

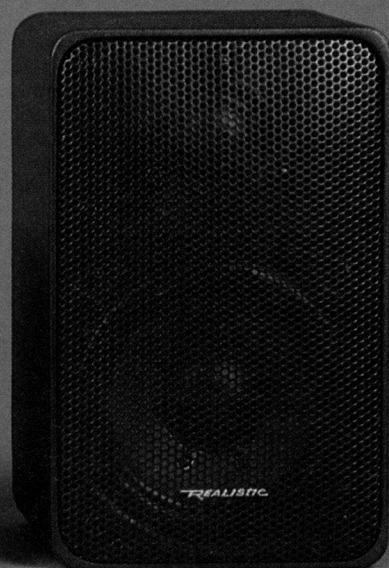
High-Performance Direct-Conversion Receivers

High dynamic range, low-distortion audio, 1.6:1 SSB filter shape factor... the latest \$4000 transceiver from Japan?

No—a diminutive PC-board direct-conversion receiver from KK7B!

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In this article I'll describe two high-performance direct-conversion receivers that are part of a series of SSB and CW receivers I've been experimenting with. Each receiver is engineered for a very specific purpose and is designed from the ground up to perform one task as well as possible. *Classic 40* is a high-dynamic-range, high-fidelity direct-conversion receiver for the 40-meter band. *Sisu* is a simple, compact, high-performance add-on receiver for use with VFO-controlled QRP transmitters. *Classic 40* and *Sisu* share a common building block—a compact 2.5 × 3.5-inch PC board that contains most of the circuitry. (I call this the R1 receiver board.)

These designs are considerably less complicated than commercial multiband, multi-mode receivers, yet they achieve performance levels equal to the best laboratory equipment. There are no bells and whistles here—the goal is the best possible *basic receiver performance*. The only constraint is reproducibility. PC boards and parts are available, so you will have no trouble building a receiver for your station.¹

A few engineering methods applied to these receivers are somewhat uncommon to amateur projects. Every circuit was analyzed and optimized using textbook engi-

neering and the computer circuit-modeling program *PSPICE1*.² Circuitry was borrowed from the amateur and professional literature, dissected to the component level, entered into the computer, and studied to discover the effects of component tolerances, audio distortion, dying batteries and a host of other real-world problems. Individual stages were then breadboarded and bench tested to confirm the computer predictions. In many cases, previously published designs were found to be at least as good as anything new that I could generate. In the few cases where I was able to make significant improvements, the best of the previously published designs was built to serve as a benchmark.

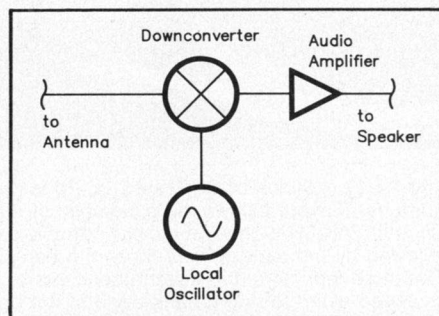


Fig 1—Block diagram of a direct-conversion receiver.

Although these designs are “optimum” in some sense of the word, each one represents only one of many possible “optimized” receivers for the same application. My intent in publishing this information is not to close the book on SSB/CW receiver design, but to add a few chapters. I hope that these designs inspire further modifications and improvements. When amateurs begin concentrating on good basic receiver performance, manufacturers will follow, and in a few years I may find a new commercial transceiver that sounds as good as my home-brew receivers.

The Classic 40

This receiver is built to show how good a direct-conversion receiver can be. Ever since direct-conversion receivers became popular in the late 1960s, authors have raved about the clean direct-conversion sound, “like a window on the band.” Yet direct-conversion receivers have also earned a reputation for a set of particularly obnoxious problems: hum, microphonics, limited dynamic range, AM broadcast detection, and insufficient audio gain and output level for comfortable listening with a speaker. Several commercial direct-conversion transceivers have suffered from all of the above ills.

The currently popular NE602-LM386 receivers, in particular the Neophyte³ and its English cousin the Sudden,^{4,5,6} have

¹Notes appear on page 28.

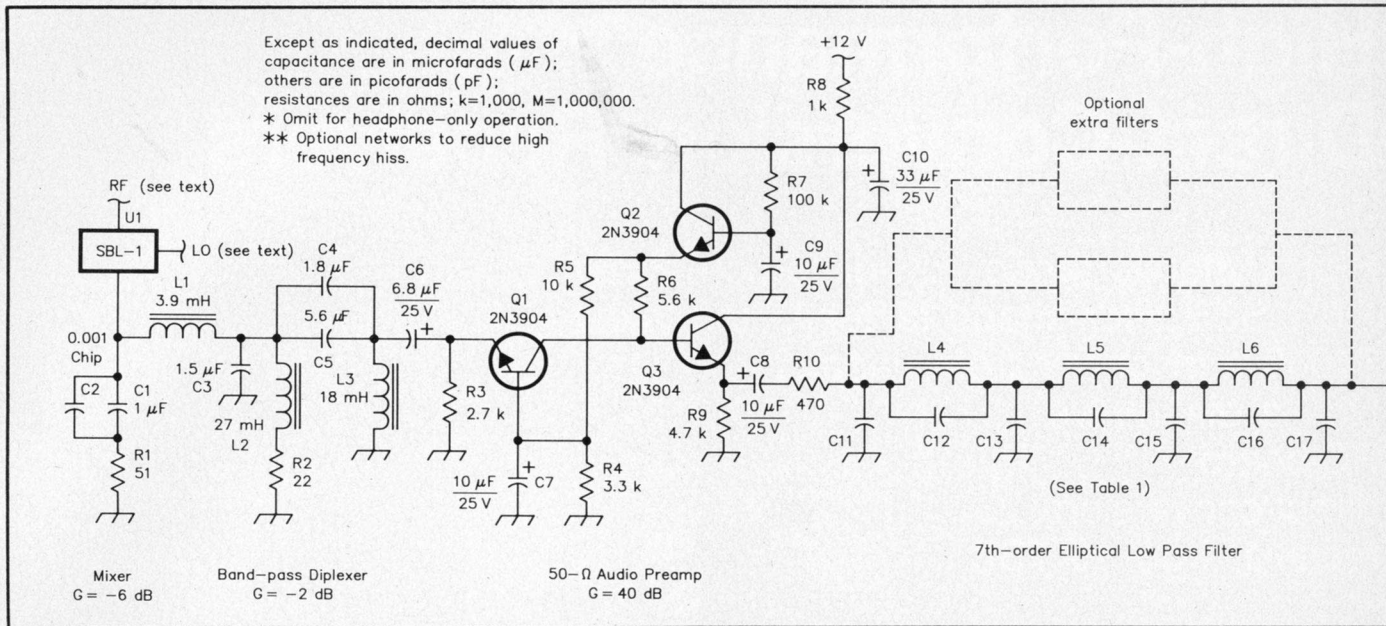


Fig 2—The R1 receiver board is the basic building block for the Classic 40 and Sisu receivers. All parts except the mixer (U1) are available from Digi-Key; kits are available (see note 1). Resistors are 5%-tolerance carbon-film or -composition units. Inductors are Toko 10RB series fixed inductors. Polarized capacitors are aluminum electrolytics rated at 25 V dc. The capacitors in the diplexer (C1, C3-C5) and 300-Hz high-pass filter (C23, C24) are Panasonic type ECQ-E(F) 100-V, 10%-tolerance miniature metalized polyester film capacitors. The capacitors in the low-pass filter (C11-C17) are Panasonic V-series 50-V, 5%-tolerance metalized film capacitors, except C12 in the 3000-Hz elliptical filter, which is a 0.0068- μF , 50-V Panasonic P-series polypropylene capacitor. C19, C21, C25, C28 and C29 are NP0 disc-ceramic capacitors. C18, C20, C22, C26 and C32 can be metalized polyester or disc-ceramic capacitors.

C2—0.001- μF chip capacitor. This part is necessary only if the board is used at VHF or UHF.

R11—500- Ω audio-taper control.
 R24—10-k Ω single-turn PC-board-mount control (Panasonic MAG14 or equivalent).

