Technical Correspondence

Edited by **Paul Pagel, N1FB** • *Associate Technical Editor*

DIRECT-CONVERSION RECEIVER NOISE FIGURE

By Rick Campbell, KK7B
Department of Electrical Engineering
Michigan Technological University
1400 Townsend Dr, Houghton, MI 49931
email **rlcampbe@mtu.edu**

◊ The noise figure of a receiver may be calculated using the "noise figure of cascaded stages" formula. The formula states that the early stages of a receiver must have a low noise figure and enough gain to override the noise contributions of the following stages. The R1 "High-Performance Direct-Conversion Receiver"[1] was designed for maximum close-in dynamic range. One of the design rules for close-in dynamic range is to keep the gain at a minimum before the high selectivity elements. The gain before the main filter element is thus a compromise between lowest noise figure and best close-in dynamic range.

Over the years, I developed a simple test for adequate noise figure and gain in the first audio preamp of a direct-conversion (D-C) receiver. If the receiver noise output increased when the local oscillator (LO) was turned on, then the noise from the mixer was greater than the noise of the audio stages in the receiver. The R1 and R2 receivers were designed using this test. The noise figure of a lossy mixer followed by a low-noise amplifier is approximately the mixer loss plus the amplifier noise figure.[2] For the R1 and R2, the mixer loss is about 6 dB, the diplexer loss is about 2 dB and the audio preamp noise figure is about 5 dB, so the total noise figure should be about 13 dB. This assumes that the audio preamp has enough gain to override the noise contributions of the following audio stages.

When the prototype Rl and R2 receivers were measured, they had disappointing 18 to 20-dB noise figures, even though they had adequate audio-preamp gain and noise figure according to the test described earlier. One possible source of noise had been neglected in the Rl and R2 design: excess mixer noise. Excess mixer noise is usually neglected in diode-mixer engineering at HF. A review of the professional literature produced several references to l/f noise in Schottky diodes, including several curves showing audio-noise levels sufficient to produce the results obtained with the Rl and R2. To look for evidence of 1/f noise, the prototype receivers were connected to an HP 3582A audio-spectrum analyzer. The LO was turned on and off to enable and disable the mixer diodes. Figure 1 is typical of the plots obtained. The change in noise spectrum is clear. The receiver noise figure is apparently dominated by mixer-diode 1/f noise, and there was nothing to be gained by reducing the noise figure of the audio preamplifier or adjusting the audio gain distribution. The Rl article was published at this time.

Dissent

Hundreds of Rl receivers were built around the world after the August 1992 *QST* article appeared. Wes Hayward, W7ZOI, built one (using ugly construction, of course!) and compared it with previous mixer-only D-C receivers used at his location. His "calibrated ears" told him that the preamp gain was low, so he modified the audio-preamp design for more gain, and noted an improvement in sensitivity. He then supported his on-the-air observations with measurements and communicated his findings to me. Maybe 1/f noise was not a fundamental limitation after all...

More Measurements

The first step was to duplicate Hayward's results. The preamp modification was added to the original R1 prototype; careful measurements revealed a noise figure of 13.5 dB. The next step was to find the flaw in the l/f noise analysis and measurements. A second set of measurements was made using the experimental setup in Figure 2. This time, instead of merely turning off the LO to disable the mixer diodes, the audio preamp was switched between the mixer IF port and a 49.9-Ω metal-film resistor. The original R1 displays little change in the receiver-output spectrum when the preamp is switched between the mixer and resistor. After Hayward's modification, a small increase in noise output occurs with the mixer connected, but the additional noise is flat across the receiver bandpass. A typical

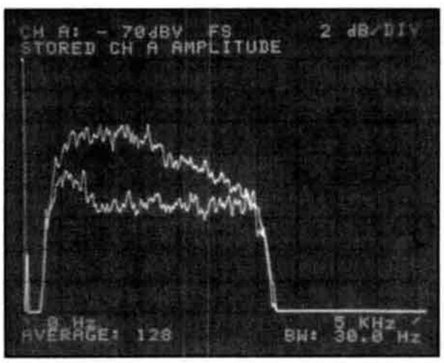

Figure 1—R1 audio-output spectrum with the receiver input connected to a 50-Ω resistor. The vertical divisions are 2 dB and the horizontal scale ranges from 0 to 5 kHz. The upper trace is with the LO on and the lower trace is with the LO off. Note the difference in the spectrum shape.

