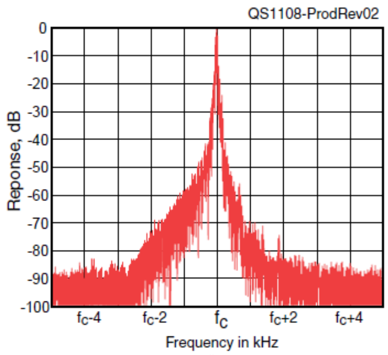
A Comparison of ARRL Lab Data For Selected Transceivers

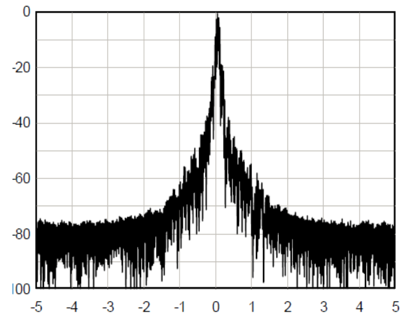
Jim Brown K9YC (Edit 7 Sept 14)

A decade of extensive work by Rob Sherwood and ARRL Labs, analyzing and documenting the receive performance of modern transceivers has resulted in a top tier of rigs offering greatly improved receiver performance. Meanwhile, transmitters have largely been ignored; the result is a mess on our bands, especially during contests. The work presented here is part of an effort to correct that situation. Let's begin by studying plots ARRL lab test data for the keying spectra 5 kHz either side of a CW signal.

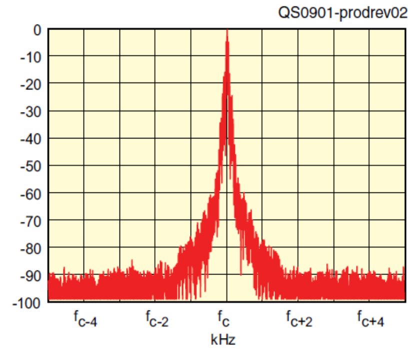
Raw Data -- Spectra With CW Keying – Clicks + IMD + Phase Noise



