EZ-Tuner - Part II

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The EZ-Tuner is a wide range automatic "memory" antenna tuner based on the versatile T-network. Using the powerful BASIC Stamp BS2sx microcontroller, the EZ-Tuner matches a wide range of balanced or unbalanced loads on all h.f. amateur bands at the legal amateur power limit. The first article in this series analyzed the design of the EZ-Tuner's switched-inductor T-Network. Now we're ready to tackle the EZ-Tuner's circuitry, including the r.f. matching section and microcontroller electronics, the program logic, and the tuner operation. Interested readers can download a complete set of schematic diagrams and fully annotated program listing from the internet.[1]

I. Design Overview:

The EZ-Tuner consists of two major sections. The first is the T-network matching circuit, which is housed in a shielded internal compartment and whose major components are two high-voltage variable capacitors, a large switched inductor, a toroidal transformer for matching balanced feedlines, and miscellaneous relays and fixed capacitors. The variable capacitors and inductor switch are turned, respectively, by two stepper motors and a rotary solenoid. A Bird Electronics r.f. wattmeter line section is mounted on the outside rear panel and measures forward and reflected r.f power. The r.f. matching circuit may be constructed as a stand-alone manual tuner.

Figure 1—Stepper motor and a rotary solenoid shafts extend into the sealed r.f. subenclosure to operate the T-network capacitors and inductor switch. The 4:1 balun is visible behind the inductor switch.

The second major section is the controller electronics, which decode the front panel pushbuttons and rotary encoders (used for manual tuning), store in memory the capacitor and inductor settings and operating frequencies, display current settings on a front-panel liquid crystal display, and move the variable capacitors and inductor switch to their appropriate positions. Most controller components mount on three small printed circuit boards, one of which contains the BS2sx microcontroller, frequency counter interface circuit, and solenoid and relay drivers. The other two boards contain identical circuits for driving the two stepper motors.

II. R.f. Matching Circuit:

As shown in Figure 2, r.f. power first passes through a Bird dual line section wattmeter and then to bypass relay K2. Two r.f. sampling elements plug into the line section, a 2500W (full scale) element for forward power and a 100W element for reverse power. Forward or reverse power is selected by meter switch S2 and displayed on front panel meter M1. Plug-in elements having lower power ratings can be used for “barefoot” operation, e.g., with 100W transceivers.

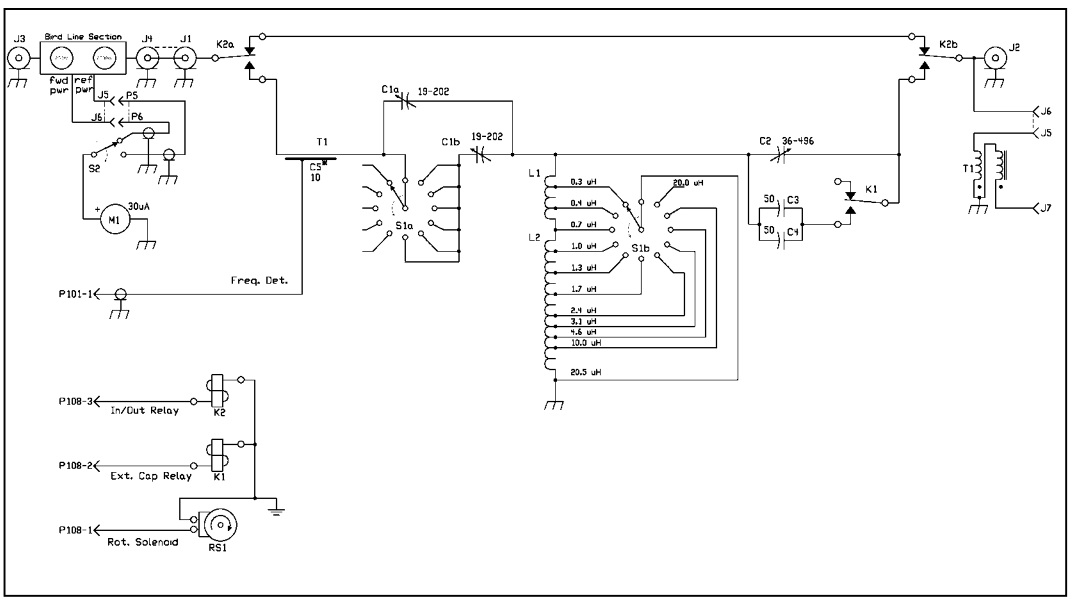

Figure 2—Schematic diagram of the EZ-Tuner matching network.