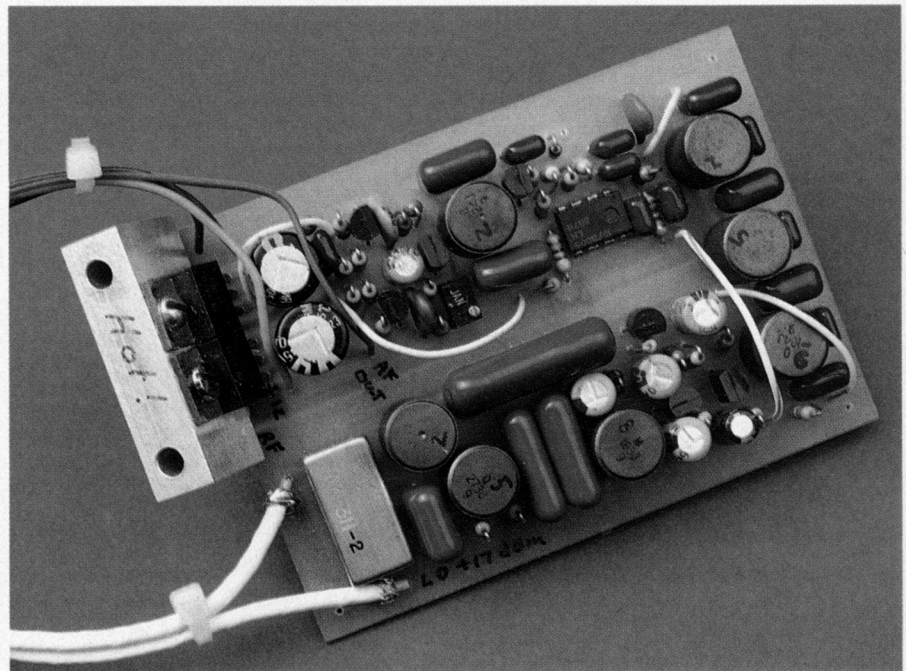
U1—Mini-Circuits SBL-1 double balanced mixer. A TAK-3H mixer may be substituted if higher dynamic range is needed (see text).

done much to prove that an adequate receiver can be built for very little money with very few components in a very small box. Unfortunately, the NE602 crumbles with a 40-meter dipole connected to the input, and the NE602-LM386 pair has noticeable distortion when driving a small speaker with multiple CW signals.

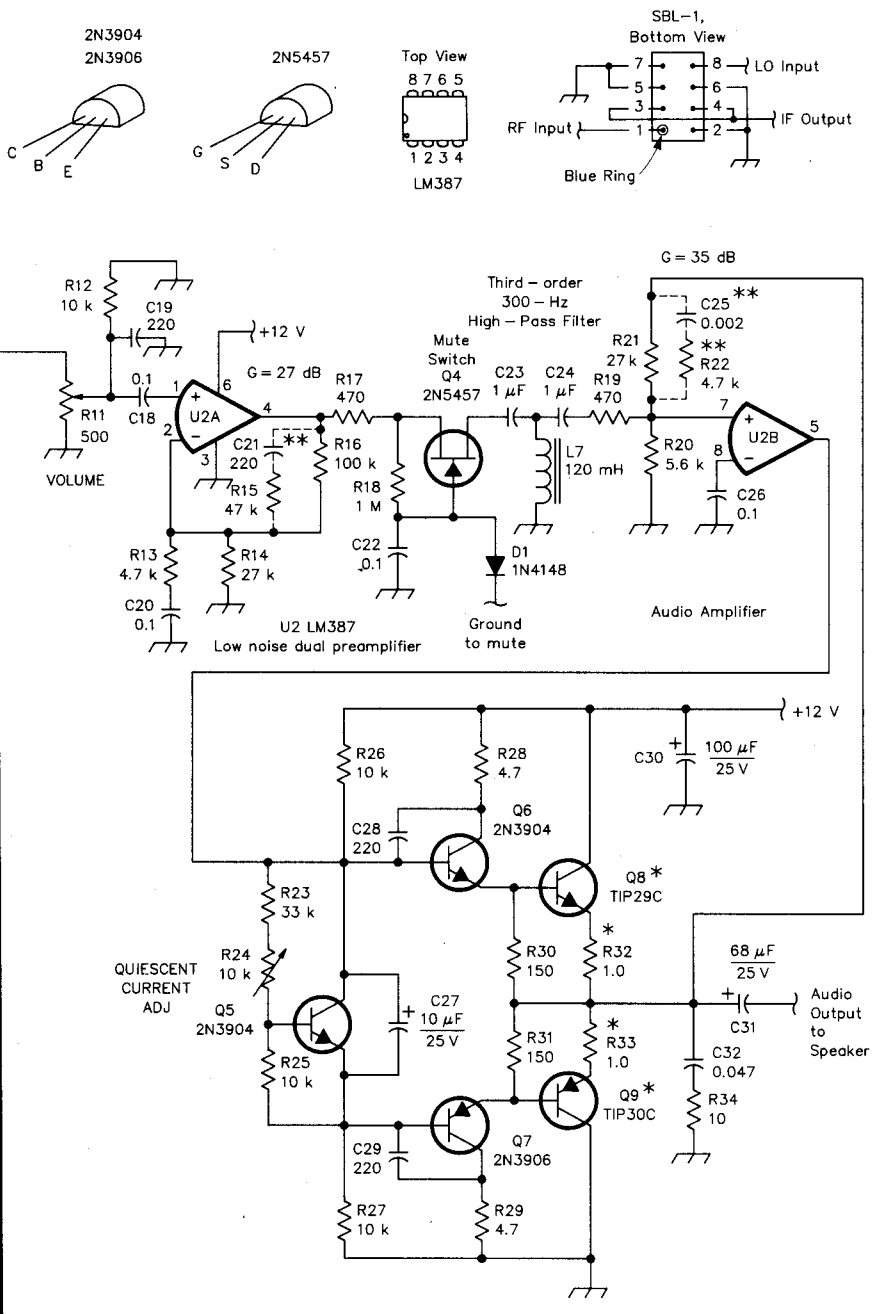
It is unfair to judge the capabilities of direct-conversion receivers by listening only to designs optimized for simplicity and low cost. A much better indication of the potential for high-performance direct-conversion receivers is the excellent design by Lewallen, An Optimized QRP Transceiver.⁷ Lewallen optimized for small size as well as high performance, which limited his engineering options and the reproducibility of his design. Lewallen's discussion of high-performance direct-conversion receiver design is mandatory reading.

In preparation for designing and building a high-dynamic-range, high-fidelity direct-conversion receiver, I built and tested a score of circuits. I tried product detectors using a single diode, a dual-gate MOSFET, a pair of back-to-back diodes, an LM1496, an XR2208, single balanced diode mixers and double balanced diode mixers. I built a direct-conversion 2-meter receiver on a superstrip (not recommended) and an NE602 20-meter receiver in a matchbox (real cute).

I didn't build all those circuits in a



The 2.5 \times 3.5-inch board R1 PC board is the heart of the Classic 40 and Sisu receivers. The board layout follows the schematic of Fig 2 fairly closely. This version uses a Mini-Circuits TAK-3H high-level mixer (in the lower-left corner of the board). The mixer is followed by the diplexer and 50-ohm preamplifier, built along the lower half of the board. The three inductors and seven capacitors of the 7th-order elliptical low-pass filter are arranged along the right-hand edge of the board. The intermediate audio amplifier, 300-Hz high-pass filter, mute switch and audio power amplifier are on the top half of the board. All that is needed to make a complete high-performance direct-conversion receiver is an RF input circuit, a VFO, a 500-ohm volume control and a speaker.



month. During the period when I was building receivers I started shaving, got my first real kiss, got my first job, joined the Navy, got married, stopped shaving, played a lot of music, climbed some big volcanoes, had children, started shaving again and went to school for a long, long time. One of the things I should have learned in school is that anything worth doing deserves a little forethought. In other words, "engage brain before plugging in soldering iron." My junk box is full of direct-conversion receivers loosely categorized as the good, the bad and the ugly. The bad designs I can blame on someone else, but the good ones are none of my doing either. They are all ugly.