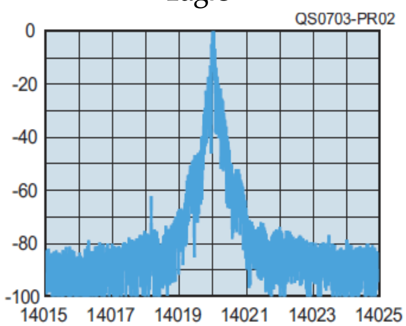
Eagle



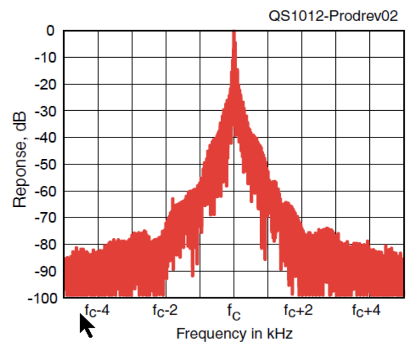
Orion II



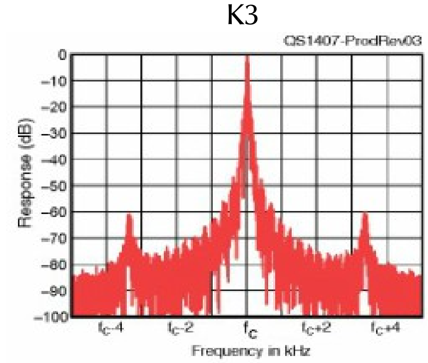
K3



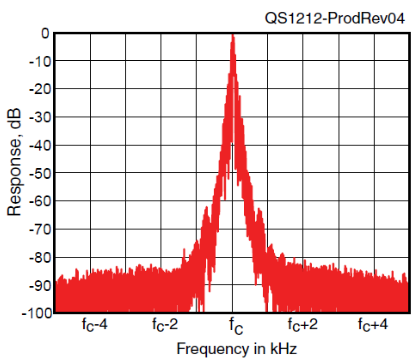
IC7800



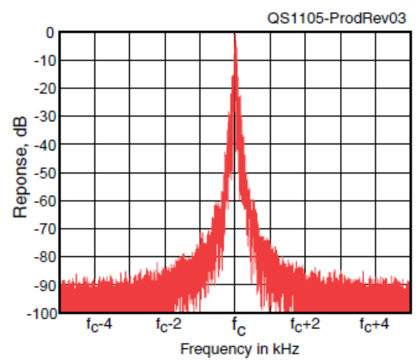
FTDX5000D



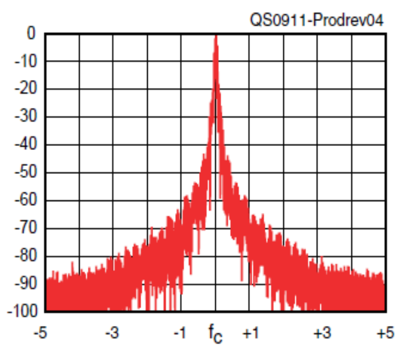
IC7100



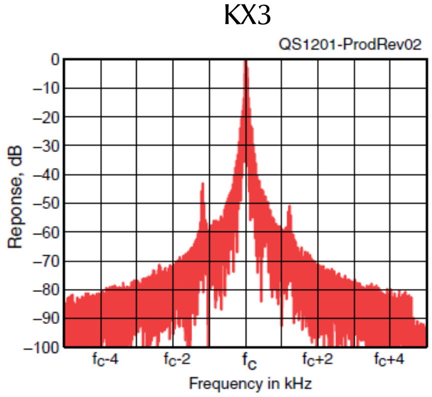
KX3



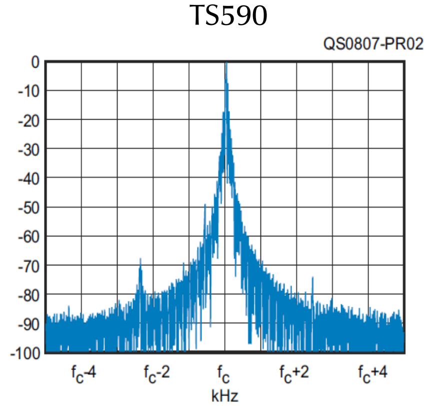
TS590



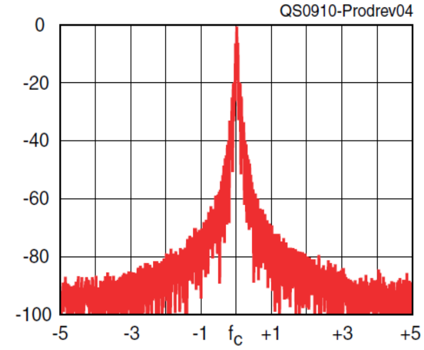
IC7600



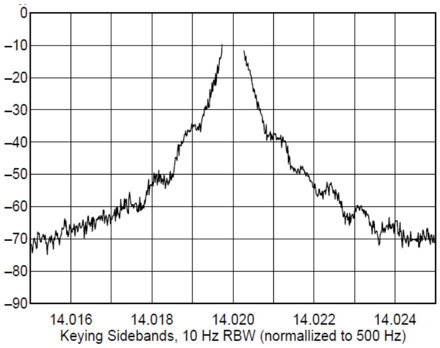
Flex 1500



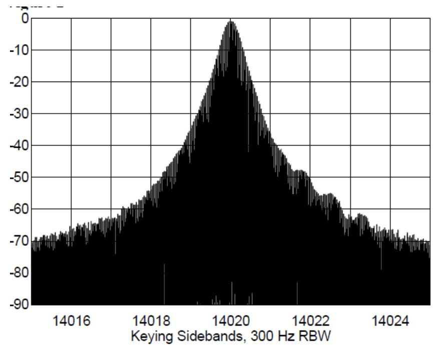
Flex 5000A



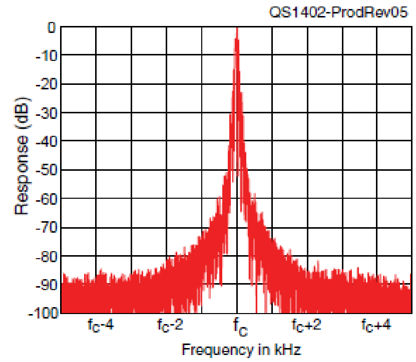
Flex 3000



FT1000 Mark V Field
10 Hz Bandwidth



FT1000 Mark V Field
300 Hz Bandwidth



TS990S

Figure 1 – The Raw Data

Over the years, I've learned that plotting corresponding data for multiple conditions or products on the same graph often leads to insights about the data. That is the approach taken here. These plots (Figure 1) by ARRL of their data make it difficult to pick points at intervals closer than 500 Hz, so that's where I've chosen to start. Even with that limitation, the plots clearly show that some radios have a much narrower keying profile than others. Compare, for example, the extremely narrow profile of the K3 with the extremely broad profile of the FTDX5000D. When does this matter? In contests, when, for example, a hundred or more legal limit CW stations are trying to fit into the 15 kHz JA window on 160M during a contest! That's 150 Hz for each of those 100 stations, and rigs like the FTDX5000 are burning four times as many channels as a K3, twice as many as an IC7800 or IC7600.

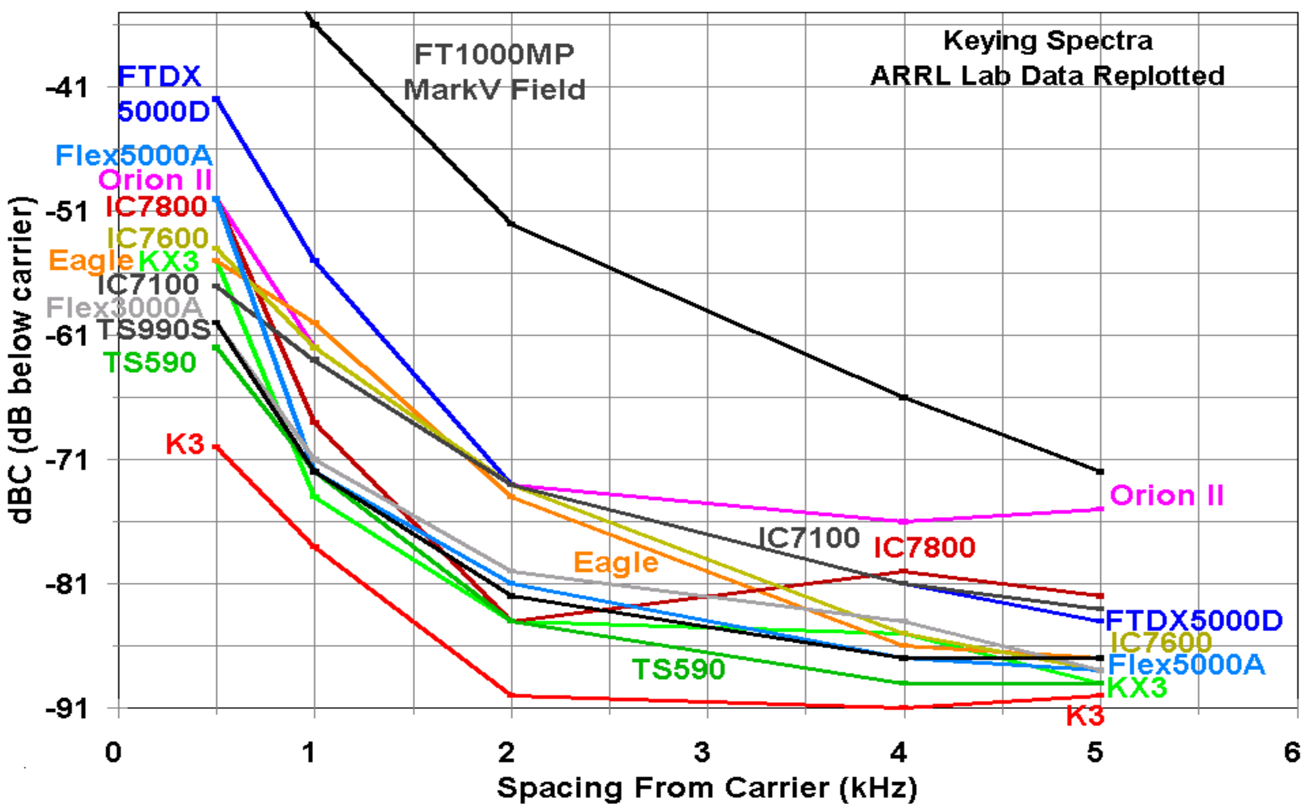


Figure 2 – The Rigs Compared For CW Spectrum

Initial Plot (Figure 2): It's no surprise that the FT1000MP Mark V Field is 20 dB worse than the worst of the rest of the field, the FTDX5000D, which itself is 7dB worse than rest of the pack at close spacing. The K3 is the cleanest by far (8dB better than the pack and 28dB better than the FTDX5000D), and the others are clustered in a 10 dB range in the middle. At the widest spacing, the differences are down to 15 dB, the Orion II is the worst, the FTDX5000 is in the middle of the pack, and the K3 is still the cleanest, but by a much smaller margin.

Much Better Plots Directly From ARRL Data Files

When I sent an early version of this work to ARRL Lab Tech Bob Allison, WB1GCM, he was kind enough to send me the raw CW spectrum data for most of these rigs, which I have imported to Libre Office and post-processed the data using a running average for better display. The first plot averages three adjacent data points, and it's still hard to see the forest for the trees. A 9-point running average yields a much better plot, but the phase noise still gets in the way of separating one rig from another. The older IC7800, Flex 5000A, and FT1000MarkV Field were measured by Bob's predecessor at the Lab, and he was not able to find files for them. He substituted IC7700 data for the missing IC7800 data. Note also that colors have changed, a byproduct of my having to process this material in LibreOffice, because my Quattro Pro machine, an ancient T41 Thinkpad, is out for repair for a hardware issue. And as N0AX suggested, the new plots show linear frequency. Another difference is that my original graph picked points at the top of each curve, while the newer ones are a running average.

