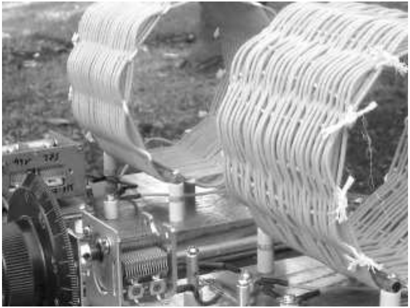
# KEVIN'S WEBSURFER HANDBOOK IV
## FOR CRYSTAL RADIO

ANTENNAS – GROUNDS & TUNING UNITS



Kevin Smith

2011

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http://www.lessmiths.com/~kjsmith/crystal/catalog.shtml

KJ Smith

NOTES



**INTRODUCTION**

The contents of this fourth handbook concerns itself primarily with antenna and grounds as applied to crystal radio (avoiding all the HF world). Finally, It was inspired by my realization that I really didn't understand antenna tuning as well as I thought I did, and especially I didn't understand the Tuggle Circuit. Very little qualitative discussion exists on the web for this in fact. The references I have rounded up here in this handbook should go a long way towards "rectifying" the situation.

In this booklet I start with a good discussion RF field strength, historically, qualitatively and quantitatively. I then bring in some considerations on grounds and especially a discussion of ground resistances regionally and locally as these are essential to modeling my, or any, antenna prior to designing a proper antenna tuner unit. What the follows are excellent resources helping with the design and understanding the functioning of a good "Tuggle Front End". The handbook will help the beginner to quickly get up to speed and allow the experienced builder to find endless new ideas. This is not a book of Hookups or circuit designs, that is covered in my Catalog of Crystal Hookups, nor is it a tutorial on Crystal Radio, that can be found in my Handbook Volume 1.

Finally, although I intend this handbook to consider the antenna / ground as part of the crystal radio system, it is true that antennas receive potentially harmful spherics as well. Due to this, I have included as a last chapter (but not as an afterthought) a section concerning lightening protection.

Much of the material in this handbook is copyright for which I have not sought permission. Therefore this is not presented for publication or copy, and certainly not for profit. It is only my personal resource. I encourage anyone finding this copy to pursue ON THE WEB the web pages identified within. I include the name of the author and web address of each section. I wish to sincerely thank every author presented for their excellent pages and ask forgiveness for my editing into this handbook.



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**References:**

1. "The "Grounds" for Lightning and EMP Protection", by Roger Block, published by PolyPhaser Corporation.

Finally, there should be a large diameter (#4 AWG or larger) copper wire connecting the equipment to the Earth ground. The shorter the wire, the better. Additional information on grounding can be found in Reference 1.

**Mains and Power Supply Protection**

Just because your radio and antenna are miles away from a lightning strike does not mean that you are protected. Lightning often strikes power lines and produces a large voltage surge or spike that can be transmitted for miles on the main power lines.

Therefore, for maximum protection, all power line interfaces should include a transient voltage surge protector. These devices are becoming quite common and inexpensive. Again, there are simple protectors and those that may include additional protection with built-in line inductors. Just make sure that the surge protector is placed between the power lines and the equipment power supply.

**Summary**

As stated at the beginning of this paper, lightning damage can be extensive and costly. We have tried to provide you with an overview of things to consider when installing a radio and antenna system but only you can determine how much protection is required. Astron Wireless Technologies, Inc. has access to various lightning protection solutions for most applications. Please call for additional information on lightning protection devices and how they can help protect your investment.



**Field Strength Calculations: A History**

Radio-Time Traveler

http://radio-timetraveller.blogspot.com/2012/12/field-strength-calculations-history.html
16 December, 2012

A previous three-part series on RADIO-TIMETRAVELLER delved into Field Strength Calculations. It covered ground conductivity's effects on signal strength, measurements quantifying signal intensity, and how to use the FCC Groundwave Conductivity Graphs to calculate expected received signal strength. Mathematical formulas, somewhere, produced those graphs. What is their history? Might we use a simplified formula to calculate expected received signal strength for our DX purposes?

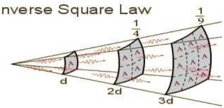
Let's continue with the story behind Field Strength Calculations and explore the 50 year quest for accuracy in calculating signal strength by mathematical formula. It is an interesting tale. We will finish with a handy field strength calculator program I wrote using a simplified formula.

When we talk about field strength, we are really talking about radio propagation - the behavior of radio waves when they are transmitted or propagated from one point on the earth to another, or into various parts of the atmosphere. In our formula quest, we will mostly be concerned with those signals that hug the ground, or "ground wave". It may surprise many who are new to the hobby of mediumwave DXing that daytime ground wave range for a mediumwave signal might extend out to as much as several hundred, and in extreme cases, nearly 1000 miles!

Accurate formulas for calculating expected signal strength at mediumwave and longwave frequencies took many years to develop. Radio originally inhabited the longwaves in its infancy. Many of Marconi's early broadcasts, including his 1905-1906 transatlantic tests, were sub-100 KHz. The trend would be decidedly upward in frequency and downward in wavelength.

At the end of World War I, a fierce battle ensued between the US government and the Department of the Navy over control of the airwaves. The Department of Commerce eventually won and became master of the air and the regulatory agency for commercial radio. They started by establishing two broadcast frequencies: 833 KHz (360 meters) and 619 KHz (485 meters). The Federal Radio Commission took charge in 1926, lasting until 1934 when the current Federal Communications Commission was formed.

Throughout the early years of radio, interest mounted to quantitatively determine the service area of broadcast stations. Engineers redoubled their efforts to derive an accurate attenuation formula. The radio world was focused on accuracy of measurements at broadcast frequencies.




"Accuracy" is the key word here. The Inverse-Square Law, as applied to physics, had been commonly known since Isaac Newton's day in the 1600s. Applied to radio, it stated that the power density of the wave is proportional to the inverse of the square of the distance from a point source. In other words, doubling the distance from a transmitter means that the power density of the radiated wave



range with low VSWR up to about 2 gHz. However, it too must be replaced after a strike although it will not necessarily warn the user by going to a short circuit so preventative maintenance is required.

The quarter wavelength shorting stub is becoming a very popular device, especially above 800 MHz where system bandwidth is generally narrow. It consists of a tuned quarter wavelength shorted coaxial type transmission line that is placed directly across the transmission line. Simple types have a narrow bandwidth, typically 10'-. bandwidth, but are low loss and inexpensive.

The optimum place to locate an input protector is at the entry point to the building where the equipment is located. Don't forget to provide a low impedance ground connection to the protector as described below. Always try to keep the lightning and the protection devices outdoors wherever possible!

**Grounding**

The most important lightning protection is a good low impedance Earth/ground connection to the associated equipment. The Earth ground connection should be a copper plated rod preferably at least 5-8 feet in length driven into the ground. This ground rod should be located as close to the equipment as possible, typically just outside of a building at the entry point of the antenna feedlines.

Greater protection can be provided by using additional ground rods spaced at least 8 feet from and connected to the original rod. Substituting plumbing, power ground return and other "so called" grounds for a ground rod is definitely not recommended.

will not discharge through the antenna. Furthermore, the boom or mast should be grounded to the mast or tower. More on this shortly. Don't forget to ground guy wires that are used on stabilize towers. They are just as likely to be hit since they extend over a wide area around the tower.

**Input Protection**

Input protection is typically provided by a lightning or surge protector at the input (or antenna side) of a radio. There are three major types of lightning protection devices for the radio input. They are the spark gap, the gas discharge tube and the quarter-wavelength (1/4) wavelength shorted stub. Each method has its pluses and minuses.

The spark gap is the oldest know lightning protection having probably been invented by Ben Franklin! Basically it consists of two balls or points closely spaced and directly across the transmission line. When a strike occurs, the high voltage present will jump across the points and be conducted to ground. RF transmission devices for 50 Ohm systems such as this have been around since the 1950's.

The shortcoming with this older device is that it may not protect against a weak or lower voltage strike. Adjustment at the factory may produce varying voltage breakdowns. Furthermore, once a strike is taken, the device may fail or short circuit so maintenance is required.

A more recently developed input protection device is the gas tube. It works in a similar manner to the spark gap but can be designed to operate reliably at much lower voltages down to 100 Volts for low power circuits and 250 Volts or higher for higher power applications. Another advantage is device is that it can be designed to operate over a very broadband frequency



at that new location is reduced to one-quarter of its previous value. But did it apply?

"Free-space" formulas calculating signal loss in the vacuum of space or "perfectly conducting earth" using the so-called inverse-square law are indeed accurate for those environments. But the Earth is not a perfect conductor, nor does it represent perfect-world conditions. Free-space formulas alone are not usable for our purposes. You will find many of them on the web, even calculators, purporting to deliver a signal strength solution for a given transmitter-to-receiver distance. They can be ignored as inaccurate. In fact, they are not even close.

Arnold Sommerfeld, 1868-1951

Mathematicians started with a "plane earth" (flat earth) theory when they first envisioned a signal attenuation formula.

Brilliant, German-born genius Arnold Sommerfeld, nominated a record 81 times for the Nobel Prize during his lifetime, solved the plane earth general problem by 1909, publishing signal attenuation graphs in 1911. Bruno Rolf, basing his work on Sommerfeld's findings, published more attenuation graphs in 1930, some 21 years later. From this information, the Federal Radio Commission compiled formulas and curves, published in 1931. They were used in hearings and allocation matters at least until 1933. It was just the beginning.

In the intervening years from 1909 to 1930, four more scientists obtained independent solutions of the Sommerfeld problem which agreed with the 1909 solution. That is, except for one difference - an inverted mathematical sign. Apparently none of these authors noticed this discrepancy until the FCC's K.A. Norton, in a letter to the editor of "Nature" in 1935, pointed it out and showed that it was responsible for the anomalies in propagation predicted by the Sommerfeld-Rolf graphs. Norton in 1936 was able to construct a universal curve for prediction of field strength at relatively short distances.

Focusing on the plane earth theory, Sommerfeld expected that the surface or ground wave would be only slightly affected by the curvature of the earth since it is guided around the earth's curve in much the same manner as an electric field can follow around the bend in a wire with a comparatively small loss of energy. This explains the general success of the Sommerfeld plane earth formula at distances far beyond the line of sight. However, two major roadblocks to accuracy still existed.

The first, and most important, was "diffraction". The other, "intermediate distance".

Out beyond what is called the "radio horizon", radio signals undergo atmospheric and ionospheric diffraction, that is, refraction and scattering caused by atmospheric


irregularities. This enables AM radio signals in low-noise environments to be received well after the transmitting antenna has dropped below the horizon. It has been shown theoretically that the ground wave attenuation factor at mediumwave frequencies is very little affected by diffraction at distances less than about 55 miles, the approximate "radio horizon" for mediumwave.



115 VAC we obtain from a line cord). Let's discuss each of them separately.

**Antenna Mounting**

It is well known that lightning statistically strikes the highest electrical conductor in an area and then follows the lowest resistance and shortest path to ground. Since antennas are usually mounted in high places, they are very susceptible to lightning strikes. Most antennas have a metallic boom and the elements are often attached directly to the boom so they are a likely target for a lightning strike.

Therefore, the antenna location and how it is mounted is probably the most controversial topic when any discussion of lightning occurs. Ben Franklin gave rise to the theory that the lightning was electricity and found this out when he almost was killed by a lightning strike conducted down the wire holding down his kite. Franklin is sometimes credited with the ball discharger and the pointed rods on houses. As a result, to this day lightning rods with grounding wires are a part of folk law and many are installed on high buildings and homes, especially in areas prone to lightning activity. Properly installed and grounded, these devices surely do work.

Nowadays, new controversy has resulted with the use of spline balls, static dischargers and wicks mounted on antennas and the top of towers. These devices are said to provide a constant discharge thus decreasing the potential for a direct strike. Some users claim a diminished amount of direct hits after installing these devices.

Suffice it is to say, if at all possible, don't mount your antenna on the highest building or tower. Place it a few feet lower and hopefully the fickle lightning bolt, if it generates a direct hit,

## The Nature of Lightning

Lightning can form and stay in the upper atmosphere. This is often a beautiful sight to behold as the bolts jump from cloud to cloud. On the other hand, when lightning leaves the clouds and strikes the ground or a tall object, it can inflict instant destruction and even death to those unfortunate to be near the strike.

The energy present in a lightning bolt can be considerable and a direct hit will inflict the maximum damage. It is estimated that a typical bolt may contain a potential of millions (1,000,000's) of volts thus generating currents up to 100,000 amperes! That is very destructive energy. At the same time, the heat in the bolt can have a temperature up to 30,000 K, hot enough to start fires.

A lightning bolt will often drag or jump along the ground. Therefore, there can be considerable damage in a wide area (even hundred's of feet) surrounding the strike. Just ask a dairy farmer what happened to his cows that tried to hide beneath a tree that had a direct lightning strike.

## Lightning Protection in General

Lightning protection must be examined from four distinct directions. First off, the place where the antenna is mounted (such as on a tower) is important. Then there must be input protection from the lightning strike itself, typically in the form of a huge and rapid build up of voltage and current at the input to the radio. Thirdly, a proper ground system must be employed to rapidly conduct the lightning bolt energy away from the radio. Finally, protection is required at the output or main power supply such as the line voltage supply (e.g. the



Norton, also in 1936, provided curves for greater distances in the diffraction region. These curves, however, were based on an incompletely developed theory. Mathematical solutions were being developed in Europe, and were two years away from completion. Europeans van der Pol and Bremmer published their paper in 1938, offering a more complete solution of the radio diffraction problem for propagation. Never-the-less, the calculation of field strength beyond the radio horizon still proved troublesome, though Norton's remarkable work clarified Sommerfeld's ground wave propagation theory.

The radio horizon at the longer wavelengths, including mediumwave, can be calculated quite simply.

$$\text{Radio Horizon} = 8\text{x}10^4/f^{1/3}\ \text{(meters)}$$

*f = frequency in MHz*

For example, the radio horizon for a station transmitting on 600 KHz is about 59 miles.

By 1940 the FCC, through the work of K. A. Norton, had developed a practical method for constructing curves approximately representing the theoretical predictions. The method used the flat earth theory of Sommerfeld out to a distance of about 80 kilometers, and the diffraction theory of van der Pol and Bremmer at relatively great distances, those in excess of 200-300 kilometers depending on frequency and ground constants.

The gap in the curve was still intermediate distances. The Watson transformation, a theory originally described in 1918 by English mathematician G.N. Watson, was an attempt to connect the two. How to incorporate it into the general theory, to calculate the intermediate distances, was still the final problem. In the curves published in 1940, the gap was simply sketched in by a draftsman.

In 1952, George A. Hufford of the National Telecommunications and Information Administration provided a basis for unifying the ground wave prediction methods of Sommerfeld with Watson's diffraction transformation. It had been 43 years since Sommerfeld's 1909 thesis. There was finally light at the end of the tunnel. New curves were added in 1954 for very low conductivity. These were quite accurate, although freehand drawing was still necessary to join the Sommerfeld curve segment to the curve segment calculated for the diffraction field at relatively great distances.

Then in 1958, Hendricus Bremmer, the same Bremmer who in 1938 brought the general solution to the diffraction problem, provided correction terms which completed the search for the practical formula. Engineers could finally calculate ground wave field strength with accuracy. It had been 50 years in the making. The formula was born.

The FCC curves were considered satisfactory for regulatory purposes until it became necessary to convert to metric units toward the end of the 1970s. In a 1979 FCC report, it was recommended that a computer program be written for recalculating the curves using the methods in Bremmer's 1949 book. The program was subsequently used to produce new FCC curves in 1985 which agree within 1 to 2 decibels with the previous curves. However, the 1979 computer program was mathematically deficient in its ability to cover all the range of intermediate distances, and the great distance values it computed were shifted upward to force a match in the middle. FCC curves drawn for the X-band, 1605-1705 KHz, are the most recent. They are the result of precise calculations of field



**What You Should Know About Lightning Protection**
http://www.astronwireless.com/topic-archives-antenna-lightning-protection.asp
By Joseph H. Reisert

## Antenna Lightning Protection

Antenna manufacturers are often asked about lightning and whether their antenna is lightning proof. This is not a simple question to answer. In this application note we will attempt to describe some of the statistical properties of lightning strikes and give some recommendations on how to best protect your installation from damage due to a lightning strike.

It is important to point out at the start that lightning protection is primarily a function of how much time and money you are willing to spend. Obviously, the more expensive the radio and the importance of system connectivity, the more robust your protection should be.

## An Introduction to Lightning

Lightning has been around since the beginning of time. In fact, at this very moment, lightning is striking somewhere on the earth. In the lower 48 US states and Canada, lightning is most prevalent in Florida (with an average of 70-100 storm days per year!) and the Rocky Mountains especially in the Colorado area (with an average of 70 storm days per year). In California and the Northern parts of the USA and Canada the likelihood of encountering lightning diminishes to about 10-30 storm days per year. Lightning is most common starting in the spring and ending in the fall with a large peak in the summer but it can occur at any time of the year.

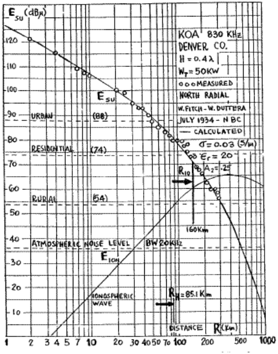
analysis, the author spends some time looking at the accuracy of *low-power SWR testers*. For the Autek RF-1, he reports *good accuracy* for loads from 12.5 to 200 Ohms. He also measures the SWR accuracy of the MFJ-259, and describes it as *very good* across the HF bands.]

Last update: Friday, May 07, 2004 01:40:39 PM



strength over the full range of distances of interest, including the previously troublesome intermediate distances.

And thus we have the short version of the history to achieve accuracy in field strength formulas. Stay tuned for the next installment, a program to calculate field strength, based on a simplified formula.




Original measured vs. calculated f/s values for KOA, Denver, 1934 compendium was available. Dan's article, *T-Time for the Analyzers*, is on page 40 of the compendium. Dan has made a number of other contributions in the area of transmission line analysis. Please see [his site] for more information.

[Epilogue 1 - The ARRL Antenna Compendium #5 has an article entitled: *Measuring Antenna SWR and Impedance*, by Francis Merceret, WB4BBH, on page 148. The author was initially looking into the reliability of SWR measurements. One way to measure SWR is to compute it from the so-called *forward* and *reflected* power. The popular *cross needle* power meter places two meter movements and two indicators in one meter case. One indicates the forward power, and other other the reverse. The intersection of the indicator lines define a point which reveals the SWR, which is indicated on a third scale. I have always found these meters a little difficult to read, and the author indicated that some models do not have high accuracy. Their strong point, in my opinion, is that they can be left in line while transmitting at full power. For purposes such as adjusting an antenna tuner for minimum SWR, these sort of meters are probably very appropriate. I just wouldn't take the SWR value too seriously, especially as it rises. The author also considered an inexpensive noise bridges and one antenna analyzer, the Autek RF-1. His conclusion is: *My results indicate that SWR bridges often do not measure capacitive loads or high SWR values accurately. I found that a noise bridge is more accurate, but that it is also much more difficult to use. The most accurate and easiest instrument to use is a modem, microprocessor-based "RF analyzer"*. When is uses the term *SWR bridges*, he is referring to the power meters that also measure SWR.]

[Epilogue 2 - The ARRL Antenna Compendium #5 has an article entitled: *Baluns in the Real (and Complex) World*, by Frank Witt, AI1H, on page 171. As part of doing some balun measurement discrepancies were due to sloppy measurement techniques.

My Excel spreadsheet data and graphs can be downloaded as Analyzers.xls

Some folks have commented that my results appear to show much more accuracy in these meters than they expected. I think that there are at least two reasons for this. First, it's very easy to introduce errors due to poor measurement technique, primarily excessive lead length. I certainly made several *lousy* measurement runs and had to continue to try to improve the quality of my test fixture. Another reason is that I was measuring what I would call a *shielded system* - a handful of resistors connected to a rather short length of transmission line sitting on my test bench The more common application for an antenna analyzer is to measure, *antennas*. Antennas are designed to pick up signals, and this can include RF from nearby sources. This RF, when presented to the antenna analyzer, can upset the reading. The W8JI calibration page discusses this issue in more detail. A common problem is trying to measure the impedance of a 160 meter vertical when you live a few miles away from an AM broadcast station. I have seen this problem also arise on a 15 meter monoband Yagi. The usual solution is to filter the signal before applying it to the analyzer, keeping the undesired signal out of the analyzer. This must be done carefully, however, since the filter itself can act as an impedance transformer. Some specialized devices exist to filter while not altering the impedance. The MFJ-731 is an example.

ARRL Antenna Compendium #7 has an article by Dan Maguire, AC6LA, which largely duplicates the work on this page. Dan and I worked independently, and we happened to exchange emails after I had finished my page, but before the



## RF Basics

Martin D. Stoehr
PMTS, ISM-RF Strategic Applications
http://pdfserv.maximintegrated.com/en/an/AN5300.pdf

### Introduction

Radio frequency (RF) can be a complex subject to navigate, but it does not have to be. If you are just getting started with radios or maybe you cannot find that old reference book about antenna aperture, this guide can help. It is intended to provide a basic understanding of RF technology, as well act as a quick reference for those who “know their stuff” but may be looking to brush up on that one niche term that they never quite understood. This document is also a useful reference for Maxim’s products and data sheets, an index to deeper analysis found in our application notes, and a general reference for all things RF.

History (How Do We Know What We Know?)
“If I have seen a little further, it is by standing on the shoulders of Giants.”
–Isaac Newton

The wireless radio technology that is so ubiquitous today is relatively new. However, there is a long and rich background that leads to our modern knowledge. The very first investigations of what we now call the RF spectrum came from early experiments in optics, electricity, and magnetism. The behavior of light was studied as far back as ancient Greece by Plato, Euclid, Ptolemy, and many others, eventually leading to Newton in the late 17th Century. From ancient triboelectric materials and chemical batteries, various theories of electricity were eventually developed by Coulomb, Volta, and Gauss. Likewise, lode stones from ancient China birthed early theories for magnetism from Kuo and Gilbert, eventually propelling the investigations of Ampere and again, Gauss.

Before the early 19th Century, electricity and magnetism were seen as separate forces. However, in 1820 Ørsted found that electric currents exerted a force on magnets, and in 1831 Faraday determined that changes in a magnetic field could induce electrical currents. In 1839, further experiments in electricity led Faraday to show that voltaic electricity (chemical battery), static electricity (triboelectric charge), and magnetically induced currents were all manifestations of the same phenomenon. In 1864, Maxwell combined these discoveries in his paper, "A Dynamical Theory of the Electromagnetic Field,"[2] ushering in our modern understanding of the subject:

Gauss's Law relates electric charge to its electric field: $\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$. The divergence of the electric field is related to the charge density.

Gauss's Law for Magnetism states that magnetic monopoles do not exist: $\nabla \cdot \mathbf{B} = 0$. The divergence of the magnetic field is zero or there is no net magnetic flux entering or leaving a volume.

Faraday's Law of Induction and the Maxwell-Faraday equation state that a changing magnetic field induces an electric field: $\nabla \times \mathbf{E} = -\frac{\partial B}{\partial t}$. The curl of the electric field is related to the change in magnetic flux density.

Ampere's Circuital Law, modified by Maxwell to include displacement current, relates the magnetic field to a current in



This gives me the convenience of the analyzer with a hopefully higher accuracy. I have built several RF networks using this technique, and the results are very accurate.

Conclusion

All of the analyzer plotted results followed the shape of the equivalent computed curve. They are clearly trying to do the job, and in most cases, come darn close. Most of the errors in my data appear in regions of large value swings. This would tend to make the test very sensitive to even slight errors on my part. I tend to consider the regions of the data where the curve is relatively flat over several megahertz. This will reduce the sensitivity to test fixture errors. In most cases, the errors seem to be no more than 5 Ohms. Errors also seem to increase as frequency increases, which could be nothing more than additional testing error.

If I miscalculated the true frequency where the cable was 1/2 wavelength, that would also slightly skew the two curves, creating additional error in the regions of large transitions.

If you use excessive test lead length, you will certainly introduce as much error as any error already in the analyzer. Perhaps the biggest lesson I learned in testing for this page was to keep lead length as short as possible. The next lesson was to use new batteries, or better yet, a beefy power supply with plenty of voltage and current.

I do hope that the next generation of analyzers will accurately resolve the sign of the reactance, and have increased accuracy around zero Ohms. For my recent applications, that would be very helpful. Frankly, I expected the errors to be much greater than I measured. I suspect that many of my unexplained

All of the analyzers are sensitive to low battery voltage. For consistency sake, use an external power supply, or fresh batteries. The MFJ-269 and CIA-HF units have a high current draw, apparently due to the power consumed by the low distortion oscillator. Batteries seem to last substantially longer in the RF-1.

I measured the current drain on the MFJ-269 and the CIA-HF at approximately 225 mA. When the MFJ-269 is placed in UHF mode, the current draw does increase by another 150 mA. If you are going to power one of these analyzers from a *wall wart*, be sure that you have at least a 500 mA supply. Make sure that the external power supply has very low ripple and noise.

## Improving Measurement Accuracy

The only technique that I have developed that improves accuracy is in the area of component measurement. I use a more accurate RF bridge to measure a given capacitor and inductor with the highest accuracy that I have available to me. This is a slow process due to the operation of the bridge, and the need for additional compensation computations.

Once I have these measurements, I measure the same components with an analyzer, and determine a simple scaling factor between the two units. I do this for a single amateur band. I then work exclusively with the analyzer, measuring inductors and capacitors with the use of the scaling factors. I move the test leads from the analyzer to the bridge before I make its measurements so that any lead inductance is folded into the scaling factor.



a wire: $\nabla \times B = \mu_0\left(J + \varepsilon_0 \frac{\partial E}{\partial t}\right)$. The curl of the magnetic flux density is related to the current density and the change in the electric field.

These four concepts formed the basis of electrodynamics or modern-day electromagnetic (EM) theory, and are referred to as Maxwell's Equations. Maxwell had unified the theories of electricity, magnetism, and optics and started the first ventures into electromagnetic-based communication.

The late 19th and early 20th Centuries saw the birth of the electrical and electromagnetic era. Continuing from Maxwell's work, Hertz, Tesla, and Marconi contributed to EM theory and early forms of practical instruments of communication. In 1887, Hertz showed that an EM wave could travel distances with a basic spark-gap transmitter and spark-gap receivers, and later linked the velocity of those waves to the speed of light. In 1891, Tesla demonstrated wireless power transmission, demonstrated wireless telegraphy in 1893, and filed for the first U.S. patent for a radio in 1897. Likewise, in 1901 and 1902 Marconi began demonstrating trans-Atlantic communication with the first example reaching from England to Newfoundland (nearly 3500km), using a kite-flown antenna.

Just as the theories behind EM communication progressed quickly, radios have also developed at an astounding rate. Wireless telegraphs first appeared in the early 1900s, and developed into the AM radio broadcasts of the 1920s. FM broadcast radio picked up with commercial backing in the 1940s. Satellite communication was quickly adopted after the launch of Sputnik in 1957. With the launch of the Telstar and others in the early '60s, the use of satellites for relay communication progressed quickly. Through the late '60 and '70s, satellites took on larger loads of long-distance communication until submarine cables rebounded with the use of fiber optics in the ’80s. Modern satellites still bear a great burden of media transmission, especially after the emergence of direct broadcast satellite services for television and other broadband media. Ground-based RF communication also progressed from simple numeric pagers in the 1980s, to cellular phones, and eventually the establishment of the ISM bands in 1985 led to our now ubiquitous use of Wi-Fi. These names and technologies mentioned above should be very familiar—these are the giants upon which we stand today.

**What Is RF?**

RF signals are a form of electromagnetic wave, such as visible light, which make up a portion of the electromagnetic (EM) spectrum. The EM spectrum encompasses all forms of light, which ranges from audible frequencies such as the ubiquitous 60Hz, through the standard radio bands which include AM Radio, FM Radio, TV channels, and other RF bands. The spectrum continues through infrared, visible, and ultra-violet light, to higher forms of EM energy like X-rays, Gama-rays, and cosmic rays.

What we refer to as the Radio or RF spectrum is between the low-frequency waves that we could hear if the EM waves were turned into air pressure waves (20Hz to 20kHz) and the high-frequency EM waves that produce infrared and visible light (1mm to 750nm for IR and 750nm to 390nm for visible (or about 400THz to 770THz)).

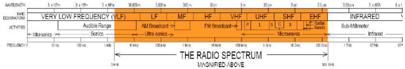



Figure 1. Radio frequency spectrum[5]



CIA-HF will not even report capacitance or inductance if the phase angle is -90 or 90. You must use special test leads. The other analyzers do not specify any special test leads.

| Pure Capacitive Reactance Test at 3.8 MHz (pf) | | | |
|---|---|---|---|
| pf | MFJ-269 | CIA-HF | RF-1 |
| 143 | 148 | 157 | 147 |
| 215 | 220 | 232 | 220 |
| 430 | 449 | 472 | 438 |
| 860 | 921 | 972 | 918 |
| 1290 | 1396 | 1500 | 1432 |

All measurements were made at 3.8 MHz.

The CIA-HF is *picky* about making capacitance and inductance measurements. The impedance angle must be within a certain range that appears to be approximately 70 degrees. I had to increase the resistance of the test leads in order to make the measurements at 143 and 215 pf.

Because of my limited supply of the 430 pf capacitors, and the need to rearrange them in several series/parallel combinations, I had to use about 4 inches of wire to make the connections. I have no doubt that this influenced the readings. The added inductance should lower the capacitive reactance, which increases the pf value. Since the errors all appear to be on the high side, this extra wire may be the issue.

In any case, the accuracy is within 10 percent, and perhaps much better if the lead length influenced the readings. The lead length issue was worse on the CIA-HF because it does not have a ground lug near the UHF connector.

The Effect of Battery Voltage and Current may not know the difference between capacitive and inductive reactance. It knows what to convert to (C or L) based upon the mode you have selected.

Measuring components is also different than general antenna/transmission line impedance measurement because the resistive component is zero, or very nearly zero. All that is being measured is a pure reactance. This is the opposite test to what was performed in the previous section, where pure resistances were measured. It is also the case that typical reactance values may be several hundred Ohms, as opposed to antenna measurements (especially vertical antennas), where resistance and reactance are usually each under 50 Ohms (near resonance).

I again visited the junk box, and found several 430 pf silver-mica capacitors that were labeled as being 1% tolerance. I connected these three parts into several series and parallel combinations in order to create a set of expected values. It is my belief and understanding that these analyzers measure reactance, without directly knowing the type of reactance, and then convert that into units of capacitance of inductance depending upon frequency and the readout (capacitance or inductance) selected by the user. If the reactance accuracy is not a function of the reactance sign, then the accuracy in measuring inductors and capacitors will be the same. In any case, I do not have any *precision inductors*, so I can't make absolute measurements.

The CIA-HF manual suggests that you measure components using test leads that include a 50 Ohm series resistor. In fact, they suggest that the accuracy of the component measurement will be greatest when the phase angle of the impedance is 45 degrees. In the absence of any resistance, the phase angle will be (nearly) -90 or +90 degrees, which is not 45 degrees. The



This RF spectrum (shown in Figure 1) is further divided into conventional bands, which are typically classified by their frequency range and broken across decades. For example, the 300MHz to 3GHz range is called the UHF band (designated by the International Telecommunication Union (ITU)). In the UHF, SHF, and EHF bands, organization such as the IEEE and NATO tend to break the bands up into smaller categories.

