have excessive capacitance, (often several nF), which translates to a heavy load on the detector. Diaphragm-type headphones (two electromagnets and a bias magnet pulling on a metal diaphragm), typically 2K impedance, lack the sensitivity of the sound-powered units. Walkman style “ear buds” are not suitable at all.

The Final Result

Gord and Don’s crystal set share many of the same features, but are also different. Both use long wire antennas, approximately 75 feet long antenna, and about 20 to 30 feet above the ground. Stations in Chicago and New York are commonplace, with stations in Washington D.C., Illinois, and Kentucky also being logged.

The schematic of Gords is shown Figure 7, and Don’s is in Figure 8.

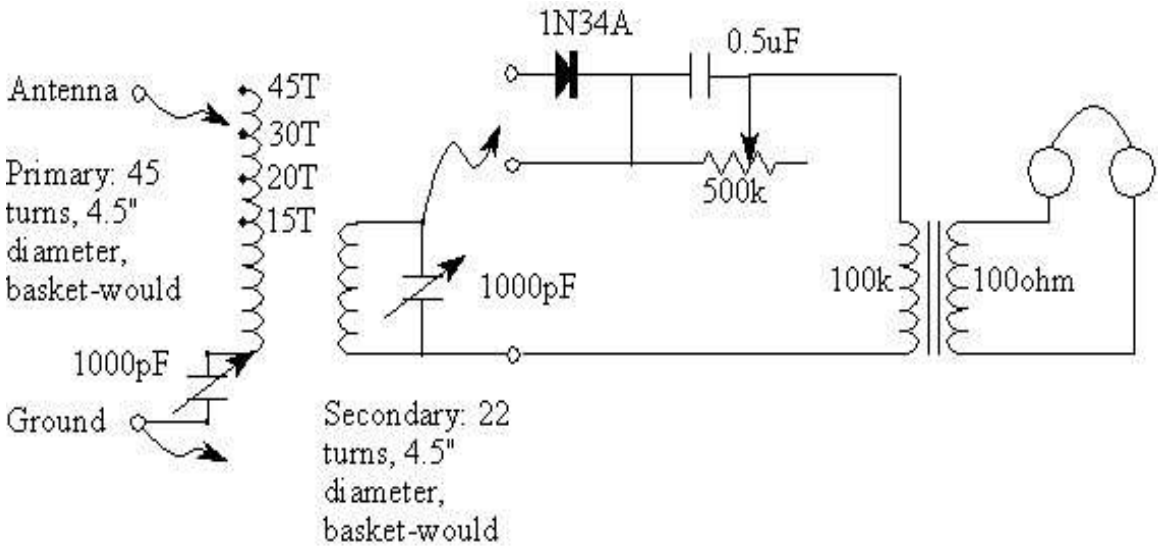

Figure 7

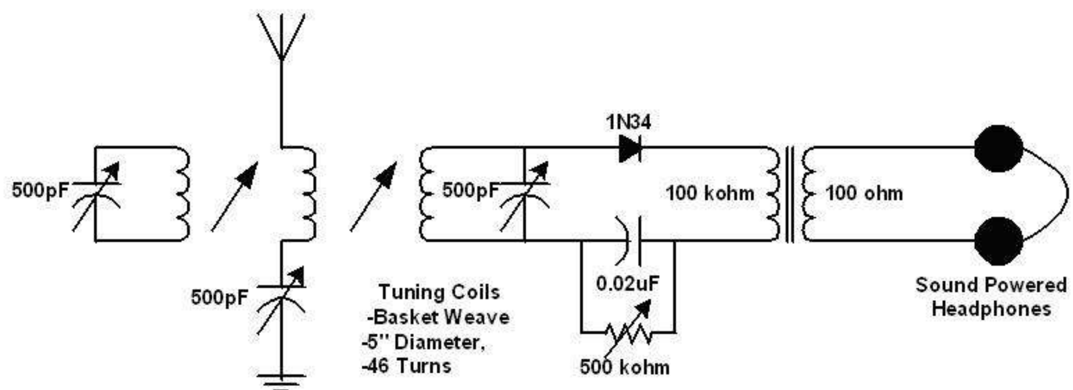

Figure 8

Gord's radio uses a pair of basket weave Litz wire (20 AWG made up of 108 strands of 40 AWG wire) coils wrapped on a form made with an odd number of quarter inch dowels (in this case, 7). The winding fixture is shown in Figure 10. The dowels are covered with large diameter drinking straws, the wire is wound around them, and the wire is held to the straws with glue-gun glue (purists would not use glue!). The input tuned circuit is composed of a 1000uF ceramic insulated variable capacitor in series with a 4.5" diameter, 45 turn basket wound coil with taps. Gord found that the series configuration works well above about 700kHz. Below 700kHz, there is not enough inductance in the 45 turn coil to resonate with his antenna capacitance, and the capacitor has to be placed in parallel with the inductor for the low end of the band. The secondary of the loose coupler is made with a 22 turn basket wound coil in parallel with a 1000uF ceramic insulated variable capacitor. These 2 inductors slide on Plexiglas rods to allow their mutual coupling to be adjusted. The set allows the coils to be moved as far apart as 15", however this is barely enough. The loose wires shown in the schematic facilitate experimentation with the input tuner and different detectors. A photograph of the completed unit is shown in Figure 9.

