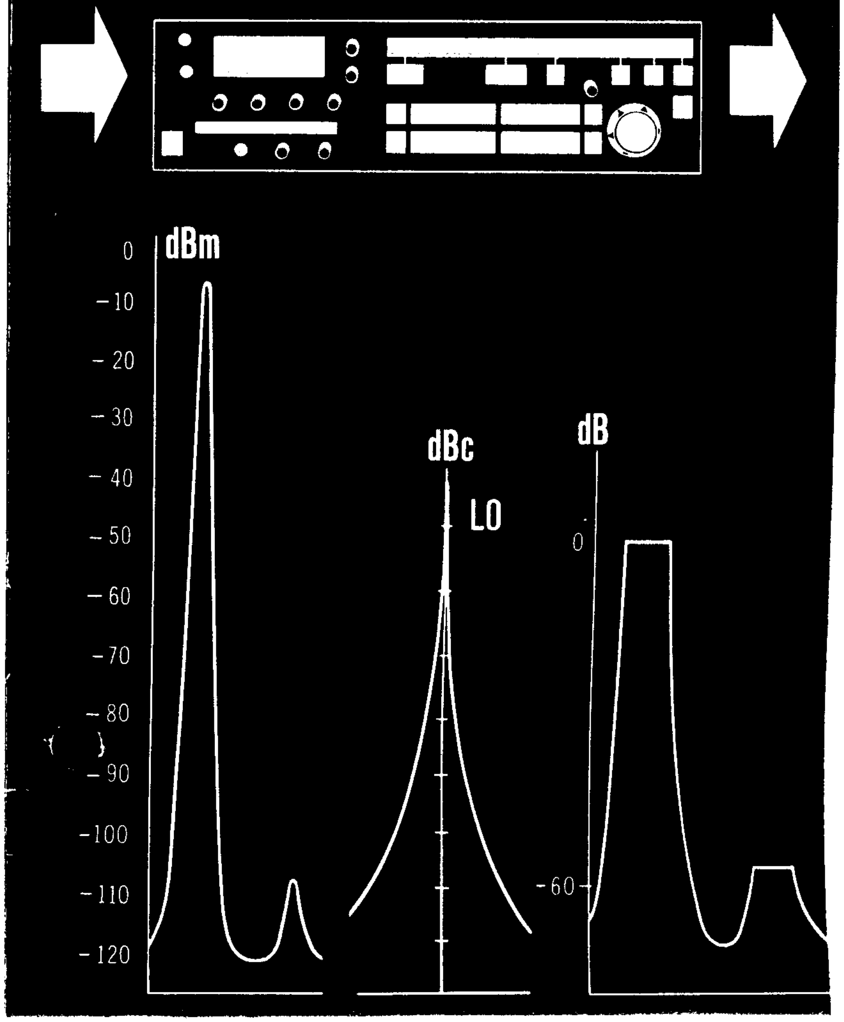
WATKINS-JOHNSON COMPANY Tech-notes

Vol. 7 No. 3 May/June 1980

Digitally Controlled VHF/UHF Receiver Design



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Printed in U.S.A.

Digitally controlled VHF/UHF receivers with synthesized local oscillators are now being installed as replacements for older, manually controlled receivers. There are, however, certain distortions in signal processing which are unique to digitally controlled synthesized receivers. The user should be aware of the differences between the digitally controlled receiver and those of the manually controlled receiver that is being replaced. These differences must be considered carefully before digitally synthesized receivers are selected to replace the already-proven, manually controlled VHF/UHF receivers now in the field.

Cost/Performance

Today's demand for ultra-high tuning accuracy, high-dynamic-range signal handling, and computer control of receivers has caused a revolutionary change in receiver design concepts. Receiver manufacturers have produced a variety of receivers, some of which offer vast improvements in particular areas of receiver performance. However, until recently, no VHF/UHF receiver has completely fulfilled the need for a general-purpose, universally acceptable, low-cost, high-performance receiver that will meet future requirements as well as present ones. The Watkins-Johnson CEI Division has designed and built a digitally controlled VHF/UHF receiver that meets these requirements at a low enough cost to make it feasible to replace manually controlled receivers. The objective of the Developmental Engineering Section was to design a digitally controlled, synthesized receiver that could be produced at approximately the same cost as present receivers, and would incorporate the same standards of workmanship. Bridging the gap between low cost and high performance requires a thorough knowledge of both receiver design and synthesizer design, two technologies that are not necessarily compatible, since the need for submicrovolt sensitivities in the presence of high-speed digital generators requires precise refinements in receiver design.