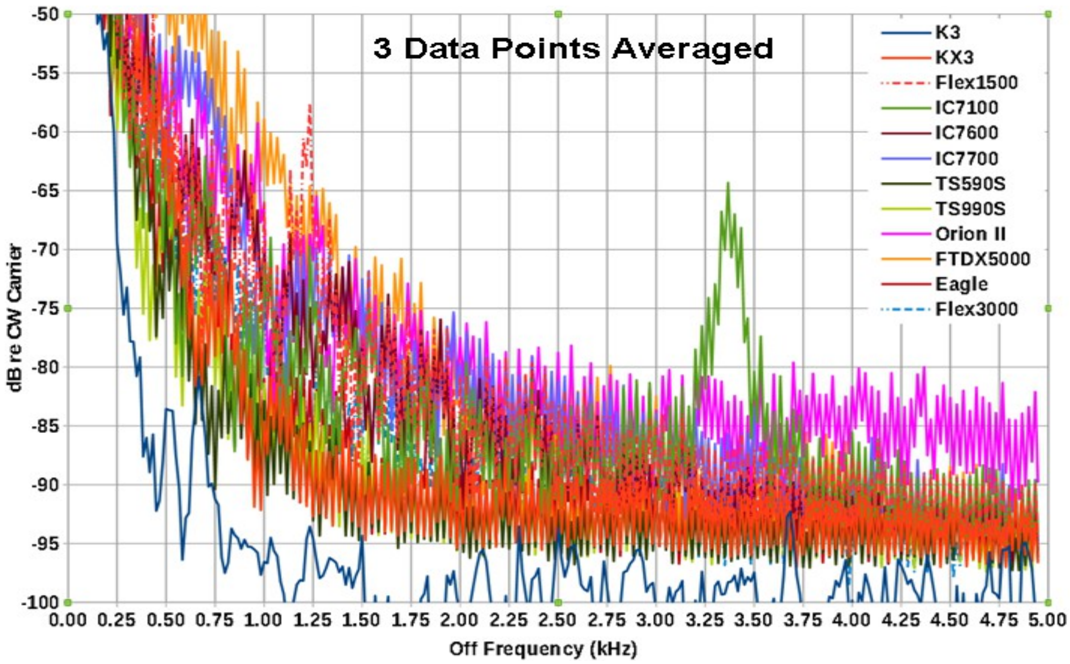


Figure 3

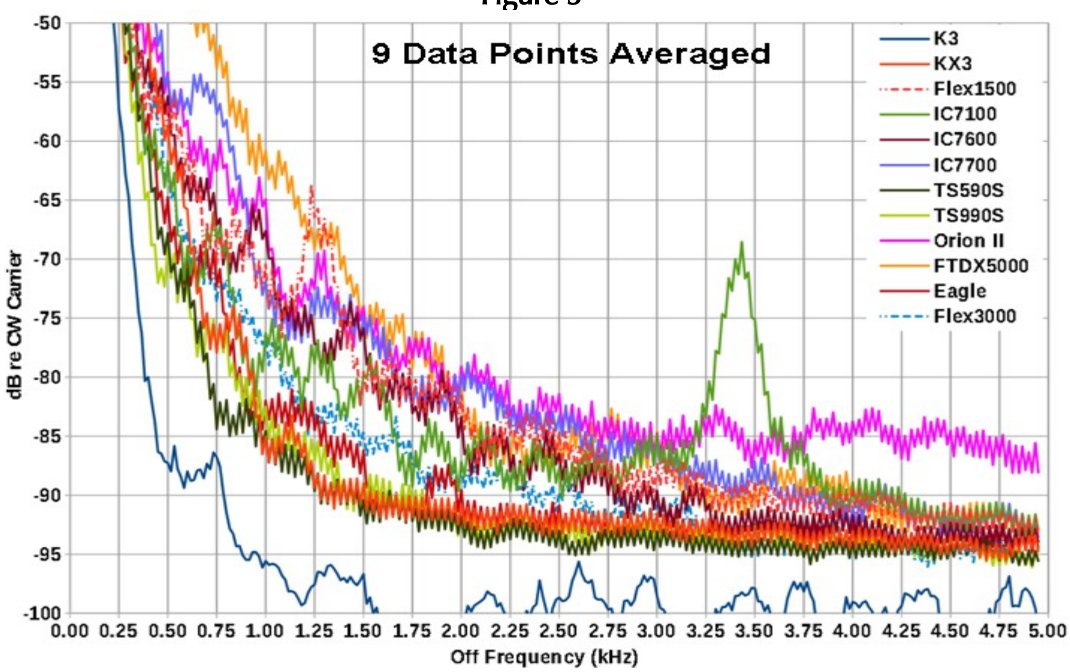


Figure 4

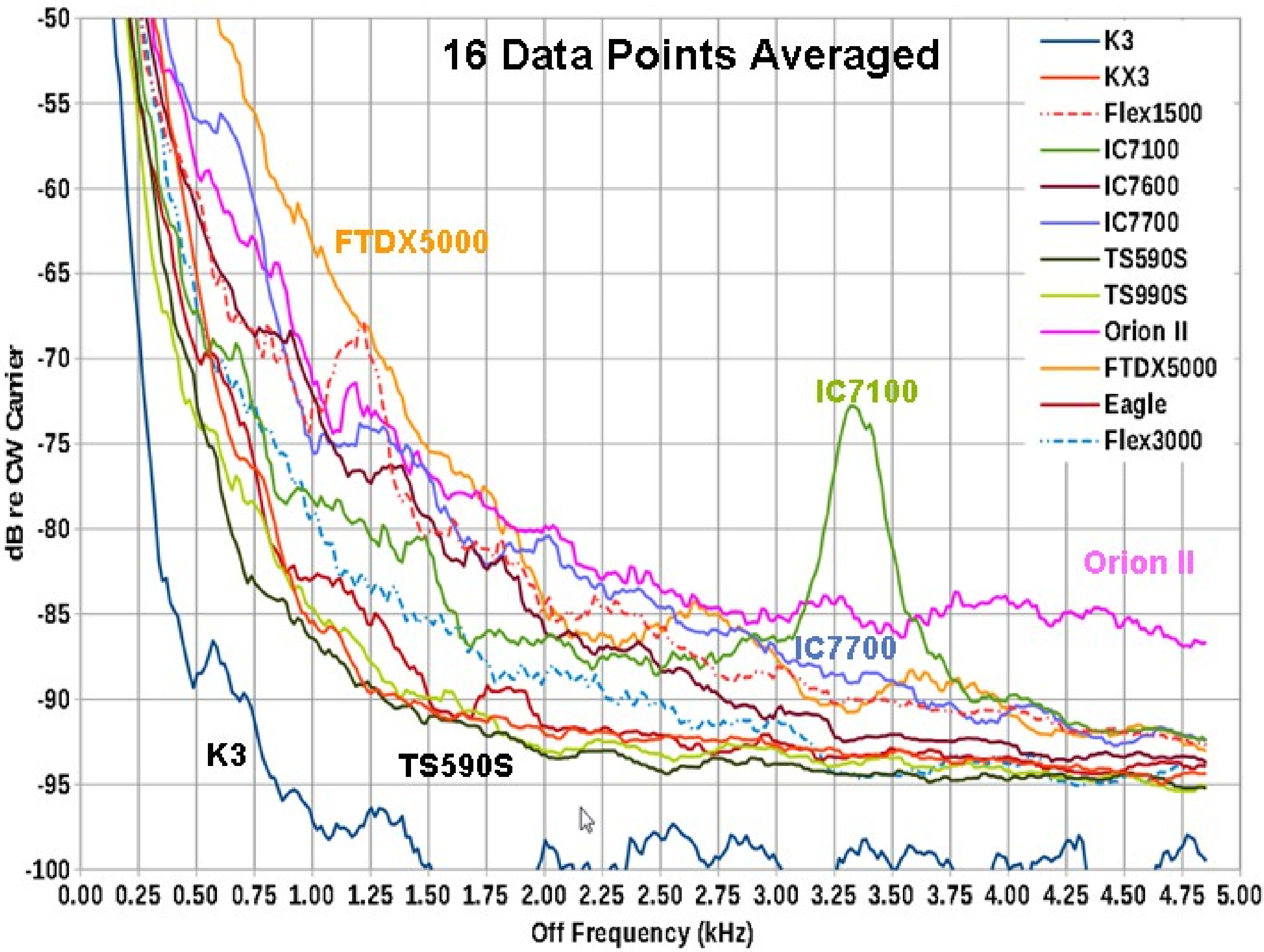


Figure 5

Analysis of Keying Spectral Data – Figures 1-5

Rise Time and Bandwidth: the Yaesu, Icom, and Kenwood rigs allow the user to adjust the rise time of CW keying. Per their manuals, the default is 4 ms for the Yaesu and Icom rigs, 6 ms for Kenwood, 5 ms for the Orion II. The Eagle is fixed at 5 ms. The slower Kenwood rigs placed second to the K3 in CW bandwidth, while the faster Icom and Yaesu rigs were significantly broader. My own on-the-air measurements (a ten mile path on 10M) with KW6S's IC7600 showed that faster rise times significantly increase signal bandwidth. See http://k9yc.com/K6XXAmpTalk.pdf We don't know the settings for those rigs that allow user adjustment of the keying rise time, but default values would be a good guess.

Plots From Electronic Data: Post-processing of the raw data (Figs 3-5) provides far better resolution, and clearly shows the contribution of phase noise and keying waveshape. Averaging essentially makes the random component of the phase noise disappear. Differences between the rigs remain about the same.

For CW, these spectral plots tell the complete story for what is happening close to the carrier, because they include the effects of keying transients, IMD and phase noise. Because the spectral distribution of pink noise band limited to 100 Hz to 5 kHz closely approximates the spectrum of speech, a comparable, but wider, plot for SSB modulated by that test signal would provide a similar result for SSB.

