Peter Chadwick, G3RZP / g8on@btinternet.com

How Much Receiver Performance Does a Contester Need? — Part 3

Selectivity

As we all know, selectivity is the ability of a receiver to reject unwanted signals close in frequency to the desired signal. Increasing signal-rejection requirements led to advances in receiver technology, one of the earliest being the superheterodyne receiver, in which the desired signal is converted to a fixed frequency where amplification and filtering are easier to do. The invention of the superhet is generally credited to an American, Edwin Armstrong, in 1915, although French engineer Lucien Levy suggested the idea in 1909, before triode tubes were available, and Alexander Meissner in Germany patented the principle in early 1915, although he never actually built a superhet (see Figure 1).

"The Basics"

Here are the basics: The signal is applied via a filter, frequently a single tuned circuit in simpler receivers, to the mixer, where it is combined with the output of an oscillator. The oscillator frequency differs from the signal frequency by the intermediate frequency (IF), and the output signal from the mixer at the IF passes through the IF filter and amplifier to the detector. The audio output of the detector is amplified and fed to the speaker, headphones, or device to convert the audio into data.

The IF filter is the principle determinant of the ability of the receiver to differentiate between wanted signals and adjacent-frequency unwanted signals. Historically, this was achieved by analog tuned-circuit types using inductors and capacitors, or by crystal or mechanical filters. As an aside, in receivers and transceivers more than about 30 years old, the filtering may have severely degraded with age. With coil-and-capacitor designs, ingress of moisture, especially into wax dipped inductors, is the most usual cause, although silver migration in silver mica capacitors also can occur, especially if there is any dc across the capacitor and/or any leakage of moisture.

Mechanical filters often used plastic foam to support parts of the filter, and this can crumble over time. In some cases, where the mechanical filter used piezoelectric ceramic transducers to drive the filter elements, the foam degradation led to acid that attacked the silver plating (these filters have been opened and repaired, provided the transducers were still good). Even crystal filters are not necessarily immune, as solder-sealed crystals can shift in frequency and/or Q can degrade, resulting from contamination of the crystal by flux fumes gradually deposited on the crystal. Mechanical filters typically use the mechanical resonance of discs, or sometimes plates, to produce the equivalent of a high-Q tuned circuit.

Ideally, the response should be a very steep roll-off in amplitude as a signal moves out of the filter's passband; today's "brick wall" digital filter response can only be approximated — but in practice, quite well — in analog filters. With Digital Signal Processing (DSP), a much-closer-to-perfect brick wall is achievable. Figure 2 shows the crystal filter response of the 1970s-era Atlas 215X transceiver, but as I'll discuss later, this is somewhat misleading, because other factors affect the ability of the receiver to reject adjacent interference — not the least of which is high-order intermodulation products that some transmitters can produce.

The usual ratio for determining the effectiveness of the filter is referred to as the *shape factor*, which is the ratio of the bandwidth at 3 or 6 dB down from the response at the center frequency and the bandwidth at (typically) 60 dB down. In Figure 2, the shape factor is 4300 ÷ 2700 or 1.59. Typical good SSB crystal filters have shape factors between 1.58 and 1.65.

Other factors that can affect the receiver performance are the amount of amplitude ripple within the passband, and, for digital modes, the phase response of the filter, i.e., how much the phase of the signal changes over the passband.

Producing narrowband filters with good shape factors at high frequencies, say 30 to 80 MHz, is difficult, especially if operation over a wide temperature range is required. This is why upconverting receivers tend not to have first IF crystal filters with narrow bandwidths and good shape factors of lower frequency filters.

Direct Conversion

One approach that has been used to minimize filter problems is "direct conversion" (see Figure 3). In a direct-conversion receiver, the oscillator is on the carrier frequency of the signal, and

