The Radio Amateur's WORKSHOP

Your DIY Guide for Ham Homebrewing

Joel R. Hallas, W1ZR

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Hallas

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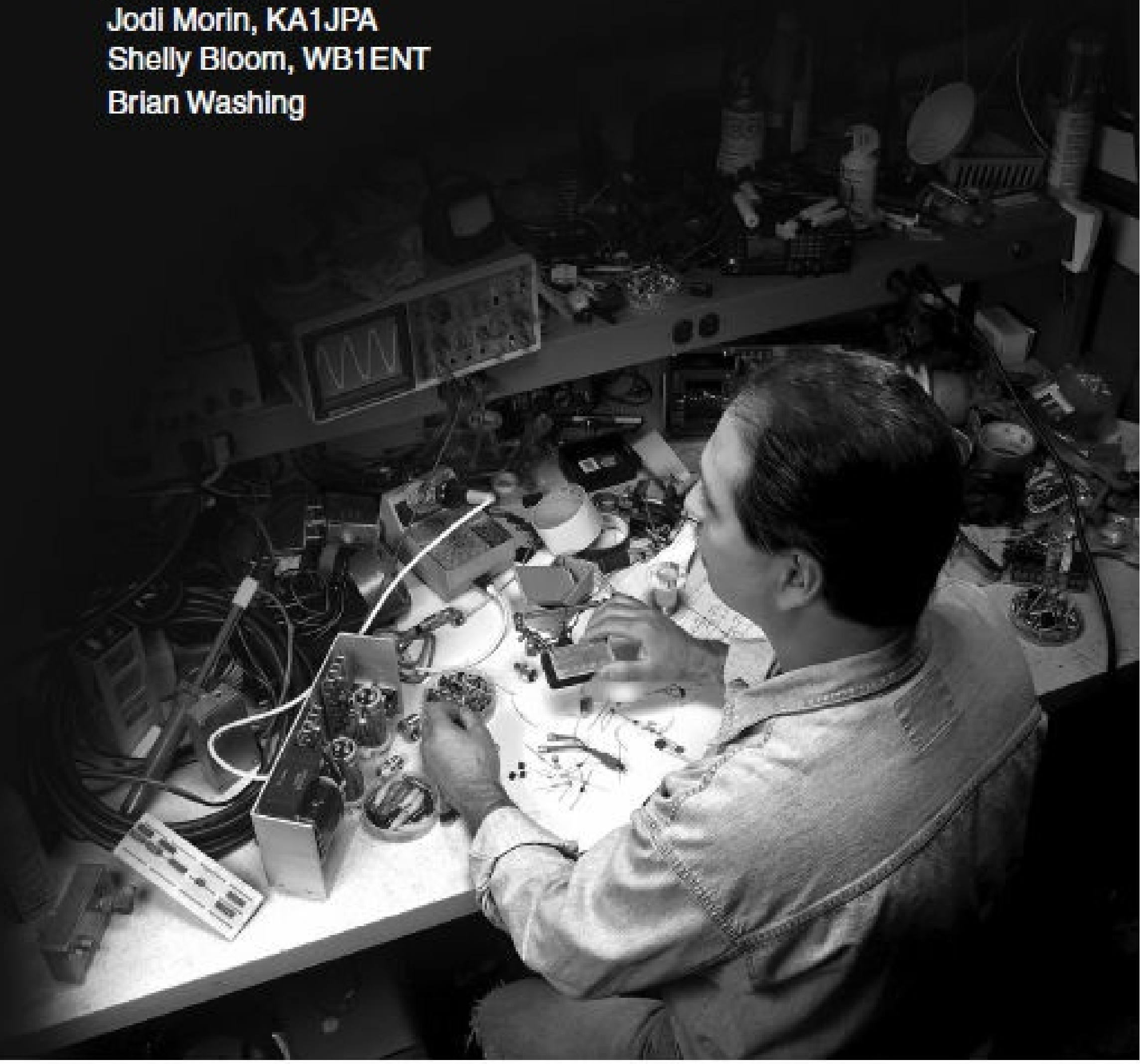

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Foreword

Amateur Radio operators have a long tradition of going beyond operating, moving into technology development, home construction, and experimentation. While such activity is in no sense required of an Amateur Radio operator, it can add to the understanding and depth of the experience as well as offer additional rewards and excitement.

This book is intended to assist readers with the information needed to set up and establish the kind of workshop and laboratory environment that will make building and maintaining equipment and antennas as productive as possible. It starts with describing the tools needed to assemble kits, then moves to antennas. Both are frequently a starting point for amateur construction activity. Subsequent chapters describe various shop and test equipment, including explanations of how tool or instrument each can be used to develop, fabricate, and evaluate projects.

As with all ARRL books, be sure to check to see if there are any last minute changes that didn't get into the book before it went to the printer. Updates and errata, if any, can be found at **www.arrl.org/notes/**.

David Sumner, K1ZZ
Executive Vice President
Newington, Connecticut
October 2015

About the ARRL

The seed for Amateur Radio was planted in the 1890s, when Guglielmo Marconi began his experiments in wireless telegraphy. Soon he was joined by dozens, then hundreds, of others who were enthusiastic about sending and receiving messages through the air—some with a commercial interest, but others solely out of a love for this new communications medium. The United States government began licensing Amateur Radio operators in 1912.

By 1914, there were thousands of Amateur Radio operators—hams—in the United States. Hiram Percy Maxim, a leading Hartford, Connecticut inventor and industrialist, saw the need for an organization to band together this fledgling group of radio experimenters. In May 1914 he founded the American Radio Relay League (ARRL) to meet that need.

Today ARRL, with approximately 155,000 members, is the largest organization of radio amateurs in the United States. The ARRL is a not-for-profit organization that:

- promotes interest in Amateur Radio communications and experimentation
- represents US radio amateurs in legislative matters, and
- maintains fraternalism and a high standard of conduct among Amateur Radio operators.

At ARRL headquarters in the Hartford suburb of Newington, the staff helps serve the needs of members. ARRL is also International Secretariat for the International Amateur Radio Union, which is made up of similar societies in 150 countries around the world.

ARRL publishes the monthly journal *QST* and an interactive digital version of *QST*, as well as newsletters and many publications covering all aspects of Amateur Radio. Its headquarters station, W1AW, transmits bulletins of interest to radio amateurs and Morse code practice sessions. The ARRL also coordinates an extensive field organization, which includes volunteers who provide technical information and other support services for radio amateurs as well as communications for public-service activities. In addition, ARRL represents US amateurs with the Federal Communications Commission and other government agencies in the US and abroad.

Membership in ARRL means much more than receiving *QST* each month. In addition to the services already described, ARRL offers membership services on a personal level, such as the Technical Information Service—where members can get answers by phone, email or the ARRL website, to all their technical and operating questions.

Full ARRL membership (available only to licensed radio amateurs) gives you a voice in how the affairs of the organization are governed. ARRL policy is set by a Board of Directors (one from each of 15 Divisions). Each year, one-third of the ARRL Board of Directors stands for election by the full members they represent. The day-to-day operation of ARRL HQ is managed by an Executive Vice President and his staff.

No matter what aspect of Amateur Radio attracts you, ARRL membership is relevant and important. There would be no Amateur Radio as we know it today were it not for the ARRL. We would be happy to welcome you as a member! (An Amateur Radio license is not required for Associate Membership.) For more information about ARRL and answers to any questions you may have about Amateur Radio, write or call:

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Chapter 1

Why Do We Need a Workshop and Lab?

This home workshop belongs to ARRL Senior Test Engineer Bob Allison, WB1GCM. He enjoys building kits, accessories and QRP gear as well as restoring vintage equipment.

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Introduction

Amateur Radio operators have a long tradition of being more than radio operators, but also of being involved in the technological aspects of the radio arts. Amateur Radio is unique among Federal Communications Commission (FCC) licensed telecommunications services in that licensed amateur operators are permitted to design and construct their own station equipment, including transmitters. While modern radio configurations and micro-miniature devices may combine to make building a transceiver a significant challenge, there are many different ways that amateurs can make good use of an appropriately furnished workshop for projects. In this book we will explore many of the options based on the different directions that amateurs choose to pursue.

Assembling and Building Electronic Kits

Building electronic kits has been a popular Amateur Radio activity since at least the days that the Heath Company offered Heathkits (1947 to 1992), starting with those made partly of surplus components readily available after World War II. The author built his first Novice transmitter and receiver from Heathkits in the 1950s, and later his first single sideband HF transceiver, a Heathkit HW-101, in 1977. The Heathkit construction manuals guided the builder in a step-by-step fashion, through the complete assembly, wiring, alignment and use of some fairly complex gear. Early kits allowed amateurs to save up to 50% of the cost of comparable factory-built equipment, while providing a significant learning experience, along with an introduction to workshop skills.

The *QST* advertisement for a 1960s vintage Heathkit DX-60B is shown in **Figure 1.1**, with a peek under the covers of one shown in **Figure 1.2**. In addition to transmitters, receivers and transceivers, Heathkit offered power amplifiers, wattmeters, station monitors, test equipment, CW keyers and other station accessories.

Figure 1.1 — Heathkit advertisement for the DX-60 transmitter kit from the December 1961 issue of *QST*.

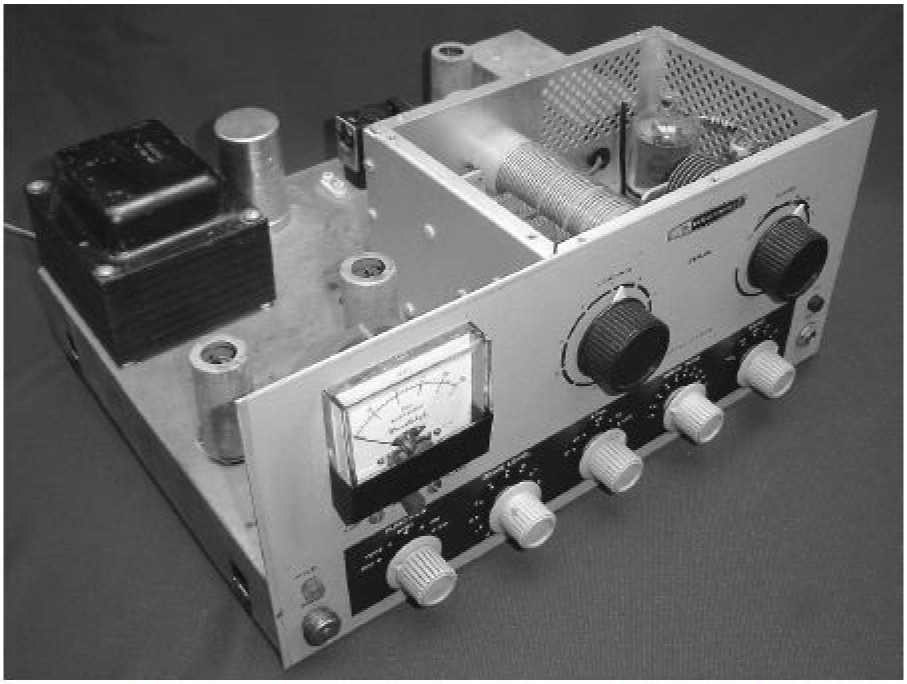

Figure 1.2 — Inside view of the Heathkit DX-60 built by Bob Allison, WB1GCM, soon after he obtained his Novice-class license. [Bob Allison, WB1GCM, photo]

Similar kits are available today from a number of vendors — ranging from simple and inexpensive low-power (QRP) radio equipment to complex and extensive gear that rivals top-of-the-line commercially available equipment in terms of features and performance.

Elecraft introduced "mechanical assembly only" kits in the form of their high-performance HF and 6 meter transceiver kit, the K3. This approach allowed the designers to incorporate the latest microelectronic circuit elements into preassembled printed circuit boards (PCBs) with the builder responsible for the hardware assembly of the boards into subassemblies and then into the supplied cabinetry.

While the mechanical assembly of the K3 is by no means trivial, it is straightforward, well described, and results in a fine piece of radio equipment. Since it only requires mechanical assembly, and needs no external test equipment, it is a good place to start a description of an amateur workshop. The hand tools needed for mechanical assembly only kits will form the basis of all other kinds of activity — so this is where we will start in Chapter 2.

Building and Testing Antennas

Many types of antennas are easy to build. A good antenna can offer performance enhancements that are far beyond what might be expected considering the cost and effort required. Amateurs can build their own antennas based on published design guidelines or try an original design, perhaps developed by using readily available antenna modeling software. The ARRL and other publishers offer many books on antennas, and it is a rare issue of *QST* that doesn't include one or two detailed antenna construction articles.

Commercially manufactured antennas usually require assembly. Many antennas are shipped boxed in pieces that are hard to tell from a kit, even though they aren't sold on that basis. It is a rare shipping company indeed that would be willing to deliver a 20 by 35 foot box containing an assembled HF triband Yagi, for example!

Building antennas generally requires only assembly, but often the parts are of a larger scale than the parts encountered in the assembly of electronic kits and so require larger tools. Antenna construction from design plans also often involves some level of parts fabrication, requiring an additional level of tools, as well as skills. Fortunately, the required skill level is usually within the scope of anyone who is a bit handy. The usual tasks involved in making antennas are measuring and cutting wire or tubing, marking and drilling holes, as well as soldering connections and terminating cables with connectors.

The initial construction of most antennas results in a semi-finished product that requires adjustment in order to work properly on the desired frequencies. The difference in dimensions between the original design and the adjusted final product can result from different environmental conditions, such as height above ground, or the electrical characteristics of nearby objects, as well as the measurement and fabrication tolerances of the builder. It is the wise constructor who includes evaluation and adjustment phases in their plans. Fortunately, in many cases no special test equipment beyond the usual station equipment is required.

Equipment Troubleshooting, Diagnosis and Repair

As with any complex electronic system, Amateur Radio equipment performance can change over time, requiring maintenance or even the repair or replacement of failed components. Even if failure hasn't occurred, it is often reassuring to verify that equipment is still working the way we expected. This often takes more than a mechanical workshop — it's generally more of a laboratory setup that can measure and confirm performance parameters with test equipment and fixtures. While such a laboratory can grow to significant proportions, as shown in **Figure 1.3**, many tasks can be supported by the use of normal station equipment supplemented by basic measurement tools.

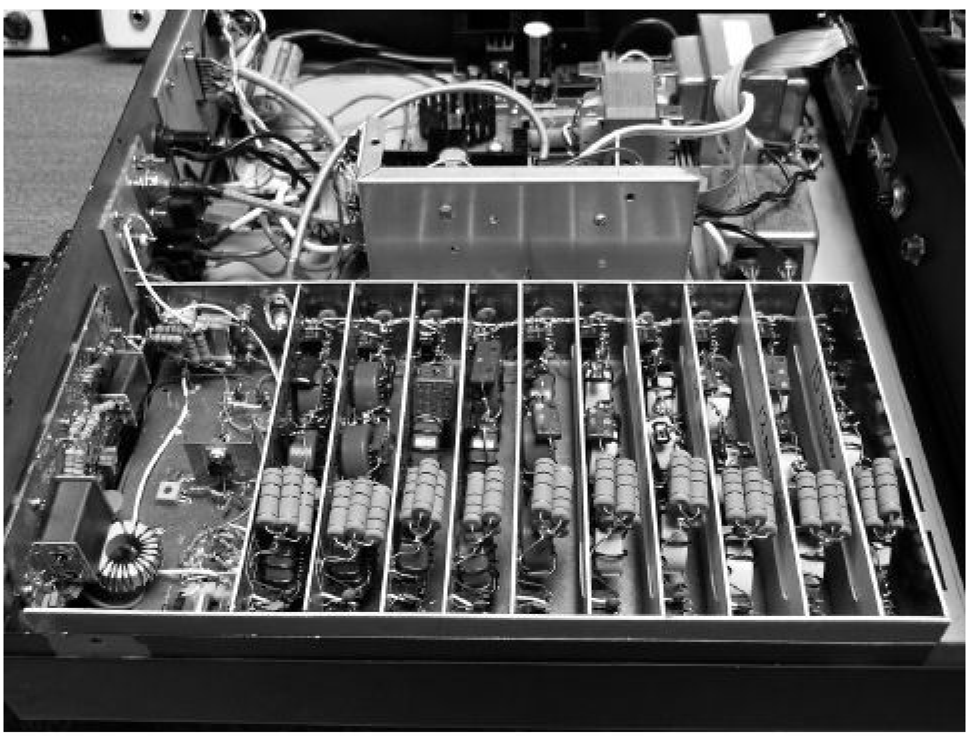

Figure 1.3 — Marcus Hansen, VE7CA, used his home lab to develop and build a high performance 100 W HF transceiver that could perform on par with the best of commercial rigs of the day. This is the 100 W amplifier with its 10 low pass filters. The power supplies can be seen in the background. Marcus's home lab suite consists of some commercial surplus and some home-made test equipment, as shown in Chapter 7. [Marcus Hansen, VE7CA, photo]

Simulation and Analysis of Circuit and Antenna Performance

While measurement capability is important to observe equipment operational parameters, it is often beneficial to be able to predict performance through computer simulation. In this way, we can understand what performance equipment and antennas should be capable of delivering. We can also explore and evaluate the benefits of new equipment or antennas before making purchases.

Simulation and analysis is more a computer/office function than that of a workshop, but the two can operate side-by-side to good effect.

Figure 1.4 — Here Wayne Yoshida, KH6WZ, uses a sander to remove excess paint and auto body filler from a reclaimed test instrument panel that will turn into the front panel of a piece of amateur station equipment. [Wayne Yoshida, KH6WZ, photo]

System Design and Development

Closely related to the analysis function is the design function, often taking place with similar tools, but in the *computer aided design* (CAD) category. Again, these are not exactly workshop tools, but for the home constructor CAD tools can be an important tool for those who start "from scratch."

Equipment Fabrication

Fabrication goes a step beyond assembly and refers to the actual manufacturing of components, enclosures or other parts. This can range from the sheet metal work needed to build anything from a simple bracket to an equipment chassis or cabinet, to the construction of basic components such as variable capacitors or inductors. Other parts can be fabricated from metal or synthetic materials using machine shop tools and skills. Starting from scratch isn't always required. **Figure 1.4** illustrates a step in reclaiming and adapting a part of a surplus test instrument cabinet into the front panel of a piece of ham gear.

Chapter 2

The Basic Workshop

This Elecraft K3, a high performance 100 W transceiver that covers 160 – 6 meters, was assembled from a kit with the use of the hand tools described in this chapter.

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Get Ready for "Mechanical Assembly Only" Kits

Elecraft introduced "mechanical assembly only" or "no-solder" kits with their high-performance HF and 6 meter transceiver, the K3. This approach allowed the designers to incorporate the latest microelectronic circuit elements in preassembled PC boards, with the builder responsible for configuring the boards into subassemblies and then into the cabinetry.

Elecraft has continued this approach to include a compact portable transceiver, the KX3; a 500 W linear amplifier, the KPA-500; a panoramic adapter display, the P-3; and a medium power automatic antenna tuner, the KAT-500. Elecraft also offers multiple add-on accessories for the K3, including a second receiver and an internal 2 meter transverter. It seems likely that this approach will continue, and others may introduce similar kits in the future.

Required Tools

While the mechanical assembly of the K3 is by no means trivial, it is straightforward, well described, and results in a fine piece of radio equipment. It requires only mechanical assembly and needs no external test equipment, so it is a good place to start a description of an amateur workshop. The hand tools needed for mechanical assembly only kits will form the basis of all other kinds of activity, so this is where we will start.

Figure 2.1 — Tools required for assembly of the Elecraft K3, all sitting on the table where the author successfully constructed his K3. The tools, K3, and assembly manual are shown on the recommended electrostatic discharge mat (see text).

Per the *Elecraft K3 Assembly Manual*, available for download from **www.elecraft.com**, the following tools are all that are required to assemble the K3:

■ #0 and #1 size Phillips screwdrivers.

■ Pliers or suitable wrenches for tightening ¼, $^3/_{16}$, and ½ inch nuts. The ½ inch size is used to tighten nuts on the front panel controls. A deep socket or nut driver is recommended for best results.

■ Long nose pliers.

- Diagonal cutters.
- Small rule capable of measuring lengths up to 1 inch (2.5 cm) with an accuracy of at least $^1/_{16}$ inch (1.6 mm).
- Allen wrenches, $^5/_{64}$ inch (2 mm) and 0.050 inch, supplied with the kit.

These tools are shown in **Figure 2.1**, along with the completed K3, all sitting on the table where the author successfully constructed his K3.

While the K3 can indeed be assembled successfully with only those tools, there are some other items that will make it go together more smoothly.

Other Recommended Tools

Elecraft strongly recommends a few tools in addition to those listed as required. These are

- Electrostatic discharge (ESD) wrist strap.
- Static dissipating work mat.

These items are usually purchased together to make sure that both the work surface and assembler are at ground potential, avoiding possible damage to sensitive electronic components from electrostatic discharge. ESD is a serious threat to many types of solid state devices, especially before they are inserted into their circuitry. It is hard to imagine a reason why anyone would elect to build a kit such as this without investing a few dollars into such a protective system.

It is important that the static dissipating mat be grounded properly to an earth ground or to the utility ground at the service entrance panel. If the workshop's electrical sockets are installed properly, the screw holding the cover on an outlet wall plate should be tied to the service entrance ground — but check to be sure. To avoid electrocution hazard, the wrist strap should be connected to the mat via a very high resistance connection.

In addition to ESD protection, the mat also provides a solid, light-colored surface that makes it easy to find a dropped part or hardware item.

Here are a few other tools that will help with construction projects and make your experience more enjoyable:

Figure 2.2 — Additional tools will make kit assembly easier. For most people, some form of vision enhancement is desirable considering the small size of some of the pieces.

■ Good lighting that can be positioned to brightly illuminate the work.

■ A close vision device. This can be the type of visor with close-up lens shown in **Figure 2.2**, an auxiliary lens that clamps to regular eyeglass frames, separate "reading" glasses, or a lens built into a light fixture. The last type can also provide the needed lighting.

■ Clamping fixtures such as the medical clamps shown in Figure 2.2. While long nose or needle nose pliers can also be used to retrieve a lock washer or other hardware item that disappears into the bowels of a partly assembled transceiver, a medical clamp can also be snapped shut to hold the item until it can be released.

■ Multiple sizes of long nose pliers and diagonal cutters. While size isn't specified in the required list, the small parts in the K3 call out for small cutters and pliers, as shown in Figure 2.1. There are places where larger sizes will work even better, and so two sizes of pliers are shown in Figure 2.2.

A clear and solid work surface is an absolute must. The work area doesn't need to be fancy, or even dedicated to the task. The author used an old hand-me-down laminate-topped dining table, but even a solid card table could be pressed into service. In some ways a non-dedicated surface has advantages — a dedicated work surface tends to become a repository for leftover parts, storage for "someday" repair projects, and a place to casually deposit tools rather than return them to their homes. Extra material on the work surface makes it harder to keep track of the parts needed for the task at hand.

Speaking of parts, one or two six-receptacle muffin tins borrowed from the kitchen can serve as a great storage bin for bolts, nuts, lock washers, and other hardware sorted by size.

Selecting Hand Tools for Your Workshop

It is difficult to overemphasize the importance of investing in good tools for the workshop. In addition to aiding in assembly, using the proper tools can help you avoid damaging your equipment. Finished panels and fasteners are especially vulnerable. We will discuss some specific tool choices so you will be a knowledgeable purchaser.

Screwdrivers

The lowly screwdriver is a tool that almost everyone has on hand before they start. You likely have a collection of different types and sizes. Those screwdrivers in the kitchen or workshop drawer have been providing service for years, tightening cabinet hinges and prying off paint lids. Are those the tools you want to use to assemble your expensive kit? Probably not! Invest in some good quality screwdrivers dedicated to your electronics workshop, and use them only for their intended purpose. **Figure 2.3** shows a number of screw head configurations discussed in this chapter.

There are two basic screwdriver configurations — the flat-blade screwdriver for slot-head screws and the cross-head driver for cross-head screws. Each has some nuances that the builder should be aware of.

Flat-blade screwdrivers — It is very important that screwdriver blades be the same size as the slots in the screw or bolt. If the blade is too wide, it will scratch the panel around the screw. If the blade is too narrow, the driver is likely to damage the slot in the screw. In addition to width, the blade thickness is important. The blade must be narrow enough to reach the bottom of the slot in order for it to stay in the slot while force is applied. If the fit is poor, the blade will likely jump free and damage both the screw head and surrounding material.

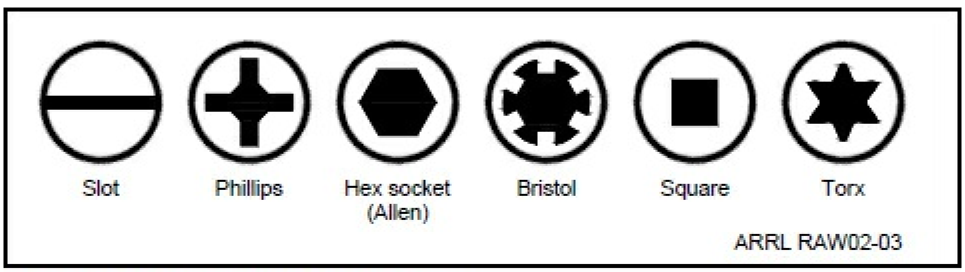


Figure 2.3 — Common screw head patterns.

Unfortunately, the typical hardware store screwdriver has some disadvantages in both regards. Most "garden variety" (pejorative intended) screwdrivers have a chisel-shaped tip in both axes. Examine the typical screwdriver tip carefully and compare it to the shape of the slot in a screw. The screw slot is of rectangular cross section in both axes. This means that the typical screwdriver is designed to be a compromise fit for any screw head.

The solution to this quandary is the *hollow-ground* screwdriver blade. A hollow-ground screwdriver blade is flat in both axes, rather than chisel-shaped. For many years, hollow-ground screwdrivers have been marketed especially to craftsmen such as finish carpenters and gunsmiths — both professions that can't tolerate damage from a slipping screwdriver blade. **Figure 2.4** compares the standard chisel-shaped blade and the hollow-ground shaped blade.

Cross-head screwdrivers — Cross-head screws are the generic name for what are often referred to as the Phillips head screws. This cross-head design, including the angles of each portion of the blade and the center hole, was patented by Henry Phillips in the 1930s with the idea that the design is well suited for automated assembly machines. Cross-head screws do have a number of advantages over slot-head screws, even for those who assemble by hand. Perhaps most important is that Phillips head screws are made in standard sizes, and so drivers and screw heads match. Elecraft uses only Phillip's head screws in their no-solder kits.

Unfortunately, as with many patented items, there are other versions that are close but not quite the same size and shape as those patented by Phillips. If you are to get the best results with Phillips head screws, it is essential that you get drivers of the same design. Fortunately, unlike slot-head drivers, it is easy to tell. Real Phillips pattern screwdrivers are labeled on the shaft with the name and size. A medium-sized Phillips driver, for example, will say "Phillips #2" on the shaft. If it doesn't say "Phillips," you can be pretty sure that it isn't.

There are also some other cross-head designs — some even better than Phillips in some ways. Most have mating screwdrivers available, but these screws are not usually encountered in the radio/electronics environment. An exception is screws built to the Japanese Industrial Standards (JIS) pattern. If your radio work will include Japanese products, you may want to consider investing in a set of JIS standard cross-head screwdrivers, available from multiple sources (try an Internet search). Just make sure you keep them separate from your Phillips drivers.

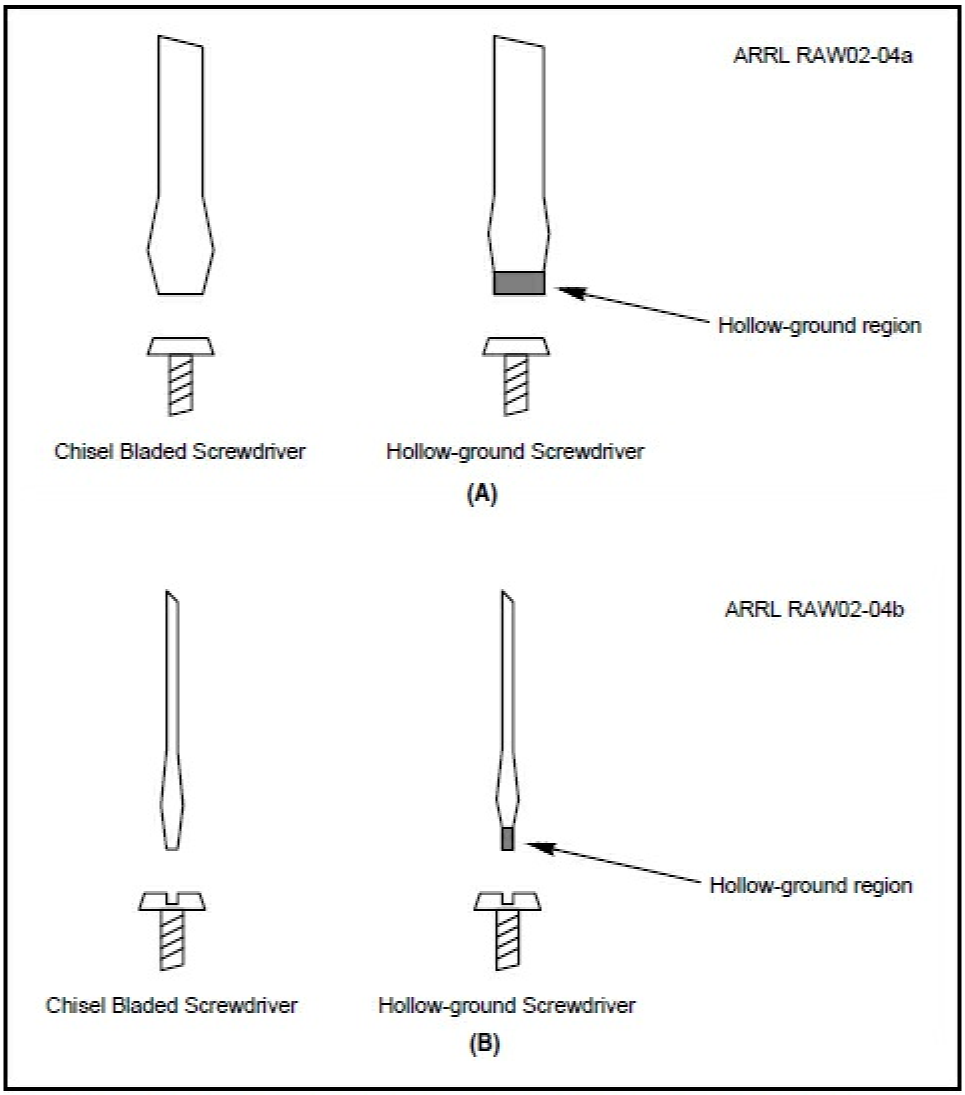


Figure 2.4 — At A, a front view of chisel and hollow-ground screwdriver blades compared to the slot in a pan-head screw. The side view comparison at B is even more striking, and perhaps more important.

Jewelers' screwdrivers — Small screwdrivers are often available packaged in sets and marketed as jewelers' screwdrivers. They can be handy, not only for repairing eyeglasses, but also for radio workshop tasks such as loosening and tightening set screws on knobs. As with other tools, the sets can be found with varying quality. The set shown in **Figure 2.5** features hollow-ground slot-head drivers, and real Phillips cross-head drivers. They have a handy rotating finger dimple on the end that can make it easy to apply just the right amount of pressure while turning the driver with the thumb and index finger.

Figure 2.5 — A set of jeweler's screwdrivers. These can be handy for many tasks, but check for quality — all are not created equal.

Other Screw Head Patterns

In addition to slot-head and cross-head screws, you may encounter screw heads requiring a hex key or Allen key. Allen head screws are frequently used for set screws in radio equipment. As shown in **Figure 2.6**, Allen keys are available in different sizes, with the larger type best left for marine and automotive use. Allen head screws come in standard sizes, both American and metric. It's important to use the correct size tool for the job.

Bristol spline drive screws are superficially similar to Allen head screws, but they are not compatible. For some reason, Collins Radio chose this type of screw for use as set screws in the knobs of their early radios.

There are a number of other common screw head patterns, such as square or Torx (a 6 point star) but they are not usually found radio equipment.

Wrenches

We've all done it on occasion, but it's poor practice to tighten a bolt into a nut holding either with a pair of pliers instead of a proper wrench! There are many types and configurations of wrenches available, and it's important to select the right one for the job at hand.

Figure 2.6 — Tools for use with screws that have hex socket heads. The tools on top and the set on the lower left are the popular Allen head wrenches, frequently used in set screws. The tools on the lower right are Bristol spline wrenches, superficially similar in appearance to Allen wrenches, but not compatible.

Figure 2.7 shows a number of hex nut (or hex screw head) grasping tools. Shown are combination wrenches that have a box wrench on one end and an open end on the other, along with an adjustable end wrench. Also shown are hex drivers (often called nut drivers), and a ratchet wrench, extension, and socket.

Consider the task at hand. For example, using an adjustable end wrench or open end wrench to tighten a control nut on an equipment panel often yields results no better than pliers. The problem with either tool is that the open ends can easily gouge the panel. Select a nut driver instead.

In any case it is important to use not only the right tool, but to apply no more than the needed torque to secure the screw or nut you are working on. The heavier size wrenches shown in Figure 2.7 are perhaps most appropriate for automotive or antenna work. For the small fasteners found in electronics gear, it is harder (but not impossible) to shear off a bolt head using a nut driver rather than a general purpose combination or ratchet wrench. A good rule of thumb is to use just enough torque to fully engage the teeth of a toothed lock washer, or compress the edge of a ring type lock washer.

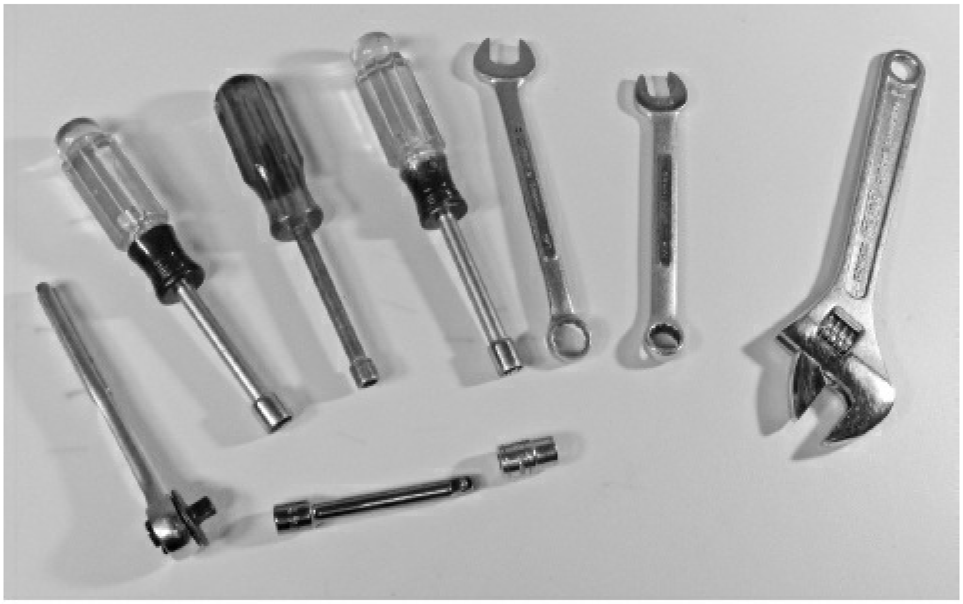


Figure 2.7 — A selection of hex head grasping tools. Shown are combination wrenches that have a box wrench on one end and an open end on the other; an adjustable end wrench; hex or nut drivers; and a ¼ inch drive ratchet wrench, extension, and socket.

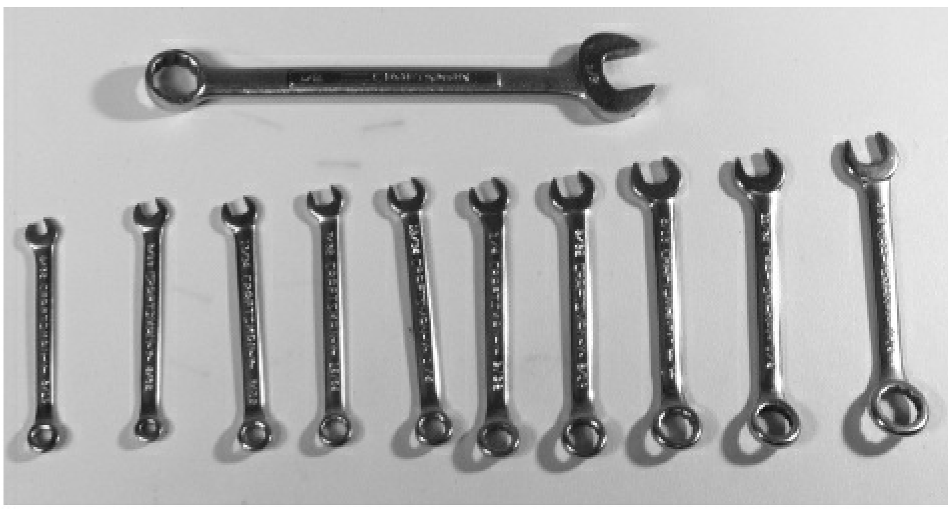


Figure 2.8 — These smaller combination wrenches, often marketed in a set as *ignition wrenches*, are frequently a better choice than their larger siblings for radio work. A typical ⅜ inch combination wrench is shown for comparison.

For those times when you need a combination wrench, consider a set of *ignition wrenches* that are smaller than typical mechanic's tools. **Figure 2.8** shows a set of ignition wrenches along with a typical ⅜ inch combination wrench (the largest ignition wrench in the set is also ⅜ inch).

Pliers and Locking-Grip Pliers

Pliers and locking-grip pliers are used to hold or bend things. They are not wrenches! There is one exception: To remove a nut that is stripped too badly for a wrench, use a pair of pliers, locking-grip pliers, or a diagonal cutter to bite into the nut and start it turning. Reserve an old tool or one dedicated to just this purpose as it is not good for the tool.

There are many different kinds of fine pliers, usually called "needle-nose" pliers, that are particularly useful in electronics work. These are intended for light jobs, such as bending or holding wires or small work pieces. Two or three of these tools with different sizes of jaws will suffice for most jobs.

Wire Cutters and Strippers

Wire cutters are primarily used to cut wires or component leads. The choice of blade style depends on the application. Diagonal blades or "dikes" are most often used to cut wire. Some delicate components can be damaged by cutting their leads with dikes because of the abrupt shock of the cut. Scissors or shears designed to cut wire should be used instead.

Specialized wire cutters are available to trim wires leads on circuit boards. These cutters are often called "flush cutters." Their cutting end is *not* designed to cut thicker wires. Use them *only* to clip smaller gauge wires, such as that on components used in circuits.

Wire strippers are available in manual and automatic styles. The manual strippers have a series of holes designed to remove insulation from a specific gauge of wire. Using the holes that are too big or too small will create nicks in the wire, which usually leads to the wire breaking at the nick. Automatic strippers grab and hold the wire for a consistent strip — some even judge the wire thickness automatically. If you strip a lot of wires, an automatic stripper may be worth the extra expense.

Wire strippers are handy, but with a little practice you can usually strip wires using a diagonal cutter or a knife. This is not the only use for a knife, so keep an assortment handy. Do not use wire cutters or strippers on anything other than wire! If you use a cutter to trim a protruding screw head or cut a hardened-steel spring, you will usually damage the blades.

Chapter 3

Soldering — The Connection Method of Choice

Soldering involves the conductors to be soldered, a stable soldering position, the right amount of heat, the right solder, and the skills described in this chapter.

Contents

Introduction to Solder and Soldering

Soldering is a method of providing a reliable, long-lasting connection between two conductors. It is particularly applicable to copper wire, terminals, and connections — including those that have been “tinned.” Some metals are not particularly well suited for regular soldering. These include aluminum and stainless steel, but there are special techniques and solders that can be employed to overcome this limitation if necessary.

While soldering has long been a key process in electronic assembly and repair, it is by no means the only connection technique. In many applications, especially connector assembly, crimping has taken over a large portion of the work. Ring terminals secured by nuts and bolts are also an effective way to connect wires to aluminum or stainless steel chassis and panels.

We’re Not Talking Plumbing Here!