Table 1. RF Spectrum Bands:

| Name | ELF | SLF | ULF | VLF | LF | MF |
|---|---|---|---|---|---|---|
| f (Hz) | $3x10^0$ – $3x10^1$ | $3x10^1$ – $3x10^2$ | $3x10^2$ – $3x10^3$ | $3x10^3$ – $3x10^4$ | $3x10^4$ – $3x10^5$ | $3x10^5$ – $3x10^6$ |
| λ (m) | $10^8 – 10^7$ | $10^7 – 10^6$ | $10^6 – 10^5$ | $10^5 – 10^4$ | $10^4 – 10^3$ | $10^3 - 10^2$ |
| Uses | NA | AC power | NA (audible) | Navigation | Maritime | AM radio |

<table>
<tr><th>Name</th><th>HF</th><th>VHF</th><th>UHF</th><th>SHF</th><th>EHF</th><th>Infrared</th></tr>
<tr><td>f (Hz)</td><td>$3x10^6$ – $3x10^7$</td><td>$3x10^7$ – $3x10^8$</td><td>$3x10^8$ – $3x10^9$</td><td>$3x10^9$ – $3x10^{10}$</td><td>$3x10^{10}$ – $3x10^{11}$</td><td>$3x10^{11}$ – $4x10^{14}$</td></tr>
<tr><td>λ (m)</td><td>$10^2 – 10^1$</td><td>$10^1 – 10^0$</td><td>$10^0 – 10^{-1}$</td><td>$10^{-1} – 10^{-2}$</td><td>$10^{-2} – 10^{-3}$</td><td>$10^{-3} – 7.5x10^{-7}$</td></tr>
<tr><td>IEEE</td><td>HF</td><td>VHF</td><td>UHF | L | S</td><td>S | C | X | Ku | K | Ka</td><td>Ka | V | W | mm</td><td></td></tr>
<tr><td>NATO</td><td></td><td></td><td>A – E</td><td>F – K</td><td>K – M</td><td></td></tr>
<tr><td>Uses</td><td>Shortwave, CB</td><td>TV, FM radio</td><td>ISM, TV, Wi-Fi®</td><td>Microwave</td><td>Radar</td><td>“Light”</td></tr>
</table>

In the United States, the Federal Communications Commission (FCC) is the governing body that manages the RF spectrum allocation and permissible uses. The role of the FCC and its foreign equivalents is necessary to provide central organization of this limited resource and to establish a framework that allows for compatible operation of the many and varied radio frequency systems. Without these regulating bodies, anyone would be able to broadcast without regard to frequency, power, bandwidth, or duty cycle—overpowering competitive and noncompetitive uses alike. This could result in monopolizing the airwaves and would possibly interfere with essential forms of command, control, and communication. For more information on how ISM radios are governed by FCC and ETSI regulations, refer to application note 1772, “Where to Go for Regulations Concerning Short-Range Devices (SRD)” and application note 3587, "FCC and ETSI Requirements for Short-Range UHF ASK-Modulated Transmitters."

## RF Glossary

### Amplitude and Power

V – Voltage: In RF systems, the voltage of a signal is typically referenced to a 50Ω load.

P – Power: In an RF system, power is typically referenced to a 50Ω load.

$P = VI = \frac{v^2}{R}$ or in a 50Ω system $P = \frac{v^2}{50}$

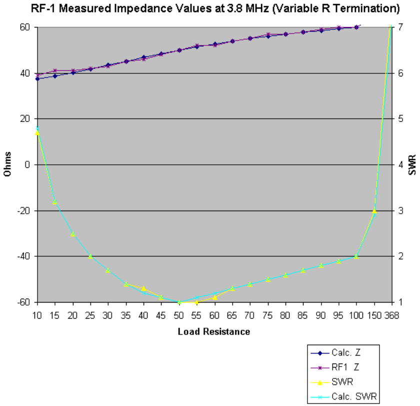
dB – Decibels: This is a unitless ratio measure (similar to %) typically used in RF systems when discussing power. The ratio "dBm" is more common in RF applications where the "m" refers to using 1mW as the referenced point. The difference between a 1W reference point (dBW) and 1mW reference point (dBm) is 30dB, that is: dBm = dBW + 30dB. When referring to voltage levels, dB is used to represent a ratio such as an output amplitude to an input amplitude.

$$L(dB) = 10 \cdot log_{10}\left(\frac{V_{Out}}{V_{In}}\right)$$

When used in RF applications, the dB is usually a power ratio based on a voltage gain.

$$G(dB) = 10 \cdot log_{10}\left(\frac{50 \cdot {V_{Out}}^2}{50 \cdot {V_{In}}^2}\right) = 20 \cdot log_{10}\left(\frac{V_{Out}}{V_{In}}\right)$$



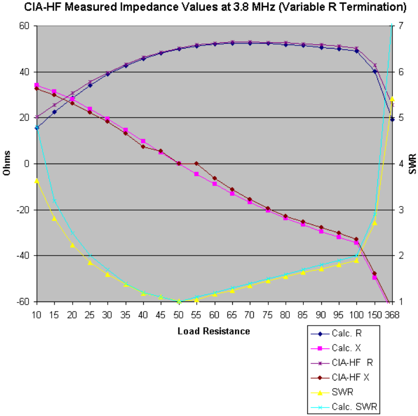



RF-1 Response at 3.8 MHz with a Complex Input
Very good for a tiny little box.

Component Measurements

Another common use of these analyzers is to measure the values of inductors and capacitors. Unlike the typical RLC (resistance, inductance, capacitance) meter, which measures at a fixed frequency, such as 1 MHz, these analyzers will make their measurements at the intended frequency of operation. It is usually the case that the analyzer measures nothing more than reactance, and then converts that into capacitance or inductance using the standard formulas. In fact, the analyzer

Very accurate tracking. Since the frequency is being held at 3.8 MHz, the deviation at higher resistances is not due to frequency. The gap does appear to be real, since the values are rather stable in this region.




CIA-HF Response at 3.8 MHz with a Complex Input

Something a little strange happened around zero reactance again. Otherwise, very close tracking.



Table 2. Power Levels in Different Units

| W | dBW $10 \cdot \log_{10}(P)$ | dBm $10 \cdot \log_{10}(1000 \cdot P)$ | V $\sqrt{50P}$ (w/ 50Ω) |
|---|---|---|---|
| 1.000 | 0 | +30 | 7.071 |
| 0.032 | -15 | +15 | 1.257 |
| 0.020 | -16.990 | +13.010 | 1.000 |
| 0.010 | -20 | +10 | 0.707 |
| 0.003 | -25 | +5 | 0.397 |
| 0.001 | -30 | 0 | 0.224 |
| 316.2µW | -35 | -5 | 0.126 |
| 100µW | -40 | -10 | 0.071 |
| 0.1nW | -100 | -70 | 70.71µV |
| 0.1pW | -130 | -100 | 2.236µV |
| 10fW | -140 | -110 | 0.707µV |
| 1fW | -150 | -120 | 0.224µV |
| 4.142E-21 (kT at 300K) | -203.8 | -173.8 | 0.455nV |

In addition to dBW and dBm, occasional use of other forms of decibels may appear. In all instances, these additional letters indicate what the base unit of reference may be: dBc is carrier referred, dBi is the gain over an isotropic antenna, and dBd is the gain over a dipole antenna.

## Field Strength

V/m – Volts per meter: This is a typical measure used for electrical field strength. It is often more common to see values with higher resolution units such as mV/m or µV/m. These measurements are subject to reference antenna gains at the TX and RX portions of the system, the fields are measured at 3m distance (FCC specified7), and are dependent upon the operating frequency (refer to application note 3815, “Radiated Power and Field Strength from UHF ISM Transmitters” for more information).

FCC field strength: for the ISM bands, the FCC defines a maximum field strength based on a linear extrapolation from the defined band end points of 3.750mV/m at 260MHz to 12.5mV/m at 470MHz7, Section 15.231. To calculate this maximum value for frequencies between 260MHz and 470MHz, use the equation:

$$E = \frac{8.75}{210} f - 7.08\overline{3}$$

Where E is the field strength (in mV/m), and f is the frequency of operation (in MHz). For any frequencies above 470MHz and under 900MHz, the FCC caps the Field Strength at 12.5mV/m. In the 902MHz to 928MHz band, the field strength limit is 500mV/m. For unit translation of E(mV/m) to E(dBuV/m) the equation is: $E = 20 \cdot log_{10}(1000 \cdot E)$

EIRP – Effective isotropic radiated power: This is a term that merges the power generated by a transmitter with the efficiency of an antenna into one term $(EIRP = P_T G_T)$. Typically these two items can be broken into the TX power (PT) and the gain of a transmitting antenna, GT(Θ,Φ). However, the antenna gain can be highly dependent on orientation, being a function of Θ (planar angle) and Φ (elevation angle) as noted. To remove these dependencies, the antenna gain can be simplified to a gain relative to an isotropic radiator, which by definition is uniform for any orientation.

To translate from Field Strength to the EIRP, use the FCC-specified equation:

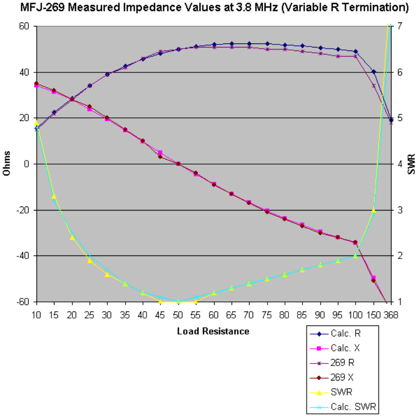
$$EIRP = 10 \cdot log_{10}(300 E^2)$$

Where EIRP is the effective isotropic radiated power (dBm) and E is the field strength (V/m). This equation assumes the field is calculated at a distance of 3m from the radiated power source.



| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 150 | 40.22 | -49.56 | 2.9 | 34 | -51 | 3 | 42.8 | -47.7 | 2.72 | 65 | 3 |
| 368 | 19.16 | -64.72 | 7.2 | 18 | -64 | 8 | 25.5 | -63.1 | 5.41 | 69 | 7.6 |

As before, the sign of the reactance was taken from the computed data. For each analyzer I created a graph comparing it to the computed values, for impedance and SWR. The Autek graph, as before, is compared against aggregate impedance, since it does not resolve Z into R and X.




MFJ-269 Response at 3.8 MHz with a Complex Input

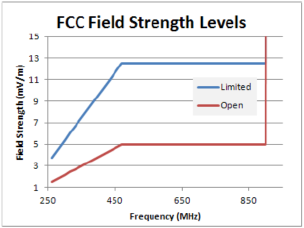
| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 25 | 34.21 | 23.89 | 2 | 34 | 25 | 1.9 | 35.6 | 22.2 | 1.86 | 42 | 2 |
| 30 | 38.87 | 19.35 | 1.7 | 39 | 20 | 1.6 | 39.5 | 18.4 | 1.6 | 43 | 1.7 |
| 35 | 42.74 | 14.55 | 1.4 | 42 | 15 | 1.4 | 43.1 | 13.2 | 1.38 | 45 | 1.4 |
| 40 | 45.83 | 9.64 | 1.2 | 46 | 10 | 1.2 | 46.3 | 7.4 | 1.19 | 46 | 1.3 |
| 45 | 48.23 | 4.76 | 1.1 | 49 | 3 | 1 | 48.4 | 5.4 | 1.11 | 48 | 1.1 |
| 50 | 50.00 | 0.00 | 1.0 | 50 | 0 | 1 | 50.2 | 0 | 1.01 | 50 | 1 |
| 55 | 51.23 | -4.57 | 1.1 | 51 | -4 | 1 | 51.8 | 0 | 1.05 | 52 | 1 |
| 60 | 52 | -8.91 | 1.2 | 51 | -9 | 1.2 | 52.5 | -6.4 | 1.17 | 52 | 1.1 |
| 65 | 52.38 | -13 | 1.3 | 51 | -13 | 1.3 | 53 | -11.3 | 1.25 | 54 | 1.3 |
| 70 | 52.45 | -16.81 | 1.4 | 51 | -15 | 1.4 | 53.1 | -15.4 | 1.35 | 55 | 1.4 |
| 75 | 52.27 | -20.34 | 1.5 | 50 | -21 | 1.5 | 52.6 | -19.5 | 1.46 | 57 | 1.5 |
| 80 | 51.89 | -23.61 | 1.6 | 50 | -24 | 1.6 | 52.6 | -22.9 | 1.55 | 57 | 1.6 |
| 85 | 51.35 | -26.63 | 1.7 | 49 | -27 | 1.7 | 52.2 | -25.3 | 1.64 | 58 | 1.7 |
| 90 | 50.69 | -29.41 | 1.8 | 48 | -30 | 1.8 | 51.9 | -27.6 | 1.71 | 59 | 1.8 |
| 95 | 49.94 | -31.96 | 1.9 | 47 | -32 | 1.9 | 51.2 | -30.3 | 1.81 | 60 | 1.9 |
| 100 | 49.12 | -34.3 | 2 | 47 | -34 | 2 | 50.4 | -32.9 | 1.9 | 60 | 2 |



Table 3. Field Strength

| f(MHz) | FCC Field Strength (mV/m) | Field Strength (dBµV/m) | EIRP (dBm) |
|---|---|---|---|
| 260 | 3.750 | 71.5 | -23.7 |
| 300 | 5.417 | 74.7 | -20.6 |
| 315 | 6.042 | 75.6 | -19.6 |
| 330 | 6.667 | 76.5 | -18.8 |
| 434 | 11.000 | 80.8 | -14.4 |
| 435 | 11.042 | 80.9 | -14.4 |
| 470 | 12.500 | 81.9 | -13.3 |
| [868] | 12.500 | 81.9 | -13.3 |
| 902 | 500 | 114 | +18.8 |
| 915 | 500 | 114 | +18.8 |
| 928 | 500 | 114 | +18.8 |

Per FCC Part 15.231, average field strength limits $G_T$ = 0dB, and d = 3m.




Per FCC Part 15.231, average field strength limits are restricted based on low-rate periodic operation (limited) or higher-rate periodic and "prohibited" uses (open).

The CIA-HF and RF-1 did a good job of measuring pure resistance, especially at values under 150 Ohms. The MFJ-269 always showed nonzero reactance, except at 50 Ohm of resistance. Practically, most antenna work does not require measuring resistance above 150 Ohms, unless open wire feeders are used.

I checked some of the resistances at other frequencies, up to 30 MHz. All of the analyzers were insensitive to frequency, and produced values nearly identical to their values at 3.8 MHz.

I then used the Lowband software to compute the complex impedance at the input of the cable when the load was set to various resistances. I connected a small noninductive trimmer pot directly to a coax connector, and set it to the different resistance values with the aid of my DMM. For each setting, I recorded the values displayed by each analyzer. Here is the data table. All values are measured in units of Ohms, except SWR, which is dimensionless.

| Complex Impedance Test at 3.8 MHz (Ohms) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Set | Lowband Computed | | | MFJ-269 | | | CIA-HF | | | RF-1 | |
| R (Load) | R (Input) | X (Input) | SWR | R | X | SWR | R | X | SWR | Z | SWR |
| 10 | 15.67 | 34.19 | 4.8 | 15 | 35 | 4.9 | 20.3 | 32.7 | 3.63 | 39 | 4.7 |
| 15 | 22.63 | 31.5 | 3.2 | 22 | 32 | 3.3 | 25.6 | 29.9 | 2.81 | 41 | 3.2 |
| 20 | 28.75 | 28 | 2.5 | 28 | 28 | 2.4 | 30.8 | 26.2 | 2.24 | 41 | 2.5 |

capacitors. We can continue to use our same piece of coax, but vary the pure resistance at the load, creating a range of complex impedance values at the input (analyzer) side. The same software previously used can be reused to compute the expected impedance values. We won't have arbitrary control over our complex impedance values, but we can at least generate values that we have some confidence in.

In the upcoming tests I'm going to hold the frequency constant at 3.8 MHz. For my current application, I'm most interested in measurements in the 160, 80, and 40 meter bands. 3.8 MHz is a representative value somewhat in the middle of the range from 1.8 MHz to 7.3 MHz.

Perhaps the simplest test is to use the analyzer as an RF resistance meter. In other words, directly connect a pure resistance to the meter and see what value is reported. Using a standard DMM, I measured a set of resistors and then tested them with the analyzers. Here are the results.

| Pure Resistance Test at 3.8 MHz (Ohms) | | | |
|---|---|---|---|
| Resistance | 69 | CIA-HF | RF-1 |
| 17.2 Ohms | 16, j 2 | 15.7, j 0 | 17 |
| 25.4 Ohms | 24, j 2 | 24.7, j 0 | 25 |
| 33.5 Ohms | 32, j 4 | 33.6, j 0 | 33 |
| 50.8 Ohms | 49, j 0 | 50.7, j 0 | 51 |
| 99.8 Ohms | 97, j 13 | 98.8, j 0 | 99 |
| 151.2 Ohms | 147, j 21 | 148.8, j 0 | 148 |
| 385.2 Ohms | 358, j 116 | 380.0, j 0 | 375 |
| 680.0 Ohms | 586, j 281 | 648.5, j 0 | 660 |

I happened to have 50 and 25 termination loads. These are completely enclosed termination resistors with an integrated BNC connector. Their actual measured values are shown in the table. The 17.2 Ohms resistor is their parallel combination, using BNC "Tee" connectors.



**RF Field Strength**
by Kenneth A. Kuhn
Jan, 6, 2008 (draft –more to come)
http://www.kennethkuhn.com/students/crystal_radios/rf_field_strength.pdf

**Introduction**

The process of building a crystal radio begins with the transmitter. Without the transmitter there would be no point in building the radio.

AM Broadcast stations in the United States operate at 10 kHz intervals between 540 kHz and 1,700 kHz using double sideband amplitude modulation with a modulation bandwidth of 5 kHz (10 kHz total channel width) and a transmitted power ranging from around 1 kW to 50 kW. The broadcast antenna is generally some form of a one-quarter to over one-half wave vertical tower (the entire tower is the antenna) with numerous onequarter wave ground radials. A quarter-wave antenna at 540 kHz would be around 139 meters high!

A quarter-wave antenna is attractive because it has a low resistive (i.e. no reactive component) impedance of around 35 ohms. For a 50 kW transmitter the applied voltage to the antenna would be around 1,300 volts rms! This impedance is not the resistance of the tower –that needs to be as low as possible for high efficiency. The impedance of the antenna is the result of the fact that power leaves the antenna as a result of radiated electromagnetic fields –that is the purpose of the antenna.

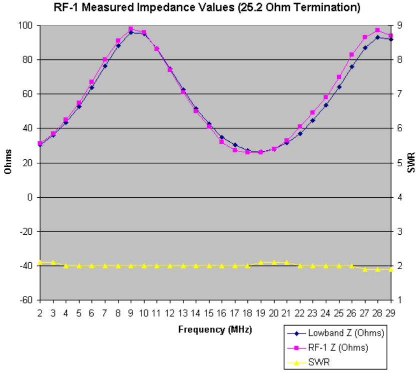
If the electrical length of the antenna is not a quarter wave then there is a reactive component in the antenna impedance. This reactance is in the way of coupling power to the antenna.

Various tuning schemes can eliminate the net reactance. Antenna designers are interested in maximizing the strength of the electromagnetic field emitted from the antenna. They also have to deal with other limitations such as maximum allowed antenna height, electrical characteristics of the soil around the antenna, and other factors. For these reasons the electrical height of the antenna may deviate from the seemingly ideal one-quarter wave. The result is an antenna that optimizes the broadcast range of the transmitter. Tuning networks can compensate for any antenna reactance.

The signal strength some distance from the transmitting tower is commonly measured in volts per meter. There is a corresponding current measured in amperes per meter obtained by dividing volts per meter by the impedance of free space, 377 ohms. There is no power dissipated in free space as the voltage and current are physically orthogonal. The voltage per meter is a cyclic gradient and is only meaningful over distances that are short (roughly 20 electrical degrees) with respect to a wavelength. Short antenna probes can measure this voltage. Amperes per meter is also a cyclic gradient and is a bit more difficult to visualize as it represents a magnetic field that would exist in response to an actual current. There is no actual current in free space which is an electrical insulator. The magnetic field can be measured using small (with respect to a wavelength) loop antenna probes in which a current is induced.

Thus, electromagnetic radiation is a combination of a cyclic voltage field and an orthogonal cyclic magnetic field. Either alone is just induction as opposed to radiation. As fields spread, the strength of an electromagnetic wave follows a one over distance law. Induction fields follow a one over distance cubed law. Thus, induction fields are useful only for very short distances.






RF-1 Frequency Sweep Data

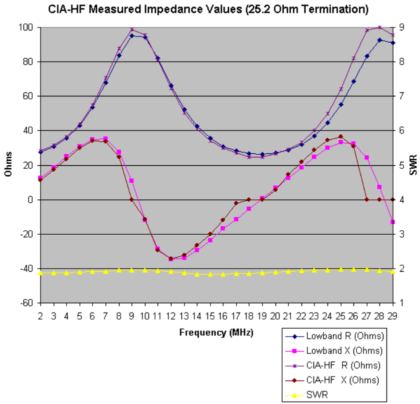
Since the RF-1 only reports impedance (Z), I took the original Lowband data and converted R and X to Z, using the standard formula ($Z = SQRT(R^2 + X^2)$). This derived data is available on the spreadsheet file which can be downloaded at the end of this page.

Impedance at a Constant Frequency

If we want to hold the analyzer at a constant frequency, but yet test its SWR and impedance accuracy, we simply must present it with a range of impedance inputs. We could certainly wire up combinations of resistors and inductors/capacitors, creating reference standards. This approach is complicated by the difficulty of obtaining accurate reference inductors and

CIA-HF

The following graph displays the recorded data when the frequency was swept from 2 through 29 MHz, and the CIA-HF was connected to the test coax with a 25.2 Ohm resistive load.




CIA-HF Frequency Sweep Data

The CIA-HF results are remarkably similar to the MFJ-269 results, although something a little strange seems to happen when the reactance is near zero.

RF-1

The following graph displays the recorded data when the frequency was swept from 2 through 29 MHz, and the RF-1 was connected to the test coax with a 25.2 Ohm resistive load.



In order to engineer a crystal radio we need to know the expected electromagnetic field strengths we intend to receive. Those strengths must be above some minimum or we will hear nothing in our headphones. Data is readily available that gives us a reasonable expectation of the amplitude of a radio wave in terms of volts per meter at a given distance from the broadcast antenna. We must understand not to interpret such data too literally as there are always variables related to terrain and various structures that will affect the data –mostly negatively but sometimes positively.

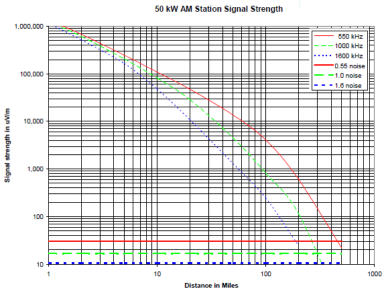


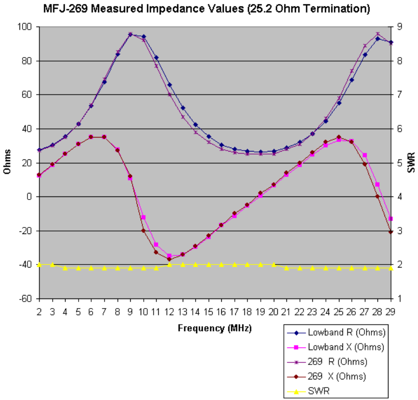

Figure 1: Signal strength with distance adapted from Reference Data for Radio Engineers, Howard W. Sams, Inc. sixth edition, pages 30-3 to 30-5

Figure 1 shows typical signal strengths for a 50 kW station during daylight hours. The voltages will be about one-third for a 5 kW transmitter. The increased drop-off with distance is due to the curvature of the earth and varies at night and with weather conditions so a significantly greater range is possible at times. The typical atmospheric noise level for a 10 kHz bandwidth is also shown although this can vary significantly with location and season. Excellent reception is when the signal strength is 100 times the noise level. Poor, but usable, reception is when the signal strength is around 5 times the noise level. The noise floor is only shown for reference. Crystal radios are typically so insensitive that the minimum usable signal is around 1000 times the noise floor.



MFJ-269

The following graph displays the recorded data when the frequency was swept from 2 through 29 MHz, and the MFJ-269 was connected to the test coax with a 25.2 Ohm resistive load.




MFJ-269 Frequency Sweep Data

This graph captures the impedance results, as well as the SWR. This is true for all three analyzers. The SWR trace is shown in yellow, and its values are labeled on the right. Ideally, the SWR would be a nearly horizontal line, at the 2.0 value. The MFJ-269 only displays whole number values.

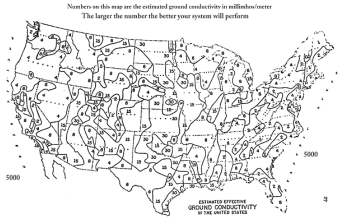
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 6 | 54 | 35 | 1.9 | 55 | 34 | 1.91 | 67 | 2.0 |
| 7 | 69 | 35 | 1.9 | 70.5 | 33.6 | 1.92 | 80 | 2.0 |
| 8 | 85 | 27 | 1.9 | 87.7 | 24.6 | 1.95 | 91 | 2.0 |
| 9 | 96 | 12 | 1.9 | 98.6 | 0 | 1.96 | 98 | 2.0 |
| 10 | 92 | -20 | 1.9 | 95.7 | -11.5 | 1.95 | 96 | 2.0 |
| 11 | 77 | -33 | 1.9 | 81.4 | -29.5 | 1.94 | 86 | 2.0 |
| 12 | 60 | -37 | 2.0 | 64.6 | -34.4 | 1.91 | 74 | 2.0 |
| 13 | 47 | -34 | 2.0 | 50.5 | -32.3 | 1.88 | 61 | 2.0 |
| 14 | 38 | -29 | 2.0 | 40.9 | -26.7 | 1.84 | 50 | 2.0 |
| 15 | 32 | -23 | 2.0 | 34.1 | -20.1 | 1.84 | 41 | 2.0 |
| 16 | 28 | -17 | 2.0 | 29.8 | -12.1 | 1.83 | 32 | 2.0 |
| 17 | 26 | -10 | 2.0 | 27 | -2.3 | 1.85 | 27 | 2.0 |
| 18 | 25 | -5 | 2.0 | 24.5 | 0 | 1.86 | 26 | 2.0 |
| 19 | 25 | 2 | 2.0 | 24.5 | 0 | 1.87 | 26 | 2.1 |
| 20 | 25 | 7 | 2.0 | 26.8 | 5.7 | 1.89 | 28 | 2.1 |
| 21 | 28 | 14 | 1.9 | 29.1 | 14.4 | 1.92 | 33 | 2.1 |
| 22 | 31 | 20 | 1.9 | 33.3 | 21.7 | 1.93 | 41 | 2.0 |
| 23 | 37 | 26 | 1.9 | 40 | 28.8 | 1.95 | 49 | 2.0 |
| 24 | 46 | 32 | 1.9 | 50 | 34.4 | 1.96 | 58 | 2.0 |
| 25 | 58 | 35 | 1.9 | 64.2 | 36.6 | 1.97 | 70 | 2.0 |
| 26 | 74 | 32 | 1.9 | 82.2 | 30.8 | 1.98 | 83 | 2.0 |
| 27 | 89 | 19 | 1.9 | 98.5 | 0 | 1.97 | 93 | 1.9 |
| 28 | 96 | 0 | 1.9 | 100 | 0 | 1.94 | 97 | 1.9 |
| 29 | 90 | -21 | 1.9 | 95.5 | 0 | 1.91 | 94 | 1.9 |

I supplied the reactance sign in the 269 and CIA-HF columns, since the devices do not indicate the sign. I obtained the sign by looking at the computed expected values. The Autek meter only reports the total impedance, not the values of the separate components. The following three subsection graphs compare each analyzer with the computed results from the Lowband software.



**Field Strength Calculations**
Radio-Time Traveler

**PART I: Ground Conductivity**
http://radio-timetraveller.blogspot.com/2011/06/field-strength-calculations-ground.html
20 June, 2011




Ground (also called soil) conductivity plays a huge role in how far the mediumwave signal travels during the daytime. Lesser known to many, station frequency is also a factor, and maybe more of one than you would think. Though one can argue successfully that frequency is not a factor in the formula for calculating received signal strength, it indeed becomes relevant as you will see. In this series, let's explore ground conductivity and station frequency and see how they relate to "how far you can hear" on the mediumwave band during the daytime. We will end with a method to calculate approximate field strength for stations of interest.

Many years ago, ground conductivity measurements were compiled into a map titled "Estimated Effective Ground Conductivity in the United States" (Figure M3) by the FCC.

This map is used for the allocations planning for placement of MW stations in the United States. The map presents optimistic ground conductivities and is used when measured conductivity is not available. This information has been used and accepted since it was compiled in 1954.

Comparison of Conductivity and Surface Material Composition

| Surface Material Composition | Conductivity |
|---|---|
| Sea Water | 5000 mS/m |
| Pastoral Land, Rich Soils, River Bottoms, Low Hills | 30 mS/m – 10 mS/m |
| Pastoral Land, Densely Wooded | 8 mS/m – 2 mS/m |
| Pastoral Land, Medium Hills, Medium Forestation, Clay Soil | 6 mS/ m – 1 mS/m |
| Rocky Soil, Steep Hills, Sandy Soil | 2 mS/m – 0.1 mS/m |
| City Industrial Areas – Average Attenuation | 1 mS/m |
| City Industrial Areas – Maximum Attenuation | 0.1 mS/m |

Soil conductance is measured in siemens per meter but most generally shown in millisiemens per meter. This is the mS/m designation you see in the accompanying chart. The siemens (symbolized S) is the Standard International (SI) unit of electrical conductance. The old term for this unit is the mho (ohm spelled backwards). Conductance (mho) is of course the opposite of resistance (ohm). As you can see, salt sea water provides the best conductance by far (5000 mS/m). The higher the value the better. Average soil runs 6-8 mS/m. Find your location on the map and see what your local conductance value is. Notice also that a distant station's receive path may transition across more than one zone.



Indeed, for all pairs of values in the table, you end up with the same SWR. Here are those equations.

$$|\rho| = \sqrt{\frac{\left((R_a - R_0)^2 + X_a^2\right)}{\left((R_a + R_0)^2 + X_a^2\right)}} \qquad EQ.1$$

$$SWR = \frac{(1 + |\rho|)}{(1 - |\rho|)} \qquad EQ.2$$

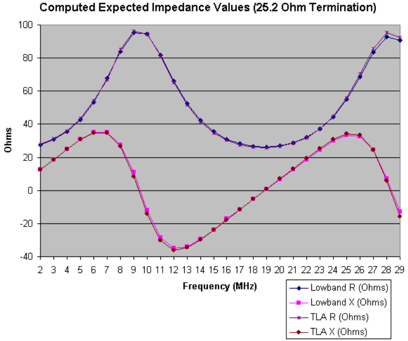
$$|\rho| = \frac{(SWR - 1)}{(SWR + 1)} \qquad EQ.3$$

Equations Relating Load Impedance to SWR

The third equation relates SWR back to the reflection coefficient (ρ). For an SWR of 2, the reflection coefficient is 0.333333... If you grind through EQ.1 with the values from the previous table, you will always end up with an answer very close to 0.333333... By the way, $R_a$ and $X_a$ are the load resistance and reactance. $R_0$ is the line impedance (50 Ohms). This equation only holds for low loss lines at low frequencies.

