Using the World's Most Accurate Frequency Standard, Part 1

Building a receiver for WWVB.

by Bob Roehrig K9EUI

How accurate is your frequency counter? Chances are it is not as good as you think it is. Even if your counter has a high stability time base of 0.1 or 0.2 ppm, it must still be checked against a known standard from time to time. I have seen many counters that are off by as much as 10 ppm, which means the measurement of a 2 meter rig would be off by more than 1 kHz. If you experiment with microwaves, it is essential that you have an accurate frequency counter.

The standard rule of thumb is that your measuring instrument should be at least 10 times more accurate than the device you are trying to measure. See the sidebar: "Comments on Frequency Counters" on page 17.

The most accurate frequency source in this country is obtained from the National Institute of Standards and Technology (NIST), formerly called the National Bureau of Standards (NBS), in Colorado. This is the organization that operates WWV. All the WWV frequencies are obtained from a cesium standard, which is the most accurate frequency source in the world. WWV is OK for setting clocks and zeroing a receiver's crystal calibrator, but it is not the ideal source for checking a frequency counter.

The best standard frequency you can get is from the LF transmissions of WWVB on 60 kHz. Because of the low frequency used, the fading and multipath problems are minimized and an almost constant signal is available. With the equipment described in this article you can easily check your local standard or countertime base to within 0.0001 parts per million, which is not possible using the HF WWV signals.

The WWVB Signal

The WWVB transmission on 60 kHz has no audio modulation. The carrier power is reduced 10 dB at the beginning of each second and held low for 0.2 to 0.8 seconds before returning to full power. This pulse width modulation is a serial binary time-of-day code used to synchronize clocks. The second form of modulation is a 45-degree advance in phase shift at 10 minutes past the hour, which is returned to normal five minutes later. This phase shift will have little effect on our use of the signal but you will see it when doing phase comparisons. The WWVB signal strength is sufficient to be received throughout most of the continental U.S.

System Block Diagram

Figure 1 shows a block diagram of the WWVB receiver/comparator. The receiver is basically a sensitive RF amplifier that amplifies the 60 kHz carrier up to a 5 volt level signal. The carrier frequency is then com-

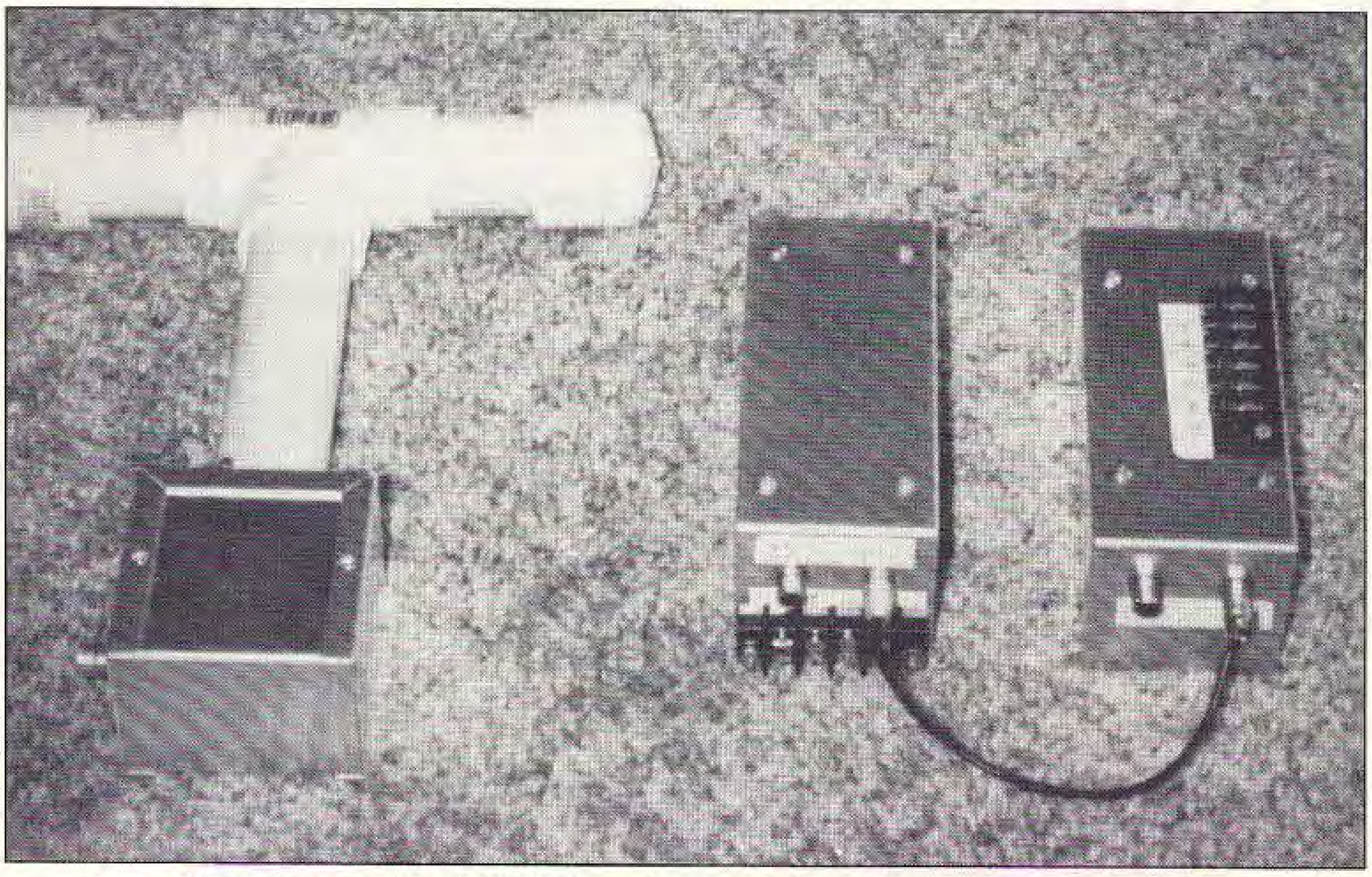

Photo A. Completed WWVB receiver modules with indoor rod antenna.