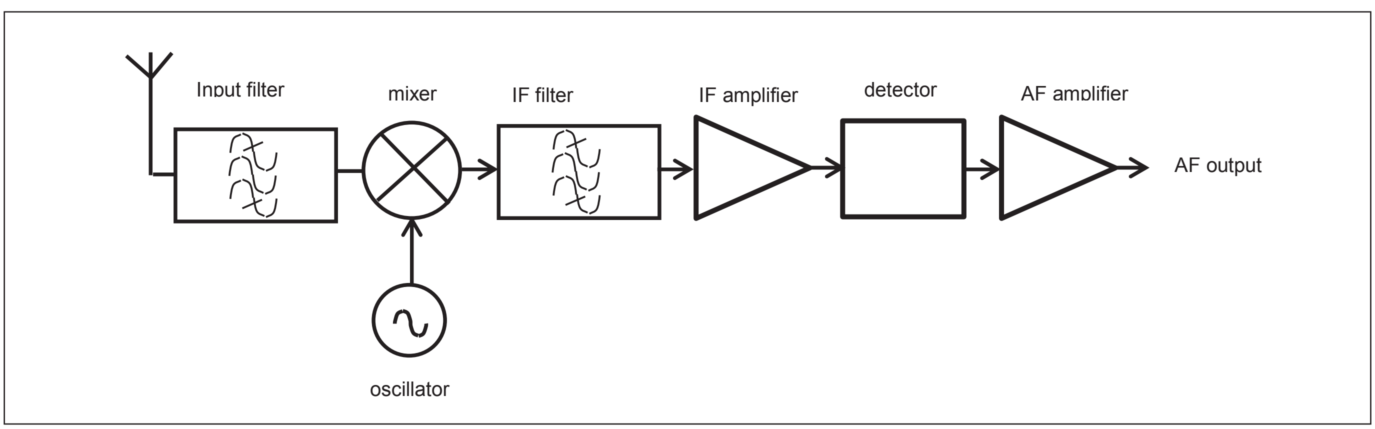

Figure 1 — The basic superheterodyne receiver.

selectivity is determined by low-pass audio filters, which can have a very steep high-frequency cutoff. I won't cover the mathematics of this architecture; suffice it to say that accuracies in the relative phase shift of 0.35° over the entire audio band are required to achieve 50 dB rejection of the unwanted sideband. As a result, this has method has not been much used for high-performance analog receivers. Implemented in digital form, however, very high-performance digital filters are possible, as is very precise control of phase shifts.

One difficulty common to both conventional superhet and analog direct-conversion receivers is the problem of phase noise, i.e, phase modulation of the local oscillator by noise. Oscillators have various sources of phase noise, which is a subject in itself. Professor Dave Leeson, then W6QHS and now W6NL, derived what is known as Leeson's equation for the spectrum of an oscillator (see Figure 4).

In the case of the direct-conversion receiver, any leakage of the local oscillator to the input ports of the mixers then mixes the phase noise with the carrier back to audio frequency, and thus can limit sensitivity. In the superhet case, the effect is to compromise rejection of signals on adjacent frequencies (see Figure 5).

The desired signal is mixed to the IF and passes through the IF filter. The strong, unwanted signal mixes with oscillator noise sidebands to also be translated into the IF passband, degrading the received signal-to-noise ratio. This is also known as *reciprocal mixing.* This raises the question of how far down must the phase noise be?

Figure 6 shows the effect in terms of compromise of the Atlas filter by the phase noise levels in the Table 1. Note that these phase noise levels possibly represented