Getting back on track, here is the impedance and SWR data recorded from the three analyzers.

| Measured Impedance Values as a Function of Frequency | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | MFJ-269 | | | CIA-HF | | | RF-1 | |
| Freq. (MHz) | R (Ohms) | X (Ohms) | SWR | R (Ohms) | X (Ohms) | SWR | Z (Ohms) | SWR |
| 2 | 27 | 13 | | 28.3 | 11.1 | 1.88 | 31 | 2.1 |
| 3 | 30 | 19 | 2.0 | 31.7 | 17.4 | 1.88 | 37 | 2.1 |
| 4 | 35 | 25 | 1.9 | 36.6 | 23.6 | 1.87 | 45 | 2.0 |
| 5 | 43 | 31 | 1.9 | 43.8 | 29.8 | 1.89 | 55 | 2.0 |

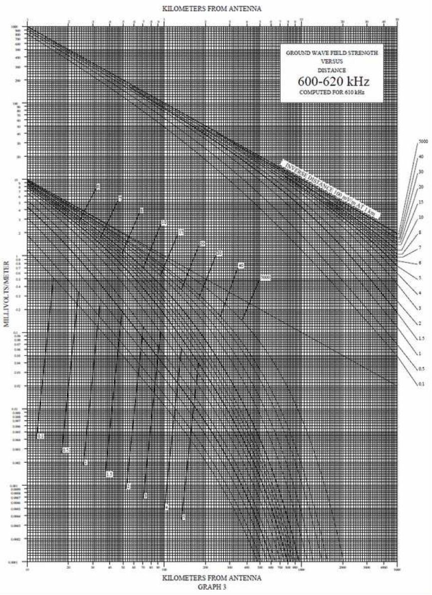



Lowband and TLA Computed Input Impedance

As the table and graph shows, the two different methods of calculating impedance diverge, especially at the extremes, but, in general they closely agree. For the purposes of future graphs related to the 2.0 SWR example, I will only compare against the Lowband data.

Here's a little diversion. You might ask yourself: *how can all of these different pairs of R and X values always result in an SWR of 2.0?* I certainly was interested in that question. The answer can be found on pages 24-6 through 24-9 of the ARRL Antenna Book, 18th Edition. Two formulae are needed. The first (EQ.1) takes the load resistance and reactance, and transmission line resistance, and computes the *magnitude of the reflection coefficient.* The second formula (EQ.2) converts the magnitude of the reflection coefficient into the SWR.






FCC Ground Wave Field Strength Versus Distance Graphs

ftp site for finding all field strength vs distance graphs from the fcc:
ftp://ftp.fcc.gov/pub/Bureaus/MB/Databases/AM_groundwave_graphs/

Equally important, the FCC also produces a series of charts known as the "Ground Wave Field Strength Versus Distance" graphs. These 20 graphs in .PDF form are grouped by mediumwave channels in the 540-1700 KHz range, and allow prediction of received signal strength by cross-referencing the distance to the receiving location with the ground conductivity factor between you and the station. These charts cover soil conductivity ranges of 0.1 mS/m to 5000 mS/m. They are still in use today. The only working link I have for them is:

Be sure to get the .PDF versions.

How well a mediumwave transmitter "gets out" is not only dependent on its power, frequency, and the ground conductivity between it and you, but also on the ground condition at its location. The following is a quote from the Standards of Good Engineering Practice Concerning Standard Broadcast Stations (550-1600 kc.), 1939, and is still relevant today:

"The ideal location of a broadcast transmitter is in a low area of marshy or 'crawfishy' soil or area, which is damp the maximum percentage of time and from which a clear view over the entire center of population may be had... The type and condition of the soil or earth immediately around a site is very important. Important, to an equal extent, is the soil or earth between the site and the principal area to be served. Sandy soil is considered the worst type, with glacial deposits and mineral-ore areas next. Alluvial, marshy areas and salt-water bogs have been found to have the least absorption of the signal."



| | | | | | | |
|---|---|---|---|---|---|---|
| 20 | 26.99 | 6.62 | 1.9 | 26.66 | 6.88 | 1.93 |
| 21 | 28.83 | 12.66 | 1.9 | 28.57 | 13.03 | 1.93 |
| 22 | 32.02 | 18.72 | 1.9 | 31.88 | 19.22 | 1.93 |
| 23 | 37.07 | 24.64 | 1.9 | 37.06 | 25.30 | 1.93 |
| 24 | 44.50 | 29.91 | 1.9 | 44.77 | 30.76 | 1.92 |
| 25 | 55.03 | 33.35 | 1.9 | 55.78 | 34.34 | 1.92 |
| 26 | 68.73 | 32.59 | 1.9 | 70.24 | 33.47 | 1.92 |
| 27 | 83.40 | 24.30 | 1.9 | 85.75 | 24.42 | 1.92 |
| 28 | 92.87 | 7.21 | 1.9 | 95.38 | 5.85 | 1.92 |
| 29 | 90.87 | -13.01 | 1.9 | 92.31 | -15.64 | 1.92 |

The Lowband software only reports SWR to tenths. The SWR does slightly drop under 2.0, but the drop is next to nothing, since the line is short, and it is a low-loss cable. As expected, the resistance cycles close to 25 and 100 Ohms, and the reactance varies between +36 (approximately) and -36 Ohms, switching signs when the resistance value reverses direction. Since I sampled at the arbitrary unit of 1 MHz, the actual value extremes are not exactly captured.

I took the resistance and reactance points and graphed them in Excel. Here is that graph.

two programs did not agree exactly, down to the last digit. I suspect that these programs could be made to produce identical results if you understood how to answer the different sets of setup questions with an eye towards how those questions drove the underlying computations, which should be identical, or at least very close.

The expected impedance values, and SWR, are shown in the following table, as a function of frequency.

| Computed Expected Impedance Values as a Function of Frequency | | | | | | |
|---|---|---|---|---|---|---|
| | Lowband Software | | | TLA Software | | |
| Freq. (MHz) | R (Ohms) | X (Ohms) | SWR | R (Ohms) | X (Ohms) | SWR |
| 2 | 27.61 | 12.42 | | 27.0 | 12.42 | 1.97 |
| 3 | 30.69 | 18.71 | 2.0 | 31.08 | 18.71 | 1.97 |
| 4 | 35.56 | 24.95 | 2.0 | 36.07 | 24.95 | 1.96 |
| 5 | 42.87 | 30.72 | 2.0 | 43.54 | 30.69 | 1.96 |
| 6 | 53.44 | 34.93 | 1.9 | 54.32 | 34.80 | 1.96 |
| 7 | 67.69 | 35.17 | 1.9 | 66.83 | 34.80 | 1.95 |
| 8 | 83.79 | 27.65 | 1.9 | 85.09 | 26.76 | 1.95 |
| 9 | 95.31 | 10.89 | 1.9 | 96.35 | 8.47 | 1.95 |
| 10 | 94.43 | -12.14 | 1.9 | 94.68 | -14.13 | 1.95 |
| 11 | 81.95 | -28.45 | 1.9 | 81.41 | -30.19 | 1.95 |
| 12 | 66.02 | -34.77 | 1.9 | 65.12 | -35.18 | 1.94 |
| 13 | 52.40 | -33.93 | 1.9 | 51.45 | -34.67 | 1.94 |
| 14 | 42.42 | -29.55 | 1.9 | 41.54 | -29.98 | 1.94 |
| 15 | 35.55 | -23.81 | 1.9 | 34.79 | -24.03 | 1.94 |
| 16 | 30.64 | -17.01 | 1.9 | 30.36 | -17.75 | 1.94 |
| 17 | 28.19 | -11.51 | 1.9 | 27.63 | -11.49 | 1.93 |
| 18 | 26.69 | -5.42 | 1.9 | 26.21 | -5.32 | 1.93 |
| 19 | 26.31 | 0.60 | 1.9 | 25.91 | 0.78 | 1.93 |

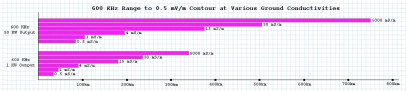


All well and good. Our transmitter is well-located, emitting a good signal traveling over perhaps many kilometers or miles to our receiving location. We either hear it or we don't depending on the natural attenuation decay between us and the transmitter. But just how do we predict the outcome? How do we (abstractly) measure a mediumwave signal's strength at the receiving end? We will use these tools and others to find out.

**PART II: Measurements**
http://radio-timetraveller.blogspot.com/2011/06/field-strength-calculations.html
23 June, 2011

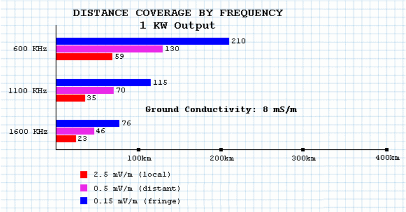
Continuing on with ground conductivity, the higher the conductivity the farther away the station's signal will be copyable. Study the accompanying graph showing the range of a 600 KHz signal at the 50KW power level at various ground conductivities. 50 kilowatts over good ground conductivity of 15 mS/m will produce a very copyable signal at a distance of 375 kilometers (233 miles). At an average to poor ground conductivity of 4 mS/m, coverage is reduced to under 200 kilometers. Excellent ground conductivity of 30 mS/m takes the same signal out to more than 500 kilometers! A purely over-seawater path (5000 mS/m) should result in a fair signal out to about 750 kilometers or some 465 miles.

Also study the graph of the transmitter with only 1KW output at 600 KHz. It gets out quite well considering its output is a mere one-fiftieth of its bigger brother! Its range is perhaps a third of the 50KW transmitter.




Take another look at the M3 map from the previous part in this series. The country is filled with pockets of different ground conductivities, some large in area, some small. The mid-section of the country has some of the best. A large portion of eastern Colorado and western Kansas are in the 15 mS/m range. Most of Kansas proper is an incredible 30 mS/m. Signals propagating eastward out of Colorado travel a long way. Northern Texas and Oklahoma also have great ground conductivity.

Frequency of operation makes an important difference in how far a signal travels. Propagation distance at the high end of the mediumwave band is less than half the distance of that at the low end for the same received signal strength. A study of the two accompanying graphs comparing the distance coverage of 600 KHz, 1100 KHz, and 1600 KHz signals clearly show this.






parameters. I also terminated the line with a 50 Ohm load and verified that the SWR was 1.0 across the entire HF range. Any errors within the transmission line itself will throw off all of the results.

For the purposes of this page, I am going to assume that my cable is 180 electrical degrees at 18.90 MHz. This value splits the difference between the three meters. If I need to know the electrical length at some other frequency, I will simply scale this ratio. At 3.8 MHz, for example, the electrical length is:

Length(degrees) = (180 degrees / 18.90 MHz) * 3.8 MHz = 36.19 degrees

The lengths will be used to determine the cable impedance transformation at various frequencies.

I connected the terminated cable to each analyzer, and swept the frequency from 2 to 29 MHz, in steps of 1 MHz. I recorded all of the information that each meter provided, placing the data into a Microsoft Excel spreadsheet. I used an external power supply or new battery with each analyzer.

But first, I used the ON4UN Lowband software (*Lowband*) to compute the expected impedance and SWR at the input of the cable. I used the *lossy* cable model (coax1.exe), which requires the specification of cable loss per 100 feet at two frequencies. For this cable, I specified 0.2 dB at 1 MHz, and 0.6 dB at 10 MHz. That data came from a web site that sells that particular cable. I further used the TLA program obtained from my ARRL Antenna Book back cover to compute the same information. Each program takes a different approach to how loss is entered. I did my best to supply the correct loss data to TLA, but this is based upon looking at typical loss curves, and selecting values. As you might imagine, the results of these and again where the SWR stepped up from 1.0 to 1.1. I used the center frequency of the region where the SWR was 1.0. This region was several hundred kilohertz wide. The values I obtained were:

| Half Wavelength Frequency of Test Cable | |
|---|---|
| Analyzer | Frequency (MHz) |
| MFJ-269 | 18.750 |
| RF-1 | 19.045 |
| CIA-HF | 19.150 |

Because of the lack of agreement, I decided to short the load end of the cable and divide the frequency in two in order to treat the line as a 90 degree section. I obtained the following values.

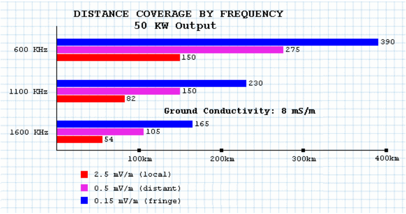
| Quarter Wavelength Frequency of Test Cable | |
|---|---|
| Analyzer | Frequency (MHz) X 2 |
| MFJ-269 | 18.726 |
| RF-1 | 19.055 |
| CIA-HF | 19.550 |

It is also possible to compute the half wavelength physical length of the cable using published data. The cable velocity factor was listed as 0.66. The formula is:

f(MHz) = (491.8 / 17.1 feet) X 0.66 VF = 18.98 MHz

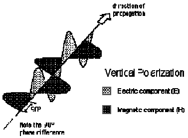
The measured frequency where this cable is a half wavelength was approximately 18.90 MHz. The frequency determined by computation was 18.98 MHz, a frequency error of slightly less than 1/2 percent. The published velocity factor closely agreed with the measured factor. I measured another cable with a 10 percent velocity factor error. To be on the safe side, I would reject lines that showed large deviations from published






The common unit used in measuring received field strength is volts per meter, or usually, millivolts per meter "mV/m". This is also the FCC requirement. An odd term, millivolts (thousandths of a volt) per meter. We all know what voltage is, but per meter of what, exactly?

Volts per meter expresses the voltage that would be induced in a one meter long wire placed parallel to the lines of flux of the received signal (remember the electrical flux from a mediumwave tower is vertical, the magnetic horizontal). This induced voltage results from the movement of the flux across the wire.



It is important to note that the E (electrical) component of an electromagnetic field is measured in a single dimension. Why? The intensity-versus-distance relation is a straight inverse rule, not the inverse square law commonly used for calculating received power density. In the perfect environment of space, if you double the distance the signal has to travel, the received voltage (in volts/meter or fraction thereof) is halved. Ten times farther away results in 1/10 of the voltage. This is known as field strength. Power density, a different method of measuring received signal strength, follows the inverse square law. That is, the density is related to the inverse of the square of the distance.

In broadcast parlance, millivolts per meter is often referred to in a different context, that being "dBu", or more accurately, dBµV/m. This is decibels above or below 1 millionth of a volt per meter. It is a convenient way to represent field strength, as the decibel is simply a ratio of values. Be sure not to confuse this dBu (lowercase "u") with the Greek "mu" ("µ") on the new model DSP ultralight radios. They are different. These radios actually measure dBµV - voltage across antenna terminals at a certain impedance, not volts per meter.

The FCC offers a conversion calculator to convert from dBu to mV/m and back.

Or, you can figure it yourself by using the following formula:

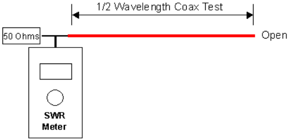
dBu = 20 * Log(mV/m * 1000)

To reverse the computation, converting dBu back to mV/m:

mV/m = (10 ^ (dBu / 20)) / 1000

But let's put received millivolts per meter into practical application, something a little more understandable. Hatfield & Dawson, Consulting Electrical Engineers out of Seattle, WA have a wealth of interesting mediumwave engineering






Determining Coax Length via the 1/2 Wavelength Method

At some frequency, this length of coax will be an electrical half wavelength. At that frequency, the open circuit at the far end of the cable will be exactly transferred to the input end. This means that the SWR meter measures nothing except the 50 Ohm resistive load, which has an SWR of 1.0. As the frequency is raised or lowered, the open half wavelength will present an impedance in parallel with the 50 Ohm load, and no matter what value that impedance is, it will result in a change in the SWR. After creating this set up, all you have to do is to sweep the frequency of the meter and look for the SWR dip to 1.0. The only caution is to make sure that your frequency is not so high that you are actually measuring a multiple of a half wavelength.

If you wish to consider the cable to be 1/4 wavelength, then you must short circuit the far end. A 90 degree cable reverses the sense of opens and shorts on its two ends. So, a shorted load appears as an open input, which is the same as the 1/2 wavelength case.

Of course I obtained three different readings from the three different meters. The CIA-HF meter actually reports a single lowest SWR frequency. On the other two meters, I recorded the frequency where the SWR stepped from 1.1 down to 1.0, A quick comment on coaxial cable loss. Cable loss does have the effect of reducing the SWR as the loss increases, either due to a longer cable, or higher frequency. We should, therefore, not demand that the SWR stay at 2.0, especially as the frequency rises. The correct SWR value will be less than 2.0. In my tests I will use calculated models of lossy cable in order to understand with the highest accuracy what our expected results should be.

I decided to duplicate the Caron experiment with my meters. I went to the old coax cabinet, and the first similar length I pulled out was 17.1 feet of RG-213 cable. I happened to have a commercial 25 Ohm termination load that measured at 25.2 Ohms with my 3 1/2 digit digital multimeter (DMM).

Before I started the first SWR measurements, I wanted to determine the electrical length of my sample coax at some frequency. Given that information, a new frequency, the load resistance, and cable attenuation, one can compute the actual impedance which should be observed at the input of the cable. If we are willing to believe those results, then we can generate a set of expected values that the analyzers should report.

The published techniques for determining cable length are usually based upon treating the cable as either a quarter wavelength or half wavelength section at some frequency. Once you have either 90 or 180 degrees at some frequency, you can scale the electrical length to the desired frequency. The following test setup is used.

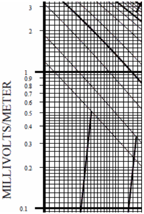


documents for perusal, floating about the web. This document seems to describe it best in terms the layman can understand.

From an engineering report by Hatfield & Dawson, 2002:

"MW radio signal strengths are measured in volts per meter (V/m). The FCC requires that MW radio stations provide a predicted 5 mV/m daytime signal and a 5 mV/m nighttime signal or a Nighttime Interference Free (NIF) signal, whichever is greater, over the city of license."

"MW radio receivers vary greatly in sensitivity and much has




been written lately about the poor performance of MW receivers built today. The general practice for broadcaster use for coverage is 2 mV/m for coverage in vehicles, 5 mV/m to 25 mV/m for in home and 25 mV/m in downtown office buildings. On a Walkman-type portable radio, you may need as much as 5 millivolts (5 mV/m) of signal to have static-free reception. The reason for these recommended signal levels is to overcome the effects of interference. Sources of interference include fluorescent lights, computers, TVs, office equipment, overhead power lines, and other appliances operating near a radio that can overload the receiver. In a city core, stations generally need more signal than this because of heavy attenuation inside large steel structures like office buildings. In your home, depending on the location, type of radio, and the utilization of any external antennas, you can have good reception with signals between 1 mV/m and 25 mV/m."

radio-locator.com produces widely used antenna pattern plots, available to interested parties over the web. These depict the expected signal coverage of the mediumwave station. radio-locator divides the signal coverage area into three distinct ranges.

1. Local (red line), the area in which the field strength is 2.5 mV/m or greater, where "....you should be able to receive the radio station on almost any radio with moderately good to very good reception".

2. Distant (purple line), the area between 0.5 and 2.5 mV/m, where "....the signal of the radio station may be weak unless you have a good car radio or a good stereo with a good antenna. You may not be able to receive the station at all on Walkmans or other portable radios".

3. Fringe (blue line), the area between 0.15 and 0.5 mV/m, where "....the station's signal will be very weak. You may be able to receive this station if you have a very good radio with a good antenna, but it's possible that interference from other stations may prevent you from picking up these stations at all." This seems to agree with Hatfield and Dawson's report.



Although the analyzers have evolved from that point, measuring SWR is still one of their most important functions.

As I was going through all of my paper and on-line resources, trying to figure out how to make accurate impedance measurements, I came across an article in ARRL Antenna Compendium #3, by Wilfred Caron, entitled: *The Hybrid Junction Admittance Bridge*. In this article, he uses an evaluation and calibration strategy which is based upon a section of coax cable, and a fixed resistor. He connected a 25 Ohm resistor to the end of a 16 foot length of RG-58 coax. What do we know about that circuit? Ignoring transmission line loss for a moment, we know that the SWR measured at the input of the cable should always be 2.0, at any frequency. In addition, the impedance measured at the cable input will change as a function of frequency, displaying both resistive and reactive values. The resistance will vary between 25 and 100 Ohms, and the reactance will swing both positive (inductive) and negative (capacitive) around zero Ohms. When the impedance is exactly the load impedance, 25 + j 0 Ohms, the line will be an electrical half wavelength, or multiple of it, at the target frequency. All of the impedance values will repeat every half wavelength. Peter Dodd, G3LDO, has used this same approach to evaluate his Autek VA-1 analyzer, and his HP4085A vector impedance meter. Those results are presented on one of his web pages.

So, for the price of a resistor and a short length of coax cable, we can present a range of impedance values to an SWR measuring device that should always read 2.0, at any frequency. In fact as we sweep frequency, the impedance values will change, but always representing a 2.0 SWR. This is conceptually similar to drawing the 2.0 SWR circle on a Smith Chart, and moving around on the circle.

While all of these analyzers can be used as RF signal generators, the CIA-HF is, by far, the most stable of the three. In order to use it as a signal generator, you must set the *width* to 0, so that the unit emits a constant signal. Otherwise, it generates RF periodically, as it takes frequency sweep readings and updates the screen. The only issue is that the analyzer then emits a tone which is in proportion to the SWR. This can be a little annoying, but it is not that loud. The quality of the CIA-HF waveform is also dependent upon battery voltage and current. If you do not provide it with sufficient power, the output waveform begins to resemble a square wave, as opposed to a sine wave.

Autek RF-1

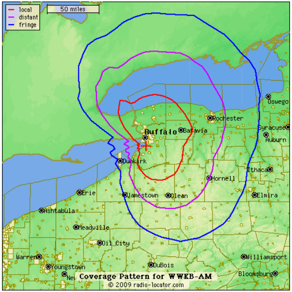
The Autek RF-1 is often noted for its very small size. It's easy to carry around, for example, to the top of an antenna tower. This unit is several years old. Unlike the MFJ and AEA units, which measure both resistance (R) and reactance (X), the RF-1 only measures total impedance (Z). Autek sells an updated model, the VA-1, which does report resistance and reactance. Both units are the least expensive of the alternatives.

My software version number is 9.7.

SWR Measurements

The initial use of the portable antenna analyzer was to measure SWR. SWR meters have been around for a long time, but they tended to be meters which we used in the radio shack, excited with transmitter power, often times hundreds of watts. They were not suited for making adjustments out at the antenna. Early antenna analyzers were nothing more than a low power variable oscillator, frequency counter, SWR sensor/bridge, and a detector meter, all placed in a battery-operated package.






Another important factor in our quest to predict received signal strength is transmitter antenna efficiency. Size does matter. The better the antenna, the better the station gets out. Returning again to Hatfield and Dawson, now discussing mediumwave antennas:

"MW antenna heights are referenced to a wavelength (this only includes the radiating portion of the tower). In MW broadcasting, 5/8 wavelength (or 225°) antennas are more efficient than ¼ wave antennas. A ¼ wavelength (or 90°) antenna is near the lower end of acceptable antenna heights. Antenna heights much below ¼ wavelength are undesirable, as efficiencies decrease dramatically below this height. A 225° antenna provides the maximum coverage and is the theoretical maximum. The efficiency decreases for antennas taller than 225°, which results in reduced coverage. In summary, taller towers are more efficient and shorter towers decrease coverage and are more difficult to work with."

So back to our quest of received signal strength prediction. Few documents are available which demonstrate how to predict "real-world" surface propagation distances at mediumwave frequencies. Many analysts use vanilla formulas for calculating free space path loss using the inverse square law, computing the path loss (in dB) from transmitter to receiver. The path loss, in turn, is used to determine the received field strength value.

Unfortunately, free space path loss assumes a perfect environment, like you would find out in space or over a perfectly conducting earth. Be wary of cute little field strength calculators on the web, their resultant field strength figures are almost an order of magnitude higher than what is seen in real life. Formulas exist which will predict field strength at mediumwave frequencies, but the math is well beyond the average person's ability.

A simpler method exists to ballpark the figure we want. We need but one more piece of information to complete the puzzle. That is the millivolt per meter level at one kilometer from the station transmitter, emanating in your direction. Using that with the FCC's Ground Wave Field Strength Versus Distance graphs and the M3 conductivity map we can estimate the received signal level in mV/m to fairly good accuracy at our location for any station.

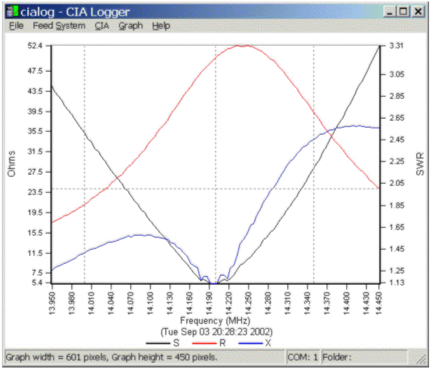
The next part of this article will show you how to do that. But let me leave you with this before we go. What information can we derive from the FCC graphs and other station data to maximize our daytime DX distance?

1. The lower frequencies propagate better per unit of distance. Stations near the low end of the broadcast band propagate nearly three times farther than ones at the highest end, for the



Shortly after I purchased my CIA-HF, I learned that the phase angle was considered to be *unreliable* under 8 degrees (-8 to +8 degrees) [on more recent units, this unreliable region has been reduced to 4 degrees). For that reason, I tend to think of the analyzer as not reporting the sign of the reactance, but if you are willing to use the Data Screen, and be careful under 8 degrees, the unit does report indeed the sign.

Here is a screen shot showing the resistance, reactance, and SWR of a dipole antenna fed with a tuner, and adjusted for resonance at 14.200 MHz. The data was transferred over a serial line from the CIA-HF to the computer, and displayed with my viewing software.



CIA-HF Data Displayed on a Computer

MFJ does make available a calibration procedure for the 259B (I have never asked about the 269). Tom, W8JI, has also placed a calibration procedure on his web site.

AEA CIA-HF

I have one of the early CIA-HF units, serial number 0341. This unit has an LCD screen which can produce actual graphs of measured data, such as SWR, impedance, resistance, and reactance. In addition, the unit has an RS-232 serial interface, which can be used to interface the analyzer with a computer. Several software packages exist. I use one that I wrote myself. Unlike the other analyzers, the CIA-HF takes a few seconds to update the screen. This makes it less useful for use while *tweaking* a control, since it takes a few seconds to see the updated data (there is a special SWR mode that updates quickly, and produces an audio tone in proportion to the SWR). The CIA-HF had several hardware updates which were added in its first year of production. My unit predates all of those upgrades.

My software version number is 1.4.

On this web page, I claim in several places that these analyzers do not report the sign of the reactance. That is certainly true for the MFJ-269 and the RF-1. The CIA-HF is a more complex story. When you are on what is called the *Data Screen*, the sign of the reactance is indicated by the sign of the impedance angle, ranging from -90 to +90 degrees. A negative value indicates capacitive reactance, and a positive value indicates inductive reactance. As best as I can tell, this is the only indication of the reactance sign. In all other data displays, the reactance or phase angle is always shown as an unsigned number. On the Data Screen, the angle has an explicit + or - sign.



same power output and same ground conductivity. The lesson: listen to the lower end of the MW band if you want extreme distance in reception.

2. Look for over-water paths. A local example: Ground conductivity around here in the Rochester, NY area is about 8 or a little less, tending towards the 6 mS/m figure judging from reception experience. Without passive loop assistance, normal daytime reception limits seem to max out at about 150 miles. That is, except for two stations: WJR-760, Detroit, MI and CKLW-800, Windsor, Ontario, Canada, near Detroit. These two are out at about 250 miles or about 400 kilometers. Why are they receivable? Most of their signal path is across water over the east-west length of Lake Erie into Rochester. Reception is routine on most simple radios with medium or better sensitivity.

3. Study station antenna patterns. The FCC web site is great for this. Virtually all stations with multiple towers have directional patterns and the FCC makes the pattern plot available in .PDF form. Study the plot and pay particular attention to your azimuth away from the station. Pick stations that push a lot of signal in your direction. They are the best prospects. Example: WXXI-1370 pattern

4. The radio-locator "fringe" 0.15 mV/m boundary seen on their plots is just that - fringe. Many stations are copyable at this boundary and beyond on a sensitive radio. Don't hesitate to try for them. Example: Denver stations KHOW-630 (only 5KW), KKZN-760 (50KW), and KOA-850 (50KW) all have excellent strength east to well past Hays, Kansas (300+ miles, or 483+ km) despite the fringe zone ending miles back towards the Kansas/Colorado state line.

The jury seems to be out on how far ground conductivity plays a role in daytime propagation. Some documents refer to the 55 kilometer figure, others to 150 kilometers. My bet is it is well beyond the 150 km figure as I have routinely heard stations at the 800 kilometer range during high daylight hours at all times of the year.

**PART III: Calculating**
Radio-Time Traveler
http://radio-timetraveller.blogspot.com/2011/06/field-strength-measurements-calculating.html
25 June, 2011

As stated in the previous post, one more piece of information is required to complete the puzzle of calculating received field strength. That is the millivolt per meter level at 1 kilometer from the station transmitter, eminating in your direction. Notice I said "eminating in your direction". It is not good enough to simply calculate the mV/m level at 1 kilometer for the station's overall power output. Two things must be accounted for that change that result and would make our field strength calculation inaccurate. They are:

1. Antenna efficiency. A mediumwave tower or array of towers will be more or less efficient depending on their radiation length(s). The FCC provides us with a figure called RMS Theoretical for every station's antenna array whether it be one tower or several, measured in mV/m. Reflected in this figure is the efficiency.

2. Pattern gain. Multiple tower arrays inherently have broadcast patterns. Meaning, of course, they aim to broadcast a majority of their signal in a certain direction to cover their market audience and/or avoid co-channel interference with



**Meet the Players**
Here are the three antenna analyzers that I owned and tested at the time of the creation of this web page. Please click on the

picture for a larger view.
Antenna Analyzers: MFJ-269, RF-1, CIA-HF

The MFJ-269 looks like the very popular MFJ-259B. There are some differences. It has a button labeled *UHF* which enables the device to operate up through the 440 MHz band. For my purposes, the primary difference is that the 269 uses a 12-bit A/D (Analog to Digital) converter, which is claimed to produce more accurate results. It is my guess that other analyzers use 8-bit A/D converters, since they are less expensive, and often available directly on the microprocessor IC. The 269 is somewhat more expensive than the 259B.

My software version number is 1.24.

results, they must be used in conjunction with a signal generator and a detector/receiver. Depending upon what you are trying to measure, several computations must be performed to arrive at the result. It can sometimes take *minutes* to make a single measurement with an impedance bridge setup. The delay is due to having to *balance* the bridge, which is a process of adjusting two controls until a very sharp null is found. Another alternative, perhaps the best, is a lab quality impedance analyzer. HP has made a number of models over the years that seem to cost well in excess of $10,000. That takes them way out of my hobby budget. So, for the money, these analyzer boxes are a great value, even with limitations and errors. Overall, their accuracy appears to be quite good.
It's also true that I tested exactly one of each of these meters - the one that I own. Each is several years old, and while I don't believe that I have ever dropped or abused them, they have been well used. I assume that there is one or more *calibration adjustments* for each analyzer, and I have no idea if my units are well-calibrated, or out of calibration.

I don't know how representative my units are of each model, or if there have been design improvements over the years that would change the results.

Finally, the battery quality and lead length will influence results. You can obtain better results if you use fresh batteries (or an external power supply) and short leads. At HF frequencies, even a few inches of wire can act as an inductor with several Ohms of reactance. I can't stress this enough. Short leads, better yet, no leads.



another station. Where you are in relation to that pattern is important. If you are in the major lobe of a 50KW station, it may be pumping upwards of 100KW towards you, or more. If you are in a sharp pattern null, it may only be beaming hundreds of watts towards you. The amount of millivolts per meter "facing you" is the important figure. The FCC provides that as well, in their pattern plots.

