By H. Ward Silver, N0AX

The ARRL Frequency Measuring Tests

It's 14,349.50 kHz—do you know where your emissions are? One-half kHz below the top of the band, right? Maybe not!

With today's digital radios, it is easy to be complacent about frequency. In the days of slide-rule dials, hams had to be ever vigilant. Calibrations against W1AW or other Official Transmitting Stations were the rule. High-stability master oscillators and 10 Hz resolution make knowing one's frequency a lot easier, but the requirements to operate within license privileges are as strong as ever.

To that end, the ARRL is sponsoring a series of measuring tests, beginning with frequency. These tests will exercise the capabilities of hams to measure important operating parameters, improve their understanding of complex radios and give them a better mental picture of their transmitted signals. The goal is a more technically aware amateur confident of compliance with FCC regulations.

PART 1—BACKGROUND

History of the Frequency Measuring Tests

The first ARRL Frequency Measuring Test (FMT) was held in October 1931 and 213 measurement reports were received.[1,2] Winners demonstrated better than 99.99% accuracy and more than half received certificates for better than 99.90% accuracy. Participation was required of all stations in the Official Relay System, including the Official Observers.[3]

Until 1980, thousands of hams participated in the FMT.[4] The tests finally lost popularity due to the rapidly improving quality of radios. Twenty years later, it's time to revisit frequency awareness.

[1]Notes appear on page 54.

Precision, Accuracy and Stability

Precision is the smallest difference in frequency that can be displayed. At 28 MHz, precision of 10 Hz is equivalent to 0.36 parts per million (ppm).

Accuracy is a measure of how close the frequency displayed by the radio is to the actual frequency. For example, my FT-1000MP manual says displayed frequency will be ±7 ppm from the actual frequency.

Stability is the ability to remain at a specific frequency over time and temperature. My FT-1000MP specification is for ±10 ppm stability from –10 to +50° C. Table 1 contains accuracy and stability data for several common radios.

Frequency Displays

What is your radio actually displaying? This varies with operating mode, as shown in Table 2 and Figure 1. A transceiver may display the receive or transmit frequency. This varies by manufacturer and may be configurable.

On CW the radio listens at a frequency

Table 1
Display Configuration Capabilities of Some Transceivers

Transceiver	*Display Resolution (default)*	*Minimum Tuning Step*	*Warm-up Drift (1st Hour)*	*Display Error After Warm-Up*
ICOM IC-781	10 Hz	10 Hz	± 1 Hz	10 Hz
Kenwood TS-2000	10 Hz	<1 Hz ("fine")	± 4 Hz	<10 Hz
Yaesu FT-1000	100 Hz	10 Hz	± 2 Hz	<100 Hz
Yaesu FT-1000MP Mark V	10 Hz	0.62 Hz (menu adjustable)	± 1 Hz	<10 Hz

Table 2
How Mode Affects the Frequency the Transceiver Displays

Mode	*Transmitted Carrier Frequency*	*Transmitted Signal Occupies*	*The Radio Displays*
CW	14,040.00 kHz	14,039.75-14,040.25 kHz Assuming a 500 Hz wide signal	14,040.0 kHz
LSB	14,200.00 kHz	14,199.70-14,197.00 kHz Assuming 300-3000 Hz audio	14,200.00 kHz
USB	14,200.00 kHz	14,200.30-14,203.00 kHz Assuming 300-3000 Hz audio	14,200.00 kHz
AM	14,200.00 kHz	14,197.00-14,203.00 kHz Assuming 300-3000 Hz audio	14,200.00 kHz
FM	29,600.00 kHz	29,603.00-29,597.00 kHz Assuming 300-3000 Hz audio	29,600.00 kHz