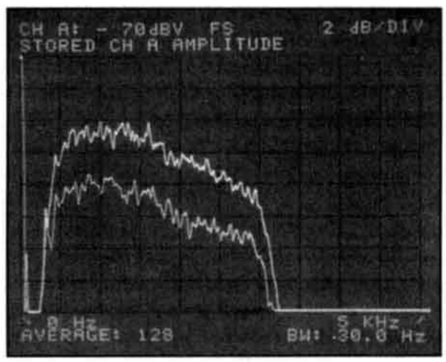

Figure 3—R1 audio output spectrum using the test setup of Figure 2. The vertical divisions are 2 dB and the horizontal scale ranges from 0 to 5 kHz. The upper trace is with the mixer connected and the lower trace is with the 49.9-Ω metal-film resistor connected. There is no difference is spectrum shape.

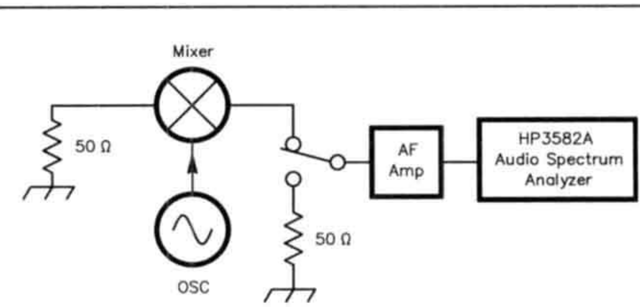

Figure 2—Mixer noise-test setup. The input to the audio preamp is connected to either the mixer with the LO on, or a 49.9-Ω metal-film resistor.

[1]Notes appear on page 84.

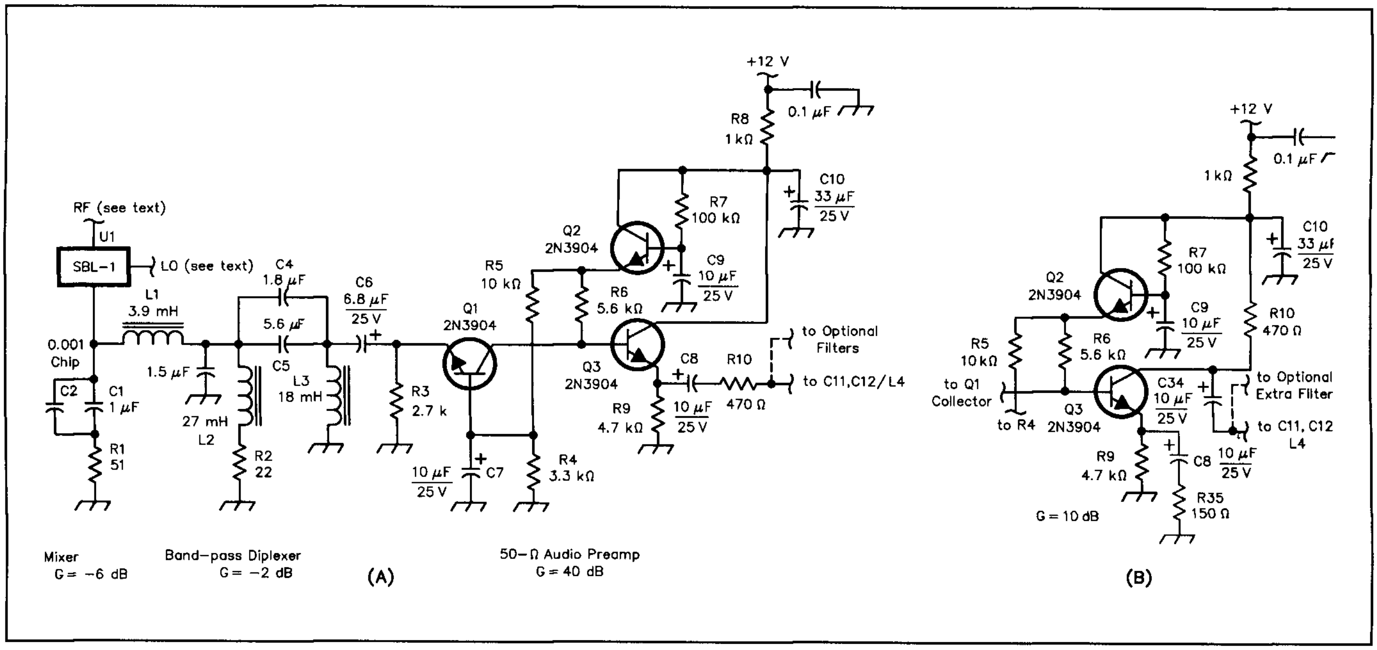

Figure 4—At A, the original R1 and R2 input-stage circuit. When the LO is off, the mixer IF port is an open circuit at audio frequencies. At B, the R1 input-stage schematic showing the modifications made by Wes Hayward, W7ZOI. This modification is included on all R1 circuit boards and kits sold by Kanga US.

output spectrum for the new measurements (Figure 3) shows no evidence of l/f noise.