None of the circuits I have copied over the years would do what I wanted—take a CW pileup on the low end of 40 meters and fill my living room with it, with no distortion, clipping or hum. The dynamic range represented by the signals in my 40-meter dipole is greater than the dynamic range of a compact disk audio recording, but the audio output of a typical 40-meter receiver sounds like an AM pocket radio. I wanted a 40-meter CW receiver with the clarity and signal-to-noise ratio of a CD player. To get it I had to start from scratch. The block diagram of a direct-conversion receiver shown in Fig 1 is deceptively simple. There are only three blocks: the downconverter, the local oscillator (LO)

Table 1
7th-Order Elliptical Low-Pass Filter Values

Component (see Fig 2)	Passband	
	1000 Hz	3000 Hz
L4, L5, L6	100 mH	33 mH
C11	0.39	0.15
C12	0.022	0.0068
C13	0.68	0.22
C14	0.1	0.033
C15	0.56	0.18
C16	0.068	0.022
C17	0.39	0.12

Note: Capacitance values are in microfarads. L4-L6 are Toko 10RB series fixed inductors and C11-C17 are 5%-tolerance metalized-film capacitors. See text.

and the audio amplifier. Fig 2 is a schematic of the receiver. Not shown are the LO and RF input circuits (discussed later). I will not discuss LOs—if there is anything about high-frequency VFOs and VXOs that hasn't already been published in the amateur literature, I don't know what it is. My VFO designs are shamelessly lifted from the numerous articles by two generations of Haywards, Lewallen and DeMaw. Maybe I can improve on them, but I haven't done it yet.

Downconverter

A product detector in a conventional superhet receiver has an easy job: downconvert the output of a narrow-bandwidth IF strip to audio. The signals at the input to the product detector have been scrubbed clean by a narrow-bandwidth crystal filter, and in most cases, a gain control of some type is used to keep all of the signals at the input to the product detector at about the same level. Since the narrow filters in a superhet precede the product detector, everything at the input is downconverted to audio, amplified a little, and sent to the speaker. A casual product detector design that works well in a superhet may provide disappointing performance as a direct-conversion receiver front end.

The first step in improving direct-conversion receivers is to throw away all the superhet product detector designs and start treating the downconverter stage as a low-noise, high-dynamic-range receiver front end. All of the rules for high-dynamic-range receiver design still apply, whether the IF is at 9 MHz or 0.3-3 kHz.

The fundamental difference between a superhet product detector and a direct-conversion receiver front end is that there are literally thousands of signals, from nanovolt to millivolt levels, simultaneously present in the direct-conversion mixer. A typical 40-meter direct-conversion receiver with a 500-kHz-bandwidth filter preceding the mixer downconverts the entire 500-kHz-wide band to low frequencies from dc to several hundred kHz, and upconverts the 500-kHz-wide band to fre-

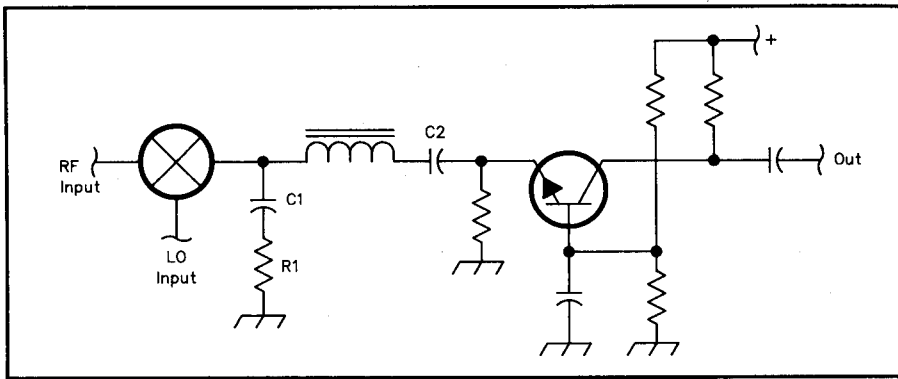


Fig 3—Several authors have attempted to properly terminate the mixer in the desired audio range by using a 50-ohm-input, grounded-base audio preamplifier as shown here.

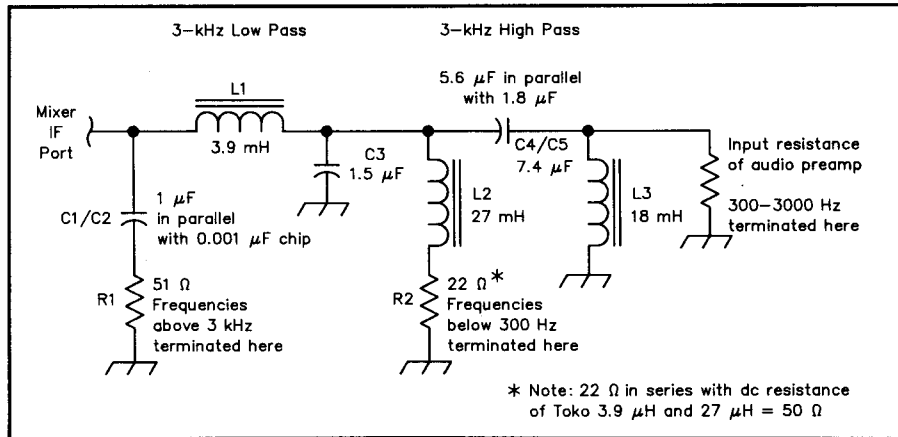


Fig 4—The diplexer shown here is used at the mixer IF port to provide a 50-ohm termination from dc to 300 Hz and 3000 Hz to daylight, and to pass 300 to 3000 Hz through to a matched low-noise amplifier.

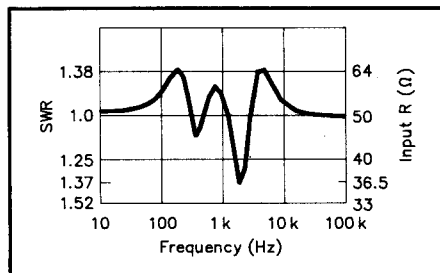


Fig 5—Input SWR and resistances of the band-pass diplexer of Fig 4 connected to Lewallen's matched audio preamp. The worst-case SWR, from dc to 500 MHz, is 1.4.

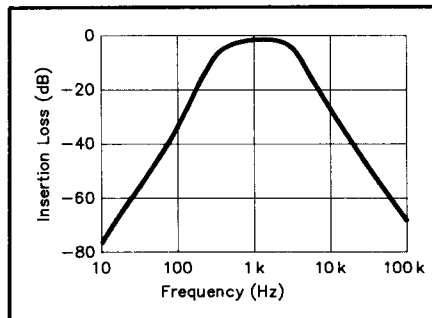


Fig 6—The mid-band insertion loss of the band-pass diplexer of Fig 4 is about 2 dB.

frequencies near 14 MHz. All of these signals are present at the input to the audio circuitry following the mixer. Basic receiver performance is largely determined by our treatment of the signals we *don't* want to hear that are present at the mixer IF port.

A requirement for high dynamic range in a receiver front end is proper termination of the mixer IF port. Several authors, notably Lewallen and Hayward, have attempted to properly terminate the mixer

in the desired audio range by using a 50-ohm-input, grounded-base audio preamplifier, as shown in Fig 3. High frequencies are terminated using a series-connected low-value capacitor (C1) and a 50-ohm resistor (R1) to ground at the mixer IF port. The dc-blocking capacitor (C2) between the IF port and the grounded-base amplifier guarantees that low frequencies are poorly terminated. This is a significant departure from standard engineering prac-

tice in an otherwise conservative design. The strongest unwanted signal of all in a direct-conversion receiver is its own leaked and radiated LO signal, complete with low-frequency sidebands picked up from interactions with the outside world. A diode-ring mixer is a nearly ideal coherent phase and amplitude detector. The subaudible frequencies at the IF port may reach millivolt levels in a direct-conversion receiver with a poorly shielded VFO. Diode ring mixer application notes stress that all frequencies present at the IF port must be properly terminated for predictable performance.

One recent receiver, A New Breed of Receiver, designed and built by Gary Breed,⁸ properly terminates the downconverter from dc to daylight by connecting a 50-ohm resistor directly from the IF port of the mixer to ground. Breed reports a complete absence of hum and microphonics in his receiver. Another receiver described in a recent *British Radio Communication* magazine uses a 50-ohm resistor straight into the inverting input (virtual ground) of a low-noise op amp.⁹ These techniques have two drawbacks: The resistor is a source of thermal noise, and the wide-bandwidth IF output of the double balanced mixer goes directly into the low-noise op amp. For high dynamic range, we need to restrict the bandwidth before the first audio amplifier, avoid resistors in the signal path, and still provide a wide-bandwidth 50-ohm termination of the mixer IF port.

The solution is simple but elegant—include a diplexer at the downconverter IF port that 1) provides a 50-ohm termination from dc to 300 Hz and 3000 Hz to daylight; and 2) passes 300 to 3000 Hz through to a matched low-noise amplifier. The design of the diplexer, shown in Fig 4, was not trivial and involved a number of trials using modern network theory and *PSPICE1* models before a final design was obtained. The *Q*s in the network are all kept low, so that components with 5% tolerance may be used.