There is only one case where we will need to do a simple extra calculation to arrive at the full millivolt per meter level for a station. That is for stations with a single tower only. I will explain why in just a minute.

So let's put together what we need. First, pick a station within reasonable distance you think you'd like to log. Note its frequency. Next, gather the following four things:

1. The ground conductivity in mS/m between you and the station. Use the M3 conductivity map. If the station path crosses a couple of zones, estimate the average ground conductivity for the entire path. The resultant figure should fall between 0.1 mS/m and 30 mS/m, or possibly higher if part of the path is over salt seawater.

2. The Ground Wave Field Strength Versus Distance graph for the frequency of the station, one of the 20 graphs published by the FCC. Several frequencies are usually grouped into one graph. The graphs are in .PDF form. Have your .PDF viewer ready.

3. You will need to find your distance to the station in kilometers, and also the reverse bearing from the station back to you. Many calculators exist on the web which will compute this information. The FCC has a good one, be sure to check out their calculator. These calculators require you to know the

latitude and longitude of both your location and the station's location.

www.wikimapia.org is a great way to determine your home latitude and longitude as it has a crosshair defining the center of the map, and thus the latitude and longitude. Move the map to your exact location and read the latitude-longitude in the web browser's address bar.

The station's latitude and longitude can be found in a couple of ways. The FCC's AM Query web page allows us to query the station by call sign. The search output will display basic information like latitude and longitude. Click on the call sign link and you will be taken to the FCC's web page for the facility (station). Example: WHAM-1180 page.

4. The last item. Get the millivolt per meter value at 1 kilometer from the station transmitter, headed your way. The method of locating this figure will depend on whether the station has one antenna tower or multiple towers in its array.

Determine if the station uses a single tower or multiple towers for the service you are interested in. This information can be found on the FCC's web page for the facility (station), as shown just above.

Note that stations may have more than one entry on the page, one for each service they operate under, i.e., UNLIMITED, DAYTIME, NIGHTTIME, CRITICAL HOURS. Be sure you are looking at the correct service. Sometimes stations use a different number of towers for day and night.

mV/m for multiple towers.

The mV/m figure is gotten from the pattern data. It's simple.



## W8WWV - Analyzing Three Antenna Analyzers

Greg Ordy

http://www.seed-solutions.com/gregordy/Amateur%20Radio/Experimentation/EvalAnalyzers.htm

### Introduction

On this page I would like to present some measurements that I made with three of the popular antenna analyzers. I became interested in their accuracy when I had an application where I wanted to make accurate measurements of relatively low impedance values. Values where the resistance and reactance were close to zero Ohms, certainly under 50 Ohms. I had no reason to doubt any of the measurements, but from time to time I would make measurements with more than one of the units and find that they might differ by up to 10 Ohms. For many applications this difference is not significant, but I decided to see if I could determine how the analyzers compared to reference values, as opposed to each other.

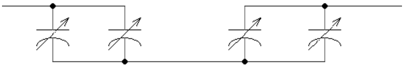
### Accuracy and Value

I'm not trying to present a detailed evaluation of these analyzers, or to rank their quality. My measurements and their accuracy are not precise enough for that purpose. While it's clear that these analyzers can report results with error, they are all a tremendous value, and a useful addition to any amateur radio station.

I call them tremendous values because I don't know how to make better measurements without spending substantially more time and/or money. Historically, impedance measurements were made with the *impedance bridge*. While a laboratory quality impedance bridge can produce excellent

**Variable Capacitor Wired Wiperless**
By Jim, Amateur Radio Station KR1S
http://theradioboard.com/rb/viewtopic.php?t=3262&postdays=0&postorder=asc&start=15

If I'm reading this correctly, a schematic would be:



For a four-section, 500-pF per section cap, the total C would be 500 pF.



Multiple tower arrays will give you the option to display the pattern plot. The pattern plot link will be under a heading that looks like this:

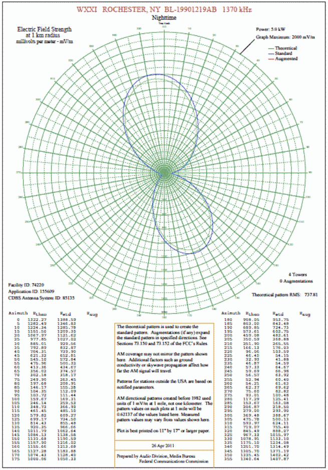
Horizontal Pattern at 1 km radius (Sections 73.150 and 73.152):
Electric Field Strength pattern plot
Pattern Data for WXXI

Either link will give us the information we need, though the "Electric Field Strength pattern plot" gives a nice graphic pattern plot for the station. Click one of the links.

RMS Theoretical values, and in some cases RMS Standard or even RMS Augmented values will be displayed for each five degrees of compass, 0-360. Find the compass bearing that most closely matches the return bearing from the station to you. We need to record one value only. Preferably, record the RMS Augmented value, if given. If not available, record the RMS Standard value. If not given, record the RMS Theoretical value. These values are in millivolts per meter and are the value of signal level the station presents towards you.

A quick definition of RMS Standard and RMS Augmented values. RMS Standard is essentially the RMS Theoretical value plus 5%. It is a "guard" against interference to other co-channel stations by overstating the RMS Theoretical calculated value. If stations have pattern augmentations, and many do, the RMS Augmented field will be present. Augmentations are enhancements or detractions to the theoretical pattern.

I'll use WXXI-1370 for the example. At night it runs 4 towers and has a roughly figure-8 pattern north-south. WXXI's return bearing to me is 204.7 degrees. Checking the FCC pattern plot for the station, we see that the 205 degree return azimuth presents a facing RMS Theoretical of 350.59 mV/m and a facing RMS Standard of 368.88 mV/m. We will use the RMS Standard value in the final calculation.




| Azimuth | $E_{theo}$ | $E_{std}$ | $E_{aug}$ |
|---|---|---|---|
| 0 | 1322.27 | 1388.59 | |
| 5 | 1282.49 | 1346.83 | |
| 10 | 1224.34 | 1285.78 | |
| 15 | 1151.50 | 1209.30 | |
| 20 | 1067.97 | 1121.62 | |
| 25 | 977.85 | 1027.02 | |
| 30 | 885.01 | 929.56 | |
| 35 | 792.89 | 832.87 | |
| 40 | 704.31 | 739.90 | |
| 45 | 621.32 | 652.81 | |
| 50 | 545.10 | 572.84 | |
| 55 | 475.96 | 500.32 | |
| 60 | 413.36 | 434.67 | |
| 65 | 356.02 | 374.57 | |
| 70 | 302.18 | 318.17 | |
| 75 | 249.90 | 263.45 | |
| 80 | 197.68 | 208.91 | |
| 85 | 146.17 | 155.28 | |
| 90 | 104.35 | 112.09 | |
| 95 | 103.72 | 111.44 | |
| 100 | 159.67 | 169.31 | |
| 105 | 246.14 | 259.53 | |
| 110 | 348.73 | 366.93 | |
| 115 | 461.45 | 485.10 | |
| 120 | 579.82 | 609.27 | |
| 125 | 699.17 | 734.50 | |
| 130 | 814.43 | 855.48 | |
| 135 | 920.35 | 966.66 | |
| 140 | 1011.79 | 1062.64 | |
| 145 | 1084.13 | 1138.58 | |
| 150 | 1133.68 | 1190.59 | |
| 155 | 1157.90 | 1216.02 | |
| 160 | 1155.66 | 1213.68 | |
| 165 | 1127.28 | 1183.88 | |
| 170 | 1074.43 | 1128.40 | |
| 175 | 1000.06 | 1050.33 | |

The theoretical pattern is used to create the standard pattern. Augmentations (if any) expand the standard pattern in specified directions. See Sections 73.150 and 73.152 of the FCC's Rules.

AM coverage may not mirror the pattern shown here. Additional factors such as ground conductivity or skywave propagation affect how far the AM signal will travel.

Patterns for stations outside the USA are based on notified parameters.

AM directional patterns created before 1982 used units of 1 mV/m at 1 mile, not one kilometer. The pattern values on such plots at 1 mile will be 0.62137 of the values listed here. Measured pattern values may vary from values shown here.

Plot is best printed on 11" by 17" or larger paper.

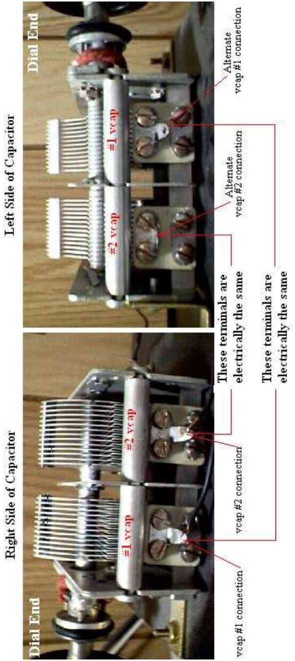
26 Apr 2011

Prepared by Audio Division, Media Bureau
Federal Communications Commission

| Azimuth | $E_{theo}$ | $E_{std}$ | $E_{aug}$ |
|---|---|---|---|
| 180 | 908.05 | 953.75 | |
| 185 | 803.00 | 843.48 | |
| 190 | 689.85 | 724.73 | |
| 195 | 573.61 | 602.75 | |
| 200 | 459.08 | 482.61 | |
| 205 | 350.59 | 368.88 | |
| 210 | 251.90 | 265.55 | |
| 215 | 166.13 | 176.03 | |
| 220 | 96.06 | 103.59 | |
| 225 | 46.40 | 54.15 | |
| 230 | 32.93 | 41.88 | |
| 235 | 46.87 | 54.59 | |
| 240 | 57.33 | 64.67 | |
| 245 | 59.69 | 66.98 | |
| 250 | 56.57 | 63.92 | |
| 255 | 52.94 | 60.40 | |
| 260 | 54.21 | 61.63 | |
| 265 | 62.37 | 69.62 | |
| 270 | 75.60 | 82.82 | |
| 275 | 93.01 | 100.48 | |
| 280 | 117.29 | 125.41 | |
| 285 | 153.67 | 163.08 | |
| 290 | 206.87 | 218.50 | |
| 295 | 279.00 | 293.90 | |
| 300 | 369.48 | 388.67 | |
| 305 | 475.78 | 500.13 | |
| 310 | 593.97 | 624.11 | |
| 315 | 719.07 | 755.40 | |
| 320 | 845.49 | 888.07 | |
| 325 | 967.33 | 1015.97 | |
| 330 | 1078.91 | 1133.10 | |
| 335 | 1175.10 | 1234.08 | |
| 340 | 1251.70 | 1314.49 | |
| 345 | 1305.70 | 1371.19 | |
| 350 | 1335.45 | 1402.42 | |
| 355 | 1340.64 | 1407.87 | |



This is my common to the frame or body of the capacitor.






Horizontal Pattern at 1 km radius (Sections 73.150 and 73.152):

Erss : 900.070
Kfactor : 480.53 Qfactor : 22.50

| Azimuth | Emin | Azimuth | Emax |
|---|---|---|---|
| 92.6 | 103.8 | 157.1 | 1218.4 |
| 228.9 | 41.1 | 244.1 | 67.1 |
| 256.6 | 60.1 | 353.6 | 1408.9 |

| Azimuth | $E_{theoretical}$ | $E_{standard}$ | Azimuth | $E_{theoretical}$ | $E_{standard}$ |
|---|---|---|---|---|---|
| 0.0 | 1322.27 | 1388.59 | 180.0 | 908.05 | 953.75 |
| 5.0 | 1282.49 | 1346.83 | 185.0 | 803.00 | 843.48 |
| 10.0 | 1224.34 | 1285.78 | 190.0 | 689.85 | 724.73 |
| 15.0 | 1151.50 | 1209.30 | 195.0 | 573.61 | 602.75 |
| 20.0 | 1067.97 | 1121.62 | 200.0 | 459.08 | 482.61 |
| 25.0 | 977.85 | 1027.02 | 205.0 | 350.59 | 368.88 |
| 30.0 | 885.01 | 929.56 | 210.0 | 251.90 | 265.55 |
| 35.0 | 792.89 | 832.87 | 215.0 | 166.13 | 176.03 |
| 40.0 | 704.31 | 739.90 | 220.0 | 96.06 | 103.59 |
| 45.0 | 621.32 | 652.81 | 225.0 | 46.40 | 54.15 |
| 50.0 | 545.10 | 572.84 | 230.0 | 32.93 | 41.88 |
| 55.0 | 475.96 | 500.32 | 235.0 | 46.87 | 54.59 |
| 60.0 | 413.36 | 434.67 | 240.0 | 57.33 | 64.67 |
| 65.0 | 356.02 | 374.57 | 245.0 | 59.69 | 66.98 |
| 70.0 | 302.18 | 318.17 | 250.0 | 56.57 | 63.92 |
| 75.0 | 249.90 | 263.45 | 255.0 | 52.94 | 60.40 |
| 80.0 | 197.68 | 208.91 | 260.0 | 54.21 | 61.63 |
| 85.0 | 146.17 | 155.28 | 265.0 | 62.37 | 69.62 |
| 90.0 | 104.35 | 112.09 | 270.0 | 75.60 | 82.82 |
| 95.0 | 103.72 | 111.44 | 275.0 | 93.01 | 100.48 |
| 100.0 | 159.67 | 169.31 | 280.0 | 117.29 | 125.41 |
| 105.0 | 246.14 | 259.53 | 285.0 | 153.67 | 163.08 |

mV/m for single tower.

A special case requiring a simple calculation. We will calculate the mV/m figure from the RMS Theoretical value.

Again go to the FCC's web page for the facility (station), as above. The RMS Theoretical value will be on this page.

Note again that stations may have more than one entry on the page, one for each service they operate under, i.e., UNLIMITED, DAYTIME, NIGHTTIME, CRITICAL HOURS. Be sure you are looking at the correct service. Sometimes stations use a different number of towers for day and night.

The FCC computes all RMS Theoretical values from a formula of course. The values are calculated for a distance of 1 kilometer. The FCC formula used generates accurate millivolt per meter values (as published) for multiple tower arrays. Single tower arrays are a special case, however, in that the published mV/m value is always based on a 1 kilowatt output power calculation. Hence, the only published single tower mV/m values we can use are those of 1 KW stations. For all others, we will do a simple calculation to arrive at the correct mV/m value. Proof of this is simple. For example, check the FCC's published figures for my local WHAM-1180 station out of Rochester, NY. This 50KW station shows a calculated RMS Theoretical value at 1 kilometer of only 376.59 mV/m. Now of course this cannot be correct for a 50KW station, as a 1 KW station running a quarter wave (.250 wavelength) monopole has an exact calculated figure of 305.768 mV/m at 1 kilometer.

376.59 mV/m would, however, be correct for a 1 KW station using the same single tower antenna that WHAM uses (a .492 wavelength antenna).

To accurately calculate the mV/m figure for WHAM (or any other single tower station, including those 1 KW stations), the following formula must be applied:

(Power in KW, distance in KM):

mV/m = RMSTheoretical x SQRoot(Power/Distance)

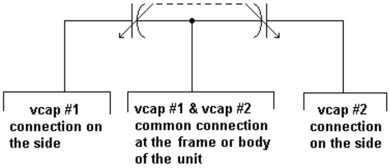
Thus in WHAM's case:

2662.89 = 376.59 * SQRoot(50/1)

WHAM's actual RMS Theoretical value is 2662.89 mV/m. And since it is a single tower antenna having an



**How to Hook Up A Variable Capacitor: Two Gang Capacitors**
by Darrel Boyd
**http://www.crystalradio.net/beginners2/caphookup.shtml**




This is the typical wiring for a two gang vcap
Refer to photo below

Next, we shall compute the bandwidths at three frequencies: 530kHz, 1MHz and 1.7MHz. Results are tabulated below.

| Freq.( kHz) | BW (kHz) | Q | $R_P$ (kΩ) | A (kΩ) | C (pF) | Ca (pF) | r (Ω) | $L_1$ (uH) |
|---|---|---|---|---|---|---|---|---|
| 530 | 5.004 | 105.9 | 354.32 | 155.50 | 450 | 200 | 30 | 152 |
| 1000 | 13.47 | 74.24 | 558.7 | 190 | 100 | 200 | 30 | 152 |
| 1700 | 24.83 | 68.49 | 487.072 | 406.8 | 31 | 200 | 30 | 152 |

Results for BW are very close to those obtained from simulation of circuit of Fig.1.b.

Ramon Vargas Patron

rvargas@inictel.gob.pe

Lima-Peru, South America

April 11th 2004



omnidirectional pattern, it presents this value of signal in all directions. Use the value you calculate for your single tower station of interest as the mV/m value that the station presents towards you.

Making The Calculation

Now we have all of our information. Let's get busy. We will use the FCC's Ground Wave Field Strength Versus Distance graph to arrive at the received mV/m signal level. Proceed with the following steps.

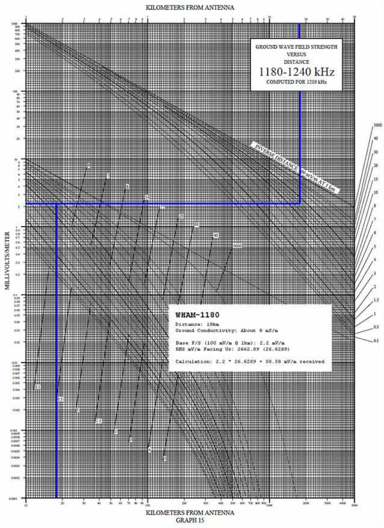
1. To make them universal, the FCC's Ground Wave Field Strength Versus Distance graphs are based on 100 mV/m levels at 1 kilometer. We simply need to calculate how many 100s our mV/m value is. Just move the decimal point left two places. In WHAM's case, 2662.89 mV/m, 26.6289 (26.6289 x 100 = 2662.89). The multiplier value we will use for WHAM is 26.6289. In WXXI's case, 368.88 mV/m, 3.6888 (3.6888 x 100 = 368.88). The multiplier value we will use for WXXI is 3.6888.

2. Find the station distance in kilometers on the graph, usually at the bottom. The bottom range is 10 to 1000 kilometers. The top range is 0.1 to 50 kilometers.

3. Draw a trace upwards (or downwards if using the top scale) until you hit the ground conductivity value curve that matches the average ground conductivity between you and the station.

4. From the previous point, draw a trace leftward to the scale on the left side of the graph. This is the base millivolt per meter level based on 100 mV/m at 1 kilometer. Multiply this value by your multiplier value. In WHAM's case, multiply times 26.6289. In WXXI's case, multiply times 3.6888. This

resultant value is the received field strength in millivolts per meter at your location.




There you have it. You have ballparked the approximate field strength of your station of interest. If done correctly, you should find this in fairly good agreement with V-Soft's figure



$$2L_1\left[C_T + C\left(1 \pm \omega_r C_T R_e\right)\right]\Delta\omega = \pm C_T R_e \left(\frac{Ca}{2Ca + C}\right)$$

Now, if $\omega_r C_T R_e << 1$, then:

$$2\Delta\omega = \pm \frac{R_e}{L_1}\left(\frac{C_T}{C_T + C}\right)\left(\frac{Ca}{2Ca + C}\right)$$

this is:

$$\Delta\omega = \pm \frac{R_e}{2L_1}\left(\frac{Ca}{2Ca + C}\right)\left(\frac{Ca}{2Ca + C}\right)$$

$$= \pm \frac{R_{s1}}{L_{eq}}\left(\frac{Ca}{2Ca + C}\right) \quad \ldots(2)$$

From part II of our study we can obtain the following expression for $R_{s1}$:

$$R_{s1} = r\left(1 + \frac{A}{R_P}\right)$$

Then, the 3dB bandwidth is given by:

$$BW = 2\Delta\omega = 2r\left(1 + \frac{A}{R_P}\right)\left(\frac{1}{L_1\left(2 + \frac{C}{Ca}\right)}\right)\left(\frac{Ca}{2Ca + C}\right) \quad \ldots(3)$$

in radians per second.

or:

$$\frac{\omega L_1}{1-\omega^2 L_1 C} - \frac{1}{\omega C_T} = \pm R_e \qquad \ldots(1)$$

Let $\omega_r$ be the resonant frequency and $\omega = \omega_r + \Delta\omega$ the frequency at a –3dB point on the amplitude curve. The left hand member of eq. (1) can be written as:

$$\frac{\omega^2 L_1 (C_T + C) - 1}{(1-\omega^2 L_1 C)\omega C_T} = \frac{(\omega_r{}^2 + 2\omega_r \Delta\omega)(C_T + C)L_1 - 1}{\left(1-(\omega_r{}^2 + 2\omega_r \Delta\omega)L_1 C\right)\omega_r C_T}$$

with the following approximations:

$$(\omega_r + \Delta\omega)C_T \approx \omega_r C_T$$

$$(\omega_r + \Delta\omega)^2 = \omega_r{}^2 + 2\omega_r \Delta\omega + \Delta\omega^2 \approx \omega_r{}^2 + 2\omega_r \Delta\omega$$

Then:

$$\frac{\omega_r{}^2 L_1 (C_T + C) + 2\omega_r (C_T + C) L_1 \Delta\omega - 1}{(1-\omega_r{}^2 L_1 C - 2\omega_r L_1 C \Delta\omega)\omega_r C_T} = \pm R_e$$

or:

$$\frac{2\omega_r (C_T + C) L_1 \Delta\omega}{\left(\frac{Ca}{2Ca + C}\right) - 2\omega_r L_1 C \Delta\omega} = \pm \omega_r C_T R_e$$

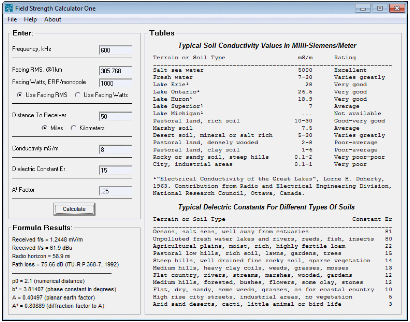
which simplifies to:



if you are near the zipcode point they based their calculation on. With a list of expected receive field strengths for various stations, you can judge the approximate sensitivity of your receiver. After a few times trying this, you will find the calculation to be rather simple to do.

**PART IV: Field Strength Calculator One**
[http://radio-timetraveller.blogspot.com/2012/12/field-strength-calculator-one.html](http://radio-timetraveller.blogspot.com/2012/12/field-strength-calculator-one.html)
20 December, 2012

Field Strength Calculator One is a program which will calculate expected received ground wave signal strength at longwave and mediumwave frequencies.




DOWNLOAD

https://app.box.com/s/g257enuzufin7kincn6y
To download, see the link at the top of the right sidebar under LATEST PROGRAMS. The sidebar at the top right will have the most current link in case the program is updated. The link will change in the case of an update, so I would avoid copying and pasting it into a forum or other web page. Come to the main page of this blog instead.

DISCUSSION

Being a mediumwave DXer and particularly a daytime mediumwave DXer, I wanted a way to determine a "ballpark" signal strength for various stations not only in my immediate area, but out to 100, 200, or even more miles distant. I was unhappy with virtually all the web-based signal strength calculators found on the internet, as they use the vanilla Inverse-Square-Law to calculate signal attenuation. Fine, if you are in an outer space vacuum or on a perfecting conducting surface, but not even close in accuracy for normal people here on Mother Earth.

The few stand-alone programs out there were either wildly expensive, too complicated to use, inaccessible, or plainly won't work on the Windows platform. I set out to accumulate information, formulas, and data to start writing the field strength calculator program. Investigating the history and ferreting out the pertinent information to arrive at a simplified formula that was reasonably accurate took some time.

The result was and is Field Strength Calculator One. It is based on the work of numerous engineers and mathematicians, who, starting about 1909, spent some 50 years developing the extremely complicated formulas to predict accurate signal strength at mediumwave frequencies. The basic, simplified formula has been known since the 1930s, being slightly



We shall now proceed to calculate the 3dB bandwidth of circuit of Fig.1.b.
Mesh current is given by:

$$I = \frac{E_a}{R_e + j\left(\frac{\omega L_1}{1-\omega^2 L_1 C} - \frac{1}{\omega C_T}\right)}$$

where:

$$C_T = \frac{CaC}{Ca + C}$$

The amplitude-frequency relationship for I is determined by:

$$I(\omega) = \frac{E_a}{\sqrt{R_e^{\,2} + \left(\frac{\omega L_1}{1-\omega^2 L_1 C} - \frac{1}{\omega C_T}\right)^2}}$$

At the -3dB points:

$$I(\omega) = \frac{E_a}{\sqrt{2}R_e}$$

The corresponding frequencies must satisfy the equation:

$$R_e^{\,2} + \left(\frac{\omega L_1}{1-\omega^2 L_1 C} - \frac{1}{\omega C_T}\right)^2 = 2R_e^{\,2}$$

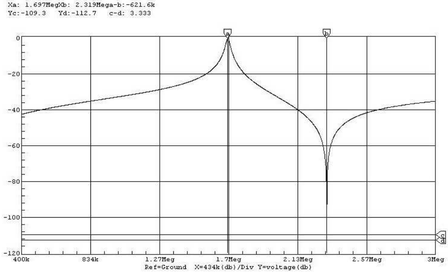



Fig.3.e Frequency response for circuit of Fig.1.b when resonance is adjusted to 1.7MHz

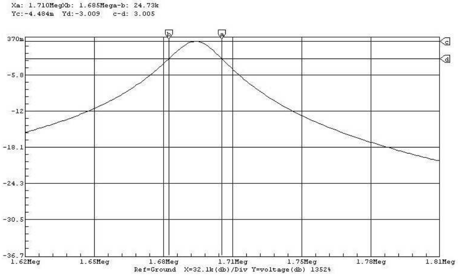



Fig.3.f 3dB bandwidth for a resonance frequency of 1.7MHz is 24.73kHz

**3dB bandwidth calculations**



modified by various people and agencies since then. It is accurate to within a couple of percent of the big programs that calculate field strength - those using additional input like the transmit and receive array heights above average ground, and the earth's topographic elevation changes along the signal path.

Simplified ground wave electrical field intensity calculations can be made by the introduction of a shadow or diffraction factor in the Sommerfeld-Norton planar earth expression. A mouthful! This simply means that a factor is computed and introduced to account for the additional attenuation caused by wave diffraction out beyond the radio horizon. It permits one to calculate the ground wave E (electrical) field well beyond the geometric and radio horizon, where E field values are close to the atmospheric noise level.

Be sure to read about the history of how this fascinating formula came about in the recent article on RADIO-TIMETRAVELLER: Field Strength Calculations: A History. Many of the terms used in the previous and next paragraphs are explained.

The simplified formula used by Field Strength Calculator One takes into account Sommerfeld's original plane earth theory, modified by diffraction factoring. It uses an exponential function which takes into account the spherical earth diffraction effects, and acts on the planar earth equation even before the radio horizon is reached, so the resultant E field values, as a function of distance produce a continuous curve, thus rounding-in difficult intermediate distances.

The long-accepted concept of "numerical distance" (p0) and "phase angle" (b) are used in all calculations, two variables determined by frequency, distance, and dielectric constants of the ground as a radio conductor. Numerical distance depends not only on frequency and ground constants, but also on the actual distance to the transmitter. Phase angle is the measure of the power factor angle of the earth.

Field Strength Calculator One returns expected received field strength in millivolts per meter and dBu (also known as dBµV/m), based on ground conductivity, earth dielectric and several other input constants. It also displays the distance to the radio horizon and the signal path loss in dB, along with several more technical parameters. The resulting output of Field Strength Calculator One should be accurate in most cases to a couple of percent in the longwave and mediumwave bands. It compares favorably to ITU program GRWAVE and currently available FCC Ground Wave Conductivity graphs.

Field strength calculations by Field Strength Calculator One are based on the works of A.Sommerfeld (1909), B.Rolf (1930), K.A.Norton (1936), H.Bremmer (1949, 1958), NTIA Report 86-203 (1986), ITU-R P.368-7 (1992), and NTIA Report 99-368 (1999).

For further information on how field strength is calculated see the Field Strength Calculations Series previously published on RADIO-TIMETRAVELLER.

INSTALL

An install file is included on the web page:
[http://radio-timetraveller.blogspot.com/2012/12/field-strength-calculator-one.html](http://radio-timetraveller.blogspot.com/2012/12/field-strength-calculator-one.html)

Included in the .zip is a readme.txt file. Be sure to have a look.



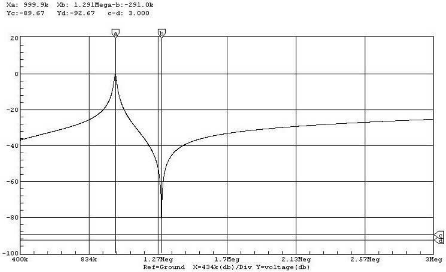



Fig.3.c Frequency response for circuit of Fig.1.b
when resonance is adjusted to 1MHz

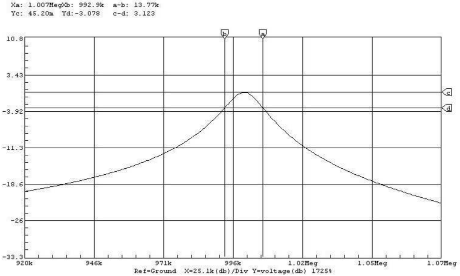



Fig.3.d 3dB bandwidth for a resonance
frequency of 1MHz is 13.77kHz

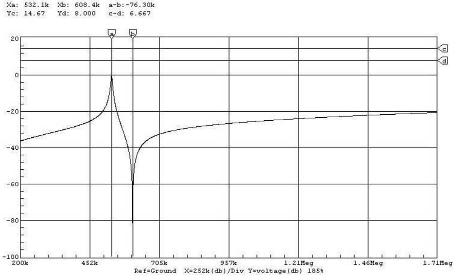



Fig.3.a Frequency response for circuit of Fig. 1.b
when resonance is adjusted to 530kHz

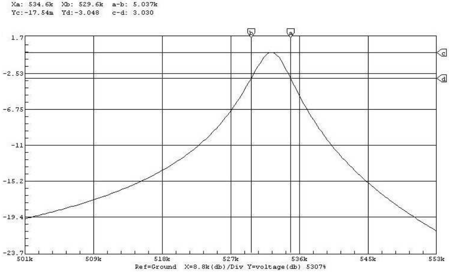



Fig.3.b 3dB bandwidth for a resonance
frequency of 530kHz is 5.037kHz



## ANTENNA AND GROUND SYSTEM

by Kenneth A. Kuhn

http://www.kennethkuhn.com/students/crystal_radios/antenna_and_ground_system.pdf

### Introduction

This article explains the basics of the antenna and ground system for a crystal radio and the associated mathematical model. The mathematical model tells us how to design the antenna input section of the radio for optimum performance.

The passing RF wave induces an RF voltage across a length of wire referred to as an antenna. The induced voltage is the signal strength in volts/meter multiplied by the electrical (not the physical) height of the antenna in meters. For antennas that are shorter than one-quarter wavelength the electrical height is roughly the wire length (including lead-in wire) in meters. There are very little directivity effects for short antennas so orientation is not really a factor –i.e. the antenna is omnidirectional. The physical height of the antenna above the earth affects the signal amplitude as there is increased attenuation of the signal close to the ground.