The error in the first set of measurements may be seen by looking at Figure 4A, the schematic of the R1 input stage. The grounded-base, low-noise audio preamp is connected to the mixer through a diplexer network. When the mixer has LO drive, the mixer IF port has an impedance of about 50 Ω. When the LO is off, the diodes are off, and the IF port is an open circuit. Turning the LO on and off thus has the effect of dramatically altering the impedance of the network connected to the input of the low-noise preamp. A detailed analysis isn't needed to see the result—simply recall that the gain of a grounded-base amplifier is approximately the ratio of the output impedance to the input impedance. Turning off the mixer diodes lowers the gain of the preamp and changes the noise spectrum by modifying the frequency response of the input network. For the Rl and R2 input networks, the difference in spectrum shape has nearly a 1/f response over much of the passband. Not only were the original measurements misleading, but the "simple test for adequate gain and noise figure" is meaningless for this particular D-C receiver topology.

Improving the Noise Figure of the R1

The mixer loss in the R1 is about 6 dB. The diplexer has a loss of a little more than 2 dB. The audio preamp has a noise figure of about 5 dB and a gain of 40 dB. The audio preamp drives the resistive filter-matching network, the low-pass filter and the filter termination/volume control. It's easy to lose much of the preamp gain before arriving at the input to the first LM387 section. The LM387 has a noise figure of about 13 dB when driven by a source with an impedance of 500 Ω. A large increase in preamp gain will improve the noise figure of the R1, but greatly reduces the close-in dynamic range. Most of the noise figure improvement can be obtained with a 10-dB increase in preamp gain.

The Hayward modification is shown in Figure 4B. It's been incorporated in all of the R1 boards sold by Kanga US, and is easily added to earlier R1 PC boards as a "flying mod." The 5 or 6-dB improvement in R1 noise figure is worthwhile on 40 and 30-meter rigs without RF preamps. For rigs with preamps, and for 80 and 160-m rigs used with full-size antennas, the improved sensitivity is probably not needed and the slight reduction in close-in dynamic range might be noticed.

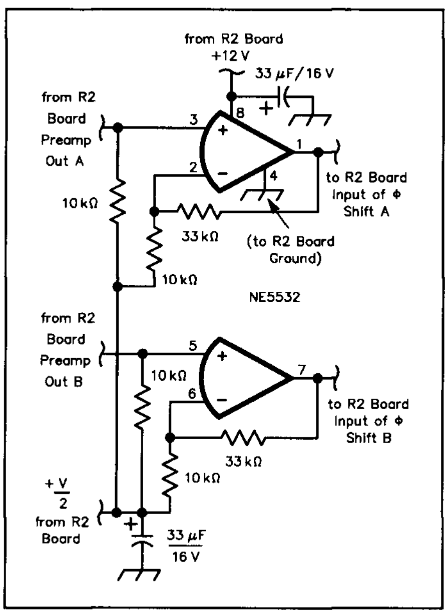

Figure 5—Audio amplifier stage added to the R2 board between the preamps and audio-phase-shift networks.

Improving the Noise Figure of the R2

In the R2, the outputs of the two preamps drive the audio-phase-shift network. The noise figure can be improved simply by using low-noise op-amps for the audio-phase-shift network and increasing the gain of the op-amp summer before the main selectivity filter. This option has not been explored in detail, but a 3 or 4-dB improvement in R2 noise figure has been noted simply by replacing the originally specified NE5514 quad op amps with TL074 low-noise op amps. (There are probably better choices, as the output drive capability of the TL074 is poor.) After changing to low-noise op amps, the gain can be adjusted by changing the feedback resistor in the op-amp summer at the outputs of the audio-phase-shift network.

Another option is to add a low-noise dual op amp between the grounded-base preamps and the phase-shift network. An NE5532 mounted on a small scrap of unetched PC board is a good choice. All of the power supply, ground, input and output connections are available on the R2 PC board near the input to the audio-phase-shift network. A 14-MHz R2 with the added dual preamp shown in Figure 5 has a measured 14-dB noise figure.