C1—Variable capacitor, dual-section 19-202 pF/section @ 3500V (Cardwell-Johnson 153-503-1).
C2—Variable capacitor 36-496 pF @ 3500V (Cardwell-Johnson 153-6-1).
C3, C4—50 pF @ 5000V ceramic transmitting capacitor (Centralab 858 or equiv.).
C5—10 pF @ 3500V custom capacitor (2.5 in. RG-58/U braid over teflon insulated # 10 wire).
K1—SPDT HV vacuum relay, 26.5V coil (Jennings RF3A or equiv.).
K2—DPDT HV vacuum relay, 26.5V coil (Kilovac H16/S1 or equiv.).
M1—Panel meter, 30 µA full scale (Coaxial Dynamics 88953-A & bezel).
L1—1.1 µH (4 turns on 1.5 in. dia, 3/16" copper tubing).
L2—20 µH (25 turns #10 tinned copper, 3 in. dia, 4 tpi - B&W 2404TL).
RS1—Rotary solenoid, 12 steps/rev. , 24 VDC/3.11A, (Ledex series 50-L).
S1—2-pole 11 position HV ceramic rotary switch (Radio Switch #86 or equiv.).
S2—1-pole 2 position rotary switch.
T1—Balun, 12 turns, #12 teflon-insulated wire, bifilar wound on 3 Amidon T-200-2 (red) toroid cores. Cores are insulated with fiberglass tape.
Wattmeter: Bird Electronics dual line section w. 100H & 2500H elements

The T-network's input capacitor C1 is a dual-section variable capacitor rated at 19-202 pF per section, and 3500 Volts. In order to preserve a low minimum capacitance on the highest frequency bands, the second section of the capacitor is used only on the six highest inductance settings and is switched into the circuit by wafer S1a on the inductance switch.

The T-network inductance is provided by L1 and L2, with S1b selecting 11 possible inductance values up to a total of 21 uH. A homemade capacitor C5 samples the r.f. voltage at the input of the matching network for the controller's internal frequency counter. The output capacitor C2 is a single section variable capacitor rated at 36-496 pF at 3500 Volts. Relay K1 adds twin 50 pF/5000V transmitting capacitors in parallel with C2 to extend the network's low-impedance matching range on 160 meters. A built-in 4:1 toroidal balun transformer can be strapped to the unbalanced output of the tuner for matching balanced feedlines.

III. Controller Highlights:

The brain of the EZ-Tuner is a Parallax BASIC Stamp BS2sx microcontroller. Having 50 MHz clock speed and 16 I/O ports, the BS2sx incorporates a real-time "P-BASIC" interpreter in its internal firmware. P-BASIC is an easily-learned programming language specifically intended for control applications.

Figure 3 shows the overall organization of the EZ-Tuner's control electronics, the heart of which is a small 3"x5" printed circuit controller board containing the BS2sx and some peripheral components. The main purpose of the controller board is to operate two unipolar stepper motors (which turn the variable capacitors), a rotary solenoid (which turns the inductor switch) and two relays.[2] In addition, the controller board receives input

