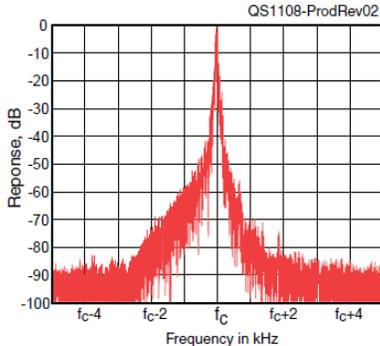


A Comparison of ARRL Lab Data For Selected Transceivers

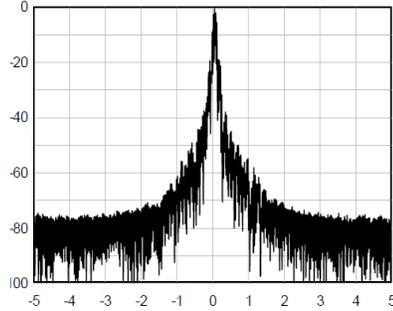
Jim Brown K9YC

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 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.

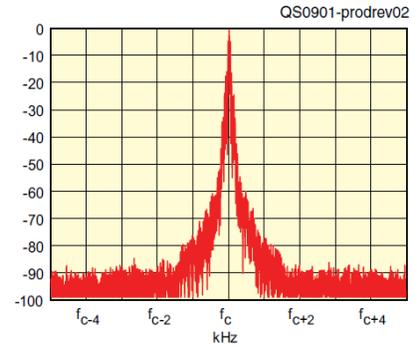
Raw Data -- Spectra With CW Keying – Clicks + IMD + Phase Noise



