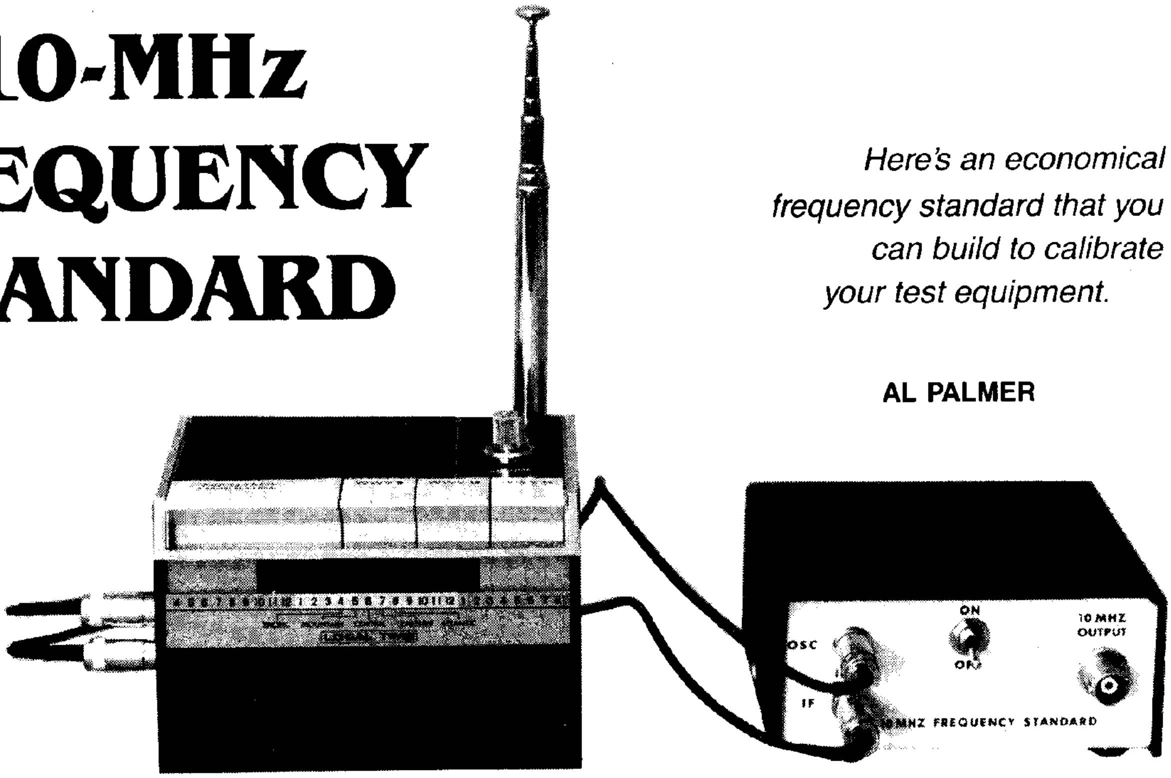
10-MHz FREQUENCY STANDARD

Here's an economical frequency standard that you can build to calibrate your test equipment.

AL PALMER



YOUR FREQUENCY COUNTER IS GOING TO need calibration—if not today, then in the near future. That's also true for any test instrument that uses a built-in reference oscillator, such as an oscilloscope or signal generator. Calibration means adjusting the instrument's built-in reference oscillator until it matches a known frequency standard. Unfortunately, a highly accurate frequency standard, such as one traceable to the *N*ational *B*ureau of *S*tandards, NBS, is far beyond the budget of most technicians and electronics hobbyists.

With the absence of an NBS-traceable standard, hobbyists usually decide to calibrate their frequency counters against a similar working model. After several calibrations, usually one against another, the law of averages dictates that eventually a frequency counter will end up calibrated to itself. The end result is that no standard at all is being maintained.

The frequency standard detailed in this article resolves the dilemma by providing a calibrator that is accurate, inexpensive, and simple enough to build. The calibrator's output is a 10-MHz square wave that is phase-locked to the WWV 10-MHz radio transmission that's traceable to the NBS in Boulder, Colorado. And, if you want more versatility, later on we'll show you how to modify the unit to phase-lock on to the WWV 2.5-MHz and 5-MHz radio transmission.

Theory of operation

Figure 1 is a block diagram of our 10-MHz frequency standard. It consists of a *Time Kube* superheterodyne AM radio which contains an RF amplifier, a mixer, a local oscillator, two IF amplifiers, a detector, and an audio amplifier. We add to that a circuit containing a mixer and PLL. (We'll call that circuit our "main circuit.")

Let's take a closer look at each stage of the radio receiver. The incoming WWV 10-MHz signal is amplified in the RF amplifier stage, and then sent to the mixer stage where it is combined with the 10.455-MHz output from the local oscillator. Because the mixer is a non-linear device, the two frequencies are heterodyned together creating two additional frequencies in the output; the sum frequency of 20.455 MHz, and the difference frequency 0.455 MHz (or 455 kHz), which is the one we are most interested in (see Table 1). The IF frequency is chosen to be 455 kHz, and the local oscillator is designed to operate 455 kHz above the frequency that's being received.

The purpose of the IF amplifiers is to select out, and amplify, only the difference signal at 455 kHz. The output of the second IF amplifier will be a narrow band of frequencies centered around 455 kHz, which contains all of the audio information present in the original transmission. The IF is then detected, amplified, and heard over the speaker.