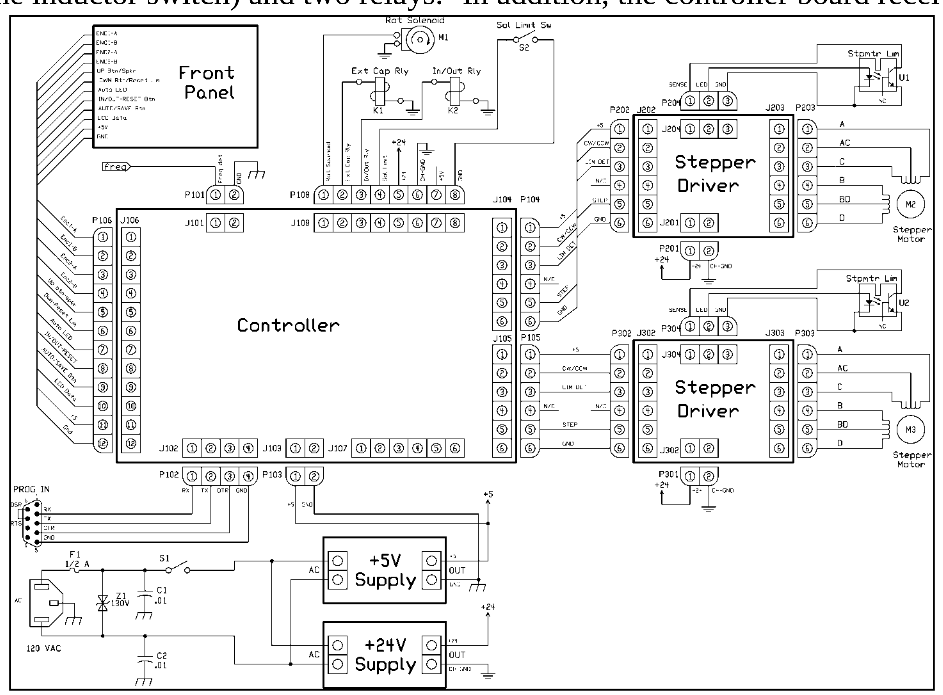

Figure 3—Block diagram of the EZ-Tuner's micorcontroller circuitry. The controller block is described in the text, and complete schematic diagrams of the other blocks can be downloaded from http://muohio.edu/~4cx250b/web/eztuner.htm

signals from several front panel controls and pushbuttons, and it also sends serial data about current capacitor and inductor settings to a front panel LCD display. The BS2sx is programmed via an ordinary DB-9 serial connector on the back panel of the EZ-Tuner.

The two stepper motors have their own optically isolated driver circuits which are contained on identical circuit boards. These driver circuits receive signals from the controller specifying the number of steps and the rotation direction (CW or CCW) and convert these to the phased voltages required by the stepper motors. Each stepper motor also has an optical limit-detect circuit. A metal disk with a narrow slot on each motor shaft blocks an LED light beam from a phototransistor, except when the capacitor plates are fully meshed. The driver circuits also contain timers, which power down the stepper motors about 200 mS after their destinations have been reached. The stepper motors, rotary solenoid and relays are powered by an unregulated +24V- 2A power supply, and the other controller circuitry by a regulated +5V-1A power supply.

Figure 5 shows the EZ-Tuner's controller board circuitry. Connector J102 receives serial programming data, while the front panel controls are connected to J106, most pins of which are in turn connected to I/O ports P0-P8 on the BS2sx. All I/O ports are specified by the software either as input or output ports. For example, ports P0-P3 are input ports, since they receive signals from the two rotary encoders, whereas port P6 is an output port, since its function is to light an LED when the tuner is in the automatic mode. Some ports serve double duty, such as P4, which in its input state detects when the UP pushbutton is pressed, but which in its output state sends a "beep" to a small speaker.

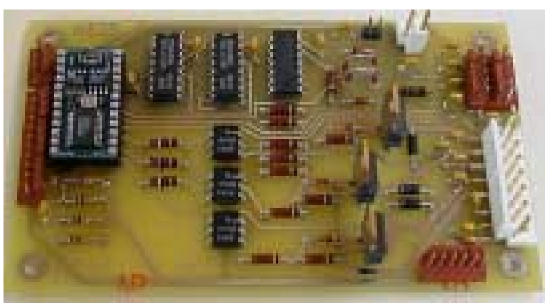

Figure 4—The BASIC Stamp BS2sx is in the left rear of the 3x5 inch printed circuit controller board.

Ports P9-P11 are connected to opto-isolators U105-U107, which control switching transistors Q101-Q103. The purpose of Q103 is to pulse the rotary solenoid with +24V; each 50 mS pulse rotates the solenoid shaft 30 degrees. Transistors Q101 and Q102, upon command from the BS2sx, activate the external capacitor relay and the in/out (bypass) relay. The purpose of U105-U107 is to keep +24V switching transients out of the low level microcontroller circuitry. The +5V circuits and the +24V circuits have separate, isolated ground returns.

The stepper motor driver boards are connected to J104 and J105. The BS2sx outputs a TTL low or high level to specify rotation sense, and a rising-edge step to advance the motors. J107 is intended for a third stepper motor. It is unused in the EZ-tuner, but is included as a convenience for those who want to use a stepper motor instead of a rotary solenoid to turn the inductor switch.

Connector J101 receives a sample of the r.f. voltage appearing at the input of the EZ-Tuner. The r.f. voltage is buffered by U106a and divided by 100 by decade dividers, U102 and U103. The divided square wave output from U102 is read by input port P15 and counted by the BS2sx to determine the transmitter's operating frequency.