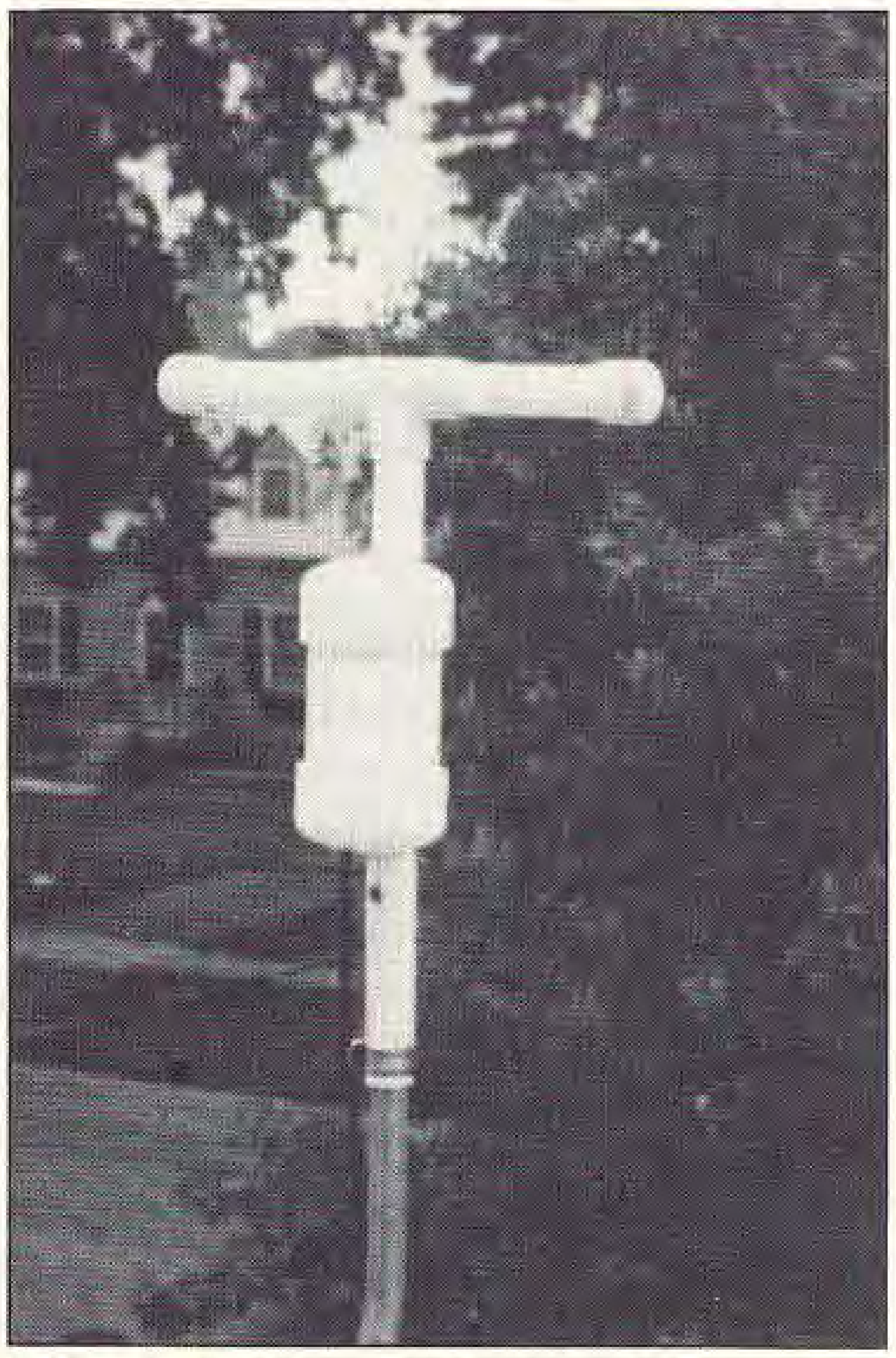

Photo B. Outdoor version of rod antenna and preamp in waterproof housing.