Although the WWV 10-MHz incoming frequency to the RF amplifier is extremely accurate, the 455-kHz IF frequency is only as stable as the local oscillator. That means: If the local oscillator drifts 100 Hz off frequency, the center frequency of the IF will also drift 100 Hz off frequency. Although that amount of drift is acceptable as far as listening to audio is concerned, the IF frequency is not accurate enough to be used as a frequency standard unless the drift is compensated for.

As shown in Fig. 1, the main circuit

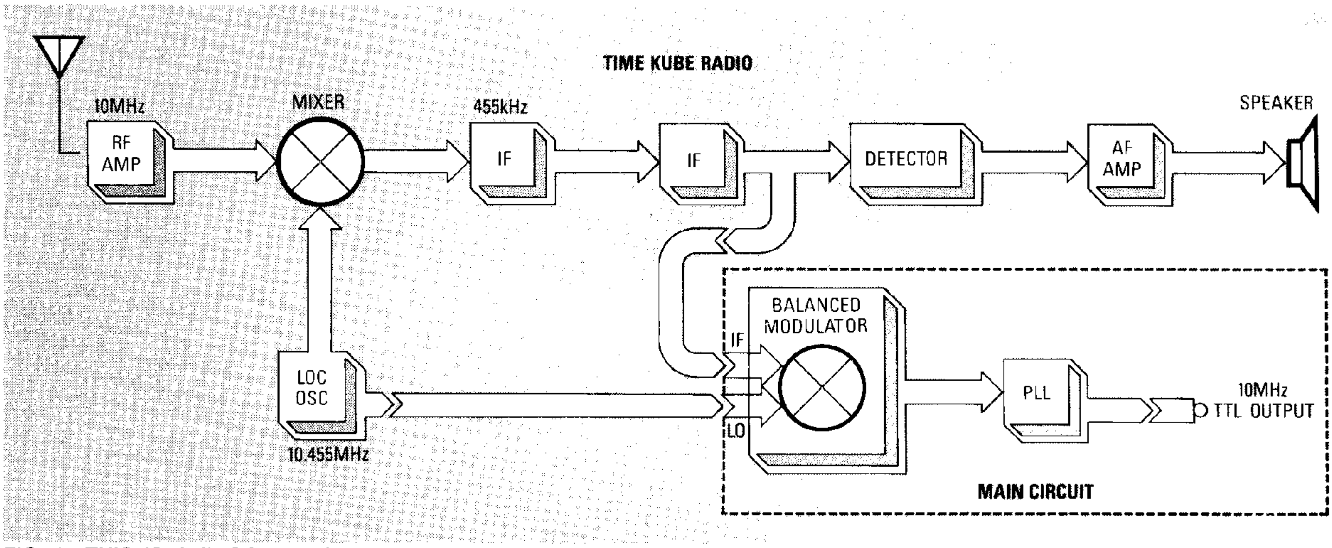


FIG. 1—THIS IS A BLOCK DIAGRAM OF the *Time Kube* radio and the main circuit. However, you can use any superheterodyne AM radio capable of receiving WWV's radio transmissions.