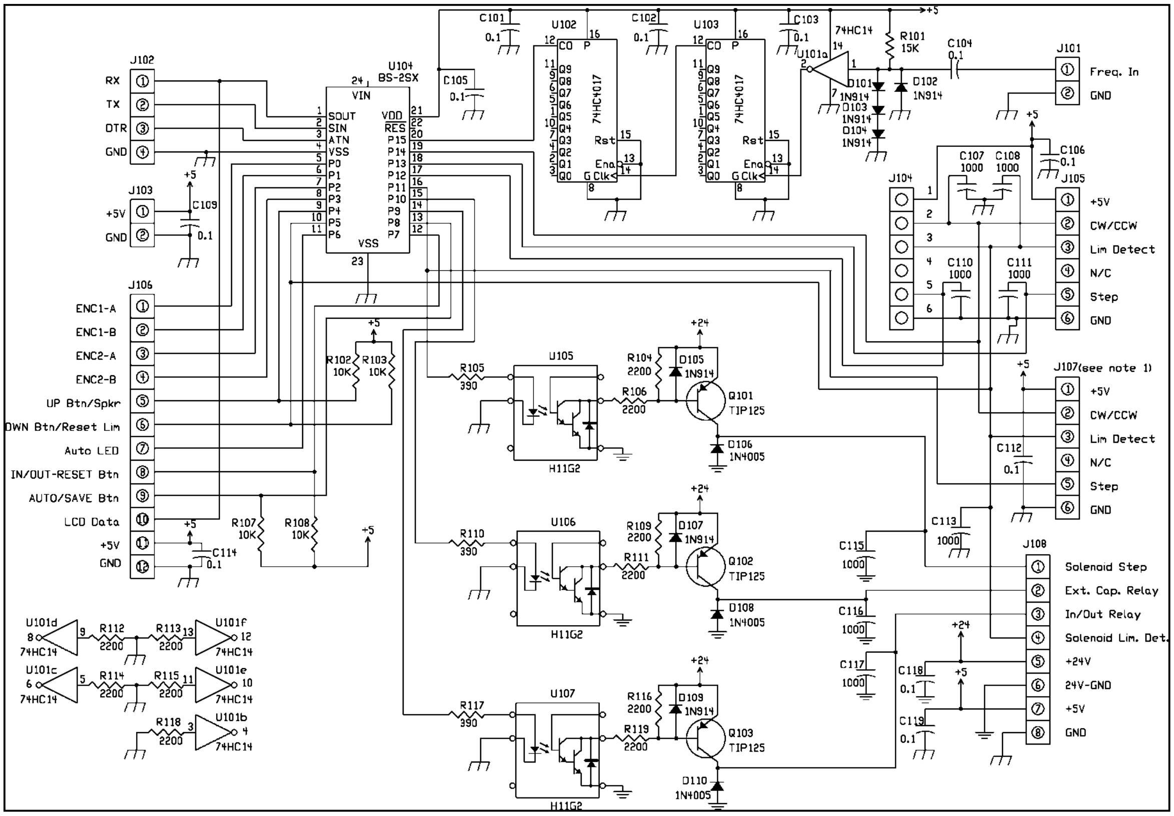

Figure 5—Schematic diagram of the controller circuit board. Parts are available from Mouser (www.mouser.com), or Digikey (www.digikey.com), or Jameco (www.Jameco.com). Equivalent parts can be substituted.

C101 - C106, C109, C112, C114, C118, C119—0.1 µF ceramic capacitor, 100V.
C107, C108, C110, C111, C113, C115, C116, C117—1000 pF ceramic capacitor, 100V.
D101 - D105, D107, D109—1N914 diode.
D106, D108, D110—1N4005 diode, 1A @ 600PIV.
J101, J102, J104 - J107—SIP header, Molex .100", no. of pins as indicated.
J103, J108—SIP header, Molex .156", no. of pins as indicated.
Q101 - Q103—TIP125 PNP power transistor.
U101—74HC14 CMOS hex inverter.
U102, U103—74HC4017 CMOS high speed decade divider/counter.
U104—BASIC Stamp BS2sx microcontroller (Parallax, Inc.).
U105 - U107—H11G2 optocoupler.
Resistors—All resistors are 1/4 Watt metal film, 5% tolerance, values as indicated.