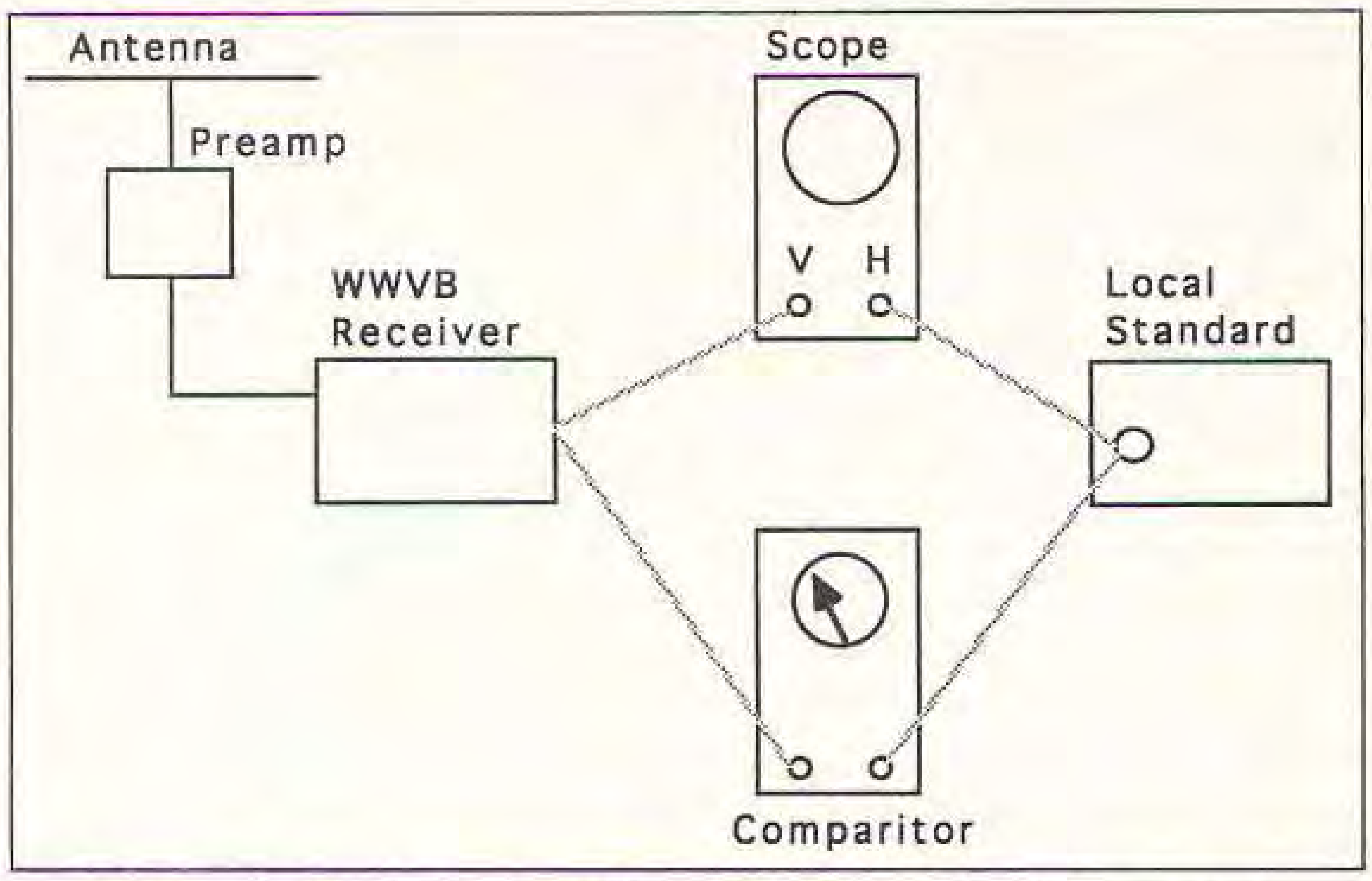

Figure 1. Block diagram of the WWVB receiver/comparator.

pared to your local standard, which may be a separate highly accurate oscillator or a stable oscillator that exists within a piece of equipment such as a frequency counter. The comparator can be either a scope, which is used to observe the Lissajous patterns showing the drift of the local standard, or a digital comparator, which shows the drift rate on a meter or chart recorder. The second part of this article will show the details of a digital comparator.

The Antenna System

This is an active antenna using cascaded followers for a high input impedance and a low output impedance. The unit should be at least 25 feet away from the receiver and is connected to the main unit with coaxial cable. Any common coax can be used since impedance matching is not a critical issue here. Power is supplied from 12 volts via a series 330 ohm resistor in the receiver and the signal is superimposed on this same conductor. The board should be mounted in a waterproof housing if it is to be mounted outdoors. (See Photos A and B.)

Two types of antenna can be used, a wire or a ferrite rod. The same preamp is used for either type antenna with just a few component changes. The antenna/preamp circuit is shown in Figure 2.

For the wire version, a 3- to 50-foot antenna is connected to J2; the length depends on the signal strength at your location. R3 is a fixed 1k resistor and C1, C4, L1, and L2 are not used. To adjust, connect the circuit as shown in Figure 3A and adjust L3 for maximum signal at 60) kHz.

A wire antenna can gather a lot of signal but may also pick up a lot of noise. Also, a longwire antenna may pick up enough HF energy from a nearby ham transmitter to damage the preamp. Therefore, I recommend putting in the extra effort to build the rod antenna.

For the preamp circuit with the rod antenna, install C1, C4 and a 1k pot for R3. C2 should be an 820 pF capacitor. C5, L3, and J2 are not used. L1 consists of a 1/2-inch by 7-1/2-inch-long ferrite rod from Amidon Associates (2216 East Gladwick St., Dominguez Hills CA 90220; 310/763-5770), Part No. R33-050-750. You will also need about 50 feet of #28 gauge enameled wire, also available from Amidon.

Starting about two inches from one end, close-wind about 4-1/2 inches of wire around the rod. Secure the ends of the windings with tape. After L1 is wound, wind a layer of electrical tape around the center portion and wind 20 turns of wire over this area for L2. Be sure to leave about two feet of wire off the ends of the windings to make connections to the preamp.