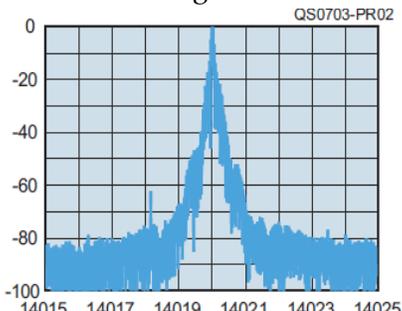
Eagle



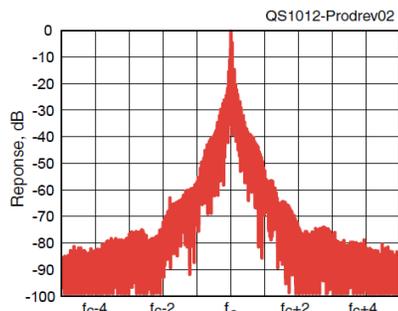
Orion II



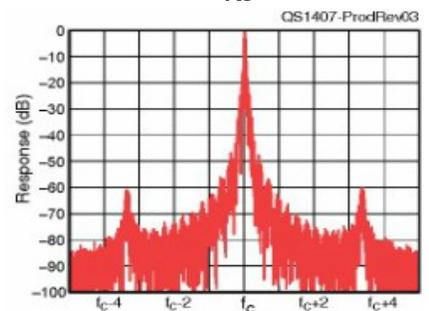
K3



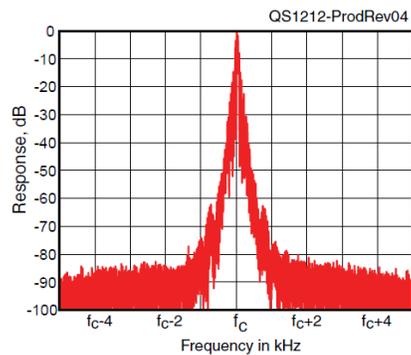
IC7800



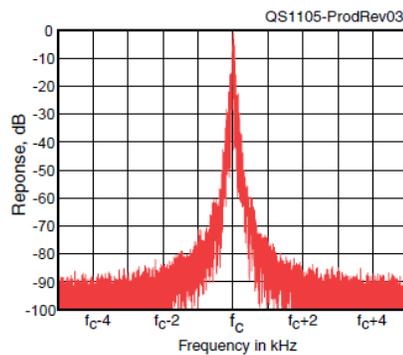
FTDX5000D



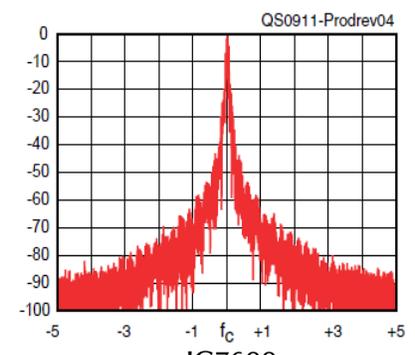
IC7100