The miniR2 Input Circuit

The miniR2 has a different design and

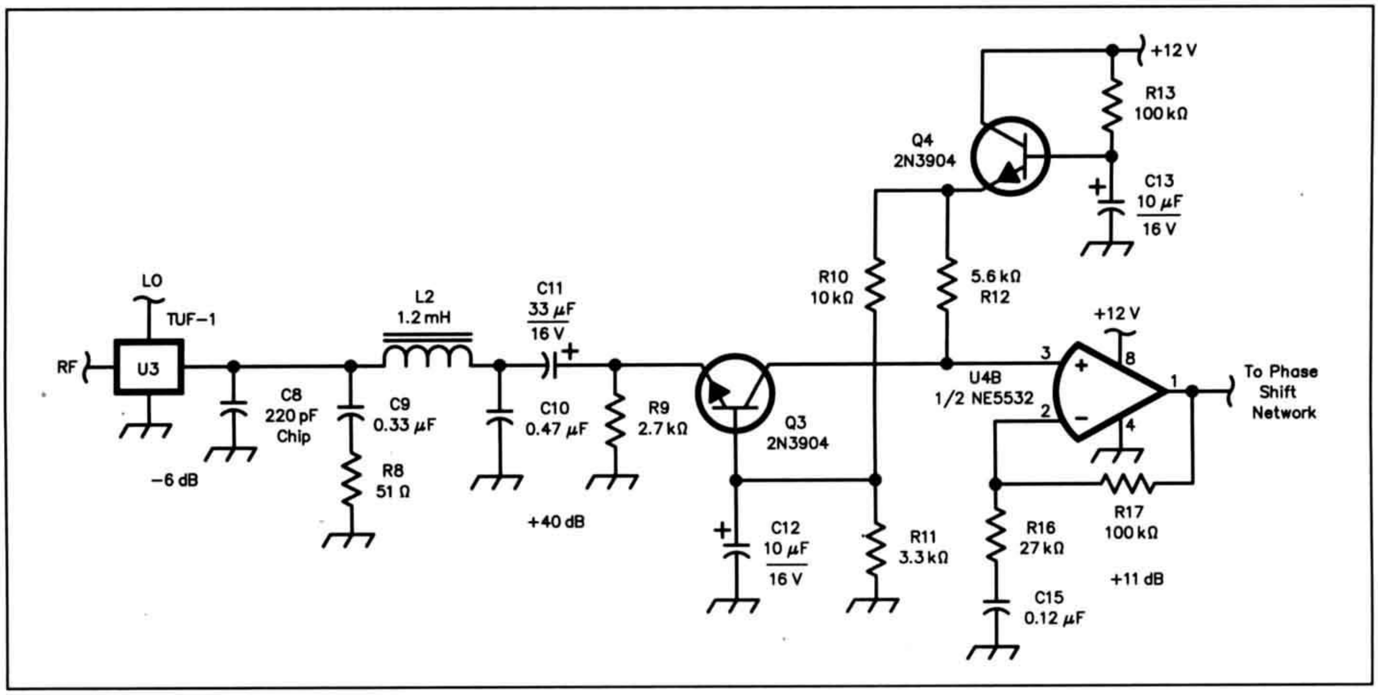

Figure 6—Audio preamplifier used in the miniR2. The overall gain of 50 dB is a reasonable compromise between close-in dynamic range and noise figure.

application emphasis than the Rl and R2. The Rl and R2 were designed for maximum close-in dynamic range. After they were introduced, many builders (including me) expressed the desire for a simpler image-reject version that didn't require hand-matched diplexer components. Other desirable qualities were reduced parts count, smaller size, reduced current drain and lower cost. The miniR2 was optimized subject to these constraints. To meet the size, cost, parts count and off-the-shelf parts requirements, the diplexers were simplified. Although they look deceptively like the version used by Roy Lewallen in his "optimized" transceiver,[3] the diplexers were actually designed to have repeatable phase and amplitude matching across the audio passband using 10%-tolerance components.

To reduce the size and current drain, the audio power-output stage was eliminated. The miniR2 drives headphones or an external powered speaker. Finally, to reduce the size, the mixers were changed to the TUF package and the low-pass filter was reduced from a 7th order to a 5th order filter.

The preamps for the miniR2 use the circuit shown in Figure 6. An NE5532 low-noise op-amp stage replaces the emitter-follower used in the original R1 and the R2. The preamp gain is set by the feedback resistor, and can be easily altered for the best compromise between noise figure and close-in dynamic range. The simplification of the diplexer network results in lower loss before the audio preamp, which reduces the system noise figure. The measured noise figure of several miniR2 receivers is about 11 dB. The improved noise figure of the miniR2 results in improved dynamic range using the ARRL Lab's standard signal spacing of 20 kHz. With standard level mixers and SSB bandwidth, the measured two-tone third-order dynamic range of a miniR2 on 14 MHz is about 96 dB. This is in the same ballpark as the best commercial receivers measured at ARRL labs.

Notes

[1]Rick Campbell, KK7B, "High Performance Direct Conversion Receivers," *QST*, Aug 1992, pp 19-28

[2]Richard Campbell, KK7B, "Low-Noise Receiver Analysis," *Proceedings of Microwave Update '91*, ARRL publication number 147, ISBN: 0-87259-370-3, pp 1-13.

[3]Roy Lewallen, W7EL, "An Optimized QRP Transceiver," *QST*, Aug 1980, pp 14-19.

[4]The Rl, R2 and miniR2 boards and kits are available from Kanga US, 3521 Spring Lake Dr, Findlay, OH 45840, tel 419-423-5643; e-mail: **kanga@bright.net.**

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