The antenna should be as long as practical and as high as practical. A quarter wavelength for 540 kHz is (300,000/4)/540 = 139 meters. A quarter-wavelength at 1700 kHz is 44 meters. For a basic crystal radio there is little to be gained by an antenna longer than about 40 meters or higher than about 8 meters –that is a substantial antenna that few have the room to construct. A minimum antenna might be about 10 meters long and about 3 meters off the ground. Anything in-between can produce acceptable performance. Advanced crystal radio enthusiasts will construct bigger and more advanced antennas but that involves a degree of engineering beyond the scope of this article.

One advanced method that the author has not had the space to try is a true dipole antenna that is one-half wavelength long (in some cases longer). Such an antenna is balanced and so does not depend on a low-impedance ground for operation. The power received by the antenna would be significantly more than that of the simple long wire antennas described in this article. With such an antenna a local station could drive a speaker to significant volume. But, the antenna is only useful over a narrow band of frequencies and is also directive so it must be oriented properly relative to the transmitting antenna.

Figure 1 shows a typical antenna and ground setup for a crystal radio. The following sections discuss each attribute.



Figures 3.a through 3.f show simulation results for circuit of Fig.1.b at resonance frequencies also of 530kHz, 1MHz and 1.7MHz. Again, r = 30 ohms and Ca = 200pF.
Re = $2Rs_1$ , and it can be easily shown that:

$$R_{s1} = r\left(1 + \frac{A}{R_p}\right)$$

The Y axis on the graphics represents voltage across Re in decibels, with Ea being a 1 volt-amplitude unmodulated carrier.

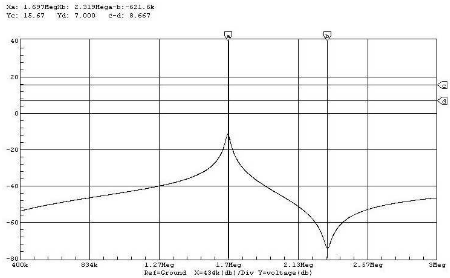



Fig.2.e Frequency response of circuit of Fig.1.a
when resonance is adjusted to 1.7MHz

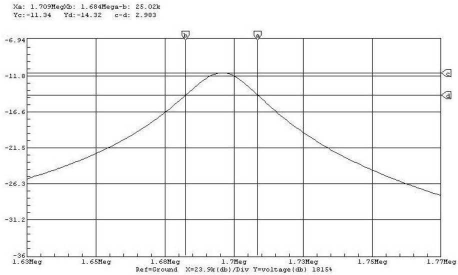



Fig.2.f 3dB bandwidth for a resonance frequency of
1.7MHz is 25.02kHz



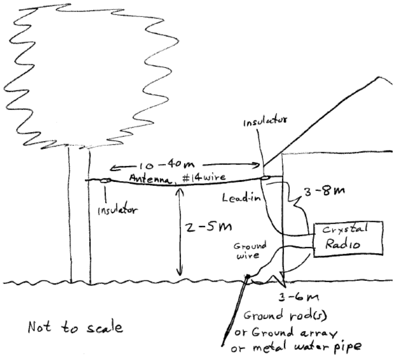



Figure 1: Basic Antenna System for a Crystal Radio

**Distal support**

If available, a tree makes a convenient support for the antenna wire. Otherwise some kind of post will have to be constructed. Never use a utility pole or any other support that is not your property –your potential liabilities could be astronomical if some accident (lightning for example) or failure causes damage to someone else’s property or person. An insulator typically made of ceramic or plastic is used to terminate the antenna wire and to connect to the antenna support usually via some kind of rope. These insulators are readily available from various hobby electronics sources. A large wood screw typically with a hook or eye end driven into a tree or other support is used as an attachment point for the rope. Do not wrap the rope around the tree as that will constrict growth in future years.

**Antenna wire**

The antenna wire is typically #14 AWG solid or stranded copper wire and may or may not be insulated. Insulation has no effect on reception but is an advantage to reduce corrosion effects. There is no advantage to using heavier wire such as #12 or #10 as the resistance of the wire is negligible compared to everything else and the added weight makes the end supports more challenging. Wire sizes of #16 and #18 also work well but are less strong –but are also lighter and will put less stress on the supports. Wire gauge sizes higher than 18 are not recommended because they are more fragile and are hard to see if they fall –you would like to not run over the wire with a lawn mower –could be very disastrous! Although low resistance is nice, it is a myth to go to great efforts for low resistance in the antenna wire as the resistance of the ground is going to be considerably higher.

The height of the antenna absolutely must be above head level for someone who might be standing on some vehicle (i.e. bicycle or motorcycle) that might possibly travel under the antenna to prevent what could be a horrible or even tragic accident –this means at least 3 meters. The antenna wire should not pass over anything such as a road or other wires such as electrical power such that if the antenna fell that a dangerous situation could result. Within practical limits the higher the antenna the more signal it will pick up. That does not extend indefinitely and there is a point of diminishing returns reached at roughly 5 meters. If it is easy for you to make the antenna higher then do so but there is little point in going to great effort to achieve that as you will only notice a difference in the extreme small signal case.



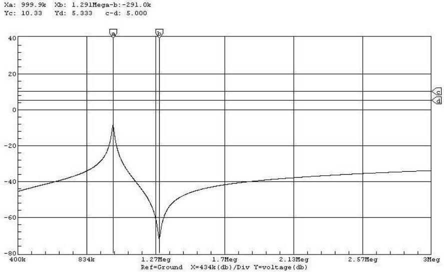



Fig.2.c Frequency response of circuit of Fig.1.a when resonance is adjusted to 1MHz

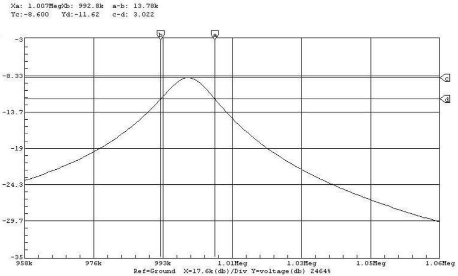



Fig.2.d 3dB Bandwidth for a resonance frequency of 1MHz is 13.78kHz

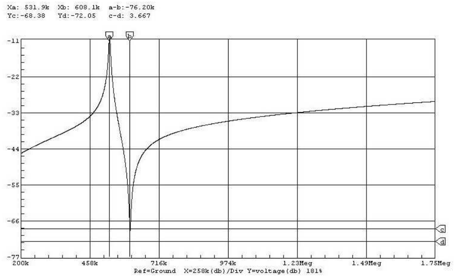



Fig.2.a Frequency response of circuit of Fig.1.a
when resonance is adjusted to 530kHz

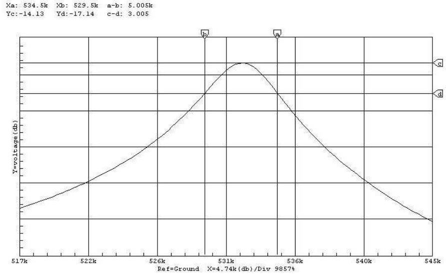



Fig.2.b 3dB bandwidth for a nominal
resonance frequency of 530kHz is 5.005kHz.
Actually, the resonance frequency is 532kHz.



**Proximal support**

This support is similar to the distal support and may be attached to either the dwelling or a convenient tree that happens to be close. An insulator supports the antenna and rope. The lead-in wire attaches to the antenna at the insulator. It is important to make sure that the support can break away without damaging the structure should something fall on the antenna wire.

**Lead-in wire**

The lead-in wire can be whatever is convenient and is often #18 wire. Since the antenna system is much shorter than one-quarter wavelength the lead-in counts as part of the antenna length. Thus, if the antenna wire was 25 meters and the lead-in wire was 5 meters, the total antenna length would be 30 meters.

**Lightning arrestor**

A lightning arrestor is an important part of the antenna system that is located outside the building and usually close to where the antenna and ground wires penetrate. A lightning arrestor consists of a spark gap that will arc when more than a few hundred volts exists across the points. Contrary to the name, a lightning arrestor will not protect you or the dwelling from a direct lighting strike. A lightning arrestor will reduce the probability of damage to your crystal set and anything nearby should lightning strike in the vicinity. A nearby strike can induce many hundreds or even thousands of volts on the antenna that could cause damage or injury. The lightning arrestor will then arc to limit the voltage to typically several tens of volts. You should never operate a crystal radio if there is any possibility of a lightning strike. A number of people install shorting switches or connections to connect the antenna to ground when the radio is not being used. This provides some measure of safety but is not absolute. Nothing can protect you or your dwelling from a direct lightning strike.

**Ground wire and ground system**

The ground wire is typically #18 copper (because that is a convenient size) and should connect to either a nearby metal water pipe or some ground system –either buried pipe or ground rod(s). It is a myth to use wide braid or other large conductor for the ground wire as the resistance of a short length of #18 is negligibly small in comparison to the earth. It is nice for the wire to be no longer than necessary because inductive reactance in the wire can interfere with the operation of the radio –but that is a small point.

Most difficulties or frustrations with crystal radios can be traced to a poor ground system. Building a good ground system is the most labor intensive and even most expensive part of a crystal radio. If you are lucky then there is a long metal water pipe located just outside the window of your crystal radio. In that special case your ground system is easy and cheap.

If you are not so lucky then one alternative is to drive three or more 2.4 meter (8 foot) ground rods straight into the ground near the house. These should be spaced roughly 2 meters apart. The quality of this ground can vary a lot depending on soil conditions and it is not likely to be as good as that of a water pipe. At the easiest, this is a very labor intensive to even impossible job if the ground is very hard. A heavy duty hammer drill can make the job easier. Otherwise you will need



Simulation results

Figures 2.a through 2.f illustrate simulation results for circuit of Fig.1.a at resonance frequencies of 530kHz, 1MHz and 1.7MHz. Assumed values for r and Ca are 30 ohms and 200pF, respectively. The values for $R_T$ are those obtained when the secondary load $R_2$ is impedance matched to the primary side (please refer to part II). Notch frequencies occurring above resonance can be observed on the graphics. The Y axis represents voltage across r in decibels with Ea being a 1volt-amplitude unmodulated carrier.

## Analysis of the Tuggle Front End – Part III

As a first approximation, the 3dB bandwidth of the antenna-ground-lossy tuner system under matched load conditions can be computed assuming that the $L_1$-C tank behaves as an equivalent constant inductance Leq in the 3dB passband, this inductance being in series with the rest of the circuit. However, this approach leads to large errors in the results, as suggested by a SPICE circuit simulation.

A precise model for accurate bandwidth computation is shown in Fig.1.a below. $R_T$ is the net RF resistance in parallel with the $L_1$-C tank at $\omega = \omega_r$ , as found in part II of our study. Ground losses Rg and antenna radiation resistance $r_a$ are accounted for by r. However, calculations on this circuit are rather tedious. Simulation shows that the circuit depicted in Fig.1.b can be alternatively employed for bandwidth computation with equivalent results to those given by the circuit of Fig.1.a. Here, Re = $2Rs_1$ (please refer to part II). Circuit calculations in this case are much more simple.

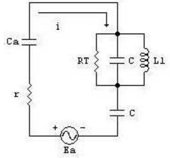



Fig.1.a Equivalent circuit for accurate 3dB bandwidth calculation

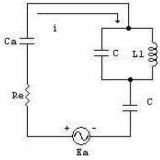



Fig.1.b Alternative circuit for bandwidth calculation as suggested by simulation



a very heavy sledge hammer and strong and enduring muscles as well as significant patience.

An alternative is to dig a shallow trench at least 0.2 meters deep and bury a 10 meter or more length of copper pipe. It helps for the soil to be wet down to the level of the pipe when the radio is being used. This can make a decent ground for radio reception although it should in no way be considered a "safety" ground.

The following table provides a general idea of the quality of the ground system.

| Ground Quality | Resistance |
|---|---|
| Excellent | < 10 ohms |
| Good | 10 to 20 ohms |
| Fair | 20 to 40 ohms |
| Poor | 40 to 100 ohms |
| Bad | > 100 ohms |

A good question is how to measure the ground resistance. This is kind of hard to do since you have access to only one wire. Where is the other end that we measure with respect to? The answer is that it is nebulous but there does exist an effective point that completes the circuit for the radio signal. The effective ground resistance can be inferred from measurements using a received signal. The method is discussed in another chapter. Mathematical model of the antenna and ground system

A simple electrical model of a short wire antenna less than one-quarter wavelength is shown in Figure 2. It consists of a voltage source equal to the induced amplitude with a small series resistance and very large series capacitive reactance. A simple electrical model of the ground circuit is a series resistance that may range from single digit ohms (an excellent ground) to several tens of ohms. A poor ground may have a series resistance of over one hundred ohms.

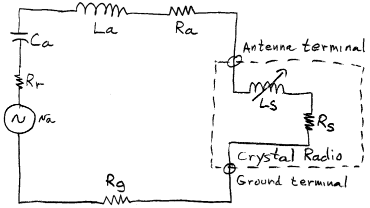



Figure 2: Simple Circuit Model for Antenna and Ground

**Signal pickup**

The radio frequency field strength is measured in volts/meter (or amperes/meter if you divide volts/meter by the free space impedance of 377 ohms). This is a cyclic voltage gradient. The voltage that will be induced in a conductor that is short in comparison to a quarter wavelength is roughly the RF signal multiplied by the length of the conductor. Proximity of the conductor to other conductive objects (such as trees and the earth) will reduce the induced voltage. This is one reason why it is desirable for the antenna to be as high as practical above the earth. There is no difference between the antenna proper and the lead-in so the total length is what counts. In Figure 2 this voltage is shown as Va.



Comments:

The values obtained for the coupling coefficient K hold for $R_2 = \frac{R_{TNK}}{3}$, as discussed previously. The transformed antenna-ground system resonance resistance, as seen from the secondary, will be equal to $R_2$, or $\frac{R_{TNK}}{3}$, as we are dealing with maximum power transfer to $R_2$. Under these conditions, the loaded Q of the secondary circuit will be 1/6 of the unloaded value. For other load conditions, the respective data should be entered into eq.(9).

f = 530 kHz
$L_1$ = 152 uH
Ca = 200 pF (assumed)
r = 30 ohms (assumed)
A = 1.555 x $10^5$ ohms
$Q_1Q_2A$ = 2.938 x $10^{10}$ ohms
K = 4.165 x $10^{-3}$
Check:

$$\frac{R_P}{1+K^2Q_1Q_2} = 82.8 kohms >> \omega_r L_{eq} = 2.214 kohms$$

f = 1 MHz
$L_1$ = 152 uH
Ca = 200 pF (assumed)
r = 30 ohms (assumed)
A = 1.9 x $10^5$ ohms
$Q_1Q_2A$ = 2.334 x $10^{10}$ ohms
K = 5.663 x $10^{-3}$
Check:

$$\frac{R_P}{1+K^2Q_1Q_2} = 113.1 kohms >> \omega_r L_{eq} = 2.387 kohms$$

f = 1.7 MHz
$L_1$ = 152 uH
Ca = 200 pF (assumed)
r = 30 ohms (assumed)
A = 4.068 x $10^5$ ohms
$Q_1Q_2A$ = 1.29 x $10^{10}$ ohms
K = 8.324 x $10^{-3}$

Check:

$$\frac{R_P}{1+K^2Q_1Q_2} = 152 kohms >> \omega_r L_{eq} = 3.498 kohms$$



**Radiation resistance**

There is an effective radiation resistance associated with the total antenna length. For electrically short antennas this may only be a few ohms but can rise to several tens of ohms as the antenna length approaches one quarter wavelength. In Figure 2 this resistance is shown as rr.

**Antenna reactance**

An antenna has both a series capacitance and series inductance that makes up a net reactance that varies with wavelength. Capacitive reactance dominates if the antenna is shorter than one-quarter wavelength and inductive reactance dominates between one quarter and one-half wavelength at which capacitive reactance dominates again for the next quarter wavelength, etc. Normal antennas for crystal radios are significantly shorter than one-quarter wavelength so there is a large capacitive reactance in series with the induced voltage. The inductive reactance reduces the net reactance somewhat for short antennas. At quarter-wave resonance the reactance terms cancel and the antenna is purely resistive. In Figure 2 these are shown as Ca and La.

**Antenna resistance**

The antenna wire has electrical resistance that is mainly due to the skin effect of the conductor since the frequency is high. This resistance is typically a few ohms and is often small in comparison with the ground resistance. In Figure 2 the antenna wire resistance is shown as Ra.

## Antenna tuner inductance

The first element typically found in a crystal radio is an adjustable inductor to neutralize the capacitive reactance of the antenna thus maximizing the power transfer from the antenna to the receiver input resistance. This is known as conjugate matching where the sum of the positive inductive reactance of the inductor and negative capacitive reactance of the antenna is zero. In Figure 2 this inductance is shown as Ls for series inductance.

## Crystal radio input resistance

The crystal radio generally appears as a pure resistance at resonance with a received signal. For optimum power transfer this resistance should be equal to the sum of the ground plus antenna plus radiation resistance. The ground resistance typically dominates this equation. The input resistance of the radio can be adjusted via taps on the tuning inductor or other matching network. For best performance it is important to match the radio to the antenna and ground system. Failure to do this results in an underperforming radio.

## Ground resistance

The ground resistance completes the circuit back to the rather nebulous point that is the effective reference for the radio frequency signal. Ideally, this resistance is less than 10 ohms but typically is in the 10 to 100 ohm range.

A single short wire antenna is unbalanced and a low-impedance ground is required to complete the RF circuit. It is easy to set up a simple wire antenna that can work well but it is a challenge to construct a low-impedance ground. Without a low-impedance ground much of the signal picked up by the



## Some experimental results

Two coils, $L_1$ and $L_2$, were wound on 4.5” diameter styrene forms using 660/46 Litz wire. $L_1$ measured 152 uH and $L_2$, 222 uH. A two-gang 475 pF variable capacitor with bakelite insulation was used to tune $L_1$. $L_2$ was tuned with a 480 pF variable capacitor with ceramic insulators.
Unloaded Qs for each of the tuned circuits were measured at three frequencies. Accordingly, the corresponding RF losses were calculated. Data is tabulated below.

| f | $Q_1$ | $Q_{2UL}$ | $Q_2$ | $R_{Pcalc}$ | $R_{TNKcalc}$ | C | $C_2$ |
|---|---|---|---|---|---|---|---|
| 530kHz | 700 | 810 | 270 | 354.32 kohms | 598.816 kohms | 450 pF | 406 pF |
| 1 MHz | 585 | 630 | 210 | 558.70 kohms | 878.766 kohms | 100 pF | 114 pF |
| 1.7 MHz | 300 | 318 | 106 | 487.072 kohms | 754.065 kohms | 31 pF | 39.5 pF |

C : two-gang 475 pF variable capacitor with bakelite insulation
$C_2$ : 480 pF variable capacitor with ceramic insulation
$Q_{2UL}$ : unloaded Q of $L_2$-$C_2$ combination
$Q_1$, $Q_2$ : defined in the text
$R_P$, $R_{TNK}$: defined in the text

Using the tabulated data, values for the optimum coupling coefficient K will be calculated for a working crystal set.

$$R_{s1} = (\omega_r L_{eq})^2 \left(\frac{N^2 L_2}{L_1}\right)\left(\frac{Q_1 Q_2}{R_P}\right)$$

$$= (\omega_r L_{eq})^2 \left(\frac{N^2 L_2}{L_1}\right)\left(\frac{1}{\omega_r L_1}\right)\left(\frac{R_2}{\omega_r L_2}\right)$$

$$= \left(\frac{L_{eq}}{L_1}\right)^2 N^2 R_2$$

$$= \left(\frac{2Ca + C}{Ca}\right)^2 N^2 R_2$$

or:

$$N^2 R_2 = \left(\frac{Ca}{2Ca + C}\right)^2 R_{s1}$$

Substituting this equivalence into eq.(13):

$$P_2 = \frac{{E_a}^2}{8R_{s1}} = P_{MAX}$$

according to eq.(10).
$P_{MAX}$ is then dissipated by $N^2R_2$ and by consequence, this power is delivered to the secondary load.



antenna will be wasted and the crystal radio will perform poorly if at all. Much frustration from poor performance of a crystal radio set is often caused by a high-impedance ground. An ideal situation is to connect the crystal radio set to a metal water pipe (either old-fashioned galvanized or preferably copper). The long exposure length to the earth produces a low-impedance ground in the low tens of ohms. The impedance is even lower if the soil is very organic and wet from a recent rain. Dry sandy soils are the worst. One common error is connecting to a metal water pipe assuming that there are no plastic pipe lengths involved.

If a metal water pipe is not available then it might be tempting to connect to the ground system of the electrical distribution in the house or building. For safety considerations I do not recommend this. In the vast majority of cases it may be alright but you never know what errors or faults may be in the system that could result in a nasty or lethal surprise. Even if safety were not an issue, because of inductance the impedance of the ground system at radio frequencies will be much higher than the impedance at 60 Hz. So, this practice is dangerous at worst or is not likely to work well at best. There are basically only two choices for constructing your own ground. One is to purchase several standard eight foot ground rods and laboriously install them spaced six or more feet apart. This can make a decent ground but is very difficult (impossible is probably more accurate) without the right equipment for installation. An easier alternative that is fine for RF (although not recommended for 60 Hz systems) is to bury a length of bare copper wire or pipe perhaps six to twelve inches below the surface of the ground. Deeper is better but the incremental improvement is probably not worth the extra labor. The total length should be fifty feet or more and parallel runs spaced several feet apart can be used to accumulate effective length. AM broadcast stations use such a system with many buried radial wires from the tower. Each wire is typically a quarter wavelength and the total wire length of all the radials is often over a mile. Such extreme measures are necessary for a high power transmitter because otherwise many thousands of watts could be wasted. The much more modest system described is fine for home use and a point of diminishing returns is quickly reached.

Figure __ shows the theoretical radiation resistance for a single wire antenna that is shorter than one-half wavelength calculated under the assumption that there are no nearby objects that interfere with the impedance. For most situations the antenna is not very far above the ground and the actual resistance will likely be somewhat less than shown. But this is a reasonable model to use for analysis.

Figure __ shows the theoretical series capacitive reactance

How much signal can be received? With a variety of impedance transformations we can obtain most any voltage or current we want but what really matters is how much power we can receive. It is power that will make audible sounds in our earphones. Assuming that there are no losses and that the load consists of an inductor with the same magnitude of reactance as the antenna capacitive reactance in series with a resistive load equal to the radiation resistance of the antenna, then the power delivered to the resistive load is:

P = (V/m/2 * L)^2 /(40*pi^2*L^2*FMHz^2 /300^2)

= (V/m)^2 *57 / FMHz^2



$$R_{s1} = \left(\omega_r L_{eq}\right)^2 \frac{K^2 Q_1 Q_2}{R_P} \quad \ldots(12)$$

Then:

$$\frac{\omega_r L_{eq} K^2 Q_2}{R_{s1}} = \frac{R_P}{\omega_r L_{eq} Q_1}$$

$$= \frac{L_1}{L_{eq}}$$

$$= \frac{Ca}{2Ca + C}$$

Then, we obtain:

$$E_2{}' = \frac{E_a}{2}\left(\frac{Ca}{2Ca + C}\right)$$

The power dissipated by $N^2R_2$ is:

$$P_2 = \frac{\left(E_2{}'\right)^2}{2N^2R_2}$$

$$= \frac{\left(\frac{E_a}{2}\right)^2\left(\frac{Ca}{2Ca + C}\right)^2}{2N^2R_2} \quad \ldots(13)$$

Eq.(12) can be written as follows:

$$E_2' = \frac{E_{Leq}}{j\omega_r L_1 + N^2 R_2} N^2 R_2$$

In crystal sets, $N^2 R_2 << \omega_r L_1$, due to the loose coupling between $L_1$ and $L_2$. Then:

$$E_2' = \frac{E_{Leq}}{j\omega_r L_1} N^2 R_2$$

$$= \frac{E_{Leq}}{j\omega_r L_1} \left[ \frac{(\omega_r L_1)^2}{R_{P1}} \right]$$

$$= \frac{E_{Leq}}{jR_{P1}} \omega_r L_1$$

Bearing in mind eq.(3):

$$E_2' = \frac{E_{Leq}}{j} K^2 Q_2$$

Substituting the value of $E_{Leq}$ given by eq.(11) into the above expression we obtain:

$$E_2' = \frac{E_a}{2R_{s1}} \omega_r L_{eq} K^2 Q_2$$

We can recall that:



**MATHEMATICAL MODEL OF A WIRE ANTENNA**
by Kenneth A. Kuhn
www.kennethkuhn.com/.../mathematical_model_of_wire_antenna.pdf

**Introduction**

Although very simple in structure, the mathematical model of a wire antenna is extremely complicated. There are so many variables that it is basically impossible to accurately model. However, a reasonable model can be derived that provides useful information and understanding. That is essential for doing engineering. An imperfect model is far better than no model. We begin with the simplest possible model (that is always a good starting point!). Then, we refine the model to include more advanced concepts. We keep refining until we have accounted for all significant variables that provides useful information.

A wire antenna consists of some length of wire at some height over the earth. Such a structure will have some capacitance to the earth, some inductance, and some resistance. The resistance term is more complicated than just the simple ohmic resistance of the wire as it includes a series term known as radiation resistance. In very simple terms radiation resistance accounts for a flow of energy between the antenna and free space involving time-dependent electromagnetic fields not considered in a simple RLC circuit. Our initial model is based on frequencies much less than that where the antenna is one-quarter wavelength resonant. For typical crystal radio applications this is not a bad model as it is rare to have the luxury of enough space to construct an antenna approaching one-quarter wavelength in the AM broadcast band.

## Capacitance

We start with the capacitance of the antenna to the earth. From the basic laws of physics, a capacitance will exist between any two conductors separated by insulation. Here, we are making the rather crude assumption that the earth is a good conductor. That turns out not to be bad as we will see that the reactance of this capacitance at frequencies in the AM broadcast band is large compared to the actual resistance of the earth. A brief but excellent derivation of the capacitance between a cylinder (i.e. the antenna wire) and a plane is provided in Reference 1. The summary result is:

$$\text{Capacitance per meter} = \frac{2 * \pi * \varepsilon 0}{\ln(2 * \text{height} / \text{diameter})} \quad \text{Eq. 1}$$

where height and wire diameter are in meters and ε0 is the permittivity of free space, 8.85 pF/meter. Note that this equation assumes that propagation time over the wire length is negligibly small. This equation also assumes that the earth is a perfect conductor.

Although there is an error when considering the composite antenna, there is no error for an incremental portion that satisfies the assumptions.

A quick example indicates that a 20 meter antenna of #14 wire (1.63 mm dia.) at a height of 3 meters would have a total capacitance of 135 pF at frequencies low enough so that the propagation time over the length is negligibly small. That is not true for broadcast band frequencies and the capacitance will be smaller as will be seen in the plots at the end.

## Inductance



$$K = \sqrt{\frac{R_P + A}{Q_1 Q_2 A}} \qquad \ldots(9)$$

which gives the value of the coupling coefficient for maximum RF power transfer to the secondary.

## Power calculations

The RF power delivered to the secondary load of Fig.1 will be at a maximum at resonance when eq.(6) is satisfied, this is, when $r + R_s = R_{s1}$. The maximum available power is then:

$$P_{MAX} = \frac{\left(\frac{E_a}{2}\right)^2}{2R_{s1}}$$

$$= \frac{E_a^{\ 2}}{8R_{s1}} \qquad \ldots(10)$$

where $E_a$ is the peak value of the voltage induced in the antenna.
The power delivered to the secondary load $R_2$ is the same as that dissipated by the coupled resistance $N^2R_2$. To compute this power we need the voltage across $L_1$ at resonance. This is the same as the voltage across $L_{eq}$ in Fig.6.a. Then:

$$E_{Leq} = \frac{E_a}{2R_{s1}} j\omega_r L_{eq} \qquad \ldots(11)$$

From Fig.5 we obtain for the voltage across $N^2R_2$:

$$= L_1\left(2+\frac{C}{Ca}\right) \quad \ldots(7)$$

being

$$\omega_r^{\ 2} = \frac{1}{L_1 C}\left(\frac{Ca+C}{2Ca+C}\right)$$

Then:

$$\left(\omega_r L_{eq}\right)^2 = \frac{1}{L_1 C}\left(\frac{Ca+C}{2Ca+C}\right)L_1^{\ 2}\left(\frac{2Ca+C}{Ca}\right)^2$$

$$= \frac{L_1}{C}\left(2+\frac{C}{Ca}\right)\left(1+\frac{C}{Ca}\right)$$

Eq.(6) is now written as:

$$\frac{L_1}{rC}\left(2+\frac{C}{Ca}\right)\left(1+\frac{C}{Ca}\right) = \frac{R_P}{K^2 Q_1 Q_2 - 1} \quad \ldots(8)$$

Letting $A = \frac{L_1}{rC}\left(2+\frac{C}{Ca}\right)\left(1+\frac{C}{Ca}\right)$, eq.(8) takes the more compact form:

$$A = \frac{R_P}{K^2 Q_1 Q_2 - 1}$$

Solving for K we obtain:



On page 141 of Reference 1 the inductance of a wire over a plane is given as

$$\text{inductance per meter} = \frac{\mu 0}{2 * \pi} * \ln(2*\text{height} / \text{diameter}) \quad \text{Eq. 2}$$

where height and wire diameter are in meters and μ0 is the permeability of free space, 4*π*1E-07 henries/meter. Equation 2 simplifies to

inductance per meter = (0.2 uH) * ln(2*height / diameter) Eq. 3

A quick example indicates that a 20 meter antenna of #14 wire (1.63 mm dia.) at a height of 3 meters would have a total inductance of 33 uH if propagation time is negligibly small. Note that Equation 2 assumes that the current is uniform over the length of the wire and that propagation time is negligibly small. The first part of the assumption can not be true for our antenna as the far end is an open circuit. The equation also assumes that the earth is a perfect conductor. The typical error for our use in antennas for crystal radios falls into the category of not bad. We are not going to worry about it as this is just a starting point and we are going to make refinements. Although there is an error when considering the composite antenna, there is no error for an incremental portion that satisfies the assumptions.

**Resistance**

The resistance of a wire antenna is the sum of the ohmic resistance including skin effect and the radiation resistance. The resistance of #14 wire including skin effect at a frequency of 1 MHz is around 0.05 ohms per meter. Thus a 20 meter antenna would have a total resistance of 1 ohm. This assumes that the current is uniform over the length which can not really be true since the far end is an open circuit. However, this is not going to be an issue for us as the resistance of the ground will be significantly larger.

The ohmic resistance represents a power loss. Radiation resistance becomes a factor when we consider the coupling of energy between the antenna and electromagnetic fields of free space. The concept is easy to understand in the case of a transmitter which delivers power to the antenna (perhaps significant power in the case of a 50 kW transmitter!) but with efficient design the heating of the antenna is very small –i.e. the power is radiated as an electromagnetic wave instead of being converted to heat –i.e. power is coupled to free space. The transmitter delivers the power to the antenna as some voltage and some in-phase current. Thus, the antenna appears to have a resistance. That resistance is known as the radiation resistance. Unlike ohmic resistance, it does not represent a power loss –it represents a power coupling to free space instead. There is no magic or optimum value for antenna impedance. However, values between single digit ohms and several hundred ohms are the easiest to interface to and so are preferred.

It is not as easy to visualize radiation resistance when the antenna is used for reception. However, the concept of reciprocity applies. Thus, however an antenna appears in the transmitting case, it appears identically in the receiving case. The calculation of radiation resistance is very complicated at the easiest. At this point in our model development we have no way to determine what the radiation resistance of our antenna might be. However, the incremental capacitance and inductance are essential for the next level model.



$$= (\omega_r L_{eq})^2 \left( \frac{1 + K^2 Q_1 Q_2}{R_P} \right)$$

$$= \frac{(\omega_r L_{eq})^2}{R_P} + (\omega_r L_{eq})^2 \frac{K^2 Q_1 Q_2}{R_P}$$

Let $R_s = \frac{(\omega_r L_{eq})^2}{R_P}$ and $R_{s1} = (\omega_r L_{eq})^2 \frac{K^2 Q_1 Q_2}{R_P}$.