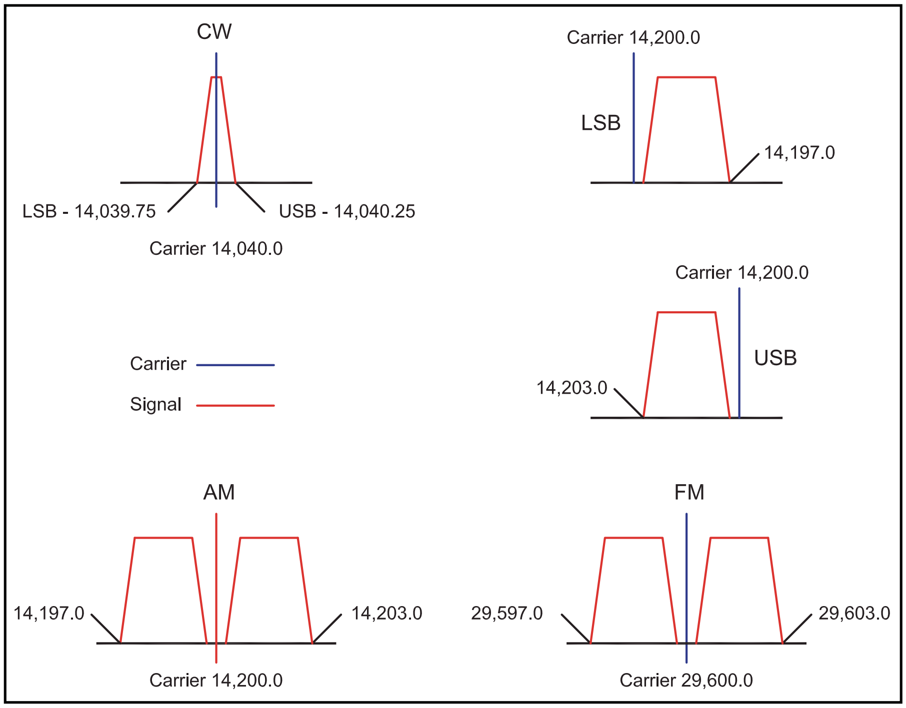

Figure 1—A depiction of how the frequency-display data in Table 2 was derived.

slightly different from that of the transmitted signal to generate the audio tone you hear. Similar considerations apply to frequency-shift keying (FSK) mark and space tones.

On AM, SSB and FM the radio displays the carrier frequency of the signal. On AM and FM, the carrier frequency is in the middle of your transmitted signal.

You must know where your transmitted signal is with respect to the displayed frequency! This is essential for both compliance with your license privileges and for operating convenience. The article cited in Note 5 provides an excellent explanation of how frequency displays actually work. It is available from the ARRL Technical Information Service at **www.arrl.org/tis/info/using-equip.html**.

Radios may also be configurable to display frequency in different ways. It is necessary to read the operator's manual carefully to determine exactly how the configuration settings and values affect the display. If you buy a used radio, be aware that the previous user may have changed the display configuration.

How Wide is a Signal?

What constitutes the limits of a signal? No signal or filter is perfect, so all signals have components, however weak, that extend beyond the main signal. How much of that spurious output is considered in determining where you are transmitting? What does the FCC consider the limits of a signal?

FCC rule 97.307(c) specifies an absolute power level of 50 mW for spurious emissions as well as a minimum amount of attenuation from the peak signal level.[6] The amount by which spurious output signal components must fall below the peak signal level varies from 30 dB for QRP, to 40 dB for "barefoot," to 44 dB for full-power HF operation.

It's a myth that CW is a zero-width emission. Any time a carrier is turned on and off, sidebands appear with a width determined by the rise and fall times. Words-per-minute has little effect. A CW signal with rise and fall times of 2 ms will be approximately 400 Hz wide. Shorter rise and fall times broaden the signal.

On phone, signal width depends on the shape of your audio and sideband filters, plus the microphone gain, compression and ALC settings. We'll discuss signal bandwidth in a subsequent article.

Band-Edge Examples

Example 1

You are operating CW on the 10 MHz band with a radio whose manufacturer specifies ±10 ppm accuracy. The radio is configured to use USB and displays the carrier frequency without including any tuning or pitch offsets. How close to the band edge can your displayed frequency be?

The worst-case difference between the displayed and actual signal frequencies is equal to one-half the signal bandwidth plus the accuracy variation. At 10 MHz, the maximum variation of 10 ppm is 100 Hz. For a CW waveform rise and fall time of 2 ms, half the signal's bandwidth of 400 Hz is 200 Hz.

When using USB, the difference is subtracted from the displayed receive frequency. This means that the lowest displayed frequency at which you can have confidence you are operating legally is 10,100.30 kHz.

Example 2

You are operating LSB on the 3.5 MHz band with a radio whose manufacturer specifies ±12 ppm accuracy and uses a 2.4 kHz filter. Assuming you are not overmodulating or splattering, how close to the General class band edge of 3850 kHz can you tune?