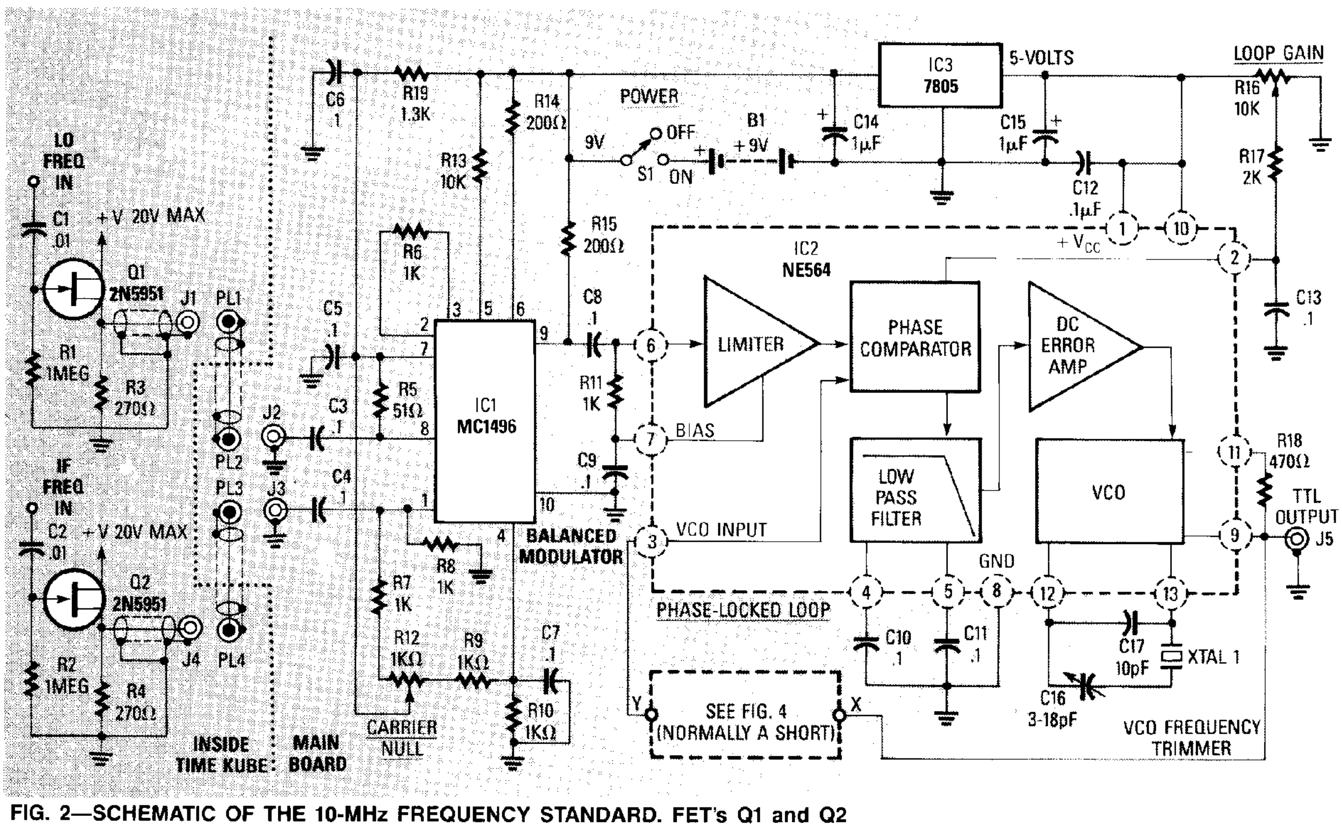


FIG. 2—SCHEMATIC OF THE 10-MHz FREQUENCY STANDARD. FET's Q1 and Q2 are installed inside the radio, and the rest of the components are installed on the main board.

consists of a balanced modulator, which is a type of mixer, and a phase-locked loop. Those two stages cancel any frequency error caused by drifting of the local oscillator, and recreates a signal as accurate as the original WWV 10-MHz signal. For example, if the local oscillator drifts up 100 Hz (10.456 MHz), and then heterodyned with the 10-MHz WWV signal, the IF-difference frequency will now be 456 kHz. When the new IF and local oscillator frquency are heterodyned in the balanced modulator (10.456 MHz − 0.456 MHz), the result is still 10 MHz. In that manner, the balanced modulator will cancel out any drifting in the radio's local oscillator.

The advantage of that approach lies in its simplicity. Any single-conversion superheterodyne short-wave receiver will work, even one where the local oscillator is not crystal-controlled. But the Radio Shack *Time Kube* is self-contained, and relatively inexpensive.

10-MHz frequency standard

Figure 2 is the schematic for the 10-MHz frequency standard. The two FET transistors are installed inside the *Time Kube*, and are used to pick up the IF and the output of the local oscillator without loading down the radio's circuitry. The balanced modulator (IC1) and phase-locked loop (IC2) are part of the main circuit board that we are going to assemble.

Instead of a diode or other nonlinear device, a balanced modulator is used, because that type of mixer produces only two frequencies instead of the usual four; it outputs only the sum and difference frequencies. The two original input frequencies are balanced out and do not appear at the output.

By using a balanced modulator, neither the 10.455-MHz input from the local oscillator, nor the 455-kHz input from the IF amplifier will be present at the output. The closest output frequency of any magnitude will be the 10.91-MHz sum frequency, but 10.91 MHz is far enough away from 10.0 MHz so as not to cause any interference. The phase-locked-loop will lock onto the 10-MHz output of the balanced modulator, and produce a 5-volt peak square wave at the WWV 10-MHz carrier frequency.

A rather unconventional crystal-controlled phase-locked loop is used for two reasons: 1—the crystal-controlled VCO will not lock up on the wrong frequency (ie. 10.91 MHz); and 2—even if the WWV-propagated signal is too weak for the PLL to frequency-lock, the output frequency's stability would be controlled by the crystal. (The crystal's accuracy is at least ±0.005%, or 50-parts-per-million, a viable reference for low accuracy of calibration when propagation of WWV is poor.)

Figure 3 shows an AC power supply that you can use in place of the 9-volt battery shown in Fig. 2. Simply connect the 12-volt output to S1, instead of the battery. The foil pattern that we'll show you shortly already has the power-supply components incorporated into it. If you want to use the foil pattern, but would prefer to use a bat-

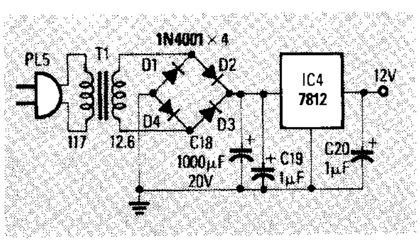


FIG. 3—HERE IS A POWER SUPPLY that you can use if you would prefer not to use a battery.

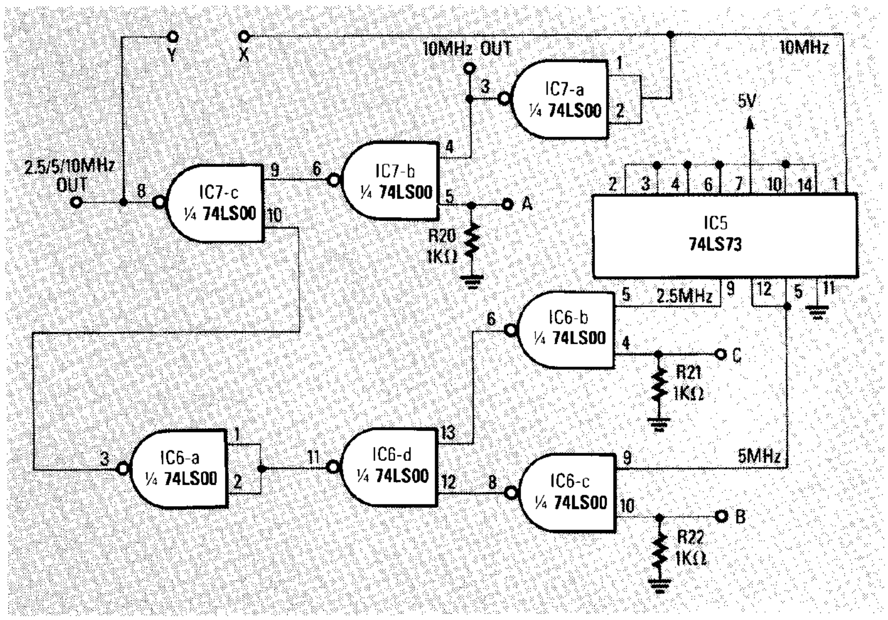


FIG. 4—THIS ADDITIONAL CIRCUITRY will enable your frequency standard to receive the 2.5- and 5-MHz WWV signals. Point "A" must be pulled high for 10 MHz, "B" high for 5 MHz, and "C" high for 2.5 MHz.