Frequency Synthesizers as Local Oscillators in Receivers

Using a synthesizer as the local oscillator (LO) provides good frequency stability and lends itself to remote control. However, there are properties of synthesizers that can degrade the overall performance of the receiver below that of a manually controlled local-oscillator receiver. The degradation of receiver performance can be categorized by an evaluation of receiver test results, as shown in Table 1.

Spectrum of Synthesizer LO

The spectral purity of all LOs can be measured by monitoring the signal-strength voltage while tuning a large -10 dBm input signal or while applying the input signal and tuning the receiver. From signal-strength meter readings, a graph of signal amplitude vs. frequency-from-carrier at different bandwidths is compiled. The signal- strength voltage is then plotted to determine spurious emission and phase noise outside the IF bandwidth. A graph of signal strength versus tuned frequency of a receiver is shown in Figure 1. The areas causing the poor performances are numbered to agree with Table 1. This test is valid only if the signal from the signal generator is of better quality (less noise contribution) than the receiver LO and has a better noise floor (120 dBc Hz to 100 kHz), and the selectivity of the receiver is considered. Spectral purity inside the IF bandwidth can be measured by the modulation on/off ratio, which gives: ultimate (S + N)/N.

The above receiver tests point out the need to understand the properties of synthesizers that affect a receiver with high selectivity and high dynamic range. The three most important parameters are:

1. Spurious output
2. Spectral purity
3. Switching speed

Table 1. Evaluation [illegible]

1.	**Effect:**	Spurious signals are tuned in across the band when the input is terminated.
	Cause:	Signal emissions from the synthesizer enter the IF by: (a) Direct radiation from chassis into RF portion of receiver. (b) Riding on synthesizer LO spectrum. (c) Conducted through power supply or chassis. (d) 1st and 2nd LO pre-mixing to produce high-order intermodulation products.
2.	**Effect:**	When a very large pure test signal is tuned, spurious signals with the IF Bandwidth response can be tuned around it.
	Cause:	Local oscillator has side bands from multiloop synthesizer or pre-mixed synthesizer.
3.	**Effect:**	A small signal of interest is eliminated by noise when a large signal is brought to within several IF Bandwidths.
	Cause:	The phase noise of the LO spectrum is too high (several IF Bandwidths away). The noise is being transferred to the IF by reciprocal mixing. NOTE Large signal must be pure and have a noise floor better than 10 log (IF BW) + NF -174 dB.
4.	**Effect:**	When listening to a medium-to-large signal there is excessive background noise.
	Cause:	Phase noise from the local oscillator within the IF bandwidth subtracts from the ultimate (S+N)/N. The noise is reduced when tuned to the exact center of the IF by conversion of FM noise to AM noise in the IF.
5.	**Effect:**	When listening to a medium-to-large unmodulated signal, other signals are audible.
	Cause:	(a) Power line related signals on local oscillator less than 80 dB down. (b) Spurious signals usually within the multiple loop synthesizer.
6.	**Effect:**	In measuring the selectivity of a narrow IF, the skirt response is broad.
	Cause:	LO phase noise mixing into the IF.
7.	**Effect:**	The receiver does not respond quickly when tuned digitally.
	Cause:	Switching speed of the synthesizer is slow (narrow loop bandwidth).

Of these three, the spectral purity response is perhaps the most important and least understood.

Figure 2 shows three LO spectrum plots. The most desirable spectrum is that of an ideal source, such as a crystal oscillator. If it were practical to incorporate several thousand crystal oscillators in a receiver design, achieving a high degree of spectral purity would not be a problem. The second spectral response is that of a voltage-controlled oscillator that can tune the LO range. Unlocked from the reference, the spectrum has poor close-in phase noise and is uncontrollable in