$R_s$ is the series term due to $R_P$ and $R_{s1}$, that coming from the coupled resistance $N^2R_2$. Now, maximum RF power transfer to $N^2R_2$ occurs when:

$$r + R_s = R_{s1}$$

or when:

$$r + \frac{(\omega_r L_{eq})^2}{R_P} = (\omega_r L_{eq})^2 \frac{K^2 Q_1 Q_2}{R_P}$$

or

$$\frac{(\omega_r L_{eq})^2}{r} = \frac{R_P}{K^2 Q_1 Q_2 - 1} \qquad \ldots(6)$$

From part I of this study we know that:

$$L_{eq} = \frac{L_1}{1 - \omega_r^2 L_1 C}$$

If $R_T >> \omega_r L_{eq} = \dfrac{\omega_r L_1}{1-\omega_r^{\ 2} L_1 C}$ (please refer to part I of this study) we can redraw the equivalent circuit of the tuner at resonance as indicated by Fig.6.a, and, by virtue of the above inequality, the resonant frequency $\omega_r$ will still be given by:

$$\omega_r^{\ 2} L_1 C \left(\frac{2Ca + C}{Ca + C}\right) = 1 \qquad \ldots(5)$$

Applying a parallel-to-series transformation, the equivalent circuit of Fig.6.b is obtained.

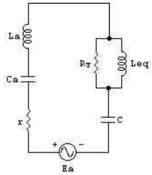



Fig.6.a Equivalent circuit of the tuner when $R_T >> \omega_r$Leq

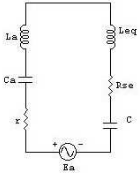



Fig.6.b Equivalent circuit after transformation

The series transformed resistance $R_{se}$ is given by:

$$R_{se} = \frac{(\omega_r L_{eq})^2}{R_T}$$



**A finite propagation time model**

This model is based on well-developed transmission line theory and treats the wire antenna as a lossy unterminated transmission line where the loss is electromagnetic radiation instead of heat. This model builds on the previous equations for capacitance and inductance and gives us a realistic picture of what goes on. In general, because there are a lot of variables that we are unable to quantify the accuracy of this model is not great. However, the model can be tweaked to provide a good fit to a specific scenario. That is what makes the model useful. It is great at providing us general information for understanding. Understanding what is going on can be more valuable than knowing specific data accurately.

The impedance looking into a transmission line is

$$Z = Z0 * \frac{(ZT/Z0) + \tanh(\alpha + j\theta)}{1 + (ZT/Z0) * \tanh(\alpha + j\theta)} \qquad \text{Eq. 4}$$

where:
Z is in ohms and is in general complex.
Z0 is the characteristic impedance of the line –often taken as real but could be complex.
ZT is the termination impedance at the end of the line and could be complex.
α is the loss over the length of the line.
θis the phase angle on the line and is equal to 2*π*length/wavelength.
j is the square root of -1.

The form of the equation I have chosen to use includes length in the α and θ terms as a matter of convenience. Other forms of the equation have the length as a multiplier on the inside of the tanh term.

If the terminating impedance is an open circuit as it will be for our wire antenna then we can write Equation 4 simply as

Z = Z0 / [tanh(α + jθ)] Eq. 5

For reference:

ex –e-x
tanh(x) = ----------- Eq. 6
ex + e-x

The Euler relations are:

ejθ = cos(θ) + j*sin(θ) Eq. 7

e-jθ = cos(θ) – j*sin(θ) Eq. 8

These relations let us write Equation 5 as

eα+jθ + e-α-jθ
Z = Z0 * ----------------
eα+jθ–e-α-jθ

eα* [cos(θ) + j*sin(θ)] + e-α* [cos(θ) –j*sin(θ)]
= Z0 * ------------------------------------------------------------
eα * [cos(θ) + j*sin(θ)] –e-α* [cos(θ) –j*sin(θ)]

(eα+ e-α)*cos(θ) + j*(eα–e-α)*sin(θ)
= Z0 * ------------------------------------------------ Eq. 9
(eα–e-α)*cos(θ) –j*(eα+ e-α)*sin(θ)



Let $Q_2 = \frac{R_2}{\omega_r L_2}$. Then:

$$R_{P1} = \frac{\omega_r L_1}{K^2 Q_2} \quad \ldots(3)$$

Next, we compute the equivalent resistance $R_T$ of the parallel combination of $R_P$ and $R_{P1}$. It is given by:

$$R_T = \frac{R_P R_{P1}}{R_P + R_{P1}}$$

Substituting $R_{P1}$ by its equivalent given by eq.(3):

$$R_T = \frac{R_P\left(\frac{\omega_r L_1}{K^2 Q_2}\right)}{R_P + \frac{\omega_r L_1}{K^2 Q_2}}$$

$$= \frac{R_P \omega_r L_1}{\omega_r L_1 + K^2 Q_2 R_P}$$

Letting $Q_1 = \frac{R_P}{\omega_r L_1}$ (unloaded Q of $L_1$-C tank) we obtain:

$$R_T = \frac{R_P}{1 + K^2 Q_1 Q_2} \quad \ldots(4)$$

Up to this point, in the tuner side we have the equivalent circuit depicted in Fig.5.

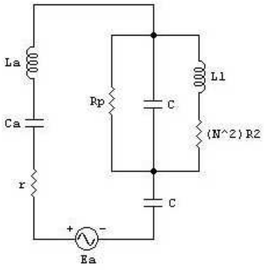



Fig.5 Equivalent circuit of the tuner with coupled secondary load

The series-coupled resistance $N^2R_2$ can be transformed into a resistance $R_{P1}$ in parallel with $R_P$. Using the known series-to-parallel "loss resistance" transformation we get:

$$R_{P1} = \frac{(\omega_r L_1)^2}{N^2 R_2} \qquad \ldots(2)$$



Although Equation 9 looks complicated it really consists of just three components and it is simple to substitute values and reduce it to a simple real plus imaginary result.

For reference: Eq. 10

```
A + jB       A + jB        C –jD       AC + BD          BC - AD
---------- = ----------- * ----------- = -------------- + j-------------
C + jD       C + jD        C –jD        C2 + D2          C2 + D2
```

Equation 10 gives us a basic method to evaluate the division of complex numbers.

When the series and shunt losses are low the characteristic impedance of a transmission line is

Z0 = sqrt(inductance per unit length / capacitance per unit length)    Eq. 11

We substitute Equations 1 and 2 into Equation 11 to obtain

```
                    [ μ0 ]
                 [ -------- * ln(2*height / diameter)]
                  [ 2 * π ]
Z0 = sqrt [---------------------------------------]                Eq. 12
                       [ 2*π*ε0 ]
                 [ ------------------------------- ]
                    [ ln(2*height / diameter) ]
```

which simplifies to

Z0 = 60.0 * ln(2*height / diameter)              Eq. 13

Thus, we make use of our previous work on the simple model.

The free-space wavelength in meters for a given frequency in MHz is

$\lambda = 300 / \text{FMHz}$ Eq. 14

The propagation velocity on wire antennas is about 95 percent of free space so we use

$\lambda = 285 / \text{FMHz}$ Eq. 15

$\theta = 2*\pi*\text{FMHz}*\text{length} / 285$ Eq. 16

So far this has not been too complicated. Now, we delve into the challenge of determining the remaining constant, α. This factor, which is a function of frequency, will determine the antenna impedance characteristics. There is no way to calculate this factor. Instead, we will use available information to fit an approximate equation to it. We begin by noting that the free space impedance of a half-wave dipole antenna is 73 ohms. Our wire antenna is only half of a dipole so the free space impedance will be nominally 37 ohms (rounded half of 73) at a frequency where the wire length is an electrical one-quarter wavelength.

However, our antenna is very close to the ground so the result must be modified. Reference 2 shows a theoretical plot of the impedance of a half-wave dipole over a perfectly conducting plane as a function of height. This plot is reproduced below.



In the transformer circuit, the impedance coupled to the primary side consists of a capacitance $C_2 / N^2$ in parallel with a resistance $N^2R_2$. Both are in parallel with the magnetizing inductance $K^2L_1$ (please see Fig.4.a).

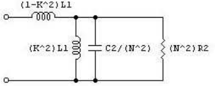


Fig.4.a Equivalent circuit as seen from the primary side

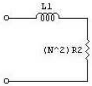


Fig.4.b Reduced equivalent at $\omega = \omega_r$

$K^2L_1$ and $C_2 / N^2$ resonate at a frequency

$$\omega_0 = \frac{1}{\sqrt{K^2 L_1 \left(\frac{C_2}{N^2}\right)}}$$

$$= \frac{1}{\sqrt{L_2 C_2}} = \omega_r$$

as

$$N^2 = K^2 \frac{L_1}{L_2}.$$

The equivalent circuit of Fig.4.a reduces to that of Fig.4.b, taking into account that for crystal set use, normally K<<1.

In this case, the net parallel resistance to be coupled to the primary is:

$$R_2 = \frac{R_{TNK}\left(\frac{R_{TNK}}{2}\right)}{R_{TNK} + \left(\frac{R_{TNK}}{2}\right)}$$

$$= \frac{R_{TNK}}{3} \qquad \ldots(1)$$

We shall work on this later.

Some circuit equivalents

In Fig.1, let´s replace $L_1$ and the coupled secondary circuit by the equivalent shown in Fig.3.a, which in turn can be replaced by the transformer circuit shown in Fig.3.b.

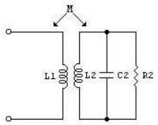



Fig.3.a Magnetically coupled circuits

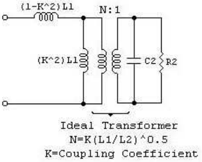



Fig.3.b Equivalent transformer circuit



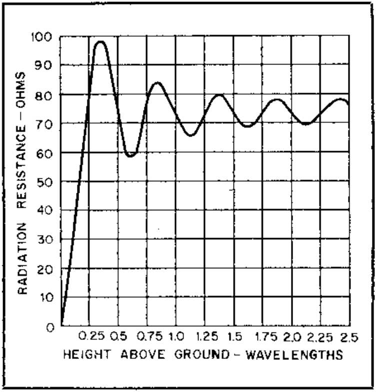



Figure 1: Theoretical impedance of half-wave dipole over perfect ground plane

Reference 2 describes that the impedance of a half-wave dipole over a realistic ground is very little affected by height over about one-half wavelength and the impedance soon attains the 73 ohm free space value.

We will use a simplified exponential to provide us with an approximate impedance of our antenna at the one-quarter wave resonant frequency. We first need a relation that converts the physical height of our antenna to height in wavelengths at the quarter-wave resonant frequency. This is provided by the following relation.

h/λ= height / wavelength = height * FMHz / 300    Eq. 17

R = 37 * (1 –e-k1*h/λ)    Eq. 18

The k1 value is chosen to be 7 because that provides the best least squares fit over the first 0.2 wavelengths of height. We can write this as

R = 37 * (1 –e-0.02333*height*FMHz)    Eq. 19

Equation 19 provides us with a target to set the appropriate value for α. At the frequency where the line length is one-quarter wave resonant, the cosine term in Equation 9 goes to zero and the sine term goes to one. This produces a real result with the imaginary part zero. It should be noted for this case that:

A = 0

B = eα–e-α

C = 0

D = 2

Using Equation 10 the above results in a resistance of

R = Z0 * (eα–e-α) / 2 = Z0 * sinh(α)    Eq. 20

We invert Equation 20 to obtain the required value for a for a given value of R as follows



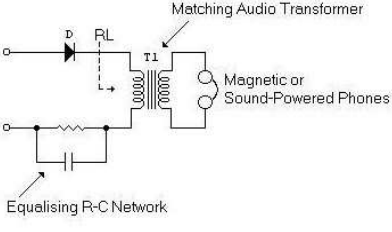



Fig. 2 Load coupled to the Tuggle tuner

Usually, it is assumed that optimum RF power transfer occurs when the antenna-ground system resonance resistance r is matched to the unloaded-secondary resonance parallel resistance $R_{TNK}$, with the diode detector´s input resistance matched to this combination. Thus,

$$\frac{1}{R_{OPT}} = \frac{1}{R_{TNK}} + \frac{1}{R_{TNK}} + \frac{1}{\left(\frac{R_{TNK}}{2}\right)}$$

or

$$R_{OPT} = \frac{R_{TNK}}{4}.$$

This is the overall parallel RF resistance of the secondary tank under matched conditions, and suggests that the unloaded Q of this tank circuit has been reduced to ¼ of its value.

## Analysis of the Tuggle Front End – Part II

We shall now consider the Tuggle tuner delivering power to a load. First, we must account for the parallel RF losses of the unloaded tuned circuits. Let $R_P$ represent the losses of the tank circuit comprising $L_1$ and C, and $R_{TNK}$ those of $L_2$ and $C_2$ (please see Fig. 1).

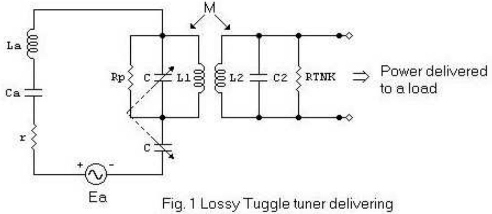



Fig. 1 Lossy Tuggle tuner delivering power to the secondary load

The load consists of a diode detector D in series with an audio load $R_L$ (usually an audio transformer matching a pair of 2k ohms DC resistance magnetic headphones or low-impedance sound powered phones to the detector) and is coupled to the tuner via the magnetic coupling existing between $L_1$ and $L_2$, being M the mutual inductance of the coils. The secondary is tuned to the same radian frequency as the primary. An schematic for the load can be seen in Fig. 2.



α= sinh-1(R/Z0) = ln[(R/Z0) + sqrt[(R/Z0)2 + 1)]]     Eq. 21

Before continuing, let us review where we are at. We know Z0 from the height and diameter of the antenna wire. We know a target resistance, R, for the antenna impedance at the one-quarter wave resonant frequency based on the height. Equation 21 lets us calculate αfor that frequency. We need to expand this so that we can calculate the appropriate αfor any frequency.

We make use of the following general knowledge about wire antennas to complete our model. At frequencies well below the one-quarter wave resonance the resistive component of the antenna impedance is practically zero. At frequencies where the antenna is many quarter wavelengths long the resistive component of the antenna impedance converges to Z0. This suggests that we have a basic scale factor on αand a multiplier based on the number of quarter wavelengths are on the line. This leads us to Eq. 22

α= k0 * Z0 * 37 * (1 –e-0.02333*height*FMHz) * (F / Fq)
where:

k0 is a constant to achieve the target quarter-wave resonant impedance
Z0 is the characteristic impedance of the antenna
height is in meters
F is the frequency in MHz

Fq = (71.25 / length) and is the frequency in MHz where the antenna is one-quarter wave resonant

The only unknown in Equation 22 is k0. We calculate k0 when F is equal to Fq. The procedure is as follows:

First we set FMHz = Fq from the above relation

R = 37 * (1 –e-0.02333*height*FMHz)    Eq. 19

Z0 = 60.0 * ln(2*height / diameter)    Eq. 13

α= sinh-1(R/Z0) = ln[(R/Z0) + sqrt[(R/Z0)2 + 1)]]    Eq. 21

k0 = α/ (Z0 * R)    Eq. 23

Studies done with this equation indicated very good results as long as the frequency was greater than the quarter-wave resonance. For lower frequencies this model gave very poor results –indicating significantly higher impedance than reality and even a negative slope in some cases. A modifier to the model was needed to highly attenuate αfor low frequencies only. The factor, (1 –1/(1 + 0.14*(F/Fq)2+ 1.0*(F/Fq)3 + 0.79*(F/Fq)4 + 50*(F/Fq)24)), was determined to significantly improve results. The factors were derived from a least squares fit to an alternative equation for short dipoles provided by reference 3 –shown below modified for only half a dipole.

R = 40*π2*(L/λ)2    Eq. 24

where L is the antenna length and λ is the wavelength, both in meters. This equation is reported to give good results up to about 0.2 wavelengths. A plot showing the fitted model to Equation 24 is shown below. Note that the model has an excellent fit to the theoretical "correct" model for wavelengths shorter than 0.2. The "correct" model under predicts the resistance for longer wavelengths and the effect of the 24th power term comes into play to bring the resistance close to the theoretical 37 ohms at 0.25 wavelengths. This is not exactly what goes on but is a simple to work with fit.



The circuit will tune up to:

$$f_{MAX} = f_{MIN}\left(\frac{C_{eqMAX}}{C_{eqMIN}}\right)^{\frac{1}{2}}$$

$$= 2.128MHz$$

If we use for C a variable capacitance with
$C_{MIN}$ = 20 pF and $C_{MAX}$ = 365 pF, then
$C_{eqMIN}$ = 38.18 pF and $C_{eqMAX}$ = 494.20 pF, giving for the required inductance L a value of 182.46 uH. The circuit will tune up to $f_{MAX}$ = 1.906 MHz.

Acknowledgements: Special thanks are given to Ben Tongue for his comments on the manuscript and for encouraging further mathematical analysis of the circuit regarding bandwidth variation with frequency, which will be done shortly.

After some algebraic manipulation we obtain:

$$\omega_r^{\,2} LC\left(\frac{2Ca + C}{Ca + C}\right) = 1 \qquad \ldots(3)$$

The equivalent capacitance resonating with L is:

$$C_{eq} = C\left(\frac{2Ca + C}{Ca + C}\right)$$

Clearly, $C_{eq} > C$.

Following is a numerical example illustrating the use of the above results.
Let C be a variable capacitance with
$C_{MIN}$ = 20 pF and $C_{MAX}$ = 475 pF.
Let also $C_a$ be 200 pF.
Then, $C_{eq}$ varies between
$C_{eqMIN}$ = 38.18 pF and $C_{eqMAX}$ = 615.74 pF.

If we wish to tune the MW broadcast band starting at 530 kHz, then the required inductance L will be:

$$L = \frac{1}{\omega_{rMIN}^{\,2} C_{eqMAX}}$$

$$= 146.45uH$$



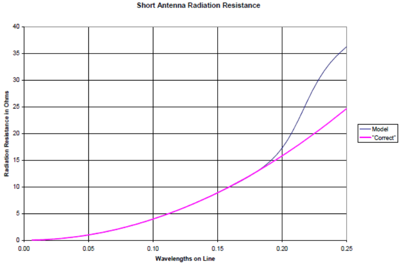



Figure 2: Model fit to short antenna radiation resistance

The complete equation for α is (using n = F/Fq) is shown below. Eq. 25

α= k0*Z0*37*(1 –e-0.02333*height*F)*n*

$$(1 - \frac{1}{1 + 0.14*n2 + 1.0*n3 + 0.79*n4 + 50*n24})$$

To calculate the approximate impedance of the antenna for any frequency we first compute the αfactor for the frequency using Equation 25. Then we compute the positive and negative exponentials using α. Next, we compute theta using Equation 16 and then the cosine and sine terms. We substitute these values into Equation 9 and use Equation 10 to solve. This is best done in a spread sheet for a range of frequencies and the results plotted. A wide range plot showing multiple quarter-wave resonances for a wire antenna is shown in Figure 3.

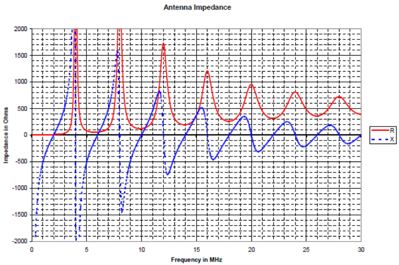



Figure 3: 2 MHz resonate antenna 5 meters off ground

The computed impedance at 2 MHz of this antenna is 7.5 ohms. The impedance at the third harmonic (6 MHz) is 55 ohms –for both resonant frequencies the reactive part is zero. It should be observed that the impedance is at a minimum and purely resistive at odd harmonics of the quarter-wave resonance. The impedance is very high at even harmonics. This figure should be viewed as illustrative rather than accurate. Although the pattern of impedance variations is true, the magnitude could vary considerably depending on actual ground conditions and the proximity of other structures. It is true that the impedance variations become smoother as the number of quarter-waves increases. Only a minimal attempt has been made to correctly model that for this model as the primary interest is in the sub quarter-wave region. More work will be done on the high frequency region at a later date. It is expected that the required effect can be obtained by the appropriate exponent on the n term that immediately follows the exponential in Eq. 25 –but some kind of short power series might be required instead. Example Antennas



This is, when:

$$\omega\left(La + \frac{L}{1-\omega^2 LC}\right) - \frac{1}{\omega\left(\frac{CaC}{Ca+C}\right)} = 0 \qquad \ldots(2)$$

which is satisfied at certain radian frequency $\omega_r$.
At this frequency, the L-C tank circuit behaves as an equivalent inductance

$$\frac{L}{1-\omega_r^{\,2} LC}$$

Usually, L is much greater than $L_a$ for antennas used in crystal set work. Then,

$$La << \frac{L}{1-\omega_r^{\,2} LC}$$

Equation (2) can be written as:

$$\frac{\omega_r L}{1-\omega_r^{\,2} LC} - \frac{1}{\omega_r\left(\frac{CaC}{Ca+C}\right)} = 0$$

We can then write:

$$\frac{\omega_r L}{1-\omega_r^{\,2} LC} = \frac{Ca+C}{\omega_r CaC}$$

…(1)

$$I = \frac{Ea}{r + j\left(\omega La - \frac{1}{\omega Ca}\right) + \overline{Z} - \frac{j}{\omega C}}$$

where:

$$\overline{Z} = \frac{1}{\overline{Y}}$$

$$\overline{Y} = \frac{1}{j\omega L} + j\omega C$$

$$= j\left(\omega C - \frac{1}{\omega L}\right)$$

$$= j\left(\frac{\omega^2 LC - 1}{\omega L}\right)$$

$$\therefore \quad \overline{Z} = \frac{1}{j}\left(\frac{\omega L}{\omega^2 LC - 1}\right)$$

or:

$$\overline{Z} = j\left(\frac{\omega L}{1 - \omega^2 LC}\right)$$

Then, $I = I_{MAX}$ when:

$$\left(\omega La - \frac{1}{\omega Ca}\right) + \left(\frac{\omega L}{1 - \omega^2 LC}\right) - \frac{1}{\omega C} = 0$$



The following plots show the typical impedance for several wire antennas. In each case #14 AWG wire was used and the solid line is the radiation resistance and the dotted line is the reactance. In all cases the radiation resistance is very low. The key feature is the capacitive reactance of the antenna.

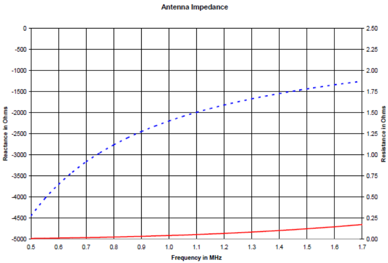



Figure 4: Antenna length = 10 m, height = 3 m

This is about as short as an antenna can be and still be practical. This antenna appears as 73 pF.

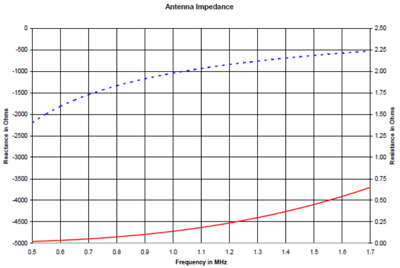



Figure 5: Antenna length = 20 m, height = 3 m

This antenna appears as 145 pF at low frequencies and 184 pF at high frequencies. The change in capacitance with frequency is because the reactance of the series inductance cancels part of the capacitive reactance.



**ANALYSIS OF THE TUGGLE FRONT END**

**By Ramon Vargas Patron**

http://www.inictel-uni.edu.pe/index.php?option=com_content&view=article&id=235&Itemid=152

**Part I:**

This article analyzes the Tuggle tuner, of common use in high-performance DX crystal sets. An equivalent circuit for the antenna-ground system with the tuner connected is shown in Fig. 1 below. It must be recognized that there is some stray capacitance of the rotor and frame of the two-gang variable capacitor to ground. This should be shown as a fixed capacitor across the bottom variable capacitor. Its presence will reduce the maximum frequency to which the circuit will tune. However, in the present analysis this stray capacitance is neglected.

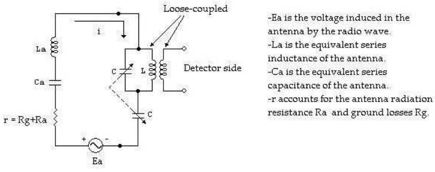



Fig. 1 The Tuggle front end connected to an antenna-ground system

The mesh current is described by:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 25 | 340 | 20 | 165 | 440 | 1400 | 30 | 50 |
| 25 | 375 | 20 | 165 | 300 | 1700 | 26 | 27 |
| | | | | | | | |
| 25 | 220 | 20 | 200 | 700 | 550 | 130 | 335 |
| 25 | 300 | 20 | 200 | 585 | 1100 | 35 | 72 |
| 25 | 375 | 20 | 200 | 300 | 1700 | 24 | 20 |

**50 ohm / 150 uH** High resistivity Earth Case sensitivities

| Ohm | pF | uH | uH | Qu | kHz | cpl | tank |
|---|---|---|---|---|---|---|---|
| Rg | Ca | La | L1 | | f | C2 | C1 |
| 50 | 220 | 20 | 150 | 475 | 550 | 128 | 476 |
| 50 | 300 | 20 | 150 | 400 | 1100 | 34 | 108 |
| 50 | 375 | 20 | 150 | 200 | 1700 | 24 | 35 |
| | | | | | | | |
| 50 | 220 | 20 | 150 | 700 | 550 | 96 | 490 |
| 50 | 260 | 20 | 150 | 640 | 750 | 53 | 256 |
| 50 | 300 | 20 | 150 | 585 | 1100 | 28 | 113 |
| 50 | 340 | 20 | 150 | 440 | 1400 | 22 | 65 |
| 50 | 375 | 20 | 150 | 300 | 1700 | 19 | 39 |
| | | | | | | | |
| 50 | 220 | 20 | 125 | 700 | 550 | 110 | 595 |
| 50 | 300 | 20 | 125 | 585 | 1100 | 31 | 139 |
| 50 | 375 | 20 | 125 | 300 | 1700 | 21 | 49 |

Kevin Smith
09/2011



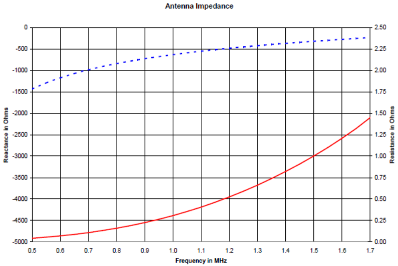



Figure 6: Antenna length = 30 m, height = 3 m

This antenna appears as 220 pF at low frequencies and 375 pF at high frequencies.

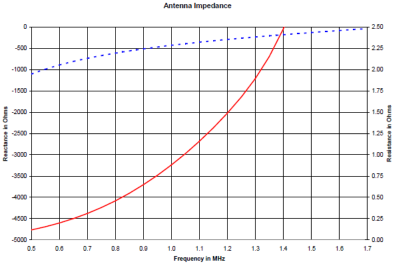



Figure 7: Antenna length = 40 m, height = 5 m

This antenna appears as 290 pF at low frequencies and is almost resonant at 1.7 MHz. This is about as long as an antenna needs to be for excellent reception. Note also that the antenna is higher. The increase in radiation resistance at higher frequencies is an indication that quarter wave resonance is being approached.

References:

1. Theory and Problems in Electromagnetics, Schaum’s Outline Series, Joseph A.
Edminister, McGraw-Hill Book Company, 1979, pages 92-93, 141.

2. The ARRL Antenna Book, edited by Gerald L. Hall, The American Radio Relay
League, Inc. Newington, CT, 1984, Fourteenth edition, page 2-20.

3. Antennas and Transmission Lines, John A. Kuecken, MFJ Enterprises, Inc., 1996,
First edition, page 64.



| Rg | Ca | La | L1 | | f | C2 | C1 |
|---|---|---|---|---|---|---|---|
| 15 | 220 | 20 | 180 | 475 | 550 | 337 | 328 |
| 15 | 300 | 20 | 180 | 400 | 1100 | 61 | 63 |
| 15 | 375 | 20 | 180 | 200 | 1700 | 40 | 10 |
| | | | | | | | |
| 15 | 220 | 20 | 180 | 700 | 550 | 220 | 352 |
| 15 | 260 | 20 | 180 | 640 | 750 | 100 | 176 |
| 15 | 300 | 20 | 180 | 585 | 1100 | 49 | 73 |
| 15 | 340 | 20 | 180 | 440 | 1400 | 37 | 37 |
| 15 | 375 | 20 | 180 | 300 | 1700 | 32 | 17 |
| | | | | | | | |
| 15 | 220 | 20 | 130 | 700 | 550 | 313 | 511 |
| 15 | 300 | 20 | 130 | 585 | 1100 | 59 | 110 |
| 15 | 375 | 20 | 130 | 300 | 1700 | 38 | 30 |
| | | | | | | | |
| 15 | 220 | 20 | 205 | 700 | 550 | 195 | 302 |
| 15 | 300 | 20 | 205 | 585 | 1100 | 45 | 61 |
| 15 | 375 | 20 | 205 | 300 | 1700 | 30 | 13 |

**25 ohm / 165 uH** "Standard" resistivity Earth Case sensitivities

| Ohm | pF | uH | uH | Qu | kHz | cpl | tank |
|---|---|---|---|---|---|---|---|
| Rg | Ca | La | L1 | | f | C2 | C1 |
| 25 | 220 | 20 | 165 | 475 | 550 | 213 | 396 |
| 25 | 300 | 20 | 165 | 400 | 1100 | 48 | 84 |
| 25 | 375 | 20 | 165 | 200 | 1700 | 32 | 22 |
| | | | | | | | |
| 25 | 220 | 20 | 150 | 700 | 550 | 164 | 462 |
| 25 | 300 | 20 | 150 | 585 | 1100 | 41 | 102 |
| 25 | 375 | 20 | 150 | 300 | 1700 | 27 | 31 |
| | | | | | | | |
| 25 | 220 | 20 | 165 | 700 | 550 | 151 | 416 |
| 25 | 260 | 20 | 165 | 640 | 750 | 76 | 213 |
| 25 | 300 | 20 | 165 | 585 | 1100 | 39 | 91 |

I strongly urge you to put down the Litz, set aside the silver-plated caps, store the holy-grail diodes and go do some research on your local ground. All the time, expense, and effort on the greatest "state-of-the-art" crystal receiver will be wasted if the ground is not attended to. If the resistivity of your earth is high in ohm-meters, get more metal in the ground or consider a counter-poise. The following table from LEM Instruments shows the relation between earth resistivity in ohm meters and actual earth resistance in ohms as a function of the earthing method used.