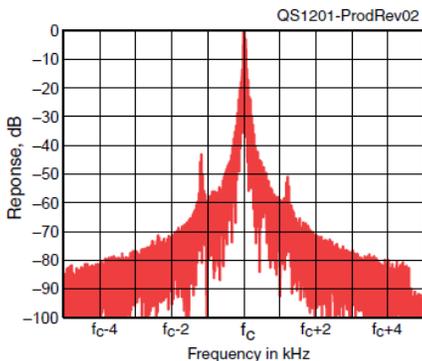
KX3



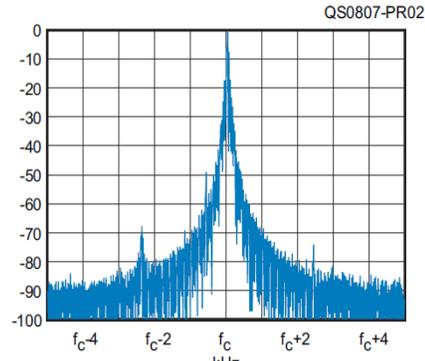
TS590



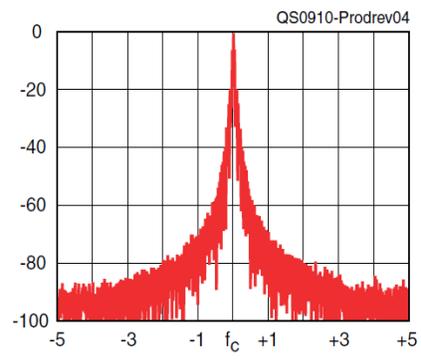
IC7600



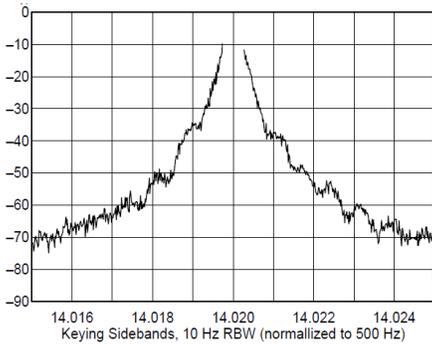
Flex 1500



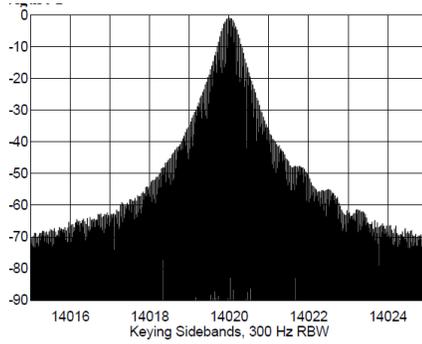
Flex 5000A



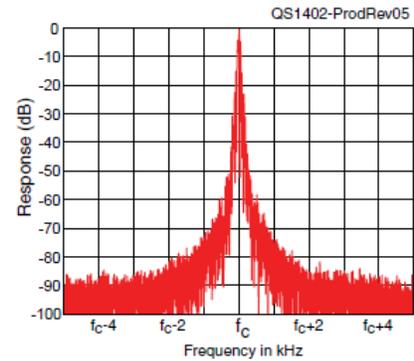
Flex 3000



