By James C. Garland, W8ZR

The EZ-Tuner

Part 1—Could this be one of the most versatile homebrew antenna tuners ever created? Let's take a closer look at this innovative design.

Although antenna tuners have always been important station accessories, their popularity has soared in recent years thanks to the development of automatic tuners. In fact, convenient, limited-range autotuners are now standard features of most HF transceivers and are a blessing for amateurs who live in antenna-restricted neighborhoods.

Unfortunately, amateurs who use linear amplifiers, who prefer antennas with open-wire feedlines, and who need to match a wide-range of VSWRs, have until now been stuck with decidedly not-so-convenient manual tuners. The EZ-Tuner is designed to meet their needs. It is just the ticket for contesters, DXers, vintage radio collectors with multiple stations, and lazybones like myself who want a hassle-free way to change bands and antennas.

The EZ-Tuner is an advanced, wide-range memory tuner that covers all the amateur bands from 1.8-30 MHz. The EZ-Tuner automatically tracks band-to-band frequency excursions, matches high or low antenna impedances up to at least a 16:1 VSWR, and handles the full power of a legal-limit amplifier. Furthermore, the EZ-Tuner is expandable, so that new features and software upgrades can be downloaded from the Internet and programmed into it through an ordinary serial port.

The EZ-Tuner is described in a three-part series. In this part, we take the mystery out of the versatile T-network (Figure 1A) and show how its most important properties can be distilled into two easy-to-use graphs. Armed with these graphs, we then walk through the design of the EZ-Tuner's matching network. Part 1 should be of interest to anyone who wants to learn about or build an antenna tuner.

Part 2 gets down to the nitty-gritty of the EZ-Tuner's design and circuitry. This part describes the RF matching network and also the microcontroller circuitry, which is based on the powerful new BASIC Stamp BS2sx. I'll also provide an overview of the software logic and tuner's operation and performance. Readers will be referred to a Web site where they can download complete circuit diagrams and software listings.

Part 3 discusses the EZ-Tuner's construction, with lots of practical details and homebrewer hints. Although the EZ-Tuner is an advanced project, intended for experienced builders (the EZ-Tuner is EZ to use, not EZ to build!), I'll show how it can be built as a stand-alone manual tuner. The manual version would be a good stopping point for those who lack the time or experience to tackle the full-blown automatic version, but who want a versatile, easy to adjust high power antenna tuner.

The Heritage of the Ultimate Transmatch

The quest for the ideal antenna tuner dates back to the early days of radio communication. The earliest tuners were often single-band breadboard contraptions with link-coupled inductors intended for end-fed wire antennas or open-wire transmission lines. The mid-'50s saw the development of general purpose, multiband desktop tuners, the best known being the

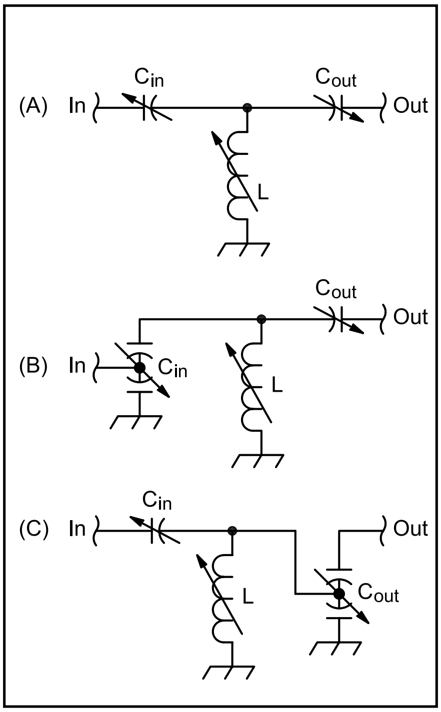


Figure 1—(A) basic T-network; (B) Ultimate Transmatch; (C) SPC tuner.

famous E.F. Johnson Matchbox, today greatly prized by collectors and still considered a top performer.