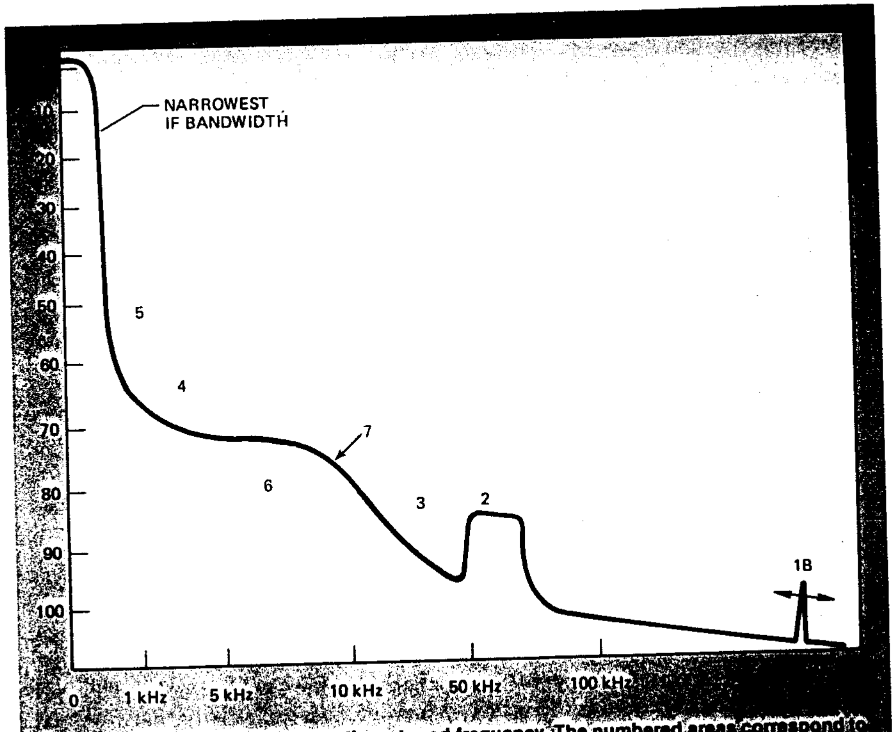

Figure 1. Calibrated signal strength vs. tuned frequency. The numbered areas correspond to the cause and effect sections of Table 1. The zero point designates the point to which both the signal generator and the receiver are tuned.

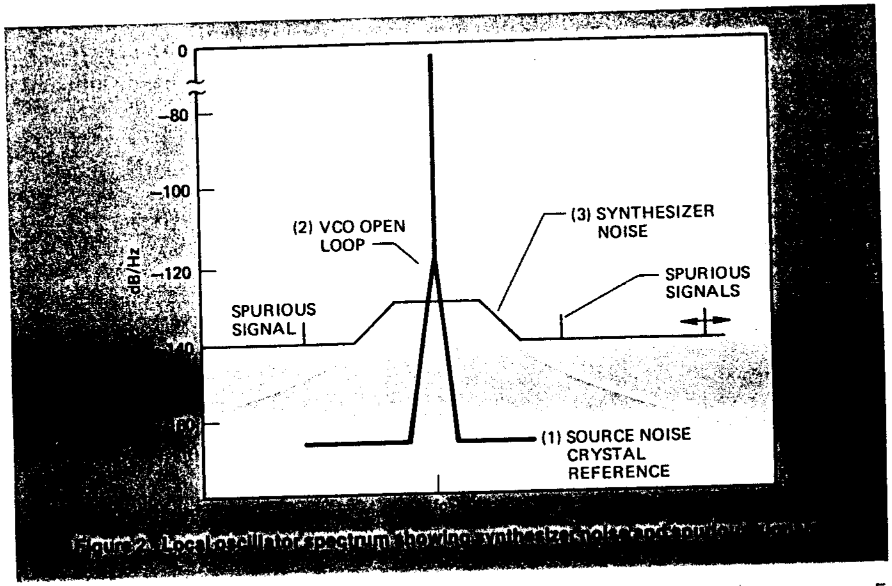

Figure 2. Local oscillator spectrum showing synthesizer noise and spurious [illegible]

exact frequency. It does, however, have a spectral response free of spurious signals. The third spectral response is that of the VCO when phase-locked to the crystal reference frequency. The close-in noise is improved, but the wideband noise is increased slightly. The close-in spurious signals are caused by the reference signal, and those that are farther out are caused by more than one synthesizer being in the system.

The response of the local oscillator can transfer to the IF spectrum in the presence of a large incoming RF signal, thereby degrading receiver performance. Therefore, it is necessary to develop a specification for spectral purity of the local oscillator based on the receiver's properties and the type of signals received.