FT1000 Mark V Field
10 Hz Bandwidth

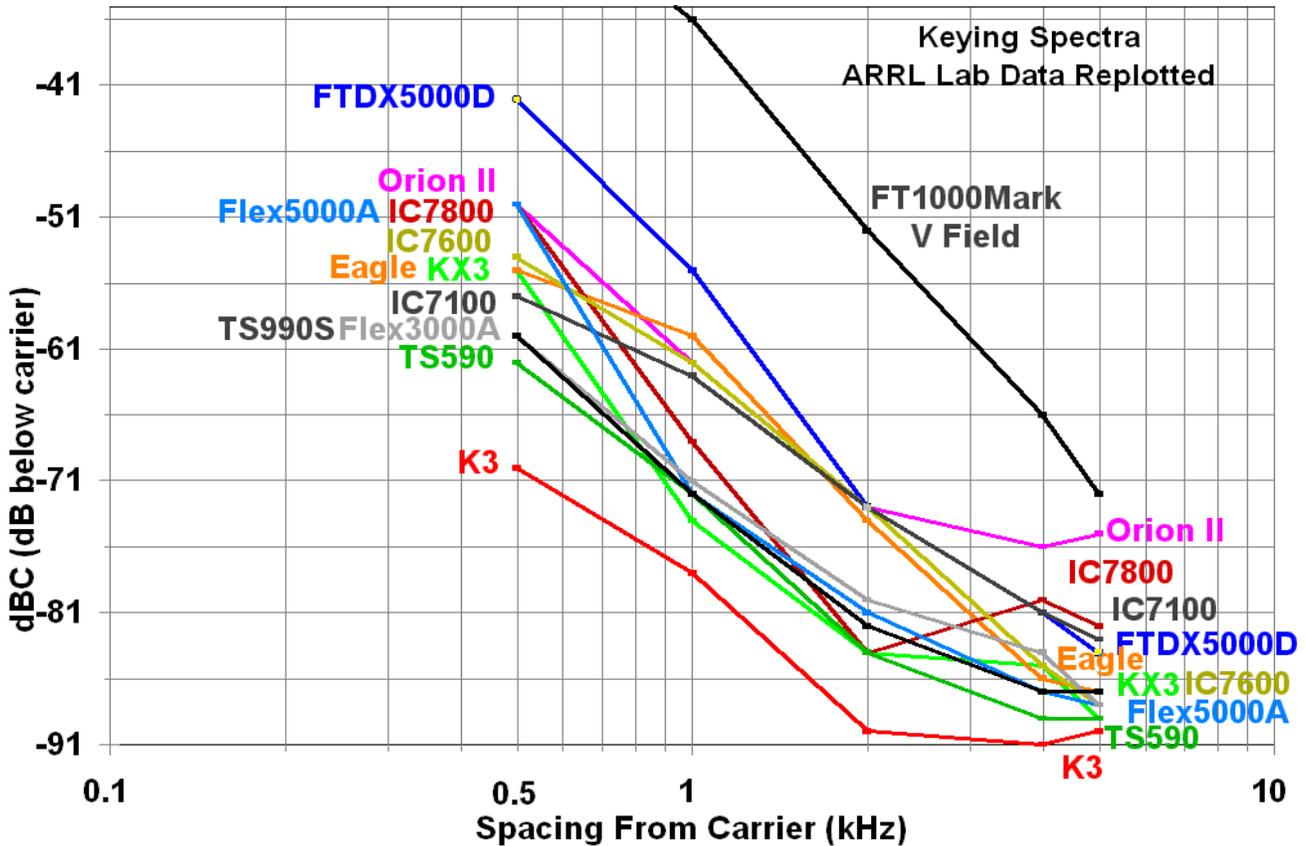


FT1000 Mark V Field
300 Hz Bandwidth



TS990S

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 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.

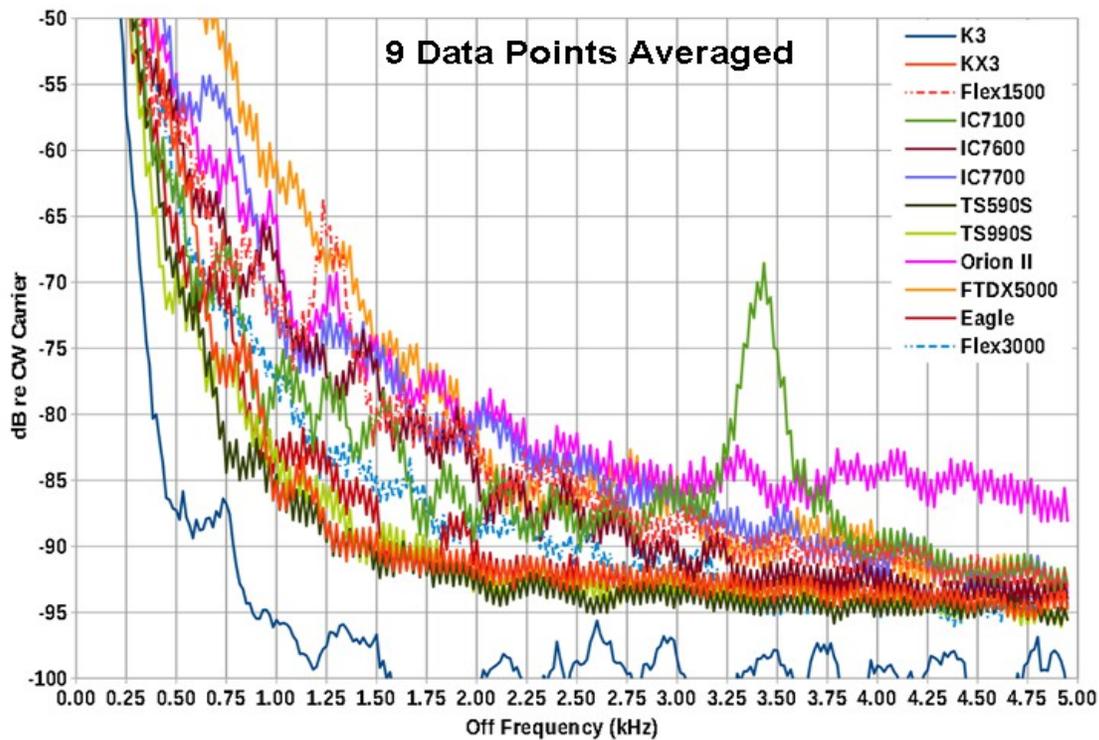
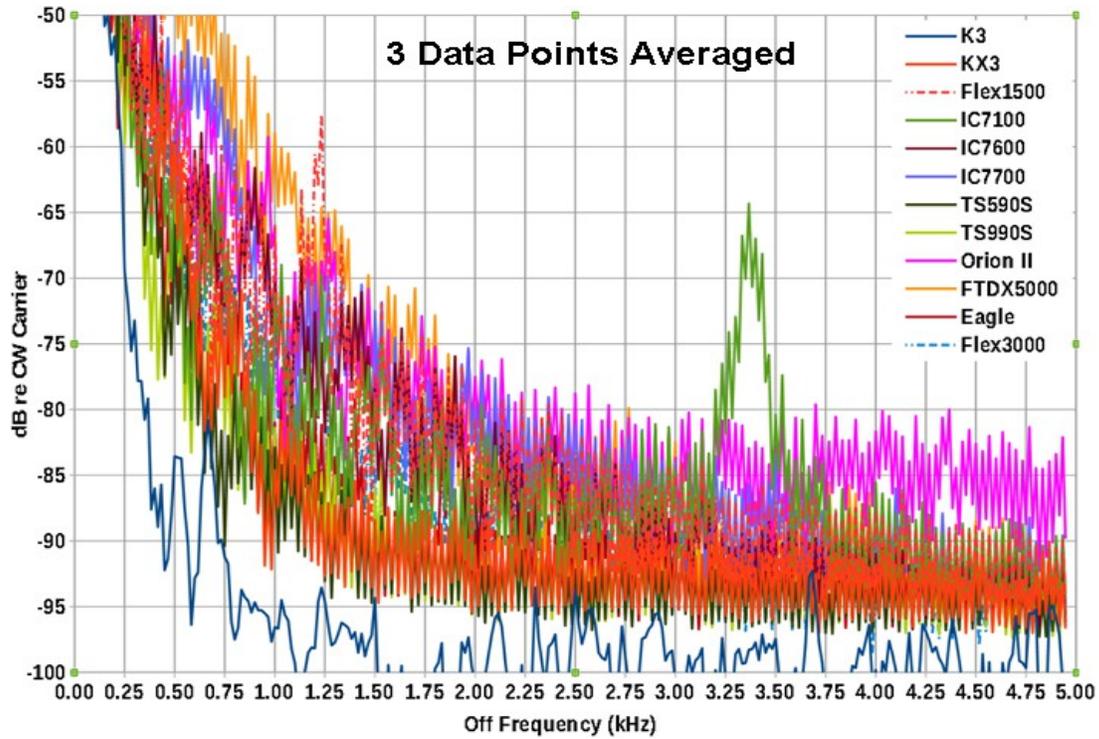