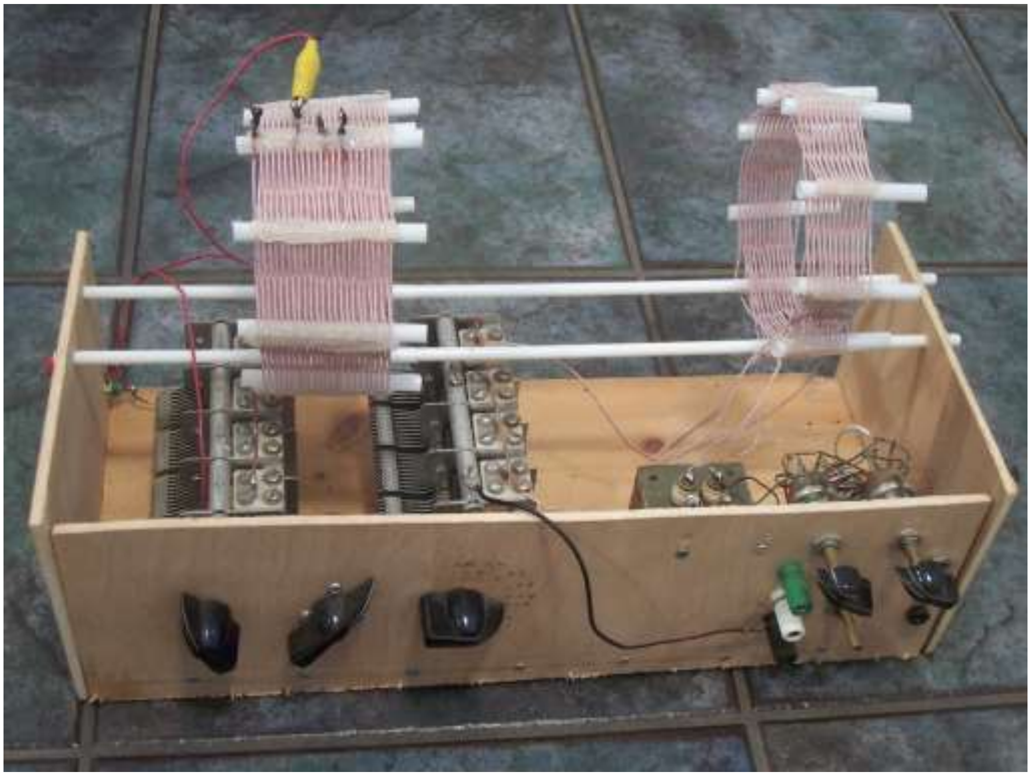

Figure 9

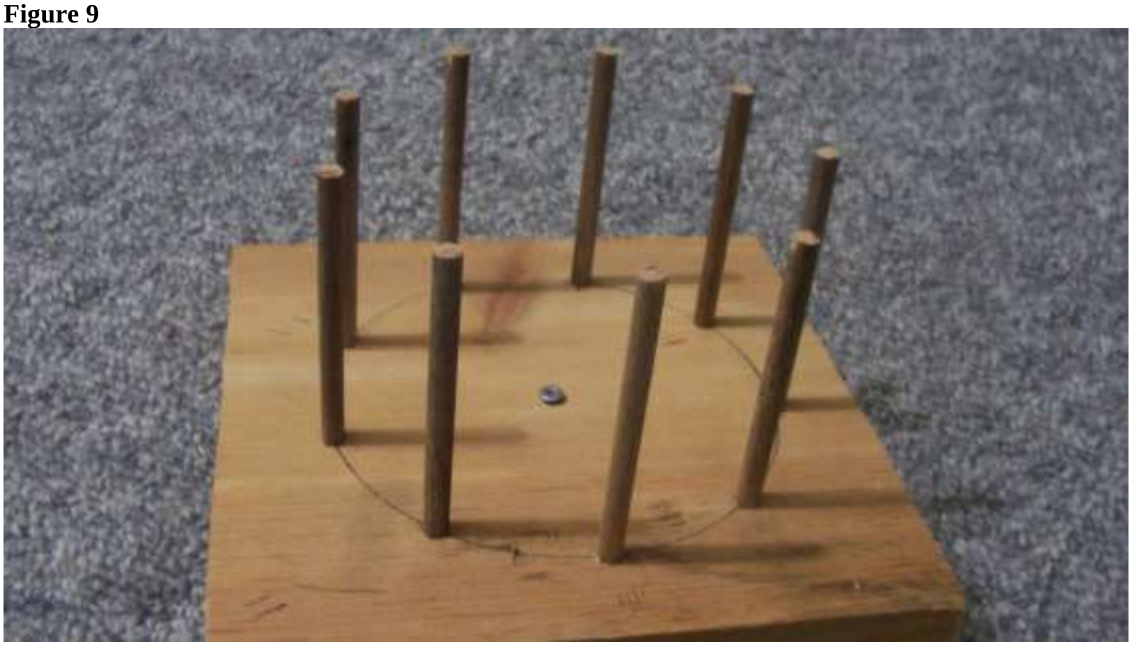

Figure 10

The detector is a IN34A, followed by an RC network that allows DC bias to build up, followed by the transformer mentioned above. Gord uses headphones made from a pair of "Deck Talkers" which were acquired at an OVRC auction.

Don’s set also uses Litz wire (16 AWG made up of 420 strands of 42 AWG wire) basket weave coils. The coils are 46 turns of 18 gauge wound this time into a 5 inch diameter coil with 13 dowels as the forms. As Don’s coils are larger, a 500pF series tuned variable capacitor works to match the antenna for the entire AM band. A second LC, this time in parallel configuration, acts as the tuner for the diode, which feeds the microphone transformer and sound powered headphones. Don chose to avoid any taps on the coils. Generally, taps and the associated switches lower the Q of the coils. Additionally, Don added an absorbing circuit to his radio. This parallel L-C network is tuned to the frequency of a strong local station. By notching out a local station, distant radio stations with operating frequencies near the local can now be tuned in. Don also added an AB detector switch to his radio to facilitate comparing diodes. Verniers on the tuning capacitors enable careful adjustments to bring in distant stations. A picture of Don’s set is shown in Figure 11.

Figure 11

Going further next time, Don would like to try “straight line tuning” capacitors. Simple round variable capacitors spread out the 10 kHz spacing between stations at the low end of the broadcast band (540 kHz), but cram them together at the high end (1600 kHz). In a straight line tuning capacitor the angle of rotation is proportional to the square root of the capacitance and therefore proportional to the resonant frequency. This configuration will make for even spacing across the entire broadcast band and make separating out distant stations at the high end of the band much easier.