The rod antenna is adjusted by first powering up the board as shown in Figure 3A and checking for regeneration. Rotate R3 throughout its range. If it does not oscillate, swap the two tickler lead connections on the board. Once oscillation is obtained, reduce the setting of R3 by about 1/16 of a turn, below the point of oscillation. Then connect the generator to points A and B and tune to resonance by adjusting the number of turns of L1 and choosing the correct value of C2, making it resonate at 60 kHz with C1 at mid-capacity.

After tuning, cover the entire winding with electrical tape. Final tuning should be done with C1 after the rod is installed in its PVC housing and its attachment to the preamp enclosure. In my case, the antenna is mounted outdoors (see Photo B) so I mounted the preamp in a 2-inch PVC tube and the antenna housing uses 3/4-inch pipe, end caps and a "T."

If you have some ferrite rods around, try them. I successfully used an 8-inch rod that was used as an AM antenna on an old stereo receiver. On this rod I wound 6 inches of wire (0.33" in diameter), which tuned to 60 kHz with two of the 820 pF caps in parallel.

The WWVB Receiver

To maintain the accuracy of the transmitted frequency, the receiver cannot modify

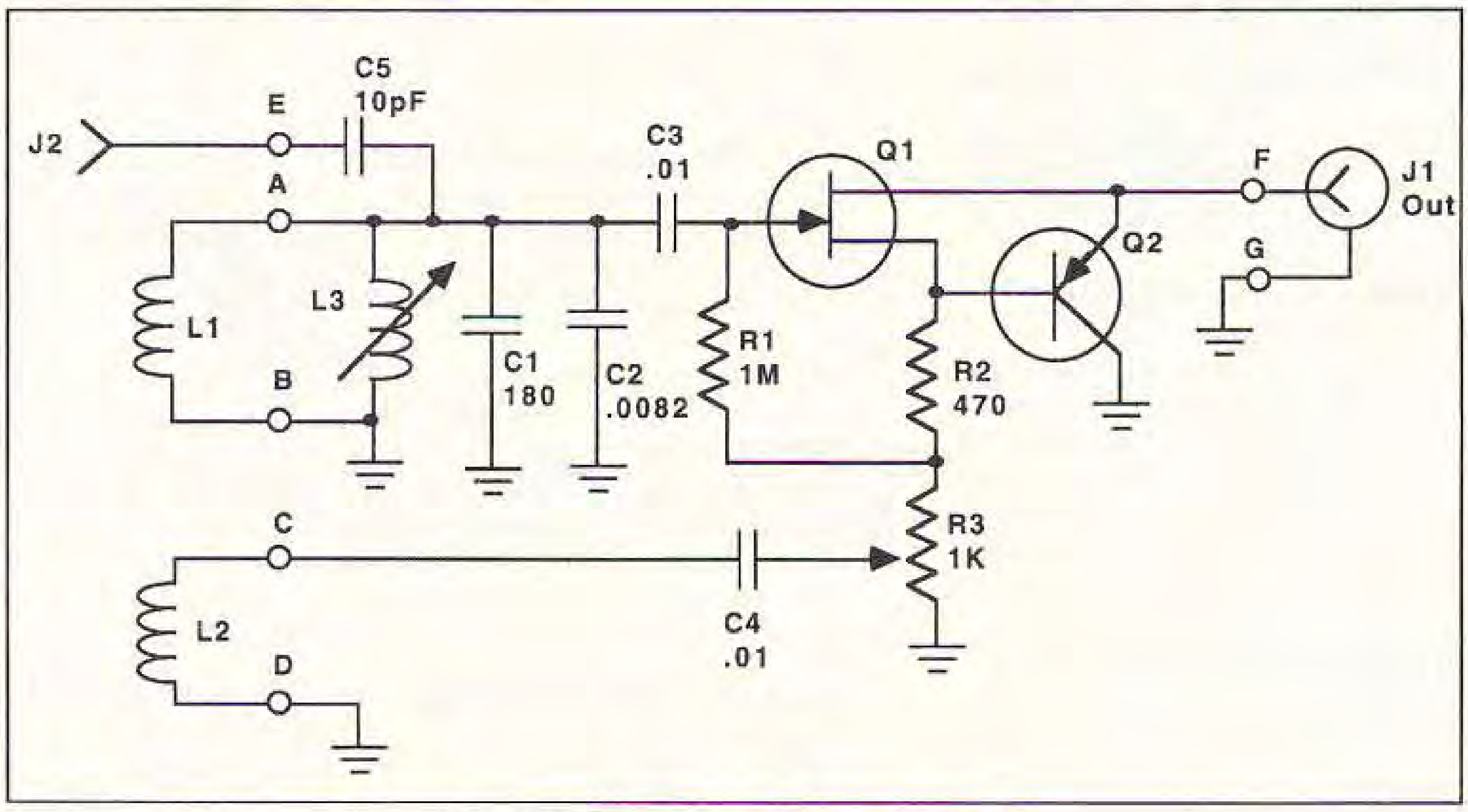

Figure 2. The antenna/preamp circuit.