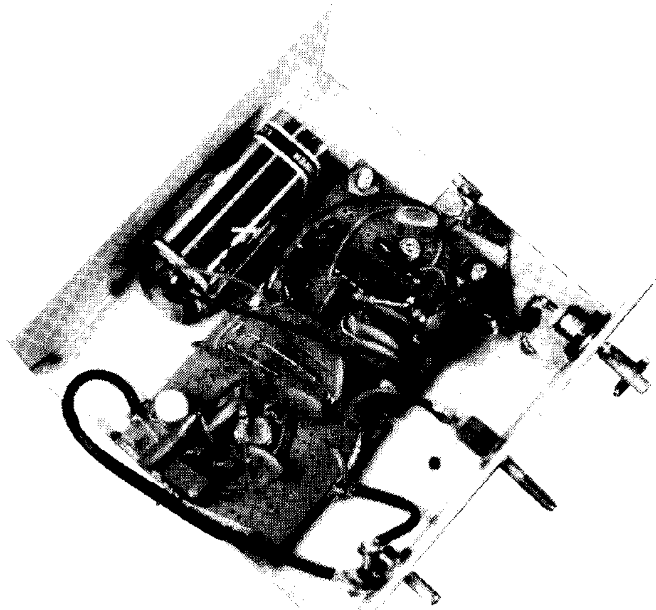


FIG. 5—THE COMPONENTS CAN BE MOUNTED on perforated-wiring board. To help shield the components, a large braided grounding wire runs around the board.

TABLE 1—IDEAL MIXER OPERATION

MIXER

INPUT	OUTPUT
10.0000 MHz RF CARRIER	10.0000 MHz (ORIGINAL)
10.4550 MHz LOCAL OSCILLATOR	10.4550 MHz (ORIGINAL)
	20.4550 MHz SUM
	.4550 MHz DIFFERENCE (IF)

BALANCED MODULATOR

INPUT	OUTPUT
.4550 MHz IF FREQUENCY	10.9100 MHz SUM
10.4550 MHz LOCAL OSCILLATOR	**10.0000 MHz DIFFERENCE**

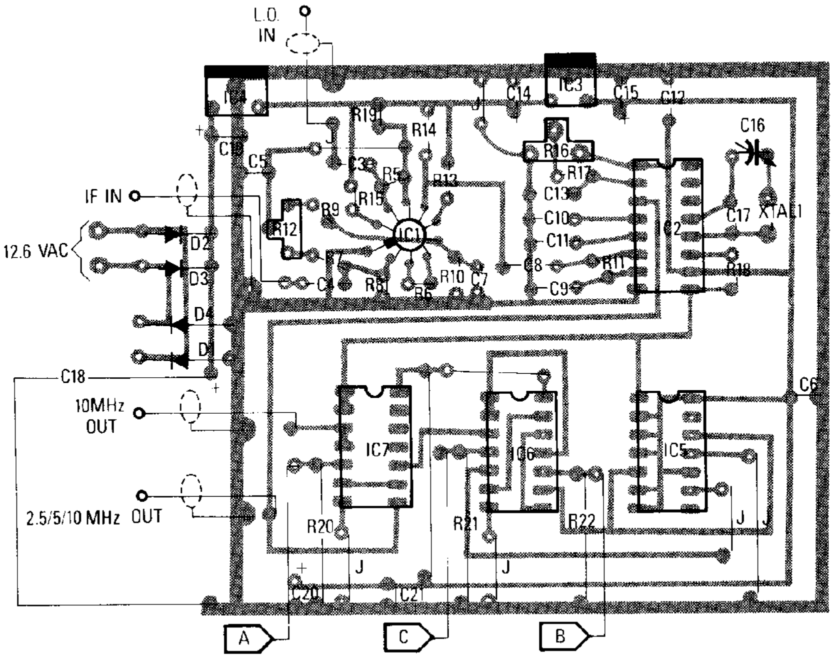


FIG. 6—PARTS PLACEMENT DIAGRAM. The foil pattern in PC Service is being used here, but the parts inside the dashed box are optional. If you don't use them, be sure to put a jumper between pins 9 and 3 of IC2.

tery, just leave the power-supply components out, and connect the battery as indicated in Fig. 2.

We mentioned before that we would show you how to modify the frequency standard to receive other WWV broadcasts. If your radio has trouble receiving the 10-MHz signal, WWV broadcasts the same information on 2.5, 5, 10, 15, and 20 MHz (we're only concerned with 2.5, 5, and 10 MHz), and perhaps either 2.5 or 5 MHz is coming in better. You will notice in Fig. 2, the connection between pins 9 and 3 of IC2 contains a dashed box that says "see Fig. 4." Normally (if you only want to receive WWV 10-MHz broadcast)that dashed box would be a direct short. However, if you want to have the added versatility of being able to receive three WWV frequencies, the circuitry in Fig. 4 should be added between points "X" and "Y."