How much do these differences matter? 6 dB is a 4X increase in transmitter power, and one S-unit on a properly calibrated meter. Few rigs are that well calibrated, except very close to S9; 3-4 dB per S-unit is more typical below about S6. 10 dB is 10X the transmitter power, 20 dB is 100X. So, in practice, the dirtier of these rigs can degrade the signal to noise ratio of signals that we are trying to copy by a factor of 10X – 30X). Another way of looking at it is that 30X turns the signal to noise ratio of of the signal from a 1.5kW rig into that of a 50W rig, and another 10 dB drags it down to that of a 5W rig.

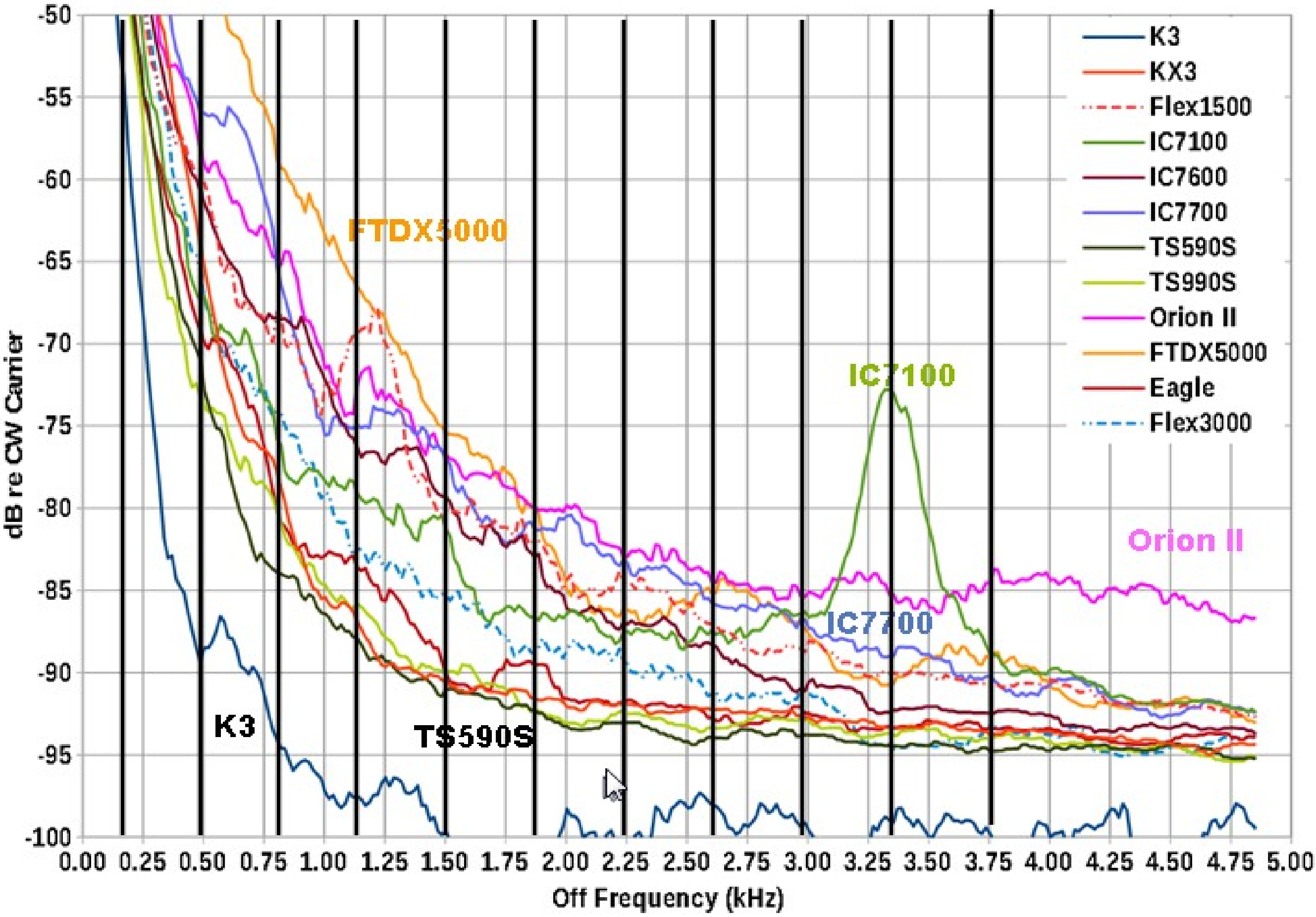


Figure 6 – 350 Hz Wide "Channels"

<u>How Much Does This Matter?</u> An active contester about 8 miles from me (and even closer to K6XX) runs an IC7600 and legal limit amplifier. When he's running (he nearly always is), he regularly chews up 5-10 kHz of whatever band he's on with his keying sidebands. With 250 Hz roofing filters in my K3 and the DSP IF screwed down to 200 Hz, I should be able to work at least a dozen or more stations either side of his run frequency, but his sidebands cover up all but the strongest. Multiply this by all the hours in a contest and that's a lot of S&P contacts I'm missing because of his dirtier signal. His dirty radio is costing ***me (and K6XX)*** points.