Soldering may have been first employed by plumbers and pipe fitters seeking to seal the joint between two copper pipes. While the plumbing and radio soldering techniques are related, there are some important differences. As a plumber once pointed out to me, “plumbing is tougher, since radio connections don’t need to hold water,” but we’ll focus on the best practices for soldering radio and electronic components.

The first major difference is in the nature of the solder itself. Radio/electronic solder generally contains a core of rosin flux designed to remove light oxidation from the metal surfaces as the solder is applied, making for a better bond. Plumbing solder generally does not contain a flux. This is because the flux could form bubbles that might result in voids that could leak. Instead, plumbers first coat the surfaces with an acid-based paste flux and then wipe it clean. This flux is not compatible with electronic parts, which can corrode as a result of contact with the acid.

Traditional electronic solder used in the US is usually an alloy composed of 60% tin and 40% lead, formed into a thin soft wire with a core of rosin flux. This is often called “60/40 solder.” The solder is supplied in a roll with different thicknesses available. The thinner solders are preferable for most tasks since they are easier to control and avoid excess solder flow.

Lead Free-Solder

In European Union countries, the Restriction of Hazardous Substance directive (RoHS) has prohibited solder containing lead for most commercial applications, including telecom equipment (with few exceptions). Equipment made for sale in the US that is also sold in European Union countries is usually RoHS compliant so that manufacturers can use the same models in multiple markets. Some other countries, and even US states (California, at this point) have restrictions on lead in consumer devices, so it may not be long before we all have to deal with lead-free solder.

Typical lead-free solders are formed of an alloy of tin and silver, with the tin percentage in the mid to high nineties. This results in a melting temperature ranging from 422 to 473° F, as compared to the 361 to 374° F for the typical 60/40 solder.[1] The melting temperature is the major difference between the two types. The higher temperature requires a different setting on variable temperature soldering stations, and it may take longer for joints to get hot enough for solder to flow. The higher temperatures may also pose some risk of damage to components designed for 60/40 soldering.

Another potential issue with lead-free solder is the potential for crystalline growth (tin whiskers) over time that can result in short circuits if soldered conductors are too close together. The tin-based solders are also harder than those made with alloys of lead. Lead-free solder joints may have less give and thus be more subject to fatigue and stress fractures.

Fortunately, there are no particular problems with using 60/40 solder to connect to boards or components that have been made with RoHS compliant solder. You need to be sure the temperature is high enough to melt the existing higher temperature solder. This allows amateurs to modify or repair RoHS compliant equipment using their usual tools and supplies.

Selecting Your Soldering Iron(s)

There is a wide range of soldering tools available, and it is important to select the right one for the task at hand. The major differences among soldering tools come down to power, temperature control mechanism, heat source, and size.

Soldering Iron Power and Temperature Control

The power rating of an electrically powered soldering iron is based on the power consumed by the iron as it comes to temperature. While not a precise measure of the heat transfer capability, power rating does provide an indication of the amount of heat available to bring the work up to temperature. In early soldering irons this was typically the major indicator of the soldering iron's usefulness.

In the days of vacuum tubes, when we used relatively large components that were not terribly temperature sensitive and point-to-point wiring between individual terminal lugs, the common ham soldering equipment was a 100/140 W "instant-heat" soldering gun as shown in **Figure 3.1**. The "instant" description was somewhat optimistic, but in comparison to earlier soldering irons that took perhaps 15 minutes to come to temperature, it was a meaningful term.

While a soldering gun is still as useful today as it was 60 years ago, it is useful only for jobs similar to those that it was designed for back then. It is particularly suited for antenna connections that tend to be made with large conductors, as well as power supplies and wiring that is of appropriate size. The heat level is much too high to safely solder to typical printed circuit (PC) boards without risk of burning the board, melting the thin copper strips, or lifting them from the substrate. If the board isn't damaged, sensitive components may be. The other risk is that the amount of solder that can accumulate on the tip can flow into unwanted areas, resulting in shorts between PC board traces.

An answer to the need for lower power soldering equipment for smaller discrete circuitry appeared in the 1950s. It was called a "soldering pencil," because of its small size compared to the larger irons or guns (see **Figure 3.2**). These were available with screw-in elements at heat levels of 23.5, 37.5, and 47.5 W. In addition, different size tips could be screwed into the heating elements to provide a wide range of capabilities. A limitation was that it was somewhat difficult to change tips while the iron was hot. Still, the iron could perform many tasks at a low cost. Similar units are still available at reasonable cost, although not all offer interchangeable tips or elements.

Figure 3.1 — A Weller 100/140 W "instant-heat" resistive soldering gun. The trigger switch has two positions, the first for 100 W and the second for 140 W. The "instant" is somewhat optimistic, but in comparison to earlier soldering irons that took perhaps 15 minutes to come to temperature, it was a meaningful term.

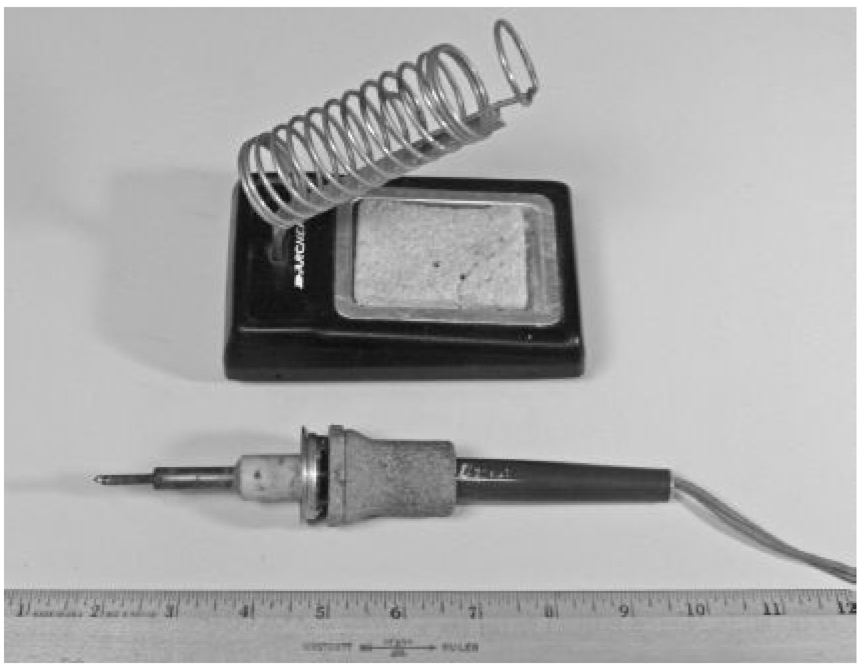


Figure 3.2 — An Ungar "soldering pencil." While this iron has a 23.5 W heating element and a medium size tip, different heating levels and tip sizes and shapes were available. While this exact unit is no longer available, there are many "pencil size" soldering irons available for the home workshop at low cost. The stand was available separately and provides a safer spot for a hot iron than laying it directly on the bench.

An improvement to the soldering pencil was a similarly sized iron with an external temperature control system. There are really two distinct categories of this "soldering station" configuration. The first, as shown in **Figure 3.3**, is an adjustable-heat soldering station. It provides continuous control of iron temperature through the knob on the base. While precise temperature control is not provided by this arrangement, it does allow easy adjustment for different conditions.

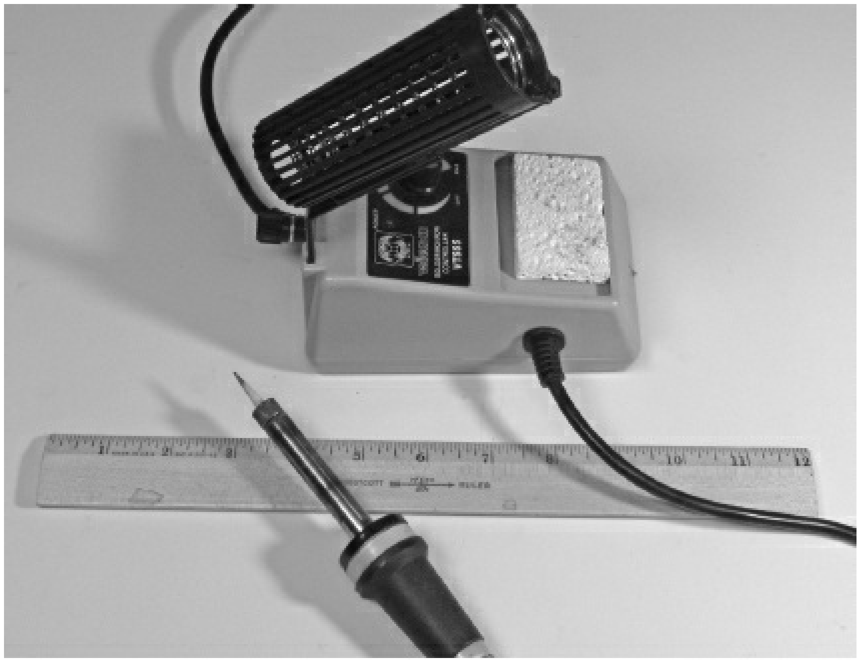


Figure 3.3 — An inexpensive soldering station. The soldering station provides continuous control of iron temperature through the knob included in the base. While precise control is not provided by this arrangement, it does allow easy adjustment for different conditions.

A more sophisticated (and more expensive) arrangement is a thermostatically temperature controlled soldering station, as shown in **Figure 3.4**. A thermostatically controlled station includes an electronic sensor in the tip that monitors the temperature and signals the control unit to increase or decrease the power applied in order to maintain the selected temperature. Generally, an indicator is provided to show that the desired temperature has been reached. The temperature can be set to deal with whatever type of solder is being used without danger of overheating components or PC structures. This system configuration is probably the best for anyone who expects to do considerable soldering work with modern equipment. While a thermostatically controlled soldering station is more expensive than the other choices, it may pay for itself by avoiding damage to the equipment.

Figure 3.4 — The Weller WD-1000 temperature controlled soldering station. This unit automatically regulates the iron tip temperature to the desired setting. The settings can be adjusted manually using the switches on the right side of the control, or three temperatures can be programmed in and accessed with a single push of the appropriate button beneath the display. [Photo courtesy of Apex Tool Group, LLC]

Soldering Iron Heat Source

The soldering irons discussed so far were all electrically powered. Early soldering irons, often called "soldering coppers," consisted of a fairly massive "tip" of copper formed with a chisel point. The tip was connected to a wooden handle by a steel shaft. The iron was heated by laying it in a flame until it became hot enough to melt solder. The extent of the tip mass determined how much material could be heated up before the material and tip temperature dropped too low to melt solder, at which point it was returned to the flame.

Electrical power made for a much more useful soldering system and is probably the most common, but it is not the only choice. Gas-fired soldering is probably the method most frequently used for soldering plumbing fixtures. Plumbers usually use a blowtorch or propane torch with the flame applied directly on the pipe near the joint to be soldered.

For radio work, a propane torch has its uses. The hardware store propane torch shown in **Figure 3.5** has a special soldering tip that is put on the end of the flame tip. I find it difficult, and potentially dangerous, to try to ignite the flame while the soldering tip is installed. Instead, I fire up the flame tip and then use pliers to slide the soldering tip on and secure the locking screw. The longer the pliers handles the better!

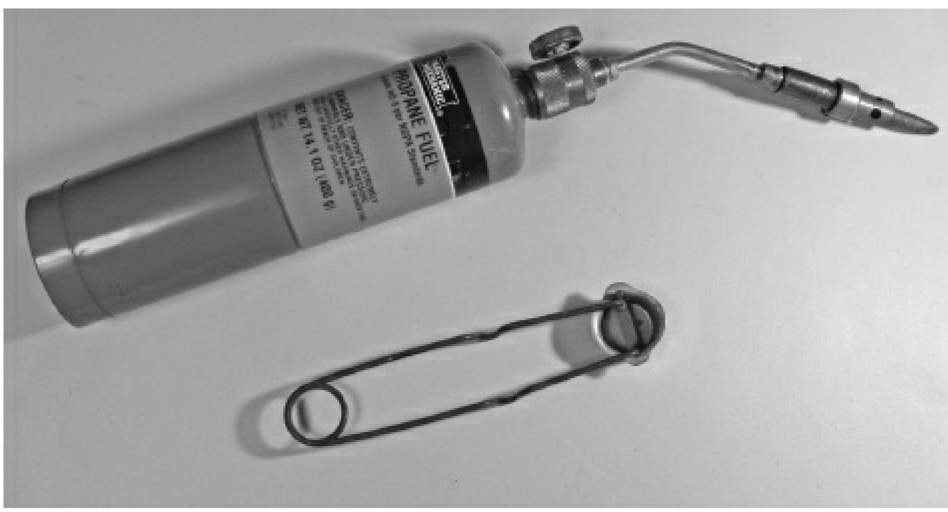


Figure 3.5 — A plumber's type of portable propane torch with a chisel-type add-on head designed for heavy-duty soldering. The igniter is used to start the flame with the tip removed and then the tip can be attached carefully with pliers.

I find the propane torch and soldering tip particularly useful for outdoor work requiring significant power. Recently, I replaced the coaxial cable for the marine VHF radio on my sailboat mast. While I could install one coax connector at home, after I pulled the cable through the mast and prepared to solder the lower connector I had some trouble. While my 140 W soldering gun is usually just up to the task in my workshop, the voltage drop in the 100-foot heavy-duty extension cord needed at the boat yard, along with the brisk on-shore wind cooling everything down, was too much for my gun. I called on the propane torch with soldering tip and had no trouble. This is not just for sailors. The same kind of conditions can be found in backyard or rooftop antenna work — just be careful not to ignite your asphalt roof shingles (don't make an ash of yourself!).

In addition to the large propane torch soldering tools, there are compact pencil-type gas-fired soldering irons available. These are generally powered by compact butane cartridges of the type used with gas-fired cigarette lighters. Six butane irons were reviewed in *QST* with the conclusion that they performed well for all but the heaviest soldering tasks. Some did reasonably well for soldering PL-

259 coax connectors.[2]

Another type of "off the grid" soldering iron is powered by a built-in battery. These are similar in size to the butane irons, and several were reviewed in *QST*.[3],[4] While there are some unit-to-unit differences, the consensus seems to be that the battery powered irons are suitable for light-duty soldering, such as soldering thin wires or components to PC boards, but they are not as powerful as the butane irons.

Preparing the Material for Soldering

The next section will discuss the actual soldering process, but first let's get prepared for the job. Successful soldering is closely tied to the preparation of the surfaces to be soldered. In order for solder to adhere to the material, typically copper, the surface must be clean. The rosin core will overcome some light oxidation, but all insulation and heavy corrosion or other material must be removed from the surface before soldering is attempted.

Removing Insulation from Wire

Much wire that is used in radio work is insulated, although bare wire is also encountered. The insulation must first be removed for solder, or anything else, to make contact with the wire. An advantage of insulated wire is that most insulation helps reduce surface oxidation by keeping the copper from being exposed to the air. A disadvantage of insulation is that during the removal process, the wire can easily be nicked. The wire can break at the nick when it is bent or flexed.

Plastics are the most common insulation materials, and they are perhaps the easiest to deal with — but only if the correct tools are used. While fancier stripping tools are available, it is hard to beat the simple "Miller" stripping tool, as shown in **Figure 3.6**. This tool was originally made by the K. Miller Company of West Springfield, Massachusetts, and is now available from others. The tool is adjustable to different wire sizes through the use of a stop screw. To use it, set the stop so that the blades do not quite contact the wire when closed. This way, they will not nick the wire, but will cut through enough of the insulation to make it easily removable. Some versions (but not my circa 1950 model) include a guide to wire size on the stop wheel.

Figure 3.6 — A classic "Miller" wire stripping tool. This sample has been in the author's family for about 60 years and is still going strong. The original manufacturer, K. Miller T & M Company from West Springfield, Massachusetts, is no longer in the picture, but similar tools are being made by others. Some offer advanced features, such as a return spring and a wire size selector.

Enamel insulated wire can be much tougher to deal with, but some types are easier to strip than others. If you buy enameled wire, look for the type that has insulation that will burn off when touched with a hot soldering iron or will melt in molten solder. Other types will have to be scraped off with fine sandpaper or a by using a hobby knife — not easy with very thin wire.

Oxidized bare copper wire can be prepared by scraping as well, although it is usually a bit easier to clean than enameled wire. Tinned copper wire can often be cleaned up by just heating the wire end with an iron and applying a bit of solder to the wire. This operation is called "tinning" and is a good idea to do for any copper wire before soldering it to its connection point. The trick is to get just enough solder on the wire to change its color to that of the solder, but not enough to make it noticeably thicker. Often there will be a bit of a blob at the end of the wire, so strip off ⅛ inch more wire than you expect to need and cut that off after it has cooled. By tinning the wire, you will know immediately whether or not you have gotten it cleaned off. If it's clean enough, the solder will flow smoothly across the surface. If not, the solder will tend to form a blob instead of flowing, and will not properly adhere to the metal.

Making the Soldered Connection

Now that we have selected our soldering iron and prepared our work, we are ready to solder — almost! A word about safety is in order here. While risks associated with soldering are not extreme, we would be remiss to not mention a few things learned from painful experience.

■ Never pick up a soldering iron by the wrong end.

■ If wearing shorts or sandals, keep exposed skin from beneath the work area. Molten solder will drip or splatter. While not great for clothing, it is even worse on exposed skin.

■ Keep your head away from the fumes that are emitted from the solder and rosin core as it melts. The vapors contain toxic substances.

■ Keep the iron in a proper holder when it is not in your hand. A hot tip can easily cause a fire,

Holding the Work in Place

In order to make a successful soldered connection, the work needs to be secured so that it can't move while the solder is being applied and especially while the connection is cooling. If the connection moves while cooling, instead of the shiny, bright appearance of a proper soldered connection, we are likely to see a crystalline appearing dull solder joint that will fail in short order.

Figure 3.7 — A "third hand" soldering tool such as this can hold your soldering work together while you apply heat and solder. This example is one of a number available from Micro-Mark (www.micromark.com), particularly suited for small work. Other types are constructed in the form of a vise, some with thermoplastic jaws. [Image ©2014, Micro-Mark, used with permission]

A vise or heavy clamp can be used to secure wires being soldered. One caveat — it is important that metal vise jaws not come into direct contact with the metal surfaces being soldered. If so, the heat from the intended joint will conduct into the mass of the vise, requiring much more thermal energy than the connection by itself should need. This often results in the material becoming hotter than necessary and potentially damaging sensitive components. If the material to be soldered has insulation, the electrical insulation is generally a good thermal insulator as well. It will keep the vise jaws from absorbing heat from the soldering iron. Or, a few pieces of thin wood or other material can be employed between the vise jaws and the work.

There are specialized fixtures designed to hold the work while it is being soldered. Sometimes called "third hands," they hold the work in place so you can use one hand for the soldering iron and the other for the solder. The unit shown in **Figure 3.7**, courtesy of Micro-Mark, is one available type.

Performing the Actual Soldering

In order to make a successful soldered connection, first make sure that the wire to be soldered is securely attached to the other side of the connection — another wire, connector, PC board, terminal and so forth — so that it won't move during the soldering process. If one side of the connection has a hole, don't just stick the wire through and hope for the best. If possible, also wrap the wire and crimp it with pliers before you solder it to make a good mechanical connection. If the hole is a good match to the wire size, as often is the case with holes in PC boards, the best you can usually do is insert the wire or lead and bend it a bit on the far side to hold it in place. Following the soldering operation, the excess wire can be trimmed off carefully.

After the connection is secured for soldering, verify that the iron is up to temperature — it should quickly melt solder touched to the tip surface. Next, apply solder to the iron tip to coat the surface and wipe off the excess with a damp sponge. This will help to avoid excess solder flowing onto the connection. Apply the iron to touch both sides of the connection, if possible, and apply solder to the connection (not to the iron) until it flows smoothly on both sides of the connection as shown in **Figure 3.8**.

Figure 3.8 — The author is soldering a pair of bare copper wires. Note that the wires are held in place by a small machinist's vise. Two strips of wood provide thermal insulation from the jaws so the heat will not be drawn away. The hot iron is applied to both wires from beneath to allow the heat to rise to the soldering region, while the solder is applied to the wire until it flows smoothly.

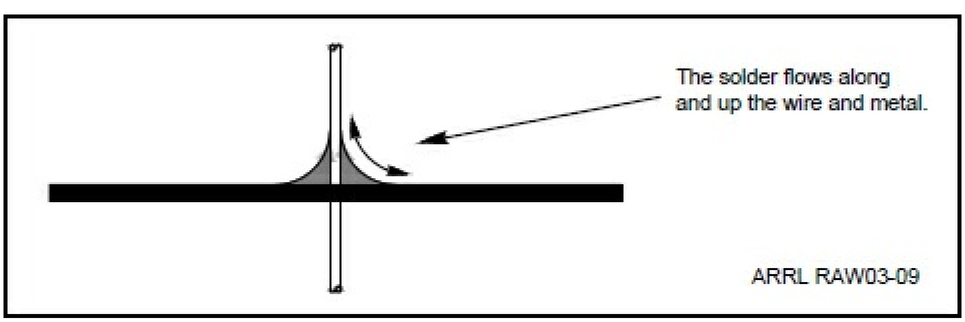


Figure 3.9 — In a properly soldered connection to a PC board, the solder flows along the metallic trace of the board as well as up the wire. The appearance is shiny. A rough surface generally means that the joint moved while cooling and the resulting "cold solder joint" will be prone to failure.

Once the solder has flowed over the connection surfaces, gently remove the heat without moving the connection. Allow the connection to return to nominal temperature (just warm to the touch) before moving the pieces.

If you are soldering a wire onto a printed circuit board, be very careful to use an iron with the right size tip. When placed at the junction of a wire and the PC board trace, the tip must not also cover the adjacent traces — that's a recipe for a short circuit between traces. The solder should just flow and look as shown in **Figure 3.9**. It should not be a blob sitting on (but not connected to) the PC board.

A Special Case — Soldering Coax to a UHF Plug

I believe it is safe to say that the majority of RF coaxial connections in Amateur Radio are made using UHF (PL-259 type) plugs and their mating sockets (SO-239 type). Since many amateurs seem to have problems soldering these connectors, it is worth spending a moment on the topic. But note that, as will be discussed in the next chapter, soldering is just one option for assembling coax cables. In addition, it is often feasible to buy commercially fabricated cable assemblies from a number of *QST* advertisers. At some point, most amateurs will need to solder a coax connector, so let's take a look at how to do it.

While cables come larger and smaller, the majority of coax cables that amateurs come into contact with are found in three sizes. The largest is the size of RG-8 and RG-213 (50 d), and RG-11 (75)) cable, as well as a number of special low loss variants. These have an outside diameter of 0.405 inch and are the size that the PL-259 was originally designed for. The next smaller size is that of RG-8X (50 x) and RG-59 (75)) cable. These are about 0.242 inch in diameter and can be used with PL-259 plugs if an adapter (type UG-176) is used. Similarly, the smaller 50) RG-58 cable requires a type UG-175 adapter to fit its 0.193 inch diameter (see **Figure 3.10**).

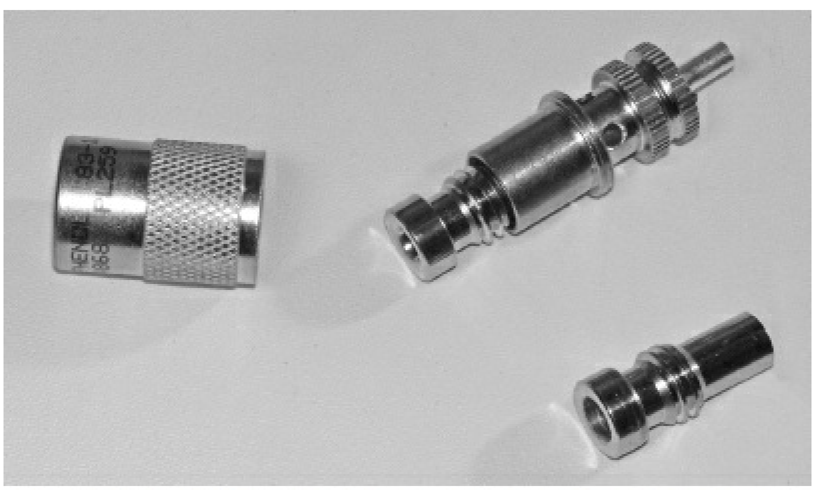


Figure 3.10 — A PL-259 UHF series coax plug along with UG-175 and UG-176 adapters. In this view, the UG-175 is partly threaded into the rear of the plug, while the UG-176 with its larger cable entry hole is below.

Each type of connector has published stripping dimensions, and special tools can be helpful. The tool shown with some RG-213 in **Figure 3.11** makes three cuts to any 0.405 inch cable as the tool is turned around the coax, automatically stripping the right amount. To assemble the coax into the connector, first put the back shell on the coax, then twist the full size coax into the rear of the connector until the outer jacket is threaded into the plugs threads. The shield should be exposed in the solder holes and the center conductor should be protruding from the center pin.

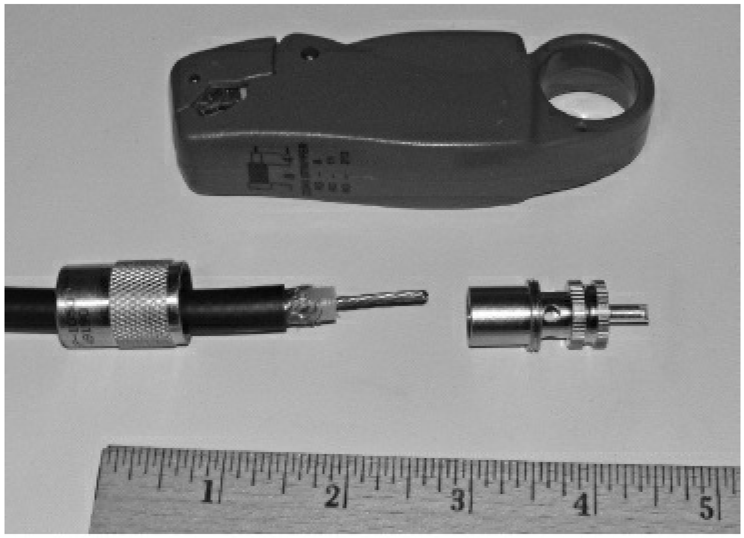


Figure 3.11 — The end of a length of RG-8 coax stripped using the special tool shown. This tool has three blades that strip the outer jacket, shield, and inner conductor in one pass. They can make this work easier.

To solder the center pin, orient the connector so that the open end of the center pin is pointing partly downward. Heat the center pin, but apply the solder to the center wire at the open end. The capillary effect will tend to suck the solder up into the pin, rather than run on the outside. If you get solder on the outside of the center pin, you will need to remove it for the pin to fit properly into an SO-239 socket. Let the connector cool. Then use a higher power iron, such as a 140 or 200 W gun, to heat the barrel of the connector until solder will flow. Apply solder through the shield solder holes, making sure that the shield wires are taking the solder. A blob of solder at the holes doesn't make a connection. Because of the high heat, there is some risk that the dielectric will soften. Make sure the cable is leaving the connector on a straight line — any bends are an invitation to a short.

The smaller diameter coax cable is a bit easier to work with in a number of ways. It is more flexible, so it will be more inclined to obey your wishes. It is easier to strip using conventional tools, although there are special strippers available for the smaller sizes as well — perhaps worth purchasing if you do this often. **Figure 3.12** shows a length of RG-59 ready to be soldered into a PL-259 plug. Note that the back shell is positioned so that it won't be forgotten. The cable is inserted into the UG-176 adapter so that the outer jacket is running the full length of the adapter. The shield is combed out and folded back over the end of the adapter, and then the shield wires are trimmed so that they are clear of the threads. The inner conductor is stripped to within ⅛ inch of the adapter and then the adapter is screwed into the plug. It is now soldered in the same manner as the larger cable.

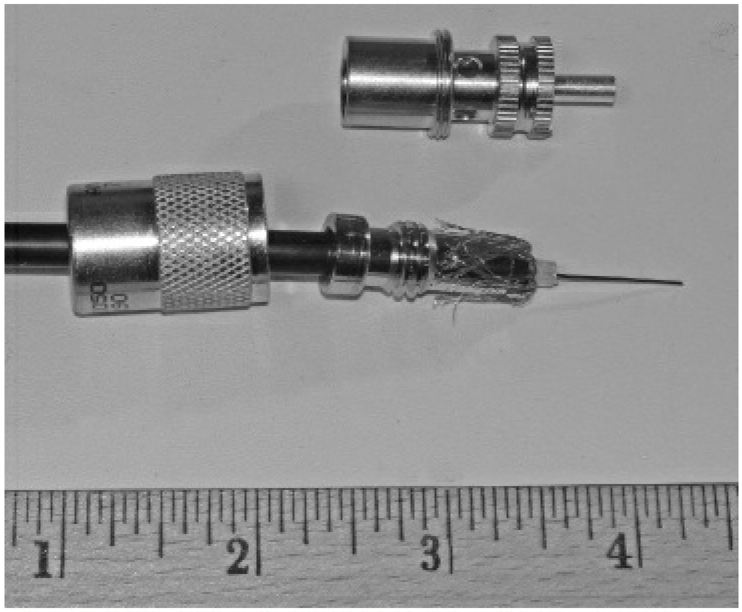


Figure 3.12 — A piece of 0.242 inch coax, here some RG-59, shown inserted into a UG-176 adapter and ready for final assembly into the PL-259. It is important to position the back shell in correct orientation behind the plug; otherwise it can't be installed after the connector is soldered.

I have to pass along a caution about the particular UHF plugs and sockets used — not all are built to the same standard. Unfortunately, in my experience, there is no such thing as a bargain UHF connector. I have found that UHF plugs and sockets made by Amphenol are of uniformly high quality and the silver-plated ones are the easiest to solder. While I am sure there are other good ones, I always go with Amphenol because they are always good. I have had inexpensive UHF plugs in which the RG-8 center conductor would not fit in the center pin, and some in which the insulation melted before the shield was soldered. Others had the wrong thread for the adapter, and some were plated with a shiny material that would not accept solder. While SO-239 sockets have fewer places to go wrong, it is common for inexpensive sockets to lose tension on the inner conductor after not nearly enough insertions.

Dealing with Surface Mount Devices

Modern equipment is often made using components without wire connecting leads. These surface mount devices (SMDs) are designed for automated assembly of PC boards. In a manufacturing environment, paper tapes of components are fed to a machine that uses numerical control to precisely position devices on the board so that their connector pads are in contact with corresponding pre-tinned pads on the PC board. Solder paste holds the components in place and once the board is fully populated all connections are made using a high temperature oven, infrared, or other techniques that apply heat to the entire board at once. (This is called reflow soldering.)

SMDs can present challenges in the home workshop, not the least of which is seeing them or identifying what you've got (see **Figure 3.13**). For the home constructor, the challenge is to position the device in alignment with its solder pads, and then hold it in place while you solder each lead. Unless it is securely positioned, the SMD has an uncanny tendency to come off the board attached to the soldering iron.

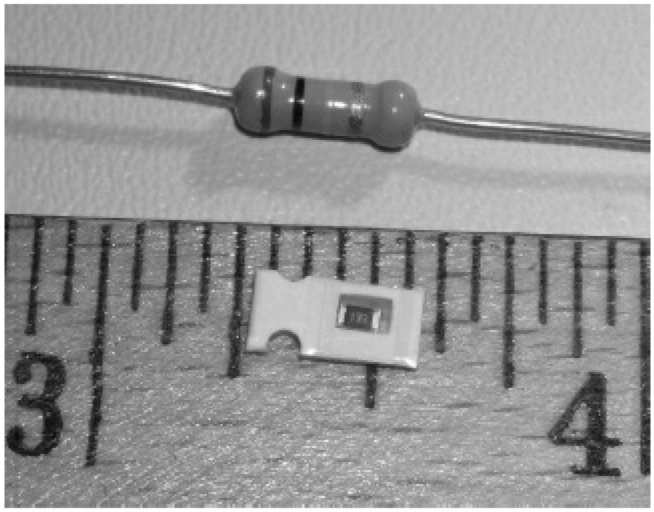


Figure 3.13 — Comparison of a surface mount resistor to a traditional ½ W leaded resistor. The surface mount resistor is within the "window" of the fiber carrier. On each end are tined connection points that must be soldered to the equivalent pads on the PC board. If you drop it on the floor, only the vacuum cleaner will find it!

In my experience, a two-terminal surface mount resistor or capacitor is not too hard to solder. If the device is held in position with a small flat-blade screwdriver, one end can be tack soldered into position using just enough heat between the sides of the joint to hold it in place. When the joint cools, the other end can be soldered more completely. After that is cool, the first side can be soldered more securely.

There have been a number of descriptions of home-fabricated devices that can be used to hold in place devices with more terminals, such as transistors and integrated circuits (ICs).[5,6] The key is to keep the SMD immobile, have enough magnification to be able to verify pad alignment, and then use a micro-tip iron to be sure you solder each pad, one at a time. It is also important to avoid touching the device itself with the soldering iron, since those on ceramic substrate can easily crack.

Checking It Twice

Any manufacturer is only as good as the Quality Control department. The same is true in the Amateur Radio workshop. After you have completed the soldering work on a chassis or PC board, take the time to carefully inspect each connection using sufficient magnification to spot problems. All soldered connections should be smooth and shiny. In addition, make sure that no unintended solder flow results in bridges between PC board traces.

Also, make sure that all intended connections have actually been soldered. I have actually found connections that I missed soldering many years after the fact — explaining strange intermittent operation of some kit-built test equipment that I assembled as a teenager, when I was too busy to double check.

Unsoldering

Soldering is fairly unique in that it is generally a reversible process. Unlike welding, in which the metal components are molecularly fused, a soldered connection can be undone by heating the joint to the same temperature that caused the solder to flow. In some cases, it is just that easy. In others, especially if multiple pins need to be unsoldered, as in the case of an integrated circuit, it can be more difficult.

Unsoldering (also called desoldering) can be required to replace a failed component, to make a modification to existing equipment, or to try a different value component during the circuit development process. During the development process, it is worthwhile to use the minimum mechanical connection needed to hold the pieces together while soldering — then it can be as easy as possible to unsolder the connection later.

Factory manufactured production equipment is often at the other extreme, with component leads tightly wrapped around terminals. These don't tend to allow easy removal without special help. Often, removing all possible solder from a connection will allow the wires to be unwrapped. This can be done simply by two methods illustrated in **Figure 3.14**. One is a special desoldering iron that heats the connection and then the vacuum bulb is used to suck the melted solder from the connection. The other is a desoldering wick that is heated and placed on the connection. The solder tends to flow into the wick's braid by capillary action. After use, the end that has wicked up solder is cut off. Either of these techniques often require multiple applications.

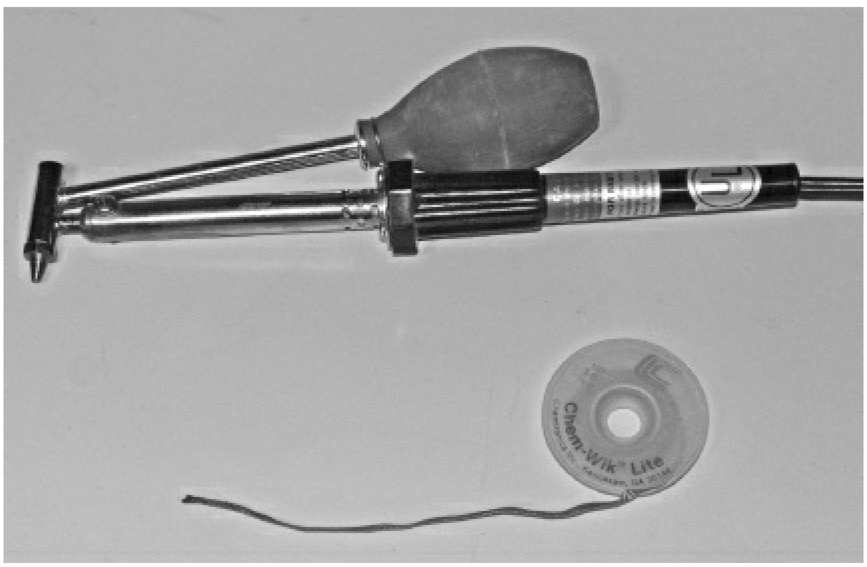


Figure 3.14 — Two desoldering tools. The one on top is a complete desoldering station with a vacuum bulb to remove molten solder. Separate "solder suckers" are also available. On the bottom is desoldering wick that is used to pull molten solder away from the connection via capillary action.

Caution is suggested for any desoldering work in areas that have very dense circuitry. It is often difficult or even impossible to remove components without special equipment. Some densely packaged equipment is made using *multilayered* PC boards in which connections to interior layers are not even accessible. Radios in this category may be best closed up and shipped off for repair. Even if you could get them apart, the chances are that the replacement parts are not readily available.

Notes

[1]**www.kester.com/knowledge-base**

[2]G. Haines, N1GY, "Product Review — A Look at Butane Powered Soldering Tools," *QST*, Aug 2008, pp 47 – 48.

[3]G. Haines, N1GY, "Product Review — A Look at Battery Powered Soldering Tools," *QST*, Jun 2007, pp 69 – 71.

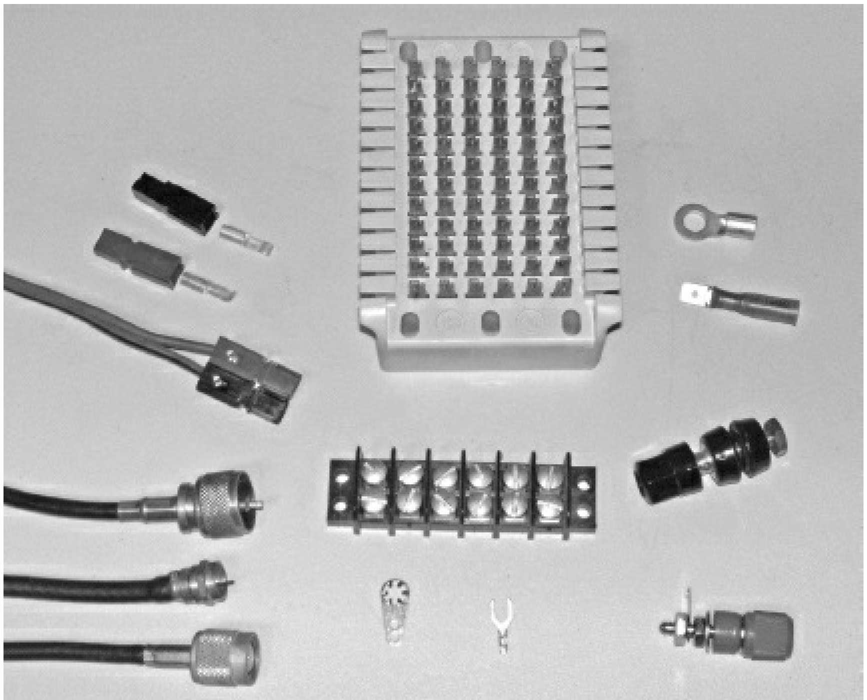
[4]G. Haines, N1GY, "Product Review — Three More Battery Powered Soldering Tools," *QST*, Feb 2009, pp 49 – 50.

[5]D. Avery, WB4RTP, "SMT Soldering (Technical Correspondence)," *QST*. Feb 2000, p 70.

[6]R. Littlefield, K1BQT, "Build a Simple SMD Workstation," *QST*, Jul 2000, pp 56 – 57.

Chapter 4

Other Connection Methods



While soldering is often the method of choice, other connection techniques have a special place in the amateur's toolkit. This view shows some connection possibilities using other popular methods.

Contents

Crimped Connections

A crimped connection is one in which a metal sleeve is compressed around a wire. Sometimes the sleeve is compressed around a braid surrounding an inner sleeve, as is the case with coaxial cable. The compression force is sufficiently strong to hold the wire in position permanently and assure a low resistance contact is made between the wire and sleeve.

The metal sleeve can be an extension of a terminal, such as a spade lug or ring terminal, or it can be a part of a connector of some sort. Any advantage of crimped connections over soldered ones is somewhat dependent on conditions. Crimping avoids the need for application of heat, which can be difficult in some circumstances. Heat is also potentially harmful to wire insulation. In some cases, a crimped connector on the end of a stranded wire will be less likely to suffer damage from metal fatigue than a soldered connector. Stranded wire wicks solder, making it less flexible and more prone to damage from movement or vibration.