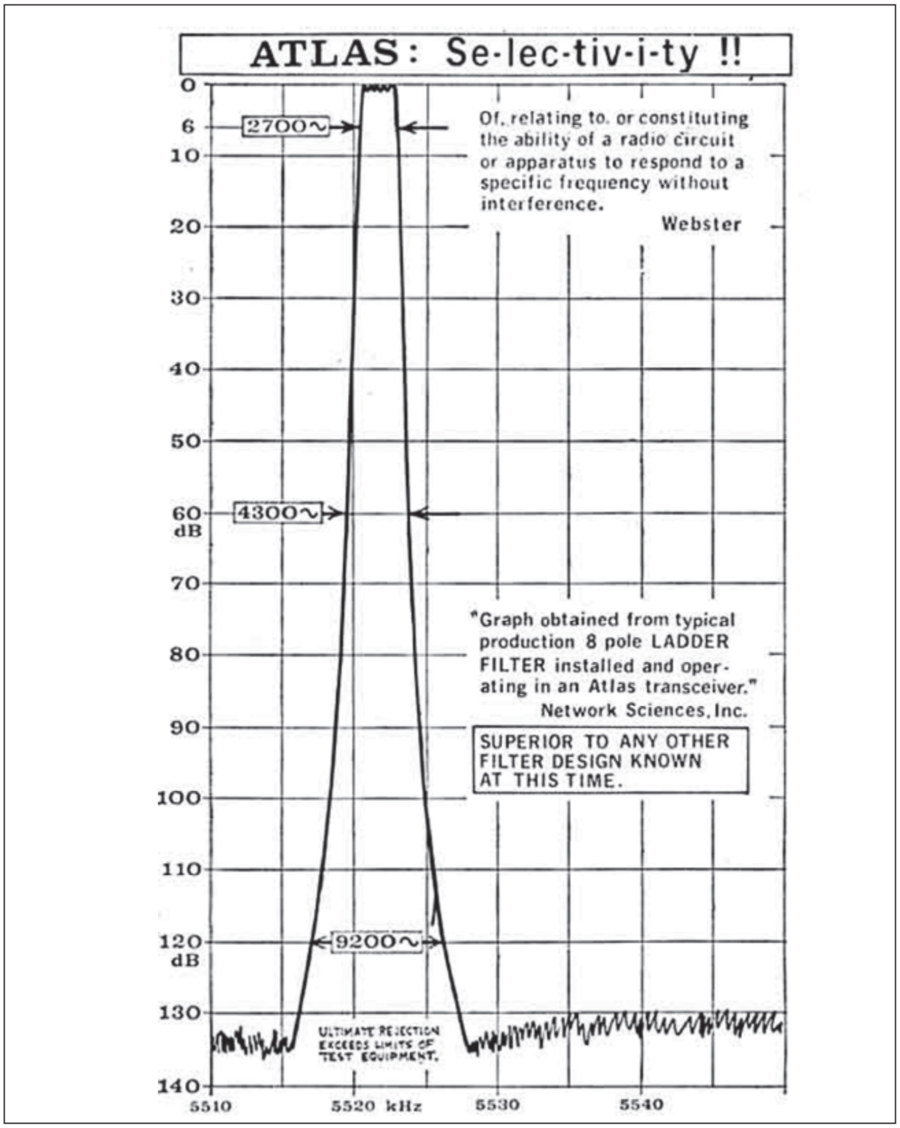

Figure 2 — Filter performance compromised by even excellent phase noise. [*RadCom*, June 1976]

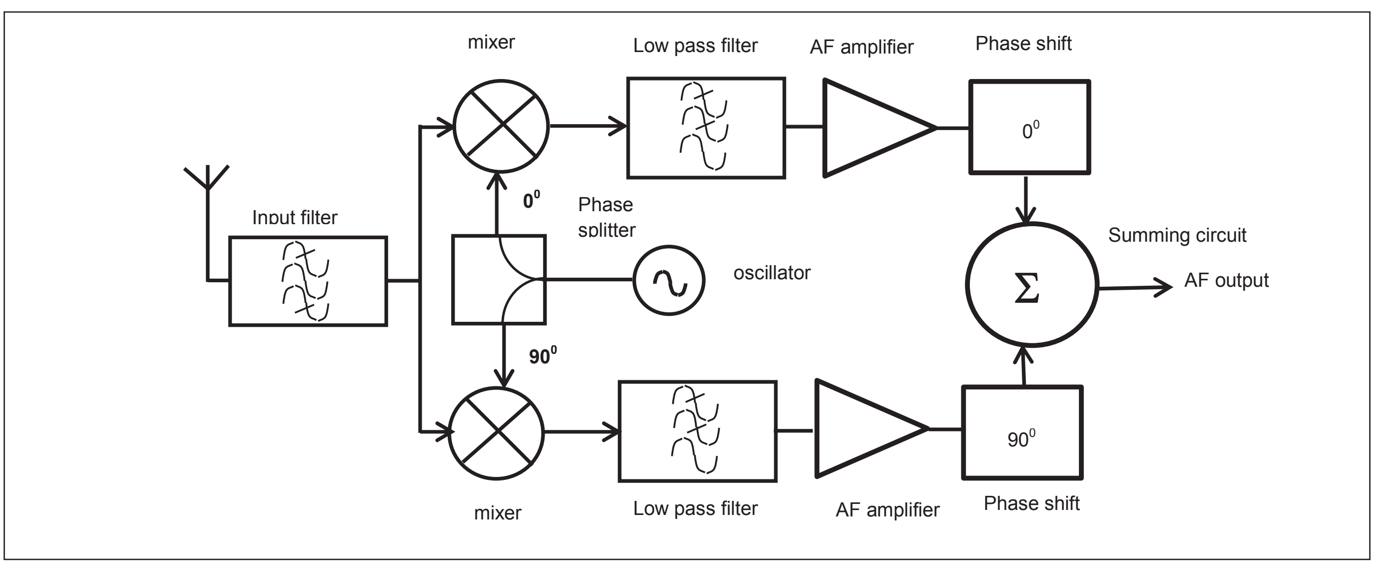

Figure 3 — The direct-conversion SSB receiver.