<u>Competitive Advantage:</u> Putting some numbers to it, consider a station running an FTDX5000D and another with a K3. Rob Sherwood's data shows the receive characteristics of the two radios to be roughly comparable, but trash from the FTDX5000D is much greater. ***In these examples, the station with the dirtier radio has a significant competitive advantage.*** The advantage comes from a) keeping others away from the dirty transmitter, which reduces QRM to the running station, and b) the dirty transmitter covers up nearby signals, preventing other stations from working them. This difference is plotted as the Red curve in Figure 7. The Blue curve shows the transmit noise advantage of an IC7600. Since 10 dB = 10X power, at 2-5 kHz from their carrier, these rigs are reducing the signal to noise of a legal limit signal to that of a 100 W signal. At 1 kHz spacing, that legal limit signal would sound like 5W with QRM from the 7600, and 500 mW with QRM from the FTDX500D. The K3 would be a flat line at 0 dB.

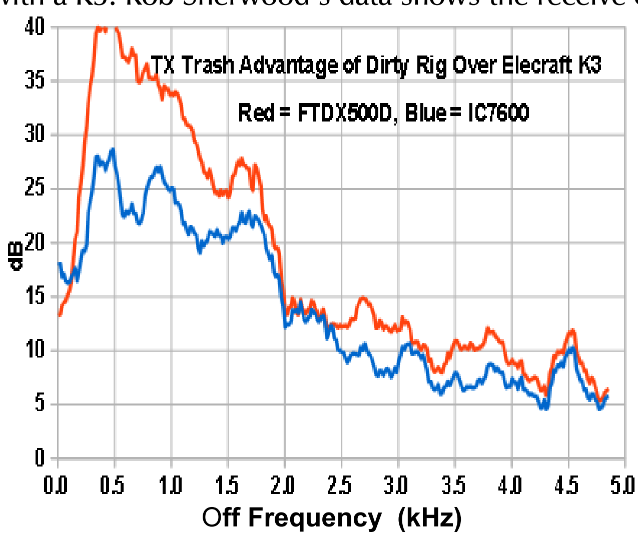


Figure 7 – Competitive Advantage

<u>Understanding The Keying Spectra Plots:</u> A keying waveform is, fundamentally, 100% amplitude modulation of a continuous carrier by some waveform that approximates a square-wave -- hence the name CW for

continuous wave. Any square wave has an infinite number of harmonics, the relative strength of which depend primarily on the shape of the switching waveform from on to off and off to on. The faster the rise and fall times, the more harmonics, and the stronger the higher harmonics compared to a waveform with slower rise and fall times. Those harmonics show up as sidebands, and the higher the order (harmonic number), the farther they are from the carrier. In a rig without IMD, that would be the end of the story, but real amplifiers have IMD, so those harmonics produce IMD, which results in more sidebands.

Rigs with cleaner keying reflect the skill of the designer in minimizing the harmonic content of the keying waveform, the level of TX IMD, and TX phase noise. Wayne Burdick, N6KR, lead designer of the K3, credits Lyle Johnson, KK7P, with development of the raised cosine "sigmoidal" shaping that achieves very good sounding CW while still achieving the very narrow bandwidth shown. That takes a lot of DSP that might have been devoted to other features (or eye candy) , but it was a design decision Elecraft was willing to make. It works well up to keying speeds approaching 100 WPM – Elecraft developed a QRQ option in firmware to make QSK work at those speeds, but the waveshape remains the same. N6KR says, "In QRQ mode, the K3's synthesizer remains at a fixed frequency, allowing shorter receiver-recovery times. This does come with a compromise, in that SPLIT and RIT are disabled." The QRQ option is chosen from a menu.

Close to the carrier, the key click spectral plots pretty much tell the whole story of what the TX is doing, because they include the effects of the keying waveform, phase noise and IMD. As we listen farther and farther off frequency from the transmitter, all that's left is phase noise.

Phase Noise

Next, I've replotted the ARRL wideband noise data in two forms. For the phase noise plots I've visually taken data off the plots printed in QST, because the data is not available in electronic form. Figure 8 shows the first 10 kHz from the carrier, and the frequency axis is linear. It's representative of what happens with a strong station close to our own frequency. It does not include the three Flex radios, which are shown in Figure 10. At the time of this writing (September 2014), the newer 6000-series Flex radios have not been tested by ARRL, but data provided by the manufacturer shows them as very good performers.