At 3850 kHz, 12 ppm is 46 Hz. Since data for a radio's SSB bandwidth is difficult to specify exactly, assume a full 3 kHz sideband width. On LSB, both the display uncertainty and the sideband width must be added to the band edge to find the displayed carrier frequency.

3850 kHz + 0.046 kHz + 3 kHz = 3853.046 rounded to 3853.05 kHz

This is the lowest displayed frequency at which your signal will be sure to meet the General class license privileges—more than 3 kHz from the band edge!

PART 2—MEASUREMENT

Practicing Frequency Measurement

Good frequency standards are the Standard Time and Frequency stations WWV, WWVH[7] and CHU.[8] WWV and WWVH modulate their AM signals with a 500 Hz tone, while CHU uses an FSK data signal. You can use these audio tones and your own ears to measure your receiver's accuracy quickly.

Tune to the highest standard you can clearly receive. Switch back and forth between USB and LSB while adjusting frequency until the audio modulation is the same pitch. The steady tones transmitted by WWV and WWVH are easier to compare. The difference between the displayed frequency and the known standard frequency is the display error.

How To Measure Frequency

It's not that difficult...

The Basics

The simplest form of frequency measurement—reading the receiver display—depends entirely on the quality of the receiver's master oscillator. If you measure your display error regularly and find it to be consistent and predictable, your measurement can be accurate to about twice

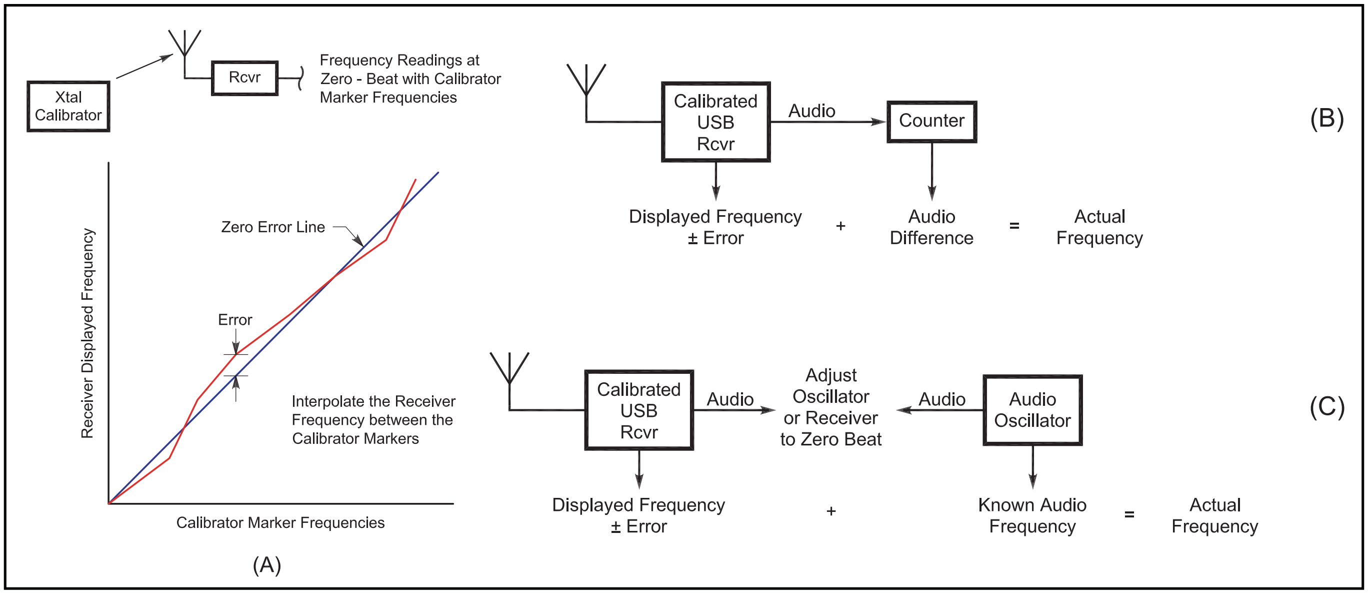

Figure 2—Three ways to make receiver-dependent measurements. The technique shown in A uses a traditional calibrator, B shows how a counter is used and C shows how to use a calibrated oscillator.

the precision of the frequency display; that is, ±10 Hz or 1 ppm at 10 MHz. As the receiver drifts, so does the measurement.