At this writing, the most frequently encountered crimped connections appear to be to 1) Anderson Powerpole connectors, typically used for dc power; and 2) various types of coaxial connectors for RF interconnections.

Powerpole Connectors

The 45 A size Anderson Powerpoles in red and black housings have become very popular for connections in 12 – 13.8 V dc power systems. The 45 A size housing accepts three different inserts, rated at 45, 30, and 15 A. The difference is only the size of the barrel for crimping the wire — they will all interconnect. Many public service communications organizations have standardized on these to facilitate equipment interoperability. A number of equipment manufacturers now use Powerpoles on the back of their radio equipment.

These connectors have the advantage of being genderless, as well as providing quick and easy connection. They stay connected until pulled apart with reasonable force, but the force required is small enough that they will generally release before equipment is accidently pulled off a shelf when an inattentive operator trips over the wire.

Figure 4.1 shows the Powerpole 45 A housings, the connector blade inserts, and some assembled connectors on cables. Note that the connector housings offer considerable flexibility as to connector orientation and terminal quantity. There are mating dovetail slots on all four sides of each body, so any number of connectors can be combined in any configuration. Colors other than red and black (such as yellow, green and white) are available. While such flexibility makes Powerpoles useful for many functions, it is important to be aware there is a *de facto* standard for Amateur Radio power system use. Unless that is followed, you will be pretty much on your own. The arrangement shown in Figure 4.1 and **Figure 4.2** follows that standard. The standard is often described as “tongue top, red right” while looking into the open connector.[1]

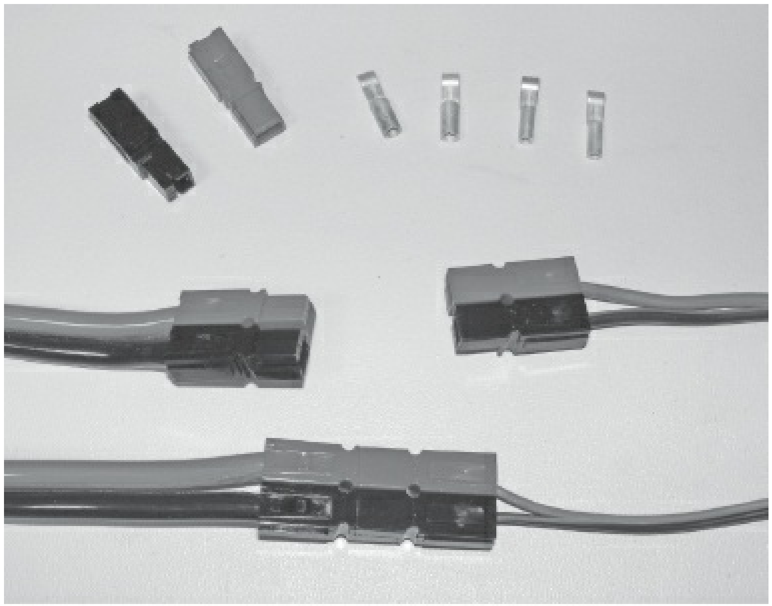


Figure 4.1 — Anderson Powerpoles — the housings (upper left), connector blades (upper right), assembled connectors on cables (center), and the cables interconnected (bottom). All are assembled per the *de facto* standard shown in Figure 4.2. Note that while the connector body is rated at 45 A, the connector inserts are available to fit different wire sizes. The two on the left are for #12 to #16 AWG, while the pair on the right will fit #16 to #20 AWG wire. While the connector blades will handle up to 45 A, that should be reserved for the blades designed for #10 to #14 AWG wire.

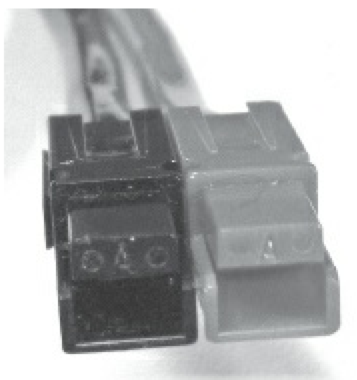


Figure 4.2 — Looking into the business end of a pair of Powerpoles assembled to the *de facto* amateur standard. The "tongue top, red right — while looking into the open connector" arrangement should be evident in this view.

While the Powerpole tubular sleeves are a natural for crimping, soldering is feasible as well. Take care that the solder stays entirely within the sleeve to avoid impeding assembly. If some solder does migrate to the outside of the sleeve, it can usually be removed with a fine-toothed file.

While it is very easy to mess up a Powerpole using solder, a crimped connection can fail as well unless the correct tool is used. For the blade and sleeve to slide fully into the housing and snap into place, the crimped sleeve has to be within the size envelope of the original sleeve. While a crimping tool with the correct die makes it an easy job (see **Figures 4.3** and **4.4**), I have seen good results come from experienced hams using general-purpose crimping tools. It generally seems to take a few passes unless you have the correct die, though.

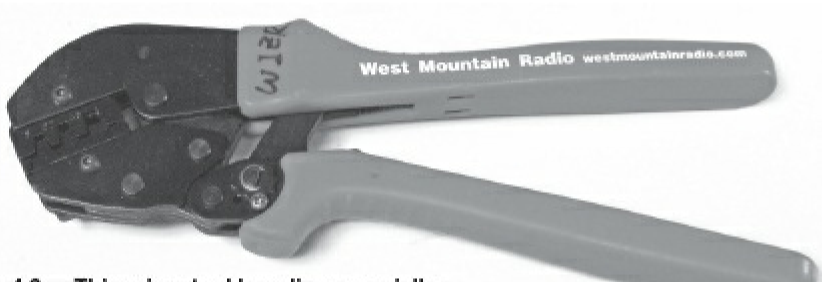


Figure 4.3 — This crimp tool has dies especially made to fit the sleeves of the three sizes available for the 45 A Powerpoles. The dies can be changed to fit other kinds of connectors, making it a versatile addition to the tool kit.

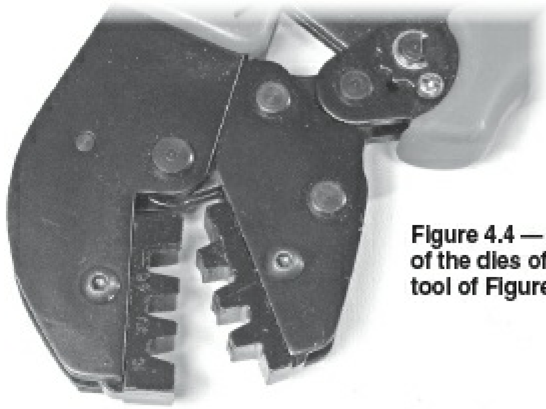


Figure 4.4 — Close-up of the dies of the crimp tool of Figure 4.3.

Once the connector sleeves are crimped, they should be pushed into the connector bodies until a distinct snap is heard and felt. Be careful to insert the positive lead into the red body with the curved part toward the tongue. It is also important that the blades be at the same distance along the wire, otherwise the extra wire on one will tend to make the housings push apart. Some folks use a quick-dry adhesive to hold the housings together, but I find they tend to stay put as long as the wires are the same length.

There is also a half circle cutout in each housing that allows for the insertion of a roll-pin to hold the pair in relative position. Conventional wisdom is that the pin is sufficiently likely to fall out and get into a nasty spot — causing sparks and smoke — that it should be avoided. I tend to agree, although I see no harm in glue. I actually find the roll-pin hole a convenient spot for a very thin tie-wrap to hold a pair of connecters together, particularly useful in a vibration-prone environment such as in a mobile installation.

Coaxial Cable Connectors

I first became aware of crimped coaxial connectors in the mid-1970s as TV type F connectors for RG-6 coaxial cable moved into my consciousness. These connectors were inexpensive devices in which the RG-6 inner conductor served as the inner pin and the combination foil and copper shield was crimped to the back shell. This made a lot of sense — cable TV was starting to roll out and installation technicians generally didn't have the capability to solder inside clients' houses. In addition, the aluminum foil shield was difficult to solder. (Cable used in CATV systems required the additional shielding to attenuate signals to avoid interference to aircraft navigation and communications systems.)

Fast forward to today, and it seems that most commercial coaxial cable assemblies come through with crimped connections. It is pretty easy to fabricate crimped coax connectors if the right tools are at hand. Fortunately, the type of crimping tool shown in Figure 4.3 can be adapted to different crimping tasks by substituting die sets (see **Figure 4.5**).

Figure 4.5 — The crimp tool of Figure 4.3 with dies changed to support crimping coax connectors. Note that there are multiple dies required to deal with various coax connector types.

While it is possible to obtain crimp-type coax connectors in which both the shield and center pin are crimped, some are available with just the shield crimped and the center conductor designed for a solder connection. In a way, this is the nature of traditional Type-N and BNC coaxial cable connector assembly, in which the center conductor is soldered and the braid is secured with a threaded clamp that is tightened with a wrench. This type of plug has the advantage that the soldering portion can be accomplished while the cable is still the original cable diameter and thus can be run through panels and partitions, perhaps to an area where soldering is impossible. The remainder of the connector assembly on the other side of the partition can then be accomplished with just wrenches.

The usual crimp-tool type dies are also available for the BNC, N and related types of connectors. This makes particular sense for the types of cable that have foil shields that can be difficult to handle with a traditional Type-N clamp connector or solder-on PL-259 UHF plug.

Binding Post, Terminal and Screw Connections

There have been many types of connectors for wires in electronic equipment over the years. Some, such as the Fahnestock clip (**Figure 4.6**), are no longer in common use, while others will always be with us. Perhaps even older than the Fahnestock clip, screw terminals (in which a wire is secured under a screw head, perhaps with a nut and washer) are still in common use. Variants include the screw terminals on ac light switches and the more radio-oriented barrier strips (**Figure 4.7**).

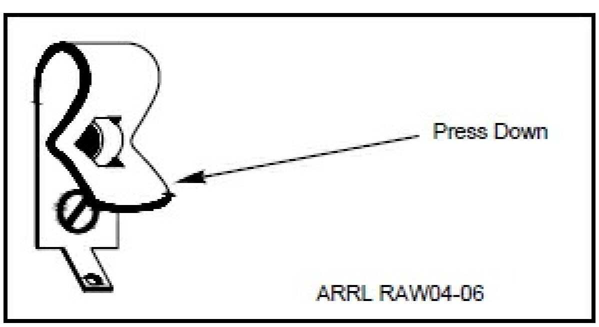


Figure 4.6 — The Fahnestock clip, a spring connector designed to attach wires to circuitry, was invented in 1907. Still available, they are rarely seen in post-World War II era equipment.

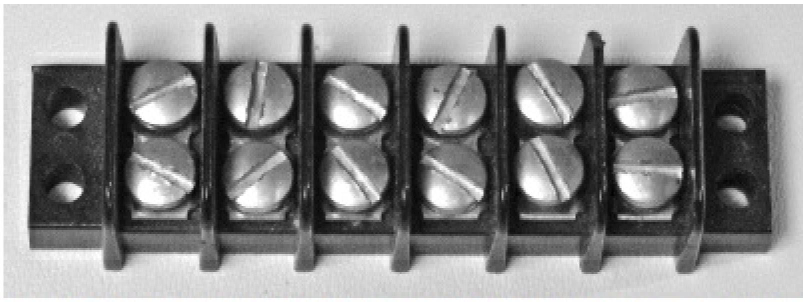


Figure 4.7 — A multi-connection barrier strip. While barrier strips are useful to connect to bare wire ends, a more solid connection will result from the use of eye or spade terminals on the wires.

The connections of Figure 4.7 have the benefit of a wire space constrained by physical barriers that help prevent properly sized bare wires from sliding out from under the tightening screw head (or even better, screw and washer). Barrier strips were long popular for connections between different chassis in racks of equipment. Their disadvantage is that they provide no protection against inadvertent contact — something that wasn't much of an issue until fairly recently — although covered barrier strips are sometimes seen.

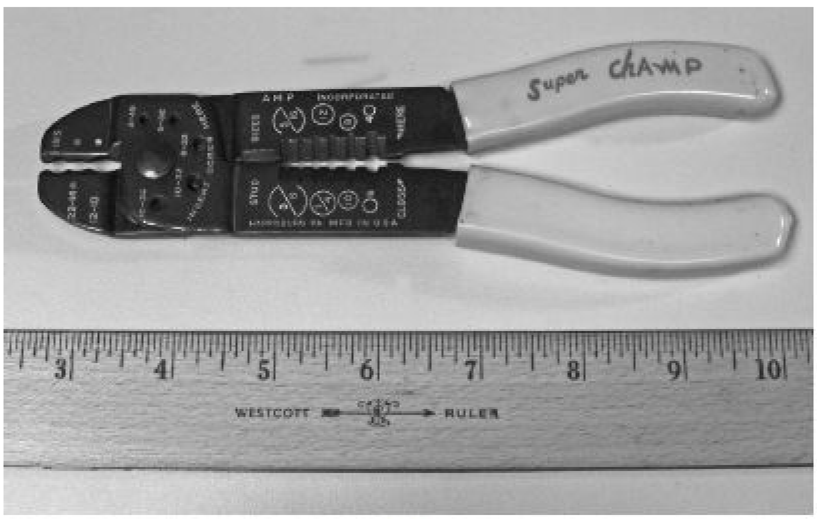
An even better way of connecting to screw terminals or barrier strips is with *eye* (also called *ring*) or *spade terminals*, as shown in **Figure 4.8**. These types of terminals are very handy, and they can be crimped using many types of tools. The same family of crimp or solder terminals includes butt-splices, flat automotive-type connectors, and other handy connector types and terminals. These are generally available in electronic retailers as well as in most hardware and auto parts stores.

Figure 4.8 — Eye or ring terminals (left) and spade terminals (right) are a convenient way to make a secure connection to a chassis, barrier strip, or any other connection under the head of a screw. The top row shows the insulated type, while the bottom row shows the uninsulated version. While eye or ring terminals are more secure, spade terminals can be removed without completely removing the screw or bolt.

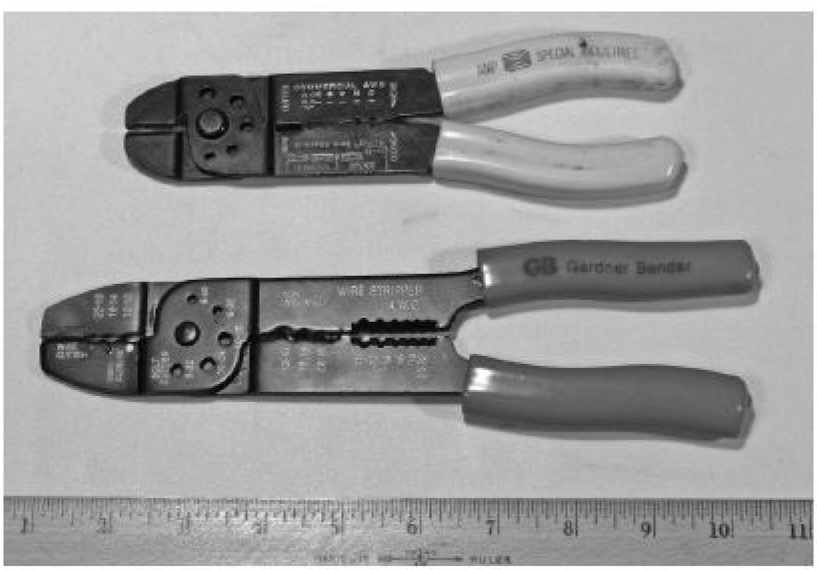
The crimp terminals with the plastic insulation over the wire sleeves come in different sizes for screw clearance and wire diameter. The wire diameter for the sleeve is indicated by the color of the insulation. This seems to be a pretty well-accepted standard: #12-10 AWG in yellow, #14-16 AWG in blue, and #16-22 AWG in red. The packages are also marked with standard screw sizes (#6, #8,

#10 and so on), so just the right configuration can be obtained. While eye terminals are less likely to be pulled out and have more contact surface than spade terminals, the spades are handy for use in tight corners that would make it difficult or dangerous to completely remove the securing screw. In either case, a lock washer can reduce the contact resistance by digging into the terminal.

I have had my Amp Super Champ tool (**Figure 4.9**) since about 1960. Unfortunately that exact tool seems to be no longer available, but similar ones are now offered by other manufacturers. My version serves as a basic crimp tool for three sizes of wire terminals and connectors that have color codes matched to dots on the tool. In addition, it includes a competent wire stripper that has wire size numbers indicated. It also will cut threaded machine screws ranging from #4-40 to #10-24 in size. The bolt cutter works very well with brass and aluminum screws as well as the smaller sizes of steel screws. It seems to be in a bit over its head while attempting the larger sizes in steel — or perhaps I'm losing my grip! The bolt cutter is also handy to verify screw diameter or thread pitch.



(A)



(B)

Figure 4.9 — At A, the author's multipurpose Amp Super Champ tool from 1960. This tool crimps, strips wire, and cuts machine screws. While the Amp Super Champ is no longer available, there are many similar tools on the market. At B, the other side of the Super Champ is shown with the currently available Gardner-Bender type GS-366 crimping tool.

The currently available Gardner-Bender type GS-366 crimping tool is similar to my Amp Super Champ (shown together in Figure 4.9). The GS-366 is a bit longer, providing additional leverage, and also includes crimp dies for the heavier uninsulated type of terminals.

Other Mechanical Connection Methods

Wire Wrap. For many years, wire wrapping was a popular connection method, particularly for low-speed analog and digital circuit prototypes during the development phase. In this method, connections were made to rigid spike terminals that were typically part of integrated circuit or other sockets that would be installed on prototype boards. Specially sized wire was tightly wrapped around the terminal using a special tool that was sometimes motorized, but more often operated by hand. A few turns would do it, and then other connections could be made to the same terminal. It was easy to use an unwrapping tool to make circuit changes.

Punch-Down Blocks. Telephone connections, on poles and in homes and offices, are frequently made using punch-down tools and punch-down blocks. **Figure 4.10** shows a punch-down tool and a small block. The block has slotted terminals, and the slots are closed by spring pressure. The special spring-loaded tool snaps insulated wire into the slot with an action that strips through the insulation, saving a step. The tool has two sides, one of which simultaneously cuts off the wire. After the first three times you cut off the wrong end of the wire, you learn to watch which side is which!

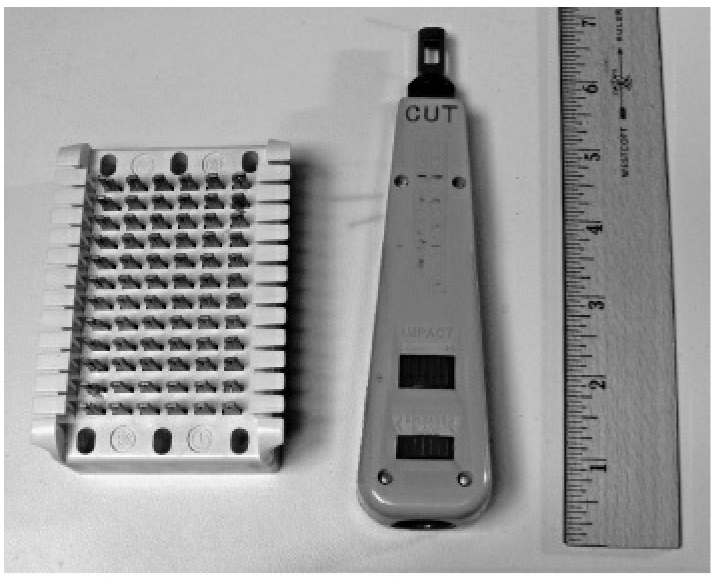


Figure 4.10 — A 12-position punch-down block with a companion spring-loaded punch-down tool. Each of the 12 rows connects straight across, allowing parallel connections of up to six leads.

Punch-down blocks are designed for audio connections, but they also can be used for lower-speed digital connections. My home 10baseT Ethernet LAN is wired using twisted pair (CAT 3) cable and punch-down blocks (see **Figure 4.11**). The 10 Mbps signaling rate is likely beyond the specified maximum for such connections, but it works fine in our small network — and some links are actually running at 100 Mbps.

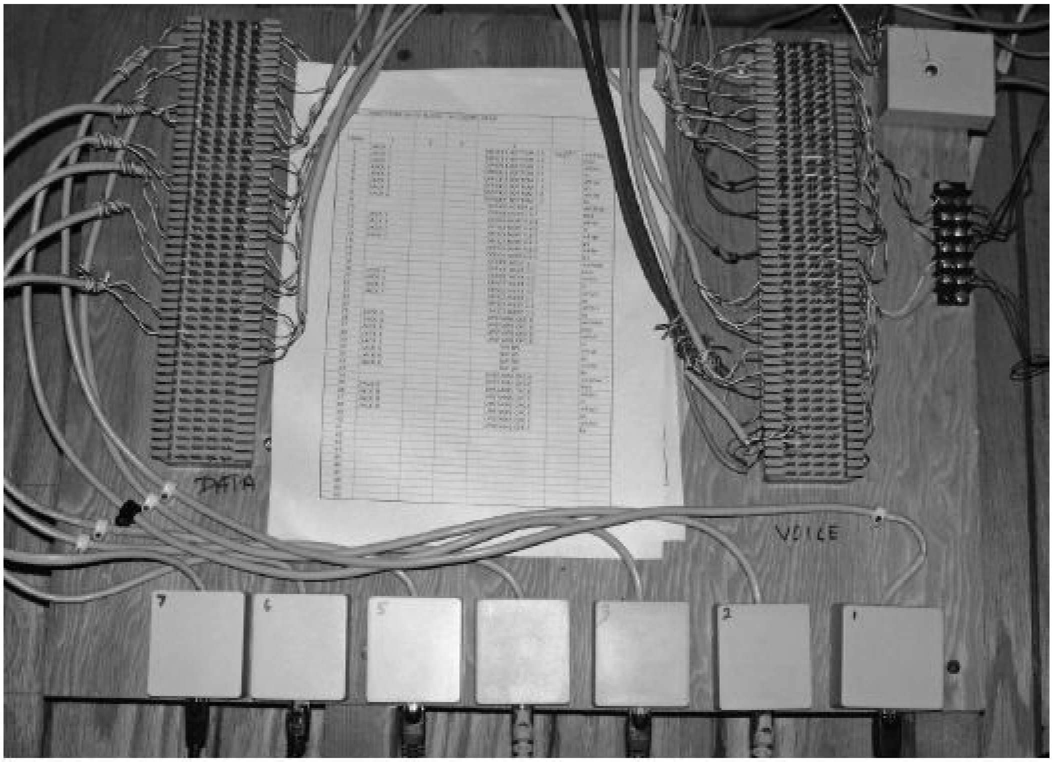


Figure 4.11 — The author's home 10baseT Ethernet LAN is wired using twisted pair (CAT-3) data cable and 50-position punch-down blocks. The left block is for the household Ethernet connections, the right for voice services. The data connections continue down to RJ-45 sockets that are patched to the local hubs and router. The four analog lines (note barrier strip termination on top right) that come into the house can easily be patched to different instrument locations.

Notes

[1] D. Schier, K1UHF, "More Power To You," *QST*, Mar 2006, pp 31 – 33.

Chapter 5

Ratchet-Up for Antenna Projects

The author's HF triband Yagi with coupled-resonator 6 meter add-on. The tribander is a commercial model, the 6 meter portion homemade. Similar tools were required to assemble each.

Contents

Same Kinds of Tools — Bigger Sizes

We can divide antennas between those made of wire and those made of tubing, although some combine elements of both. While operations will be similar, the tools needed are somewhat different. For either category, the tools required are of the same general categories as encountered in earlier chapters, but they tend to be larger because antenna materials are generally larger than comparable materials within electronic equipment.

It can be argued that any size or type of wire can be used to make wire antennas, and that may be almost true in terms of electrical performance. On the other hand, for serious outdoor wire antennas that we want to install for long-term use, we will be much better off using heavier and stronger wire than used inside most equipment. Attempting to use the precision pliers and wire cutters used for radio work on heavier wire will generally be difficult and will likely destroy the usefulness of the tools for fine work.

With some notable exceptions, the tools needed for assembly of antennas made of tubing, such as vertical radiators and rotatable horizontal arrays, are of similar types to those required for kit building, except that bigger tools are required for the larger fasteners usually employed. The screwdrivers and wrenches are of a size often encountered for general and automotive use, such as ⅜ inch wide blade screwdrivers and wrenches in sizes from ⅜ to 9/16 inches (⅜, 7/16, ½ and 9/16 inches, or comparable metric sizes if working with antennas made outside the US). Combination wrenches in these sizes will prove useful, as will ⅜ inch drive socket wrenches, with ratchet handles and extensions — perhaps already available in your workshop for other purposes. And of course an accurate measuring tape is important to be sure the antenna element lengths are correct.

Working with Wire Antennas

It can be argued that construction of improved wire antennas can result in the most improvement per dollar of any radio construction project. It is also often the easiest and most likely to be successful construction task an amateur can undertake. There is nothing like the satisfaction one gets from building a simple-to-make antenna out of a few scraps of wire and then hearing the bands jump to life as the fruit of your labor!

While wire antennas can indeed work if made from light gauge wire, they will generally not last very long if installed outdoors. Wire antennas subject to the elements are best made from wire that won't stretch and won't break. This also means that transitions and junctions need to receive particular attention to avoid concentrations of stress.

My favorite wire for making outdoor HF antennas has become insulated #13 AWG stranded copper-plated steel wire. This wire strikes a balance between strength and durability versus ease of fabrication. While it can't be counted on to hold up a large tree, it is very tough and long-lasting if properly installed. This means avoiding kinks in the wire and making smooth transitions at junctions. For me, this means using thimbles and wire clamps to secure ends, unless the end insulators provide sufficient support for wide radius bends. It also means keeping the connections completely out of the regions of structural stress. **Figure 5.1** shows the kind of tools needed to work with this material, in comparison to similar types of tools used for electronic work.

Figure 5.1 — Comparison of tools for making wire antennas with those for electronic component work. The larger ones on the left are for the larger size antenna wire.

Figure 5.2 shows the thimbles and clamps that I use. Galvanized products are typically used by gardeners to support newly planted trees and are available in most hardware or garden stores. Unfortunately, in my experience, since they have been made outside the US, the galvanizing does not hold up as well as it used to. If you are going to be putting up antennas in salt-air environments, or if you expect to make frequent adjustments, you may want to consider getting stainless hardware from marine dealers. The stainless material looks and works the same way as the galvanized units, costs a lot more, but will be workable for many years, rather than for a few months,

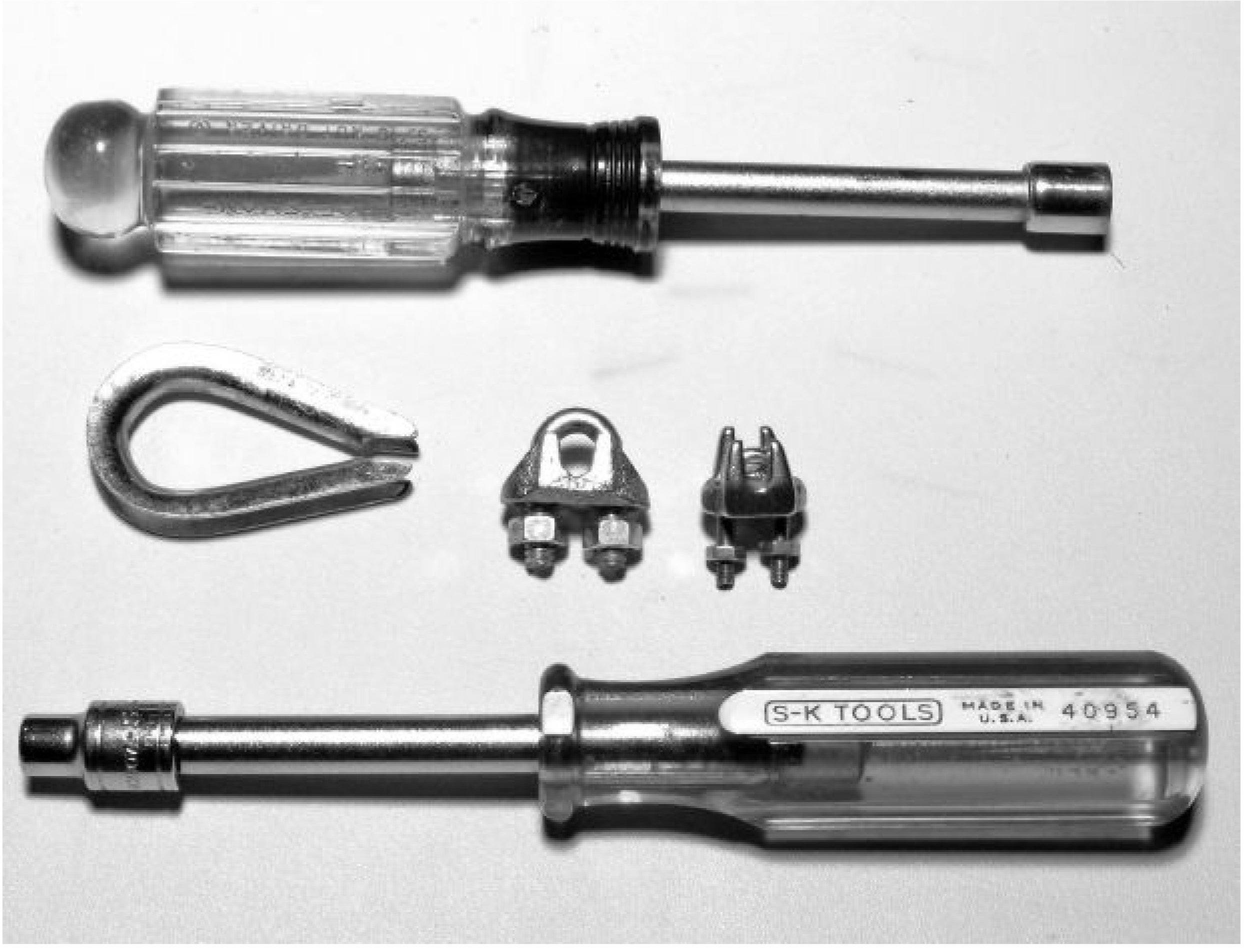


Figure 5.2 — Hardware store galvanized thimbles and wire clamps suggested for terminating serious antenna wire. As discussed in the text, more expensive stainless steel parts, available at boaters' supply stores will hold up longer, especially in salt-air environments. You will want to tighten them with nut drivers as shown. They now come with metric size nuts — 7 mm for the smaller, 8 mm for the larger. While the 8 mm nuts can be tightened with a 5⁄16 inch nutdriver, there is no hope for the 7 mm size. I use a 7 mm socket and ¼ inch drive handle.

Figures 5.3 and **5.4** show the clamps used to secure the wire to center and end insulators, respectively. In this case, both insulators provided for a smooth and large bend radius turn so that thimbles were not required. The photos show the clamps installed in alternate directions. I have since received input suggesting that it is better to put the wider part of the clamps on the side with the long wire length since that will better distribute the stress of the wire under tension.

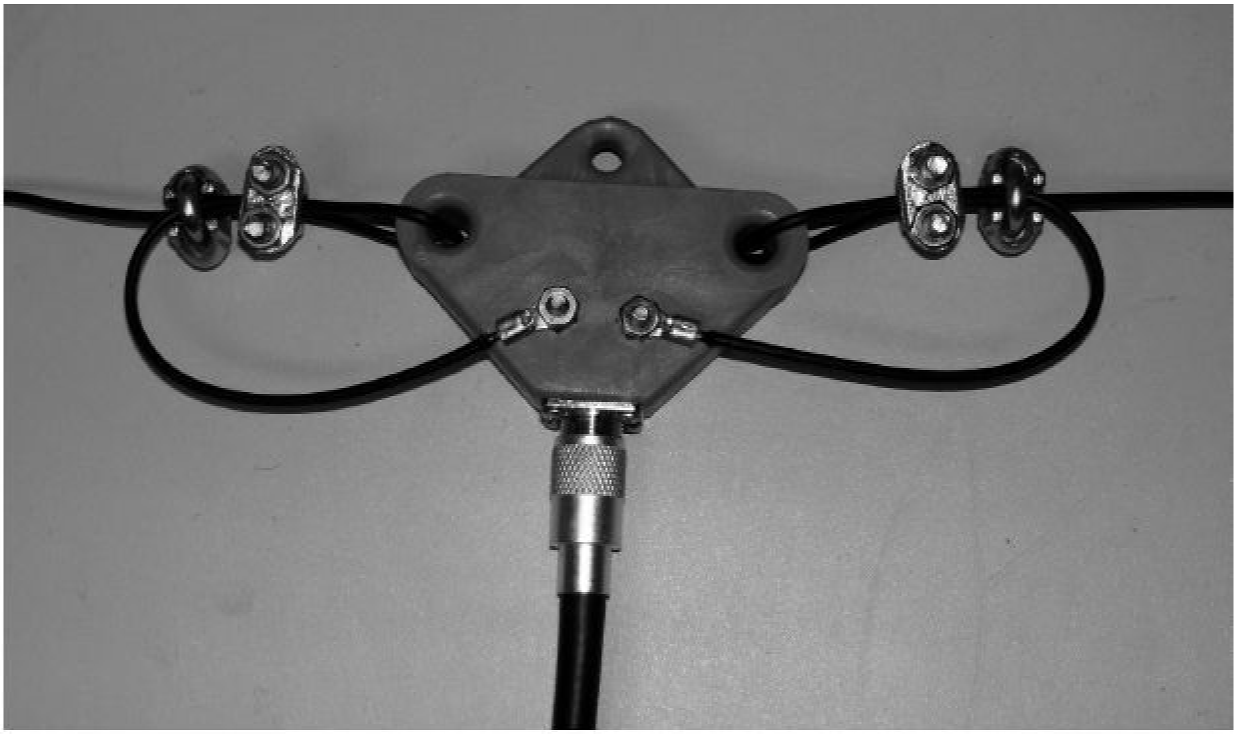


Figure 5.3 — Antenna wire terminated at a commercial dipole center insulator using the cable clamps of Figure 5.2. Because of the smooth edges and wide width of the insulator, the thimbles were not deemed necessary in this installation. Note that the connections to the feed line are made on the side of the clamps that remove all stress from the connection.

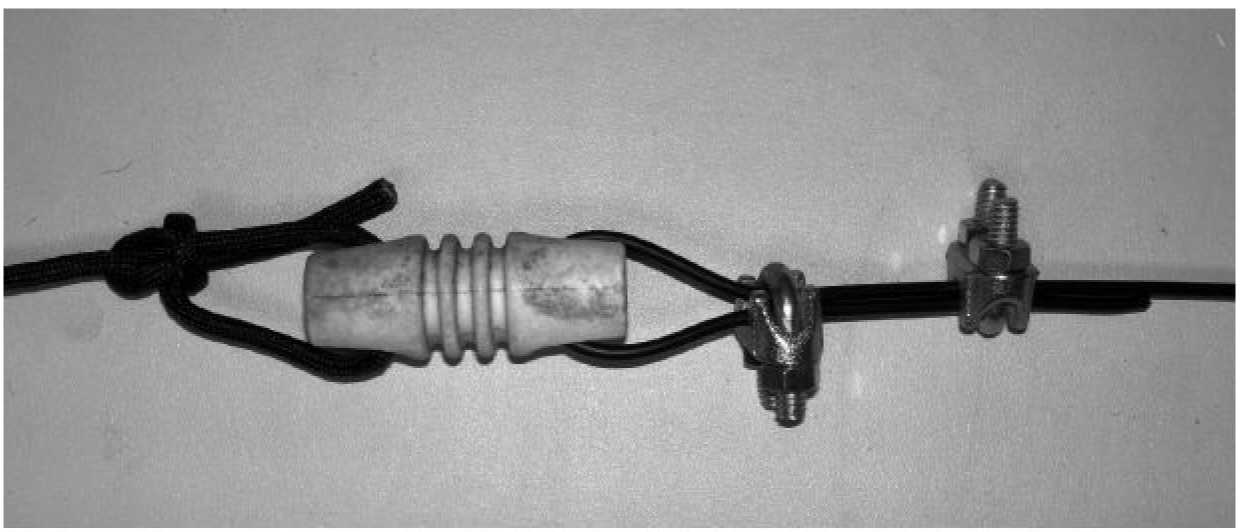


Figure 5.4 — Antenna wire terminated at a dipole end insulator. Again, because of the smooth edges and wide width of the insulator, thimbles were not required in this case.

Assembling and Building Antennas from Tubing

Commercially available HF Yagi and vertical antennas, as well as all but the smallest VHF and UHF antennas, of necessity are shipped in pieces so they can fit on the delivery truck. This is definitely a case of "some assembly required." In a sense, the main difference between manufactured and home built antennas of this type is that the former come with pre-cut, and sometimes marked, pieces of tubing. If building your own antennas, you will need to find a dimensioned design, or design your own, figure out the dimensions, and then cut the pieces to length.

This is a bit of an oversimplification, since many commercial antennas, especially antennas that cover multiple bands, include proprietary components such as traps or matching networks that can introduce additional complexity and may be difficult to duplicate. Still, if you pick your projects carefully, a homemade antenna may be not much more difficult to construct than one from a box of parts provided by a commercial manufacturer.

In terms of workshop equipment, the tools required will be similar, except that the home-brewer will, at a minimum, need to be able to measure, cut, and sometimes drill tubing. There are a number of ways to cut tubing, including using a lowly hacksaw, or for better results a band saw, or even a table saw with the appropriate blade. One of the easiest and cleanest ways to cut round tubing, in my experience, is to use a tubing cutter, such as is shown in **Figure 5.5**. The tubing cutter is inexpensive and easy to use — just be sure to start with light pressure on the cutting wheel to avoid bending the wheel. Spin it around where you want the cut and then tighten a bit and spin some more until the tubing is cut. It will leave a smooth outside edge, but a burr on the inside that will need to be dealt with if smaller tubing is to fit inside.

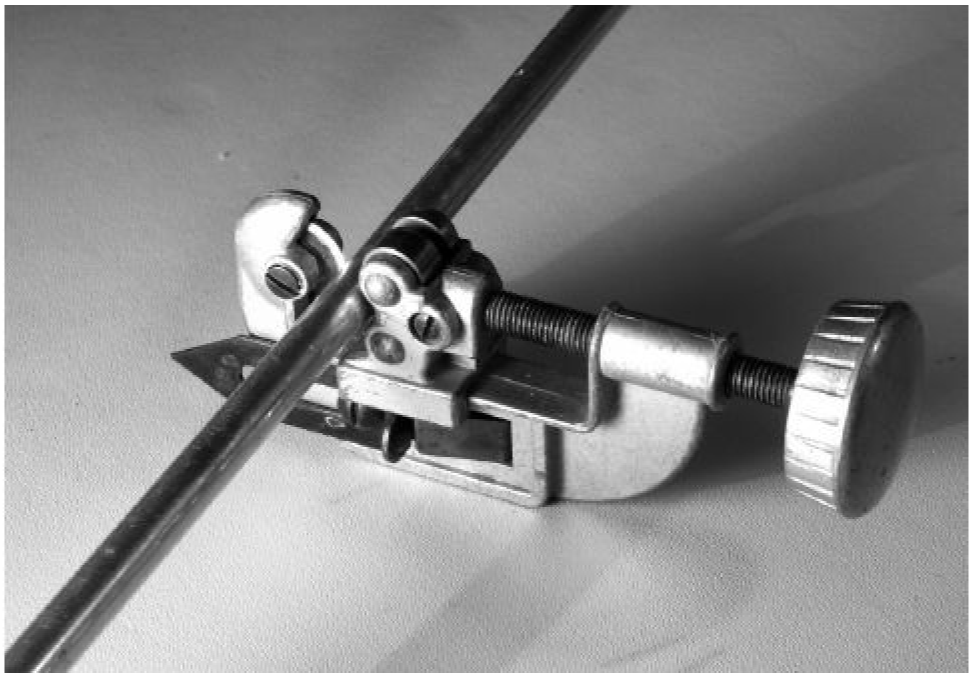


Figure 5.5 — A simple hardware store tubing cutter easily makes smooth, square cuts from pieces of aluminum or copper tubing. The reaming blade, shown extended in this photo, allows removal of the ridge formed inside the cut ends — important to remove only if smaller tubing must telescope into the end.