Parts List, Figure 2

(All fixed resistors 1/4 watt)

R1	1 Meg	
R2	470 ohms	
R3 *	1k	
R3 **	1k pot	Digi-Key #36C13
L1,2 **	See text	
L3 *	800 µH	Digi-Key #TK1725
C1 **	10-180 pF trimmer	Digi-Key #SG3014
C2 *	0.0082 µF	Digi-Key #P3822
C2 **	820 pF (see text)	Digi-Key #P3821
C3	0.01 µF	Digi-Key #P4513
C4 **	0.01 µF	Digi-Key #p4513
C5 *	10 pF	Digi-Key #4837
Q1	MPF102	Digi-Key #MPF102
Q2	2N2907	Digi-Key #2N2907
J1	Output connector: BNC, Phono, or coaxial UHF	
J2 *	Antenna connector: Pin or bananna jack	

The enclosure for indoor use is 4" x 2-1/8" x 1-5/8" minibox: Radio Shack #270-239 or Digikey #L114ND.

* Use these parts for the wire antenna version only.

** Use these parts for the ferrite rod antenna version only.

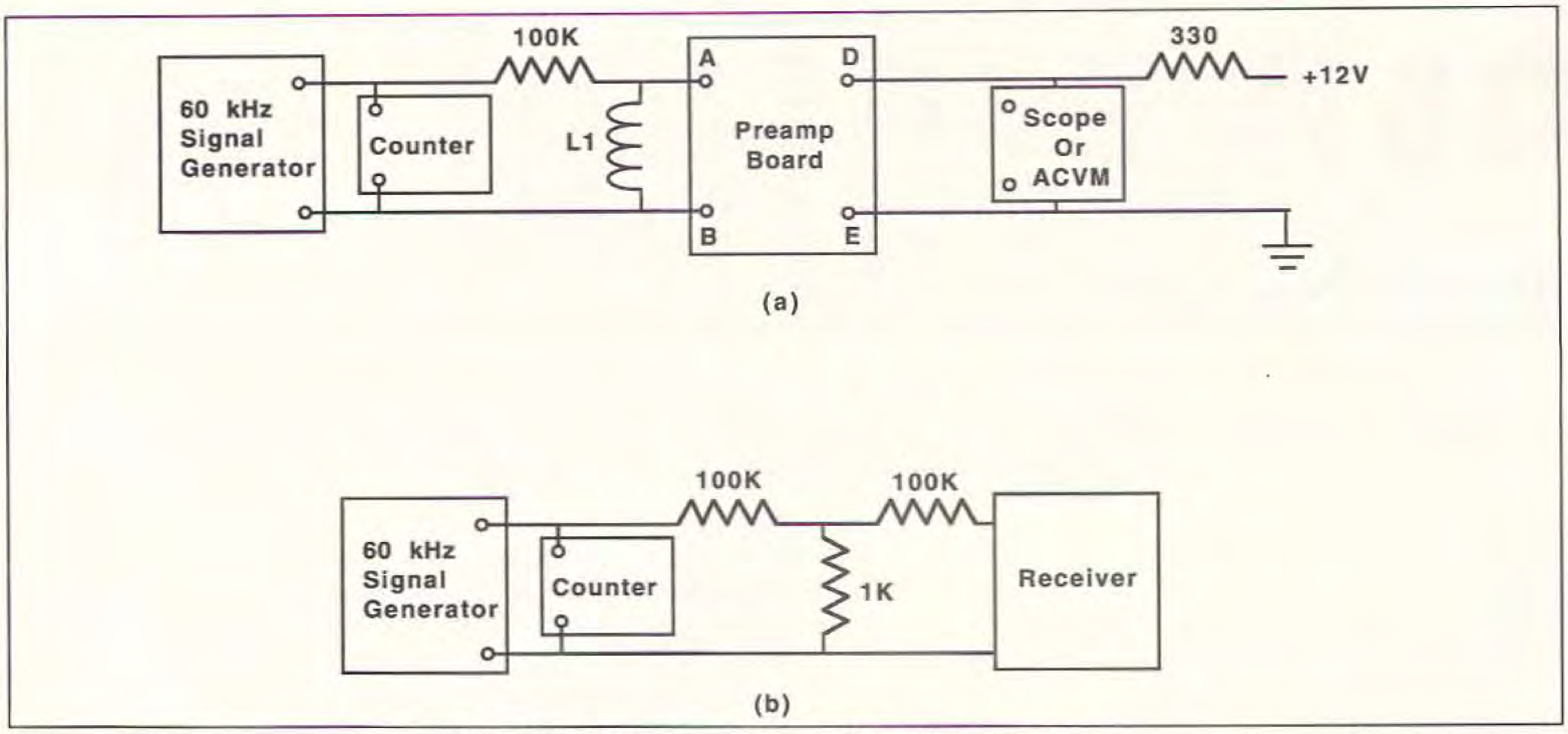

Figure 3. A) Preamp tuning setup; B) Receiver tuning setup.

the frequency in any way, so we must use a TRF system rather than a superhet. Because the entire receiver operates on a single frequency, it must be well-shielded and is therefore built in two separate minibox modules to prevent self-oscillation. RF connections between modules are via coaxial connectors and cables and other connections are provided by barrier-strip screw connections. The receiver design is the result of many months of trying many different circuits and the discreet component version shown here proved to be the most stable and reliable of many that were tried.

The two receiver boards are mounted in the miniboxes using 3/4-inch spacers and 4-40 hardware. The jacks and barrier strips are mounted on the ends and tops of the boxes. The covers may then be mounted to a rack panel or to a cabinet base, as desired. In my final unit, I also included a multi-position switch so I can monitor other functions with the 50 µA meter.