In the future, Don would like to play with different mineral detectors. Cats whiskers with Galena or Iron Pyrite, or Perikon detectors of Chalcopyrite and Zinicite, will probably not give as good performance and a 1N34A but would add a historic interest.

Crystal radios work on incredibly low power. Gord measured the power of a weak radio station (just barely audible) from Montreal during the day (the day is the best time to do this, as signal conditions are much more constant, however true long-distance reception is far better at night). He replaced the detector with 100kOhm resistor and measured the RF voltage across the resistor (essentially out of the loose coupler) with a high impedance probe and an HP RMS voltmeter. He made the assumption that the detector has a 100kOhm input impedance, which is a guess at best, however it gets us into the ballpark. He measured 25mV RMS, which translates to under 10nW. This energy will be converted to DC and audio by the detector (even at 100% modulation only a third of the power of an AM signal is audio information), so with detector inefficiency, the power present at the earphone is a fraction of 1nW. Audio transducers generally have low efficiency, though a sound powered transducer will be better than most. The sensitivity of the human ear is amazing; the threshold of hearing is generally considered to be about 0.001nW/square metre.

Conclusions

So, it is true, a crystal set can receive radio stations from over 1000 km away. To accomplish this feat, the four key elements, antenna, tuner, detector and audio transducer, all need to be optimized. There is no magic involved, just some attention to detail and an investment of time. No single item is particularly scarce or expensive; even the sound powered headphones and the Litz wire have been available at OVRC auctions. With some time and creativity, the experimenter will be richly rewarded. There is something magical about tuning into a radio station over a 1000 km away using only its radiated power.