Elements can be attached to Yagi booms in a number of ways. Some prefer drilling holes for elements to pass right through the boom and then using set screws to hold the elements in place. Others drill holes to mount element attachment clamps. The trick with either method is to make sure that the holes are drilled perpendicular to and in the center of the boom, all along the same line. If not done fairly precisely, the elements will not be parallel. While not usually a big issue in terms of performance, it provides clear evidence of poor craftsmanship to anyone who glances upward. Round booms are the hardest to work with, while those of rectangular or square cross section are easier. In either case, it is very difficult to achieve good results without a drill press and a jig to force the boom-to-element alignment.

My preferred method is to use clamps on both the elements and boom, along with a gusset plate, as shown in **Figure 5.6**. The plate can be either insulating or conductive, depending on the design details. If the boom and elements are in electrical contact, an element length correction will need to be made if dimensions were derived from element dimensions alone.

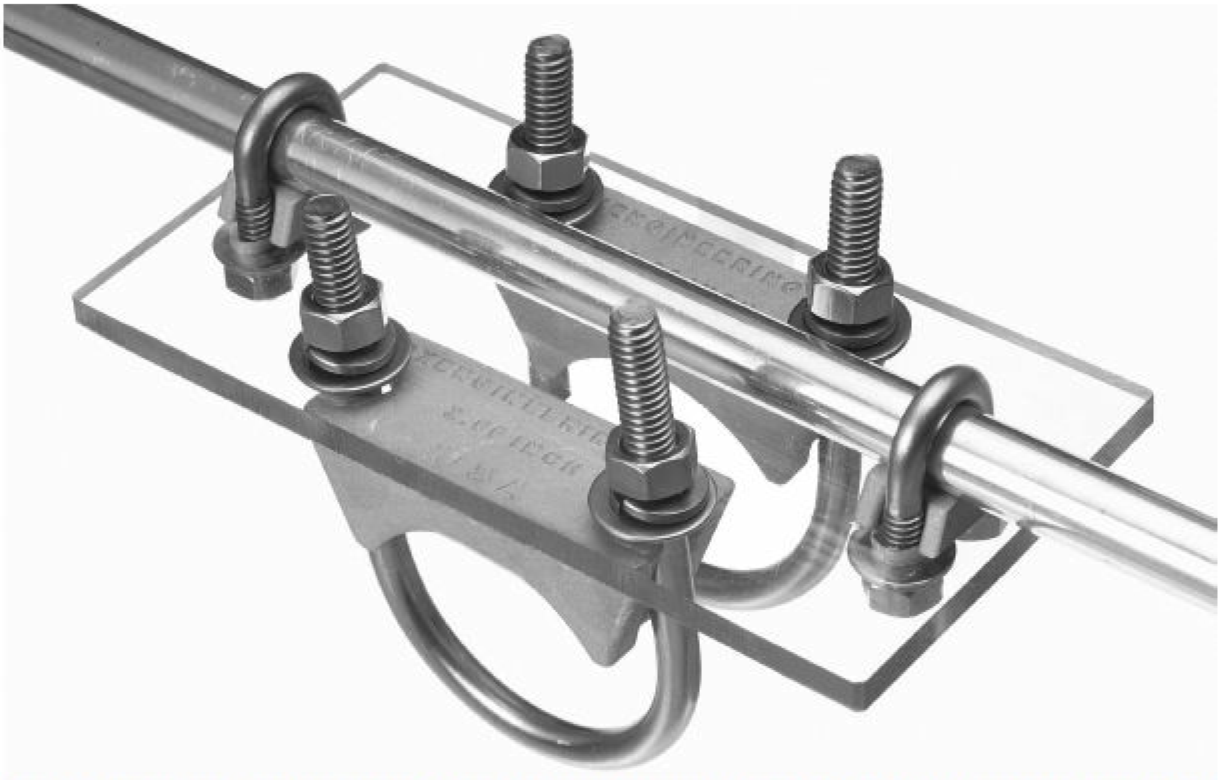


Figure 5.6 — The author made use of DX Engineering (www.dxengineering.com) stainless steel saddle clamps to hold the elements of his 6 meter coupled-resonator Yagi to the boom via a polycarbonate insulating mounting plate.

Once the pieces are cut to length, most of the assembly of either a home-built or purchased antenna requires careful measurement and tightening of various types of clamps. Clamps fasteners generally require wrenches, with the ratchet type (see **Figure 5.7**) often saving a lot of effort. Be sure not to tighten excessively, since it doesn't seem to take much tightening to go from "just right" to crushed tubing!

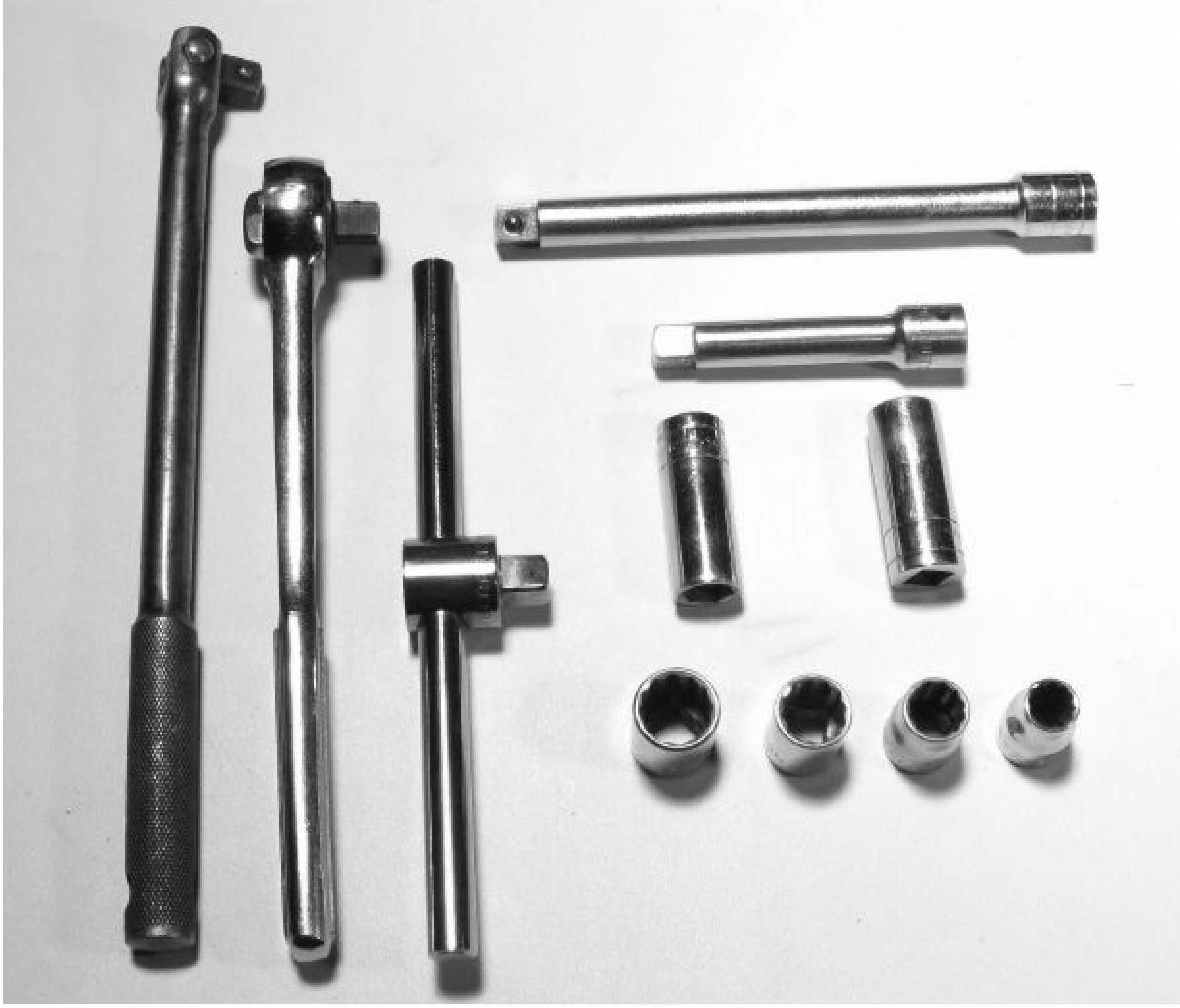


Figure 5.7 — Selection of ⅜ inch drive socket wrenches and extension bars, with ratchet, bar, and T-handles. While $\frac{5}{16}$, ⅜, $\frac{7}{16}$, ½, and $\frac{9}{16}$ inch sizes are most frequently needed, it is often more economical to buy a packaged set than individual wrenches. The extra-long ("deep") sockets are handy for clamps with long threaded sections.

Some antenna tasks are well suited to drilling and tapping to provide holes that are threaded for normal size machine screws. In many cases, the wall thickness of tubing is insufficient to provide long enough thread length to make a secure connection, in which case self-tapping screws will generally have an advantage, because they provide additional grip range if the tapped hole is a bit smaller than would be the case for the usual tap. Still, drilling and tapping are appropriate into thicker metal, or even plastic parts. **Figure 5.8** shows a series of taps and tap wrenches that can be used for the task. It is critical that the tap be well lubricated with machine oil and that the tap be backed out every few turns to remove the filings. Proper lubrication is especially important when tapping aluminum, which can seize, breaking a tap.

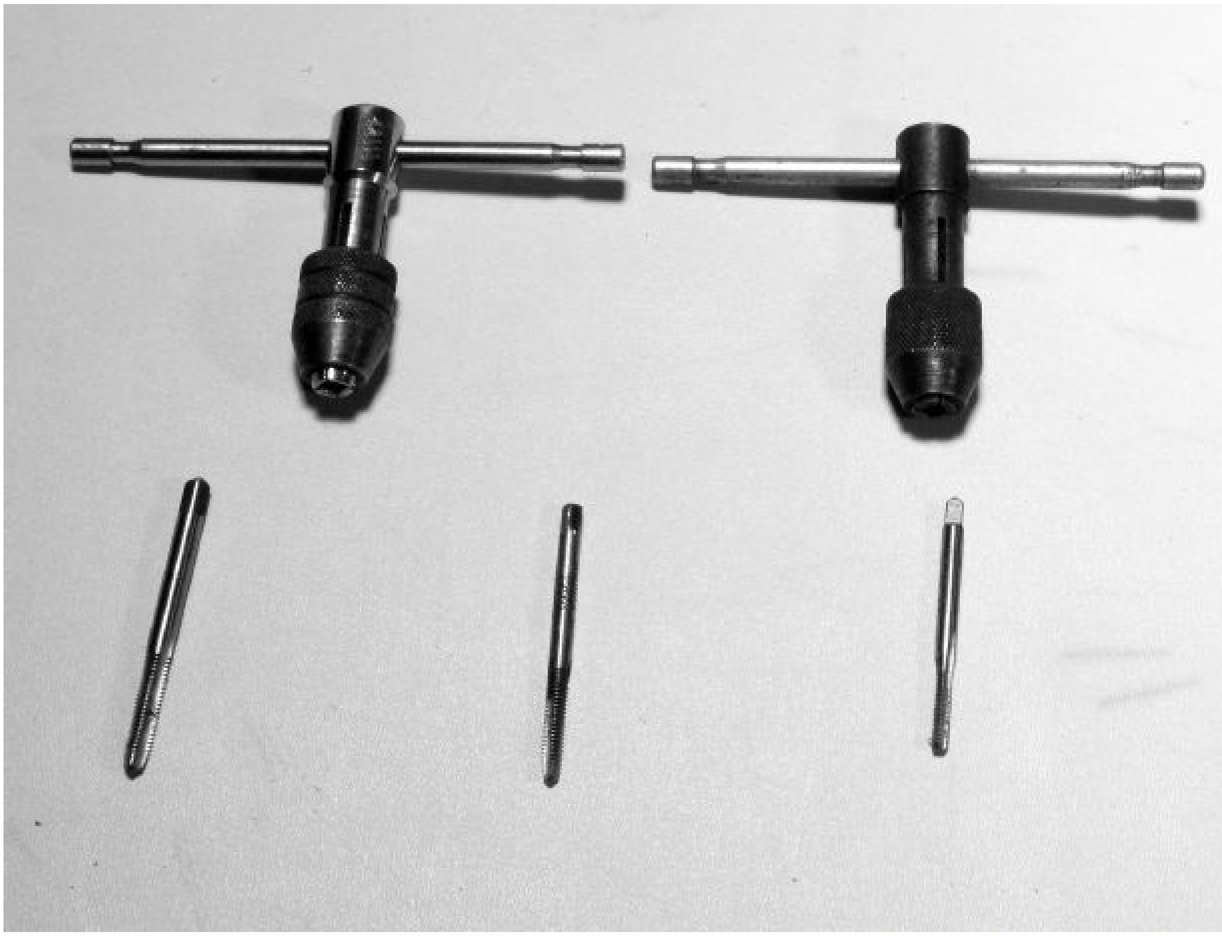


Figure 5.8 — Taps and tap wrenches used to thread holes in plastic or metal. It is important that the appropriate number-sized drills be used for both the clearance and tap holes (see Table 5.1).

It is important to use the correct size drill bit for both the tapped and clearance holes. Note that the drill sizes are specified by drill number, rather than the usual hardware store fractional inch sizes. *The ARRL Handbook* provides a summary table, with the key sizes summarized in **Table 5.1**.[1]

Table 5.1
Numbered Drill Sizes for Tap (Aluminum) and Clearance Holes for Common Machine Screws

Screw Size	*Tap Hole*	*Clearance Hole*
2-56	50	44
4-40	43	33
6-32	36	28
8-32	29	19
10-24	25	11
10-32	21	11
12-24	16	1

Antenna Dimension Measurement Requirements

Whether building an antenna of your own design or assembling a manufactured product, it is important to understand the measurement tolerances required to achieve the intended results. Rather than being expressed in absolute terms, the tolerance will generally be a function of both the design frequency and the bandwidth of the antenna. While each antenna will be somewhat different in these regards, and different parts (element lengths versus spacing, for example) will have somewhat different sensitivities.

Since amateur operation takes place over a band of frequencies, it is generally not terribly critical that matching be exact at a specific frequency, but rather that it be close to the center of the band of interest. Each antenna and each application will be somewhat different, but to get an idea of the change in antenna operation based on dimensions, we have arbitrarily selected that we would like to know how much change in driven element length it would take to shift the resonant frequency of the antenna by 5% of the 2:1 SWR bandwidth. Of course, particularly with Yagi designs, this will differ significantly depending on the exact design. Still, the examples shown in **Table 5.2**, based on *EZNEC* modeling of representative antennas, should be useful to illustrate the relationships and help establish target tolerances for your project.[2]

Table 5.2

Dimension Tolerances for Shift of 5% of 2:1 SWR Bandwidth

Antenna Configuration	*2:1 SWR Bandwidth (kHz)*	*5% Bandwidth (kHz)*	*Tolerance (inches)*
80 Meter Dipole #14 AWG	240	12	7.2
20 Meter Dipole #14 AWG	1080	54	1.3
6 Meter Dipole #14 AWG	3250	163	0.48
2 Meter Dipole #14 AWG	13,600	680	0.18
20 Meter 3-Element Yagi	300	15	0.44
2 Meter 4-Element Yagi	3600	180	0.06

Notes

[1] *The ARRL Handbook for Radio Communications,* 2016 Edition, Table 23.3. Available from Amateur Radio dealers or the ARRL Bookstore (**www.arrl/org/shop**).

[2] Several versions of *EZNEC* antenna modeling software are available from developer Roy Lewallen, W7EL, at **www.eznec.com**.

Chapter 6

Basic Measurements for the Workshop

Sooner or later, every ham will need to measure circuit components and transmitter output power. Here are some of the tools that can be used for those tasks.

Contents

Basic Measurements You'll Want to Make

A radio amateur seems to often need to measure quantities such as voltage, current, resistance, and RF power — even if not in the midst of a particular project. Measurement of dc and ac voltage is important to determine if equipment is receiving the required input levels to assure proper operation. It is also always reassuring to know that your transmitter is putting out the power it is designed to transmit when the key is down.

If the transmitter happens to be putting out lower than expected power, we shift into diagnostic mode. Perhaps it's time to verify that it is still receiving the proper input voltage. Has it changed from the baseline measurements you made on installation, for example? How about that antenna system? Is the impedance or standing wave ratio (SWR) within specification? Has the antenna system changed its characteristics since you put it up?

Resistance measurements are handy for identifying parts that have faded color codes, but they are probably used to verify connectivity more often than any other task. Are those connections shorted? Is there a break in a cable wire?

All of these tasks are best done with the basic measurement tools we will describe in this chapter.

The Volt-Ohm-Milliammeter — A Good Place to Start

The basic volt-ohm-milliammeter, VOM for short, is a test instrument that can measure voltage (ac and dc), resistance, and current (often dc only). The first VOMs were analog instruments consisting of an electromechanical meter movement with multiple scales, a function switch, and a range switch. Jacks are usually provided for test lead connections, and there is generally a ZERO adjustment knob for resistance measurements.

The author's 50-year-old Simpson 270RT VOM (**Figure 6.1**) is representative of a basic instrument. This classic meter is a higher accuracy cousin of the popular Simpson 260 and has a mirror scale and built-in roll-top carry case. The Simpson 260 and its close competitor the Triplett 630 have probably been the most popular VOM models since before World War II. Newer versions of each are still in production.

What's in a VOM?

A VOM is a fairly straightforward test instrument built around a milliammeter panel meter. The milliammeter, typically with a full-scale range of 0.05 to 1 mA dc, can be switched directly across the test leads to measure dc current, just as you would with a simple panel meter. To measure higher levels of current on my Simpson meter, the range selector switches progressively lower valued shunt resistors across the meter to effectively raise the maximum current in steps of 1, 10, 100, and 500 mA full scale. There is a special jack to measure up to 10 A. The specified accuracy is less than 2% of the full scale range. The meter includes black scales reading to 10, 50 and 250 full scale for dc current and voltage measurements. It is up to the operator to keep track of the significant figures. For example, if the meter is set to the 500 mA range, the scale that reads to 50 is used. The user must remember to multiply the reading by 10 to obtain the actual current.

Figure 6.1 — The author's 50-year-old Simpson 270RT VOM is representative of the basic volt-ohm-milliammeter (VOM) functionality.

Measurement of dc voltage is made by switching in series "multiplying" resistors to allow measurement of voltage with resultant full-scale readings of 0.25, 2.5, 10, 50, 250, 1000, and 5000 V. The 0.25 and 5000 V ranges are accessed by jacks dedicated for the purpose. A major limitation of the classic VOM design is that during voltage measurements, the input impedance of the meter is that of the multiplying resistor plus the effective meter resistance. This is often referred to as the meter's *sensitivity* and is typically 20,000 Ω/V (the V refers to the full-scale setting). For example, while measuring at the 0.25 V range, the VOM has an impedance of 5000 Ω If you were measuring a circuit that has a 5000 Ω series resistance, for example, the meter would draw enough current to only indicate half the voltage that would have been there if the meter were not connected. In a similar manner, the shunt resistors used during current measurements tend to reduce the current in the measured circuit. Less-sensitive meters can have sensitivities as low as 1000 Ω/V.

For ac voltage measurements, a full-wave bridge rectifier and filter are used to convert the ac to dc, and then measurements are made at the 2.5, 10, 50, 250, and 1000 V full-scale values. Because the rectifier is nonlinear, separate red scales are provided for ac measurements with full-scale values of 10, 50, and 250 V. As with the dc measurements, the user must select the proper scale and keep track of the needed zeros. It is important that the red scales be used for ac voltage measurement. The Simpson 260 is specified to measure ac voltage over a frequency range of 20 Hz to 100 kHz within its specified accuracy of less than 3%. There is no provision for measurement of ac current.

An additional jack labeled OUTPUT is provided for audio measurements (a kind of ac). This jack includes a series capacitor to remove any dc component of the signal (signals measured on a transistor or vacuum-tube element have a mix of ac and dc). In addition, a DECIBEL scale is provided. This is useful for measuring audio signals. If the circuit you are measuring has an impedance of 600 Ω, the readings will correspond to decibels referenced to a milliwatt (dBm).

The third function of the VOM is measurement of electrical resistance. This is based on a current measurement through the circuit under test with internal batteries in the VOM providing the power. There is a single resistance scale, with 0 on the far right, ∞ (infinity) on the left, and three ranges: R × 1, R × 10, and R × 100. It is important for resistance measurement that there be no voltage in the circuit being measured. At a minimum that will make for an erroneous measurement, and worst case it might destroy the meter. It is also important that you keep in mind that resistance measurements imply that you are applying voltage to the circuit under test, and it is possible to damage components by applying inappropriate voltages to them.

Because the internal battery voltage will change over time, a ZERO adjustment is provided. The procedure is to short the two test leads together and adjust the ZERO OHMS knob for a reading of 0 Ω. This adjustment needs to be made again if you change scales, since different batteries may be used for the different ranges. The adjustment not only compensates for battery aging, but also automatically compensates for any resistance in the test leads.

Figure 6.2 — A RadioShack portable VOM shown next to the Simpson 270RT from Figure 6.1.

In addition to the classic full-size meters that have been around for many years, there have also been more compact versions such as the hand-held Triplett 310 and Simpson 160 VOMs. Other manufacturers have offered budget priced versions for years, as exemplified by the RadioShack model shown next to the Simpson 270RT in **Figure 6.2**. While they are easier to carry, and perhaps drop, the smaller units' meter scales offer less readout precision.

Solving the Circuit Loading Problem

Not long after VOMs became popular, a new device was introduced to solve the circuit loading problem inherent in the design of the VOM. The vacuum-tube voltmeter, VTVM for short, added a vacuum-tube dc amplifier between the device under test and the meter. The amplifier had an input impedance of typically 10 MΩ or higher, making it easy to measure even low voltages with minimal circuit loading. The down side was the need to wait for the unit's vacuum-tube amplifier to warm up and stabilize. The VTVM started out as a laboratory instrument, but after World War II, the Heath Company introduced the V-7 VTVM kit (see **Figure 6.3**), a reasonably priced unit that became one of their most popular products.

Figure 6.3 — A Heathkit V-7A vacuum-tube voltmeter (VTVM) from the 1950s. This solved the VOM circuit loading problem by offering an input impedance of 11 MΩ.

With the advent of inexpensive solid-state devices, the VTVM's amplifier functionality was taken over by transistors — especially field effect transistors (FETs) that have a very high input impedance. With the FET amplifiers, we were back to compact, battery powered instruments with no need to wait for tubes to warm up.

The Next Step — The Digital Multimeter

Right on the heels of inexpensive amplifiers came inexpensive digital displays. The combination of a solid-state amplifier and analog-to-digital converter resulted in the *digital multimeter* or DMM (**Figure 6.4**). A digital multimeter has replaced the traditional VOM for many users. While the VOM can do all that it used to and has a few advantages over the DMM, some DMM models can perform a number of additional functions that a VOM can't.

Figure 6.4 — Representative digital multimeters (DMMs). The larger Fluke model is a professional quality unit, while the smaller Ideal unit on the left is typical of an autoranging "toolbox" DMM.

Basic DMMs offer functionality similar to VOMs and typically have two and a half digits of display resolution — about what can be read from a meter scale. More advanced, and typically more expensive, DMMs may offer:

■ Auto ranging. No need to set a range switch — the DMM figures it out.

■ Measurement of capacitance — very handy.

■ Frequency counter functionality. This may be useful, but most don't extend into the RF region, often stopping at a few hundred kHz. Also, the number of display digits may be a limitation.

■ Built-in transistor and diode parameter measurement and test capability.

■ Additional display digits providing improved resolution.

■ Temperature measurement capability, generally with a remote probe that can be inserted into equipment.

On the other hand, a VOM has a few advantages of its own:

■ An analog meter is generally easier to use to detect changes and direction of change. This can be important during equipment alignment. Some DMMs have a bar graph that is intended to solve this problem — but check the response time.

■ Most VOMs can read higher voltages, typically into the kilovolt range. Many DMMs are limited to hundreds of volts. In some cases, special external high-voltage probes are available. Whether or not this is important will depend on the kinds of equipment that you need to measure. This will likely be an issue for those who maintain vacuum-tube high-power linear amplifiers, or vintage HF transceivers in the 100 W range that use vacuum tubes in the final RF amplifier stages.

Features to Look For — There's Basic and There's What You May Need

There are many potential choices for your first measuring system. Both VOMs and DMMs seem to be available starting in the price range of tens of dollars, with both fairly quickly getting up into the multiple hundreds of dollars. As with most purchase choices, the available units at the very bottom tend to be lower in quality and offer fewer features. Those near the top are often very good, but may not be worth the extra money to most users.

In the middle there are lots of choices. If you are faced with the need to choose between a DMM or VOM, it would be hard for me to suggest a VOM. The DMM has many advantages, including higher resolution and generally higher accuracy. In most cases, the DMM is less likely to suffer damage due to handling — analog meter movements are easy to ruin.

Table 6.1

Representative Subset of One Manufacturer's Digital Multimeter Offerings

B&K Model	*Digits*	*Max V dc*	*Accuracy (±%)*	*Auto Range*	*Capacitance*	*Frequency*	*Transistor*	*MSRP ($)**
2405A	2.5	600	2	no	no	no	Diode	32
2407A	2.5	600	1.2	yes	no	no	Diode	47
2705B	3.75	1000	1	yes	no	no	Diode	68
2707B	3.5	1000	0.8	no	yes	20 MHz	Yes, hFE	95
2709B	3.75	1000	0.5	yes	yes	66 MHz	Diode	105
388B	3.75	1000	0.5	yes	yes	4 MHz	Yes, hFE	139
389A	3.75	1000	0.25	yes	yes	66 MHz	Diode	159
2831E**	4.5	1000	0.03	yes	yes	1 MHz	Diode	339

*Most units do not include tests leads. Various lead sets are available, typically starting at $10. Prices as of mid-2015.

**The model 2831E is a larger bench type unit that includes a USB interface for computer control and data storage. The other units are hand held units.

Of the added features that DMMs offer with increasing price, I think the most beneficial might be capacitance measurement. I say this because, unless you have a 1950s Eico capacitance tester in the basement (yes, I do), a capacitance meter in another form is not likely to be something that you quickly acquire. Autoranging may be handy, but — unlike the range switch of a VOM — you won't bend the needle on a DMM by being on the wrong range. Besides, it is always a good idea to know what you expect the voltage to be before you stick a probe in the circuit!

There are many DMM manufacturers, and most offer models at various price points. Some market leaders, such as Fluke (**www.fluke-direct.com**), specialize in industrial and laboratory grade meters that are priced accordingly. A company that has been around for a while and offers many DMM models starting at lower prices is B&K Precision (**www.bkprecision.com**). The B&K DMMs may be representative of the market segment most applicable to the ham workshop. **Table 6.1** and **Figures 6.5** to **6.7** shows some of their available models to give an idea of the range of features and prices. All features are not shown in the table. For example, some include a logic probe. Others measure true RMS ac voltages, rather than computed values based on rectified and filtered ac presented as dc.

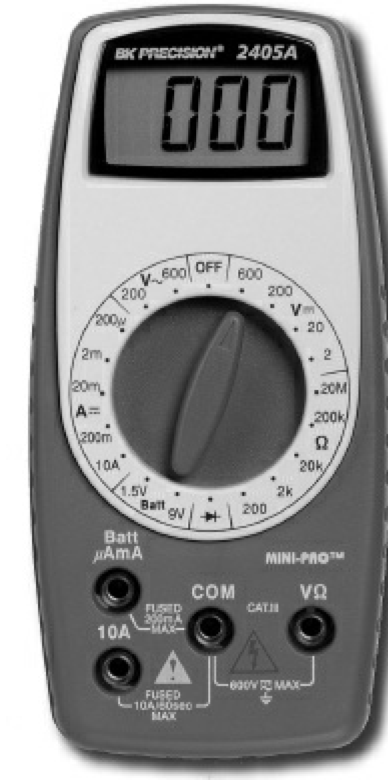


Figure 6.5 — A B&K Precision model 2405A DMM. This is a basic 2.5 digit display, manual ranging, tool-box type model priced at about $32 (as of mid-2015) that does almost everything that a VOM can do. [Photo courtesy of B&K Precision]

Figure 6.6 — A B&K Precision model 2709B DMM. This unit is auto-ranging, measures dc voltage to 1000 V, true RMS ac voltage to 750 V, capacitance, frequency to 66 MHz, and checks diodes. It has a 3.75 digit display and lists for $105 (as of mid-2015). [Photo courtesy of B&K Precision]

Figure 6.7 — A B&K Precision model 2831E bench-type DMM. This unit lists for $339 (as of mid-2015) but includes additional features such as a USB computer interface and dual 4.5-digit displays that allow two simultaneous measurements. The similar 5491B at $409 adds an RS-232 computer port. [Photo courtesy of B&K Precision]

A DMM identified as a "bench type" often includes computer interface capability that can be used to either remotely control the meter or export data to the computer. The full specifications of all models are available on the B&K Precision website, but other manufacturers have competitive offerings. Do not look at these descriptions as recommendations, rather as samples of what is offered at different price levels. And yes, they are generally available from retailers at prices somewhat lower than the manufacturer's suggested retail price (MSRP).

Identifying and Checking Components

A major function of whatever type of instrument(s) you choose is to measure the parameters of electrical components such as resistors, solid-state devices, inductors, or capacitors. There are even special instruments designed for that function, as shown in **Figure 6.8**, but most amateurs will select a general purpose DMM that covers their needs.

Figure 6.8 — A special purpose DMM designed to measure the value of resistors, capacitors and inductors.

While measuring resistors is something that even the most basic VOM or DMM can accomplish, it is important to make sure that you know just what it is that you are measuring. This is most likely a problem with resistors that are connected within equipment. The problem is that not only is the value of the resistor being measured, but the measurement also includes whatever components or devices are connected directly or indirectly to the ends of the resistor. To resolve this, there are two possible approaches — either disconnect one end of the resistor being measured from the circuit, or analyze the circuit to see what resultant equivalent circuit should be expected.

The same kind of considerations apply to the measurement of any components. While a DMM with capacitance measuring capability can determine the value of a capacitor, whether that value will read the same within a circuit depends on the other components within the circuit. Even a minimal VOM can be used to determine if a capacitor is shorted — but not if there is a low impedance element across it.

While VOMs can measure to determine if a capacitor is shorted or not, they generally cannot directly measure the value of a capacitor. One test that they can make is to determine whether or not a capacitor with a value in the μF range, such as an electrolytic, is working at all. Just observe the ohmmeter scale as you first touch the leads to the capacitor. If set on a high resistance scale, you should observe an initial meter deflection as the capacitor charges to the ohmmeter voltage. Once it is fully charged, in a time proportional to the capacitance value and internal ohmmeter resistance, it should show a value near infinity if it's not leaky.

Measuring inductors on most meters is a matter of measuring the resistance of the coil to determine if there is continuity. If there is resistance, chances are the coil is intact. If the meter reads infinite resistance, that indicates that either the winding has opened — often due to excessive current — or one of the connections has come loose from a terminal. The latter is generally much easier to repair.

Checking Solid-State Devices

Advanced DMMs often have dedicated connections that allow directly measuring the characteristics of diodes and sometimes transistors. Even if your meter doesn't have that capability, it is possible to use an ohmmeter to provide a quick check on whether or not a device is open or shorted. In order to do this, it is important to know what the polarity is of the voltage source used by your ohmmeter. In my experience, most VOMs have a positive voltage on the positive lead, but my DMM is hooked up the other way. Check yours with another meter so you know what you have.

Checking diodes. If the positive lead of an ohmmeter on a low (R × 1) scale is connected to the anode of a diode and the negative lead to the cathode, the diode will be operating in its conduction state and current should flow. The meter will indicate a low value of resistance, usually around 10 Ω or less. Exact values depend on the type of diode. If it doesn't read in that range, it either means that you have it hooked up backward, or that the diode is open — likely burned out by excessive current. If it reads 0 Ω on the (R × 1) scale it is likely shorted, and if so, will read the same if the leads are reversed.

Typical DMMs with a diode checking provision provide an additional test. On mine, if a diode is placed across the leads in the direction that will conduct, the forward voltage drop is displayed. This should be between 0.5 and 0.6 V for silicon diodes and less than 0.3 V for germanium diodes. Some special purpose diodes may show a lower forward voltage drop.

If the forward direction seems to be good, turn the diode around and measure in the reverse direction on a higher range. If the diode is good, the meter should indicate a high value — an ideal diode would read infinity. A typical diode should read 1 MΩ or more, depending on type. If it reads the same in either direction, it is not functioning as a diode.

Checking junction transistors. Junction transistors, examined two leads at a time, act a lot like diodes. The base-to-emitter junction of an NPN transistor will act like a diode with the base as the anode, and it can be measured the same way as the diode. The base-to-collector junction should act the same way, again with the base as the anode. The emitter-to-collector junction should show an open circuit in either direction, with the base not connected.

For a PNP transistor, the polarities noted above will be reversed, but otherwise expect the same results. Use care to make sure that the voltage from the ohmmeter does not exceed the breakdown voltage of the junction — usually the (R × 1) scale of a VOM has the lowest applied voltage.

Measuring RF Power and Standing Wave Ratio (SWR)

What distinguishes Amateur Radio operators from most other electronic hobbyists is that they can transmit signals over the air. This operation requires connection between transmitters and antennas, and unless we can measure what happens between them, we won't know what we're really sending toward our antenna. In this section, we'll discuss measuring the actual power leaving the transmitter toward the antenna, and the corresponding reflected power caused by mismatch.

Measuring Transmitter Power

The typical RF power meter used by amateurs is inserted into the coaxial transmission line between the transmitter and antenna system. A line sampler steals a miniscule amount of RF as the signal passes through, and a calibrated meter indicates the power that is going by. The most common types of RF power meters in current use indicate not only the amount of power, but also the direction of the power. Such meters are called directional wattmeters for obvious reasons. The Bird model 43 shown in **Figure 6.9** is a popular classic that has been in use for decades.

Figure 6.9 — The author's Bird model 43 directional wattmeter. Different elements or "slugs" are inserted into the front, depending on the frequency range and power level being measured. The slug can be rotated to change the direction of power measurement.

The significance of the direction of power transmission is that an antenna system that is matched to its design impedance, often the 50Ω characteristic impedance of common coaxial transmission lines, will indicate forward power, but no reflected power. This means that all the outgoing power, except that lost due to line attenuation, is delivered directly to the load. If there is reflected power indicated, the net power delivered is the forward power minus the reflected power.

Standing Wave Ratio

A matched condition with no reflected power results in a voltage that is constant along the transmission line, except for a reduction due to line loss. If there is reflected power, at any point on the line the voltage is the sum of that from the forward wave plus that of the reflected wave. This variation is fixed along the length of the line with the result that the distance dependent voltage has the appearance of a *standing wave*. The ratio of the highest voltage on the line to the lowest is called the *standing-wave ratio* or SWR. The SWR can be no lower than 1:1, indicating that the voltage is constant along the line — a matched condition. A line with reflected power greater than 0 will have an SWR higher than 1:1. The value can be found from the two power levels as follows:

$$SWR = \left(\frac{1+\sqrt{P_R/P_F}}{1-\sqrt{P_R/P_F}} \right)$$

where P_R is the reflected power and P_F is forward power, both in same units.

For example, if the forward power is 125 W and the reflected power is 25 W, the net delivered power is 125 – 25 = 100 W. The SWR would be:

$$SWR = \left(\frac{1+\sqrt{25/125}}{1-\sqrt{25/125}} \right) = 2.62:1$$

Thus, knowing either the SWR or the forward and reflected power can provide similar information about the match condition of the transmission system.

Many modern transceivers include RF metering within their circuitry, often allowing a reading of transmitter power output (forward power) and SWR. If your transceiver's metering has sufficient readability and accuracy, you may not need a separate instrument if you're only interested in what is happening to the antenna system connected to that radio. Some transceivers do reduce power in the presence of higher-than-specified SWR (typically 2:1) to protect the transmitter. Data taken at higher values of SWR may be less accurate than needed for antenna analysis, arguing for an external device.

The meter in **Figure 6.10** is a 1970s vintage Heathkit HM-102 power meter that can measure either power or SWR over the HF range. The SWR meter function is similar to many SWR-only meters. To measure SWR, first set the FUNCTION switch to SET, then set the meter to full scale with the SENSITIVITY control. Then switch to SWR to read the SWR directly on the meter scale. The HM-102 has a remote sensor that can be inserted into the antenna feed line away from the operating position — at the rear of the equipment, for example. The meter and controls remain at the operating position. The sensor can be inserted in a space at the rear of the enclosure if remote sensing is not needed.

Figure 6.10 — This 1970s vintage Heathkit HM-102 power meter can measure forward power as well as SWR over the HF range. It has a remote sensor that can be inserted into the antenna feed system away from the operating position.

Another approach to measuring and indicating both power and SWR is the cross-needle meter, as illustrated in **Figure 6.11**. The MFJ-862, a VHF/UHF unit, measures forward and reflected power simultaneously with meter movements on the right and left edge of the display. The point at which the meter needles intersect can be used to determine the SWR by looking at the scale in the middle. This type of meter is available from a number of manufacturers, with models covering other power and frequency ranges.

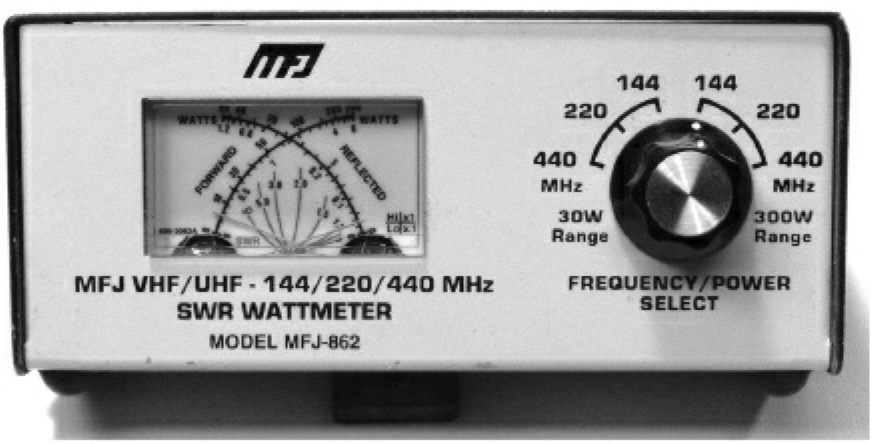


Figure 6.11 — An MFJ-862 VHF/UHF wattmeter. This unit provides simultaneous reading of forward and reflected power over the specified power and frequency ranges. The SWR can be read directly from the point of intersection of the two pointers.

Another type of RF power meter is one that also provides displays through a connected PC. The Array Solutions PowerMaster (**Figure 6.12**) includes a standalone display that can be used to monitor transmit peak and average power as well as SWR. Display and controls are also available onscreen with a connected PC and application software (**Figure 6.13**). In addition to monitoring power and

SWR, the PowerMaster can be set to sound an alarm or disconnect an amplifier key line if power or SWR thresholds are exceeded. It is calibrated — traceable to the National Institute of Standards and Technology (NIST) — and sensors are available for different power levels and frequency ranges.

Figure 6.12 — Array Solutions PowerMaster (www.arraysolutions.com) power meter. This measurement system can function as a standalone instrument with its built-in display, or provide output to a connected PC, as shown in Figure 6.13.

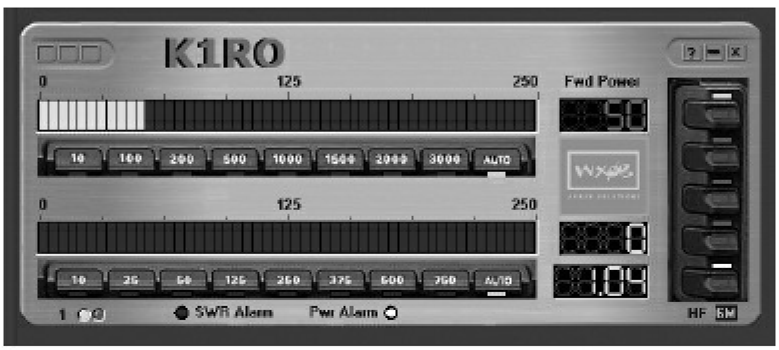


Figure 6.13 — The PowerMaster can display measured data and wattmeter controls on a computer screen, and a miniature version of the display can be monitored while running other applications such as logging software.