Figure 4 shows the RF amplifier portion

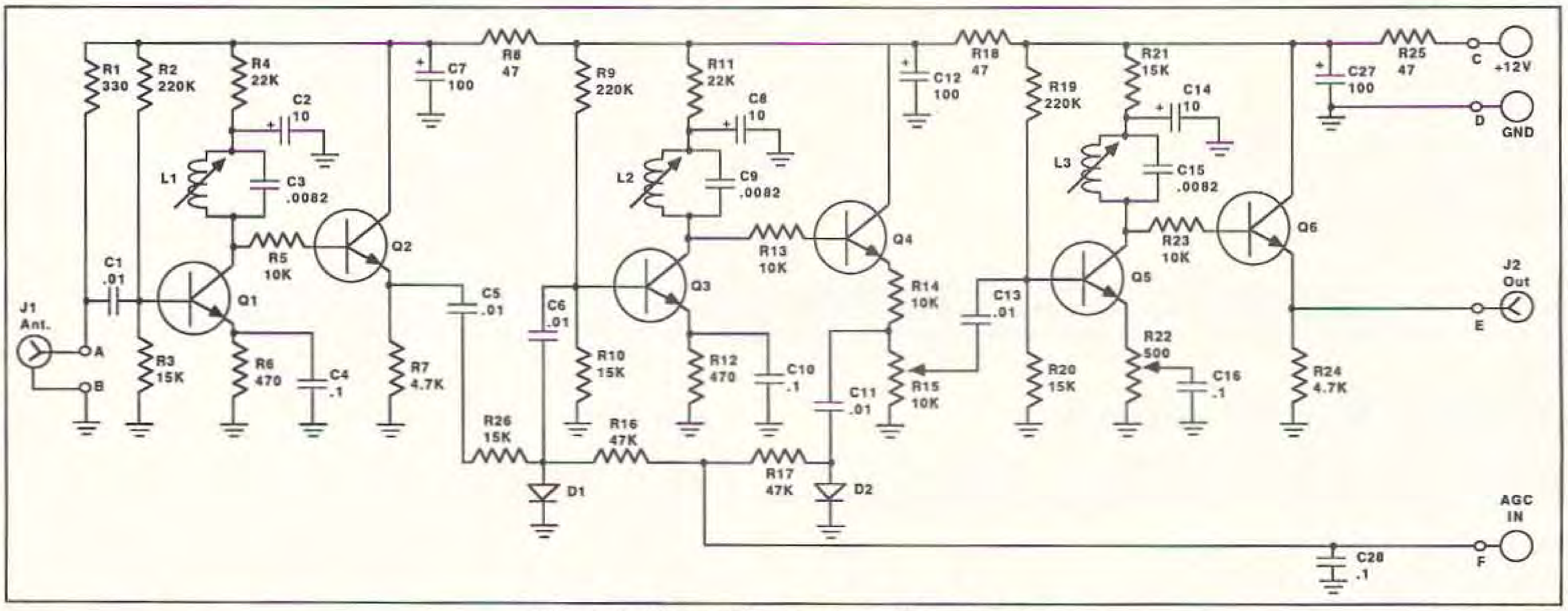

Figure 4. RF amplifier portion of the receiver.

Parts List, Figure 4

(All fixed resistors 1/4 watt)			R22	500 ohm pot	Digi-Key #36C52
R1	330 ohms		C1,5,6,11,13	0.01 µF	Digi-Key #P4513
R2,9,19	220k		C4,10,16,28	0.1 µF	Digi-Key #P4525
R3,10,20,21,26	15k		C3,9,15	0.0082 µF	Digi-Key #P3822
R4,11	22k		C2,8,10	10 µF	Digi-Key #P807
R5,13,14,23	10k		C7,12,27	100 µF	Digi-Key #P833
R6,12	470 ohms		L1,2,3	800 µH	Digi-Key #TK1725
R7,24	4.7k		Q1-6	2N2222 or equiv.	
R8,18,25	47 ohms		D1,2	1N34A	Radio Shack #276-1123
R16,17	47k		J1,2	BNC, phono or UHF coaxial connectors	
R15	10k pot	Digi-Key #36C14	Enclosure: Digi-Key #L116ND or Radio Shack #270-238		

of the receiver. It consists of three stages of tuned amplifiers with emitter followers. The followers and low collector current in the tuned stages help preserve the high Q of the coils to maintain selectivity. AGC is applied to two stages. As the signal strength increases, the AGC detector provides a higher DC voltage. This voltage is applied to diodes D1 and D2. The higher the current that passes through these diodes, the more the signal voltage is shunted to ground. During normal operation the output of this section of the receiver is about a 1 volt P-P sine wave.

Figure 5 shows the remaining amplifier stages and the AGC detector. The normal signal level at TP1 is about 5 volts P-P. The carrier is rectified by D2 and D3. Q6 is a follower to isolate the slow AGC time constant circuit from the detector. C7 is charged to several volts through R23. The discharge time constant is via D5, R24, and R25. The AGC voltage developed across C7 is dropped to less than a volt by D5. The higher AGC voltage is reduced in this way, rather than with a voltage divider, to maintain a greater dynamic range. The slow-responding circuit sets the AGC level relative to the average signal level, rather than allowing it to follow the 10 dB carrier reduction that occurs each second. The slow AGC voltage is available at board point J while the fast AGC voltage is at point H. These two voltages can be used to drive a detector to decode the time-of-day pulse information. This decoded information can be used to operate a self-setting digital clock. If you are interested in such a clock project, drop me a card and let me know.

Stages Q3 through Q5 amplify the main received signal and provide a 5 volt TTL compatible output. This signal is used to drive the 60 kHz input of the comparator unit or to connect to the scope.