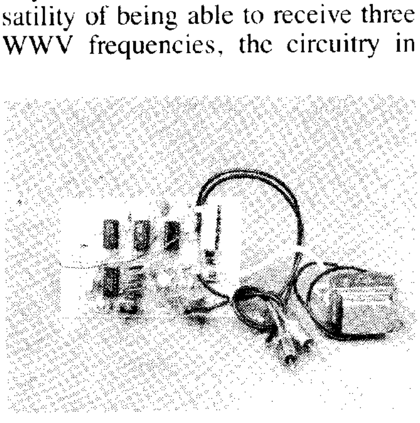


FIG. 7—SHOWN HERE is the completely assembled PC board. Note that this board contains all of the components.

An ancillary benefit from the modification is the ability to select a 2.5 MHz or 5-MHz calibrated output, instead of just the 10-MHz PLL output.

With the modifications, the unit will operate as follows: Assume that the *Time Kube* is tuned in to 5 MHz. The RF input is now 5 MHz, the local oscillator is now 5.455 MHz, and the IF is 455 kHz. The output from the balanced modulator is the difference between the local oscillator and the IF—exactly 5 MHz. The PLL has a free-running frequency of 10 MHz, so in order for it to lock on to the WWV 5-MHz signal, the 10-MHz signal has to be divided by two; to receive the WWV 2.5-MHz signal, the 10-MHz signal has to be divided by four.

When you wish to receive the WWV 10-MHz signal, point "A" must be pulled high; when you wish to receive the 5-MHz WWV signal, point "B" must be pulled high; and when you wish to receive the WWV 2.5-MHz signal point "C" must be pulled high. At the same time, the corresponding frequency must be selected on the *Time Kube* radio. (Note that not all radios can receive the three mentioned frequencies.) Use Fig. 4 as a wiring guide for the additional switches that are required, and mount the board and switches in a cabinet as you see fit.

PARTS LIST

All resistors are ¼-watt, 5%, unless otherwise noted.
R1, R2—1 Megohm
R3, R4—270 ohms
R5—51 ohms
R6–R11—1000 ohms
R12—1000 ohm potentiometer
R13—10,000 ohms
R14, R15—200 ohms
R16—10,000 ohm potentiometer
R17—2000 ohms
R18—470 ohms
R19—1300 ohms
Capacitors
C1, C2—0.01µF, ceramic disc
C3–C13, C21—0.1µF, ceramic disc
C14, C15—1µF, 35 volts, tantalum
C16—3–30pF trimmer
C17—10pF, 5%, silver-dipped mica
Semiconductors
IC1—MC1496, balanced modulator, metal-can package
IC2—NE564, phase-locked loop
IC3—7805, 5-volt regulator
Q1, Q2—2N5951, FET transistor
Other components
XTAL1—10 MHz
B1—9-volt battery
S1—SPST toggle switch
J1–J4—phono jacks
J5—BNC jack
PL1–PL4—phono plugs
Miscellaneous: Perforated-construction or PC board, hardware, metal chassis, 50-ohm coax cable, and battery clip.
The following components are for the optional power supply.
C18—1000µF, 20 volts, electrolytic
C19, C20—1µF, 35 volts, tantalum
D1–D4—1N4001 rectifier diode
IC4—7812, 12-volt regulator
T1—117/12.6 volt, 1 amp transformer
PL5—AC plug and line cord
The following components are optional. They are to be used only if you would like to be able to receive all three of the WWV frequencies.
R20–R22—1000 ohms
IC5—74LS73, dual JK flip flop
IC6, IC7—74LS00, quad nand gate

Construction

Two FET transistors, Q1 and Q2, are used to prevent the main board from loading down the radio's circuits. The FET's should be mounted inside the radio cabinet, using the shortest possible lead lengths to keep them from de-tuning the radio's local oscillator and IF amplifier. Terminate the outputs with RCA jacks mounted on the radio's cabinet. (See the pho-