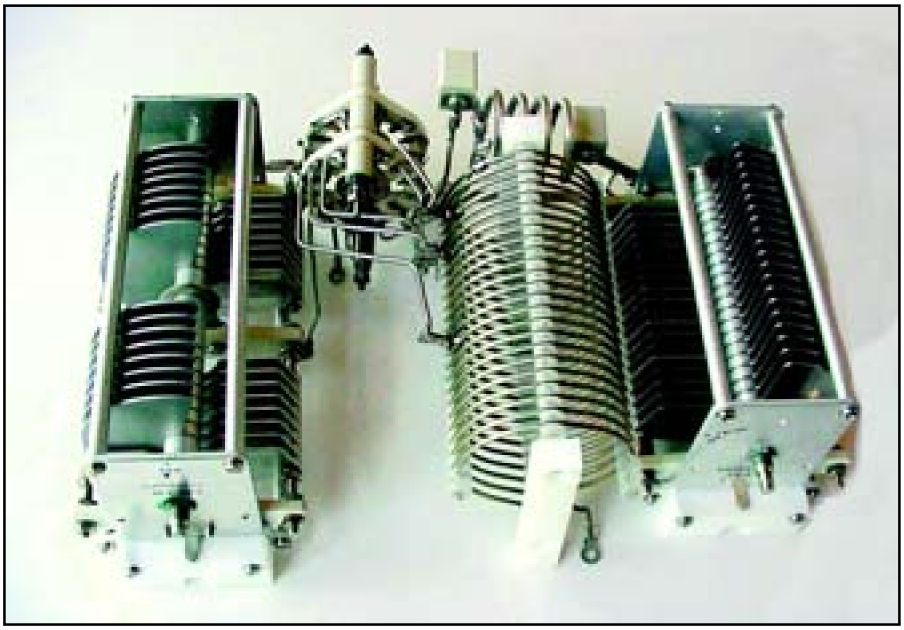
The ARRL technical staff has a long history of advancing the state of the art of antenna tuners. A case in point is the "Ultimate Transmatch," designed by the late Lew McCoy, W1ICP, and introduced to *QST* readers in July 1970. So-called because it could match the proverbial wet noodle, the Ultimate Transmatch was subsequently featured in *ARRL Handbooks* of the 1970s and over the years became a favorite of builders.

The Ultimate Transmatch was a variation of the simple T-network (Figures 1A and 1B), with the transmitter RF fed to the mid-point of a split-stator capacitor. Subsequent experimentation showed that the split-stator capacitor was unneeded, and in later designs it was replaced by an ordinary single-stator capacitor.

In the 1980s, *ARRL Handbooks* rolled out another variation of the T-match antenna tuner. Known as the "SPC" tuner (for series-parallel capacitance), this variation used a dual-section variable capacitor, one section of which was in series with the output, and the other in parallel with the inductor (Figure 1C). Initially, it seemed that the SPC tuner had great promise, notably good harmonic suppression and wide matching range, with modest-sized components. However, the SPC design was found to be excessively lossy, especially for low-impedance loads, and despite its advantages it was abandoned after a few years.

The 1990s saw significant advances in antenna tuner design. There were excellent theoretical treatments by Bill Sabin, WØIYH, and the development of sophisticated computer simulation programs by Dean Straw, N6BV, and others.[1] These programs made it possible for builders to estimate the matching range, internal losses, and peak RF voltages in their tuners before lifting a soldering iron. Furthermore, new diagnostic techniques also became available during the '90s, thanks primarily to Frank Witt, AI1H, and these techniques have allowed builders to evaluate the matching range and efficiency of their completed tuners.[2]

In spite of all this progress, the quest for the ideal antenna tuner continues. A *QST* review of several commercial, legal-limit antenna tuners[3] showed just how difficult it is to design an easy-to-use, low-loss tuner with a wide matching range. More than any other piece of amateur equipment, antenna tuners inevitably reflect frustrating trade-offs and compromises.