A device that could easily also fit in the following chapter on advanced measurements is the LP-100A from Telepost (www.telepostinc.com). This unit (**see Figure 6.14**) starts with a standalone processor and display unit that can measure power and SWR with both digital displays and quick responding bar graphs that can be used for antenna system adjustments. The device can also measure complex (vector) load impedance. It is calibrated — NIST traceable — and can monitor up to two probes simultaneously. In addition, more sophisticated functions are available using a connected PC (see **Figure 6.15**).

Figure 6.14 — The LP-100 in-line power meter from Telepost (www.telepostinc.com). This measurement system not only indicates forward and reflected power (peak and average), but can also indicate the complex impedance of the load.

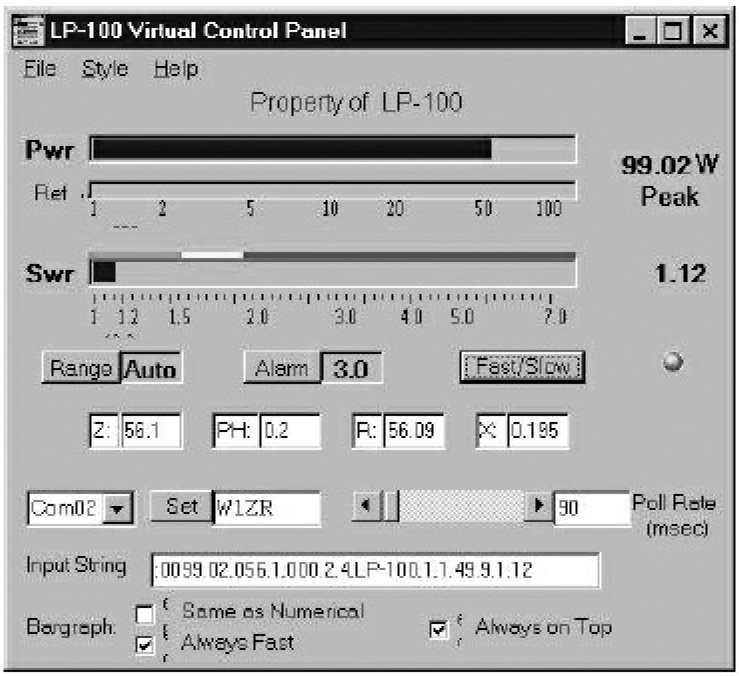
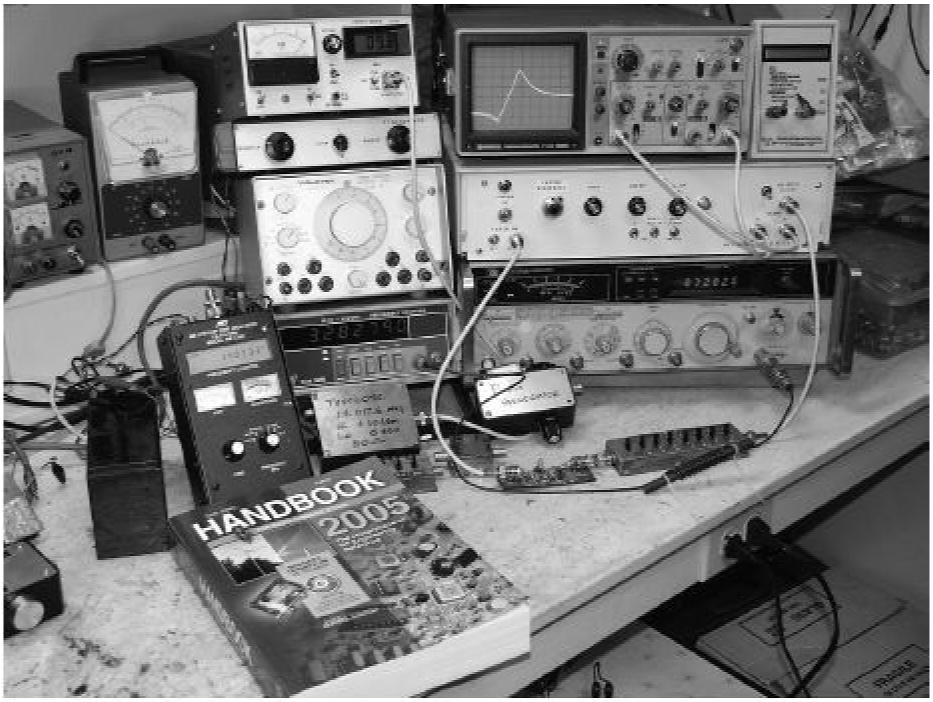


Figure 6.15 — The LP-100 can provide additional information to a connected PC using supplied software via this control panel.

Chapter 7

Advanced Measurements for the Workshop



The advanced Amateur Radio laboratory, such as this one at the station of Markus Hansen, VE7CA, can rival a professional development lab — but they don't have to.

Contents

Analyzing Antenna Systems

In the last chapter, we described basic antenna system measurements — the power going toward the antenna and the SWR resulting from a mismatch. These are important parameters, but a serious limitation of the basic test equipment previously described is that we are limited to measurements on frequencies that our licenses permit us to transmit on. While this may not be a problem if we just want to verify proper operation with an existing amateur-band antenna, it may make it difficult if we are trying to develop a new one.

Yes, we can determine the design dimensions using computer simulation, as discussed in the next chapter, but frequently the first pass with the antenna in the air shows that it doesn't resonate in the band. Determining whether the antenna is too long or too short is much easier with an *antenna analyzer* that can measure the antenna system characteristics on any frequency in its range.

Selecting and Using Antenna Analyzers

This is a topic that could take a whole book to describe. In fact, I wrote one.[1] Without duplicating that volume, we can say that an antenna analyzer emits a weak enough signal that it will not be a bother to other users of the band. It will be legal to use under FCC Part 15 rules outside of as well as inside amateur bands, a major advantage over the devices discussed in the previous chapter. In addition to the flexibility of multiple frequency measurements, most antenna analyzers provide additional information beyond that of typical power meters.

There are many different antenna analyzers on the market, each useful within its range of operational parameters. Some cover the HF range, some VHF, and some extend from MF to UHF. Not surprisingly, the price tends to expand with the coverage — so pick the one that meets your current and projected needs. Similarly, the measurement data provided can be quite different. The least capable units provide just the SWR, perhaps the most useful parameter, but not the only one.

More capable units offer additional functionality. If you are just going to check HF antennas, all but the least capable will have sufficient frequency resolution and accuracy. The better units will be useful for many other functions, and they are quite accurate in their indicated frequency and other data provided. Some indicate the magnitude of the impedance — useful in some applications — but those that show the vector components (resistive and reactive) separately are much more useful, in my opinion. It is also a plus if the analyzer indicates the sign of the reactance so you know if it is inductive or capacitive reactance. That knowledge makes it much easier to design a matching network. If the analyzer doesn't indicate the sign, all is not lost. Just slowly increase the measurement frequency. If the reactance increases, it is inductive; if it decreases, it is capacitive. The only pitfall here is to watch carefully to make sure that that the reactance doesn't go through zero as you make a small change in frequency.

One factor that makes antenna analyzers so useful is that they are composed of a number of internal functions, many of which are usable for other laboratory tasks in addition to antenna analysis. **Figure 7.1** shows the elements of an antenna analyzer, providing a glimpse into its capabilities.

Keep in mind that while an antenna analyzer is fundamentally designed to measure and display the impedance characteristics of an antenna system, it can't tell whether or not it is connected to an antenna. Thus it will indicate the impedance of whatever load, component or circuit is connected. In this respect, it can serve as a kind of network analyzer. For a general circuit element, knowing the impedance at a frequency implies that it is simple to determine the reactance. With that information, we can determine the value of inductance, capacitance, or resistance of an unknown component. Some analyzers even make the calculation for you and display the component values directly.

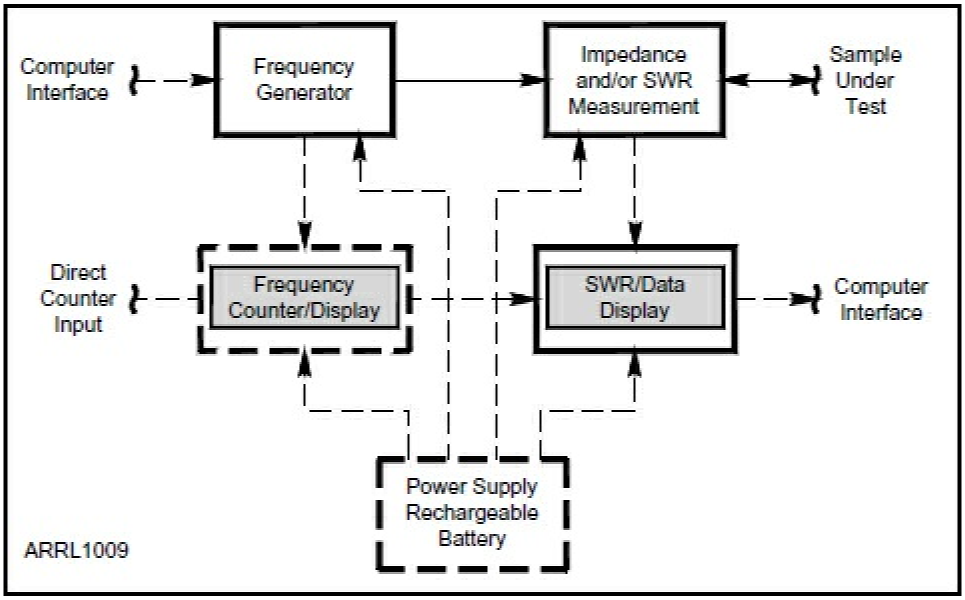


Figure 7.1 — Block diagram showing the elements of typical antenna analyzers. The items shown with dashed lines might not be a part of every model, resulting in a wide range of capabilities, features, and prices.

In the process of measuring antenna parameters, the analyzer generates a signal at the frequency of interest. While different analyzers have different degrees of frequency resolution, they all can be used as a test signal for receiver alignment and calibration to the extent of their accuracy and readout resolution. As noted in Figure 7.1, some units indicate frequency with a frequency counter. Some include a separate input for the counter, allowing it to be used for general frequency measurement — again, within its limits of resolution and precision.

Many current analyzers have been tested in *QST* Product Reviews. These reviews are all available to ARRL members on the ARRL website at **www.arrl.org/product-review**. It is probably worth the cost of membership to be able to look over the reviews of analyzers that you are considering. The key parameters, in my opinion, fall into the following categories:

■ *Frequency range* — The frequency range should include at least the frequencies of the antennas and other equipment that you plan to work on or develop.

■ *Available output data* — While an indication of SWR may be useful, especially for tuning antennas connected with a transmission line, also having the complex impedance data (resistive and reactive parts separately) available will make the device much more useful for both antenna work and for other measurement functions.

■ *Display resolution and options* — The nature and details of the display are important. The number of display digits will determine the measurement precision, while having more simultaneous data windows will provide useful flexibility. Advanced functions, supported by computer processing and display, can provide a whole different dimension to the analysis.

Figure 7.2 is a view of the author's RigExpert AA-54 antenna analyzer. There are a number of models of RigExpert analyzers. The numerical portion of the model number indicates the highest analysis frequency (in this case, 54 MHz). There are other differences as well, so check the RigExpert website to find out what's currently available (www.rigexpert.net). RigExpert analyzers use a keypad entry method to select individual or multiple frequencies, as well as swept frequency ranges, as shown in **Figures 7.3** to **7.6**. In addition, offline PC processing of saved data can present additional information, as illustrated in **Figure 7.7**.

Figure 7.2 — A RigExpert AA-54 antenna analyzer. This is one of a number of antenna analyzers that can measure antenna system properties on any frequency in its range, as well as provide other functionality. It features a swept frequency analysis function with graphical output and additional data is available when connected to a PC.

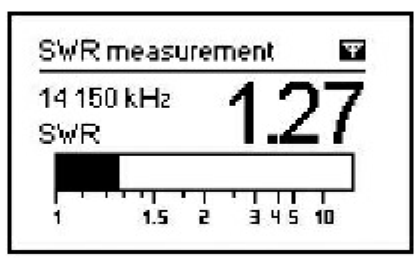


Figure 7.3 — This RigExpert display mode shows the SWR at a single frequency. The virtual bar graph is helpful while making adjustments.

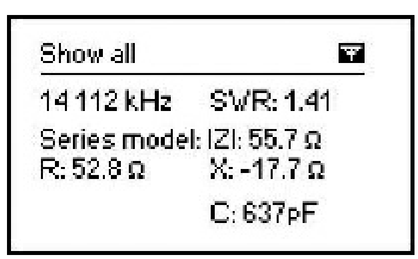


Figure 7.4 — This RigExpert display mode shows the SWR as well as complex impedance data at a single frequency. Note that it has determined that the reactance is negative and in addition to the impedance shows the value of the equivalent capacitance. This function can be used to identify unknown components.

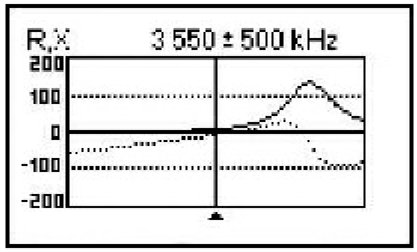


Figure 7.5 — This graph illustrates the RigExpert swept frequency display mode showing real and imaginary (R ± *j*X) impedance of a load from 3050 to 4050 kHz. The SWR could also be plotted in a similar manner.

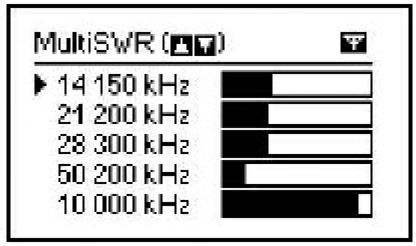


Figure 7.6 — This RigExpert display mode shows the SWR at five frequencies simultaneously. This is very useful while making adjustment to multi-frequency antennas that are likely to interact. Multiple virtual bar graphs can also be selected to aid in making adjustments.

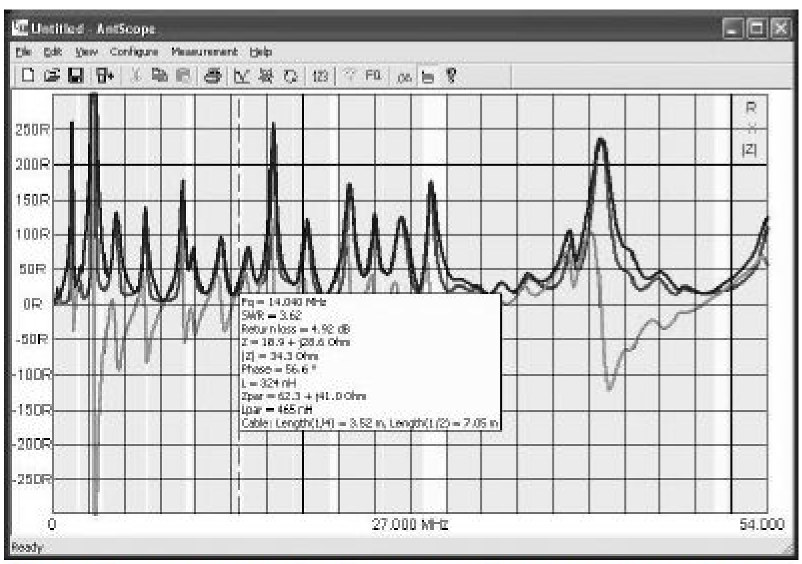


Figure 7.7 — Impedance data presented graphically on a connected PC using the RigExpert provided *Antennascope* software. The data is much more useful as seen on a full-sized PC screen in color. Impedance data and other measurements can be saved on a PC for comparison to later measurements. That's useful to track performance over time to spot any degradation or other changes.

Another very popular family of antenna analyzers is offered by MFJ (**www.mfjenterprises.com**). Their MFJ-269 (see **Figure 7.8**) and its relatives use a frequency counter to indicate the tunable measurement frequency. A real plus is that the counter is available to measure other signals as well (check details of the model you're considering to be sure). In contrast, the RigExpert analyzers generate a stable and accurate frequency by entering in the frequency digits directly. A benefit of the AA-54 and the higher-frequency versions is that it can provide graphical swept frequency data displayed on the screen or on a connected PC. It also can display the SWR of a multiband or wideband antenna on up to five frequencies simultaneously — very handy for adjusting a multiband antenna that has interactions between the adjustments on multiple bands.

Figure 7.8 — An MFJ-269 antenna analyzer. In addition to its antenna analysis functions, this unit is particularly useful because the frequency counter can be accessed independently.

The preceding analyzers represent two different approaches to antenna analyzer architecture. There are many other antenna analyzer manufacturers and approaches out there — check my book (see Note 1) or search the *QST* archives for antenna analyzer reviews to get the whole story.

Note that a *vector network analyzer* (VNA) is another device that can be used as an antenna analyzer. It can do much more, and costs considerably more. The VNA also requires a connected PC to operate, so it will be discussed in more detail in the next chapter.

Generating Signals

A fundamental function of the amateur laboratory is to be able to generate signals — typically with a device not surprisingly called a *signal generator*. Signal generators are typically used to measure the capabilities of a receiver with a signal of known characteristics. In addition, they are critical for making the adjustments required to align receivers for optimum performance. Signal generators can often be used as substitute local oscillators in heterodyne systems during development. They can even serve as test sources for evaluation of transmitter amplifiers. For troubleshooting a receiver, the signal generator can be used to inject signals directly into different stages to estimate stage gain as well as to locate breaks in the signal chain.

Signal generators come in various flavors and styles, ranging from the very inexpensive to incredibly expensive professional grade units. All signal generators share some characteristics, and the difference in prices can be attributed to the difference in how well they accomplish their functions. The basic parameters come down to:

■ *Frequency range* — Signal generators not only need to cover the operational frequencies of receivers, but also all the internal frequencies of subsystems used within a receiver, particularly the intermediate frequencies (IF).

■ *Output level adjustment* — To be useful, a signal generator must have a known output level that is adjustable in known increments. This is a major differentiator between generator types.

■ *Frequency calibration and resolution* — The best signal generators make use of accurate frequency sources indicated on a digital display with resolution to 1 Hz or less. This is best done using a frequency synthesizer, although some signal generators achieve similar results using a tuned oscillator and a frequency counter.

■ *Frequency stability and purity* — It is very important that generators stay on the same frequency throughout a measurement or series of measurements. It is also important that generators do not generate signals on additional frequencies (spurs) that can be confused with the desired signals. This can be an issue with generators that use poorly designed frequency synthesizers.

■ *Modulation* — Most signal generators provide for amplitude modulation, either internally or with provision for external modulating signal inputs. This can be very useful for evaluating analog receivers. Some generators also have provision for pulse inputs that can result in a wide range of modulating waveforms.

Specialized Amateur Signal Generators

There are a few specialized amateur-oriented signal generators available. A particularly useful, if quite specialized, generator was the Elecraft XG-1 that was available in 2005 for $39 as a kit.[2] This unit (see **Figure 7.9**) was designed to verify proper operation, rather than to serve as a diagnostic tool, but within limits it can serve both functions.

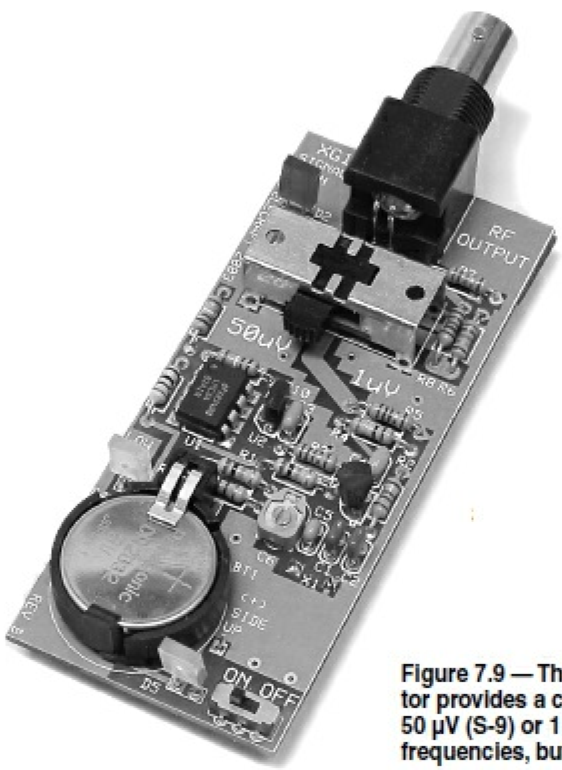


Figure 7.9 — The Elecraft XG-1 receiver calibrator. This generator provides a crystal-controlled output on 7240 kHz at either 50 μV (S-9) or 1 μV (S-3.3). It can also be used on harmonic frequencies, but will not have a calibrated level.

The XG-1 generated a single crystal-controlled frequency of 7040 kHz and provided selectable calibrated outputs of 1 μV or 50 TV at that frequency. It could thus check the basic operation of a receiver on 40 meters, including a spot check of frequency calibration and sensitivity as well as S meter calibration. A signal at 50 cV should be quite strong in any functioning receiver, and should indicate S-9 on the S meter if it is calibrated per the accepted Collins standard. If the receiver is working well, the 1 lV signal should be audible above the receiver noise and, if all is per standard, the meter should indicate about ⅓ of an S unit above S-3.

The harmonics of the 7040 kHz oscillator should be easily heard at sufficient level to check operation on 20, 15, and 10 meters, although the level will not be calibrated. A similar XG-2 is now available except it has three crystals, one each for 80, 40, and 20 meters. The XG-2 is priced at $80 in kit form.

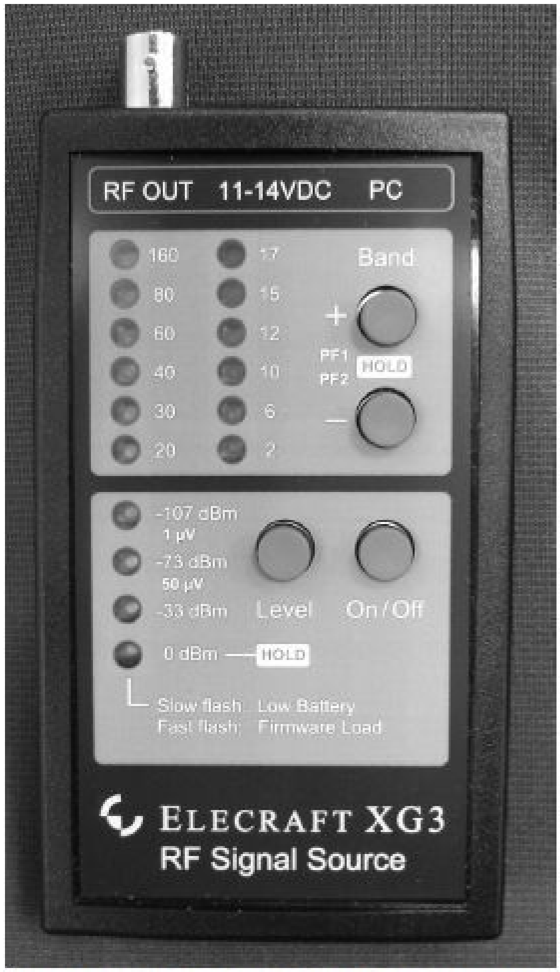


Figure 7.10 — The Elecraft XG-3 RF Signal Source. This generator provides synthesized RF signals from 1 to 200 MHz at four selectable output levels, 0 dBm, –33 dBm (40 dB over S-9), –73 dBm (S-9), and –107 dBm (1 µV).

As this is written, the XG series has evolved into the XG-3 RF signal source (see **Figure 7.10**). The XG-3 is a programmable, pocket sized RF signal generator that provides output from 1.5 to 1400 MHz (to 200 MHz on fundamentals). Four commonly used selectable output levels provide test signals at 0 dBm, –33 dBm (40 dB over S-9), –73 dBm (S-9), and –107 dBm (1 µV). There are 12 memory channels that can memorize frequencies within each amateur band, or anywhere in its range. This unit is available for $180 including a programming/remote control cable.[3]

Service Shop Signal Generators

The bottom end of the signal generator range has been the type used for radio service work since the beginning. This type of generator typically covers the range from the usual broadcast receiver IF frequencies (typically 262 kHz for auto radios, 455 kHz for AM, and 10.7 MHz for FM table radios) to the upper end of the HF spectrum (30 MHz) or higher. The generator output is typically adjustable, but neither calibrated nor leveled across the frequency range. Most provide internal amplitude modulation and have provision for external amplitude modulation as well. While these signal generators can be useful for receiver alignment, the frequency accuracy and resolution are generally not good enough to use for calibrating the frequency of a communications receiver. This can be finessed if a frequency counter or another receiver of known accuracy and calibration is available to use to set and monitor the generator frequency.

Figure 7.11 shows a Heathkit SG-8 RF signal generator from the 1950s designed for broadcast and shortwave radio service. This unit covers from 200 kHz through 111 MHz on fundamental frequencies, covering typical auto and home radio IF frequencies (262 and 455 kHz), through the HF bands, and beyond the top of the FM broadcast band (108 MHz). Internal and external AM modulation are supported, along with an adjustable (but not calibrated) RF output.

Figure 7.11 — A Heathkit SG-8 RF signal generator from the 1950s designed for broadcast and shortwave radio service. This unit covers from 200 kHz through 111 MHz on fundamental frequencies. Internal and external AM modulation is supported, along with an adjustable (but not calibrated) RF output. The scratches and mixed knob style are the consequences of many years of hard service.

A somewhat more capable signal generator from the same period is shown in **Figure 7.12**. This generator includes added touches intended to facilitate analog TV servicing, including expanded frequency coverage and modulation designed to result in horizontal bars on the TV screen.

Figure 7.12 — A somewhat more capable signal generator from the same period with added touches intended to facilitate analog TV servicing. This is a Superior Instruments TV-50 signal generator that includes modulation designed to result in horizontal or vertical bars on an analog TV screen, as well as cross hatch and dot patterns.

Be Careful — Switch to Safety!

If you elect to make use of signal generators or other bargain test equipment from the middle of the last century, there are some cautions that are worth turning into upgrades.

AC Power Connections

The typical flea market 1950s vintage test equipment was powered via a two-wire line cord with a non-polarized line plug. This results in potential shock hazard to the user, as well as the potential to cause damage to the connected equipment. Figure 7.A shows the circuit of the power supply in my Heathkit SG-8 signal generator. It's typical of the power supply found in many pieces of equipment of the period. Note the 0.01 µF capacitors from each side of the line to the chassis, designed to eliminate RF noise from the line. These become leaky over time. When that happens, the chassis and cabinet (including the ground side of the **OUTPUT** connection) will often be at a voltage approaching 120 V ac. While the impedance is high, it can still offer a serious shock, especially if you are connecting to a grounded radio.

Because this power supply includes a power transformer, unlike the so-called ***ac-dc*** sets (see below), the fix is straightforward. My recommendations are to replace the two-wire cord with a proper three-wire grounded cord and plug set. The green (ground) wire should be connected directly to the chassis. The black (hot) wire should be fused and then go to the on/off switch, and the white (neutral) wire should go directly to the non-switched end of the transformer primary as shown in Figure 7.B. While you're there, you might as well clip out those pesky 0.01 µF capacitors; they aren't particularly effective anyway.

Selenium Rectifier

The SG-8 power supply includes an early type of solid-state rectifier called a ***selenium rectifier stack***. These consist of a number of series connected square plates making a distinctive stack. While selenium rectifiers do work, they have a propensity to fail. When (not if) they fail, they emit a dwelling-filling stench that is likely toxic. I suggest that the rectifier be replaced by a modern silicon rectifier diode with ratings appropriate to the voltage and current.

Electrolytic Capacitors

The 20 µF electrolytic filter capacitors, and any other electrolytics seen in the unit, should be checked. These are good candidates for replacement, as are any wax paper capacitors.

AC-DC Powered Equipment

Power transformers are relatively expensive. One way to design a power supply for low-cost tube-type equipment is to avoid a power transformer altogether and use the ac line directly for both filament and high-voltage power. This was commonly done in the classic "five-tube broadcast radio" that was almost universally used during the period. The radios used a special set of five vacuum tubes. The tubes had a common filament current requirement and had different filament voltages that could be all tied together in series and placed across the ac line.* In some cases, if there weren't enough tubes to add up to the total line voltage, a resistance was used instead. Often the resistance was provided by a separate wire in the line cord.

Of course, the problem with this arrangement is that, unlike a transformer-operated radio, the power supply common — typically the chassis — was connected directly to one side of the ac line. That, combined with the non-polarized plug of the period, meant that there was a 50% chance that the chassis was at a 120 V ac potential! To protect the user, the manufacturers used plastic knobs on the controls and either a plastic cabinet, or a metal cabinet insulated from the chassis. This, of course, didn't protect the person repairing or aligning such a radio.

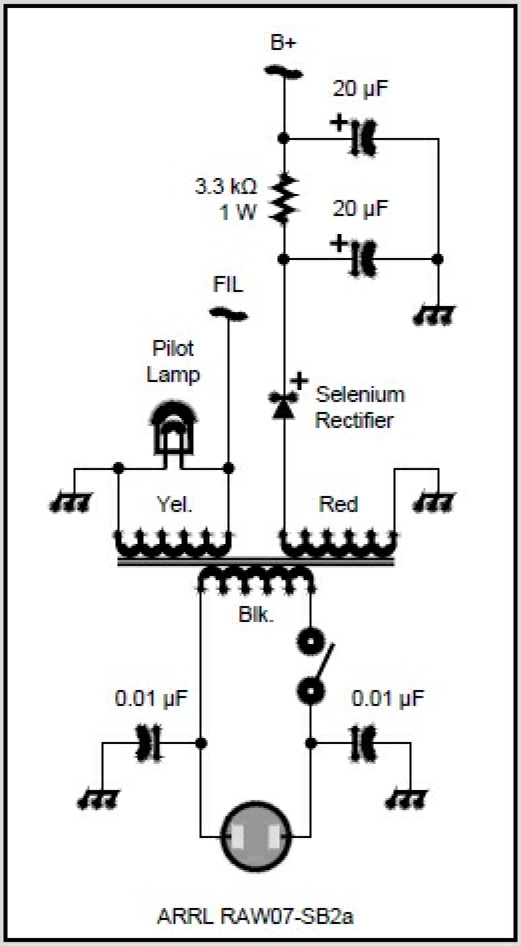


Figure 7.A — Schematic diagram of the power supply section of a 1950s era Heathkit SG-8 signal generator before modifications.

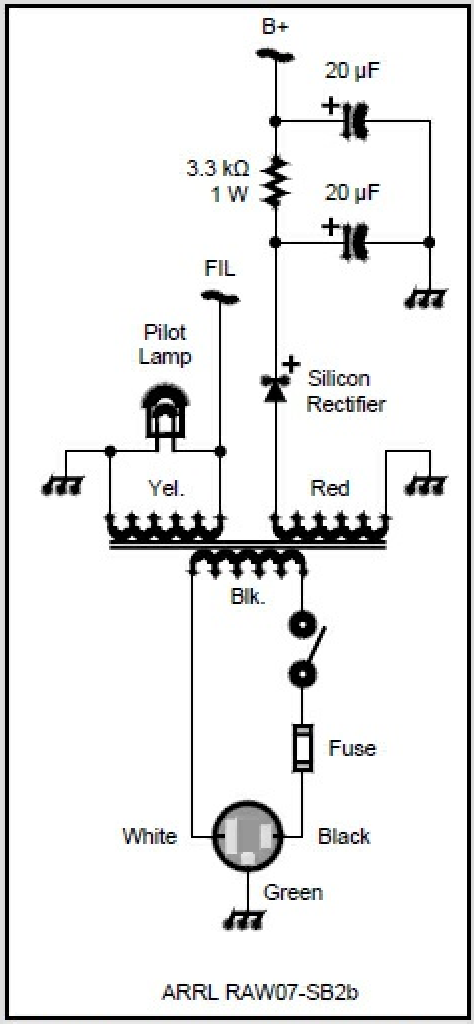


Figure 7.B — Schematic diagram of the power supply section of a Heathkit SG-8 signal generator after suggested modifications. Note the change to a three-wire grounded plug and wiring, the addition of the fuse, the change of rectifier types and the elimination of the 0.01 µF capacitors that were connected directly from the incoming ac line to the chassis.

I haven't encountered test equipment with this arrangement, but it might be out there. In addition to broadcast radios, this approach was used in some entry-level ham gear, such as the classic Hallicrafters S-38 and National SW-54 receivers. There were also some ac-dc versions of transformer operated sets, so keep your eyes out for them if you restore vacuum tube equipment.

The best way to deal with ac-dc equipment, if you can't avoid it altogether, is to obtain a 1:1 isolation transformer of sufficient ratings to remove the direct connection of the radio chassis to the ac line.

*The typical tube lineup in the miniature-tube era consisted of a 12BE6 pentagrid converter, 12BA6 IF amplifier, 12AV6 detector, AVC and first audio amplifier, 50C5 audio output amplifier, and 35W4 rectifier. Note that the filament voltages (indicated by the leading digits) add to 121.

A signal generator with limited capabilities can be improved significantly with outboard accessories that are also useful in many other functions. To compensate for insufficient frequency resolution, the signal can be coupled into an accurately calibrated receiver or tied to a frequency counter. To partly compensate for unknown output amplitude, a step attenuator can be used. If a communications receiver with a calibrated S meter is available, setting the generator to provide a reading of S-9 on the receiver is equivalent to an output level of 50 µV. The step attenuator can then be used to provide known increments (typically in 1 dB steps) below that. The known change in level provided by the attenuator can be also be used to measure stage gain, even if absolute calibration is not available. **Figure 7.13** shows a commercial step attenuator and frequency counter used with the Heathkit SG-8 signal generator.

Figure 7.13 — A signal generator with limited capability can be improved significantly with outboard accessories that are useful in many other functions — a frequency counter and a step-attenuator (available from Elecraft and MFJ, in addition to commercial surplus). While the signal generator won't provide a calibrated output level, the known change in level provided by the attenuator can be used to measure improvement in gain.

Military Surplus Signal Generators

Military electronic equipment is known for its ruggedness and quality of construction. Surplus equipment has been used in ham shacks for many years, especially following World War II and the Korean War. Some radio equipment continues to appear from various outlets, although many recent items are too specialized to be easily adapted to ham use.

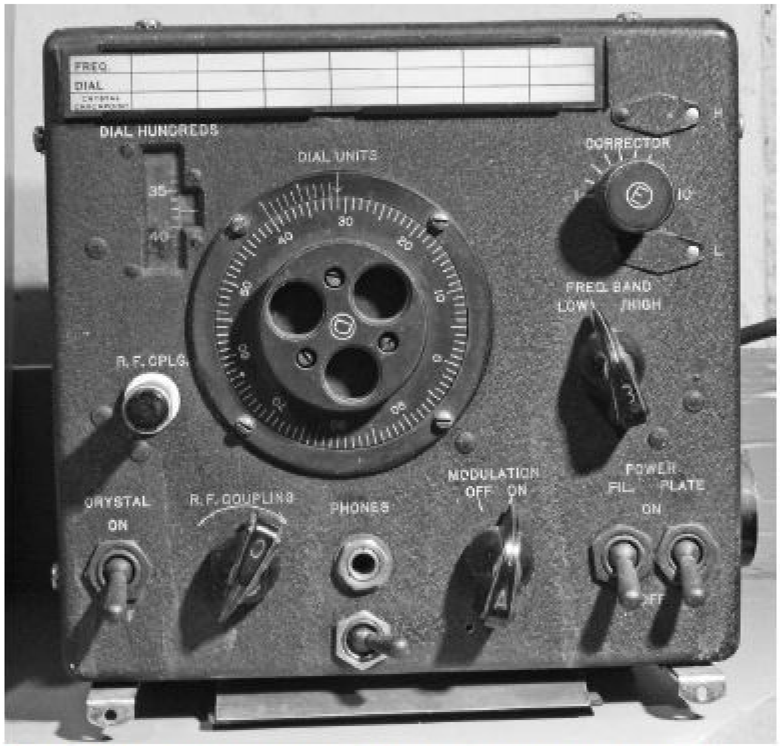


Figure 7.14 — The World War II surplus BC-221 heterodyne frequency meter can be used as a stable and calibrated signal source for receiver adjustment. The unit generates signals from 125 to 250 kHz and from 2000 to 4000 kHz. In the 2000 kHz range, each division on the main dial represents about 0.5 kHz. The vernier allows setting to ⅒ division. Through the use of harmonics, and with the precision micrometer tuning adjustment and the calibration book, it can be used to generate accurate frequency signals from 125 to 20,000 kHz. It includes a detector so that it can also be used to measure transmitter signal frequency by heterodyning.

As with radio equipment, the military used many types of test equipment both for operational support and depot level maintenance. In some cases, the maintenance shop units were commercial designs used directly, sometimes with military nomenclature. Many special-purpose test sets were developed and fielded as well.

The World War II surplus LM or BC-221 heterodyne frequency meter shown in **Figure 7.14** is an example of operational support equipment. While this generator was designed to calibrate the frequency settings of aircraft radio equipment without exposing them to enemy RDF positioning, it can also be used as a stable and calibrated signal source for receiver adjustment. The unit generates fundamental frequency signals from 125 to 250 kHz and from 2000 to 4000 kHz. Through the use of harmonics and with the precision micrometer tuning adjustment and a calibration book, it can be used to generate accurate frequency signals from 125 to 20,000 kHz. The calibration books were laboriously generated for each individual serial numbered unit.

The BC-221 includes a detector so that it can also be used to measure transmitter signal frequency by heterodyning. Mine came with a separate ac power supply, but many were designed for portable operation, running from dry batteries that were housed in the lower part of an expanded cabinet.

An example of depot level special test equipment is shown in **Figure 7.15**. This US Army surplus URM-25 signal generator was intended to service military receivers such as the R-390 of the late 1950s. It provides wide frequency range (10 kHz to 50 MHz) and a calibrated output level (but not an easily adjusted calibrated attenuator). This unit is a much more stable frequency source than the superficially similar service type generators. The URM-25 is built into a travel case with removable front cover. A related unit, the URM-26 covers from 4 to 405 MHz.

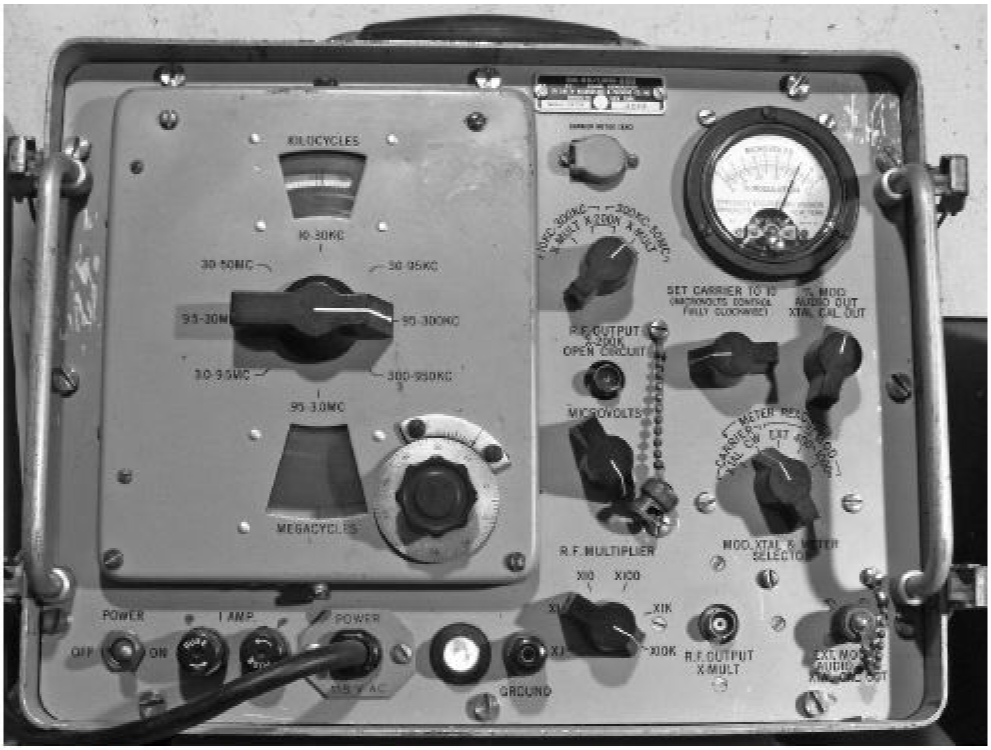


Figure 7.15 — The military surplus URM-25 signal generator was intended to service military receivers such as the R-390 of the late 1950s. It offers wide frequency range (10 kHz to 50 MHz) and a calibrated output level, but not an easily adjusted calibrated attenuator. The URM-25 provides a much more stable frequency source than its commercial contemporaries.