Since the terminating impedance is fixed at 50 ohms, it is impractical to design the network using just surplus 88-mH toroids. Excellent lines of fixed, self-shielding inductors are made by Toko (available from Digi-Key) and HiQ (available from Mouser). They are much smaller than telephone toroids and offer a wide range of inductances at reasonable cost. The Toko inductors used in the network shown here have finite *Q*, with series resistances of tens of ohms.

The series resistances were included in both the network theory and computer models in order to synthesize a network that would work with non-ideal parts. Fig 5 shows the input SWR and resistances of the band-pass diplexer connected to Lewallen's matched audio preamp. The worst case SWR, from dc to 500 MHz, is 1.4.

Fig 6 shows the passband insertion loss of the band-pass diplexer, primarily due to the losses in the inductors. The mid-band insertion loss is 2 dB. The noise figure of Lewallen's preamp, driven by a 50-ohm source, is 5.1 dB,¹⁰ so the noise figure of the diplexer-preamp combination is about 7 dB.

The best published direct-conversion receiver tested on the bench was from Lewallen's Optimized QRP Transceiver. Significant improvements in selectivity, close-in dynamic range and hum suppression were obtained by adding the diplexer network shown in Fig 4 between the mixer and Lewallen's matched low-noise amplifier. It is not at all clear whether the improvements are primarily due to proper mixer termination or better selectivity, since the band-pass diplexer offers both. I'll let you know when I figure it out!

Most modern engineering texts frown on the use of inductors in audio filter networks. Isn't it possible to build a diplexer using active filters with op amps, or even digital filters? The problem is dynamic range. Literally all the signals in the world are present at the input of the network shown in Fig 4. The dynamic range of a Toko inductor is limited on the low end by picoamp noise currents in the warm, lossy wire, to milliamps on the high end, where the ferrite core saturates. The dynamic range of the inductor is thus about 180 dB. No available op amp or practical digital filter even comes close. This is one application where an old fashioned RLC network clearly outperforms the latest active network.

Audio Amplifier

The audio amplifier chain has three stages: a low-noise preamplifier to properly terminate the downconverter and set the receiver noise figure; an intermediate stage to provide needed gain; and a low-distortion power amplifier stage to drive a speaker. A low-pass filter between the preamplifier and intermediate amplifier sets the upper edge of the audio passband, and a 300-Hz high-pass filter between the intermediate amplifier and power amplifier stages removes the last traces of hum from the audio output.

50-Ohm Input Preamplifier

A significant effort was made to design a low-noise audio preamplifier with a 50-ohm matched input. A noise figure of less than 1 dB was obtained at the expense of a step-up transformer and poor match at the input. My final design is nearly identical to the grounded-base amplifiers published 10 years ago by Lewallen and Hayward. I have retained the active decoupler used by Lewallen, and added an emitter follower to the output to drive the following low-pass filter. This amplifier has a gain of 40 dB, a noise figure around 5 dB, and is well matched to 50 ohms.

The preamplifier must handle the entire range of signal levels at the output of the diplexer, since it is in the circuit before the volume control. It was designed to handle signal levels from 10 nanovolts to 10 millivolts without distortion. The distortion-free dynamic range of the audio preamplifier stage is a good complement to the dynamic range of the SBL-1 double balanced mixer—the preamplifier adds little noise to the signal, and begins to distort at about the same input level as the mixer.

Low-Pass Filters

The low-impedance output of the audio preamplifier drives a low-pass filter designed for 500-ohm terminations on both ends. The PC-board artwork accommodates a number of designs, from a simple 3rd-order Butterworth to a 7th-order elliptical. The 3000-Hz SSB 7th-order elliptical filter designed by Niewiadomski¹¹ and the scaled 1000-Hz CW version shown in Fig 2 (C11-C17 and L4-L6) and Table 1 are excellent choices for use in crowded bands. The 6- to 60-dB shape factors of receivers with these filters in place are competitive with the best crystal filters. The use of off-the-shelf 5%-tolerance components in the SSB filter results in a fair amount of unpredictable passband ripple.

Since the Classic 40 was designed for high-fidelity sound, I opted to use a 5th-order Butterworth filter with 4-kHz bandwidth instead of the 7th-order elliptical filter. See Fig 7. The Butterworth design is more tolerant of component variations. Fig 8 is a plot of the measured passband of two different receivers with 7th-order elliptical SSB filters, and the Classic 40 with a 5th-order Butterworth filter. The elliptical designs really cut through the QRM, but the Classic 40 with the Butterworth filter sounds great.

Signal levels are high enough at the input to the low-pass filter, and impedance levels low enough, that it is possible to build additional filters on separate boards and select them with a switch, as shown with the dotted lines in Fig 2. The preamp output impedance is close to 50 ohms, so a series resistor is used to establish the filter driving impedance. The required 500-ohm output termination is provided by the **VOLUME** control. Fig 9 shows the *PSPICE1* calculated responses of the 1000 Hz and 3000 Hz 7th-order elliptical low-pass filters, and the measured response of the complete receiver with the 1000-Hz filter in place. The measured -6 dB bandwidth of the receiver with the 1000-Hz low-pass filter is 580 Hz, and the -60 dB bandwidth is 1210 Hz, for a shape factor of 2.1:1. The passband is flat, with rounded corners, no ripple and no ringing.

Lewallen and others have pointed out that elliptical filters are not the best choice for time-domain signals, particularly high-speed CW. The receiver with a 1000-Hz elliptical low-pass filter sounds very good

at 25 words per minute. Maybe if I change it to a Bessel filter I'll be able to copy 50!

The output of the low-pass filter is the ideal place to pick off a signal for digital signal processing (DSP) experiments and applications. The entire receiver is linear to this point (no AGC or other forms of distortion), so the usual drawbacks to audio filtering do not apply.

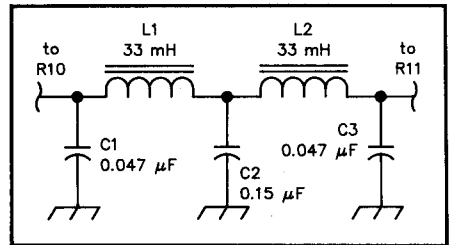


Fig 7—If you enjoy high-fidelity listening, you can replace the 7th-order elliptical low-pass filter shown in Fig 2 (L4-L6, C11-C17) with this 5th-order Butterworth filter (bandwidth = 4 kHz). The elliptical filter cuts through the QRM better, but the Butterworth filter sounds great. L1 and L2 are Toko 10RB-series fixed inductors and C1-C3 are 50-V Panasonic V-series 5%-tolerance metalized-film capacitors.

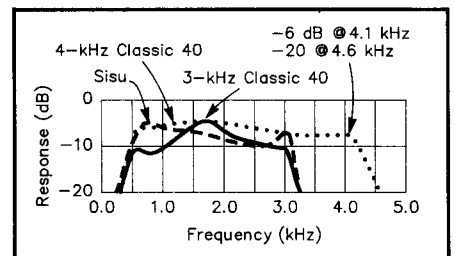


Fig 8—This graph shows the measured passband response of three different receivers: a Classic 40 with a 3-kHz elliptical filter; a Classic 40 with a 4-kHz Butterworth filter; and a Sisu receiver with a 3-kHz elliptical filter.

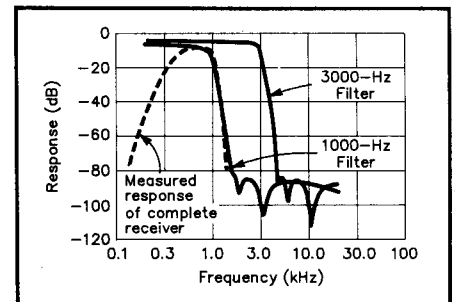
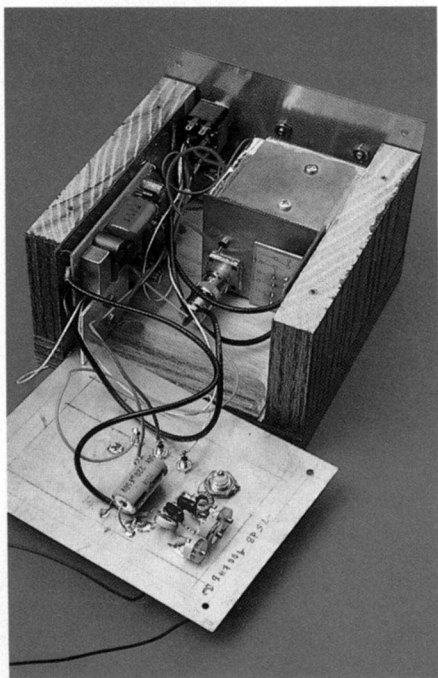


Fig 9—This graph shows the *PSPICE1* calculated responses of the 1000-Hz and 3000-Hz elliptical low-pass filters, and the measured response of a complete receiver with 1000-Hz filter in place. The measured -6 dB bandwidth is 580 Hz, and the -60 dB bandwidth is 1210 Hz, for a shape factor of 2.1:1. Using the calculated response of the 3-kHz filter, the shape factor is 1.6:1 for the SSB filter.