Spectral Properties of Local Oscillators in Receivers

The degree of spectral purity of the local oscillator has been shown to affect the reception of even the best receivers. To understand these effects, it is necessary to examine what occurs when a high-level, low-phase-noise signal is tuned in by a receiver with a synthesized LO, such as that shown in Figure 3. When a receiver with an ideal LO and a narrow IF (e.g., 20 kHz) is tuned through a high-level, low-phase-noise signal (100 μV in amplitude) and a small signal (10 μV in amplitude) that is 100 kHz away from the large signal, the output response of the receiver will appear as shown in Figure 4.

Figure 5 depicts a synthesized LO output of poor spectral purity. The IF output is the power density multiplication of both the IF response and the LO spectrum, including any spurious signals on the LO. It can be seen that the small close-in signal will not be in the output response; the phase noise of the LO completely masks it out. Sideband noise is limiting the usable dynamic range and apparent selectivity of the receivers (see the section on reciprocal mixing in the glossary that follows). If the receiver had a communications-specified LO, then this degradation would not occur.

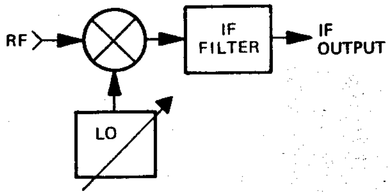

Figure 3. Receiver block diagram.

Communications-Oriented Receiver

A particular phase noise requirement can be specified for the communications intelligence-oriented receiver. The communications requirement is based on the signal-to-noise (S/N) ratio needed, skirt selectivity, narrowest and widest IF bandwidth and IF shape factor; for example:

1. IF output S/N ratio: 40 dB
2. Narrowest IF bandwidth:
   10 kHz; widest, 300 kHz
3. Ultimate IF selectivity:
   skirt ratio, 4:1

The noise power in the 10 kHz IF refers to the power in a 1 Hz bandwidth and is 10 log 10 kHz = 40 dB. Therefore, up to 5 kHz from the carrier the noise should be down 80 dB/Hz. At 20 kHz from the carrier (4:1 shape factor), the noise in 1 Hz is 110 dB (70 dB + 40 dB). The noise power should then decrease at a rate of 20 dB per decade. A receiver with these specifications and with a synthesizer LO having the above spectral purity should not degrade receiver performance. A graph of phase noise and spurious requirements of a communications-oriented receiver with several common bandwidths is shown in Figure 6.

The resultant spectral purity requirement is difficult to achieve with a synthesizer. The close-in phase noise requires a wide loop bandwidth, suggesting a single synthesizer. However, a single synthesizer will limit the frequency resolution. A narrow loop bandwidth will have the resolution and low phase noise farther out from the carrier, but will have high phase noise close to the carrier and have poor frequency switching speed.

The AM and FM ultimate signal-to-noise ratio measurement of a receiver tuning a high-level signal can be made worse by the use of a synthesizer as the LO. The test for AM S/N ratio within the IF bandwidth is to tune a high-level 50% AM-modulated signal and read the level at the AM detector. The signal generator modulation is then turned off and the new reading indicates the noise present. Typical S/N ratios of manual receivers are better than 50 dB. When these same measurements are repeated on a receiver with a synthesized LO, the results are quite different (depending on