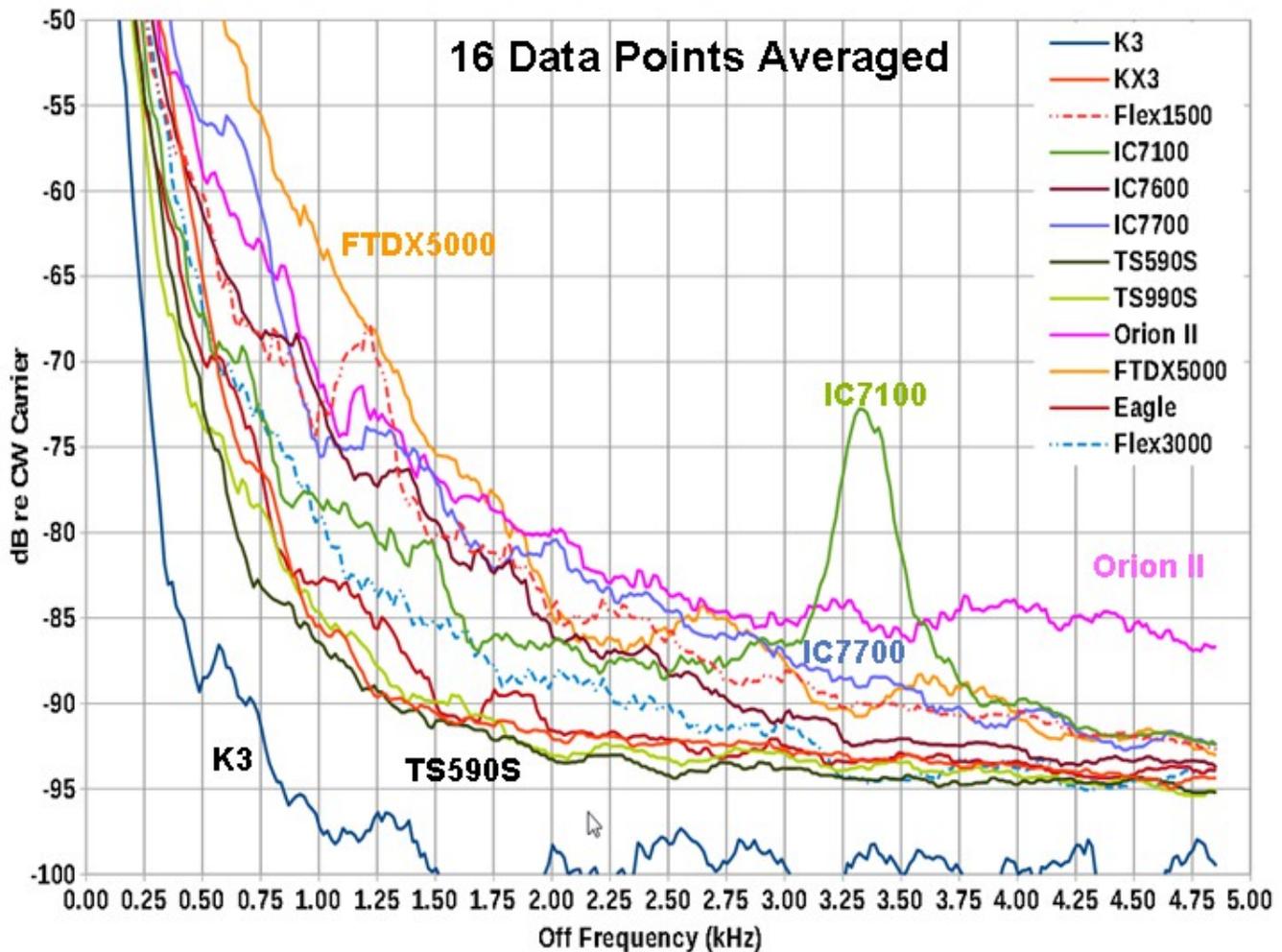
The Rigs Compared For CW Spectrum

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.





Analysis of Keying Spectral Data

Initial Log Plot: It's no surprise that the FT1000 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 spacings, 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.

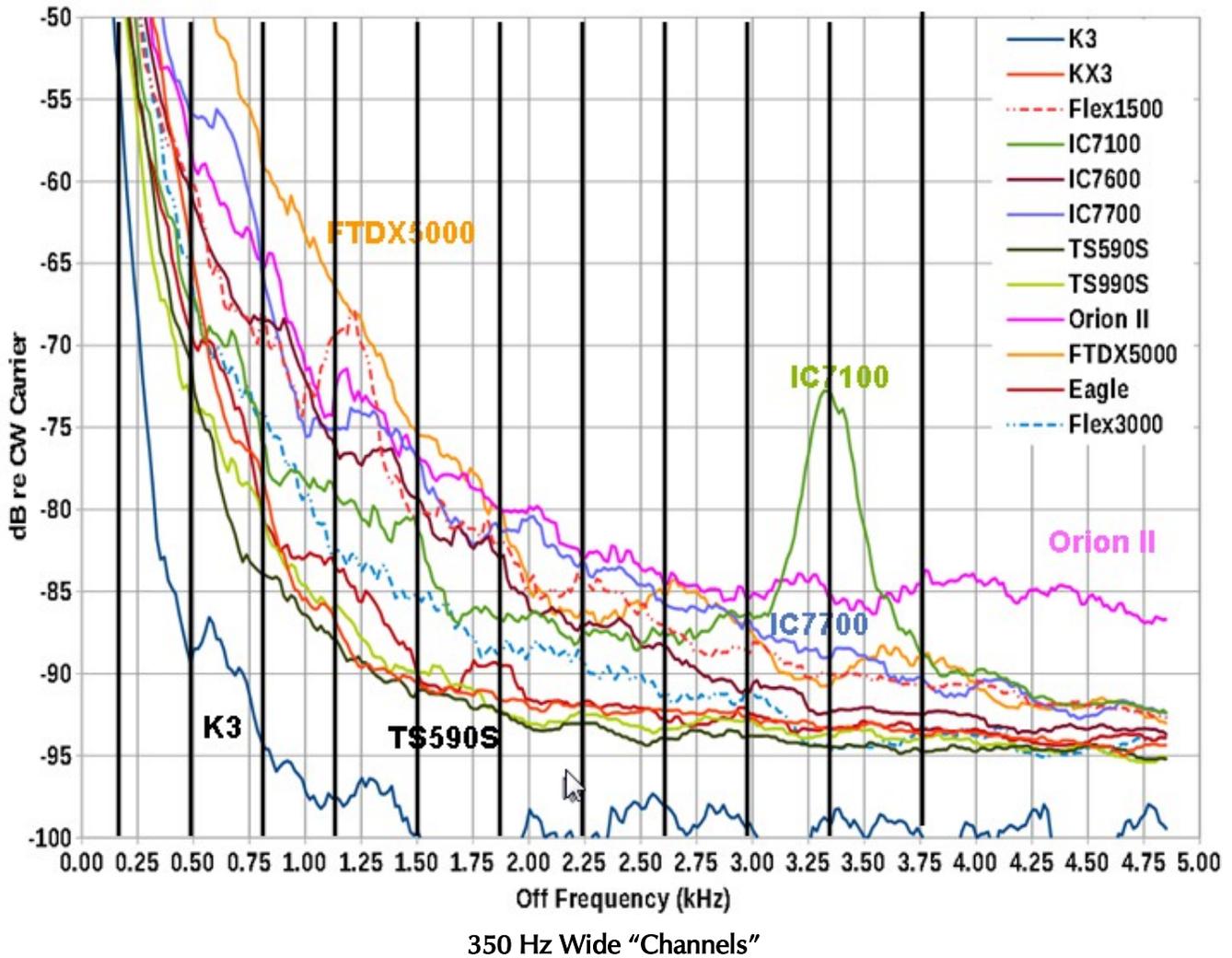
Rise Time and Bandwidth: the Yaesu, Icom, and Kenwood rigs allow the user to adjust the rise time of CW keying. Per their manuals, the default is 4 ms for the Yaesu and Icom rigs, 6 ms for Kenwood, 5 ms for the Orion II. The Eagle is fixed at 5 ms. The slower Kenwood rigs placed second to the K3 in CW 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 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, yielding an average value. Differences between the rigs remain about the same.