Laboratory Grade Surplus Signal Generators

High quality signal generators of the type used in laboratories can be purchased for many thousands of dollars — a hard sell for most hams who would rather purchase a top of the line transceiver. They are also available as used items on auction sites. Typical units use synthesized frequency sources with digital readouts to 1 – 100 Hz resolution and generate signals over a wide frequency range.

Often equipment that is not current, but of fairly recent vintage, can be found for significantly less money than current equipment. The HP-8657A signal generator, for example, covers 100 kHz to 1040 MHz and includes a precision output level attenuator adjustable from +13 to –127 dBm (see **Figure 7.16**).

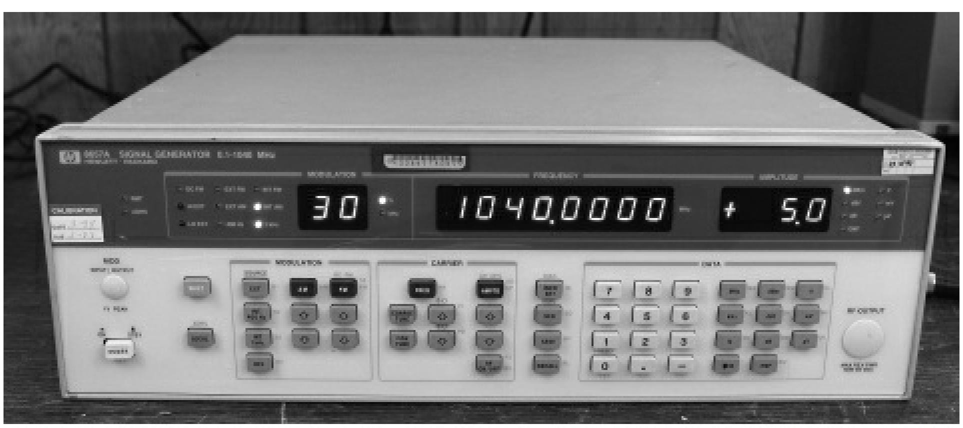


Figure 7.16 — The HP-8657A signal generator covers 100 kHz to 1040 MHz and includes a precision output level adjustable from +17 to –143.5 dBm. [Photo by Dustan Dennington / DennLec.com]

For many amateurs, going back a generation or two can result in excellent quality equipment more than adequate for amateur use, especially if paired with a frequency counter to compensate for the relatively low resolution of the frequency dials. Equipment such as the HP-606 (HF), HP-608 (upper

HF to VHF), or the earlier Measurements Corporation 80 B series (2 – 400 MHz) generators were in many labs in the 1970s and can still do a good job for hams. These can often be found at hamfests or auction sites for as little as $100.

The Antenna Analyzer as a Signal Generator

As mentioned in our discussion of antenna analyzers, they include a circuit that generates signals. Many include accurate frequency counters or synthesizers that output signals of a level at the high end of that desired for receiver calibration.

Aligning Receivers and Other Equipment

One of the major functions of a signal generator is to generate the signals needed to align equipment, especially receivers. Receiver alignment requires some fairly straightforward steps — but there are pitfalls to avoid along the path. Figure 7.C is a block diagram of a traditional superheterodyne receiver that applies to receivers used from below the AM broadcast band to the microwave region — just the frequencies change. The general rule is to start from the back and work toward the antenna.

♦ First inject a signal into the IF stage on the input side of the IF filter. If the filter is tunable, make sure that you have set the generator to the exact specified IF frequency. If the filter is fixed, such as a crystal or mechanical filter, rock the generator back and forth near the specified IF frequency and set it to the center of the filter passband, even if it isn't the exact frequency — the filter will define the actual IF in this case.

Now adjust any variable tuning devices. These are typically interstage IF transformers, usually with a trimmer capacitor or slug-tuned inductor on both the primary and secondary. Be sure to use the appropriate sized alignment tool that fits the slug or trimmer (see Figure 7.D). Note that the primary and secondary inductors often share the same coil form but have separate slugs. Some hex type alignment tools have an extended bit that allows them to turn the lower slug without disturbing the upper.

♦ Next set the frequency of the VFO so that the position of the tuning dial results in the correct frequency, The frequency read on a counter should be the dial frequency plus or minus the IF frequency. For example, in the typical broadcast receiver (as well as many communications receivers), the IF is often 455 kHz, and the VFO is generally above the received frequency. If the tuning range is 550 to 1700 kHz, that means that the VFO should tune from (550 + 455) = 1005 kHz to (1700 + 455) = 2155 kHz. If you're working on a communications receiver, check the specifications. They often use a VFO frequency below the received frequency of the top band or two for improved stability.

The typical L-C tuned VFO with a variable tuning capacitor will have both an adjustable inductor and trimmer capacitor. The usual rule is to adjust the inductor at the bottom of the frequency range and the trimmer at the top. Repeat until they are both correct. Sometimes it helps to get a sense of which way the adjustments are going and go slightly beyond one or the other to help them come in as needed. Again, be sure to use the correct alignment tool and make sure that any metal parts (such as chassis covers) are in place, since they can change the tuning. If the covers don't have holes for alignment tools, often a temporary cover with holes can be substituted for the actual cover. When complete, spot check throughout the range to make sure that the calibration is correct. If not, sometimes the outer plate of the oscillator section is in segments that can be bent carefully to result in calibration across the band.

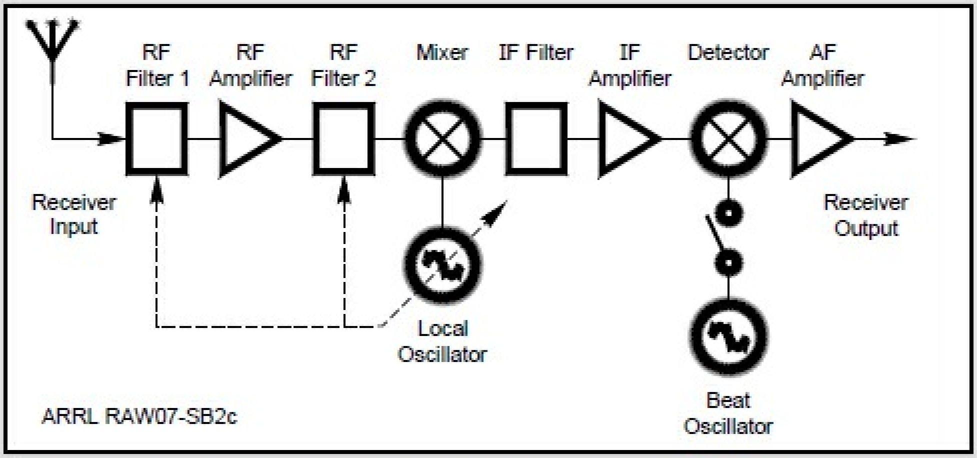


Figure C — Block diagram of a traditional superheterodyne receiver. The alignment of such a receiver is one of the primary uses of signal generators. Note the dotted line between the VFO and RF filter tuning. That indicates that they are ganged and must be adjusted to track properly.

♦ The RF stage filters are last. In most receivers, the RF tuning is tuned simultaneously with the VFO so that the RF filters are set to the received frequency automatically. This is called ***gang tuning*** and is indicated by the dotted lines on a schematic diagram. If the RF filters are properly adjusted, the RF stage is said to ***track*** the VFO frequency.

To properly tune the RF filters, the antenna connection must be terminated with a simulated antenna. For a communications receiver, this can be the nominal input impedance, typically 300 Ω for early receivers and 50 Ω for more recent ones. A carbon or other noninductive resistor can be used. Broadcast receivers often specify a complex impedance. The RF filters are then tuned in the same manner as the VFO — the inductor slug at the low end of the band and the trimmer capacitor at the high end — back and forth until no additional improvement can be made.

The one concern here is that the RF stage be tuned to the appropriate mixer product and not the ***image*** frequency. This is not usually a problem with the typical broadcast set, but becomes a major issue as the RF frequency gets high above the IF frequency. Consider, for example, a receiver with a 455 kHz IF tuned to 25 MHz. In this case, the VFO is often below the receiver frequency, at 24.545 MHz. Note that with that VFO setting, the receiver could equally well receive 24.090 MHz depending on the tuning of the RF filter. The intended and image frequencies are separated by twice the IF frequency. Be sure that the correct one is selected at each spot on the dial.

Figure D — Selection of alignment tools from the author's tool box. Note that there are both hex and slotted types. The slotted tools include ones with both protruding and recessed bits. Screwdrivers should be avoided for this task to eliminate tuning changes from the metal shanks as well as a risk of shorting a trimmer to the chassis.

Antenna analyzers generally have a fixed and specified output level that remains fairly constant over the frequency range. Thus, with the addition of a calibrated step attenuator as shown in Figure 7.13, a reasonable approximation of receiver sensitivity can be determined.

Making Your Own Signal Generator

Since you are putting together your own laboratory, you could also consider making your own signal generator. There have been a number of projects in *QST*, *The ARRL Handbook*, and other Amateur Radio magazines describing such projects. One of the slickest HF signal generators could be easily assembled from a pair of kits originally offered by the Northern California QRP Club (**www.norcalqrp.org**). These were described in a pair of *QST* articles in 2006 and 2007.[4,5]

Unfortunately, the kits are no longer available, but the articles provide schematics and parts lists. An advanced amateur might be able to pull them together if the integrated circuits are still available. Still, it gives you an idea of what can be done. The generator is designed to serve multiple purposes — primarily as a receiver or transmitter variable frequency oscillator — and so is designed for a fixed output. A calibrated step attenuator would be required to make it useful for many signal generator projects.

Measuring Signals

Measuring signals involves the examination of various parameters of signals, whether they are generated locally (as in transmitters) or received from distant sources. The key parameters include signal frequency, amplitude, bandwidth, and distortion products.

Measuring Signal Frequency

Signal frequency is pretty straightforward to measure, especially if the signal is reasonably narrow.

A calibrated receiver (see **Figure 7.17**) covering the signal's frequency can be used for measuring the frequency of distant signals. If an accurately calibrated receiver is not available, you can combine a received signal tone and one from a signal generator, and then adjust the frequency until the beat between the signals is at a null, or reaches 0 Hz. Then measure the frequency of the signal from the signal generator with a frequency counter — that's also the frequency of the received signal. If a BC-221 heterodyne frequency meter (Figure 7.14) is used, the process can be done in one step.

Figure 7.17 — The Collins 51J4 receiver from the 1950s can read frequency to less than 1 kHz — about as good as the analog technology of its day, and better than almost all other contemporary receivers. Most current HF transceivers can read frequency to 1 Hz, three orders of magnitude higher resolution.

Frequency counters are likely the most commonly used frequency measurement devices in current use. Frequency counters are available at many price points, and at different levels of accuracy. It is easy to believe that the number of digits of the display implies something about the measurement accuracy, but that really is a measure of precision — not accuracy. The absolute accuracy of a counter is no better than the accuracy of the time base that the counter uses. My personal counter is one formerly made by Ramsey Electronics (see **Figure 7.18**), and it is definitely at the low end of the range. Many counters feature an input for a precision external clock that can be derived from a cesium-beam standard or from a laboratory-type GPS receiver. Such external standards, often at 10 MHz, can be used to improve the frequency accuracy of many devices including counters, synthesizers, and even advanced amateur transceivers that include the capability to accept an external reference.

Figure 7.18 — An inexpensive frequency counter. This one is a Ramsey Electronics CT-90 from 1998.

Measuring Signal Amplitude

Measurement of amplitude of transmitted signals was discussed in the context of measuring forward and reflected power in the previous chapter. Received signal strength can be determined by using a stable communications receiver or modern transceiver with a calibrated S meter. The S meter can be used to compare signal levels. If the receive antenna is sufficiently characterized, the S meter can be used to determine absolute signal strength — especially with of line-of-sight signals.

For more accurate comparisons of received signal strength — to determine the front-to-back ratio of a rotatable antenna, for example — a step attenuator in the antenna line can be used. First disable the transmit function — the precision resistors in the attenuator won't last long with 100 W or more applied! Measure and record the S meter reading with the rear of the antenna pointed toward the signal source with the attenuator set to 0 dB. Then swing the beam around 180° and, with all receiver controls untouched, adjust the attenuator so that the S meter reading matches that recorded for the first measurement. The amount of attenuation required equals the front-to-back ratio.

Measuring Signal Bandwidth and Distortion

The optimum device for examining the detailed characteristics of signals is a device called a *spectrum analyzer*. The spectrum analyzer consists of a swept-frequency receiver with a two-dimensional display synchronized to the sweep so that it has a horizontal axis calibrated directly in frequency. The amplitude of signals that the analyzer detects are indicated on the vertical axis, generally in a logarithmic scale, so that the amplitude of different signal components can be displayed.

Historically, spectrum analyzers were beyond the resources of most amateurs. There have been many alternatives available, including receivers or transceivers with panoramic displays that are basically spectrum analyzers. They have a limitation, though — most panoramic displays can't observe the transmitted signal from the same transceiver. In recent years, less expensive analyzers have become available to amateurs. One example is the Rigol Technologies DSA815-TG spectrum analyzer, described in a *QST* product review (see **Figure 7.19**).[6] At the time, the base analyzer (DSA815) was priced at $1295, while the reviewed unit, with tracking generator that supports swept frequency analysis, was $200 more.

Figure 7.19 — A Rigol Technologies DSA815-TG spectrum analyzer. This unit offers many capabilities and has a cost in the range of many HF transceivers.

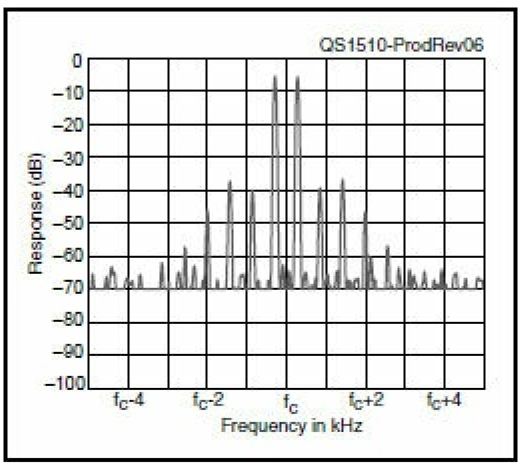


Figure 7.20 — Spectrum analyzer plot of the spectrum of an SSB transmitter undergoing two-tone testing in the ARRL Laboratory. The two signal components at the center represent the original signals, equal amplitude and 2 kHz apart. Their voltage levels are adjusted to 6 dB below the 0 dB reference because the spectrum is shared between the two. The third-order IMD products (the signal components immediately to the left and right of the original signals at the center) are down approximately 40 dB from full carrier output, the 0 dB reference.

A typical use for a spectrum analyzer is measurement of SSB transmitter distortion products. For this test, audio tones on two frequencies are applied simultaneously to the transmitter's MIC INPUT port. If the transmitter is distortion free, the only signal components observed on the analyzer screen will be the two audio tones that appear above or below the suppressed carrier frequency. (Their position relative to the carrier frequency depends on whether the upper or lower sideband is being transmitted.)

In a real SSB transmitter, with less than completely linear stages, there will be *intermodulation distortion* (*IMD*), resulting in spurious signals that can be observed on the analyzer. Any amplifier will exhibit some unwanted mixing products during operation. In an amateur transmitter there is amplification in the audio stage (microphone preamp) that is used to modulate the driving stage(s) and the final amplifier stage, so there are several opportunities for generation of unwanted products in a transmitted signal.

Transmitter IMD is best observed on a spectrum analyzer, as shown in **Figure 7.20**. The most measureable unwanted products are *odd-order products*. The third, fifth, seventh, ninth, and higher order transmitted products add to the distortion of the transmitted signal. If these levels are high enough, they will cause interference (splatter) and simultaneously reduce the transmitter's effectiveness. Good amateur practice is to minimize them.

CW transmitters can also generate spurious signals. Every time the transmitter is keyed, the transmitter responds with sidebands around the carrier frequency. While well-adjusted transmitters keep their spectrum within perhaps 100 Hz, most generate wider bandwidth signals. The spectrum display of **Figure 7.21** is fairly typical of a clean transmitter. Note that CW keying speed has some effect on transmitted signal width.

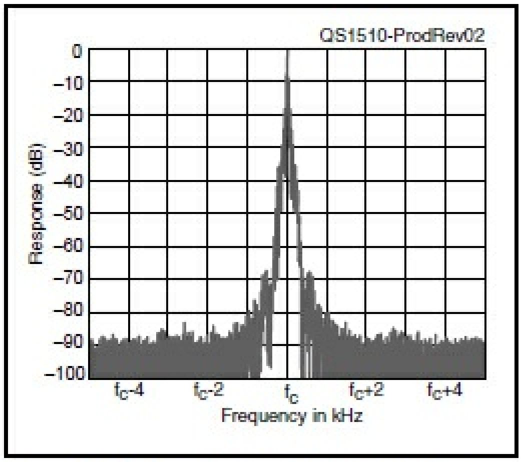


Figure 7.21 — Spectrum analyzer plot of the spectrum of a CW transmitter being tested for keying sidebands in the ARRL Laboratory. The transmitter is being keyed at 60 WPM.

While a spectrum analyzer is arguably the most convenient method of making transmitter measurements, it is not the only way. A manually tuned receiver with capability for narrow bandwidth, slow tuning rate, and sufficient frequency stability can make the same kind of measurements — as long as the signals stay there for the duration of the measurements. Of course, if you are making two-tone SSB or CW keying tests, the signals can stay on as long as the test takes — as long as the transmitter's duty cycle specifications are observed. One limitation of using the station receiver is that it generally can't be part of the transceiver you are trying to test, since almost all are muted during transmit.

The preceding discussion covered signal measurements in the *frequency domain*, that is with frequency on the horizontal axis (x-axis) of the display and amplitude on the vertical axis (y-axis). It is also meaningful to use a *time domain* measurement system, such as an oscilloscope, to analyze the waveforms of signals at various portions of the transmit or receive chain. While an oscilloscope will not directly show the spurious signals that can result from distortion, a 'scope can examine the modulating waveform to find distortion or examine early stages in which overloading can introduce waveforms that generate wide signals.

Oscilloscopes have been available to amateurs as kits since at least the 1950s. The author still has his Eico 460, a 5-inch dc-coupled oscilloscope he built from a kit in 1965. Many very competent 'scopes have been available from commercial surplus sources over the years. For example, the author has a Tektronix 561A dual-trace model (**Figure 7.22**) that replaced the Eico 460 on his bench.

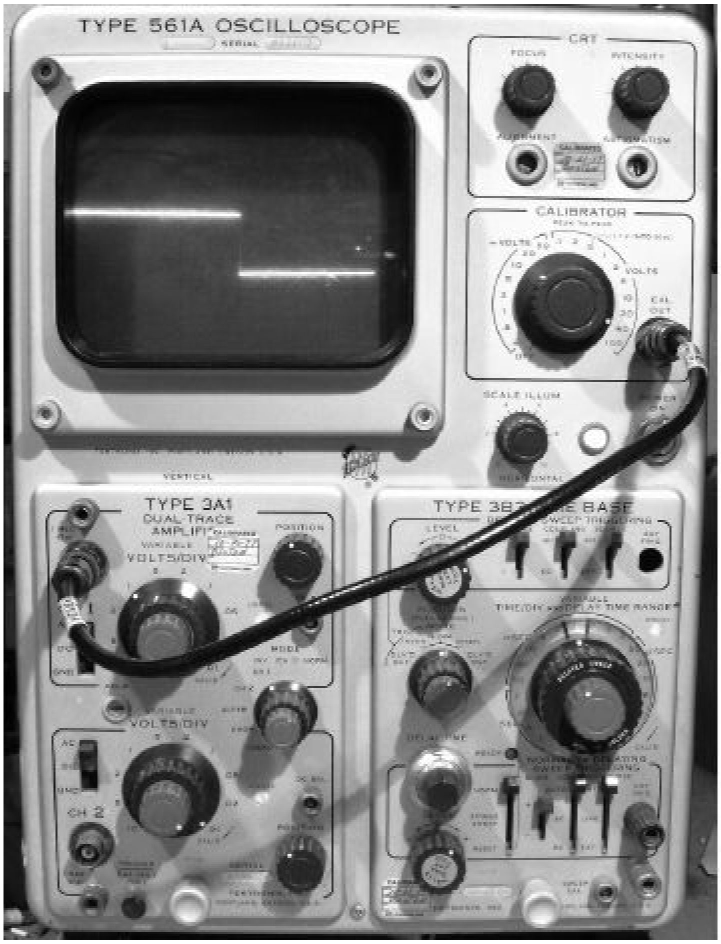


Figure 7.22 — The author's vintage Tektronix 561A dual-trace oscilloscope. This is typical of the many scopes of its era and includes the capability to accept plug-in drawers to change both the horizontal time base and vertical input ranges. The delayed sweep function allows detailed examination of a portion of a waveform.

In recent years, some modern solid-state oscilloscopes have become available to amateurs at reasonable prices (at least compared to lab-grade models). *QST* reviewed two examples, the Rigol DS1052E (see **Figure 7.23**) and Tektronix TBS1042 (see **Figure 7.24**).[7] These are both highly capable digital storage oscilloscopes (DSOs) with the capability to perform off-line processing on observed data. It is worth mentioning that, as noted in the review, the TBS1042 can also perform a fast Fourier transform to generate the spectrum display of a two-tone SSB transceiver test (see **Figure 7.25**).

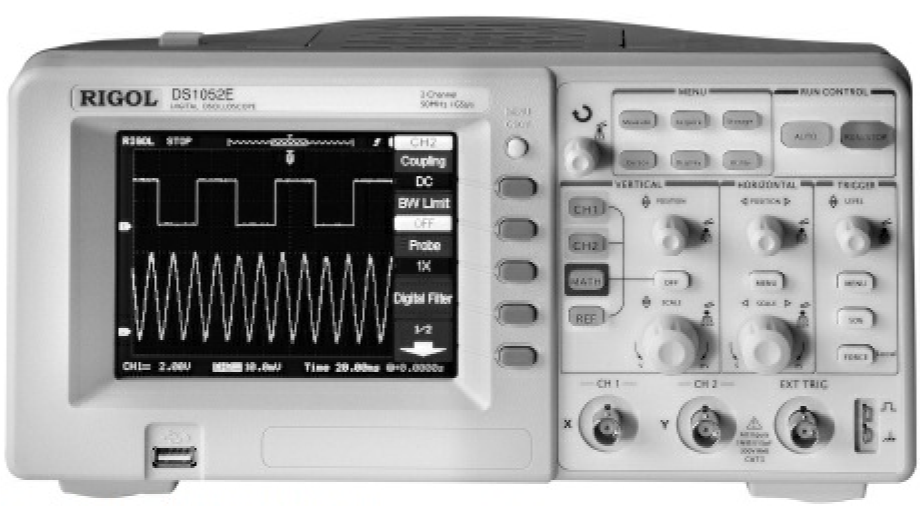


Figure 7.23 — Rigol DS1052E digital storage oscilloscope.

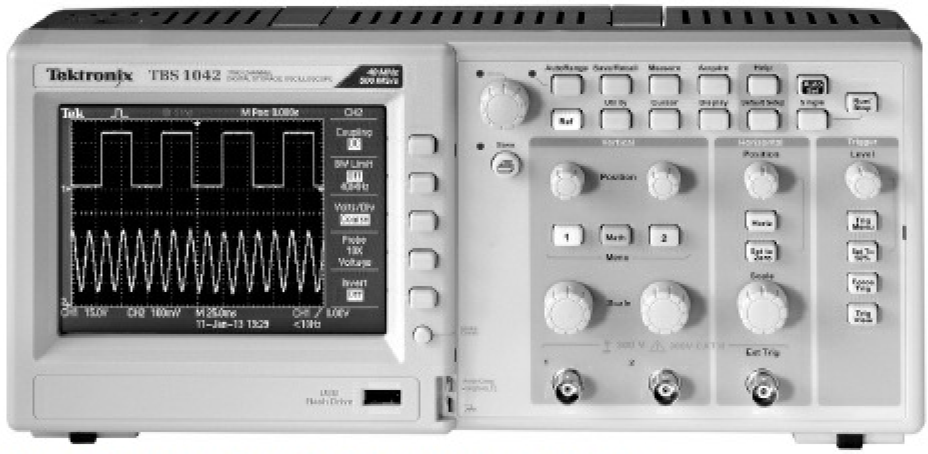


Figure 7.24 — Tektronix TBS1042 digital storage oscilloscope.

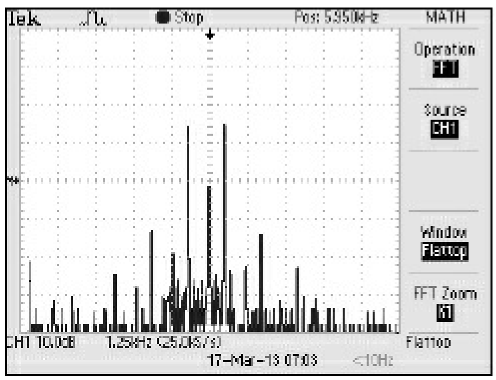


Figure 7.25 — FFT display of the spectrum of an SSB transmitter two-tone test on a Tektronix TBS1042 digital storage oscilloscope.

Swept Frequency Analysis

The capability to perform swept frequency analysis is important for many potential activities within the amateur workshop. In this test setup, the frequency of a signal generator applied to a DUT (device under test, such as a filter or amplifier) is swept across a defined frequency band in order to observe the response as frequency changes. The output of the DUT is observed with some sort of amplitude detector, these days usually a spectrum analyzer. It could also be a receiver, oscilloscope, microwattmeter or other device. Detector response is displayed graphically over a frequency range — the display visually indicates the bandwidth characteristics of the DUT.

Swept frequency analysis can certainly be accomplished manually by adjusting the signal generator frequency in small steps, recording the output, and then plotting it on a piece of graph paper as shown in **Figure 7.26**. The difficulties appear if you are trying to adjust interacting elements, such as a multisection filter, for a particular result. While such adjustments are almost impossible — or at least very tedious — using repetitive manual plotting, automated swept frequency techniques make the task feasible.

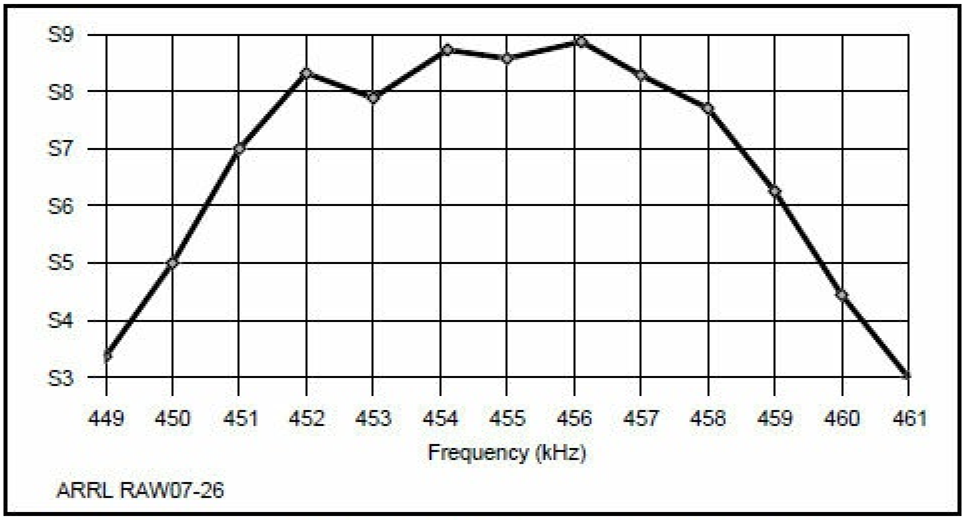


Figure 7.26 — Representative bandwidth plot of a 455 kHz IF system taken with a signal generator and communications receiver. The manual readings are from the receiver's S meter (if calibrated per standards, each S unit represents a change of 6 dB). The frequency intervals are selected to show the key features of the response with actual data shown with an X. Lines are drawn between the data points to show the curve shape. Automated swept frequency analysis is much less labor intensive, particularly if you are trying to adjust the shape of the result.

Traditional swept frequency signal generators worked by applying a sawtooth waveform to a voltage variable tuning element. Some even used a motorized variable tuning capacitor. The sweep generator also included a separate output with a synchronizing pulse at the beginning of each sweep.

The output of the DUT would be applied to an amplitude detector connected to the vertical input of an oscilloscope. The oscilloscope's horizontal sweep would be set to start with the sync pulse from the generator and make one sweep per pulse. The result would be a swept frequency response plot.

Amplitude calibration would be accomplished by replacing the DUT with a step attenuator. With attenuation of 0 dB, the 'scope response would be noted and, back in the day, recorded with a crayon line on the 'scope screen. Additional marks at key points, such as –3 dB, –10 dB and –60 dB would also be indicated on the screen. Now the filter or amplifier response could be adjusted while observing the output across the band all at one time. (Yes, I had a part-time job tuning microwave filters while a part-time undergrad in the mid-1960s.)

These days, the job is much simpler with the use of a spectrum analyzer and tracking generator. The Rigol Technologies DSA815-TG spectrum analyzer described earlier includes an optional tracking generator. In this case, the spectrum analyzer, with its display already calibrated in amplitude versus frequency, runs the show. It provides a generator output that tracks the frequency being displayed. A typical swept frequency response measurement from the *QST* Product Review is shown in **Figures 7.27** and **7.28**.

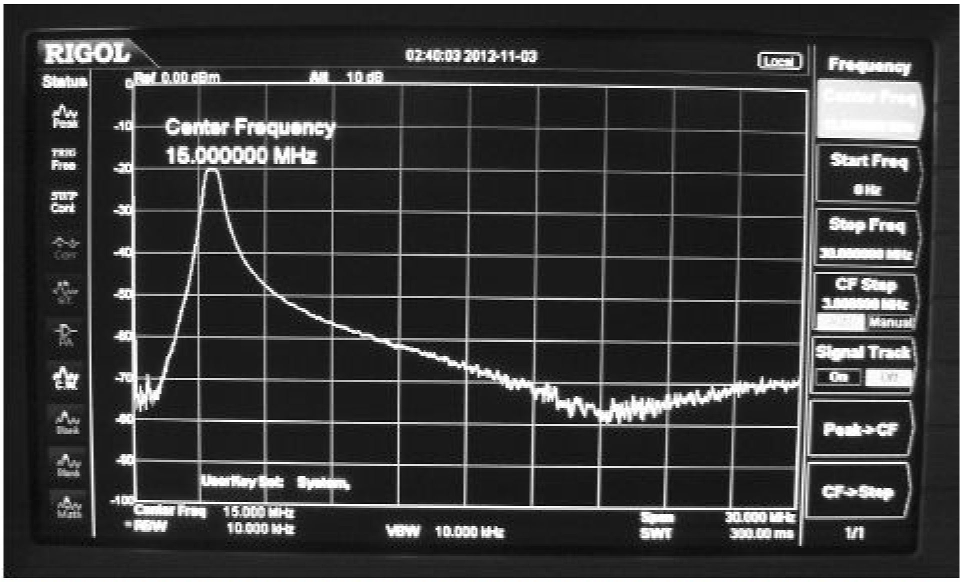


Figure 7.27 — Swept frequency response display using a Rigol Technologies DSA815-TG spectrum analyzer with internal tracking generator. The device being tested is an 80 meter band-pass filter.

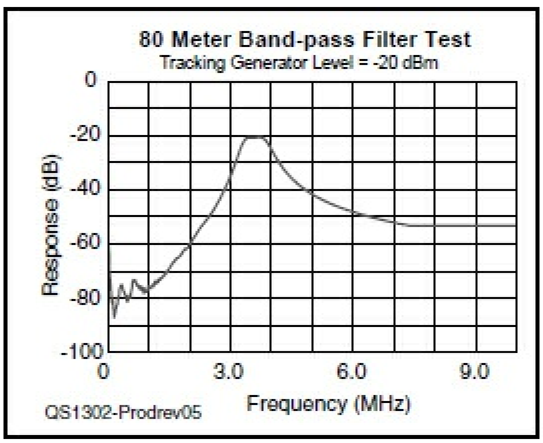


Figure 7.28 — Test results of Figure 7.27 exported to computer graphing software to allow closer examination of a portion of the results off-line.

Note that a *vector network analyzer* is another device that can be used for swept frequency analysis. It also requires a connected PC to operate, so it will be discussed in more detail in the next chapter.

Notes

[1]J. Hallas, W1ZR, *Understanding Your Antenna Analyzer*. Available from your ARRL dealer or the ARRL Bookstore (**www.arrl.org/shop**).

[2]M. Tracy, KC1SX, "Product Review — Elecraft XG1 Receiver Test Oscillator," *QST*, Apr 2005, pp 78 – 79.

[3]R. Allison, WB1GCM, "Product Review — Elecraft XG-3 RF Signal Source," *QST*, Nov 2011, pp 58 – 60.

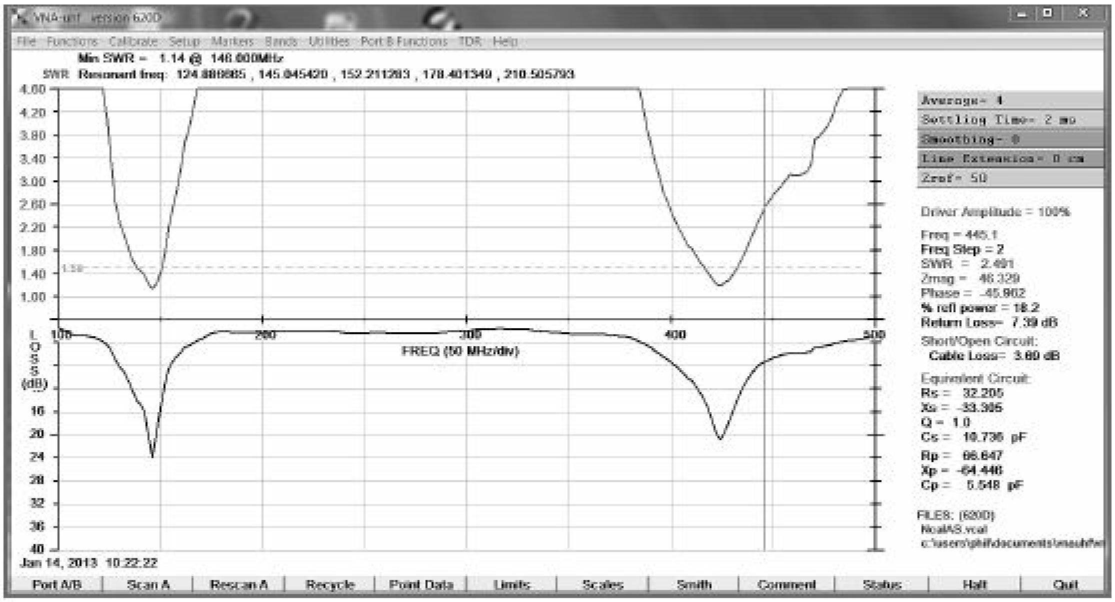
[4]B. Okas, W3CD, "The NorCal Frequency Counter, FCC-1," *QST*, Sep 2006, pp 28 – 32.

[5]B. Okas, W3CD, "The FCC-2 Frequency Synthesizer," *QST*, Feb 2007, pp 31 – 35.

[6]R. Allison, WB1GCM, "Product Review — Rigol Technologies DSA815-TG Spectrum Analyzer," *QST*, Feb 2013, pp 55 – 58.

[7] P. Salas, AD5X, "Product Review — Rigol DS1052E-and Tektronix TBS1042 Oscilloscopes," *QST*, Oct 2013, pp 49 – 52.

The Personal Computer in the Workshop and Laboratory



The PC can make a big difference to workshop and laboratory operations, both as a data depository and as an integral part of test equipment and design or analysis processes. This screenshot is of a vector network analyzer output taken by Phil Salas, AD5X.

Contents

Devices that Work with Your PC

In the previous chapters, we have made note of a number of laboratory devices that provide an interface to a PC, in addition to their function as a standalone device. These have included power meters, as exemplified by the Telepost LP-100 vector power meter, the RigExpert AA series of antenna analyzers, and other devices. This capability allows for double duty — summary or granular data for normal operational use or high-resolution information that can be saved and analyzed off-line for those occasions when needed. This makes for very flexible and multifunctional test systems.

In addition, there are many test systems that work only with a connected PC. While there is no reason that such devices can't be used in the field in conjunction with portable PCs, there is no question that the added devices and cables make them somewhat more cumbersome for field use. This forms no limitation in the lab, as long as a PC meeting system requirements is available. There are countless varieties of data acquisition and measurement systems available in this category, with more being announced almost daily. We will not endeavor to be all-inclusive here, but will describe some that we feel are likely to be of particular interest.

RF Power Metering

We have noted that there are many standalone power meters that can be used to observe transmitted power. There is one that originally was offered as a PC display-only device, the WaveNode WN series of wattmeters. The current WN-2d model includes a separate standalone display (**Figure 8.1**) that has two dual-color 16-segment LED tuning bar displays. One indicates SWR, showing green for SWR below the SWR threshold (default 3:1) and red above. The other shows power with a scale to 100% of the full scale (default of 2000 W, settable by the PC software). There is also an LCD display providing numerical indication of peak and average power and SWR for any of up to four remote power sensors. This device is included in this section because it really is a computer driven system, in spite of the standalone display.[1]

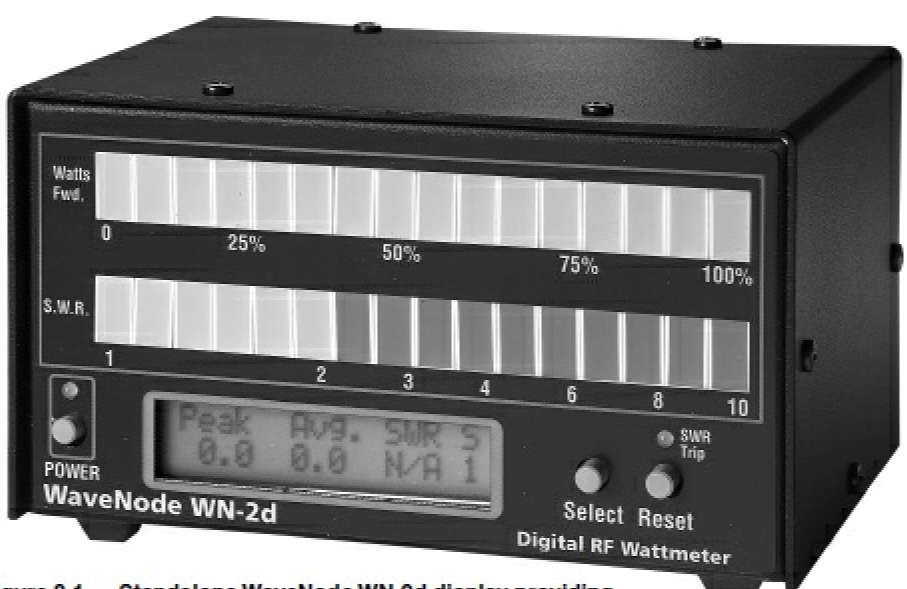


Figure 8.1 — Standalone WaveNode WN-2d display providing numerical indication of peak power, average power, and SWR for any of up to four remote power sensors.

The power of this device comes through when used with the station computer. While this could be viewed as test equipment, in my view it is more at home as a part of the operational station equipment. The unit with PC software running goes beyond duty as a power meter, including providing measurement and control of power and SWR of up to four RF sensor outputs as well as up to four auxiliary inputs that can be used to monitor other functions that can be represented as dc voltage levels. These could correspond to power supply overvoltage or even equipment temperature. They can trigger alarms or relay closures that could be used to switch faulty equipment offline, for example. The different sensors can be in different parts of the same signal path — for example at the input and output of an amplifier — or can monitor different transmitters on different frequency ranges. The basic display is shown in **Figure 8.2**.