Receiver Adjustments

On the RF amplifier board, set R15 and R22 to mid-range. Connect the test equipment to the RF amplifier module alone using the scheme shown in Figure 3B. Using the scope or an AC voltmeter, set the generator to 60 kHz at a level of 150 mV RMS. This is equivalent to a 30 microvolt signal at the actual receiver input. Observe the output signal at J2 with the scope. Carefully adjust the three coils for maximum signal using a nonmetallic tool. The level should end up being about 1 volt P-P.

After alignment is complete, place the cover on the box of the module, then connect the cables between the two receiver units: RF amplifier J2 connects to amplifier unit J1, and "F" of both units are connected together. Temporarily ground the AGC line "F." With the 150 mV signal applied as before, there should be a 6 volt P-P sine wave at TP1. The signal may be slightly clipped at the top and bottom of the waveform. J2 should have a 5 volt square wave. TP2 should read about 6 VDC and TP3 should be about 3.3 VDC.

Remove the short from "F." The signal at TP1 should drop to around 4 volts P-P and TP3 should read around 1.8 volts. If all is well, changing the generator output from 150 mV up to 1.5 volts (a change of 20 dB) should show no more than about a 6 dB change at TP1. With the 50 uA S-meter connected, it should read around mid-scale with the 150 mV input and around 45 uA with the 1.5 volt input.

The receiver will operate with an actual input level of only 3 microvolts with R15 and R22 at maximum level (counterclockwise rotation). With nothing connected to the receiver input, there will be a 5 volt square wave at output J2. This will be close to 60 kHz and is not an oscillation but just the amplification of internal noise. Any useful signal will override this so it is not of concern.

Finally, disconnect the generator and turn it off or change its frequency so the receiver won't pick it up. Connect the cable from the antenna unit and observe the TP1 signal. You should see the 60 kHz signal, around 6 volts P-P or so, dropping in level every second. The signal should be a fairly clean sine wave.

The final gain adjustment is made while

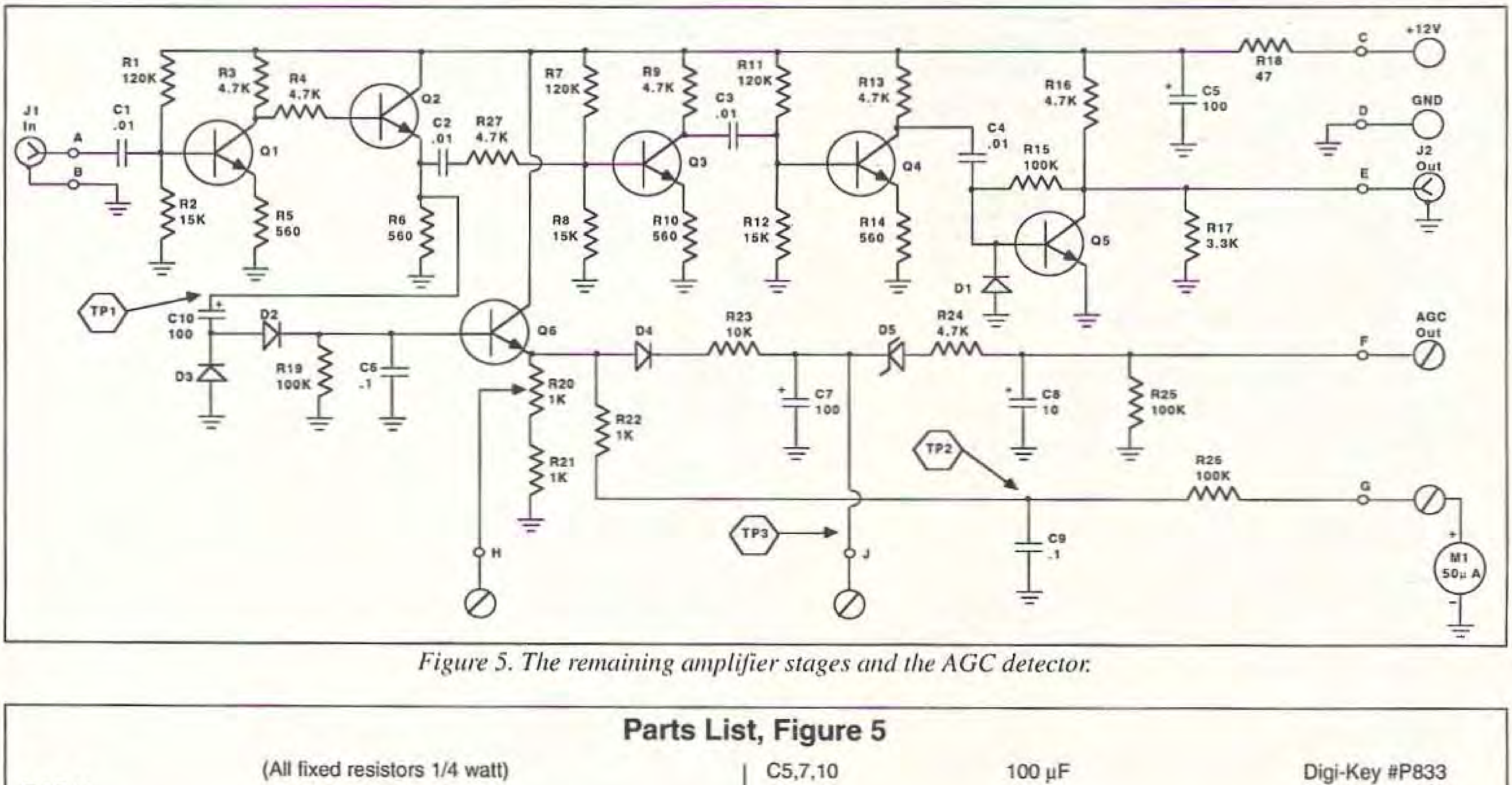

Figure 5. The remaining amplifier stages and the AGC detector.