the best available in amateur equipment at the time. A simple equation is that phase noise-limited dynamic range (PNDR) is

$$PNDR_{dB} = -174 + NF - \alpha$$

where NF is the noise figure of the receiver in dB and α is the phase noise in dBm/Hz of the local oscillator at any given offset.

If the phase noise is not flat within a band equal to receiver bandwidth, then strictly the integral of the phase noise slope over the bandwidth at that offset should be used. For most practical purposes, the assumption that, over even an average AM bandwidth, the phase noise more than half a bandwidth away from the center frequency is flat is adequate.

Assume a dipole on 7 MHz in the clear in a quiet, rural area producing 1 µV of noise: To have a degradation of 3 dB in receiver noise floor with the phase noise levels in Table 1 because of reciprocal mixing on an unwanted signal 10 kHz away would require an unwanted signal of 354 mV, and even that makes the unlikely assumption that the unwanted signal is at least 10 dB better in wideband noise performance than the receiver phase noise. This is the sort of signal level that would be received at about 1.5 miles on 7 MHz over good ground from a transmitter radiating 400 W. With typical performance of SSB transmitters manufactured since 2000, high-order intermodulation products would be some 50 dB down, causing splatter some 60 dB or so above the noise, thus making the use of the very high phase noise-limited dynamic range somewhat academic. On CW, the practical use of more than 95 to 100 dB of dynamic range (here including the intermodulation-limited dynamic range, the reciprocal mixing dynamic range, and the blocking dynamic range) is again doubtful for the average amateur, especially as such a low 7-MHz noise level requires a location at the lower end of the quiet rural environment. In fact, the signal levels in the table in Part 1 of this series (see Table 2) showed no signals larger than –10 dBm at any time on 7 MHz, including international broadcast stations. As far as third-order intermodulation distortion (IMD3) is concerned, every 1 dB drop in input signal will theoretically introduce (in a conventional receiver) a 3 dB drop in IMD3. Phase noise is more insidious, because a 1 dB drop in input signal will produce a 1 dB drop in phase noise effects. If we take the case of five signals between –20 and –10 dBm, and assume an average of –15dBm and a separation from the wanted signal of more than 20 kHz, for the receiver phase noise from each to be 10 dB below the noise floor set by the external noise from the dipole (i.e., –117 dBm), the phase noise at that offset needs to –102 dBc in the bandwidth equal to that of the receiver — or in SSB, about –136 dBc/Hz.[1] This means that the K3S exceeds the requirements by about 10 dB for one signal. But, because there are five signals of that level, the total noise is 7 dB higher. It is fair to say that few amateurs will have that low a noise level, and conversely, places far enough away from population centers to have such a low noise level are, in general, far enough away from big transmitters not to see such large signals except on special occasions.