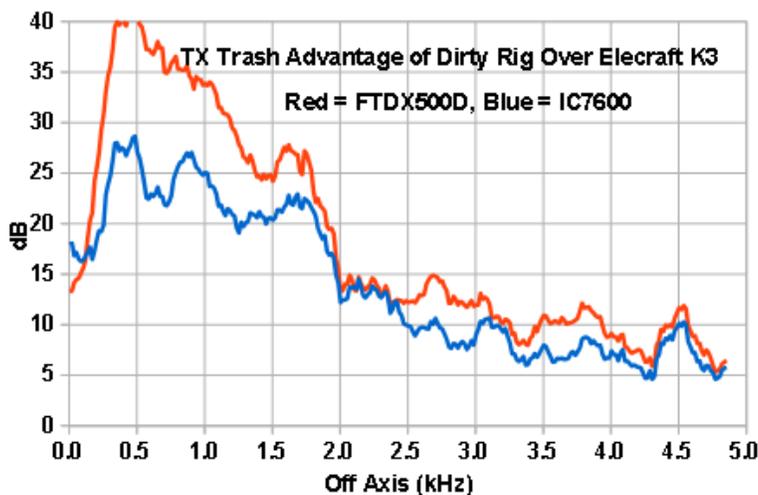
For CW, these spectral plots tell the complete story for what is happening close to the carrier, because they include the effects of keying transients, IMD and phase noise. Because the spectral distribution of pink noise band limited to 100 Hz to 5 kHz closely approximates the spectrum of speech, a comparable, 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 reduce the range of signals that we can copy by a factor of 10X – 300X the transmitted (and received)

signal strength. Another way of looking at it is that 15dB of trash turns a 1.5kW signal into a 50W signal, and another 10 dB drags it down to 5W.



How Much Does This Matter? An active contester about 8 miles from me (and even closer to K6XX) runs an IC7600 and legal limit amplifier. When he's running (which 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.



Competitive Advantage: 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.* This difference is plotted as the Red curve in the graph at left. The Blue curve shows the transmit noise advantage of an IC7600

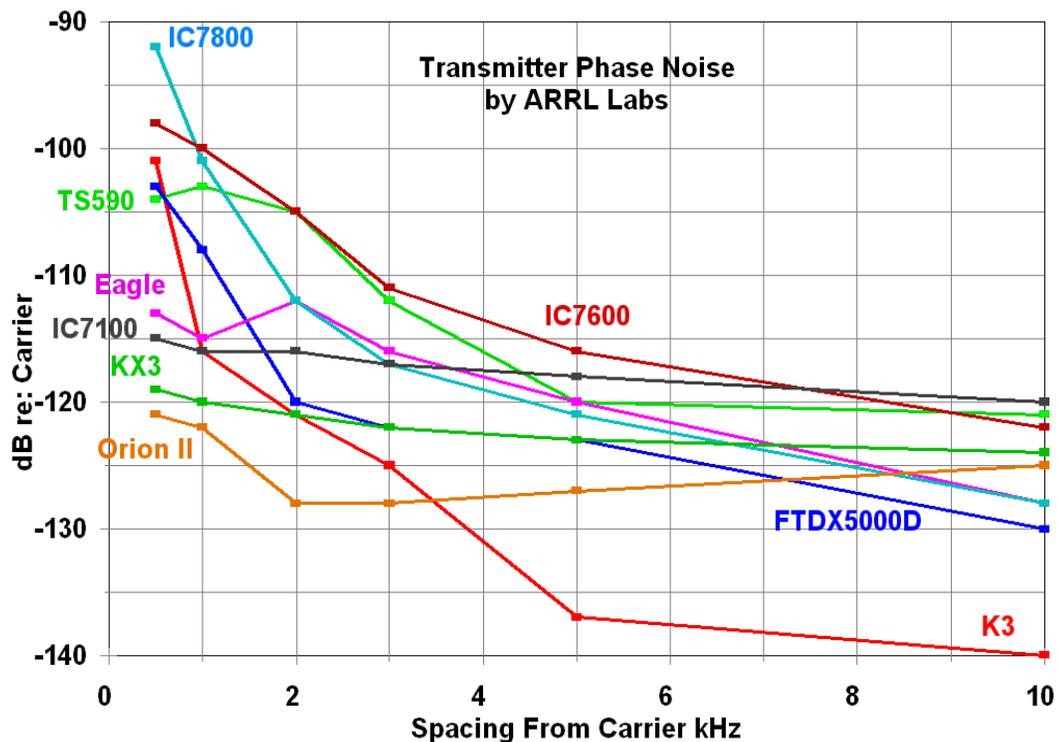
Understanding The Keying Spectra Plots: A keying waveform is, fundamentally, 100% amplitude modulation of a continuous carrier by some waveform that approximates a square-wave -- hence the name CW for continuous wave. Any square wave has an infinite number of harmonics, the relative strength of which 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 higher order harmonics will be stronger. 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.