IV. Software Description and Program Flow:

The logic flow of the EZ-Tuner's control program is lengthy but straightforward. Upon powering up, the controller displays a startup message on the LCD display and begins an initialization sequence that homes the inductor switch, moves the variable capacitors to their fully-meshed positions, and zeros the internal software counters.

After initialization, the controller then executes an auto-recovery routine. The capacitors and inductor are restored to their last-used settings, the tuner is toggled on-line, and the automatic mode is selected. This auto-recovery feature means that the EZ-tuner can be operated remotely, without concern about power failures.

In its automatic mode, the tuner looks continuously for an r.f. carrier at its input. When it finds a carrier of approximately 10W or more, it measures the frequency to verify that it is in a valid amateur band and then moves the capacitors and inductor switch to the appropriate stored settings. Once the settings have been reached, which typically take about 1 second, the values are displayed on the LCD display.

The software subdivides the amateur bands into 134 frequency segments, which range in width from 10 kHz on 160 meters, to 50 kHz on 10 meters. If the user has not previously stored capacitor and inductor settings for a particular segment, the tuner defaults to settings corresponding to a 50 ohm (1:1 VSWR) match. These 50 ohm "presets" are stored in the BS2sx's EEPROM at the time the control program is loaded.

Figure 6—The serial programming port is visible on the bottom left of the rear panel of the EZ-Tuner. A Bird dual line section measures forward and reflected r.f. power.

If the operator subsequently changes frequency or bands, the EZ-Tuner automatically tracks the changes, updating the settings and display as necessary. In the automatic mode, the tuner can also be stepped through its memories by pressing the front panel *up* and *down* buttons, with the LCD display indicating the lower frequency end of each stored segment.

The EZ-Tuner is toggled into its manual mode either by briefly pressing the *mode/store* button, or by turning either of the front panel knobs. In the manual mode, the knobs tune the variable capacitors with a 5:1 electronic "vernier," and the *up* and *down* buttons step the inductor switch through its 11 possible positions. The LCD display always indicates the updated settings.

Pushing the *mode/store* button for 0.5 seconds stores the current settings in memory. Briefly pressing the *off-line/reset* button toggles the tuner online or off-line, with the change in status confirmed by a message on the LCD display. Pushing the *off-line/reset* button for 0.5 seconds resets the EZ-Tuner's microcontroller and initiates the power-up sequence. Short beeps confirm brief button presses, while musical 3-tone beeps confirm extended presses.

The EZ-Tuner's frequency-measuring routine illustrates the power of the BASIC Stamp programming language. Measuring the transmitter frequency is more complicated than one might imagine, because an *ssb* or *cw* transmission has dead periods that can lead to frequency measurement errors. To overcome this problem, the EZ-Tuner measures the frequency three times. The first time, it briefly polls input port P15 (for 400uS) just to see if a signal is present. If no signal is detected, then no further polling takes place. If a signal is detected, then port P15 is polled again for 100mS, the longer polling time being necessary to obtain an accurate measurement. Finally P15 is polled yet again for 100mS seconds, and in order for a valid frequency to be recorded, both the 2nd and 3rd measurements must agree. All of this logic is implemented in just five P-BASIC program steps:[3]

```
COUNT 15, 1, x                  'count voltage steps at P15 for 400us, store result in "x"
IF x=0 THEN skip                'jump to program labeled "skip" if no signal present
COUNT 15, 250, freq             'otherwise count again for 100mS, store result in "freq"
COUNT 15, 250, freq1            'count a third time for 100mS, store result in "freq1"
IF NOT freq=freq1 THEN skip     'jump to "skip" if 2nd and 3rd measurements differ
                                'and continue if they agree
```

The EZ-Tuner's actual frequency-measuring routine is a bit more complicated than shown here, because the code also corrects for timing inaccuracies in the BS2sx internal clock and for rotary encoder "slippage" during the times the counting gate is open. Nevertheless, the example illustrates the ease with which rather complex operations can be implemented.

Figure 7—In the manual mode, knob-turned optical encoders adjust the variable capacitors, and pushbuttons rotate the inductor switch . In the automatic mode, the pushbuttons ramp the EZ-Tuner through its 134 memories.