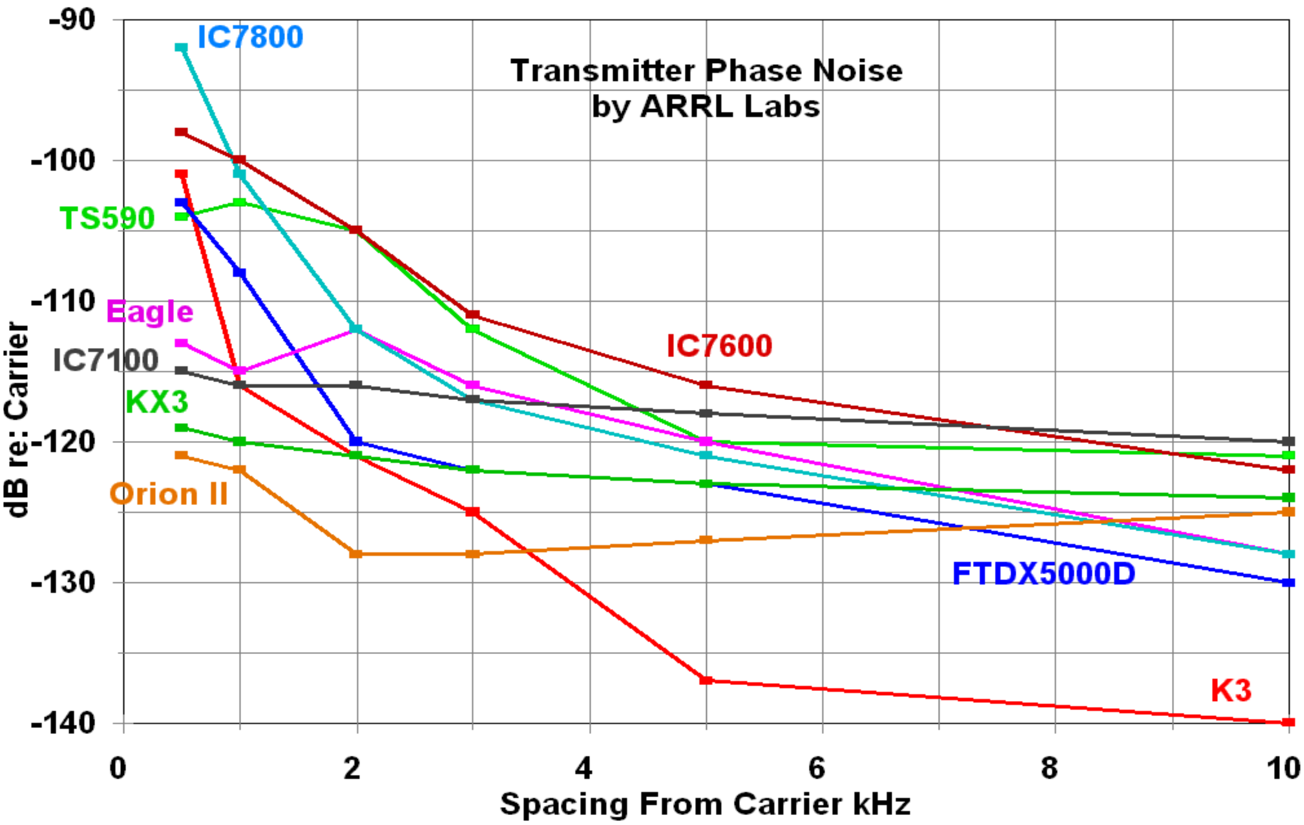


Figure 8 – Phase Noise Close To the Carrier

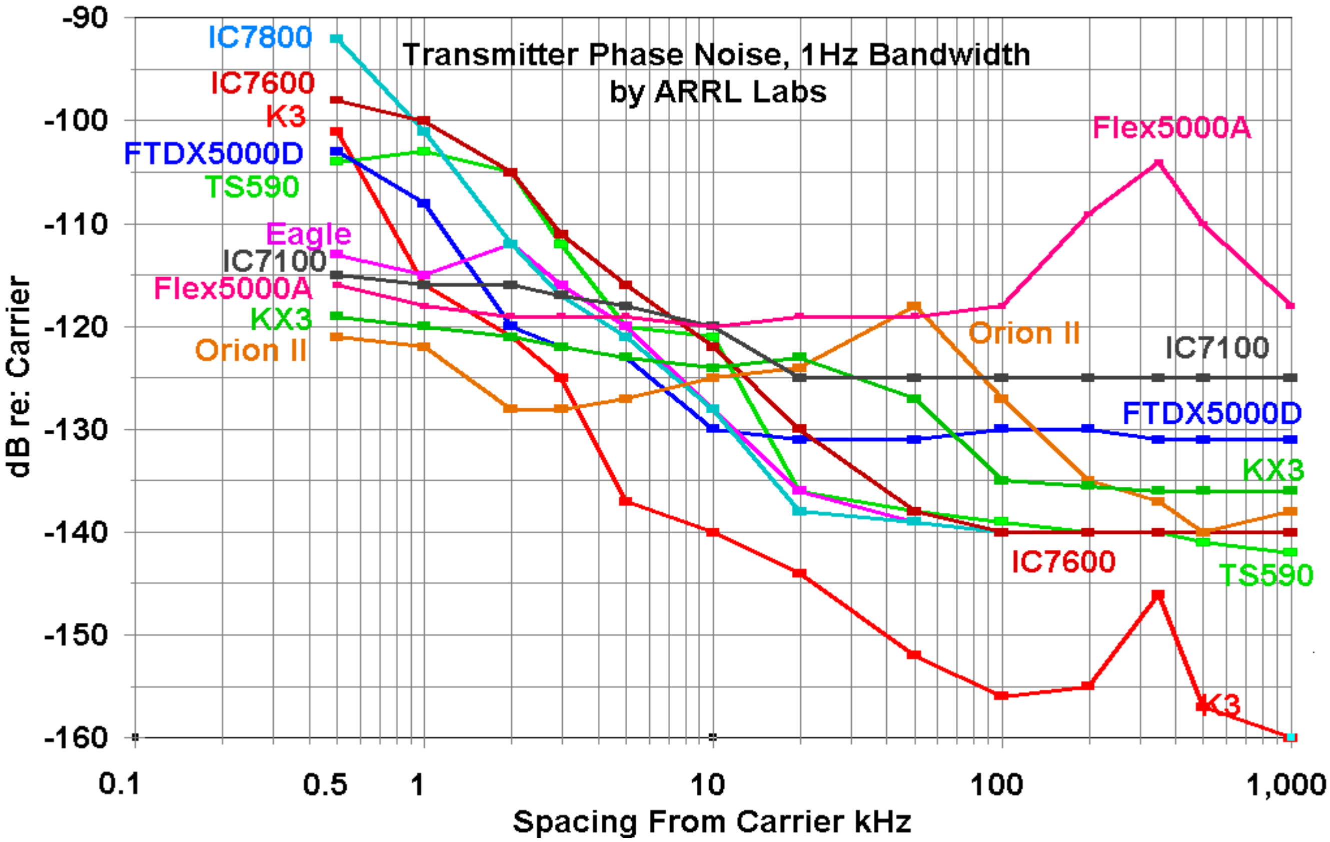


Figure 9 – Phase Noise 1 MHz Either Side of Carrier

Figure 9 shows the full extent of the published ARRL data, to 1 MHz, for noise in a 1 Hz bandwidth, and the frequency axis is logarithmic. Several rigs have been added to this plot and the one that follows. This plot is useful in predicting which rigs create the least QRM when used at a multi-transmitter site like Field Day, a multi-op contesting station, or on a DXpedition. Wideband noise is also important to VHF+ operators using the radio as a transverter base for weak signal work.