Figure 2 shows three other techniques that use the receiver to make comparisons using a calibrator, calibrated oscillator or frequency counter. Figure 2A shows the traditional calibrator measurement. The calibrator generates markers every few kilohertz. The receiver's error is charted across the band by zero-beating the receiver at each of the calibrator's markers. Interpolation is used between marker frequencies. *The ARRL Handbook* describes a crystal calibrator that can generate markers on all of the amateur HF bands.[9]

Figure 2B shows a counter used with a receiver tuned to an unknown frequency within ±5 kHz of the test frequency. The receiver stays tuned to this frequency. When the test signal appears, its audio tone is measured by the counter. If the receiver's oscillator drifts during the measurement, that error will be included in the test source's frequency. Figure 2C shows a calibrated oscillator used in the same way.

In Figures 3A and B, no direct reading of receiver frequency is made. The method of Figure 3A requires calibrator markers every 10 kHz and a frequency counter. The receiver is tuned to within ±5 kHz of the test signal and the audio from the nearest marker is measured by the counter. When the test signal appears, the markers are removed and the audio from the test signal is measured. Since the marker frequency is known, the test signal frequency is the marker frequency plus the difference in audio frequencies.

In Figure 3B the markers are replaced with a transmitter connected to a dummy load and counter. The transmitter is then tuned until the operator detects zero beat. Frequency is read directly from the counter.

When performing zero-beat measurements, the receiver AGC should be set to FAST or turned OFF. This minimizes AGC-induced level changes that might mask or interfere with the low-frequency beat. At beat frequencies below 10 Hz, the beat will only be audible as a slow rise and fall of the received signal strength or of the signal's modulation.

There are many variations on these basic themes. Feel free to experiment! For readers interested in the history of frequency measurement by amateurs, Note 10 describes the use of the BC-221 frequency meter (see Figure 4).

Effects of Sky Wave Propagation

Another source of error is Doppler shift of the reflected signal due to vertical movement of the ionosphere's reflecting layers. This can introduce transient errors of less than 1 ppm generally lasting no more than a few seconds.

Stations near the limits of ground wave propagation may experience very short duration errors due to interference between sky and ground wave signals. For stations relying on sky wave signals, taking measurements at regular intervals and averaging them minimizes the temporary Doppler shifts errors.

Reducing and Compensating for Errors

The two most effective methods of reducing error are to eliminate temperature changes and to make repeated, regular measurements.

Temperature changes affect the physical characteristics of the oscillators, causing changes in frequency. Simply leaving the equipment on for several hours before the tests greatly enhances stability. If possible, the equipment should be in a room kept at a stable temperature. Frequency standards are best left on continuously. Spreadsheets can be used to average or otherwise process the data so that offsets, drift and repetitive errors can be removed.

What the Heck is Zero-Beat?

The term "zero beat" has been around ham radio a long time. While the original usage has drifted, the intent remains the same. Zero beat is the condition in which two signals are transmitted with exactly the same carrier frequency.

Back in the "good old days" (or "dark ages" depending on when you were first licensed) receivers and transmitters were completely separate. The receiver was tuned to the desired frequency and then the transmitter would output a very low-power "spotting" signal (this is where the term "Spot" comes from). The two signals caused a beat frequency in the receiver equal to their difference. When both signals were on the same frequency, the beat frequency dropped to zero—"zero beat." On CW you tuned to the received signal directly and on AM, to the carrier. On SSB there is no beat to zero, but the condition of being exactly on frequency is still called zero beat.