Intermediate Audio Amplifier

The wiper of the **VOLUME** control is connected to the input of the intermediate amplifier, one section of an LM387 low-noise stereo preamplifier.

The requirements for an audio amplifier for SSB are not too severe, since the speech signal occupies the entire bandwidth, and the in-band intermod products present in the transmitted signal are seldom more than 30 dB down. CW is an entirely different story. A pileup on the low end of the 40-meter CW band may result in 30 or 40 independent signals all transmitting at once within a 1-kHz band. The strong signals are often 30 or 40 dB stronger than the desired signal. In a typical amateur receiver, the audio and IF intermod products from the strong signals are stronger than the weak signals. Many amateurs are not aware of this problem, however, because once a strong signal appears in the passband, the AGC turns down the gain, and all the weak signals are lost in the noise anyway. Experienced CW contest operators often turn off the AGC (if possible!) when the band is crowded, and are all too familiar with the audio distortion that ultimately limits the ability to recover weak CW sig-



Classic 40 is enclosed in a solid-oak wraparound case with a polished-brass front panel and a piece of unetched PC-board material for the back panel. The front panel is $4 \times 5\frac{1}{2}$ inches, and the box is $5\frac{1}{2}$ inches deep. The VFO is completely enclosed in a soldered-shut PC board case, but the receiver board is unshielded inside the wooden box. A simple two-resonator band-pass filter is built on the back panel. This unit is an early prototype: The audio amplifier power-output stage and 5th-order Butterworth filter are on separate PC boards. (studio photos by Kirk Kleinschmidt, NT0Z)

nals in a crowded band.

The intermediate audio amplifier and power-output stage were designed for good intermod and total-harmonic-distortion performance. These designs were copied from high-fidelity audio references^{12,13} and modified for the restricted bandwidths necessary for communications. The LM387 was chosen for its low noise and single supply operation.

The audio output stage uses the second section of the LM387 as a gain element driving a Darlington complementary symmetry pair. The only drawbacks to this circuit are the unavoidable high parts count and the high (about 100 mA) quiescent current in the class AB output transistors. For portable operation with low-impedance headphones, Q8, Q9, R32 and R33 can be omitted, at a great saving in current drain. For operation with high-impedance headphones, the output of the LM387 can be connected directly to the dc blocking capacitor, and all of the external transistors may be eliminated. Total current drain will then be 10 or 15 mA.

The potentiometer R24 sets the quiescent current for the output transistors. I've had good results adjusting R24 for 100 mA total board current. If you omit the final transistors and associated parts and use low-current-drain headphone-only operation, R24 has little effect and can be replaced with a jumper.

Between the intermediate and power stages are an FET switch (Q4) and a 300-Hz high-pass filter (C23, L7, C24). The FET switch mutes the receiver during transmit, and the high-pass filter removes the last traces of 60-Hz hum. The time constant of the FET switch is set by R18 and C22, and may be modified for any convenient recovery time. In one version of the Classic 40, the time constant was set to many seconds, to simulate the warm up of a classic tube receiver! The FET switch is a ground-to-mute circuit, so the mute terminal may simply be ignored if muting is not needed.

The total gain of the three audio stages is 102 dB. The loss of the mixer and all the LC filtering is about 22 dB, for a net gain of about 80 dB. This is enough for comfortable speaker or headphone listening on 80 and 40 meters at night. Experimenters may increase the gain by changing the feedback resistors in the LM387 stages, but be careful—100 dB is already quite a bit of audio gain on a single small board.

Notice that the negative lead of the power supply must be connected at the collector of the PNP output transistor (Q9). The quiescent current drawn by the output transistors is 100 mA, and this much current flowing through a 1 microhm resistance will have a voltage drop of 0.1 microvolt—10 times greater than the weakest signals in the audio preamp stage. Grounding rules are entirely different for audio and RF circuitry.

The circuit built on the single-sided PC-board layout offered in the template package described in note 1 is stable, as long as the supply leads are connected at the indicated points and a low-pass filter is used between the preamp and intermediate amp stages. The circuit will oscillate at a frequency well above the audio range if the low-pass filter is omitted, and it may oscillate at a low audio frequency if the power supply leads are connected to the input side of the board. As long as the negative supply lead is connected at the audio output stage, it is acceptable to have other ground connections to the board—for example mounting screws to a metal box and the shields of the RF and LO coax. The important thing is to make sure that the current for the audio power transistors does not flow through the ground traces near the preamplifier input. Magnetic coupling from the speaker, speaker wires or power supply wires to the input inductors may cause audio-frequency oscillation. This can be cured by moving the speaker or wires.

There is no low-pass filtering after the **VOLUME** control. This is not a problem when using a speaker, but the high-frequency hiss is noticeable on headphones, especially when using a narrow CW filter. The high-frequency noise is also easy to observe on an oscilloscope or wide-bandwidth audio voltmeter, and may introduce errors into noise figure and minimum-detectable-signal measurements. The optional networks indicated in Fig 2 (R15, C21 and R22, C25) may be added across the LM387 feedback resistors to reduce the high-frequency hiss.

Automatic Gain Control

A human operator can copy one CW signal when several are present in the passband, even when the desired signal is considerably weaker than the interfering signals. An AGC system measures the total power in the passband and adjusts the system gain to keep the total power constant. When more than one signal is present, the output level of the desired signal will fluctuate as the signal environment changes. This limits the effectiveness of audio filtering and digital signal processing schemes in a receiver with AGC. It also reduces the intelligibility of signals presented to the ear and brain.

Historically, AGC has been needed in receivers with AM detectors, because the dynamic range of simple half-wave diode detectors is very limited.¹⁴ In a multimode superhet receiver, the output of the IF strip is switched between several demodulators, and it is convenient to leave the AGC on for all modes. Once the receiver has AGC, it is possible to greatly relax the dynamic range requirements of all the stages after the first IF filter. Over the past several decades, the design of IF amplifiers, product detectors and audio amplifiers has become so relaxed that AGC is now neces-

sary to maintain any semblance of linearity in most receivers. Only the most expensive models permit the AGC to be turned off.

There is no question that AGC is a convenience for some types of casual operation, and even a necessity for some more demanding applications like mobile SSB and traffic nets. Two quotes from the 1966 *ARRL Handbook* are still true 25 years later: "Automatic regulation of the gain of the receiver in inverse proportion to the signal strength is an operating convenience in phone reception" and "If the selectivity ahead of the AGC rectifier isn't good, strong adjacent-channel signals may develop AGC voltages that will reduce the receiver gain while listening to weak signals."

A receiver with AGC is constantly readjusting its gain to approximate the desired output level. It is always close, but never quite right, and always changing. Just as pro rally drivers require manual transmissions and professional photographers use manual focus cameras, serious radio amateurs need manual gain control. I offer no apologies for leaving AGC out of this receiver—it is considerably more difficult to design a receiver that works well without AGC than to include an AGC loop. A receiver with high dynamic range all the way from antenna connector to speaker leads sounds great, and opens up a world of possibilities for advanced analog and digital signal processing. In the near future, AGC, noise blanking, SSB and CW filtering and digital mode demodulation may all be performed by a single DSP chip set.

R1 Receiver PC Board

The downconverter, diplexer, 50-ohm preamplifier, low-pass filter, intermediate audio amplifier, 300-Hz high-pass filter, mute switch and audio power amplifier are all built on a single 2.5 × 3.5-inch PC board (see note 1). All that is needed to make a complete high-performance direct-conversion receiver is an RF input circuit, a VFO, a 500-ohm volume control, and a speaker.