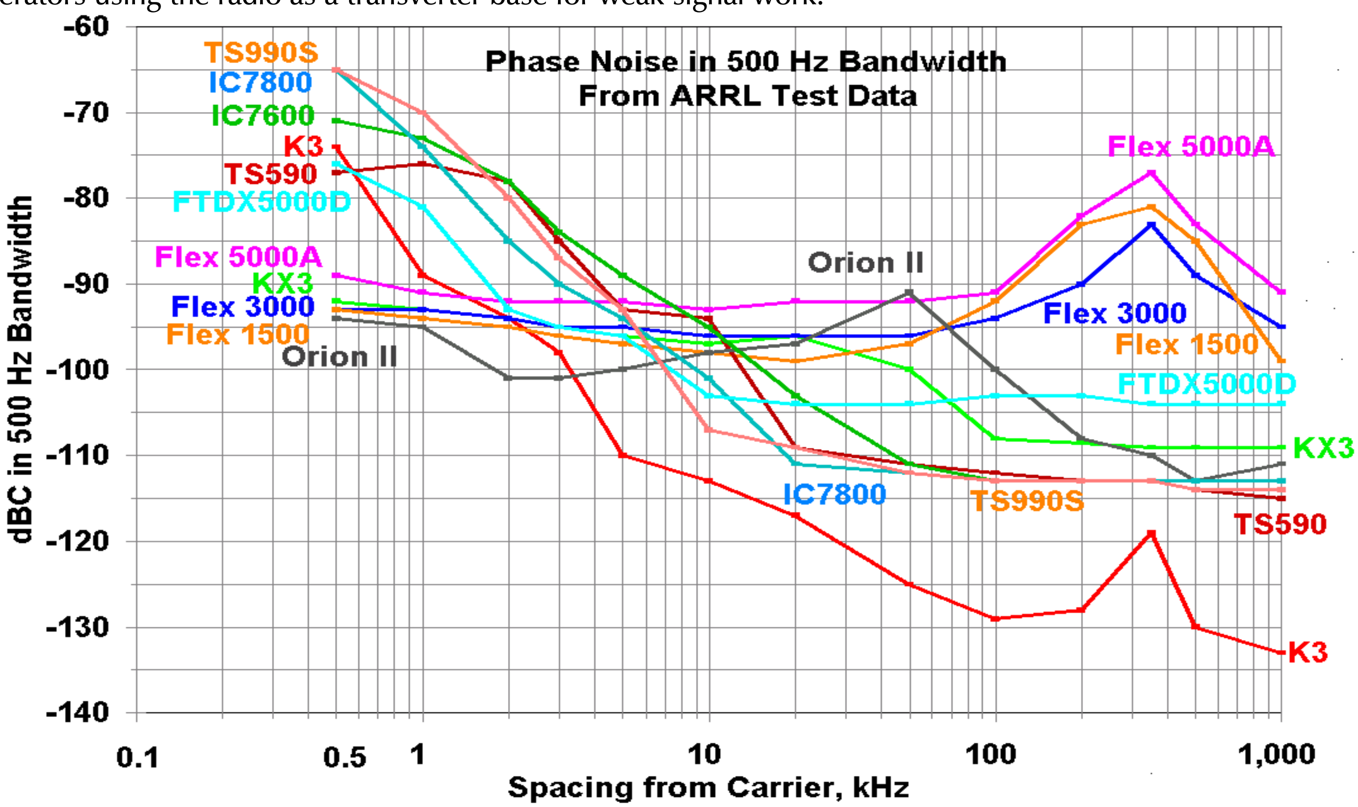


Figure 10 – Phase Noise Either Side of a Carrier

Figure 10 shows noise in a 500 Hz bandwidth, computed from the data by adding 10 log BW, which for 500 Hz is 27 dB. ***Not all plots show all radios – as I've added radios to the data set, I've omitted a few of the radios from each plot in the interest of clarity. In the 500 Hz plot, I've included all three Flex radios that ARRL has measured, which filled up the graph, so I omitted the Ten Tec Eagle and the IC7100. The relative performance does not change between the two plots.***

Now, with the ARRL dB/Hz data to a 500 Hz receiver bandwidth, we can better appreciate the significance of these data. For most of these radios, the transmitted CW spectrum 5 kHz from the carrier is mostly phase noise, and this agrees with what we saw on the CW keying spectral plots.

That 350 kHz Bump: Note the broad peak about 350 kHz from the carrier in all three Flex radios and the K3, which SM5BSZ discussed at length in this link. http://sm5bsz.com/dynrange/dubus313.pdf The Orion II has a similar peak around 50 kHz from the carrier. I purposely tried to choose data points that showed as much as practical of the data. Remember that I'm carefully eyeballing data points from a printed graph, the graph is only so big, and there are only so many hours in the day. More data points would, of course, have made these plots smoother, but I believe that these plots present the differences between radios fairly.

From a TX point of view, the K3 is clearly the superior rig for a multi-transmitter operation with CW and SSB on the same band, but careful examination of the raw data Figure 11) show that a 350 kHz separation should be avoided for stations with antennas in very close proximity. The raw data also shows that the peak in the K3 is much narrower and 30 dB lower in amplitude than on the Flex rigs. We'll use this information when we set up for a CQP county expedition next month with simultaneous CW and SSB on 80, 40, 20, and 15M when those respective bands are most active.

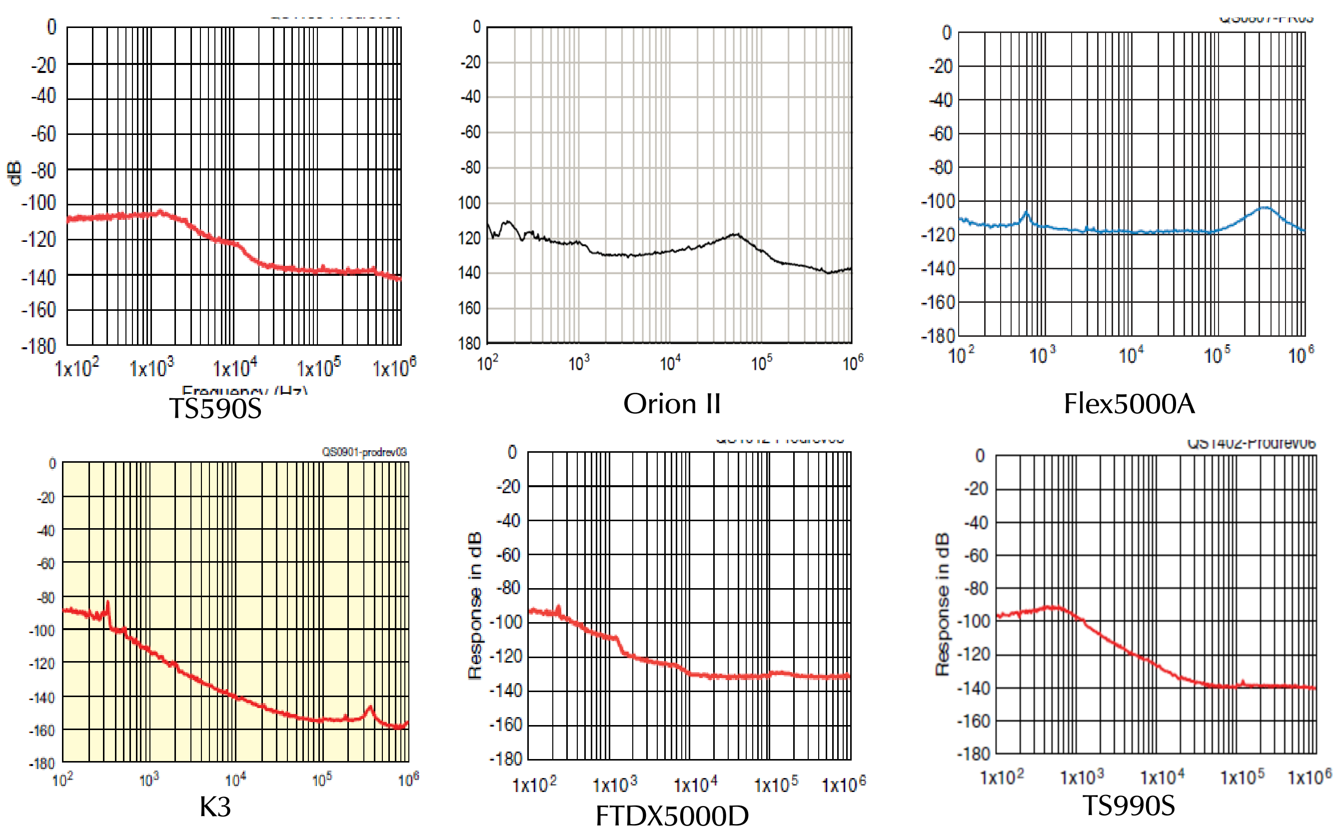


Figure 11 -- Selected Raw ARRL Lab Phase Noise Data

How Does This Correspond to What We Hear? The data presented here documents RF trash produced by the transceiver. A power amplifier will add its own noise and IMD to the transmitted signal, depending on how it is designed and operated. These issues are addressed in the K6XX talk previously referenced. What we hear can also be strongly affected by the ability of our receivers to handle strong signals, as well as the phase noise in our own receivers.

What should we expect (demand?) from Ham manufacturers? With CW bandwidth so strongly dependent on rise time and shaping of the CW waveform, why should any settings faster than the cleanest for normal CW speeds be made accessible to the operator? Why should the rise time be adjustable at all? Elecraft was able to beat the pack to a narrow CW footprint by a wide margin by careful waveshaping, with no user access to settings, and their CW is good to 100 wpm.