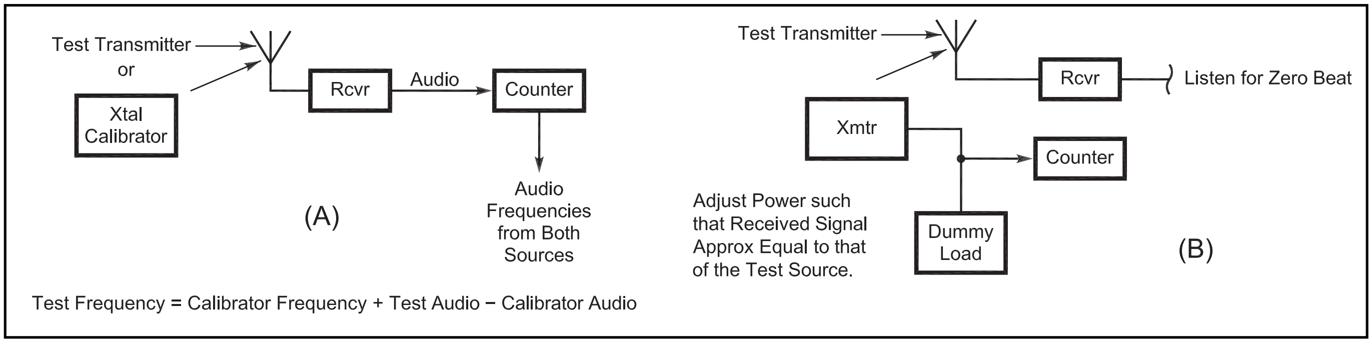

Figure 3—Measuring frequency with a calibrator independent of the receiver. The method used at A requires calibrator markers every 10 kHz and a frequency counter. At B, the markers are replaced with a transmitter connected to a dummy load and counter.

PA0PCR

Figure 4—The SCR-221/BC-221 frequency meter, a precision instrument used in both military and civilian applications.

The 2002 ARRL Frequency Measuring Test

Schedule

The first W1AW FMT will run November 7, 2002 at 0245Z (November 6, 2002, 9:45 PM EST). It will replace the W1AW Phone Bulletin normally scheduled at that time. It is recommended that participants listen to W1AW's transmissions prior to the event to get an idea of conditions and to see which band (or bands) will be best for measurement purposes.

Format

The FMT will begin with a general W1AW (*QST*) call beginning exactly at 0245Z sent simultaneously on four amateur frequencies. The test will consist of 20-second key-down transmissions, followed by a series of dits, followed by station identification.

The test will last for a period of approximately 5 minutes total. The test will end with a series of Vs, followed by station identification. W1AW will identify before, during and after the transmissions.

The approximate frequencies are as follows:

80 meters	3580 kHz
40 meters	7047 kHz
20 meters	14,048 kHz
15 meters	21,068 kHz

Reporting and Results

The submitted report should include the time of reception, frequency measured and signal report, in addition to name, call and location. If possible, participants should submit reports on more than one band (but not necessarily on all four).

A Certificate of Participation will be available to all entrants. Those entrants who come closest to the measured frequency as measured by the ARRL Laboratory will be listed in the test report and will also receive special recognition on their certificate.

Entries should be postmarked by December 6, 2002 to be eligible. Send entries to W1AW/FMT, 225 Main St, Newington CT 06111, USA.

If you would like more information about the equipment that will be in use at W1AW to generate the test signals, take a look at **www.arrl.org/w1aw.html**. For more information about the FMT, including a Frequently Asked Questions list, copies of the articles listed in the Notes and updates to test schedules, a Web page has been prepared at **www.arrl.org/w1aw/fmt**.

In Conclusion

As Amateur Radio prepares to enter its second century, fundamentals remain vitally important. The techniques of frequency measurement are within the capabilities of nearly everyone—we hope we'll see your report!

Notes

[1]Handy and Lamb, "The Frequency Measuring Test," *QST*, Sep 1931, p 36. This article and others mentioned in the Notes are available at **www.arrl.org/w1aw/fmt**.

[2]Handy, "Frequency Measuring Test Results," *QST*, Jan 1932.

[3]Official Observers were required to demonstrate an accuracy of at least 71.43 ppm to receive Class 1 status.

[4]Wood, "Try the FMT!!!," *QST*, Jul 1970, p 54.

[5]Newkirk, WJ1Z, "What Your Frequency Display Really Tells You," *QST*, Aug 1991, p 28, and Sep 1991, p 26.

[6]Part 97.307(c), *The ARRL's FCC Rule Book*, 12th Ed. (Newington, CT: ARRL). ARRL Order No. 7857 from ARRL Publication Sales, 1-888-277-5289 (toll-free) or from *ARRLWeb* (**www.arrl.org/shop/**).

[7]**www.boulder.nist.gov/timefreq/stations/wwv.html**.

[8]**www.nrc.ca/inms/time/chu.html**.

[9]*ARRL Handbook for Radio Amateurs* 79th Ed. (Newington: ARRL), "A Marker Generator with Selectable Output," p 26.16.

[10]Sapp, W4AWY, "Frequency Measurement with the LM/BC-221," *QST*, Sep 1965, p 28.

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