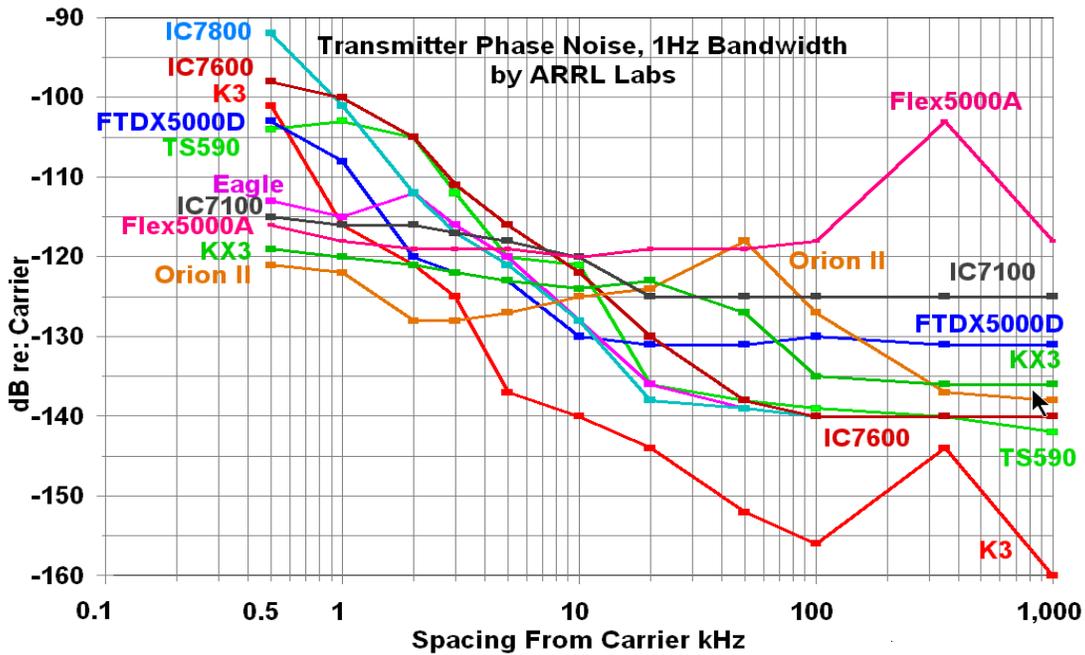
Rigs with cleaner keying reflect the skill of the designer in minimizing the harmonic content of the keying waveform, the level of TX IMD, and TX phase noise. Wayne Burdick, N6KR, lead designer of the K3, credits Lyle Johnson, KK7P, with development of the raised cosine "sigmoidal" shaping that achieves very good sounding CW while still achieving the very narrow bandwidth shown. That takes a lot of DSP, but it was a design compromise 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.