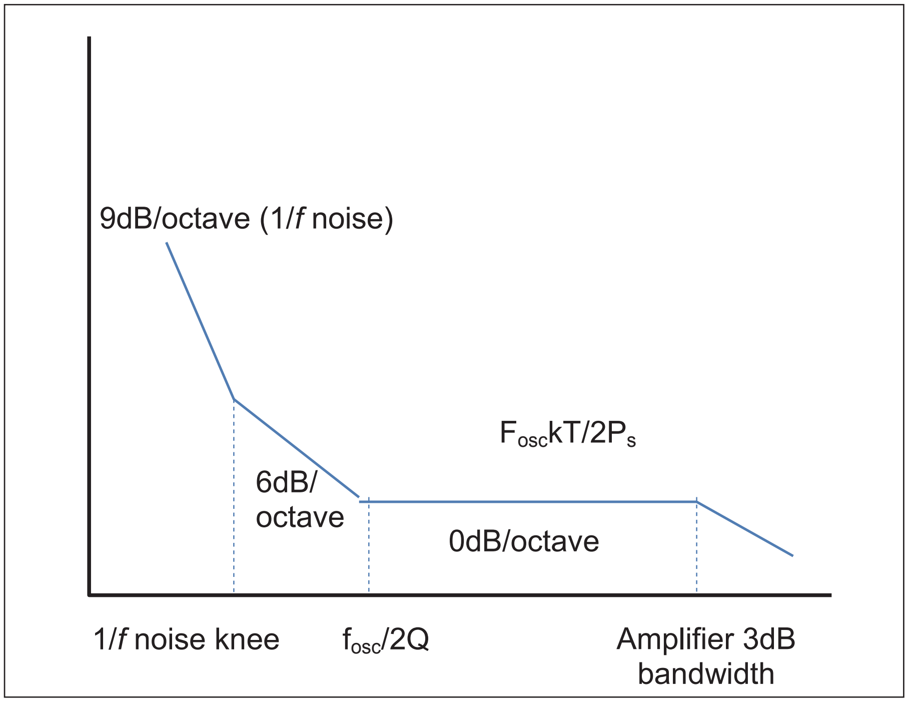

Figure 4 — Professor Dave Leeson, then W6QHS and now W6NL, derived what is known as Leeson's equation for the spectrum of an oscillator

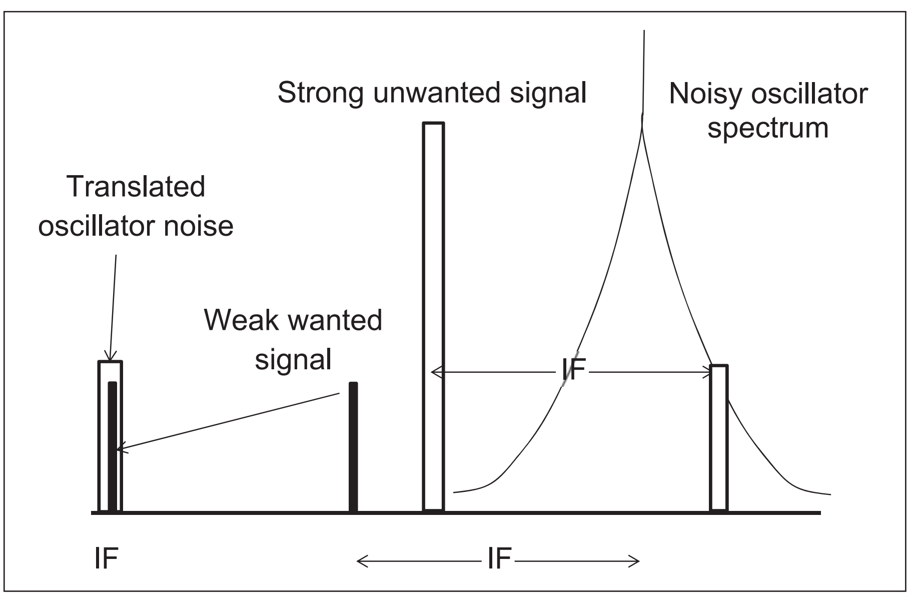

Figure 5 —

Points to Ponder

What can we deduce regarding the necessary parameters for a receiver for contesting? The first point is that usable sensitivity will generally be determined by external noise, especially for those

Table 1 — Phase noise-defined selectivity.		
Offset (kHz)	**Noise (dBc/Hz)**	**Noise in 2700 Hz dB**
3.5	–130	–96
5.0	–134	–100
10.0	–142	–108
20.0	–144	–110
30.0	–145	–111