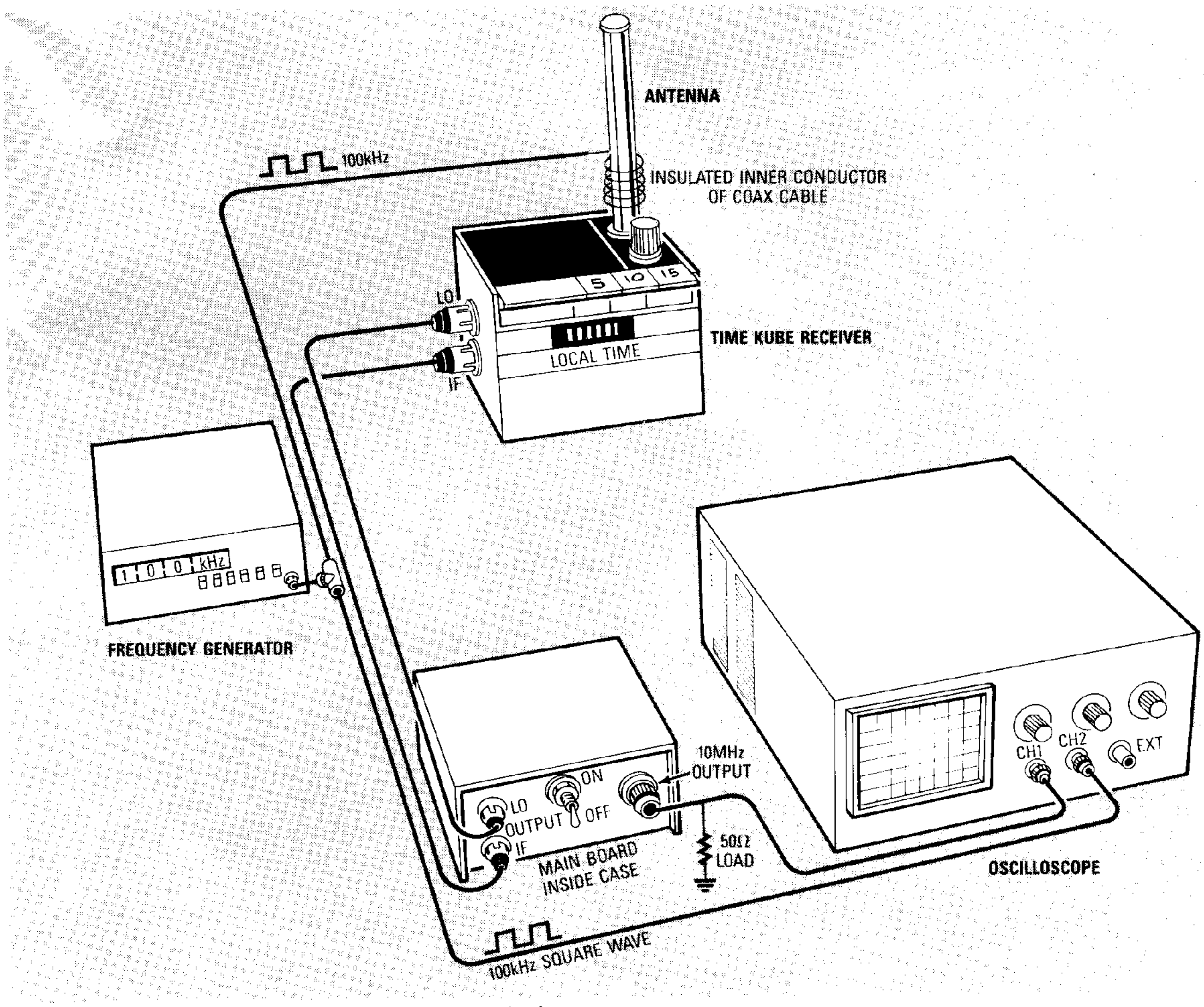


FIG. 8—TEST SETUP for the 10-MHz frequency standard.

tograph in the opening of this article.) The power consumed by the FET transistors is minimal, and can be tapped from the radio's power supply as long as it's less than 20 volts.

Now you have to figure out where to tap off the *Time Kube's* local oscillator and IF frequencies. Whether you use Radio Shack's *Time Kube 12-158*, or the *Weather Time Kube 12-148*, the local oscillator and IF connection points are the same. The points are easy to locate if you have Radio Shack's service manual showing the schematic and the parts layout. In both radios, the local oscillator is a single-transistor and crystal-controlled. The transistor's emitter is the best point to tap off the local-oscillator frequency. In both radios, the IF signal can be tapped off from AM-detector D1's cathode, which immediately follows the second (last) IF transformer.

In constructing the main board, you can use perforated construction board and point-to-point wiring (if you wish) as shown in Fig. 5. However, another alternative is to use the foil pattern shown in PC Service. That pattern is for the 3-output frequency standard, and if you want to use it for the 1-output unit you have to connect a jumper between pins 9 and 3 of IC2, and leave the additional components off the board.

A Parts-Placement diagram is shown in Fig. 6. Note that the parts specified in the Parts List for use only with the 3-output unit are optional. If you leave them out, just be sure to put a jumper between pins 9 and 3 of IC2. Also note, that the 3–30 pF variable capacitor, C16, may need a bit of customizing in order to make it fit on the board. Just make sure that the middle terminal, and one of the side terminals, are soldered to the appropriate pads. Figure 7 shows a photograph of the fully assembled PC board.

If you use point-to-point wiring, it

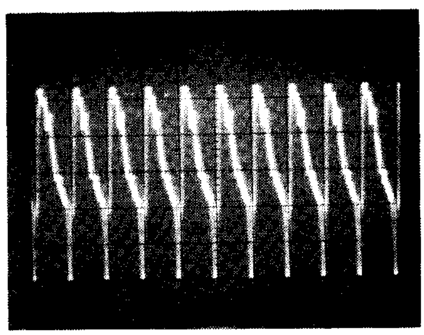


FIG. 9—HERE IS THE PLL's 5-volt peak TTL-compatible output.

is important to ensure that a good ground is available all around the board. That is best accomplished by running a piece of thickly braided shielding around the edge of the perforated circuit board. The braiding is attached to the metal chassis by heavy screws at both ends, and at the center of the perforated wiring board. The component layout is not critical; however, lead lengths should be kept as