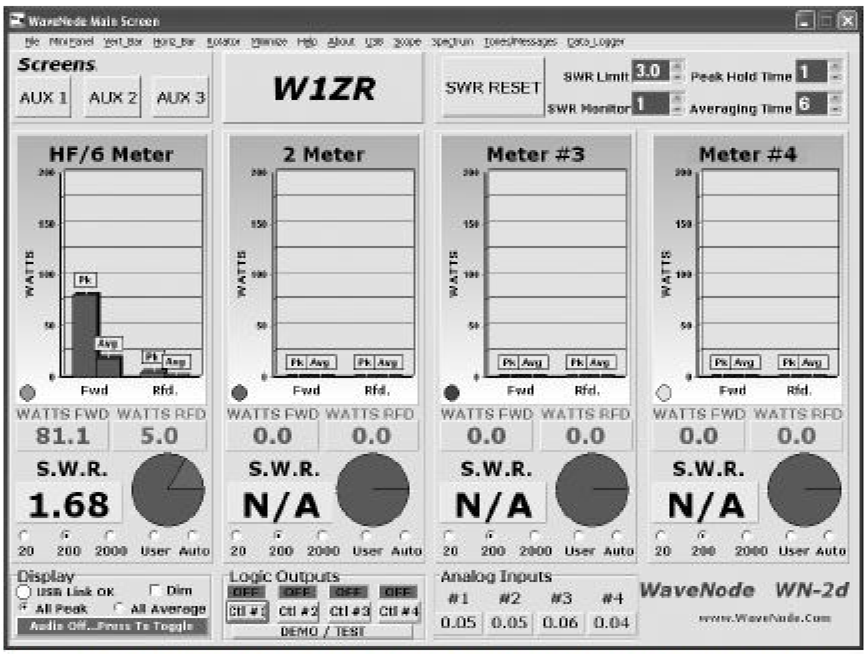


Figure 8.2 — Screenshot of the WaveNode WN-2d primary display. The peak and average power of each of four sensors is shown, along with the SWR and other indications.

While the display in Figure 8.2 has a lot of information, it is likely more data than one would like to see during normal station operation. **Figure 8.3** shows reduced size displays that can be used along with other operating software during normal operations. There are a number of other functions that can provide useful information, such as processing the input and output power of an amplifier to calculate and display gain as a function of frequency, or gathering statistical data about transmit power over time, for example — all far beyond the capabilities of the typical standalone power meter.

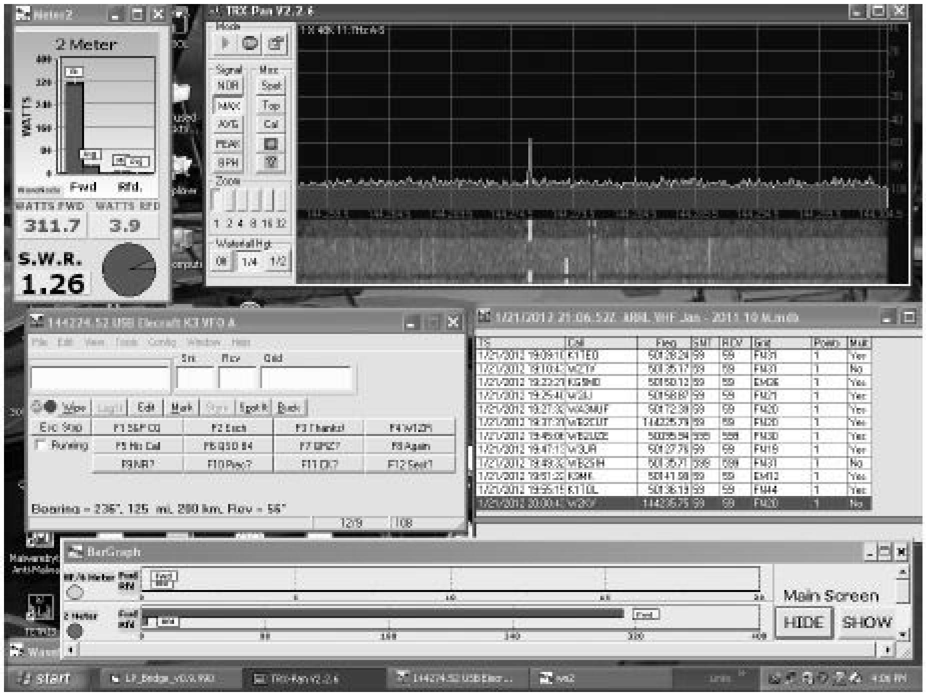


Figure 8.3 — This view is a screenshot of the W1ZR station computer with two windows for the *N1MM* contest logging program and a panadapter display window along with three reduced WaveNode displays, one along the bottom and two at upper left.

Vector Network Analyzer

The vector network analyzer (VNA) is an advanced piece of test equipment that has reached the amateur marketplace over the last few years and offers significant capabilities. The VNA uses swept measurements to test the parameters of devices known as *two-ports*. Consider a two-port as a black box with an input and an output. If a signal is applied to the input, the VNA will determine and plot both the magnitude and phase (hence "vector") of the signal at the output. It will also determine the magnitude and phase of the impedance of the input port, so it can act just as an antenna analyzer (the VNA sees an antenna as a "one-port" network). Any of the parameters and relationships between them can be analyzed and displayed as linear plots or Smith charts (see **Figure 8.4**).

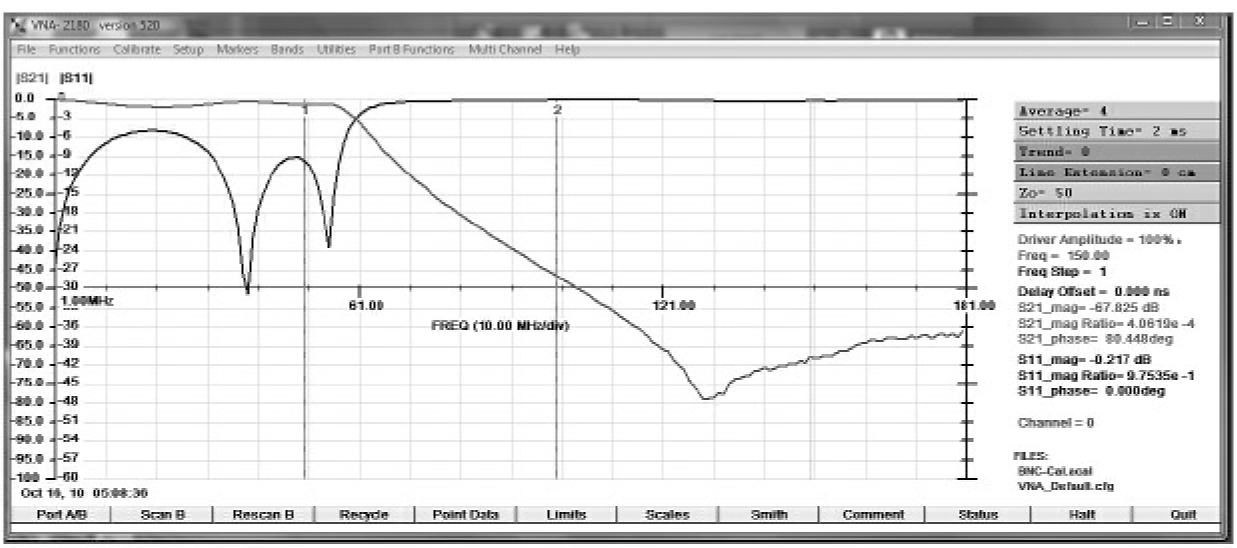


Figure 8.4 — Swept response of a low-pass filter taken by Phil Salas, AD5X, using an Array Solutions VNA 2180 vector network analyzer.

A VNA for amateur use was described in a *QEX* construction article in 2006 by members of TAPR (originally Tucson Amateur Packet Radio, a major organization supporting the Amateur Radio digital communications community).[2] This was licensed to TEN-TEC and offered by them for some time, but is no longer available.[3] Currently, Array Solutions (**www.arraysolutions.com**), offers both one-port analyzers (think antenna analyzer) that cover 5 kHz to 180 MHz (the AIM 4170D) and 5 kHz to 1 GHz (AIMuhf) and two-port VNAs that cover both ranges (the VNA 2180 and VNAuhf). The VNAuhf (**Figure 8.5**) was reviewed in *QST*.[4]

Figure 8.5 — The Array Solutions VNAuhf vector network analyzer. Its apparent simplicity hides the wide ranging capabilities.

While a VNA is a natural for evaluation of passive two-ports such as filters and attenuators, it can be equally at home measuring the passband phase and amplitude response of active systems such as amplifiers, as long as the input and output power level limits are observed.

Spectrum Analyzers

While software defined radios (SDRs) are commonly used for receiving applications, they can also find a place in the lab, serving as a spectrum analyzer. Many can share the various commonly available software packages that can deliver spectrum analyzer displays. Even very inexpensive SDR receiver packages can look the same on the screen, the difference between lower cost and higher cost units showing up in such areas as dynamic range. The screenshot in **Figure 8.6**, showing activity in a segment of 20 meters using a Telepost LP-PAN panadapter SDR over the PC running *NaP3* SDR software, should give the idea.

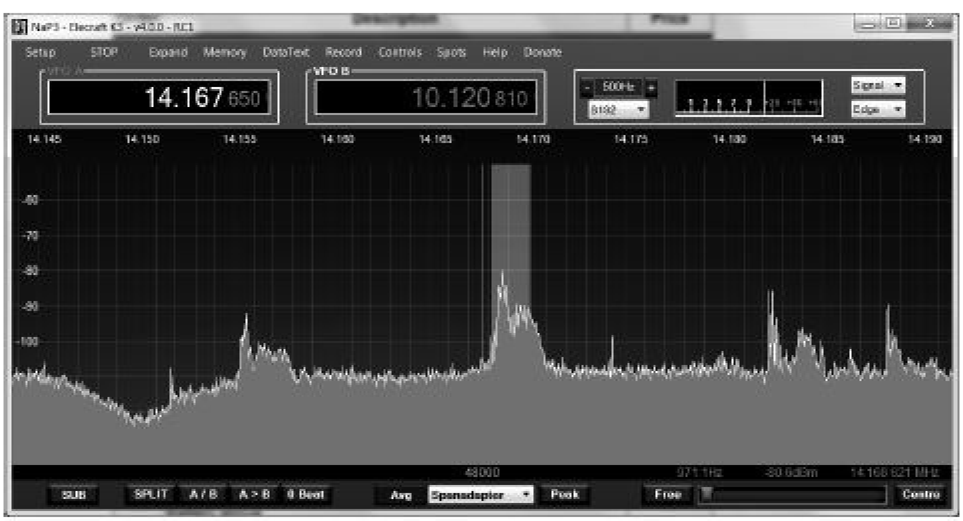


Figure 8.6 — Screenshot of activity in a segment of 20 meters using a Telepost LP-PAN panadapter SDR connected to the IF output of an Elecraft K3 transceiver and a PC running *NaP3* SDR software. This can serve as a spectrum analyzer for either off-the-air or in-lab signals within its frequency range. Some SDRs can cover a much wider frequency range than the connected Elecraft K3 transceiver, making them more suitable for general laboratory use.

Antenna Simulation and Modeling

You may well wonder how it is that a person can determine just how well and in which directions an antenna will radiate. This has been an age-old problem and traditionally was best settled on an *antenna range*. This is a large open space with appropriate towers and measuring equipment so that the actual directivity and gain of an antenna can be determined by measurement. Of course there have always been theoretical methods to determine antenna performance, but they have often suffered from a lack of inclusion of all of the important factors. Key elements excluded have often been the effects of ground reflections and antenna interaction with other nearby objects, such as support structures. Vehicle structure must be considered for mobile, airborne, or shipboard antennas. Fortunately, in our 21st century computer-oriented society, we have software tools that may help you avoid the need to climb towers!

The radiation from an antenna can be determined by dividing up the antenna into a large number of segments, adding up the radiation from each of the segments, considering both magnitude and phase, and determining the result as the energy combines at some distant location at a particular angle with respect to the antenna. Antenna simulation programs divide up the antenna structures into small increments, the assumption being that they are small enough so that the current leaving a segment is (almost) the same as the current entering, and determine the vector sum of the effects of each "mini antenna" at a distant location. Other structures not connected to the antenna can also be modeled, and the signals that are induced in them will be part of the calculation.

The result can be an effective tool to predict how a particular antenna will function, without having to actually construct and measure the way it really works. As with any simulation, your mileage may vary, but under most circumstances modeling provides at least a good starting point.

Numerical Electromagnetics Code

The *Numerical Electromagnetics Code (NEC)* is a family of powerful antenna analysis tools that form the basis of a number of antenna analysis programs. The most commonly encountered version is *NEC-2*, which is freely available and is used as the calculating engine on most entry level programs. *NEC-2* has some limitations, most of which are overcome by the *NEC-4* versions used in some professional programs, but *NEC-4* requires a relatively expensive license and is subject to US export restrictions. Some popular *NEC* based analysis programs include *4NEC2*, *EZNEC* and *NEC-WIN PLUS*. They all make use of the same *NEC* core, so all should provide comparable accuracy of results. The differences are in the user interface and input and output languages. All require the user to somehow describe the antenna to be analyzed, the environment around it (ground characteristics, for example), and the output information desired.

I have been an *EZNEC* user since the early days, so I am most familiar with it. The "EZ" part of the name comes from the fact that this *Windows* implementation is easy to deal with. *EZNEC* is available from its developer, Roy Lewallen, W7EL (**www.eznec.com**). The program is available in a number of versions, including a free demo version with no time limit. The demo is restricted in size to 20 segments, plenty for simple antennas.

Getting Your Feet Wet with *EZNEC*

If you follow along with this section, you will get an understanding of how to use *EZNEC* to model simple antennas and obtain results very quickly. It is important to note that as antennas get more complicated, or very close to the ground, a number of complications make accurate results more difficult to obtain. Look at the information on the *EZNEC* website or the HELP screens in the program itself. Consider other sources such as *Antenna Modeling for Beginners* by Ward Silver, NØAX, to get a sense of the modeling limits.[5]

To use *EZNEC*, bring up the program and you will see the main menu as shown in **Figure 8.7**. Start setting it up by defining a simple antenna, or use one of the samples that comes with the program. On the main menu, click the WIRES button and enter the physical dimensions of your antenna in X, Y and Z coordinates, wire size or diameter, and pick a segment quantity (see **Figure 8.8**). The free demo version has a limit of 20 segments, and the basic version a limit of 500 segments.

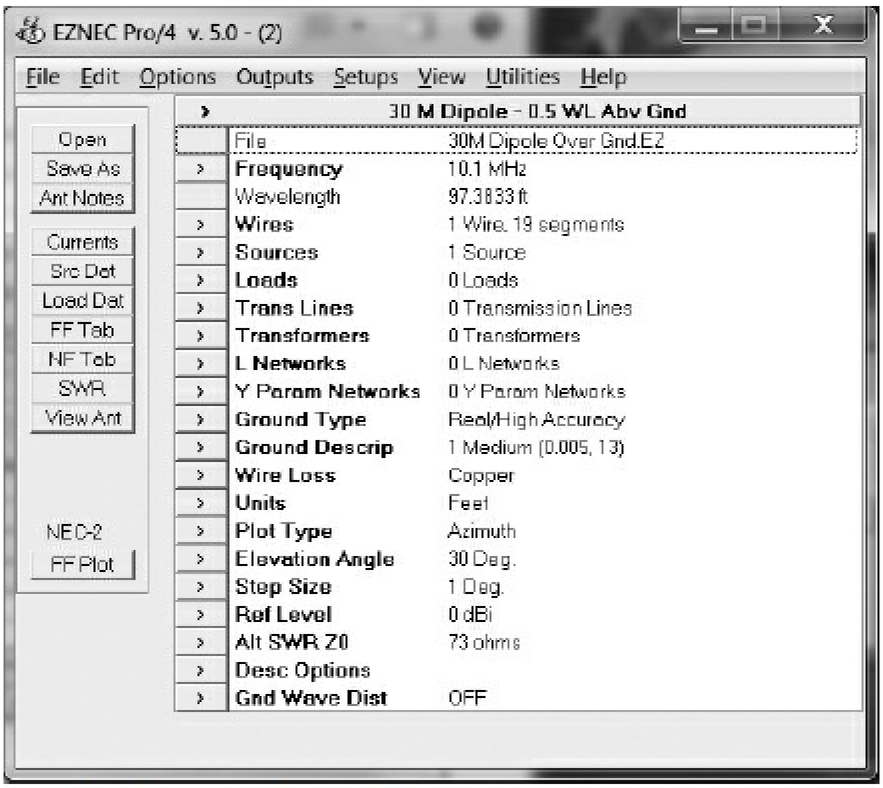


Figure 8.7 — Screenshot of the *EZNEC* main menu. The buttons on the left of the center panel bring up configuration choices.

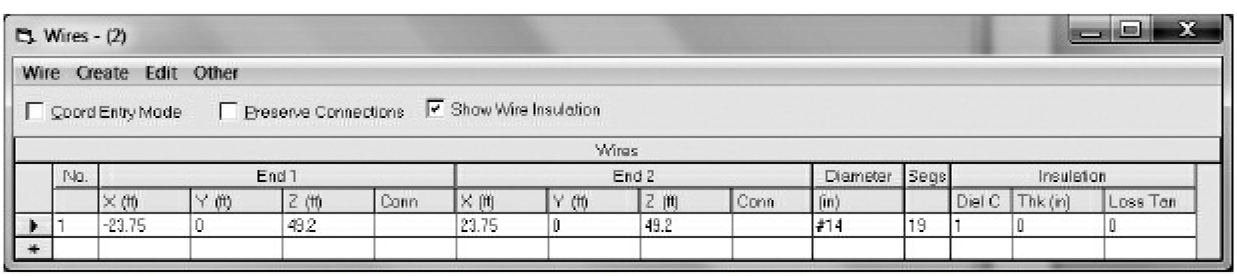


Figure 8.8 — Screenshot of the *EZNEC* WIRES entry panel. This is where the antenna physical dimensions are entered. Here we have defined a 30 meter dipole of #14 AWG wire up ½ wavelength (49.2 feet). Note that we have specified 19 segments, a bit more than the minimum but still enough to work with the *EZNEC* free demo version.

The number of segments may be the least intuitive entry, but a good rule of thumb is to use enough segments so that each one is no longer than ½0 wavelength. This means a minimum of 10 segments should work for a simple dipole (11 allows for a center feed point in a single wire). More segments makes for more accuracy but longer computation time (not much of a problem with modern PCs). *EZNEC* will provide warnings if the segments are too small or too large.

On the SOURCES tab (see **Figure 8.9**), indicate which wires will be connected to sources, as well as the location where the source connection will go in terms of percentage distance from one end. In this case, the source connects to Wire 1 at 50% from the end — in other words, the dipole is fed right at the center. Pick the type of ground you want from the GROUND tab choices. That's all it takes to model an antenna.

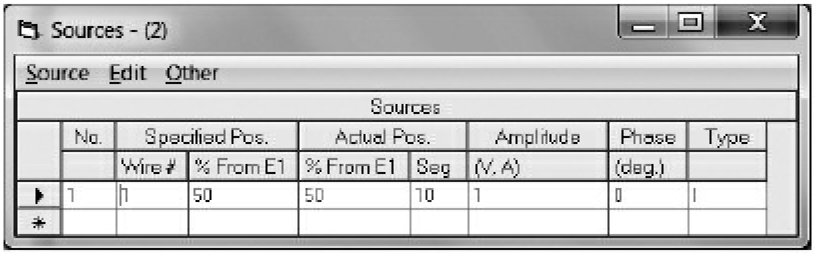


Figure 8.9 — Screenshot of the *EZNEC* SOURCES entry panel. Here we have defined a current source to be located 50% from end 1 of wire 1 (our only wire). The fact that we selected an odd number of segments makes the source end up in the antenna center. The magnitude and phase don't matter unless we have multiple sources, or are interested in the actual current in each segment.

To determine the results, you may select the SWR tab and give the program a range of frequencies over which to determine the antenna's impedance and SWR (see **Figure 8.10**). The default is 50 Ω, but you can select other impedances on the main menu (ALT SWR Z0 button). If you want a plot of the antenna pattern, you can select azimuth or elevation plots on the PLOT TYPE tab and then hit the FF PLOT to see the results (see **Figure 8.11**). It takes less time to do it than talk about it!

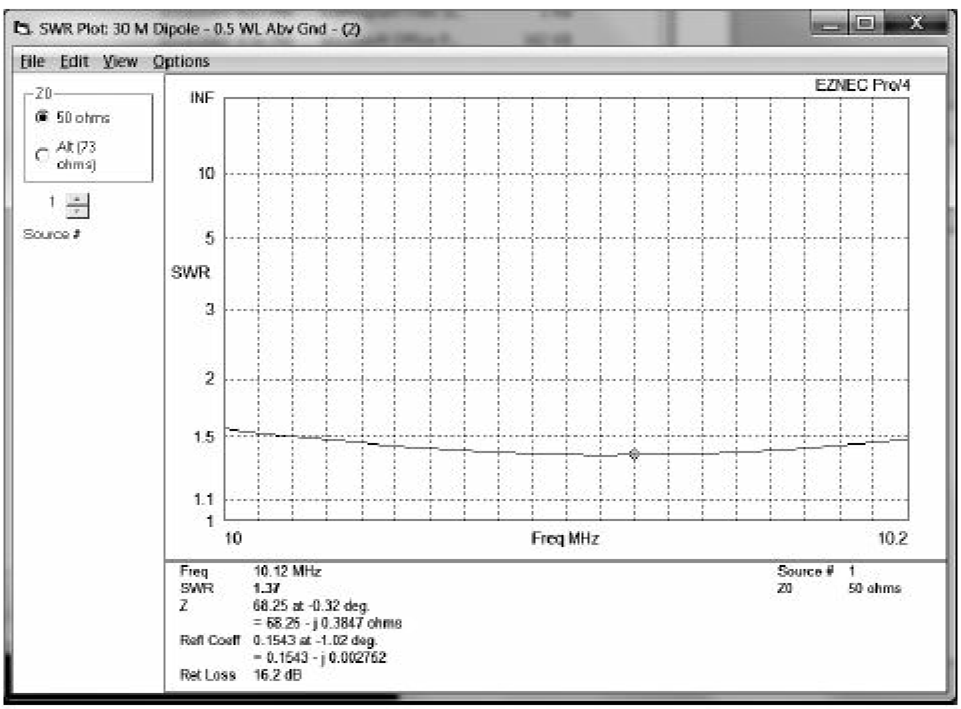


Figure 8.10 — Screenshot of the *EZNEC* SWR result display. We have selected the frequency range and increment and get a display that we can compare to an antenna analyzer plot. Note that here we have clicked on the x-axis corresponding to a frequency of 10.12 MHz and get not just the SWR, but also detailed impedance data for that frequency.

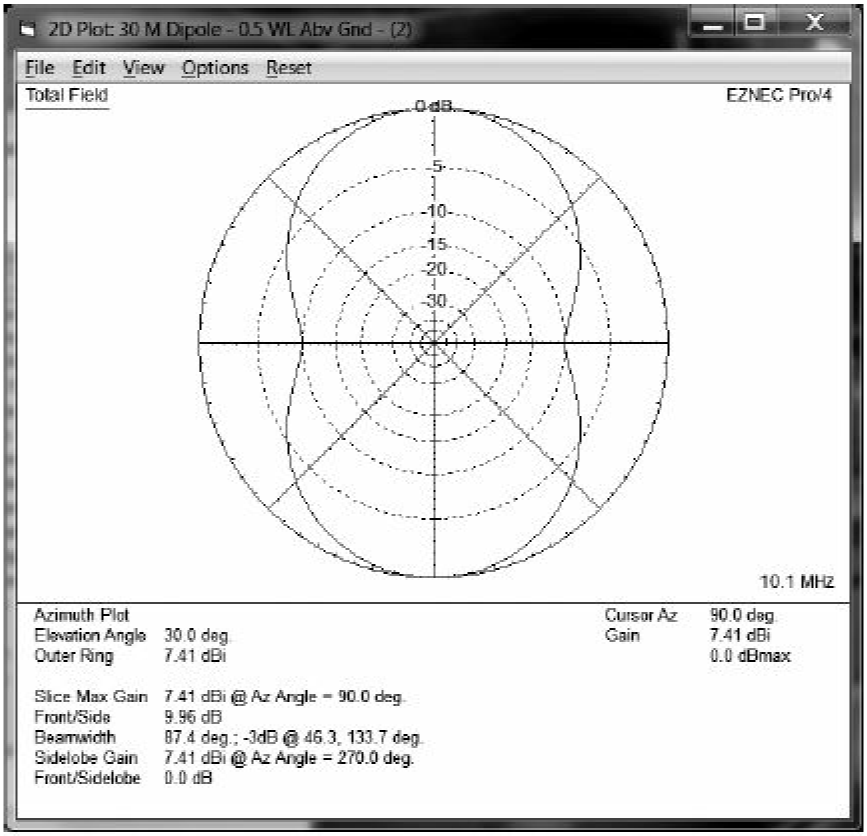


Figure 8.11 — Screenshot of an *EZNEC* azimuth far-field plot. Note that on the main menu we had selected that we wanted the plot at an elevation angle of 30°. As with the SWR plot, we can get detailed information by clicking at different azimuth angles around the plot.

Of course there are some refinements and details that make it even more useful, but I expect you will find out about them as you need them. If you want to find out the effect of changing the length, you can adjust the dimensions in the WIRES tab and run it again. If you're interested in finding out how it works at another frequency, just enter another frequency in the FREQUENCY tab and hit FF PLOT again. This is a very powerful tool!

Transmission Line Analysis

Analyzing antennas is fine, but we generally need to know what is happening at some distance from an antenna that is connected by a *transmission line*. *EZNEC* includes the capability to analyze transmission lines as part of the antenna model. This can be very useful, but there are times when it is beneficial to analyze a transmission line on its own merits. One example would be to determine the impedance at an antenna based on impedance measurements taken at the station end of the line. There are many cases in which lines are used independently from antennas, and a tool to predict what will happen can be quite useful.

There are a number of ways to perform such an analysis, including calculating the results in closed form from transmission line equations. Many years ago, Philip H. Smith developed a graphical technique to determine the impedance at a point on a transmission line based on its electrical length and terminating impedance. This process required special *Smith Charts* that are still available from the ARRL Store and other locations.[6] In addition, there are software programs that implement the process automatically.[7]

The tool that I use the most is *Transmission Line for Windows* (*TLW*), one of the PC software programs that is provided on the CD-ROM that comes with *The ARRL Antenna Book*.[8] The CD also includes other useful antenna related programs, as well as the contents of the book and *EZNEC* models of many of the antennas described in the book.

TLW painlessly allows one to enter a value of impedance that can be obtained from measurement, antenna modeling, or inferred from an SWR or measurement or analysis of conditions at either end of a transmission line. The program then displays the complex impedance at the other end, along with and including the effects of line loss (see **Figure 8.12**). All you need to know is the type of line (which is entered from a pull-down window) the line length, and the frequency. This provides just what you need to know in order to design an antenna system or an antenna tuner.

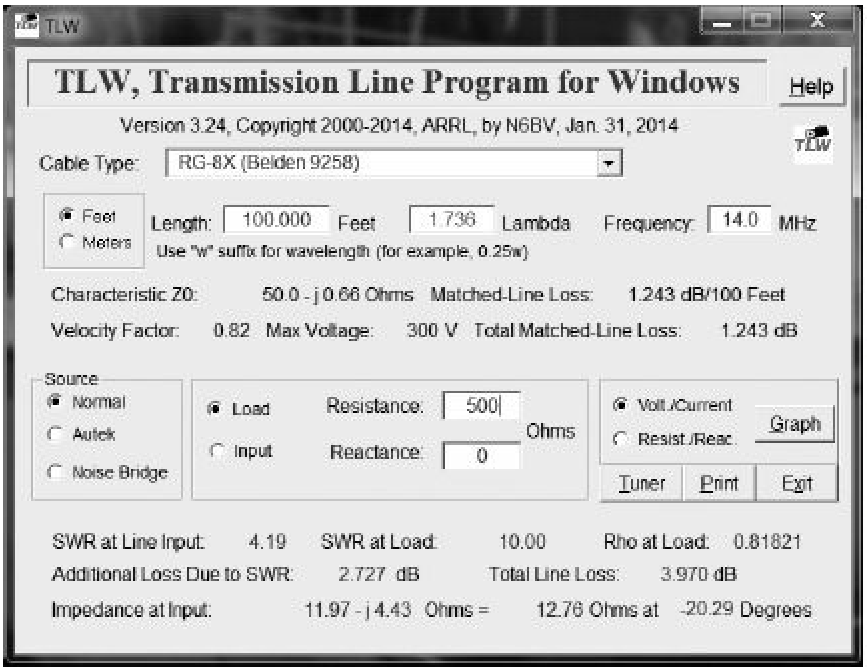


Figure 8.12 — An example of a *TLW* transmission line analysis. In this case, a 100 foot length of RG-8X is terminated with a resistive load of 500 Ω (10:1 SWR) at 14 MHz. The impedance at the input is seen at the bottom of the screen — note the transformation of the impedance — as well as the loss of the mismatched line. If you have data taken at the input of the transmission line, just click the INPUT button rather than the LOAD button and enter the data. Clicking the TUNER button will allow the software to design an antenna tuner to match this load.

In addition to the analysis function, *TLW* also can design an antenna tuner, in your choice of topology, that will match the load predicted by *TLW* to 50 Ω. The program then calculates the tuner loss and specifies the voltages and currents on all the components (see **Figure 8.13**.)

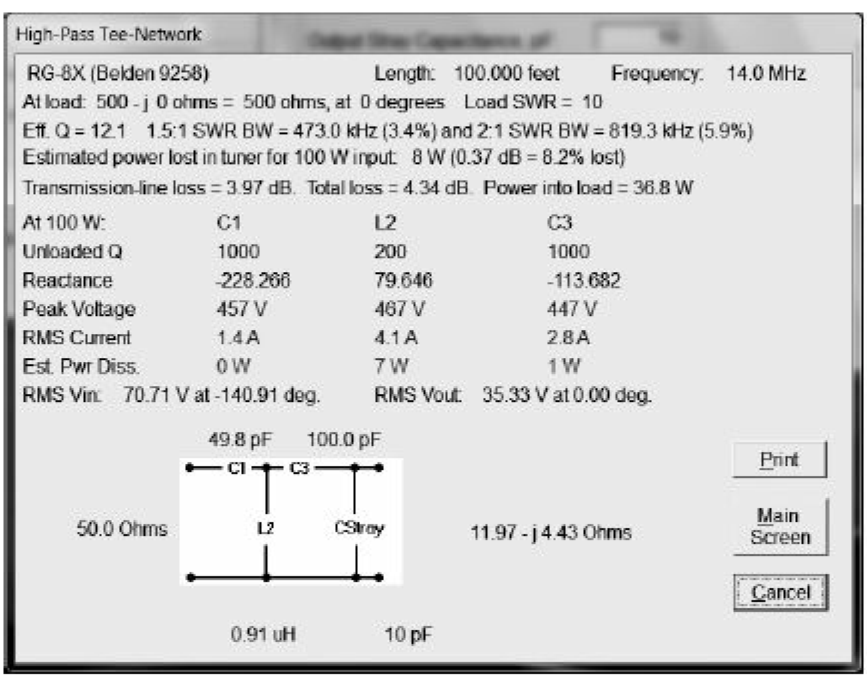


Figure 8.13 — Clicking the TUNER button, seen in Figure 8.12, results in a choice of tuner configurations (L-network, pi-network, or T-network). We selected a high-pass T-network and a power of 100 W. *TLW* designs the tuner in this configuration needed to match the 11.97 –*j*4.43 Ω at the input of the transmission line to the 50 Ω needed by most transceivers. In addition to specifying the components needed, *TLW* shows the stress on each, and the loss through the tuner.

Circuit Design, Simulation, and Analysis

There have been circuit analysis and design programs around for a long time. In the 1970s, I used IBM's *Electronic Circuit Analysis Program* (*ECAP*), designed to work on its 1620 minicomputer, as well as the USAF Weapons Laboratory *SCEPTRE* program, designed to simulate circuit action under nuclear stresses, to attempt to model very large networks.

Software has come a long way since those days! We no longer need to punch and then take a deck of punched cards to a card reader for data entry, but perhaps more importantly, the input languages have become much more user friendly. Programs such as *SPICE* (*Simulation Program with Integrated Circuit Emphasis*) not only make data entry easier, but also include models of integrated circuits so the analyst need not generate detailed models of each chip in the circuit.

SPICE Software

Early versions of *SPICE*, which came not that long after the programs mentioned above, had a similar textual interface structure. That is, circuit elements were identified in a listing with a line for a component including the nodes on each side and the value. *SPICE* versions now have a *Windows* oriented graphical interface that allows circuit connectivity to be entered by selecting a part type and dragging it into the circuit diagram. While the original *SPICE* software is freely available, the many enhanced versions available from different developers may or may not be available without purchasing a license.

One fully capable version that is currently available at no cost is *LTSPICE IV* from Linear Technologies (**www.linear.com**). This is particularly suited for analyzing applications of their power system products, but is generally useful for other work. In addition, their website includes example circuits and documentation on how to use the program.

I used *LTSPICE IV* to analyze a variation of an audio amplifier circuit that I presented in my first book, *Basic Radio*.[9] I first used a built-in graphical editor to draw the circuit as shown in **Figure 8.14**. This is the low impedance version, with an added low-pass RC filter to provide a high-frequency roll off to make the frequency response analysis more interesting. Note that the 2N2222 NPN transistor was a component from the *LTSPICE* library, thus I did not have to enter the parameters defining it. The library contains many analog and digital integrated circuits, as well as other devices. There are a number of useful outputs available from *SPICE*, once you have defined the circuit using the EDIT SIMULATION CMND under the SIMULATE button, including checking the dc operating point, transient analysis, noise analysis, and ac small-signal frequency response. I chose the latter for this example with the results shown in **Figure 8.15**. Note that it shows the gain and phase response over the frequency range I selected. If you are developing a circuit, this allows adjusting any needed component parameters to obtain the desired results before you take out your soldering iron.

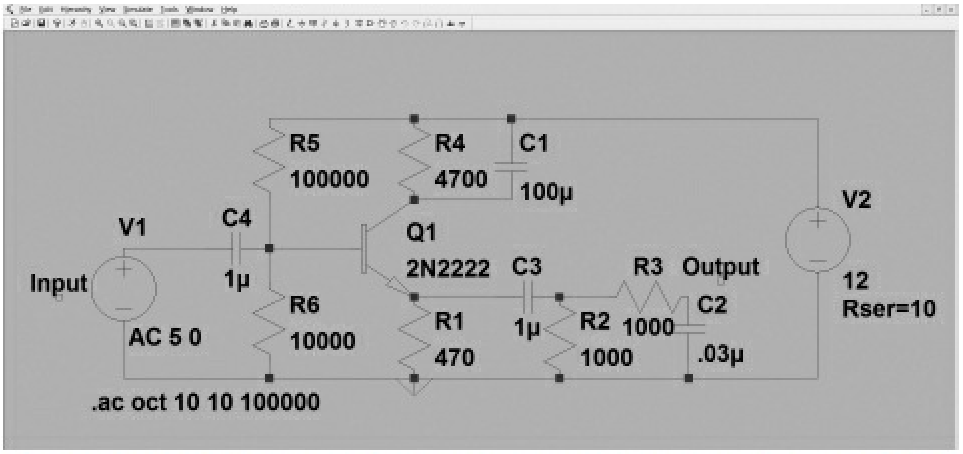


Figure 8.14 — Schematic diagram of the *Basic Radio* audio preamplifier circuit, as entered into *LTSPICE IV*. The 2N2222 transistor used was in the program library, so I just needed to call out its part number to have the program use its specified properties.

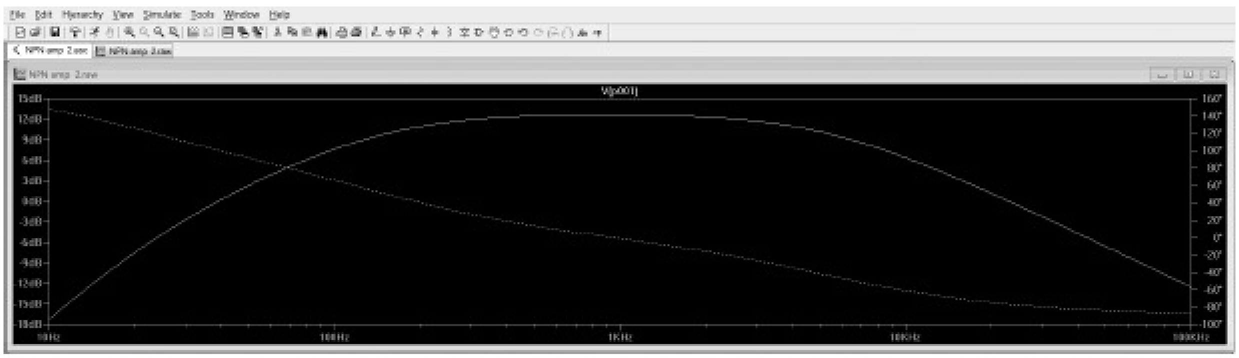


Figure 8.15 — The ac small-signal analysis of the audio preamp modeled in Figure 8.14. The solid line is the amplitude response with the scale on left-hand side of the plot showing 12 dB mid-band gain, and a smooth response from 100 Hz to 5 kHz. The phase response is shown with the dotted line and the scale on the right edge of the plot.

ELSIE Software

Another handy network design and analysis program is *ELSIE* (pronounced L-C, **Figure 8.16**). This is traditionally focused on ladder type networks, such as are often used for filters and attenuators, but the newest version can do much more. The student version of the software (limited to seven poles) is available for non-professional use at no cost from **www.tonnesoftware.com/elsie.html**.

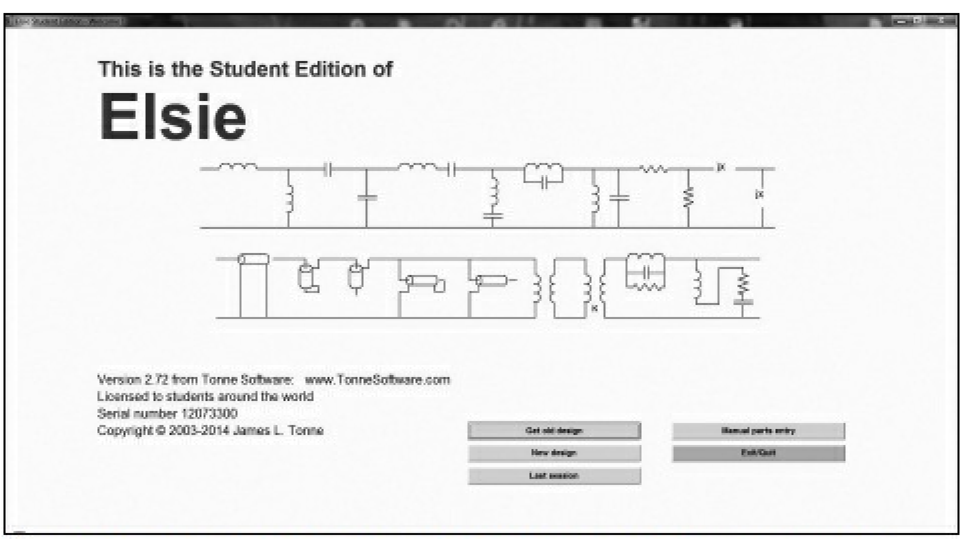


Figure 8.16 — The student edition of *ELSIE* from Tonne Software is available for free download and is powerful enough to design useful filters from several families.

This is an actual *computer-aided design* program. Unlike software that analyzes your designs, *ELSIE* actually designs the filter to meet your requirements specified as shown in **Figure 8.17**. It is also possible to manually enter a design you wish to use. **Figure 8.18A** shows *ELSIE*'s design of a seven-pole Bessel function band-pass filter with a center frequency of 9 MHz and a passband of 50 kHz. By clicking the ANALYSIS tab, I can see the resulting frequency response as shown in **Figure 8.18B**. I could then go back and adjust component values if I wanted to modify the results.