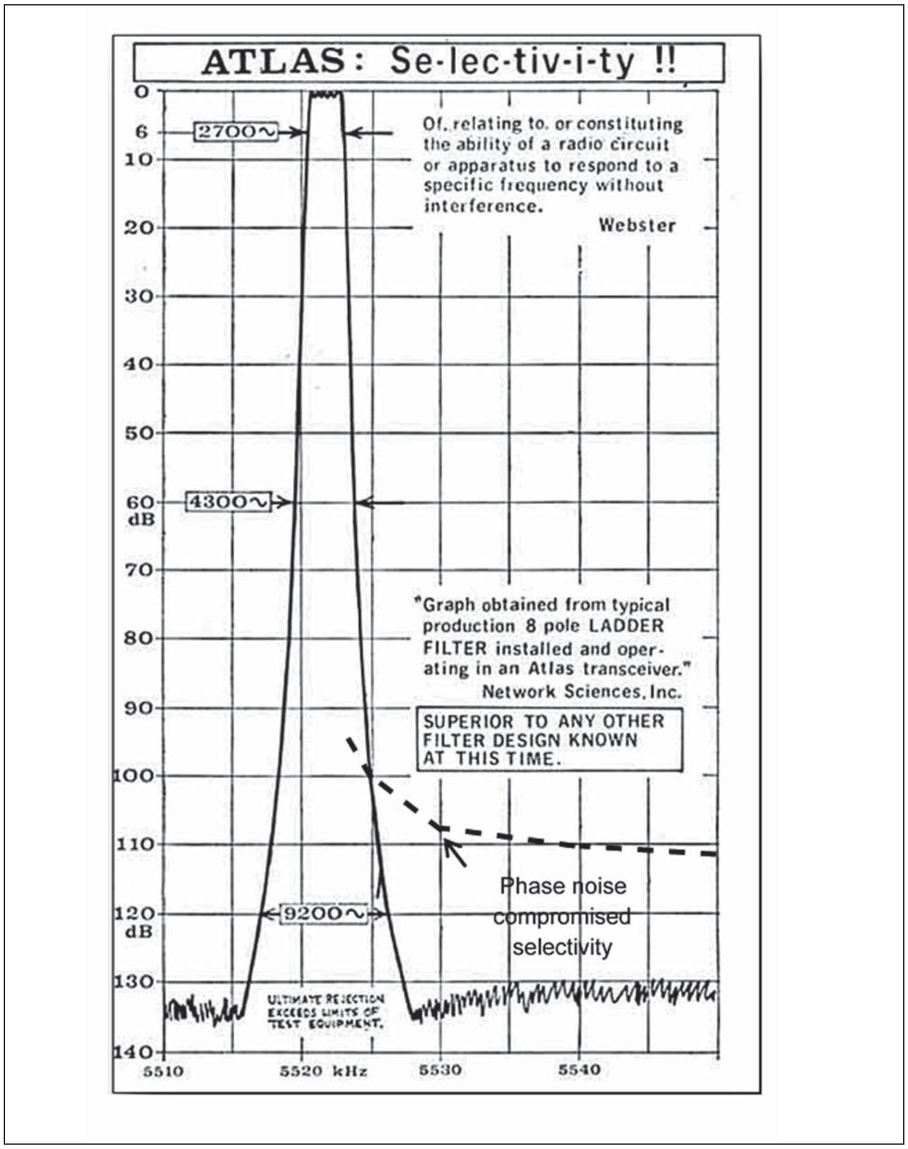

Figure 6 — Filter performance compromised by even excellent phase noise. [Courtesy RSGB *RadCom*, June 1976]

not located in a rural or electrically quiet, rural environment, — unless the receiving antenna is exceptionally inefficient. This is occasionally purposely done to obtain a low noise on the LF bands – some people have used a length of wire lying on the ground for a 160-meter receiving antenna and followed it by a preamplifier to be able to pull DX out of the noise. Such applications are rather specialized, though, and generally use auxiliary equipment.

The ability to dig out weak signals is a function of selectivity — effectively the filters, phase noise, also known as reciprocal mixing, and intermodulation — on some occasions, it's a combination of all three. It has been shown above that on 7 MHz, generally considered the most demanding band in Europe, the phase noise-limited dynamic range needs to be on the order of 102 dB or so if the location is very quiet, and around 95 to 100 dB for most amateurs because of external noise.

Similarly, a 3rd-order intercept point (IP3) of +26 dBm is desirable for the very quiet situation. This gives a 95 dB spurious-free dynamic range (SFDR is 2/3 of IP3 – noise floor) and is, in most cases, somewhat more than can be used, because of external noise limitations. Thus a SFDR of around 95 to 100 dB is adequate. Achieving the + 26 dBm IP3 is slightly more difficult until one realizes that an SSB receiver noise floor of –120 dBm represents a noise figure of around 30 dB, and a 15-dB attenuator in front of a 15-dB noise figure receiver provides a big increase in IMD performance.