V. Operation and Performance:

In the automatic mode, the tuner instantly tracks transmitter frequency changes. However, in order to take advantage of this feature, it is first necessary to adjust the tuner manually for each antenna and band segment of interest and then to store the settings in the tuner's memory. Pressing the *mode/store* button for 0.5 seconds overwrites the default 50 Ω presets with the current capacitor and inductor values. This process needs to be done only once for each band segment, since the tuner memory retains settings indefinitely

Manually adjusting the EZ-Tuner is not difficult, especially compared to adjusting a roller inductor tuner. However, as with any T-network transmatch, it is important to minimize power loss in the matching network at high power levels. For example, under key-down conditions at the amateur legal limit, a 1dB power loss means about 315W of heat are dissipated in the tuner's components.

Fortunately, there are two factors that mitigate this problem. The first is that the duty cycle of *ssb* or *cw* signals is significantly lower than 50%, which greatly reduces the average heat load on tuner components. Secondly, losses in a properly adjusted T-network are generally a worry only with low impedance loads. This fact does not imply that users should avoid matching low impedances, but only that care be taken with extended transmissions (e.g., with RTTY) at high power levels.

Table I summarizes the matching performance of the EZ-Tuner on all h.f. amateur bands. For each load resistance (up to a 16:1 VSWR) and amateur band, the table shows the best inductor switch setting for a match, and the approximate power loss in the matching components. Because of the versatility of the T-network, most loads can be matched with several inductance settings. Using the minimum available inductance assures the lowest possible loss.

			Amateur Band (m)								
SWR	***Load***		*160*	*80*	*40*	*30*	*20*	*17*	*15*	*12*	*10*
16:1	*3.1Ω*	Tap #	10	8	4,5	3	2	2	1	1	1
		Loss	25%	25%	16%	18%	24%	24%	14%	16%	19%
8:1	*6.3Ω*	Tap #	10	8	4,5	3	2	2	1	1	1
		Loss	17%	17%	--	11%	15%	15%	--	--	11%
4:1	*12.5Ω*	Tap #	10	8	4,5	3	2,3	2	1	1	1
		Loss	11%	11%	--	--	--	--	--	--	--
2:1	*25Ω*	Tap #	10	8	6	3,4	3	2	1,2	1	1
		Loss	--	--	--	--	--	--	--	--	--
1:1	*50Ω*	Tap #	10	8,9	6	4,5	3,4	3	2	1,2	1
		Loss	--		--	--	--	--	--	--	--
2:1	*100Ω*	Tap #	11	9	6,7	5,6	4	3	2	2	1
		Loss	--	--	--	--	--	--	--	--	--
4:1	*200Ω*	Tap #	11	9,10	7	6	4,5	3	*	2	1#
		Loss	--		--	--	--	--	*	--	--
8:1	*400Ω*	Tap #	11	10	7,8	6	5	3#,4#	3	2#	2
		Loss	--	--	--	--	--	--	--	--	--
16:1	*800Ω*	Tap #	11	10	8	6	5	4	3	*	2
		Loss	--	--	--	--	--	--	--	*	--

Notes:

(1) Table shows the preferred inductor tap number for each band and load. If two numbers are shown in a category, either provides a suitable (low loss) 1:1 match. A pound sign (#) means only a partial match (VSWR≤1.7) can be obtained, and an asterisk (*) signifies no match is possible.

(2) Loss is the estimated percentage of transmitter power dissipated as heat in the tuner for the given tap number. If more than two taps are listed, the loss is that corresponding to the first number. If no power loss is shown, it means the loss is 10% or less.

From the table, we see that there is not a large performance price to pay for the convenience of the EZ-Tuner's switched inductor. There are only two narrow gaps in the matching range, one on the 15 meter and one on the 12 meter band, and these could probably have been eliminated by tweaking the inductor tap positions. Furthermore, although it is not evident from the table, the EZ-Tuner will tune at least a 32:1 VSWR mismatch on most bands. It will also match a full range of impedances on a future 60 meter band (5.3 MHz), recently proposed by the ARRL.

Part III of this series will focus on the construction of the EZ-Tuner. Here, we will proved construction hints, a procedure for positioning the inductor taps, and advice for parts selection and substitution. Information will also be provided for programming the EZ-tuner and for building a manual version of the tuner. (To be continued...)

References:

[1] http://www.muohio.edu/~4cx250b/web/eztuner.htm

[2] A complete circuit description and parts listing of the stepper controller boards are in the schematic diagram package from Ref. 1. The stepper motors are dual-shaft Superior Electric Slo-Syn models M061-FD-6102 and are rated at 11.2V @ 0.44A and 200 steps/revolution.

[3] A programming manual for the BASIC Stamp BS2sx can be downloaded free from http://www.parallaxinc.com