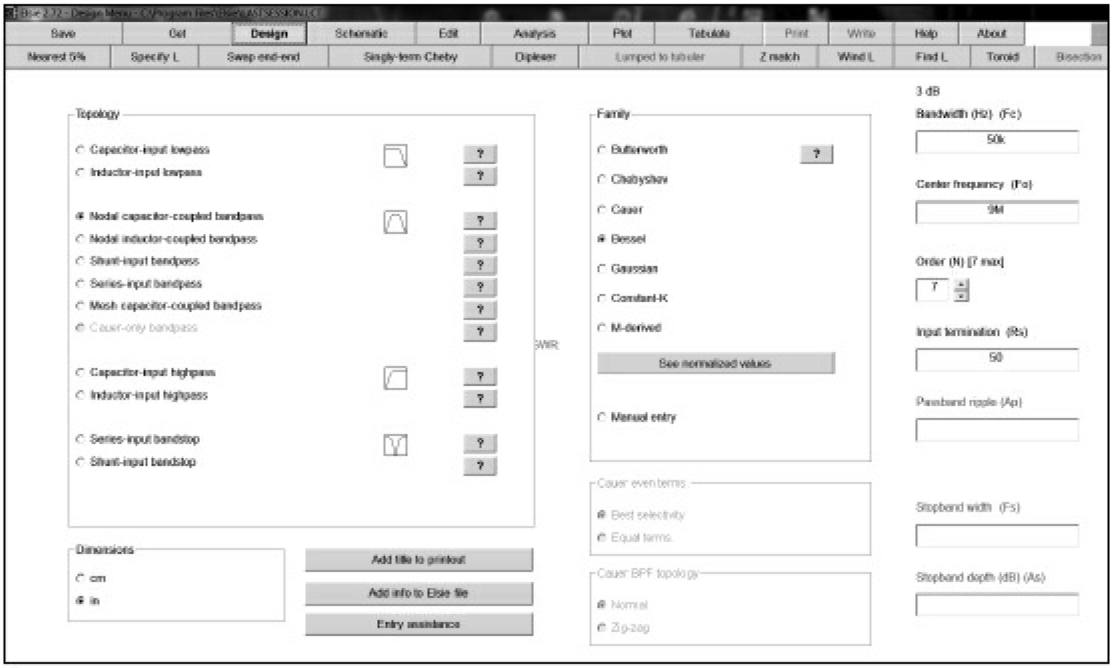


Figure 8.17 — The DESIGN parameter entry input sheet from the *ELSIE* main screen. Note that the desired filter parameters are entered here, requesting an up to seven-pole (L-C combination) design — the limit of the free student version.

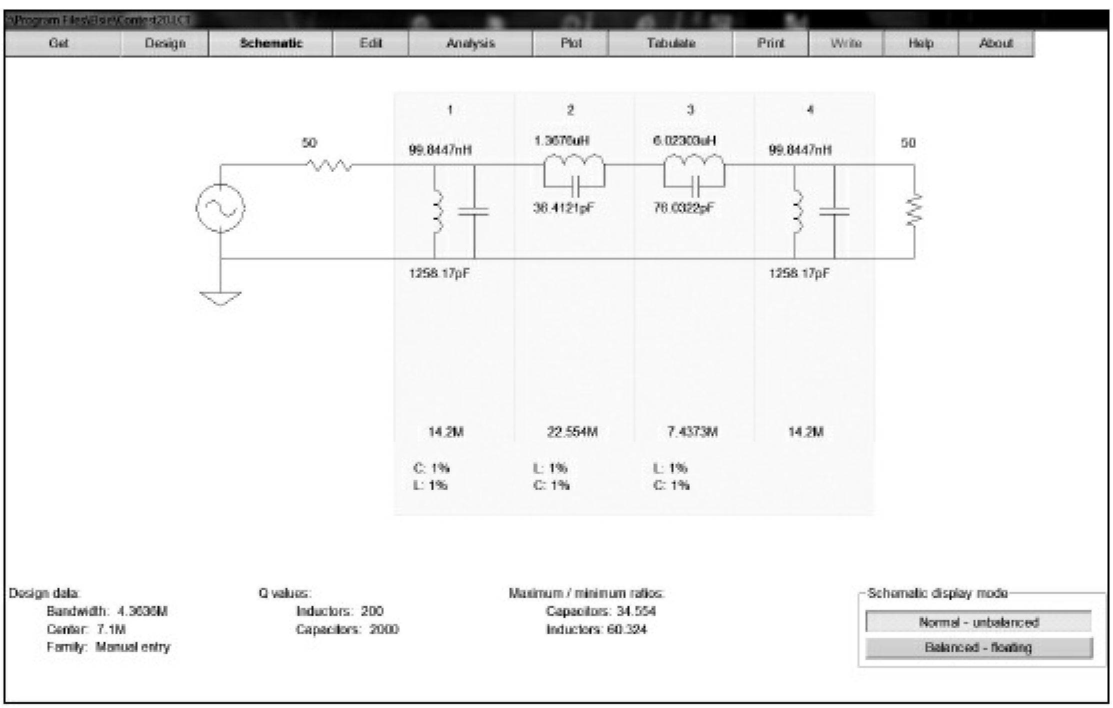


Figure 8.18A — The schematic diagram of the filter *ELSIE* designed to meet my requirements.

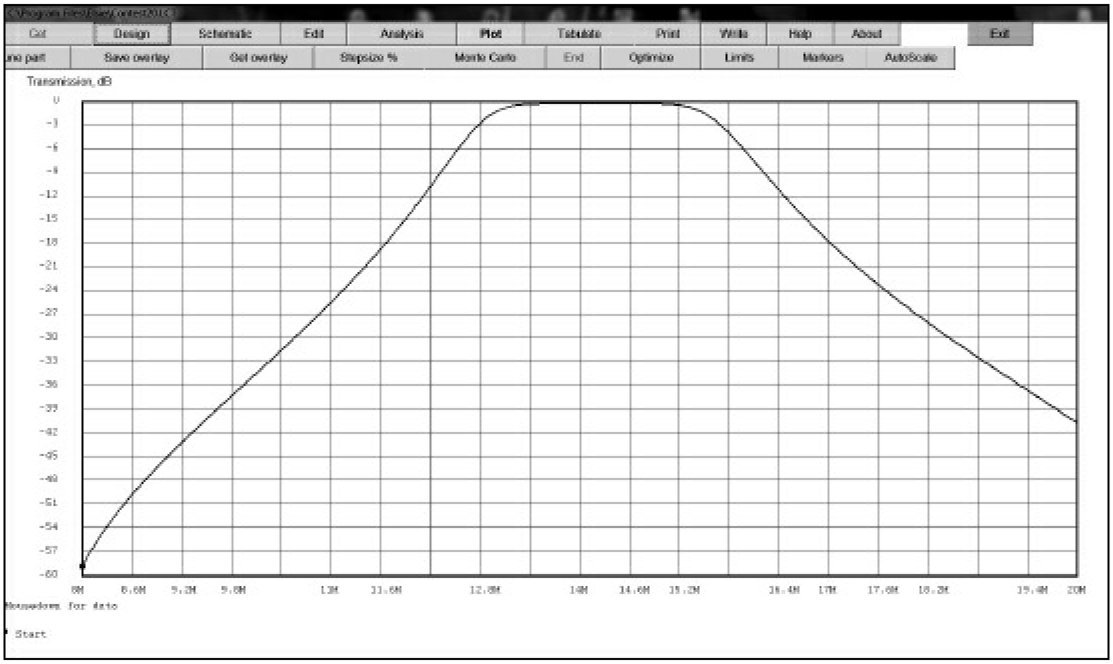


Figure 8.18B — This is the frequency response of the filter *ELSIE* designed, obtained by clicking the ANALYSIS tab and selecting the desired viewing parameters.

Computer-Aided Manufacturing

Express PCB

ExpressPCB and its companion *ExpressSCH* are programs that are available without charge (**expresspcb.com**) and actually go somewhat beyond computer-aided design into the realm of computer-aided *manufacturing*. *ExpressSCH* allows you to generate a schematic of a circuit that you would like to turn into a printed circuit board (PCB). *ExpressPCB* then allows you to manually enter your circuit components into a PCB layout (see **Figure 8.19** for the component side), then draw the solder mask on the underside (**Figure 8.20**). **Figure 8.21** shows the silkscreen image.

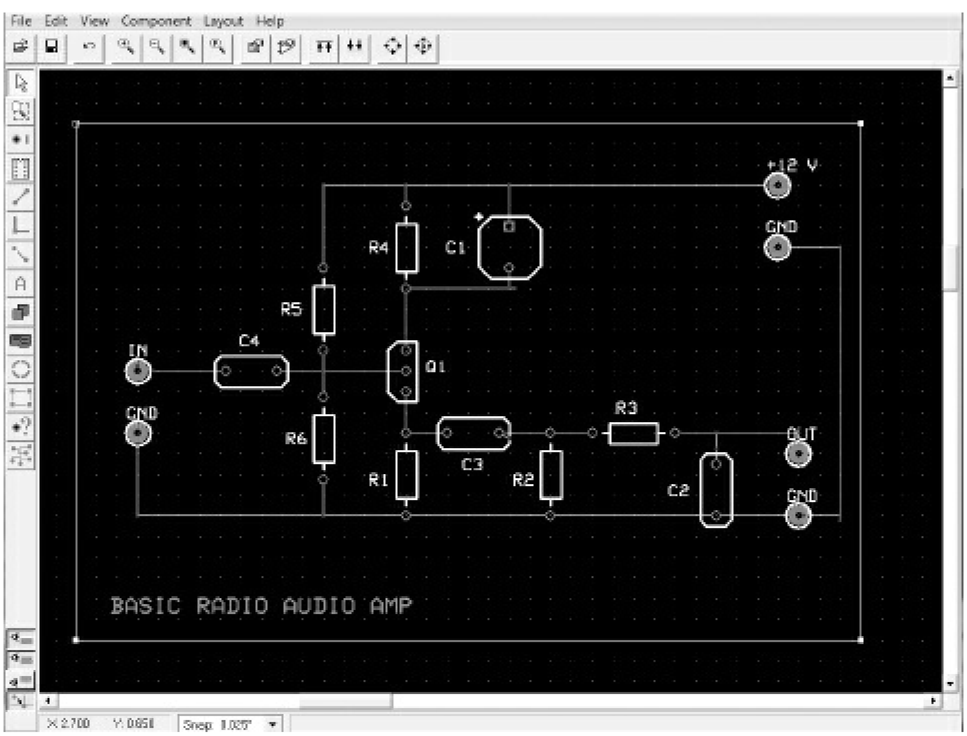


Figure 8.19 — A PC board layout diagram generated using *ExpressPCB* software.

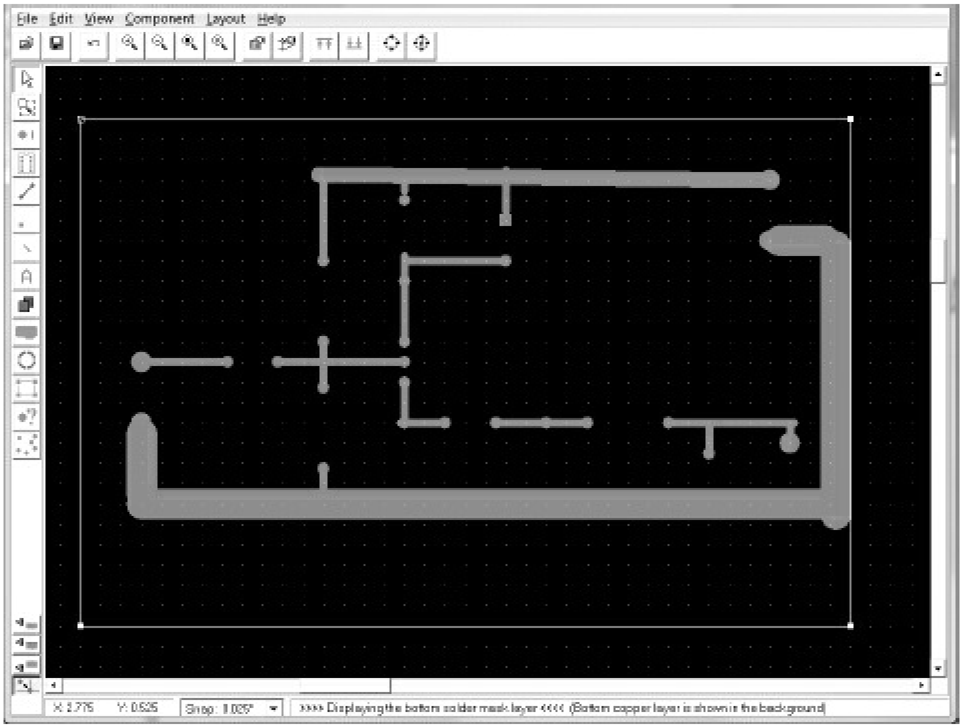


Figure 8.20 — A shot of the solder mask I generated to go with the layout in Figure 8.19.

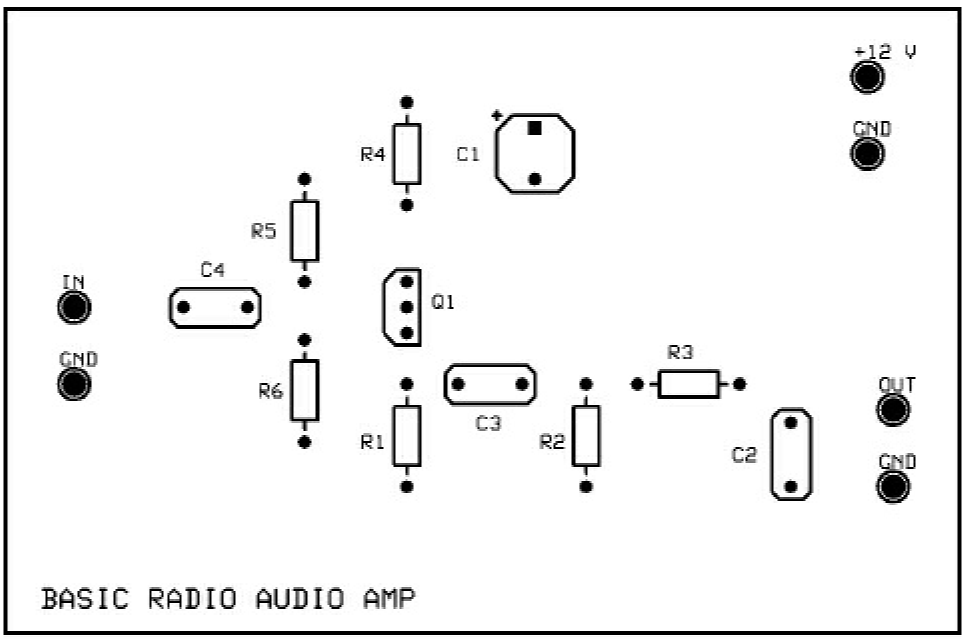


Figure 8.21 — The silkscreen output on the board's component side.

Their business is to then make the boards and ship them to you. This works out reasonably well for a group project, but is expensive if you only want one or two boards (about $90 for two small boards as we write this). You can print PDF drawings of the boards at no charge and then transfer them to some other mechanism, such as using a photo enlarger and photo-resist and then etch them yourself. FAR Circuits (**www.farcircuits.net**) will make boards from your *ExpressPCB* files for a base price of $0.50 per square inch or $5.00 minimum per board for single sided, etched, drilled, and solder coated finished board. A film shot is required for the solder side and the legend at $10.00 per shot.

As an aside, FAR Circuits offers PC boards for a large number of circuits that have been in *QST* and other magazine articles. They also offer many parts and other supplies needed for PC board work.

The PC as a Design Tool and Data Repository

We have discussed a number of radio and electronics specific computer tools that can be used to predict the way our designs and projects will work when they are complete. Of course, this was not intended to be a comprehensive list, but to give you an idea of what kinds of tools are available. While design and analysis programs can be tremendously useful, it is important to remember that some of the basic PC software designed for office or personal use can also be used in support of workshop projects.

It has long been considered good practice for lab engineers to maintain a laboratory notebook, in which they recorded their activity, along with diagrams indicating what they had constructed, tabulations of their results, and a summary of their findings. Such a notebook typically has serial numbered pages, signed and dated by the engineer, to avoid after-the-fact entries and purging of wild goose chases. They often formed the basis for patent filings and became historical records for company archives.

Table 8.1
Antenna Tuner Settings — 135 Foot Dipole (Antenna # 4)

					AMP SET	
FREQ	*C*	*IMPED*	*L*	*SWR*	*Load*	*Tune*
1.8	2.3	H3	22 - 9.2	15.5	0.0	8.0
1.85	0.2	H3	21 - 5.1	16.6		
3.55	9.3	H2	11 - 7.9	6.3	4.0	5.8
3.8	10.0	H1	14 - 9.0	9.3	8.8	4.7
3.965	6.3	H1	14 - 9.0	8.2	7,5	2.0
4.0	6.3	H1	14 - 9.0	8.2	1.0	4.5
5.3	2.2	H2	9 - 8.0	9.3		
7.0	5.5	L2	4 - 3.6	6.4	4.9	2.9
7.2	4.6	L2	3 - 1.0	5.3		
10.1-.15	4.7	H1	5 - 9.6	2.5		
14.0	3.2	H1	3 - 4.6	6.6	7.0	1.5
14.2	2.2	H1	4 - 8.7	8.7	7.0	1.4
18.068-.168	1.3	L1	2 - 7.4	2.5	7.0	2 (15M)
21.0	2.9	L1	3 - 5.7	4.2	6.2	1.5
21.2	2.7	L1	2 - 3.3	4.9		
21.3	2.7	L1	2 - 2.1	4.9	6.0	1.3
24.890-.990	1.7	L1	3 - 6.1	1.8	5.8	2 (10M)
28.0	1.0	L1	2 - 6.5	3.1	5.0	2.0
28.5	0.5	L1	2 - 9.4	6.5	4.5	2.0
29.0	0.7	H1	1 - 3.2	3.5		

As hams, we don't generally have a need for that level of formality — not to say that patents don't sometimes result from our work. For our uses, *MS Word, PowerPoint*, or *Excel* files can often serve the same purpose. If filed on the PC's hard drive in a way that can be easily retrieved, they can provide a historical baseline and record that can be invaluable.

Table 8.1 was created from an *MS Excel* worksheet that I use to record a number of important characteristics of one of my station antenna systems. It is in daily use to allow presetting of my antenna tuner to known settings for each band portion. In addition, the SWR field indicates the measured SWR of the antenna without the tuner, so I can check to see if there have been any changes to the antenna due to component failure or other causes. The right two columns are for tuning my station linear amplifier. Again — having the known settings available reduces the stress on components that would result if I were to tune from scratch each time.

Notes

[1]J. Hallas, W1ZR, "Product Review — WaveNode WN-2d Station Monitoring System," *QST*, Jul 2012, pp 47 – 50.

[2]T. McDermott and K. Ireland, "A Low-Cost 100 MHz Vector Network Analyzer with USB Interface," *QEX*, Jul/Aug 2004, pp 3 – 14.

[3]M. Tracy, KC1SX, "Product Review — Ten-Tec/TAPR 6000 Vector Network Analyzer." *QST*, Jul 2006, pp 68 – 71.

[4]P. Salas, AD5X, "Product Review — Array Solutions VNAuhf Vector Network Analyzer," *QST*, Jul 2013, pp 49 – 50.

[5]W. Silver, NØAX, *Antenna Modeling for Beginners*. Available from your ARRL dealer or the ARRL Bookstore (**www.arrl.org/shop**).

[6]Expanded Smith Charts, package of five. Available from your ARRL dealer or the ARRL Bookstore (**www.arrl.org/shop**).

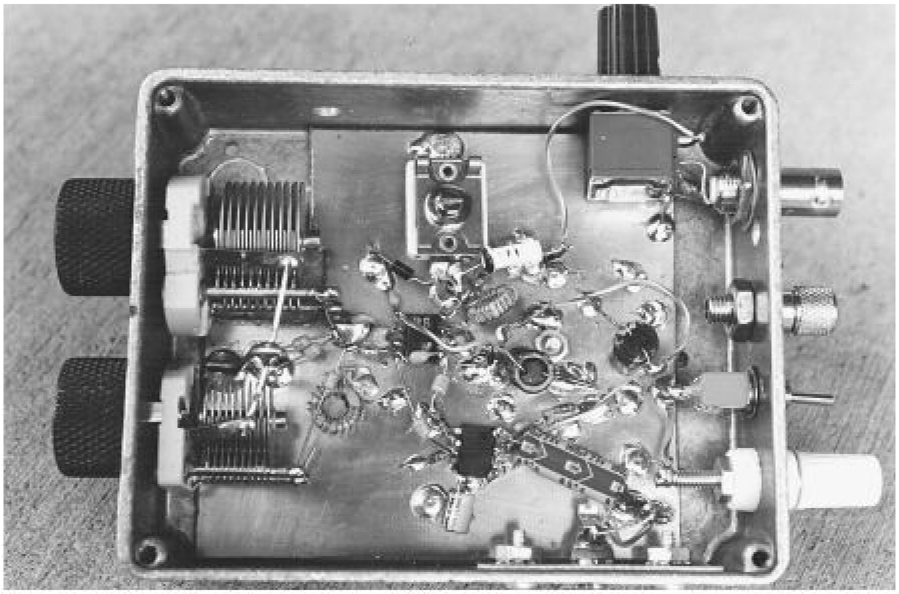
[7]An Internet search for Smith Chart software will bring up a number of sources.

[8]*The ARRL Antenna Book,* 23rd Edition. Available from your ARRL dealer or the ARRL Bookstore (**www.arrl.org/shop**).

[9]J. Hallas, W1ZR, *Basic Radio*. Available from your ARRL dealer or the ARRL Bookstore (**www.arrl.org/shop**).

Chapter 9

Wrapping It Up



Whether your project is of your own design, or adapted from a published project, you will want to put it to use. This direct-conversion receiver, from *Experimental Methods in RF Design*, makes use of the "ugly construction" method, but looks delightful from the other side of the box.[1]

Contents

Pulling Your Project Together

Having a design in place — whether an original or perhaps a composite of published material — is one thing. Pulling it together and making the transition from some sketches in your lab notebook to a working device is what separates those who dream from those who do!

The steps involved are fairly straightforward, and we will outline some approaches to each in this chapter. They can be summarized as follows:

- Make a prototype to confirm the functionality of the design.
- Test the prototype to make sure it operates as expected under all conditions. Modify the design as needed and reconfirm.
- Either make a "production" version or clean up the prototype for long term use.
- Package the system in a form that can be used as a piece of operating equipment.
- Document and photograph everything you did, including test results at every step, in case you want to do it again, or submit it for publication.

Making a Prototype and then Final Circuitry

We often think of circuit boards as the wiring method of choice, and they often are the best way to go, but point-to-point wiring is more appropriate for some projects. This is often the case for straightforward projects such as power supplies, or other subsystems that have relatively few components that require interconnection by heavy wiring. In such cases, running appropriately sized wire between component terminals, sometimes augmented by terminal strips, makes the most sense. The under chassis view of the high power HF linear amplifier shown in **Figure 9.1** illustrates the point.

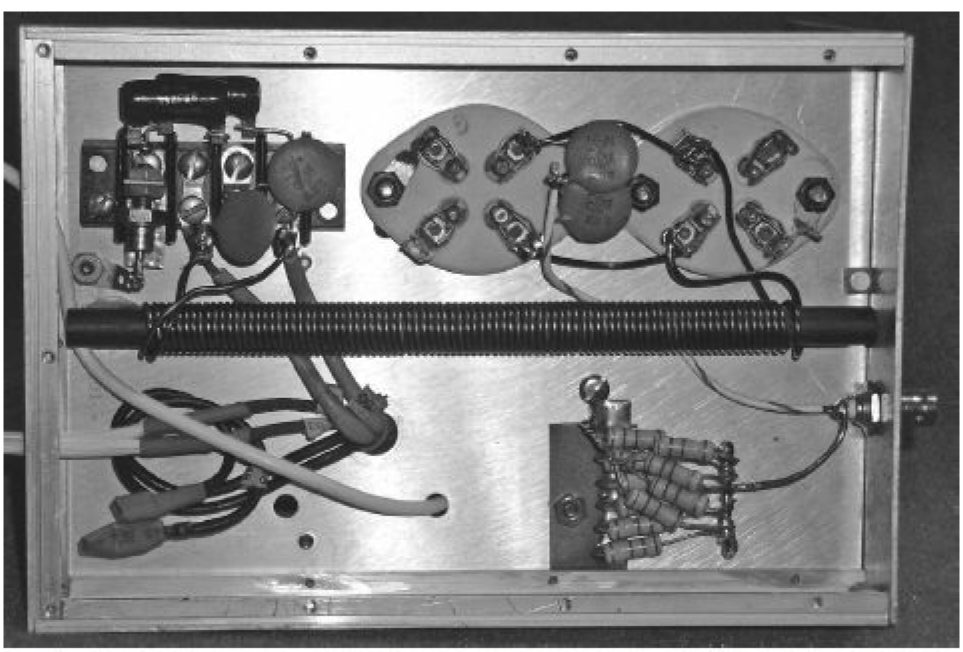


Figure 9.1 — This high-power HF linear amplifier uses point-to-point wiring, without the need for a printed circuit board.

For most circuits made with modern miniature and subminiature circuit components, some kind of board connection arrangement will be more suitable. In the previous chapter, we discussed a number of possibilities for the design and fabrication of etched PC boards, including obtaining premade boards for published projects. While it is possible to make your own etched circuit PC boards, I have avoided this due to the need to work with hazardous chemicals and their associated toxic vapors. Many hams have made PC boards using a variety of techniques described in *QST* and *The ARRL Handbook* over the years.

For prototype or even one-off completed projects, there are a number of simple methods that can be as effective, yet avoid the hazards. These techniques, and prototyping in general, are often referred to as *bread-boarding*, in recognition that early amateur projects were often built on kitchen bread boards. Some techniques are:

■ *Perforated project board*. These boards are cut to size from fiber board stock that is predrilled to accept component leads. Boards are available with regularly spaced holes, with a spacing that can be selected to match various socket types, as well as with special patterns designed for dual in-line integrated circuits or their sockets. These are best suited for digital circuit or low frequency analog use, since there is no solid ground structure that can help avoid coupling between high-frequency circuit components. **Figures 9.2** and **9.3** show an example of a simple audio amplifier circuit built on perforated board.

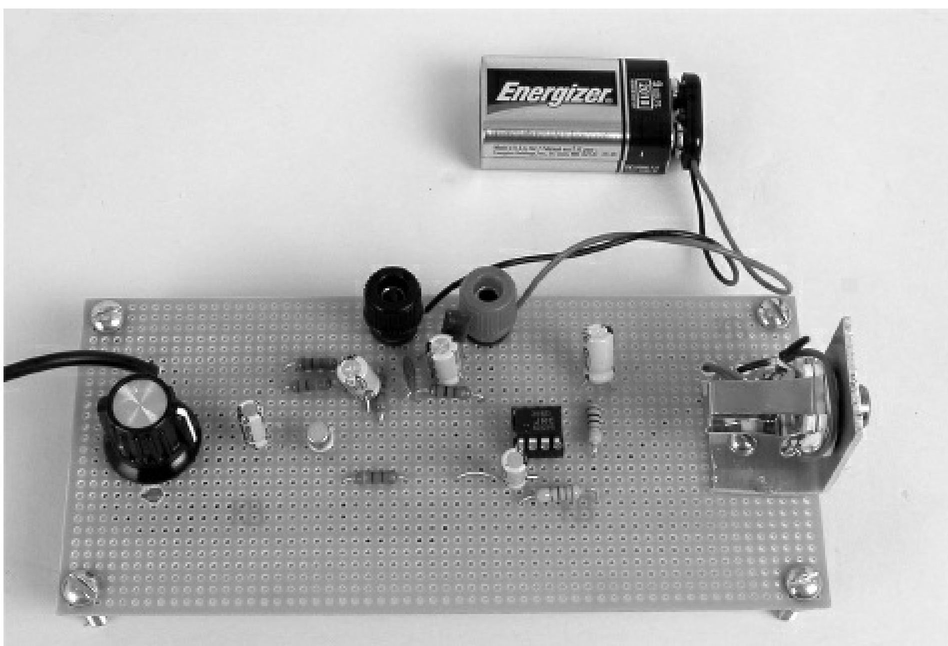


Figure 9.2 — Photo of the top side of an audio-frequency amplifier built on perforated board.

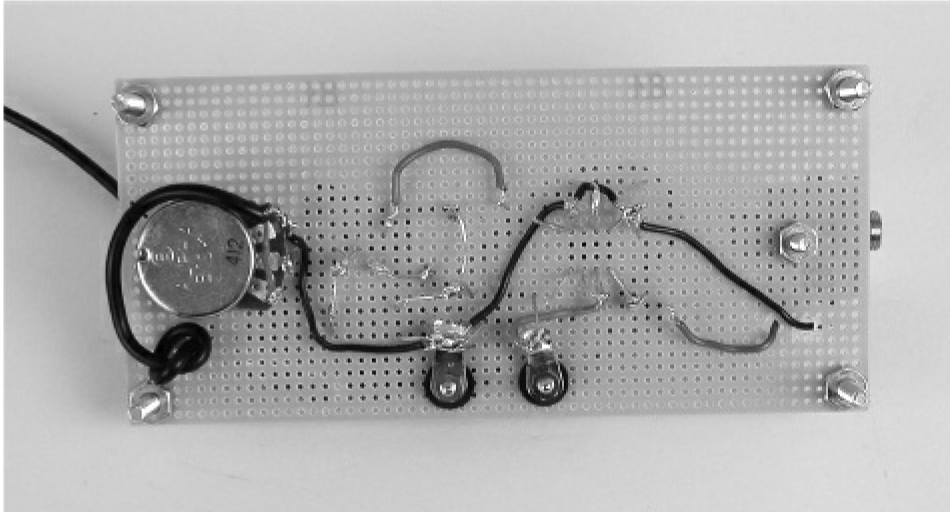


Figure 9.3 — Photo of the bottom side of the audio-frequency amplifier shown in Figure 9.2.

■ *Ground-plane construction*. More suitable for RF circuitry is a technique known as *ground-plane* construction. In this method, a piece of copper plated circuit board is used as a ground plane, with the ground side of all components soldered directly to the copper foil with short leads and the components generally standing up to serve as terminals for other connections as shown in **Figure 9.4**. This technique was popularly known as “dead-bug” style, due to the appearance of integrated circuits on their backs with their “legs” up, but is now commonly referred to as *ugly construction*, perhaps for obvious reasons.

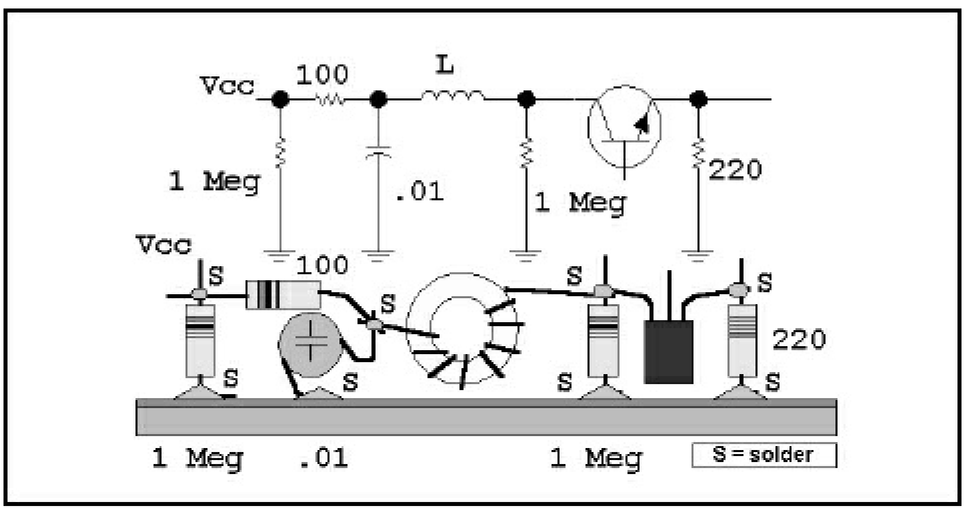


Figure 9.4 — Illustration of the ground plane breadboarding method, also known as *dead-bug* or *ugly construction*. In spite of the sound of the name, the short ground connections make this method suitable for RF circuitry. From *Experimental Methods in RF Design*.

■ *The Manhattan technique*. This method is a variation of the ground-plane method, described above, in which small pieces of PC board stock are glued to the ground plane to provide terminal connection points for components. Note that this could be used as part of the ground plane method to provide additional support for components that are between ground connected components. See **Figure 9.5** for details.

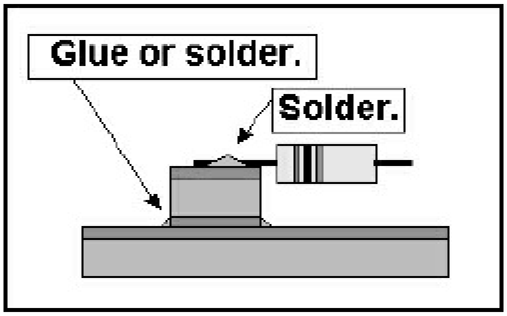


Figure 9.5 — Illustration of the Manhattan breadboarding method. From *Experimental Methods in RF Design*.

At this stage, before any final packaging begins, thoroughly evaluate the project in terms of performance to make sure that it meets all design objectives. Now is the time to make any changes that might change the final configuration. Document all test methods and results in your lab notebook, as well as on your PC.

Putting It in a Box

Before projects can be put to use they generally need to be installed in a chassis or metal project box. While these used to be readily available at your local radio-TV wholesale outlet, they seem to have disappeared not long after TV sets converted to solid state, eliminating much of the replacement vacuum-tube market. Smaller project boxes have been available at retail electronic outlets, but they seem to be headed for extinction as we write this. Fortunately, companies such as Bud Industries and Hammond Manufacturing still make both die-cast and folded aluminum chassis and mini boxes, just as they always have. They are now available from electronic industrial wholesale outlets and some can even be found on Amazon. There are some other alternatives to buying a ready-made chassis. A few *QST* articles have described the construction and use of a sheet metal brake that can be used to transform some hardware store aluminum sheet into a custom-sized chassis.[2,3] The technique is shown in **Figures 9.6** and **9.7**.

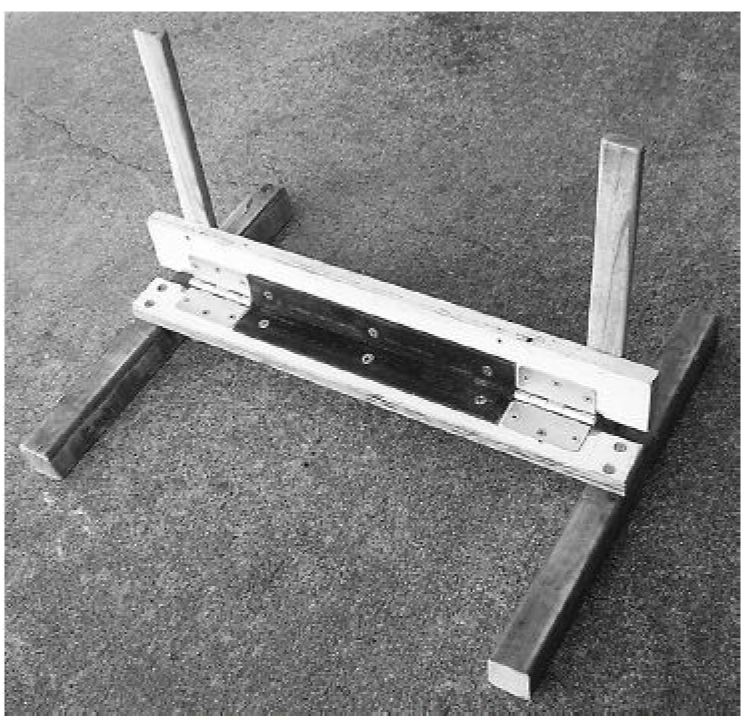


Figure 9.6 — A home-made metal bending brake made from wood, some door hinges and metal mending plates. This can be used to fabricate bent aluminum chassis boxes, but read reference 3 before you start.

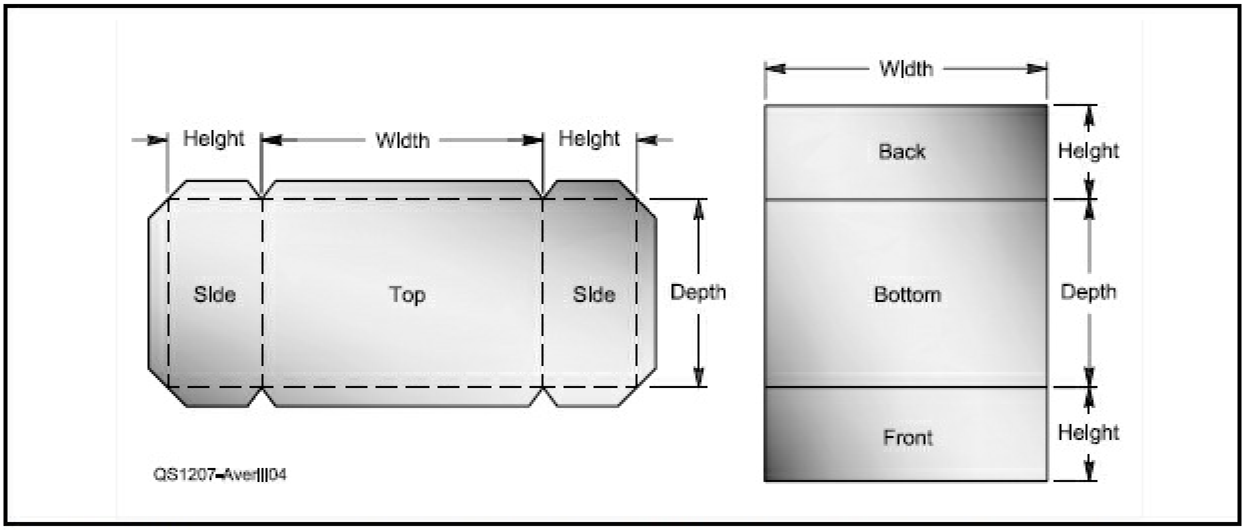


Figure 9.7 — Making a pattern and transferring it to the material is key. But try it first with a piece of scrap to calibrate the required material at the bends.

While a bent or die-cast chassis box makes for a very suitable enclosure, it is also possible to make a box out of flat sheet and angle aluminum, with the angle stock serving in place of the bends. While a sheet metal shear is a great way to make cuts in aluminum sheet (watch your fingers!), it also can be done with a fine-bladed saw, especially if the edge is clamped between two pieces of wood before cutting.

The usual approach is to attach the circuit board or boards inside the box using metal or insulated stand-off posts with threaded ends. One end is attached to the board corners, the other to matching holes in the chassis. Connections are then brought out from the board to appropriate power, signal, or control connectors on the sides of the chassis.

With packaging complete, repeat the testing done in the previous section — you'll be glad you documented all the previous testing that you thought you'd remember the details of! This set of test results should reflect the actual operational performance after the device becomes part of your station. There may be differences between this set of data and that recorded during board level tests, and it is important to understand the cause and decide whether or not design changes are required. The difference in capacitances to the cabinet may make changes in performance, as can the characteristics of interconnecting cables and connectors. Again, photograph and document everything. Now enjoy the satisfaction of having something you built with your own hands become a part of your station!

Notes

[1]W. Hayward, W7ZOI, R. Campbell, KK7B, and B. Larkin, W7PUA, *Experimental Methods in RF Design*. Available from your ARRL dealer or **www.arrl.org/shop.**

[2]L.B. Cebik, W4RNL, "A Homebrew, Light-Duty Metal Brake," *QST*, Oct 1996, pp 41 – 43.

[3]G. Averill, K4EOR, "A Homebrew, Light-Duty Metal Brake Revisited," *QST*, Aug 2012, pp 33 – 35; Feedback, Jan 2013 *QST*, p 57.