**Models and Data:**

**10 ohm / 220 uH** Lowest resistivity Earth Case sensitivities

| Ohm | pF | uH | uH | Qu | kHz | cpl | tank |
|---|---|---|---|---|---|---|---|
| Rg | Ca | La | L1 | | f | C2 | C1 |
| 10 | 220 | 20 | 220 | 475 | 550 | 442 | 228 |
| 10 | 300 | 20 | 220 | 400 | 1100 | 68 | 36 |
| 10 | 375 | 20 | 220 | 200 | 1700 | 44 | -3 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 10 | 220 | 20 | 220 | 700 | 550 | 273 | 255 |
| 10 | 260 | 20 | 220 | 640 | 750 | 114 | 122 |
| 10 | 300 | 20 | 220 | 585 | 1100 | 55 | 47 |
| 10 | 340 | 20 | 220 | 440 | 1400 | 41 | 20 |
| 10 | 375 | 20 | 220 | 300 | 1700 | 36 | 5 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 10 | 220 | 20 | 200 | 700 | 550 | 304 | 287 |
| 10 | 300 | 20 | 200 | 585 | 1100 | 58 | 54 |
| 10 | 375 | 20 | 200 | 300 | 1700 | 38 | 7 |

**15 ohm / 180 uH** Low resistivity Earth Case sensitivities

| Ohm | pF | uH | uH | Qu | kHz | cpl | tank |
|---|---|---|---|---|---|---|---|



**GROUNDS**
**by Jim Lux**
http://home.earthlink.net/~jimlux/hv/grounds.htm

The following discussions are really applicable to line frequencies. For higher frequencies, dielectric loss must be considered, as well as skin effect. For lower frequencies (i.e. DC) consideration should be given to electrolytic effects such as polarization.

The dominant effect for a ground is the current distribution within the earth. The ground rod or wire itself typically has negligible resistance, as does the interface between the rod and soil. As such, the soil conductivity has a very large influence on the ground resistance.

Resistivity of different soils and resistance of a single rod. The rod, in the table below, is a standard rod 5/8 inch in diameter and 10 feet long (16 mm diam by 3m long) Data taken from IEEE Std 142-1991.

| Soil Description | Group Symbol | Avg Resistivity (kohm cm) | Resistance of rod (ohm) |
|---|---|---|---|
| Well graded gravel, gravel-sand mixtures, little or no fines | GW | 60-100 | 180-300 |
| Poorly graded gravels, gravel -sand mixtures, little or no fines | GP | 100-250 | 300-750 |

| Soil Description | Group Symbol | Avg Resistivity (kohm cm) | Resistance of rod (ohm) |
|---|---|---|---|
| Silty sands, porly graded sand-silts mixtures | SM | 10-50 | 30-150 |
| Clayey sands, poorly graded sand-clay mixtures | SC | 2-20 | 15-60 |
| Silty or clyey fine sands with slight plasticity | ML | 3-8 | 9-24 |
| Fine sandy or silty soils, elastic silts | MH | 8-30 | 24-90 |
| Gravelly clays, sandy clays, silty clays, lean clays | CL | 2.5-6 | 17-18 |
| Inorganic clays of high plasticity | CH | 1-5.5 | 3-16 |

Note 1) ohm M = kohm cm * 10
2) for the last two, clays, the resistivity is highly dependent on soil moisture.

**Effect of Moisture Content on Soil Resistivity**
The following table gives resistivity (ohm M) for three types of soil, for moisture contents from 2% to 24% by weight. Data taken from IEEE Std 142-1991.
Note: ohm M = kohm cm * 10

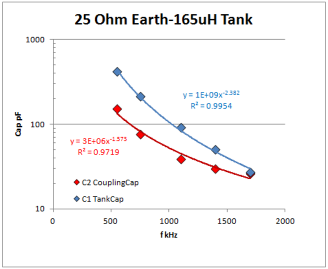


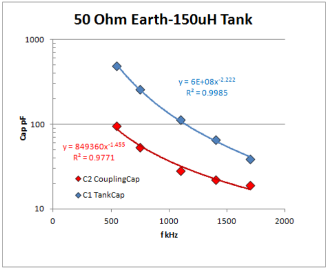
represent increasing earth resistance presented to the ATU from a very low 10 ohms to a fairly high 50 ohms. Actual earths can go up to two orders of magnitude higher. I chose L1 inductances such that the maximum needed capacitance would approach 500pFs, easily found on many variable caps. With respect to the coupling cap (C2, red curve), as the earth resistivity increases the needed capacitance declines. The tank cap value needs to resonate with the inductor and increases with smaller-value inductance. In searching for a 500pF max cap value, the choice of inductance needs to decrease with increasing earth resistance. Parameters other than Rg, L1 and C1-C2 have minor impact on the models.

**Conclusions:**

From the plots one can readily see that above 10 ohm earth the two variable capacitors on the ATU do not track well. As the earth resistivity increases, the worse the tracking. Most locations are not blessed with a low resistivity earth and this needs to be factored into the ATU design. There is little to be done, changing the design coil inductance will change the needed capacitance on BOTH C1 and C2, (larger L1 leads to smaller C1 and C2 for resonance and vice versa). A possible solution well worth trying is to use a dual-gang capacitor where one section has a different value than the other, the above plots give an easy way to decide the max values needed. Use the smaller gang on the coupling circuit and the larget on the tank. Experience tells us that ganging the capacitors on a "Tuggle" front end works well, but from the models I have to imagine one might squeeze a bit more performance by giving up the convenience of one-dial tuning on the ATU, especially where your earth has a fairly high resistance.

The best design concept will be to know first and critically your earth resistance. If this is just a guessed-at parameter then




The above plots show the calculated capacitance versus frequency for four different models of Earth Resistivity / Tank Inductance. In each case I maintain the same log capacitance vs frequency scale for easy comparison. The cases modeled



| Moisture content (% by weight) | Top Soil | Sandy Loam | Red Clay |
|---|---|---|---|
| 2 | | 185 | |
| 4 | | 60 | |
| 6 | 135 | 38 | |
| 8 | 90 | 28 | |
| 10 | 60 | 22 | |
| 12 | 35 | 17 | 180 |
| 14 | 25 | 14 | 55 |
| 16 | 20 | 12 | 20 |
| 18 | 15 | 10 | 14 |
| 20 | 12 | 9 | 10 |
| 22 | 10 | 8 | 9 |
| 24 | 10 | 7 | 8 |

**Effect of Temperature on Soil Resitivity**

The following table gives variation in soil resistivity with temperature. The significant transition is at the freezing point, and above that the resitivity drops fairly linearly with temperature. I'm not sure about the double entry for 0 degrees.. perhaps it represents the variability at the transition temperature? Data taken from IEEE Std 142-1991.

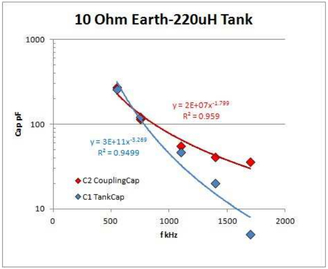
| Temperature (deg C) | Resistivity (kohm cm) |
|---|---|
| -5 | 70 |
| 0 | 30 |
| 0 (?) | 10 |
| 10 | 8 |
| 20 | 7 |
| 30 | 6 |
| 40 | 5 |
| 50 | 4 |

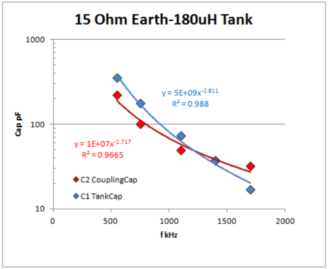
Note: ohm M = kohm cm * 10

Calculation of Resistance to Earth
An expression, accurate to 15%, for a single 10ft (3m) rod 5/8" (16mm) in diameter is:
Rground(rod) = rho/335 ohms
where rho is in ohm-cm. (ohm-cm = ohm M *100)

**Multiple rods**
Multiple ground rods are often used particularly where high currents may be involved. The ground resistance is not simply the resistance of one rod, divided by the number of rods, unless the rods are very far apart. However, even though the ground resistance of the combination may not be all that much better than a single rod, the current is shared among the rods, reducing the current per rod. A guideline from IEEE Std 152-1991 to avoid "smoking rods" is:
Max Current(amps) = 34.8E3 * d * L / sqrt(rho * t)
where:
d is the rod diameter in meters
L is the rod length in meters
rho is the soil resistivity in **ohm meters**





1) Frequency is chosen per your interest, I have taken models at F = 550-1100-1700 kHz.

2) Coil inductance one has control over when winding. I have chosen base values that resonate with about 400pF tank capacitance, with some sensitivities.

3) Unloaded Q I do not have. For modeling I have taken Vargas's measures for a 4.5" coil wound with 660/46 Litz wire. I assume this will be about as good a coil as one can wind. I also made a sensitivity for lower Q. Q is a function of frequency and I have used the appropriate value of Q to match the modeled frequency.

4) Series Resistance is basically what the earth and ground system will deliver plus a small 1-2 ohm contribution from Ra and Rr. I have modeled four cases 10, 15, 25 and 50 ohms. The first two cases reflect my needs on the Gulf Coast with low resistivity soil. The 25 ohm case is a "typical" or "standard" grround. Finally, many will have much higher resistivity soils and you need to know just how difficult things can get!

5) Series capacitance I based for my specific antenna on the model of Ken Kuhn (Mathematical Model of Wire Antenna). The capacitance of a 30m antenna 3m high he calculated to range from 220pF and low frequencies to 375pF and high frequencies. I input the correct capacitance to match the frequency modeled.

6) Series inductance I just input 20 uH every time.

The data and plots for four different scenarios follow:



t is the duration of the current in seconds (and is valid for short times only)

The text of IEEE Std 142-1991 claims that for 1 ft 5/8" rod (32 cm x 16 mm) this expression yields 116A in 2500 ohm cm soil and 58A for 10,000 ohm-cm soil, however I don't get these numbers.

Here's a table of some formulae to calculate ground resistance for combinations of rods. This table is taken from IEEE Std 142-1991, but it's cited there as coming from: Dwight, H.B.,"Calculation of resistance to ground", *AIEE Transactions*, vol 55, Dec 1936, pp 1319-1328.

| **Description** | **expression for R** |
|---|---|
| Hemisphere, radius a | =rho/(2*pi*a) |
| One rod, Length L, radius a | =rho/(2*pi*L)*(ln(4*L/a)-1) |
| Two ground rods spacing s, s>L | =rho/(4*pi*L)*(ln(4*L/a)-1) +<br>rho/(4*pi*s)*<br>(1- 1/3 * (L/s)^2+ 1/5 * (L/s)^4)-...) |
| Two rods, spacing s, s<L | =rho/(2*pi*L)*(ln(4*L/a)- ln(4*L/s)<br>- 2+ 1/2 * s/L- 1/16 * (s/L)^2<br>+ 1/512 * (s/L)^4-...) |
| Buried horizontal wire, length 2L, depth s/2 | =rho/(4*pi*L)*(ln(4*L/a)+ln(4*L/s)<br>- 2+ 1/2 * s/L- 1/16 * (s/L)^2<br>+ 1/512 * (s/L)^4-...) |
| right angle turn of wire, Arm length L, depth s/2<br>(essentially 2 arms at right angles) | =rho/(4*pi*L)*(ln(2*L/a)+ln(2*L/s)<br>- 0.2373+ 0.2146 * s/L+ 0.1035 * (s/L)^2<br>- 0.0424 * (s/L)^4...)<br>* I'm not sure of this one, the sign pattern is very different from the others! |
| 3 point star | =rho/(6*pi*L)*(ln(2*L/a)+ln(2*L/s)<br>+ 1.071- 0.209 * s/L+ 0.238 * s^2/L^2<br>- 0.054* s^4/L^4- ...) |

| Description | expression for R |
|---|---|
| 4 point star (cross) | =rho/(8*pi*L)*(ln(2*L/a)+ln(2*L/s)<br>+ 2.912- 1.071 * s/L+ 0.645 * s^2/L^2<br>- 0.145 * s^4/L^4- ...) |
| 6 point star | =rho/(12*pi*L)*(ln(2*L/a)+ln(2*L/s)<br>+ 6.851- 3.128 * s/L+ 1.758 * s^2/L^2<br>- 0.490 * s^4/L^4- ...) |
| 8 point star | =rho/(16*pi*L)*(ln(2*L/a)+ln(2*L/s)<br>+ 10.98- 5.51 * s/L+ 3.26 * s^2/L^2<br>- 1.17 * s^4/L^4- ...) |
| ring of wire, diameter of ring D, diameter of wire d, depth s/2 | =rho/(2*pi^2*D)*(ln(8*D/s)+ln(4*D/s)) |
| buried horizontal strip length 2L, section a x b, depth s/2, b<a/8 | =rho/(4*pi*L)*( ln(4*L/a)<br>+ (a^2 - pi*a*b)/(2*(a+b)^2)<br>+ ln(4*L/s)- 1+ s/(2*L)- s^2/(16*L^2)<br>+ s^4/(512*L^4)- ...) |
| buried horizontal round plate, radius a, depth s/2 | = rho/(8*a) +rho/(4*pi*s) *<br>( 1- 7/12 * (a/s)^2+ 33/40 * (a/s)^4- ...) |
| buried vertical round plate, radius a, depth | = rho/(8*a) +rho/(4*pi*s) *<br>( 1- 7/24 * (a/s)^2+ 99/320 * (a/s)^4- ...) |

hv/grounds.htm - 18 March 2003 –
Jim Lux



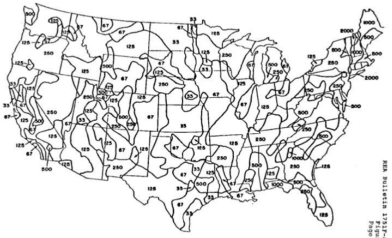



FIGURE 2
Estimated Average Earth Resistivity in U.S. (ohm-meters)

**Modeling:**

All the above discussion is great but... What is important really? The following section presents the results of applying different parameters to get a feel for the sensitivity of it all. To begin with I need explain my base assumptions. All the models are based on Kleijer's calculation spreadsheet which requires inputs for the following parameters:

Frequency
Coil inductance
LC circuit Q unloaded
* Complex impedance of antenna or
Series Resistance (Rg+Ra+Rr)
Series Capacitance Ca
Series Inductance La

* If the series values are given, the complex impedance is calculated.

of typical ranges in ohm meters for some different soils follows:

| | | | | |
|---|---|---|---|---|
| Loam | 5 | - | 50 | ohm meter |
| Clay | 4 | - | 100 | |
| Sand/Gravel | 50 | - | 1,000 | |
| Limestone | 5 | - | 10,000 | |
| Sandstone | 20 | - | 2,000 | |
| Granite | 1,000 | - | 2,000 | |
| Slates | 600 | - | 5,000 | |

Moisture up to about 17% dramatically lowers resistivity, mineral salts are needed and pure water is an insulator, and as the temperature approaches freezing the resistivity also rises dramatically. All this factors into your estimation of Rg. The actual resistivity seen by the circuit depends on the earth resistivity and the type of grounding system you have installed. The more metal in the ground, and deeper, the lower the resistance. Know thy earth! A map of USA soil resistivity follows:



**Map of Effective Ground Conductivity in the USA**
REA Bulletin 1751F-802
http://www.rurdev.usda.gov/SupportDocuments/UTP_Bulletins_1751F-802.pdf

1. GENERAL

1.1 Ground, is defined as a conducting connection by which a circuit or equipment is connected to the earth. The connection is used for establishing and maintaining the potential of the earth, or approximately that potential, on the circuit or equipment connected to it. A "ground" consists of a grounding conductor, a grounding electrode, a grounding connector which attaches the grounding conductor to the ground electrode, and the soil in contact with the ground electrode.

1.2 Using Grounds in Protection Applications:

1.2.1 For natural phenomena, such as lightning, grounds are used to discharge the system of current before customer or personnel can be injured or vulnerable system components can be damaged.

1.2.2 For potentials due to faults in electric power systems with ground return, grounds aid in ensuring rapid operation of the power system protective relays by providing additional low resistance fault current paths. The low resistance path provides the means for the removal of the potential as rapidly as possible. The ground should drain the potential before personnel are injured or the telephone system damaged.

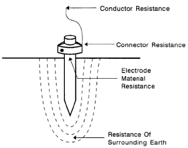
1.3 Ground Resistance: Ideally, a ground should be of zero ohms resistance. In reality, this value cannot be obtained due to the series resistances shown in Figure 1: Components of Resistance in a Ground Connection. Grounding theory and methods for obtaining a ground of the smallest practical resistance will be discussed in subsequent paragraphs.

## 2. PHENOMENA AFFECTING GROUND RESISTANCE

2.1 Introduction: A grounding electrode cannot be driven into the soil with the expectation of obtaining a good, low resistance, ground. Many factors, both natural and human, may affect results. Some of the factors include:

2.1.1 **Earth Resistivity**: The electrical resistivity of the earth (resistance of the earth to the flow of current) is of major importance. The unit of earth resistivity, the ohm·meter, is defined as the resistance, in ohms, between opposite faces of a cube of earth one cubic meter in volume. An alternative unit of measurement, the ohm·centimeter, is defined as the resistance in ohms, between opposite faces of a one centimeter cube of earth. To convert ohm·meters to ohm·centimeters, multiply by the former by 100.

Figure 1: Components of Resistance in a Ground Connection




2.1.1.1 Earth resistivity varies over a considerable range. Within the United States it varies from a few ohm·meters along some coasts to many thousands of ohm·meters in rocky, mountainous country. Figure 2: Estimated Average Earth Resistivity in U.S. provides very general data on average surface earth resistivity throughout the United States.



inductance L1 and capacitance C1. The capacitance and inductance of the ATU is needed to tune out the reactance of the various components of the antenna for which we do not have data. What to do?

Without an antenna analyzer (expensive) one can only estimate the many component values based on published antenna models. Ken Khun's engineering page has a number of nice models and a good discussion of the antenna parameters we will be trying to understand and use. For my personal setup my antenna consists of about 75' of 14awg wire averaging about 10-12' high and with another 25' of lead-in. For such an antenna Khun models a 30m antenna 3m high which approximates my situation closely enough. Wire resistance is negligible as is the radiation resistance which he shows to vary between some 0.1 to 1.5 ohms. Such an antenna is capacitive by nature and will have about 220 - 375pF along with some small 20uH inductance, not too far off a standard "dummy" antenna. This pretty much leaves earth resistance Rg as the main unknown parameter.

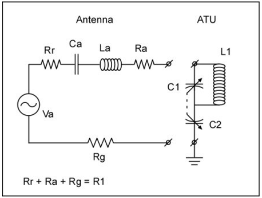
For Rg one has the option of punting and taking the "Standard" value of 25 ohms. In my modeling I have found this parameter to be critical and highly sensitive. I do not recommend guessing here, it is recommended one go to the internet page of their state, county, or local government and search for reports on ground or soil resistivity (or conductivity). As this is an important agricultural and engineering parameter, it has been surveyed for most places and should be available with some effort. Effort well rewarded. Earth resistivity for the Texas Gulf Coast is a mercifully low 10 - 15 ohm meters, but for many regions this will not be the case.

Earth resistivity depends on a number of variables including the material, moisture, mineral salt, and temperature. A table and for this I am deeply in his debt. My hat's off to Dick, thanks so much.

The following discussion presents the results of many models cranked through the design calculator. I wished to understand what factors play main roles and which have minor parts.

For a conventional detector-circuit coil one can pretty much control all the main factors, really only the inductance and capacitance of the circuit. The main and only surprise comes in the form of "stray capacitance" resulting from the spacing of the coil wires. This can readily be 1) guessed at and 2) minimized by good coil winding technique. For the antenna circuit by contrast many of the needed parameters, earth resistance, antenna capacitance and inductance, and antenna resistance in the forms of actual wire resistance and radiation resistance are, for most of us, unknown and only guessed at. The following figure illustrates the antenna and ATU with a list of the main "components" that need to be understood and/or modeled.

The Antenna Equivalent Circuit consists of an AC voltage source Va (the signal of interest), in series with some radiation resistance Rr, antenna capacitance Ca, antenna inductance La, antenna resistance Rr, and finally a ground resistance Rg for the return path to complete the circuit. In addition the ATU consists of a coupling capacitance C2, and a tank with





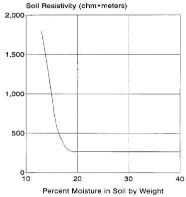

2.1.1.2 In addition to regional variations, earth resistivity may vary widely within very small distances due to local soil conditions. Table I lists typical ranges of earth resistivity for various soil types. This table should be useful in selecting locations at which a ground is to be installed.

TABLE I: RESISTIVITY OF VARIOUS SOILS

| SOIL | RESISTIVITY RANGE (ohm·meters) |
|---|---|
| Loam | 5 - 50 |
| Clay | 4 - 100 |
| Sand/Gravel | 50 - 1,000 |
| Limestone | 5 - 10,000 |
| Sandstone | 20 - 2,000 |
| Granite | 1,000 - 2,000 |
| Slates | 600 - 5,000 |

2.1.2 **Soil Moisture**: Nearly any soil, with a zero moisture content, is an insulator. Fortunately, this condition is rarely encountered except in desert areas or during periods of extreme drought. Figure 3: Typical Variation of Soil Resistivity with Moisture illustrates the typical affect of moisture on soil resistivity. It should be noted that above 17% moisture by weight additional moisture has little effect. Below this figure resistivity rises rapidly until, at 2% moisture it reaches 100 times its value at 17% moisture. Thus, a good ground connection should always be in contact with soil having a ground water content in excess of 17%. Local well drillers

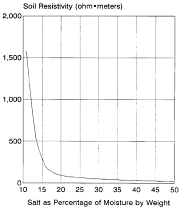
Figure 3: Typical Variation of Soil Resistivity with Moisture



should be able to provide information concerning the depth of the water table in their areas. Water content alone does not provide a good ground in many areas so do not be misled by moisture depth only. (See Soil Mineral Content section to follow).

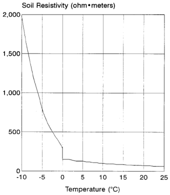
2.1.3 **Soil Mineral Content**: Water with no mineral salt content is nearly as good an insulator as soil with no moisture content. Figure 4: Typical Effect of Mineral Salt on Earth Resistivity illustrates the effect of mineral salt content on soil resistivity. Soils which lack adequate soluble mineral salts may be encountered from time to time.

Figure 4: Typical Effect of Mineral Salt on Earth Resistivity




2.1.4 **Temperature**: As the temperature of soil decreases, resistivity increases. When the soil temperature drops below the freezing point of water, resistivity increases rapidly, as shown in Figure 5: Typical Variation of Soil Resistivity with Temperature.

Figure 5: Typical Variation of Soil Resistivity with Temperature






**Notes on simulations for a Tuggle Front End**
http://www.lessmiths.com/~kjsmith/crystal/atu.shtml
By Kevin Smith

**Introduction:**

When designing my radios I always make extensive use of Mike Peebles and Dan Petersen's "Professor Coil" spreadsheet. This tool along with the many tutorials and explanations online have vastly eased the design work around homebrew coil winding. We can now model a coil with good accuracy prior to the actual job and thus better match the coil to the other components we plan to include. One quickly becomes aware that most coils for the broadcast band vary around a nominal 220 or so uH. More than this and most variable capacitors will have too much bottom-end capacitance to tune the top of the band. Less than this and you need caps with fairly high values when fully meshed, 500+pF or more.

All the above is pretty straight forward. On the other hand, when I have been reviewing double-tuned set designs, I often note that the coil used for the ATU (antenna tuning unit) will have an inductance quite a bit lower than the main tank coil. Professor Coil doesn’t address this aspect of coil design and I have found little discussion online concerning ATU design. Mostly this seems to be dealt with in passing or as a digression when dealing with other subjects. The most useful web sites for addressing this aspect of crystal set design include Dick Kleijer's excellent work and Ramon Vargas's detailed analysis of the "Tuggle Front End", that’s about it. Neither site discusses the ramifications of varying different parameters such as the Earth Resistance, Coil Inductance, etc although Kleijier's site includes a great calculator page to allow one to ask these questions. In my explorations of ATU design (primarily Tuggle) I have made extensive use of Kleijier'e page

# APPENDIX C MEASUREMENT OF SOIL RESISTIVITY

## 1. GENERAL

1.1 Soil Resistivity Measurements are commonly made with a test instrument that uses the four-terminal fall of potential method. The test instrument has four terminals that are connected to four electrodes arranged at equal distances along a straight line (shown in Figure C1: "Four-Terminal" Method for Measurement of Soil Resistivity). Internally the instrument contains a current circuit and a voltage circuit. The current source can be a handdriven a.c. generator or a voltage reversing vibrator that causes a current to flow between the two outer electrodes (Terminals C1 and C2). A potential is measured between the inner electrodes (Terminals P1 and P2). The voltage and current circuits are coupled within the test set to provide a reading in ohms.

1.2 The Theory for This Measurement was developed by Dr. Frank Wenner of the U.S. Bureau of Standards in 1915 and published in Report No. 258, Bulletin of Bureau of Standards, Vol. 12, No. 3, October 11, 1915, "A Method of Measuring Earth Resistivity." Dr. Wenner established that, if the test electrode depth is small compared to the distance between the electrodes, the following equation applies to determine the average soil resistivity to a depth equal to the distance between the electrodes:

$\rho = 2\pi AR = 6.28AR$

Where: q = Average soil resistivity to depth equal to A, in ohm·centimeters

$\pi = 3.1416$

A = Distance between electrodes, in centimeters

R = Test instrument resistance reading, in ohms
Note: Divide ohm·centimeters by 100 to convert to ohm·meters.

1.3 Ground Test Instruments generally use an alternating voltage source with a frequency not related to power system fundamental frequencies or their harmonics. This avoids the effects of polarization and foreign earth currents which could produce erroneous results.

1.4 Objectives of Soil Resistivity Measurements: The first is to determine the type of earth connection required to provide the objective resistance to earth. The second is to define any geological limitations that might be present, such as a rock layer, that would restrict installation of the grounding system.

2. BASIC SOIL RESISTIVITY MEASUREMENT

2.1 Introduction: The depth to which the average soil resistivity is desired determines the distance (A) between the test electrodes. This distance will typically be the length of the ground electrode to be installed plus the depth below the earth's surface to which it will be driven. A measurement should be taken with test electrode spacings of one-half, one, two and four times the length of the proposed ground electrode. This will identify the presence of large deviations in the soil resistivity. Place four test electrodes along a base line in relation to the proposed vertical ground electrode location as shown in Figure C2: "Four-Terminal" Method for Measuring soil Resistivity. The test electrodes should be driven into the soil to a depth equal to A/20. Depths for test electrodes for various distances (A) are shown in Table C-I.

TABLE C-I



When we disconnect the antenna from the antenna tuner, the resonance frequency of the circuit will increase to value f2.
This is because Cp is no longer part of the tuned circuit.
f2=1/(2.pi.√(L5.C6)
The frequency shift of the circuit is equal to: f2-f

The loaded Q of the circuit
If we connect the antenna (via C4) to the LC circuit, the Q of the circuit will degrease.
The Q we have then is called the Q of the loaded circuit (or the loaded Q).
If the LC circuit is well matched to the antenna, the loaded Q will be halve the value of the unloaded Q.

**Step 4**
Now we have X8 we can calculate also XP with the formula:
$Xp=(R1^2 + X8^2)/X8$

XP is a capacitor which is parallel to C6.
XP represents a capacitor value of: Cp=1/(2.pi.f.XP), and this is in parallel with C6

**Step 5**
For resonance of the circuit must apply:
$f=1/(2.pi.\sqrt{(L5.Ctotal)}$

Or:

$Ctotal = C6+CP = (1/(2.pi.f))^2/L5$ if we substract the value of CP, the value of C6 is left.

**Step 6**
Finally we want to know the value of C4.
We already had X8.

With the formula XC4=X8+XL2-XC3 we can calculate the impedance of C4.
And then with C4= 1/(2.pi.f.XC4) calculate the value of C4.
Now we know all values of the matched circuit.

Sometimes, XC4 will have a negative value, in that case it is not possible to get a match by means of a variable capacitor on the place of C4.
As an alternative, we then can replace C4 by a coil with value:
L4= -XC4/(2.pi.f)

Frequency shift when disconnecting the antenna



Test Electrode Depths for Various Distances Between Electrodes Distance Between

| Electrodes (A) | | Test Electrode Depth (B) | |
|---|---|---|---|
| Feet | Meters | Inches | Centimeters |
| 5 | 1.52 | 3.0 | 8 |
| 8 | 2.44 | 5.0 | 13 |
| 10 | 3.05 | 6.0 | 15 |
| 16 | 4.88 | 10.0 | 25 |
| 20 | 6.10 | 12.0 | 30 |
| 30 | 9.14 | 18.0 | 46 |
| 40 | 12.19 | 24.0 | 61 |
| 50 | 15.4 | 30.0 | 76 |

2.2 Performing the Measurement: Connect the leads from the four test electrodes to the proper terminals on the test set, C1, P1, P2 and C2. Complete the measurement as described by the manufacturer of the test equipment. Calculate the soil resistivity by the equation in Paragraph 1.2 and record results.

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Figures
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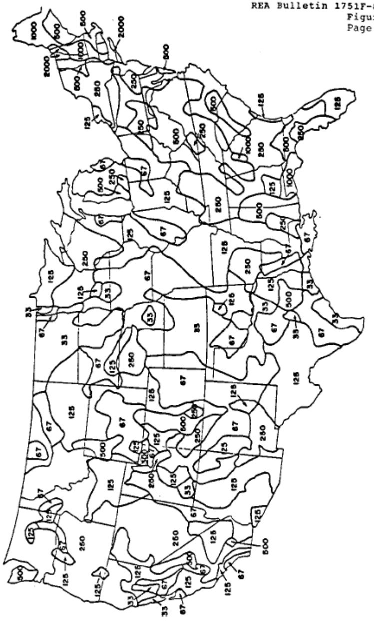


FIGURE 2 Estimated Average Earth Resistivity in U.S. (ohm meters)



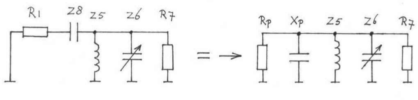
**Step 2**

The antenna can be considered as 3 separate components, R1, Z2 and Z3

We take the sum of Z2, Z3 and variable capacitor Z4, we consider this sum as one capacitor with impedance value Z8.

So Z8=Z2+Z3+Z4= -JX8

Z8 must provide the match between resistor R1 and R7




**Step 3**

Z8 in series with R1 can be converted to a parallel circuit RP, XP met de formulas:

$RP=(R1^2 + X8^2)/R1$ $XP=(R1^2 + X8^2)/X8$ however, we can't use these formulas yet, because X8 not known yet.

For impedance match, parallel resistor RP must be equal to parallel resistor R7.

So: RP=R7

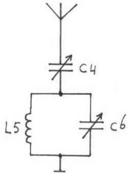
From this follows:

$(R1^2 + X8^2)/R1 = R7$

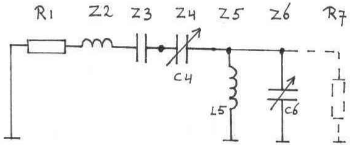
$R1^2 + X8^2 = R7.R1$

$X8^2 = R7.R1 - R1^2$

$X8= \sqrt{(R7.R1 - R1^2)}$




The antenna tuner




The antenna tuner split into separate impedances.
R1, Z2 and Z3 represents the antenna.
R7 is not a real resistor, but represents the losses in parallel circuit L5, C6

**Step 1**
Choose a frequency, calculate the complex impedance of the coil: Z5=+J(2.pi.f.L5)
Calculate the parallel resistor (R7) of the circuit L5 C6 with the formula: R7=2.pi.f.L5.Q
Resistor R7 represents the losses occurring in L5 and C6.