The major components of the EZ-Tuner's T-network. Construction details will appear in Parts 2 and 3 of this series of articles.

The T-Network and the Quest for the Ideal Antenna Tuner

Today, because of its impressive ability to match nearly any load, the basic T-network of Figure 1A remains the most popular choice for general-purpose high-power antenna tuners.[4] However, as many of us have learned to our dismay, the T-network tuner can be finicky, and if improperly adjusted has an unfortunate tendency to self-destruct. All too often, melted components, scorched capacitor plates and vaporized switch contacts are the price one pays for the T-network's wide tuning range.

The T-network's greatest strength is also its greatest weakness. Simply put, the T-network is hard to tune because it is so versatile. Consider, for instance, the typical T-network antenna tuner, consisting of two variable capacitors, a roller inductor, and a VSWR or reflected power meter. (Often, a 4:1 toroidal transformer is also added to the input or output for matching balanced transmission lines.)

What makes this tuner difficult to adjust is that, for almost any load, there is a wide range of settings that yields a 1:1 VSWR. Unfortunately, many of these settings can result in excessive internal heating or damaging peak voltages. Because the VSWR or reflected power meter doesn't differentiate between "good" and "bad" settings, the first sign of impending disaster is often a flashover, a burning smell or smoke. We know that somewhere, hidden in all those turns of the roller inductor, is just the right inductance needed for the perfect match. The rub is finding that one particular spot on the coil.

Roller tuners have other disadvantages. Cranking a turns counter dial is tedious, quality roller inductors don't come cheap, and the rolling contact is a source of heating and intermittent contact. Given their druthers, most amateurs would prefer the convenience of a tuner with a bandswitched fixed inductor…*if* they could be assured that they wouldn't pay too high a price in loss of efficiency and matching range.

The EZ-Tuner probably comes as close to satisfying this desire as is currently possible. The secret to its design lies the particular choices of inductances, selected out of the T-network's infinity of possibilities. So how do we make those choices?

Simplifying the T-Network

It is not generally known that the T-network's matching combinations fall into simple patterns. Figure 2 illustrates these patterns for the 160-meter amateur band for resistive loads varying between 3.125 Ω and 800 Ω.[5] These loads correspond to VSWRs ranging up to 16:1, and the curves assume losses typical for transmitting capacitors and inductors.

The axes of Figure 2 correspond to the values of C_{in} and C_{out} in the circuit of Figure 1A. Constant VSWR values (resistive load impedances) are shown as straight lines (except for some curvature at the highest impedances) which extrapolate to the origin. The 50 Ω line corresponds to a 1:1 VSWR and has a slope of one (45 degrees). Also shown in the figure are curves of constant inductance spanning the range from 8-26 μH. These curves,

[1]Notes appear on page 43.

in combination with the VSWR lines, show at a glance nearly the entire 1.8 MHz matching capability of the T-network for resistive loads.[6]

To illustrate how to use the figure, suppose we have a 14 μH inductor and we want to know what capacitances will be required to match a low-impedance 6.25 Ω load (8:1 VSWR) at 1.8 MHz. By noting where the 14 μH curve intersects the 6.25 Ω line, we see that values of C_{in} =160 pF and C_{out} =400 pF are required to give a match. If we specify any one of the values of the three network components, the figure tells us the remaining two values.

But what if want to know the matching values on a different band? It turns out that Figure 2 can give the matching range at any frequency by simply multiplying the frequency and dividing the capacitances and inductances by the same factor. For instance, we can translate our 1.8 MHz example to 28.8 MHz by dividing the results by 16, since 28.8 MHz/1.8 MHz = 16. Thus we find that L = 14 μH / 16 = 0.88 μH, C_{in} = 160 pF/16 = 10 pF, and C_{out} = 400 pF/16 = 25 pF. These values will match a 6.25 Ω load at 28.8 MHz.