There is little wasted space on the circuit board, but assembly is straightforward. Due to the tight layout, component substitutions may be difficult, but this should not be a major problem—all of the parts except for the mixer are available from Digi-Key.

Some care should be taken in selecting capacitors for the diplexer, low-pass filter and high-pass filter. The tolerances need to be tight to get the best performance from this receiver. In the low-pass filter (C11-C17), I used Panasonic V-series 50-V, 5%-tolerance metalized film capacitors. The V-series capacitors go only as low as 0.01 μF , so for C12 in the 3000-Hz elliptical filter I used a 0.0068- μF , 50-V Panasonic P-series polypropylene capacitor (2% tolerance). In the diplexer (C1, C3-C5) and 300-Hz high-pass filter (C23,

C24), I used Panasonic type ECQ-E(F) 100-V miniature metalized polyester film capacitors. Although these capacitors are specified at 10% tolerance, I measured many of them and they were within about 4% of rated value. The other nonpolarized capacitors are not critical and can be disc ceramic or metalized polyester film units.

It's important to use the Toko 10RB series fixed, self-shielding inductors specified, since their characteristics are designed into the circuit. An acceptable alternative is the HiQ series of inductors sold by Mouser. The HiQ parts have wire leads instead of pins, though, so it takes a little work to fit them on the R1 PC board.

C1 is a metalized polyester 1- μF capacitor that feeds the high frequencies to a 51-ohm resistor. If the R1 board is used at VHF or UHF, a chip capacitor of about 0.001 μF should be added in parallel with C1 to make sure all of the high-frequency energy at the input to the diplexer "sees" the 51-ohm resistor. The PC artwork has a spot on the foil side for the chip capacitor to be added.

The TIP29 and TIP30 audio-output transistors require a small heat sink. I've used scrap pieces of 1/8- or 1/4-inch aluminum plate to dissipate the heat.

The R1 board is very easy to use, as there are few interconnections and all are low impedances. The inductors in the audio stages will pick up hum from 60-Hz magnetic fields, so the board should not be mounted in the same box as an ac power transformer. On the bright side, the preamplifier active decoupler and the power supply rejection of the LM387 are so good that the R1 board is perfectly happy running on an inexpensive 12-V-dc plug-in wall transformer.

Local Oscillator

I have not included a VFO circuit here, but the amateur literature is full of good designs. For HF operation, any of the VFO circuits published by DeMaw, the Haywards and Lewallen are recommended.^{15,16,17} I have copied most of them, and never had

any problems. My favorite is from Lewallen's Optimized QRP Transceiver, since it works as well as any, with fewer parts. Another good choice is the VFO/buffer portion of the Haywards' Ugly Weekender; PC boards are available from FAR Circuits.¹⁸

The LO level should be close to the value specified by the mixer manufacturer, +7 dBm in most cases. Some double balanced mixers will work fine with LO injection down to 0 dBm, with slightly reduced intermod performance. For best performance in high-density signal environments, high-level double balanced mixers are worth considering.

In any case, the LO should be well shielded, with the signal brought into the mixer through coax. A source of many of the problems associated with direct-conversion receivers is LO radiation, interaction with the local electrical environment, and subsequent pickup by the antenna. Two well-known cures for these problems are 1) completely shielding the VFO in a soldered-shut box; and 2) using a balun, balanced feed line and a balanced antenna system. A direct-conversion receiver with an unenclosed VFO, a speaker on one end and a few feet of wire stuck in the other end may not just hum, it may howl!

RF Input

The double balanced mixer RF port is nearly 50 ohms, and a filter should be used between the antenna and the mixer. In early tests an "Adequate Transmatch" (the Ultimate Transmatch circuit from the *ARRL Handbook*, hastily assembled with junk-box parts) was used between the open-wire feed line on the 40-meter dipole and the mixer port, with excellent results. The only drawback was that 15-meter signals could be heard leaking through when the band was open.

Later versions have all used a simple two-resonator band-pass filter built on a separate piece of unetched board (see Fig 10). It would have been simple to include a pattern for the filter on the main

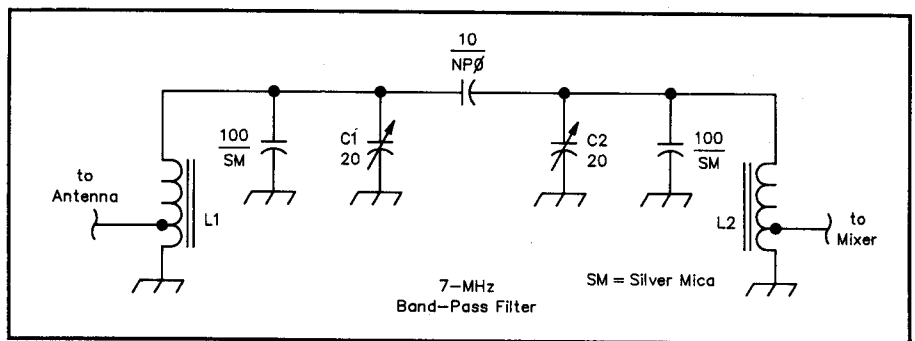


Fig 10—Here's one design for a 40-meter band-pass filter to provide RF-input selectivity for the Classic 40.

C1, C2—3-20 pF film trimmer (Digi-Key SG3007 or equiv).

L1, L2—32 turns of #26 enameled wire on a T-50-6 toroidal, powdered-iron core. Tap 5 turns up from the ground end.

PC board, but this receiver works fine from 10 kHz to 750 MHz (depending on the choice of double balanced mixer), so the RF filter is left off the board for maximum flexibility. Appendix 2 of *Solid State Design* (see note 17) contains excellent information on designing and building band-pass filters for many different frequencies.

Packaging

A receiver this good deserves a nice box. As shown in the photographs, Classic 40 is enclosed in a solid oak wraparound case with polished brass front panel, black lettering and a National Velvet Vernier dial that I picked up at a flea market. The only controls other than the tuning dial are the volume control and on-off switch. The front panel is $4 \times 5\frac{1}{2}$ inches, and the box is $5\frac{1}{2}$ inches deep. The VFO is completely enclosed in a soldered-shut PC board case, but the receiver board is unshielded inside the wooden box. It looks as good as it sounds, on the picnic table with a dipole thrown up in some nearby trees, or in the corner of the living room.

Sisu

The basic R1 PC board works so well with different LOs on different bands that I built a second version for an entirely different purpose—to transceive with any of the popular QRP transmitter circuits. A number of CW transceiver circuits have been published in recent years,^{19,20,21,22} but most have used the NE602 as a product detector, with its attendant dynamic range and distortion problems. Sisu was built to provide a high-performance receiver that can be easily tacked on to a VFO-controlled CW transmitter. Only three interconnec-

tions are needed: an RF-input line from the TR switch, an LO line with +7 dBm from the VFO, and a mute line from the key. Some RF selectivity is needed. This can be provided by the low-pass filter in the transmitter output stage, or the antenna tuner, if one is used, or by an outboard filter as in the Classic 40. Lewallen's Optimized QRP Transceiver and Roger Hayward's The Ugly Weekender II²³ illustrate the necessary interconnections.

Sisu has been tested on several bands from 160 meters through 432 MHz, with excellent results. Above 40 meters, a preamp is useful for digging out weak signals, but even at 432, with just a VXO and a single stripline filter in the RF line, the local SSB and CW signals come booming in. This receiver would mate nicely with a little 222.1 DSB CW transmitter for grid hopping during the June VHF contest.

Sisu is not an acronym for Signal Interface Sensing Unit. Sisu is a Finnish word for a character trait. A person with *sisu* is able to quietly get the job done, without complaining or begging for attention, in circumstances where most people would quit. This little receiver has *sisu*.