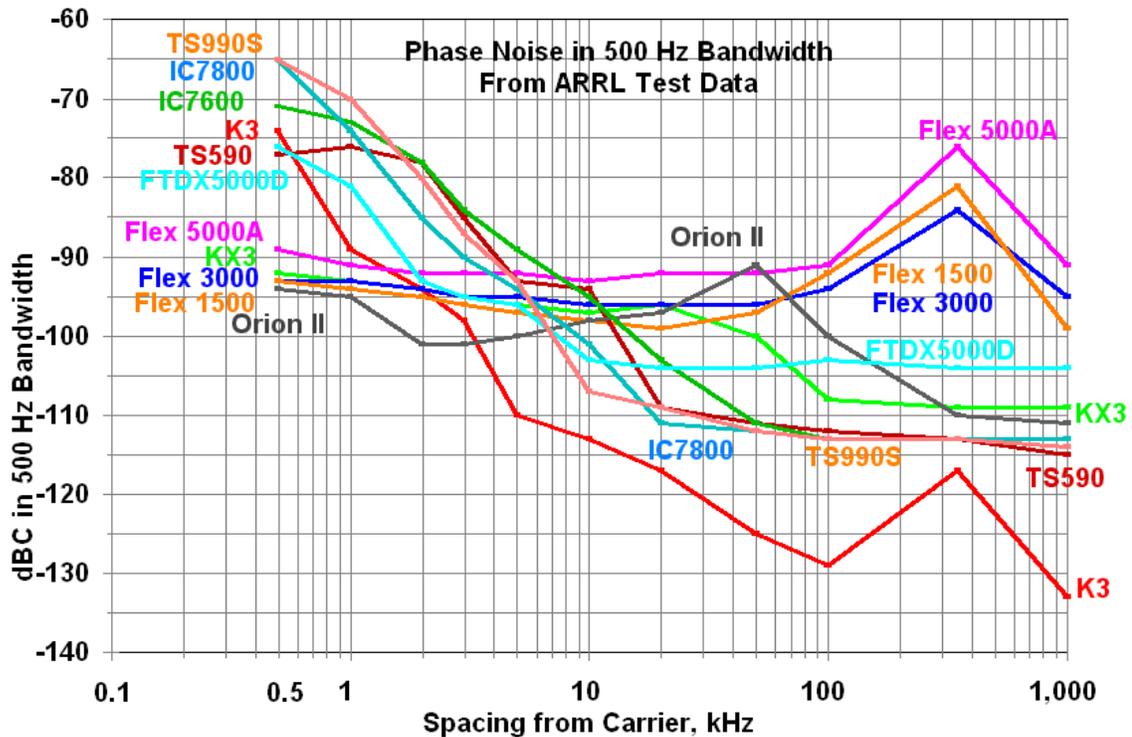
Phase Noise

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. The first plot shows the first 10 kHz from the carrier, and the frequency axis is linear. It's representative of what happens with a strongstation close to your own frequency. It does not include the three Flex radios, which are shown on the other plots. 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.





The second plot (above) 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. 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. Additional rigs have been added to this plot and the one that follows.



The third plot (above) 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.

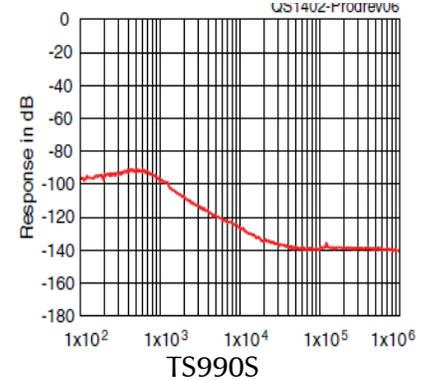
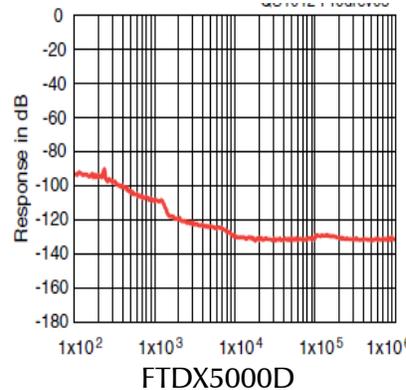
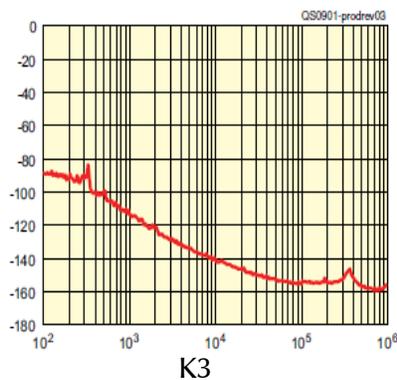
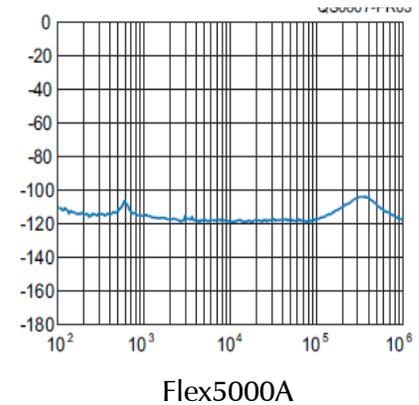
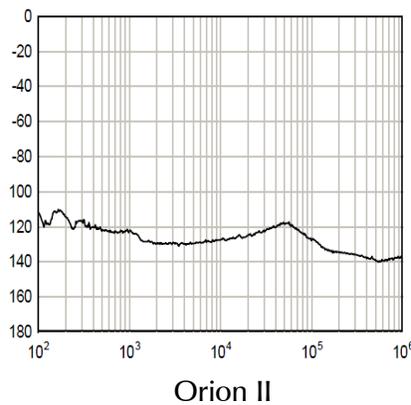
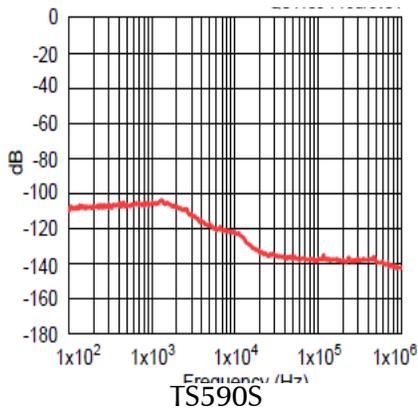
Now, with the ARRL dB/Hz data to a 500 Hz receiver bandwidth, we can better appreciate the significance of these data. For most of these radios, the transmitted CW spectrum 5 kHz from the carrier is mostly phase noise, and this agrees with what we saw on the CW keying spectral plots.

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, had made these plots smoother, but I believe that they fairly present the differences between radios.

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 (next page) show that a 350 kHz separation should be avoided. 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.

Selected 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? From ARRL Product Reviews? 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? 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 twice the price? If an *el cheapo grande* do-everything wonder 100W rig covering 160M to 440 MHz selling for \$1,100 transmits phase noise 20 dB louder than a real radio, why doesn't the ARRL review say that in plain English? And why don't product reviews state (or even suggest) that such radios should not be used to drive a power amp?

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