Example: a 160-Meter Antenna Tuner

Now let us introduce some other design considerations with a practical example. Suppose we wish to build a 160-meter legal-limit antenna tuner that uses a fixed inductor and a bandswitch. We want to use as few taps as possible on the inductor and keep losses in the network components below about 25% (corresponding to a 1-dB loss). We have two variable capacitors, each tuning 36-496 pF and rated at 3.5 kV.[7] Our goal is to find the optimum inductances for our tuner.

To begin, we draw horizontal lines corresponding roughly to the minimum and maximum values of C_{in} on the vertical axis of Figure 2, and the corresponding (vertical) lines for C_{out} on the horizontal axis. These four lines intersect to form a rectangle, the interior of which defines the possible matching range of our hypothetical tuner. Since all of the inductance curves between 12 μH and 26 μH intersect all of the VSWR curves within this rectangle, we know that any inductance between 12 μH and 26 μH will provide a match to a 50-Ω transmitter.

Before we choose one of these inductances, however, we need to remember that Figure 2 says nothing about network losses. For this information, we turn to Figure 3, which plots the power loss in a T-network as a function of inductance. The power loss is shown as the percentage of transmitter power dissipated as heat in the network components. Each curve in Figure 3 corresponds to a different load, and the curves span the full range of low and high resistances, up to a 16:1 VSWR mismatch. For example, the figure tells us that a T-network matching a 6.25 Ω load with an L=14 μH inductance at 1.80 MHz will absorb about 23% of the transmitter power.

Note that the power loss percentages of Figure 3 depend on the properties of our actual inductor and capacitors. The percentages shown in the figure assume typical values for transmitting-type components: Q=200 for L, and Q= 1000 for C_{in} and C_{out}. (These are the default choices used in the simulation software *TLA*, which was used to generate the data on which these curves are based.) Most of this power loss occurs in the inductor, so if our analysis shows excessive loss, we can always compensate by using heavier wire or copper tubing.

Note also that the 1.80-MHz curves of Figure 3 can be scaled with frequency, just as we did for the curves of Figure 2. For instance, by multiplying the frequency and dividing the inductance by 16, we see that that at 28.8 MHz, a network with a 0.88 μH inductance will also dissipate 23% when matching 6.25 Ω.

As we inspect Figure 3, we see that for loads greater than 12.5 Ω any inductance in the range of 12-26 μH will result in power loss below 25%. However, low impedance loads below 12.5 Ω can create significant problems. In fact, we need an inductance of no more than 10 μH to hold the power loss below our 25% goal. Unfortunately, we have already learned from Figure 2 that an inductance of 12-26 μH is needed to provide a match. A 10 μH inductance will not let us match these small resistances, because our variable capacitors don't have enough maximum capacitance.

Fortunately, we can solve this quandary by using *two* values of inductance to cover the range, and by padding the output capacitor with a small fixed capacitor. Referring again to Figure 2, we see that if we pad the output capacitor with 100 pF, so that it tunes 136-592 pF, we can use a 10 μH inductance to match loads of 50 Ω and below. We can use a second inductance of, say, 20 μH to match loads greater than 50 Ω, and in both cases we will have held the power loss below our specified limit. We can cover the 160-meter band with only two positions on our inductor switch. Success!

Now we still haven't dealt with the

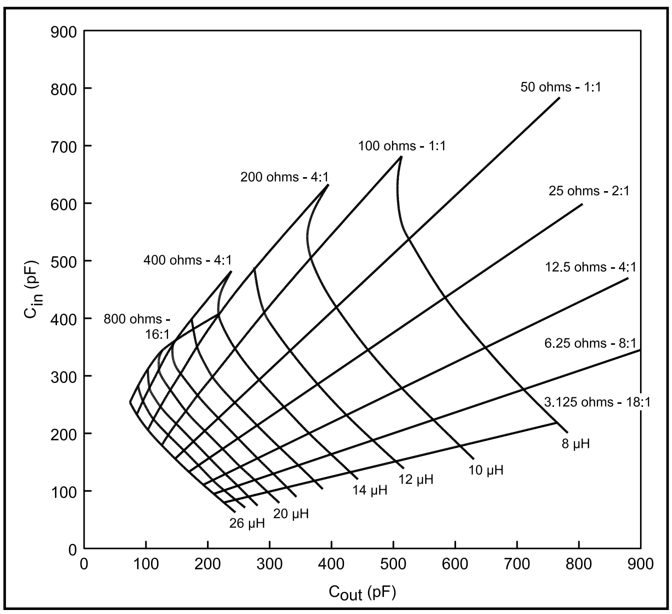


Figure 2—T-network constant VSWR curves at 1.8 MHz.