Spurious Responses

Other factors can affect receiver performance for contesting, such as spurious responses. These have two manifestations. The first is the internal spurious, a signal appearing with no antenna connected on SSB — a carrier generated by the various internal oscillators. In the days of transceivers with VFOs covering from 5 to 5.5 MHz (and tuning "backwards"), it was usual to find this at 21.2 MHz — the 4th harmonic of the VFO. That wasn't always the only spurious response. In multiple-conversion superhets, a common problem was *m* times the first local oscillator ± *n* times the 2nd oscillator equaling the signal, image, first, or second intermediate frequencies; values of *m* + *n* up to 50 have been known to cause problems.

The other is the external spurious response, i.e., the receiver hears signals where it is not supposed to be tuned. The classic superhet with a 455-kHz IF suffered this on 20 meters. The oscillator frequency typically would be 455 kHz higher than the signal frequency, and a large signal from the 19-meter broadcast band would mix in the IF passband. This is the well-known image frequency problem.

Other spurious responses include breakthrough into the first, and more unusually, to a second IF, and those responses caused by discrete spurious sidebands on the local oscillator, especially in designs using a direct digital synthesizer (DDS). These spurs can be very hard to find in the laboratory and only actual on-air use can show some of them up.

Gain Control Distribution

Gain control distribution is rarely measured in reviews. Consider a receiver where the gain control is a variable attenuator in the antenna lead. Regardless of signal level at the antenna, the signal-to-noise ratio at the output will always be the same for a constant output level, whereas the signal-to-noise ratio is expected to rise with an increase in signal level. The test for this parameter is to set the input level to give a 20 dB signal plus noise-to-noise ratio with the AGC off, and then increase the input signal level by 20 dB and reduce the RF gain control to get the same output level. The signal-to-noise ratio is measured again, and would ideally be

Table 2 — Predicted noise levels from a half-wave dipole in the clear in various locations. All figures are rounded. Dipole μV is the PD delivered to a 75-Ω load. S meter readings based on S-9 = 50 μV. These numbers represent the median: 80% will lie within a window between 4 and 11 dB wide, depending on time, and a further 6 to 8.4 dB depending on location within the categories specified. This suggests a worst-case spread of as much as19.4 dB.

Band	Location	dBμV/m	μV/m	Dipole μV	S Meter
160	City	10	3	76	9 + 3 dB
	Suburban	7	2	51	9 + 1 dB
	Rural	0	1	25	8
	Quiet Rural	–13	0.2	5	6
80	City	10	3	41	9
	Suburban	5	2	27	8
	Rural	0	1	14	7
	Quiet Rural	–15	0.2	3	5
40	City	7	2	14	7
	Suburban	2	1.3	9	6
	Rural	-5	0.6	4	5
	Quiet Rural*	–12	0.25	2	4
10	City	1	1.1	2	5
	Suburban	–4	0.6	1	4
	Rural	–10	0.3	0.5	3
	Quiet Rural*	–16	0.2	0.3	2

* = primarily galactic noise.

40 dB. This is generally not achieved, and some commercial specifications demand a minimum of 35 dB.

Where a SINAD (Signal plus Noise plus Distortion to Noise + Distortion) ratio is used), audio distortion of better than 1% would be required for a 40 dB SINAD ratio, and even 35 dB requires distortion slightly better than 2%. Poor gain control distribution can lead to increased operator fatigue, especially in designs where the signal-to-noise ratio is not as good as it could be. This is often a problem where the IF noise bandwidth before the detector is very wide — typical of many integrated circuit IF strips — and post-demodulation AF filtering is inadequate. Limiting the IF bandwidth *prior* to demodulation has advantages in maintaining demodulator linearity, in addition to providing AF filtering.

When operator fatigue is considered, the ergonomics of the equipment become important. Where the whole operation is controlled by mouse and keyboard, software must be designed for good ergonomics.

Peter E. Chadwick, G3RZP, was born in 1947, the son of G8ON, he has been a volunteer for RSGB since 1983, was president in 1993 and appointed Honorary Life Vice President in 2011. He is a Senior Member of the IEEE, a Technical Consultant to the IARU whom he has represented many times at the ITU since 1997. He has 16 expired patents and over 40 publications in amateur and professional publications, and is at the top of the DXCC Honor Roll with all current entities confirmed. He is married to G4FNC; they met at the Cray Valley Radio Society (G3RCV) in South East London.

Notes

[1] Receiver Parameters for Contesters, Peter E. Chadwick, G3RZP, *NCJ*, March/April 2007