If a range of settings for audio processing increases the transmitted splatter, why are those settings available to the operator and suggested in the manual as somehow acceptable? I find this quote from the Kenwood 590 Manual particularly questionable. *Speech Processor Settings: "HARD is a setting that you choose so as to increase talk power while tolerating some distortion and SOFT is a setting to minimize rasping distorted audio. Select either of the two settings according to your predilection and operational circumstances."* Why is distortion OK? To the extent that it gets through the transmit sideband filter, distortion results in splatter!

The cumulative result of many hundreds of rigs spewing 20 dB more trash than necessary is a significant increase in everyone's received noise. If one vendor can build radios 20 dB cleaner than the pack, why can't the pack do it too, especially in flagship radios selling at 3-4 times the price?

Comparing Other Products Not Listed: Since publishing early versions of this report, I've received several emails asking about products not listed here. We can get a pretty good approximation of their performance by downloading their ARRL test data and comparing comparable plots of keying spectra and phase noise spectra with those shown here. I just did that for a dozen or so rigs, and have these general comments.

Bad Behavior Runs In Families. Of the major manufacturers, Yaesu transceivers are, by far, the dirtiest in every price class – indeed, there is little difference between the keying trash from their lowest and highest cost rigs. Icom mid- and high-priced rigs come next, with low cost rigs falling in with Yaesu. Moving along in the direction of cleaner comes Kenwood, with Ten Tec falling between Icom and Kenwood, as does the Elecraft KX3/KXPA100. Of the low cost rigs, the TS590S has the cleanest keying spectra, and phase noise comparable to much more expensive Icoms. The older Flex rigs have acceptable keying spectra, but phase noise is atrocious. Much is expected of the new Flex 6000 series; data provided by Flex looks very good, and ARRL Lab tests are eagerly awaited.

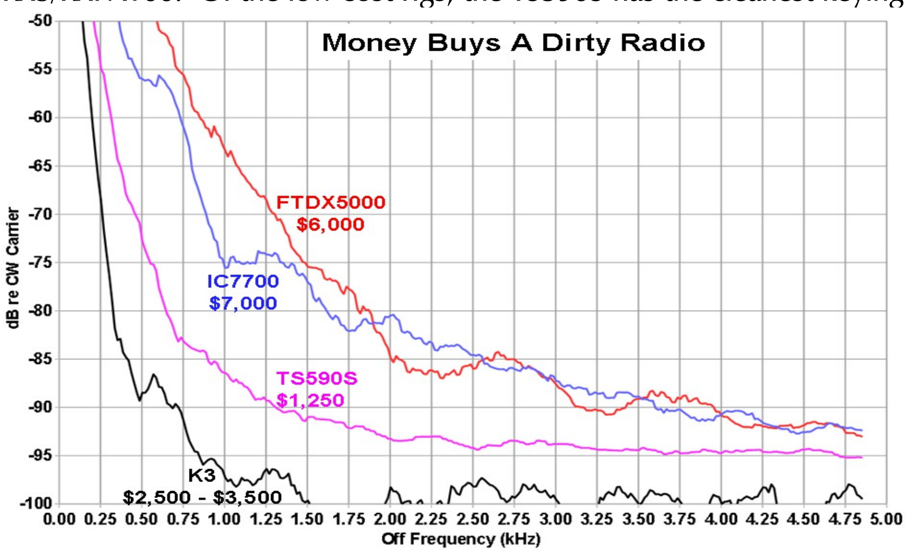


Figure 12 – Keying Bandwidth and Price

Figure 12 compares the keying bandwidth of the very expensive Icom IC7700 and Yaesu FTDX5000 with Kenwood's inexpensive TS590S and the mid-priced Elecraft K3. If Kenwood can do this for $1,250, why can't Icom and Yaesu? And why should we let Icom and Yaesu get away with spewing all this trash?

Improving ARRL Product Reviews: Transmitters should be tested in SSB mode with shaped pink noise fed to the microphone input, for a spectral plot of +/- 20 kHz. The only shaping needed is a 6 dB octave-wide peak centered around 3 kHz, which approximates the response of communications mics (see, for example, the response curve of a Shure 444, which is typical of the breed). This yields a total response for SSB that includes sideband suppression, modulation, distortion and phase noise; low frequency components of the noise provide speech-like variations in level. We need four more of those horizontal "good to bad" slider displays in each product review for transmitted phase noise, close in and wideband, CW keying bandwidth for -60dBc, and -50 dB (re:PEP) bandwidth for SSB with shaped pink noise. For phase noise, the close-in value an average of values at 5, 7, 10, 15, 25 kHz, the wideband value an average of values at100 kHz, 200 kHz, 400 kHz, 700 kHz, 1 MHz. If a rig transmits phase noise 20 dB louder than competing radios, the ARRL review should say that in plain English, and state that such radios should not be used to drive a power amplifier.

FCC Rules 97.307 (a) ***No amateur station transmission shall occupy more bandwidth than necessary for the information rate and emission type being transmitted, in accordance with good amateur practice***. Figure 12 clearly shows that Yaesu and Icom transceivers are using 3 times more bandwidth than Kenwood and 5 times more than Elecraft. As I read the Rules, this puts anyone using them in violation of 97.307 (a). ARRL product reviews should say so! Now, I'm not suggesting that thousands of vintage rigs should be taken off the air, but at the very least we should discourage the marketing of new products that are dirty.

Sidebar: Comments From N6KR

Thanks for your analysis of transmitted phase and keying noise of various transceivers. I'd like to provide a couple of technical details, and to give credit where it is due.

To achieve the excellent results shown in your paper for the K3, we used a combination of four techniques:

1. A hybrid PLL/DDS synthesizer with a very high C/L ratio VCO: Many of the radios shown in your plots use unfiltered DDS for their VFO, or in the case of PLL designs, VCOs with a much lower C/L ratio than the K3. Both of these design decisions can increase phase noise and dynamic artifacts. To preserve a consistently high C/L ratio, we use up to 128 different C/L combinations as the VCO is band-switched. (This is in contrast to the usual 1, 2, or 3 VCO C/L ranges used in other rigs.) We also used very narrow-band crystal filtering of the DDS output to completely remove any of the usual spurs due to quantization, etc. John Grebenkemper, KI6WX, assisted greatly with the synthesizer design.

2. Transmit ALC with long time-constant, pre-calculated power calibration, and virtually no dynamic artifacts: The K3's transmit ALC is, in effect, open-loop in relation to keying waveform rise/fall timing. In other words, we do not apply power corrections over short periods, since this can distort the keying envelope. This is especially noticeable in CW mode but applies to T/R switching in other modes as well.

3. Conversion to a low I.F., with both RX and TX signals running through a narrow crystal filter: This band-limits I.F. noise from early stages (DSP and D-to-A converter) and helps establish a very low transmit noise floor ahead of the main mixer. Even in speech modes, all fast ALC is applied ahead of the crystal filter, which I believe is unique to the K3.

4. Sigmoidal keying waveform applied at the DSP: Our DSP engineer (Lyle Johnson, KK7P) studied the sidebands resulting from various sigmoidal and raise-cosine modulation envelopes. He selected the one that provided the smallest keying bandwidth consistent with rise and fall times of approximately 4 ms.

One clarification. The reason we created the K3's "QRQ mode" was to provide faster full break-in at very high code speeds (up to 100 WPM). The keying dynamics and phase noise are the same with QRQ mode either on or off; they are not "soft" with QRQ mode on. The KPA500 amplifier also switches very fast, so it is fully compatible with either mode.

73, Wayne N6KR