Speaker

Amateur receivers used to require external speakers. These days, little 3-inch speakers of remarkably low fidelity have become standard in amateur equipment. It seems to make little sense to put a good quality speaker on the output of a radio with IF distortion, hyperactive AGC and a 10% THD audio amp, but even the poorest radios will benefit from a high-quality external speaker. Conversely, a distortion-free radio will sound awful con-

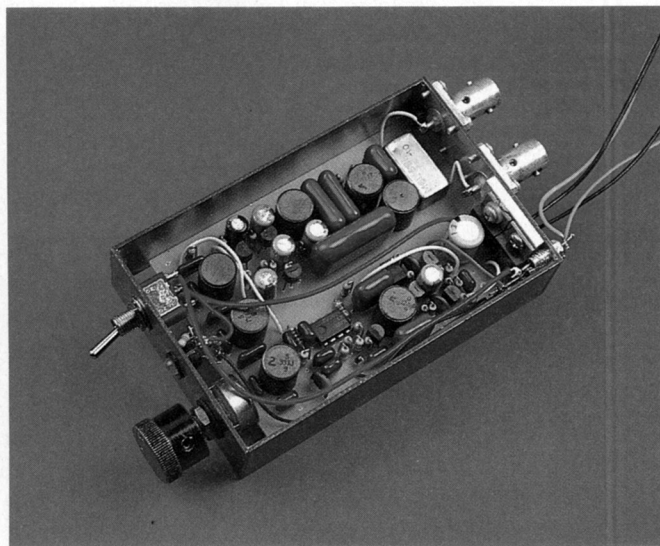
nected to an unenclosed 3-inch speaker lying on the bench.

My favorite speaker for Amateur Radio applications is the compact Minimus 7, available for \$49.95 from Radio Shack. It is too heavy for portable work, unless you are combining QRP operation with bodybuilding. I "built" a good portable speaker by buying a 3-inch stereo speaker with the heaviest magnet I could carry and mounting it in a cardboard box. A $3 \times 4 \times 2$ -inch cardboard box with all the seams taped shut sounds pretty good for speech and CW.

Measurements

It is one thing to listen to a receiver on the 40-meter band and determine subjectively that it is an improvement over previous designs—it is another thing to take it into the lab and measure its performance. Three receivers were measured for gain, sensitivity/noise figure, 3rd-order intercept point and minimum detectable AM signal. All measurements were done in the CW portion of the 40-meter band. The results are shown in Table 2.

Table 2 has some good news and some bad news. The good news is that the 3rd-order intercept point and blocking performance are outstanding, equal to the best available amateur equipment. This is to be expected, since the 3rd-order intercept point measurements are made with 20-kHz and 40-kHz signal-generator spacing, and the band-pass diplexer effectively terminates these IF signals in a resistive load. The only nonlinear component seen by the 20-kHz and 40-kHz offset carriers is the double balanced mixer, and it performs exactly as specified in the data sheet.



Sisu is a compact version of the R1 board configured to transceive with any of the popular QRP transmitter circuits. Only three interconnections are needed: an RF-input line from the TR switch, an LO line from the VFO and a mute line from the key. RF selectivity can be provided by the low-pass filter in the transmitter output stage, an antenna tuner, or an outboard filter as in the Classic 40.



Although the R1 board wasn't designed to be particularly compact, Sisu with a companion VFO takes up little tabletop space. (photo by the author)

Table 2
Measured Receiver Performance

Radio	Receiver Bandwidth	Minimum Discernible Signal	Intercept Point	IMD Dynamic Range	Noise Figure	AM Sensitivity
Classic 40	3.5 kHz	-118 dBm	+12 dBm	87 dB	20 dB	3 mV
Sisu	2.7 kHz	-119 dBm	+15 dBm	90 dB	20 dB	3 mV
R1 with high-level mixer	0.6 kHz	-128 dBm	+19 dBm	98 dB	18 dB	2.5 mV

The bad news is that the noise figure is higher than expected. I initially suspected that the measurements were in error, but minimum-detectable-signal measurements confirm the measured noise figures. This disappointing performance was a puzzle. The loss of the 40-meter RF filter was measured at less than 0.5 dB. The mixer loss was measured at 6 dB, and the data sheet said "noise figure within 1 dB of conversion loss." The band-pass diplexer loss is about 2 dB, and the 50-ohm preamplifier noise figure is 5 dB. The noise figure of this receiver front end should have been about 14 dB. The measured noise figures are 4 to 6 dB worse.

A number of tests revealed that excess noise was present at the mixer IF port. The following quote from page 1.4 of the 1990 Merrimac *RF & Microwave Processing* book²⁴ supplied the answer: "The noise introduced by the mixer consists of the conversion loss (SSB), thermal noise in the series resistance of the diodes and other components, and the 1/f noise figure produced by the Schottky Barrier diodes which is only appreciable below 10 kHz."

More information was found in the Hewlett Packard *Microwave and RF Designers Catalog*, pages 4-68 and 4-69.²⁵ A plot on page 4-69 shows the noise performance of various mixer diodes with IFs from 1 MHz down to 100 Hz. Even the best diodes have 14 dB more noise at 100 Hz than at 20 kHz.

I confirmed the 1/f noise contribution by measuring the spot minimum detectable signal of Sisu at a series of audio output frequencies from 300 to 3000 Hz using an HP3582A audio spectrum analyzer.

I don't know how to reduce the 1/f noise. It may be possible to improve the noise figure a few dB by using a home-brew double balanced mixer with low-flicker-noise diodes. On 160, 80 and 40 meters, a 20-dB noise figure is good enough, as long as the receiver is properly matched to a full-sized dipole. Above 40 meters, a preamp may be necessary. The preamp will reduce the intercept point and the dynamic range. Fortunately, the intercept point is so high that reducing it by 10 or 20 dB with a preamp still leaves a very good receiver.

Classic 40 and Sisu, with standard-level double balanced mixers, have two-tone dynamic range near 90 dB, low audio distortion, zero spurious responses (aside from the audio image), and no synthesizer noise. For operation in hostile RF environments, a 98 dB dynamic range can be obtained by replacing the standard-level double balanced mixer with a high-level TAK-3H mixer.

Conclusion

How does the Classic 40 sound? Like a compact disk recording of CW signals straight off the air. I have compared it side-by-side in the corner of my living room with radios by Collins, Kenwood, Yaesu and

ICOM, using a pair of identical Minimus 7 speakers. The other radios all sound about the same, but the clarity and presence of the Classic 40 is instantly recognizable. A good CW pileup sounds like music, and subtle differences between SSB transmitters are instantly recognizable. There are no whistles, birdies or other spurious sounds from this receiver. It is silent with the antenna disconnected, over the entire tuning range. I am pleased. The audio gain was chosen for comfortable listening using a speaker in a quiet room with a 40-meter dipole. If the volume control is set for a just-audible 40-meter noise floor, then the amplifier clipping level is 60 dB higher! (The clipping level is only about 45 dB above the noise floor in FM stereo broadcasting.)

What are the shortcomings of the Classic 40? First, it is a simple direct-conversion receiver with no provision for removing the audio image. This is fine for casual operating, since the receiver sounds so good with multiple signals, but for serious work, having twice as many interfering signals in the audio passband is a major drawback.

Second, the tuning rate is rather quick and the frequency readout poor. It is tempting to try and count the VFO directly with a simple frequency counter, but beware! The audio amplifier has 100 dB gain. Any attempt to run a frequency counter on the same battery, let alone in the same box, as a 100-dB-gain audio amplifier is probably doomed to failure because of all the digital noise you'll hear. A battery-powered counter in a separate shielded box with a high-isolation preamp is one possibility that might serve for portable work.

Third, the low-distortion audio amp sucks the batteries dry in a few hours. Overall receiver current drain is more than 100 mA at 12 V, which compares favorably with most commercial gear, but is a factor of 10 larger than a Neophyte or Sudden receiver using ICs designed for portable telephones.

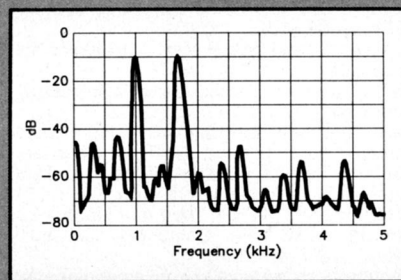
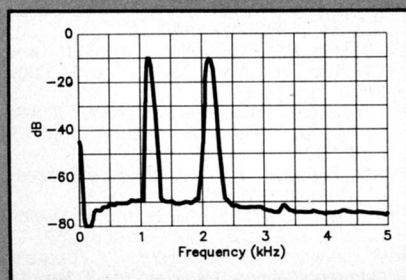
Finally, the R1 board is large. The inductors and capacitors take a fair amount of board real estate, even when packed closely together. The 2.5- x 3.5-inch circuit board doesn't even contain a VFO or RF-input filter. An entire Neophyte receiver circuit can be built in a 1.375 x 2 x 0.675-inch matchbox, and the Sudden kit from Blue Rose Electronics uses all surface-mount components on a postage-stamp-sized circuit board! The Classic 40 runs circles around them in performance, but they win the prizes for being cute.