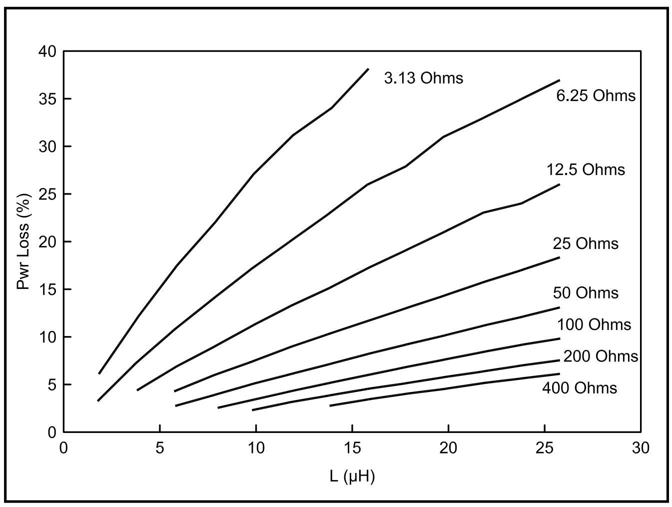


Figure 3—Power loss in the T-network at 1.8 MHz.

A front-panel LCD "turns counter" shows the capacitor and inductor settings, as well as the operating frequency.

problem of high peak voltages. Although it would not be difficult to draw a third figure that shows peak RF voltages in the T-network, we needn't bother. Instead, we will use the rule of thumb that peak voltages will be below 3.5 kV at the legal limit of 1500 W, so long as we design for network losses below about 25%.

EZ-Tuner Inductances

The 160-meter example illustrates the point that good T-network design involves the interplay between matching range and power loss. By extending these procedures to other bands, it is not hard to design a switched T-network antenna tuner that covers all nine amateur bands from 1.8-30 MHz. Because the majority of amateur bands are harmonically related, most inductance choices are used on several bands, thus minimizing the required number of switch contacts.

The design objective for the EZ-Tuner was to use no more than eleven inductance values to match up to a 16:1 VSWR on all nine HF bands, with no more than a 1-dB power loss and 1500 W power handling capability, while holding power loss to about 1 dB. (There are 11 positions on a 30 degree-indexed rotary switch.) Table 1 shows the selected values. The EZ-Tuner generally meets or exceeds these design goals. In fact, on most bands, it can match a 32:1 VSWR, and it also satisfactorily tunes the new 60-meter amateur band recently proposed by the ARRL. The capacitance ranges assumed in the computations are 19-402 pF for C_{in}, and 36-496 pF for C_{out}.

Parts 2 and 3 cover the construction of the EZ-Tuner and provide circuit description and additional information about matching performance. I will also give practical hints for accurately positioning the coil taps without special equipment. Stay tuned!

Notes

[1]The program *TL* ("Transmission Line"), or its successors *TLA* ("Transmission Line—Advanced") and *TLW* (Transmission Line—*Windows*) are provided with recent editions of *The ARRL Antenna Book*.

[2]See "How to Evaluate your Antenna Tuner" (in two parts) by Frank Witt, AI1H, *QST*, April and May 1995.

[3]See *QST* Product Review, March 1997: "*QST* Compares: Four High-Power Antenna Tuners."