Parts List, Figure 5

	(All fixed resistors 1/4 watt)		C5,7,10	100 µF	Digi-Key #P833
R1,7,11	120k		C6,9	0.1 µF	Digi-Key #P4525
R2,8,12	15k		C8	10 µF	Digi-Key #P807
R3,4,9,13,16,24,27	4.7k		D1-4	1N914 or 1N4148	
R5,6,10,14	560 ohms		D5	3.9V zener, 1N4730A or 1N5228B	
R15,19,25,26	100k		Q1-6	2N2222 or equiv.	
R17	3.3k		J1-3	BNC, phono, or UHF coaxial connectors	
R18	47 ohms		M1*	50 µA meter	
R21,22	1k				
R23	10k		*Various models available from Fair Radio Co., 1016 E. Eureka, Box 1105,		
R20	1k pot	Digi-Key #36C13	Lima OH 45802; (419) 227-6573		
C1-4	0.01 µF	Digi-Key #P4513	Enclosure: Digi-Key #L116ND or Radio Shack 270-238		

observing the signal at its strongest period, usually around noon local time, or four or five hours after sunset. Adjust R15 and R22 on the RF amplifier board for maximum signal at TP1, without clipping. The AGC will then compensate for lower signal levels at other times of day. Maximum signal should peak no higher than 45 µA on the S-meter.

During use, if the meter shows erratic fluctuations other than the normal 1 pps time code drops, it indicates atmospheric disturbances that may affect the signals usefulness. If the meter does not show the 10 dB drops each second, it may be that the noise level is high or you are getting interference. If the meter is steady, the unit may be oscillating because the antenna is too close to the receiver.

Phase Comparisons

The simple form of phase comparison between WWVB and your local standard is done with the setup shown in Figure 1, using a scope. The receiver output is fed to the vertical scope input and the local standard is fed to the horizontal input. The 60 kHz signal and your local standard are compared by observing the rotation of the Lissajous pattern. Alternatively, connect the local signal to the external sync input to synchronize the scope's horizontal oscillator. The comparison will then be a slow drift of the waveform across the screen. In any case, your local standard must be an integer value of 60 kHz.

If your frequency counter time base is your local standard, you can probably find a point in the countertime base divider chain that provides 10 kHz. This would be a good choice of signal to compare to the 60 kHz. At 10 kHz, to achieve an accuracy of 1 part in 10^8, it will take over two hours of comparison time.

Whatever the accuracy you are trying to achieve, it takes 100 times as long to observe a 10 kHz signal drift as it does 1 MHz. For that reason, the serious user of this equipment should consider building a simple digital phase comparator. This will be discussed in the second part of this three-part series.

Using the Receiver for Other Frequencies

WWVB is usable in most of North America. In other parts of the world there are other LF standard frequency transmissions that may be of use. I cannot vouch for the accuracy of the following list but I have seen these stations mentioned in various publications from time to time. There may also be others that I have not heard of. The station must emit a CW carrier and not have FSK keying as many military stations do.

Location	Call	Freq., kHz
U.K.	MSF	60
Germany	DCF77	77.5
Switzerland	HBG	75
Japan	JJF	40
Czechoslovakia	OMA	50
Irkutsk, Russia	RTZ	50

The receiver can be tuned for these other frequencies by selecting different values for C3, C9, and C15 as follows:

40 kHz	0.018 µF
50 kHz	0.012 µF
75 kHz	5300 pF
77.5 kHz	5000 pF

C2 on the antenna preamp board must also be changed as necessary.

I encourage any correspondence regarding this project (314 S. Harrison St., Batavia IL 60510); however, if you expect a response, please include an SASE. A full set of boards for this project can be obtained for $11 plus $1.50 S & H from FAR Circuits, 18N640 Field Court, Dundee IL 60118. 73

Comments on Frequency Counters

If you are planning to purchase a frequency counter, consider the following:

1. The counter specs should state the accuracy and frequency of the time base. Accuracy should be expressed in terms of drift with temperature change. The time base should be one using a "standard" frequency, such as 1, 3, 5, or 10 MHz. Avoid counters which have a nonstandard time base, such as 3.579545 MHz. Nonstandard frequencies generally mean cheap crystals. Also, they cannot easily be compared to a known standard.

2. A good counter should have an output connector which allows you to easily check the internal oscillator.

3. The better counters have an external time base input that allows you to use a more accurate oscillator than the internal one.

4. Unless you can use an external time base, you should consider buying the counter with the high stability time base option, if available, but again, make sure it has an output connector so you can check it.

I have counters made by Hewlett-Packard, Fluke, Anadex, and others. All of these either met the above requirements or were easily modified to do so. Even my synthesized signal generator has an external time base input, so all my units are run from my "house" standard.

5. There are other counters available than those advertised in the amateur publications, such as those I mentioned above. If you frequent hamfests, keep an eye out for older commercial-grade counters. Sometimes excellent units can be purchased inexpensively. The owner may just want to get rid of it because it is not as small as more modern counters.