**Soil Survey of Harris County, Texas**
**[http://texashistory.unt.edu/ark:/67531/metapth130219/m1/148/](http://texashistory.unt.edu/ark:/67531/metapth130219/m1/148/)**

Soil Survey of Harris County, Texas

TABLE 13.--ELECTRICAL RESISTIVITY AND CORROSION POTENTIAL OF SELECTED SOILS

| Soil name | Depth | Electrical resistivity | Corrosion potential for uncoated steel |
|---|---|---|---|
| | Feet | Ohms/cm[1] | |
| Addicks loam (Three profiles) | 0-3 | 1,400-2,000 | High. |
| | 3-6 | 1,100-1,600 | High. |
| | 6-9 | 700-1,200 | High. |
| | 9-12 | 900-1,900 | High. |
| | 12-15 | 1,000-1,600 | High. |
| | 15-18 | 700-2,700 | High to moderate. |
| Aldine very fine sandy loam. (One profile) | 0-3 | 2,200 | Moderate.[1] |
| | 3-6 | 1,000 | High. |
| | 6-9 | 930 | High. |
| | 9-12 | 1,400 | High. |
| | 12-15 | 1,900 | High. |
| | 15-18 | ----- | ---------- |
| Aris fine sandy loam (One profile) | 0-3 | 2,400 | Moderate.[1] |
| | 3-6 | 1,300 | High. |
| | 6-9 | 700 | High. |
| | 9-12 | 600 | High. |
| | 12-15 | 700 | High. |
| | 15-18 | 900 | High. |
| Beaumont clay (Three profiles) | 0-3 | 500-1,400 | High. |
| | 3-6 | 400-900 | High. |
| | 6-9 | 300-1,000 | High. |
| | 9-12 | 200-600 | High. |
| | 12-15 | 300-700 | High. |
| | 15-18 | 600 | High. |
| Bernard clay loam (Three profiles) | 0-3 | 700-1,500 | High. |
| | 3-6 | 600-900 | High. |
| | 6-9 | 500-1,100 | High. |
| | 9-12 | 500-1,800 | High. |
| | 12-15 | 400-2,100 | High to moderate. |
| | 15-18 | 300-1,600 | High. |
| Boy loamy fine sand (Two profiles) | 0-3 | 155,000-452,000 | Low. |
| | 3-6 | 172,100-359,000 | Low. |
| | 6-9 | 73,300-287,000 | Low. |
| | 9-12 | 56,300-125,300 | Low. |
| | 12-15 | 50,000-73,700 | Low. |
| | 15-18 | 44,200-53,700 | Low. |
| Clodine loam (One profile) | 0-3 | 2,400 | Moderate.[1] |
| | 3-6 | 1,500 | High. |
| | 6-9 | 1,100 | High. |
| | 9-12 | 930 | High. |
| | 12-15 | 800 | High. |
| | 15-18 | 930 | High. |
| Edna fine sandy loam (Two profiles) | 0-3 | 400-1,200 | High. |
| | 3-6 | 500-1,800 | High. |
| | 6-9 | 700-1,600 | High. |
| | 9-12 | 1,000-3,800 | High to moderate. |
| | 12-15 | 1,900-2,900 | High to moderate. |
| | 15-18 | 1,600-3,000 | High to moderate. |
| Gessner loam (Two profiles) | 0-3 | 2,400-6,500 | Moderate to low.[1] |
| | 3-6 | 1,400-1,600 | High. |
| | 6-9 | 2,700-2,900 | Moderate. |
| | 9-12 | 6,700-9,600 | Low. |
| | 12-15 | 4,000-8,800 | Moderate to low. |
| | 15-18 | 2,800-15,500 | Moderate to low. |

See footnote at end of table.

Ohm M = Ohm cm * 0.01

**Harris County Summary (@ 1 – 2 m depth):**

| | | |
|---|---|---|
| Loam | 11 - 16 | ohm M |
| VF Sandy Laom | 10 | |
| Sandy Loam | 13 | |
| Clay | 6 - 9 | |
| Clay Loam | 6 - 9 | |
| Fine Sand | 11k – 34k | |
| Loam | 15 | |
| Fine Sandy Loam | 5 - 16 | |
| Loam | 14 - 16 | |

**Equation of single rod resistance of earthing:**

$R_{rod}=\rho/2\pi L_r .[\ln(8L_r/d)-1]$

ρ: is the resistivity of the soil in Ω•m

Lr: is the length of the ground rod in m

D: is the diameter of the ground rod in m

| Type of Soil | Soil resistivity $R_E$ | Earthing resistance (Ω) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Earthing rod m depth | | | Earthing strip m | | |
| | Ω m | 3 | 6 | 10 | 5 | 10 | 20 |
| Moist humus soil, moor soil, swamp | 30 | 10 | 5 | 3 | 12 | 6 | 3 |
| Farming soil loamy and clay soils | 100 | 33 | 17 | 10 | 40 | 20 | 10 |
| Sandy clay soil | 150 | 50 | 25 | 15 | 60 | 30 | 15 |
| Moisty sandy soi | 300 | 66 | 33 | 20 | 80 | 40 | 20 |
| Dry sand soil | 1000 | 330 | 165 | 100 | 400 | 200 | 100 |
| Concrete 1: 5 | 400 | - | - | - | 160 | 80 | 40 |
| Moist gravel | 500 | 160 | 80 | 48 | 200 | 100 | 50 |
| Dry gravel | 1000 | 330 | 165 | 100 | 400 | 200 | 100 |
| Stoney soil | 30,000 | 1000 | 500 | 300 | 1200 | 600 | 300 |
| Rock | $10^7$ | - | - | - | - | - | - |

LEM Instruments Brochure



| | |
|---|---|
| =X8 (Ω) | =C6+CP (pF) |
| =XP (Ω) | =XC4 (Ω) |
| =CP (pF) | =Frequency without antenna (kHz) |

Calculating the component values.

Here is explained what the calculator is calculating.
To calculate the component values, we need the following data:

The frequency.
The induction value of the coil (L5).
The unloaded Q of the LC circuit
The complex impedance of the antenna

The complex impedance of the antenna is build up with a certain resistor R1 which is in series with a coil (L2) and a capacitor (C3).

The values of R1, L2, and C3 are depending on many factors, like frequency, antenna length, height of antenna above ground, etc.

The impedance of the antenna is: Zantenna = R1+Z2+Z3 = R1+J(XL2 - XC3).

With a short antenna (shorter then 1/4 wavelength) XC3 will have a higher value then XL2, the result is a capacitive complex impedance for the antenna, so with a minus sign in front of the J.

Click on "calculate".

| | | |
|---|---|---|
| Frequency: | kHz | |
| Coil value ($L_5$): | µH | |
| Unloaded Q of LC circuit: | | |
| Complex impedance of antenna: | +J Ω | << Delete values |
| Series components of antenna: | Ω (resistor)<br>µH (coil)<br>pF (capacitor) | << delete values<br><< Use standard values |
| | Calculate Reset | |
| Complex impedance of antenna | 0 +J 0 Ω | |
| Parallel resistance of LC circuit | 0 Ω | |
| Value of $C_6$ | 0 pF | |
| Value of $C_4$ | 0 pF | alternative: µH |
| Frequency shift when disconnecting antenna | 0 kHz | |

Extra information as used in the calculations below:

| | |
|---|---|
| 0 =$X_S$ (Ω) | 0 =$C_6$+$C_P$ (pF) |
| 0 =$X_P$ (Ω) | 0 =$X_{C4}$ (Ω) |
| 0 =$C_P$ (pF) | 0 =Frequency without antenna (kHz) |

Frequency: kHz
Coil value (L5): µH
Unloaded Q of LC circuit:
Complex impedance of antenna: Ω
Series components of antenna: Ω (resistor)
µH (coil)
pF (capacitor)

Complex impedance of antenna Ω
Parallel resistance of LC circuit Ω
Value of C6 pF
Value of C4 pF alternative: µH
Frequency shift when
disconnecting antenna kHz

Extra information as used in the calculations below:



# How to measure the impedance of an AM-band antenna-ground system, what one can do with the results, along with some measurements

By Ben H. Tongue
[http://www.bentongue.com/xtalset/20MeaAGs/20MeaAGs.html](http://www.bentongue.com/xtalset/20MeaAGs/20MeaAGs.html)

Quick Summary: This Article describes a method to measure the series capacitive and resistive parameters of the impedance of an antenna-ground system vs frequency. Results from measurements on an attic antenna are given.

Schematic using a half wave rectifier Schematic using a full wave rectifier

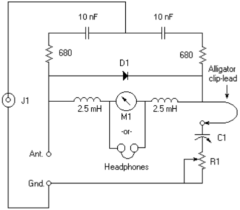


Fig. 1 - Ver. A of Antenna-ground measurement bridge.

The circuit in Fig. 1 was inspired by an Article in The Crystal Set Society Newsletter of Jan 1, 1995. It was written by Edward Richley. He used a 1 MHz crystal oscillator for his source, so had no problem with using a 200 uA meter. I use a sine wave function generator for my RF source, but a radio Service man's oscillator may also be used if it has enough output. Either of these sources cannot supply as much signal as the xtal oscillator, so I had to increase sensitivity. That's what the 2.5 mH chokes and 5 nF caps are for. The 2.5 mH chokes eliminate RF loading by any resistive component of the meter or phones on the diode detector. The 5 nF caps eliminate resistive DC loading on the detector from the two 680 ohm resistors. I lay out the components breadboard style on a nonconductive table to minimize stray capacity, keep connections short, and especially keep the signal source lead of J1 away from the connections to each end of D1. In my setup D1 is a 1N34A, M1 is a 0-20 uA DC meter, R1 is a 75 ohm non-inductive carbon pot and C1 is a two gang variable cap of 365 pF per section. I parallel the two sections when the antenna capacitance is above 365 pF. A lower sensitivity meter can be used than the one used here, at the cost of a requiring a higher applied signal to J1.

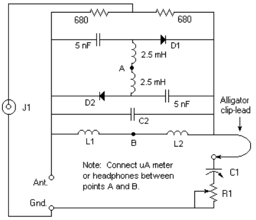



Fig. 2 - Ver. B of Antenna-ground measurement bridge.

If a sensitive enough meter is not available, a pair of high impedance phones (2000 ohms DC resistance) or preferably, a sound powered pair with the elements wired in series can be used. In this case, the generator must have its AM audio modulation turned on at its highest level. A modulation frequency of about 1 kHz is recommended. If the meter is used, do not connect the phones. If phones are used, do not connect a meter.

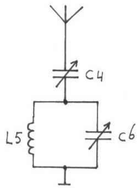
To use the bridge, tune the generator to a frequency of interest. Adjust C1 and R1 for minimum deflection on M1 or a null of the modulation tone in the phones. Increase the RF signal to J1 as much as possible in order to get the sharpest and most



## CALCULATING COMPONENT VALUES FOR AN ANTENNA TUNER

Dick Kleijer crystal-radio.eu
http://www.crystal-radio.eu/entunercalc.htm

In this article we are going to match a parallel LC circuit to an antenna.




Matching means, connecting LC circuit and antenna in such a way that there is maximum power transfer from antenna to LC circuit.
This article makes use of complex impedances, a explanation about this you can find here (external link).

There are several ways of matching the antenna to the LC circuit, I discuss here only the matching via a variable capacitor between antenna and LC circuit.

With the next calculator, the component values of this antenna tuner can be calculated.
Enter: frequency, value of the coil in the LC circuit (L5) and the unloaded Q of the LC circuit L5, C6
Also enter the complex impedance of the antenna, or the series component values of the antenna.
(when you enter both complex impedance, and series components, the complex impedance is used, and not the series components).
If you don't know the antenna impedance, use the standard values for the series components: 25 Ω, 20 µH en 200 pF.

Now with various settings of C1, the frequency range of the circuit, the voltage across coil L1, and the Q (across coil L1) are measured.

The measured voltages are Volt peak-peak.

The frequency range can be slightly influenced by the measuring amplifier which was connected across coil L1.



precise null. Measure the resistance of R1 with an ohmmeter. Use any desired method to measure C1. I use the cap. measurement range of my Fluke DVM. I'm sure the reader does not need to be reminded that this test involves radiating a weak RF signal from the antenna when making the measurements, so the length of time the generator is on should be kept as short as possible.

Possible issues: More sensitivity is needed or interference from antenna pickup of local stations obscures the bridge null.

If insufficient signal is available from the RF generator to provide satisfactory meter readings, one can use the more sensitive broadband circuit shown in Fig. 2. The values of L1 and L2 are 2.5 mH and C2 is set to zero in the broadband version. A full wave rectifier is used instead of the half wave one used in Fig.1 and it gives about twice the output. One can also change from using 1N34A diodes and try Schottky Zero Bias detector diodes such as the Agilent HSMS-2850 in either circuit. The HSMS-2855 Zero Bias diode is especially suitable for use in the circuit shown in Fig. 2 since it is a package having two independent diodes, one for D1 and the other for D2. One must be cautious when using the HSMS-2855 because the diodes can be damaged by the application of too strong a signal to J1. This can happen if the signal generator signal is very strong when the bridge is greatly unbalanced. It's best to start with a weak signal, balance the bridge, then increase the signal if necessary.

If the signal from the RF generator is not strong enough to override local pickup, thus obscuring the meter null, selectivity may be added to the bridge shown in Fig. 2 by making use of C2 and changing L1 and L2. If L1 and L2 are changed to, say, 10 uH inductors and C2 is made equal to 1200 pF, the bridge will be tuned to about 1 MHz. These changes will reduce the influence of local pickup upon measurement of antenna-ground impedance at 1 MHz. One suitable 10 uH inductor is Mouser's "Fastron" #434-23-100.

If one uses headphones instead of a meter as the null indicator, even greater sensitivity can be achieved by AF modulating the bridge signal generator and connecting a parallel L/C tuned to the modulating frequency of the generator across the phones. This will filter out much of the interfering cross talk from local pickup and pass the modulation tone with little loss. Suggested values are L=47 mH and C=0.5 uF if the modulating frequency used is about 1 kHz. A low cost coil having an inductance of 47 mH and a Q of about 9 at 1 kHz is available from Mouser as a Fastron Plugable Shielded coil, #434-02-473J ($1.20 each). Greater selectivity against cross-talk can be obtained by decreasing the inductance and increasing the capacitor.

I live about 9 miles from WOR and 12 from WABC, both 50 kW stations. 10 volts peak-to peak applied to the bridge overrides the local radio station pickup sufficiently to provide a clear null on the meter when using the circuit shown in Fig. 1 when using a 1N34A diode. A useable null with an applied signal of only 1.5 volts p-p can be obtained when using the circuit in Fig. 2 with zero bias detector diodes, sound-powered phones instead of a meter and the parallel LC filter.

**Notes:**

* If the RF source has too great a harmonic content, the bridge balance null will become less deep and sharp. That's why I used a sine wave function generator to assure a low harmonic content. If one uses a function generator for pure sine waves, make sure the symmetry control is set for best symmetry (minimum reading on the bridge microampmeter). In April



L12, only the outermost winding is removed to reduce inductance a little bit. This reduced the total wirelenght from 15 to 14.5 meters.

The frame of this antenna unit is made of 8mm polyethene sheet.

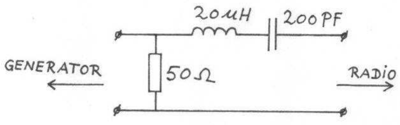
Tuning capacitor C2 is driven via a 1:5 vernier drive, so we can tune it very accurate. Tuning capacitor C1 has no vernier drive.

**Experiments:**

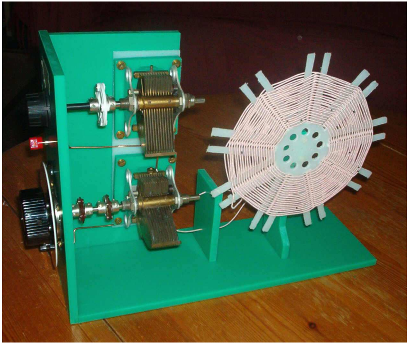
During the measurements the antenna unit is connected to the signalgenerator via a dummy antenna.

The dummy antenna.

Made with a resistor of 50 Ohm, a coil of 20 uH, and a capacitor of 200 pF. The 50 Ohm output resistance of the signal generator is in parallel with the 50 Ohm resistor.




The dummy antenna makes the receiver input is driven with a impedance of 25 Ohm in series with 20 uH in series with 200 pF.. This is about the impedance of a average longwire antenna. With the dummy antenna connected to the generator (but without the receiver connected), the output voltage of the generator is adjusted to 50 mV peak-peak.



The circuit L1,C2 has a high impedance (e.g. 1 M.Ohm). But the antenna has a low impedance (e.g. 10 Ohm), tuning capacitor C1 forms a impedance match between this high and low impedance.

With a certain value of C1, there wil be maximum power transfer from antenna to the circuit L1,C2. Then there is maximum voltage across the coil L1, and maximum sensitivity of the receiver. At low frequencies we must for instance adjust C1 to 100 pF, and at high frequencies to 20 pF, but these values are depending on the (lenght of) antenna we connect to it. For the circuit Q however, the lower the value of C1, the higher the Q. More information about this, you wil find here.

Coil L1 is wound with litzwire 660x 0.04mm (660/46 AWG), on a polypropylene former. This coil is described here as coil



2004 Tom Polk published a description and schematic for a low distortion medium wave home brew signal generator. It looks very good, and can be found at:
http://www.beecavewoods.com/testequipment/sinewave.html

* If the resistance of a specific antenna-ground system is greater than 100 ohms, use a pot of a higher value than 100 ohms.

* A typical antenna-ground system will show a capacitance of a few hundred pF at the low end of the BC band. Because of the series inductance in the system, the measured capacitance will rise at higher frequencies. At a high enough frequency the system will go into series resonance and the bridge will not be able to be balanced. To measure the system series resistance at or above this resonance, place a hi Q capacitor of, say 100 to 220 pF in series with the antenna. That will raise the resonant frequency sufficiently so that the capacitor-antenna-ground circuit will be capacitive, a null can be obtained and the resistive component determined. An NPO ceramic or mica cap should be OK.

* At my location, detected signals from local strong stations show up as fluctuations at about 15% of full scale on the meter, but are not strong enough to obscure the bridge nulls from of the signal generator's signal.

* Unless the signal generator connected to J1 is battery powered (most aren't), it is important to put a common-mode radio frequency choke in the power line to the generator. I made mine by bundling a length of 18 ga. lamp cord into an 18 turn coil having a 9 inch diameter, and then fitting a male AC plug on one end and a female socket on the other. The turns were kept together using twist ties.

**What can one do with the measurement results?**

The main practical thing one can do with the bridge is to Measure and Monitor antenna-ground circuit resistance. This resistance comes primarily from the physical ground, not the antenna and ground connecting leads or radiation resistance of the antenna. Any increase in the antenna-ground resistance serves to reduce the signal power available from the antenna. Any decrease, of course increases it. A halving of the antenna-ground system resistance provides a 3 dB increase in available signal power, if one properly rematches to the crystal radio set input circuit.

Measure: One can experiment with different grounds and various ground paralleling schemes to come up with the one that has the lowest resistance. Use of this one will result in maximizing the available signal power (more volume). Experiments using a counterpoise ground can be made.
Monitor: As has been recently been posted on the Yahoo Club: thecrystalsetradioclub, earth ground resistance deteriorates (increases) over time. This results in a gradual decrease in available signal power (less volume). Periodic measurement can alert one if this is happening so steps can be taken to correct the problem.

The other thing one can do, if one is mathematically engineering a crystal radio set, is to use the R and C values as parameters in the design. See Article #22.

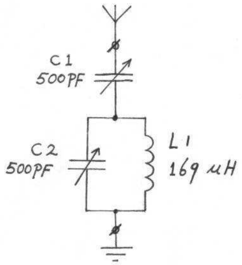
**Measurement results on an indoor attic antenna system:**

My present external (as opposed to loop) antenna is in the attic. The horizontal element used to be made up of 7 twisted strands of #26 copper wire (17 ga.), suspended by strings about 1 1/2 feet below the peak of an asphalt shingled roof. It runs



**EXPERIMENTS WITH AN ANTENNA TUNER UNIT**
Dick Kleijer crystal-radio.eu
http://www.crystal-radio.eu/enantunittest1.htm

Here some measurements done with my "antenna unit1".




Schematic of the antenna unit 1.

The antenna unit has a tuned circuit L1, C2.

If we only look at L1 and C2, then the tuning range is 550 - 2184 kHz. But if we also connect the antenna and earth, the frequency of the circuit will decrease, so we can also receive the lowest mediumwave frequency of 530 kHz.

Variable capacitor C1 and the antenna and earth are also a part of the tuned circuit, but the antenna and earth also give reduction of circuit Q.

along under the peak and parallel to it for 53 feet. The wire is about 24 feet above ground level. The lead-in, connected to the center of the horizontal wire, runs horizontally, at a right angles for about 9 feet and then drops down vertically to the crystal radio set location, about four feet above ground level. The ground system consists of a connection to the cold water supply in parallel with a connection to the hot water baseboard heating system. To achieve a low inductance ground connection I use 300 ohm TV twinlead, both conductors soldered in parallel, for each lead. The addition of a connection to the AC neutral does not seem to reduce the inductance or resistance of this antenna-ground system. I always suggest trying the addition of a connection to the AC neutral. Sometimes it helps.

The measured antenna-ground system capacitance was 295 pF at 0.5 MHz, 325 at 1.0 MHz, 410 at 1.5 MHz and and 660 at 2.0 MHz initially. The respective series resistances measured: 17, 12, 10 and 14 ohms. The equivalent reactance elements of this antenna are a capacitance of 285 pF in series with an inductance of 12.5 uH. Since my ground is composed of the house cold water supply pipes in parallel with the the hot water baseboard heating system pipes, much of the capacitance from the horizontal attic antenna wire is to them and the roof, not a real resistive earth ground. That, I think explains the low resistance and high capacitance readings. Probably the ground system is acting as a sort of counterpoise.

I decided to see if I could get greater signal pickup by changing to a very crude simulation of a flattop antenna. To do this, I paralleled the antenna wire with a piece of TV twinlead connected to it at each end and at the point of down-lead takeoff. The twinlead was separated from the 7/26 wire by about 2 1/2 feet. The new measured antenna-ground system parameters became: Capacitance: 430 pF at 0.5 MHz, 510 at

1.0 MHz and 860 at 1.5 MHz. The respective series resistance values became: 15, 12 and 11 ohms. The equivalent reactance elements became a capacitance of 405 pF in series with an inductance of 14.2 uH. Signal pickup increased by a negligible 0.8 dB at 710 kHz, and even that was, I'm sure, within experimental error.

One may want to compare these equivalent impedance components with the 'Standard Dummy Antenna', as specified in 1938 by the IRE (Institute of Radio Engineers) in 'Standards on Radio Receivers'. My reference for this is Terman's Radio Engineer's Handbook, first edition, 1943, pp 973 and 974. A rather complex equivalent circuit for the antenna is shown on page 974. It is stated that a simpler alternative network, given in footnote #2 on page 973, can be used when only the BC band is of interest. It consists of the series combination of a 200 pF capacitor, 25 ohm resistor and 20 uH inductor. Terman states that the two antenna equivalent circuits have closely the same impedance characteristics in the BC band. The impedance graph on page 974 and the impedance from the series combination of 200 pF, 25 ohm resistor and 20 uH differ, particularly in the resistive curve in the complex equivalent circuit. The 25 ohm resistance in the simplified circuit is probably taken from the resistance in the complex circuit, at the geometric center of the BC band. This resistance is shown as constant in the simplified circuit, and as a strong function of frequency in the more complex circuit. It is suggested that the complex equivalent circuit is theoretically derived, assuming a perfect ground and therefore does not include the resistance of the ground return path. The ground circuit can easily add 15-50 or more ohms to the circuit.

#20 Published: 11/24/01; Revised 04/16/2004




of -j14 ohms. The negative sign indicates a capacitor is needed. Here is the value for 1650 kHz:
XC=1/(2*pi*F*C)

Solving for C, we get:
C=1/(2*pi*F*XC)

C=1/(6.28*1650 kHz*14)
C=6,890 pf
This is a huge capacitor and would probably be a combination of fixed and variable capacitors.

Now, referring to the first antenna example before we added more capacitance, we can see what value of reactance is required to bring the antenna into resonance. Since that antenna had an impedance of 20 - j34 ohms, we would need a series inductor to combine with the capacitance of -j34 ohms. This inductance is:

XL= 2*pi*F*L

Solving for L we get: L=XL/(2*pi*F)

L=34/(6.28*1650 kHz) L=3.28 uH

These calculations were all done at the higher end of the broadcast band. When moving down to 530 kHz, the antennas we have been analyzing would have smaller resistance and higher negative reactance.

=-j241 ohms (capacitance has a minus sign)

The value of this complex impedance is:
= 20 + j207 - j241 ohms
= 20 - j34 ohms

As mentioned earlier the use of complex numbers allows us to simply add the resistance and reactance. The sign of the reactive component -j34 is negative and indicates the antenna is capacitive. It is also shorter than the resonant length ( at resonance XL + XC = 0).

Now if you increase the capacitance of the antenna to ground with a flat top section, where the series capacitance increases to 500 pF, here is what happens:
XC=1/(2*pi*F*C)
=193 ohms
= -j193 ohms

The value of this new complex impedance is:
=20 + j207 - j193 ohms
=20 + j14 ohms

The sign of the reactive component is now positive, indicating the antenna is inductive, or long compared to resonance.

Use of the complex number notations also lets you figure what value of series reactance you would need to bring the antenna circuit into resonance. You could tune out the reactance and then match the remaining resistance to the input of the crystal set.

Referring to our last set of complex numbers: 20 + j14, you could bring the antenna circuit into resonance with a reactance



From Terman's Radio Engineer's Handbook, first edition, 1943, pp 973 and 974.

## MEASUREMENTS ON RADIO RECEIVERS

**35. Receiver Characteristics and Their Determination.**[1]—Radio receivers are tested by employing an artificial signal from a standard signal generator to provide a voltage corresponding to that induced in the receiving antenna. This voltage is ordinarily applied to the receiver through a network, termed a dummy antenna, having characteristics such that the receiver views substantially the same impedance as it would in normal operation with an actual antenna. The receiver output is then observed by replacing the loud-speaker or telephone receivers by a suitable resistance load, with which is associated a power indicator.

The dummy antenna recommended for use in testing broadcast receivers is given in Fig. 78.[2] The impedance of this network in the frequency range 540 to 1,600 kc approximates that of the typical open-wire antenna resonant at about 2,500 kc, and having a capacity of the order of 200 μμf. At higher frequencies the network approaches a constant impedance of 400 ohms, and so resembles a nonresonant transmission line of corresponding impedance.

[2] Where tests are to be made only in the standard broadcast frequency range, an alternative network consisting of a capacity of 200 μμf, resistance of 25 ohms, and an inductance of 20 μh, all connected in series, is commonly used. Such a dummy antenna has practically the same impedance as the recommended network in this frequency range.

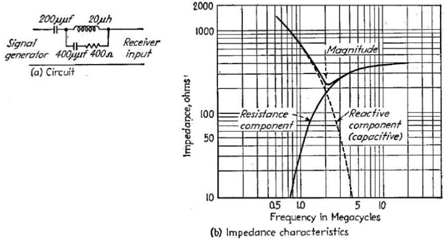



Fig. 78.—Standard dummy antenna used for testing broadcast receivers, together with its impedance characteristic.

## Working With Antenna Impedance

Jack Bryant
Birmingham Crystal Radio Group
http://www.crystalradio.us/antennas/impedance.htm

This is an elaboration of a post I made on the Rap 'N Tap Discussion group. The objective was to explain how a multi-wire flat top antenna adds capacitance to the antenna, while making it more inductive. This is an exercise in complex numbers. For example the expression 20 + j40 displays 20 ohms resistance and 40 ohms of inductive reactance. The complex number approach allows us to simply add series resistance, capacitance and inductance. The resistance remains constant when the frequency changes. However, the reactance of an inductor increases with frequency. The reactance of a capacitor decreases with frequency.

For purposes of illustration, assume an antenna with the following parameters for R, L and C in series for F=1650 kHz (our frequency of interest):

Rtotal = 20 ohms (total of radiation resistance and losses, including ground losses, since we are using a Marconi type antenna, i.e., worked against ground.)

L = 20 uh; the reactance is calculated as:
XL= 2*pi*F*L (where 2*pi =6.28, F is in hertz, and L in henries)
=207 ohms
=+j207 ohms(inductance has a plus sign)

C = 400 pF; the reactance is calculated as:
Xc=1/(2*pi*F*C) (Where F is in hertz and C in farads)
=241 ohms

## ANTENNA MATCHING

by Kenneth A. Kuhn

www.kennethkuhn.com/students/crystal_radios/antenna_matching.pdf

As discussed in an earlier chapter the ten to thirty meter antenna used for crystal radios has a very low resistance and a high capacitive reactance. The ground resistance discussed previously is typically in the several tens of ohms and is effectively in series with the antenna. As an example, an antenna/ground system may have an impedance of 20 –j1000 ohms at 1 MHz. For maximum power transfer from the antenna to the resonant circuit the input impedance of the set should be a conjugate match –that is have similar resistance but the reactance will be equal in magnitude but opposite in sign. For the example this means that the crystal set should have an input resistance of about 20 ohms and a reactance of about +j1000 ohms (160 uH) at 1 MHz. The positive reactance is obtained by an inductance in series with the antenna circuit. This inductance should be variable to tune out the capacitive reactance of the antenna across the AM broadcast band. Tuning is not sharp as the Q of resonance is low. Table 1 shows some typical values. Note that the inductance tuning range becomes wider for longer antennas since the capacitive reactance drops rapidly as the length approaches one-quarter wavelength at the upper end of the AM band. It is important that this series inductance have very low losses or the advantage of using it will vanish –a lossy inductor could be worse than nothing.

| Antenna Length | Typical Antenna XC @ 550 kHz | Typical Antenna XC @ 1.7 MHz | Antenna series Inductor tuning range |
|---|---|---|---|
| 10 m - | j4040 ohms - | j1250 ohms | 1200 –120 uH |
| 15 - | j2680 - | j780 | 780 – 70 |
| 20 - | j1990 - | j530 | 580 – 50 |
| 25 - | j1580 - | j360 | 460 – 30 |
| 30 - | j1290 - | j240 | 370 – 20 |

*Table 1: Antenna series inductance tuning range*

One effect of not tuning out the reactance of the antenna is that the resonant frequency of the tuned circuit will shift because the antenna becomes a reactive load. One way to know if the series inductance has been tuned to the right value is that the station is received at the calibration point –assuming the radio tuning was calibrated.

The next issue is creating a low input impedance of several tens of ohms. There are two ways to do this and they are essentially the same. One method is wind a turn or so of wire near the ground end of the coil of resonant circuit –one end of the wire goes to the series inductor to the antenna and the other end connects to ground. This small winding transforms the low antenna/ground impedance to a high impedance across the coil. The other method is to make a tap a turn or so above the ground end of the coil of the resonant circuit to accomplish the same effect. If the winding or tap is too few turns then there is an impedance mismatch and a weak signal will result although selectivity will be relatively sharp. If the winding or tap has too many turns then the coil is overloaded by the antenna/ground impedance which also results in weak signals and the selectivity will be broad. The optimum is the point of proper impedance match although it is not very critical. The



issue is how to determine the proper point. A second issue is that the required impedance level varies across the AM broadcast band. Thus, the tap should be variable.

If the coil is wound on a ferrite toroid core which enables a high degree of flux coupling from turn to turn then it is fairly easy to calculate at what turn a tap should be for the desired impedance transformation. However, our coil is typically an air-core solenoid which has a complicated flux relationship. Calculation is difficult and very error prone. The best way is to make a variety of taps and measure the impedance using laboratory methods and note the results. I will present the data of just such an experiment on a typical coil for crystal radios when this article continues …