[4]For tuners dedicated to specific antennas, many amateurs swear by the simple L-network. However, the L-network cannot match both high and low-impedance loads without changing its configuration, and this shortcoming generally makes it unsuitable for a general-purpose antenna tuner.

[5]The program *TLA*, by Dean Straw, N6BV, was used to generate the data for Figures 2 and 3.

[6]Note that Figure 3 does not cover the extreme matching limits of the T-network. Instead it shows the practical range of importance to antenna tuner designers. Note also that the capacitance and inductance curves could be relabeled as reactances, rather than picofarads and microhenrys. Doing so would make the curves frequency-independent, but at a sacrifice in intuitiveness and usability.

[7]These are the ratings of the Cardwell-Johnson 153-6-1 capacitor.

Table 1

EZ-Tuner Inductance Table

Tap No.	*Inductance (µH)*	*Amateur Bands (meters)*
1	0.3	10,12,15,17
2	0.4	10,12,15,17,20
3	0.7	15,17,20,30
4	1.0	17,20,30,40
5	1.3	20,30,40
6	1.7	30,40
7	2.4	30,40
8	3.1	40,80
9	4.6	80
10	10.0	80,160
11	20.5	160

James C. Garland, W8ZR, has been a licensed amateur for 47 years, having been first licensed in 1955 as WNØZKE at age 12. In 1969, he operated in England as G5APG, and then moved to Ohio in 1970. Over the years, Jim has been interested in HF DXing and contesting, but his primary interest has been in homebrewing. He's built numerous rigs, amplifiers and other projects over the years. He also collects vintage rigs.

Professionally, he is president of Miami University in Oxford, Ohio, a position he has held for six years. (Miami University, as you might imagine, is the most ham-friendly university around!)

He has a PhD in solid state physics from Cornell University. His research area is experimental condensed matter physics, and he has published more than 100 technical articles in physics journals.

You can contact the author at 310 E High St, Oxford, OH 45056; **w8zr@arrl.net**.

NEW PRODUCTS

MFJ'S POCKET-SIZE CODE READER NEEDS NO CABLES

◊ If your Morse code is a bit on the rusty side, MFJ's new Model 461 mini code reader may be just the boost you need to smooth out the rough spots—and all without cumbersome power and audio cables. Simply place the compact reader near your receiver's speaker, wait until the "lock" LED flashes in sync with the received code

and watch the decoded copy scroll across the LCD. The device locks on and tracks code elements up to 99 words per minute.

The full-featured reader has four display modes, a two-line LCD that displays 32 characters (each ¼-inch high), a 140-character "instant replay" buffer and a received code speed display.

Prices: $79.95 (MFJ-461 Morse reader); $6.95 (MFJ-26B protective pouch); $14.95 (MFJ-5161 DB-9 serial cable); $5.95 (MFJ-5162 optional audio input cable). For more information, contact your favorite Amateur Radio products dealer or MFJ, 300 Industrial Park Rd, Starkville, MS 39759; tel 800-647-1800, fax 662-323-6551; **mfj@mfjenterprises.com**; **www.mfjenterprises.com**.

STRAYS

DON BOSTROM, N6IC

Becky Windsor displays a jacket with a plethora of patches from years of International DX Conventions. This year's event will be April 26-28 at the Holiday Inn Visalia, California. For more information, see www.qsl.net/visalia2002/index.html or contact Don Bostrom, N6IC, 4447 Atoll Ave, Sherman Oaks, CA 91423, n6ic@arrl.net.

RADIO-TELEGRAPHY BOOK

◊ *The Art and Skill of Radio-Telegraphy*, Third Revised Edition, by William G. Pierpont, NØHFF, has been published and printed by the Radio Amateur Educational Society (**www.raes.ab.ca/book.html**); edited by Dave Clarke, VE6LX.

The book focuses on how to go about learning Morse code and improving one's CW capability, as well as enjoying it in communicating. It covers the problems that many have run into, including the speed plateau, and tells how to overcome those problems. This book contains 34 chapters and an Appendix with information about many of the world's highest speed operators.