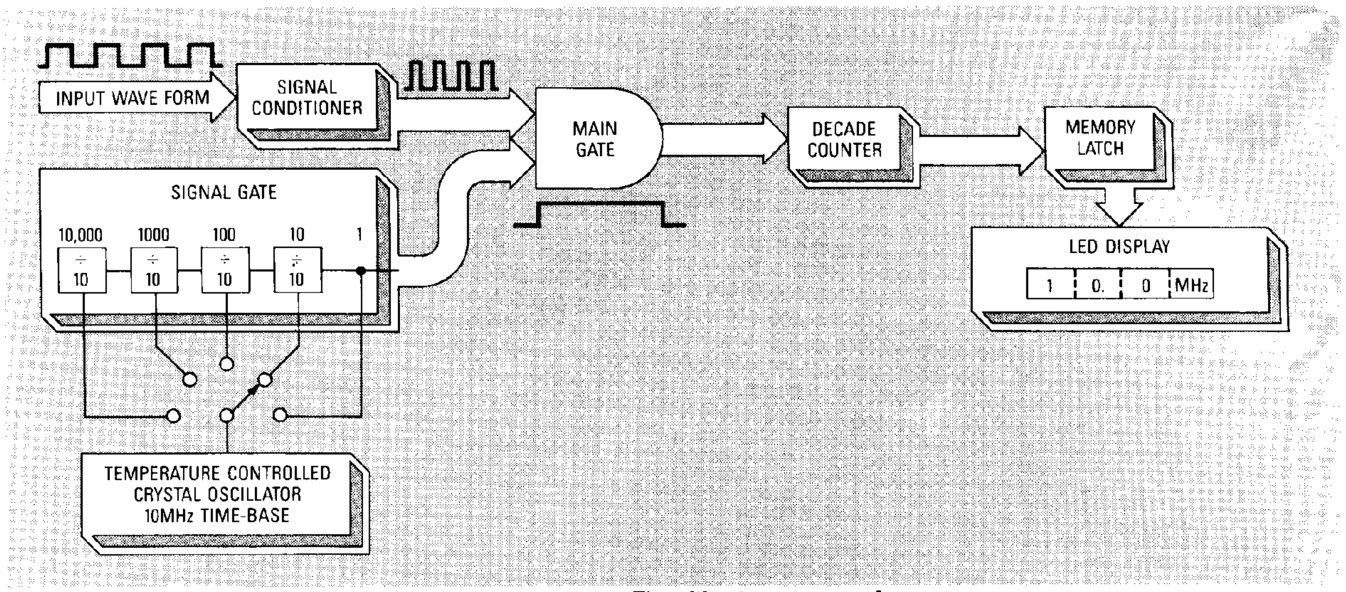


FIG. 10—HERE IS A BLOCK DIAGRAM of a frequency counter. The ultimate accuracy of your counter depends on the accuracy and stability of its time base.

short as possible (see Fig. 5). The perforated wiring board should be mounted in a metal box that is connected to the power supply's ground. For best results, an outside antenna should be connected to the receiver to ensure maximum signal strength.

Alignment

For alignment purposes, you will need an oscilloscope for waveform analysis, and a plastic alignment tool to adjust the trimmer components.

The first step is to balance the two inputs to IC1. Connect the radio's local-oscillator output, *but not the IF output*, to the main board via 50-ohm coax cable. Adjust the balance potentiometer (carrier null), R12, for a minimum-amplitude signal at pin 9 of IC1. The reasoning behind that adjustment is quite simple. When only one signal is input to a balanced modulator there is no heterodyning—therefore, no sum-and-difference output frequencies—and the original input frequency is highly attenuated.

The second step is to adjust the free-running frequency of the PLL's VCO to as close to 10 MHz as possible. That can be done using an oscilloscope, by adjusting trimmer-capacitor C16 so that the period of one complete output cycle is 0.1 μs.

Testing

Before attempting to lock onto the actual 10-MHz WWV signal, let's first test the 10-MHz *Time Kube* receiver and the locking ability of the PLL circuitry. That way you know that the calibration system is working. If you extend the receiver's antenna and the audio output is unintelligible, the chances are that WWV reception is poor. In that case, you'll want to use a directional outdoor antenna, or possibly try WWV reception at different times of the day or night.

Figure 8 shows the test setup. The frequency generator outputs a 100-kHz square wave. By wrapping the insulated center conductor (that carries the square wave from the generator) around the *Time Kube's* antenna, the 100th harmonic will be inductively coupled to the radio's antenna input, which is tuned to 10 MHz. Connect the *Time Kube's* local oscillator and IF outputs, via 50-ohm coax cable, to the main board's inputs. The Phase-Lock-Loop 10-MHz square-wave output is then coupled to CH-1 of your oscilloscope using a 50-ohm termination.

While triggering off the frequency generator's 100-kHz square wave on CH-2, tune the generator in and out a little. Eventually you will find a spot where the 10-MHz harmonic is picked up and the PLL output will lock-up (the 10-MHz signal will be displayed on CH-1). Adjust the PLL's loop-gain trimmer, R16, until the calibrator output can most easily lock onto the 10-MHz input signal. The PLL's 10-MHz output is a 5-volt square wave, as shown in Fig. 9.

Your frequency counter

A digital frequency counter is an instrument that can measure the frequency of any periodic waveform—a sine wave, a square wave, a triangular wave, etc. The frequency of that waveform is then shown on the counter's digital display.

Figure 10 shows a block diagram of a digital frequency counter. Keep in mind that it's the counter's crystal-controlled reference oscillator (time base) that will be calibrated. Once calibrated against the WWV signal, your counter can be used as a secondary reference source (now traceable to NBS) to measure other repetitive waveforms.

The input to the counter is fed into a signal conditioner that outputs one electrical pulse per input cycle. Those pulses having a constant amplitude and width drive the decade counters that follow. The signal-gate output controls the length of time that the main gate will allow the input pulses to pass into the decade counters. For example, when you set the counter for 0.1μs divisions, you're adjusting the length of time that the signal gate asserts the main gate. The frequency counter's time-base oscillator is used as a clock, and therefore must be as accurate as possible.

A counter's accuracy is dependent upon several factors, but it's the time-base generator that determines the ultimate accuracy of your measurement. Quite often, the difference in cost of one counter over another depends on the quality of the time base. You can consult the time-base specifications of your counter for its performance data.

Counter calibration

Now it's time to calibrate your frequency counter. First, connect the calibrator's 10-MHz square-wave output to the input of your counter, just as if you were going to measure the frequency of any other signal. Adjust the counter's time-base trimmer until the digital readout displays 10 MHz. That's it! Your frequency counter is now calibrated to the National Bureau of Standards WWV 10-MHz radio transmission, and is accurate enough to be used to calibrate your other test equipment.