Next Steps

The band-pass diplexer network between the mixer and audio amplifier offers a textbook solution to the selectivity and mixer termination problem, and results in an exceptionally well-behaved receiver with predictable performance. Is it optimized?

Why It Sounds So Good

These drawings show the measured output spectrum of two direct-conversion 40-meter receivers. Each receiver is being driven by two strong CW signals 600 to 800 Hz apart in the passband. In Sisu (left), receiver noise and all intermodulation products are 62 dB below each tone. In a typical NE602-LM386 receiver (right), best-case IM products are 34 dB below either tone.



Not necessarily! Although this receiver's AM rejection is about 20 dB better than an NE602-LM386 receiver tested under identical conditions, there is still room for improvement. Hayward and Lewallen have experimentally determined that AM suppression improves when the mixer IF port is ac coupled. I measured an improvement in AM suppression on the 40-meter band by removing the 22-ohm low-frequency termination resistor from the diplexer circuit in Fig 3. Removing this resistor also improved the LO-to-RF-port isolation in the double balanced mixer. Do these results hold at other frequencies, with other mixers? Is the dynamic range still predictable? I don't know, and the current textbooks don't say! We need some more work in this area, and then a set of updated textbooks!

Future Receivers

The R1 board can be used as a building block for other receiver designs. I've used it in several other projects, following the design and construction philosophy presented in "A Progressive Communications Receiver" by Lawson and Hayward.²⁶ The designs are:

1) *R2*, a *single-signal* direct-conversion receiver or IF for use on any frequency from VLF to microwaves.

2) *20-Meter Microscope*, a super-selectivity, low-distortion, crunch-proof superhet for 20-meter CW.

3) *PCR 144*, a laboratory-grade two-channel 144-MHz receiver used as an IF for advanced propagation experiments, exploration of binaural signal processing techniques, and as a tunable front end for DSP experiments.

Acknowledgments

The Classic 40 receiver design was conceived, the engineering tasks identified, and much of the circuitry imagined during the 14-hour drive home after a pleasant chat with the Rev. George Dobbs, G3RJV of the G-QRP Society at the Dayton HamVention in 1991. I would like to thank him for his leadership in keeping the home-brewing side of Amateur Radio alive, and for providing all those back issues of *SPRAT* to read at the rest stops on the way home. This work follows the long tradition in Amateur Radio of improving on previous receiver designs. I hope I have kept the standards as high as the authors cited in the references. Wes Hayward, W7ZOI, and Roy Lewallen, W7EL, have been most helpful during the review period of this manuscript. Thanks are also due to Jim Davey, WA8NLC, for all the hours on the phone, fax, E-mail, 75 meters and 40 meters discussing this project.

Notes

¹Etched, plated and drilled PC boards (double-sided with plated-through holes) and parts kits for the R1 board are available from Applied Radio Science, PO Box 225, Houghton, MI 49931. Prices: PC board only, \$10; board and



A classic portable station: Ricky, the author's son, with a Classic 40, antenna tuner, 20-mW CW transmitter, key, battery and speaker. (photo by the author)

parts kit, \$75 for a receiver with 1-kHz or 3-kHz elliptical filter, \$70 for a receiver with a 4-kHz Butterworth filter. Please specify filter type when ordering. An etching template/part-overlay package for a single-sided version of the R1 PC board is available from the ARRL for an SASE. Address your request for the CAMPBELL R1 BOARD TEMPLATE to Technical Department Secretary, ARRL, 225 Main St, Newington, CT 06111. All parts except the SBL-1 mixer are available from Digi-Key, PO Box 677, Thief River Falls, MN 56701-0677, tel 800-344-4539. One source for the SBL-1 mixer is Oak Hills Research, 20879 Madison St, Big Rapids, MI 49307, tel 616-796-0920.

²*SPICE1* Circuit Analysis Software is available from the Microsim Corp, 20 Fairbanks, Irvine, CA 92718, tel 714-770-3022.

³J. Dillon, "The Neophyte Receiver," *QST*, Feb 1988, pp 14-18.

⁴G. Dobbs, "The 'Sudden' Receiver," *SPRAT* no. 58, Spring 1989, pp 16-19.

⁵G. Dobbs, "The Sudden Receiver," *73 Amateur Radio Today*, Oct 1991, pp 8-12.

⁶"The Sudden Receiver Goes SMD," *SPRAT* no. 61, Winter 1989-90, pp 19-20. (Kit available from Blue Rose Electronics, 538 Liverpool Road, Great Sankey, Warrington. WA5 3LU England.)

⁷R. Lewallen, "An Optimized QRP Transceiver," *QST*, Aug 1980, pp 14-19; also see Feedback, *QST*, Nov 1980, p 53. The Optimized QRP Transceiver also appears on pages 30-37 to 30-40 of *The 1992 ARRL Handbook*, and in the second printing of *QRP Classics* (available from the ARRL Bookshelf as #3169).

⁸G. Breed, "A New Breed of Receiver," *QST*, Jan 1988, pp 16-23.

⁹N. Hamilton, "Improving Direct Conversion Receiver Design," *Radio Communication*, Apr 1991, pp 39-44.

¹⁰Roy Lewallen and Wes Hayward, private correspondence.

¹¹S. Niewiadomski, "Passive Audio Filter Design," *Ham Radio*, Sep 1985, pp 17-30.

¹²See Chapter 2 of the *National Semiconductor Audio/Radio Handbook 1980*, M. Giles ed., National Semiconductor Corporation, 2900 Semiconductor Drive, Santa Clara, CA 95051.

¹³P. Horowitz and W. Hill, *The Art of Electronics*, 2nd ed. (New York: Cambridge University Press, 1989), pp 91-96.

¹⁴Although this view is valid from an engineering standpoint, it may be more instructional to say that AGC (originally AVC, for *automatic volume*

control) has historically been necessary for AM reception because people don't like being blasted out of their chairs by loud radios. Invented in 1926 by Harold A. Wheeler of the Hazeltine Corporation, AVC was the radio industry's solution to the problem of "two-hand" AM-broadcast reception. Before AVC, the wide strength difference between local and distant stations required broadcast listeners to tune with one hand and ride audio gain with the other. Listener convenience, not detector dynamic range, put AVC in "virtually every radio on the market" by 1932. See Robert E. Grinder and George H. Fathauer, *The Radio Collector's Directory and Price Guide* (1986: Scottsdale, AZ, 1986), pp 47-48.—WJZ

¹⁵D. DeMaw, "Build a Universal VFO," *QST*, Jun 1991, pp 27-29.

¹⁶D. DeMaw, "Transmitter Design—Emphasis on Anatomy Part 1," in *QRP Classics*, pp 75-78 (available from the ARRL Bookshelf as #3169).

¹⁷W. Hayward and D. DeMaw, *Solid State Design for the Radio Amateur*, available from the ARRL Bookshelf as #0402.

¹⁸R. Hayward and W. Hayward, "The 'Ugly Weekender,'" *QST*, Aug 1981, pp 18-21. The Ugly Weekender also appears on pages 30-33 to 30-36 of *The 1992 ARRL Handbook*. Etched, plated and drilled PC boards for the VFO/buffer are available from FAR Circuits, 18N640 Field Ct, Dundee, IL 60118-9269. Price is \$4; add \$1.50 for shipping and handling to each order. Use the board's AUX OUT output for the correct drive level for the SBL-1 mixer.

¹⁹Z. Lau, "The QRP Three Bander," *QST*, Oct 1989, pp 25-30.

²⁰G. Breed, "A Portable QRP CW Transceiver for 20 and 30 Meters," *The 1992 ARRL Handbook*, pp 30-26 to 30-32.

²¹R. Littlefield, "The QRP-15 CW transceiver," *CQ*, Sep 1990, pp 43-49.

²²I. Keyser and G. Dobbs, "The CSP 14 MHz CW/SSB Transceiver," *SPRAT* no. 67, Summer 1991, pp 21-29

²³R. Hayward, "The 'Ugly Weekender' II: Adding a Junk-Box Receiver," *QST*, Jun 1992, pp 27-30.

²⁴1990 Merrimac *RF & Microwave Processing M-90* book, p 1.4.

²⁵Hewlett Packard *Microwave and RF Designers Catalog 1990-1991*, pp 4-68 and 4-69.

²⁶W. Hayward and J. Lawson, "A Progressive Communications Receiver," *QST*, Nov 1981, pp 11-21. Also in Chapter 30 of recent editions of *The ARRL Handbook*. QST