Parts-per-million

Oscillator accuracy is usually expressed in parts-per-million (ppm), or sometimes as a percentage. One ppm is equivalent to 1×10^{-6}, or 1 divided by 1,000,000. That is equal to ± 0.000001. To get the accuracy in percentage, simply multiply by 100; that gives you $\pm 0.0001\%$. If the time-base has a frequency of 1 MHz, and an accuracy of 1 ppm, then it can be off by ± 1 Hz and still be within specifications.

As another example, suppose that a time base is specified as having an accuracy of 5%. That percentage represented as a decimal is equal to 0.05, or 5 parts per hundred, or 50 parts per thousand, or 50,000 parts per million. If you have a 1-MHz time base with an accuracy of 5%, then your oscillator's frequency can be off by ± 50 kHz, and still be within specifications. That doesn't sound too good for a 1-MHz oscillator, but if the time base is an audio oscillator, then 5% accuracy might be acceptable. In that case, the accuracy is 50 parts per thousand, or ± 50 Hz at 1 kHz.

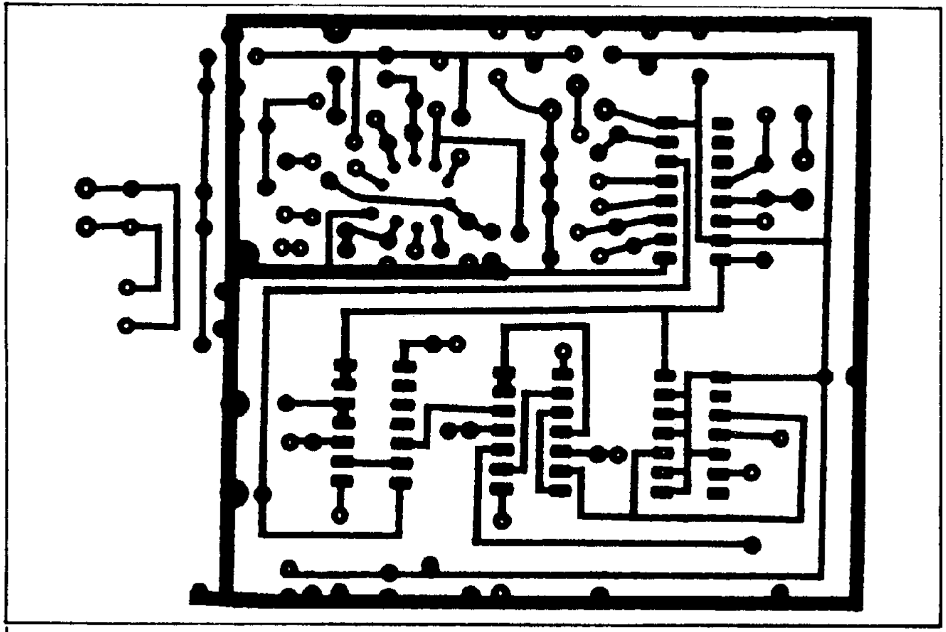
The WWV radio transmission

The most obvious sounds heard on WWV are the pulses that mark the seconds in each minute. At alternate minutes during most of each hour, a 500-Hz or 600-Hz tone is broadcast. A 440-Hz tone (the musical note "A" above middle "C") is broadcast once each hour, and can provide an hourly marker for chart recorders.

There has been a controversy over the years regarding whether the WWV signal, as received via ionospheric propagation, is accurate enough to calibrate the reference oscillators used in today's moderately priced frequency counters. A letter from John Henning that appeared in the "Letters" column of the June 1982 issue of **Radio-Electronics** takes the position that: "WWV as received via ionospheric propagation is not accurate enough to adjust the standard contained in many of today's moderately priced frequency counters." In contradiction to that statement, contacts at the Oscillator Characterization, Time and Frequency Division, Center for Basic Standards at NBS in Boulder Colorado say: "The WWV signal as received via ionospheric propagation is accurate enough to calibrate moderately priced (below $250) commercial frequency counters." Let's examine the reasoning behind that statement.

The RF transmission at WWV, which is controlled by their cesium atomic clock, is transmitted on 2.5, 5, 10, 15, and 20 MHz, and has an accuracy of at least 1 part per 100 billion at the time of transmission. However, the RF wave propagates by skipping between Earth and the ionosphere. The ionospheric skip is principally caused by the F_2 layer, whose height and density above Earth varies at different times of the day and night. The most stable propagation occurs during the daylight hours and during nighttime. (Most signal corruption occurs at sunrise and sunset, when the ionosphere's height above Earth is moving either up or down.) That movement causes a Doppler shift in the WWV RF-carrier as it is refracted back to Earth. The worst case would yield an RF-carrier accuracy of 0.1 parts-per-million (± 1 Hz per 10 MHz), but usually the accuracy would be much better.

Let's assume the WWV carrier's worst-case accuracy is 0.1 part per million. As a rule of thumb, to calibrate any device, your frequency standard should have an accuracy one order of magnitude better than the oscillator your calibrating. Therefore, because most moderately priced frequency counters have a reference-oscillator accuracy from 1 to 10 parts-per-million, the 10-MHz WWV RF transmission is useful as a calibration signal. On the other hand, if your reference oscillator is accurate to 0.1 part per million, or better, then the WWV signal is not accurate enough for your purposes. **R-E**



THE 10-MHz FREQUENCY STANDARD can be assembled on this PC board.