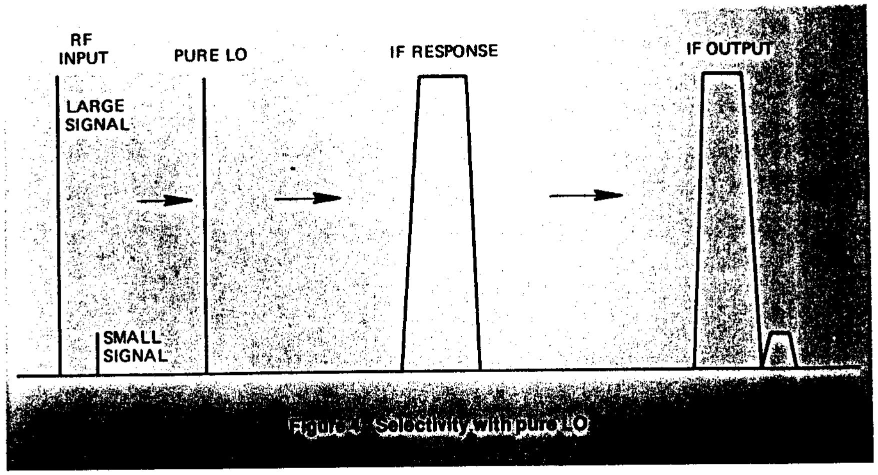

Figure 4. Selectivity with pure LO

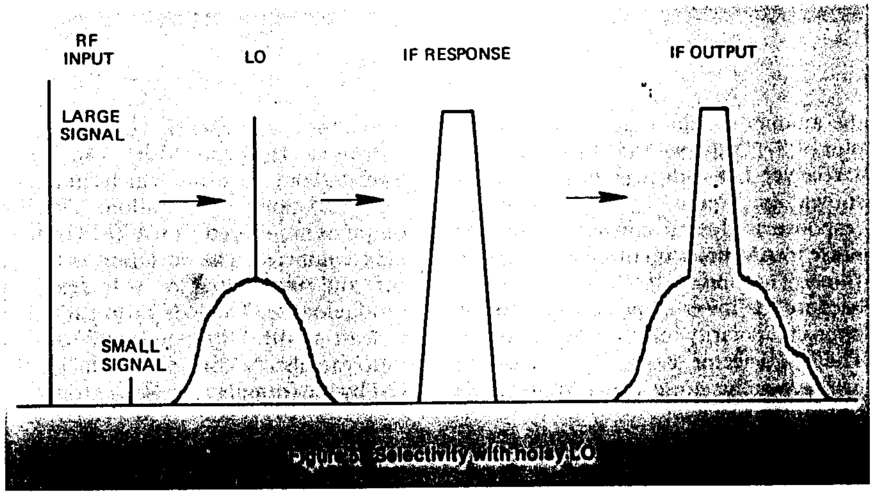

Figure 5. Selectivity with noisy LO

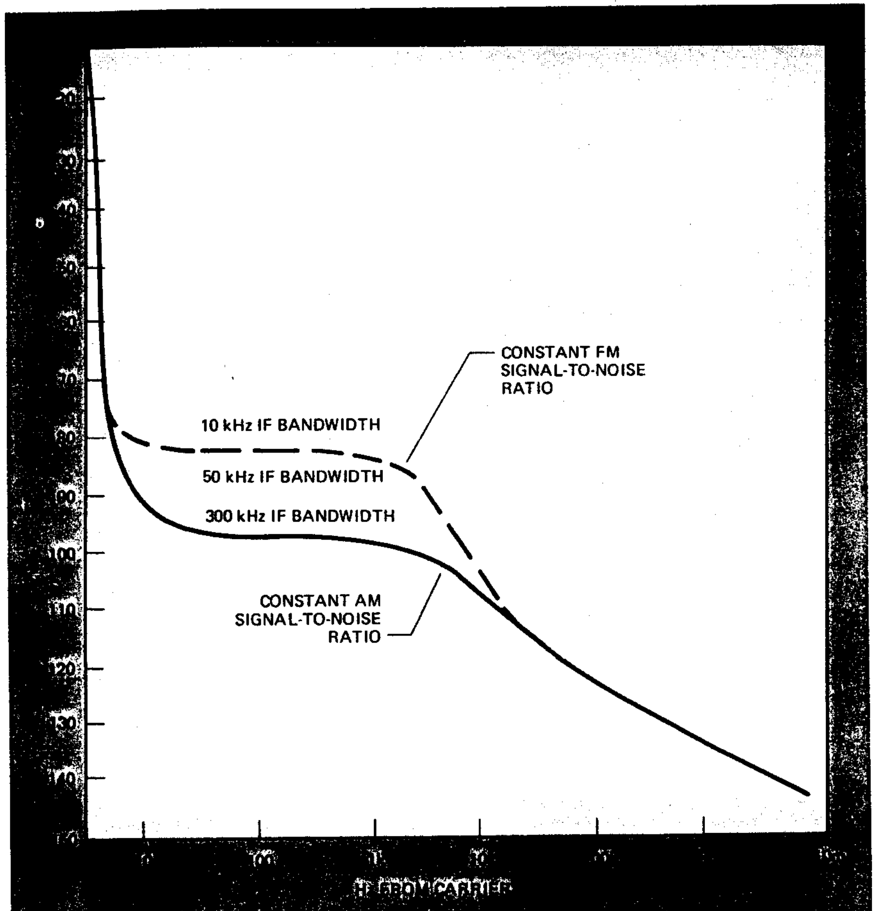

Figure 6. Local oscillator purity requirements for communications receiver.

the amount of phase noise present). A plot of S/N ratio vs. tuned frequency of a receiver LO with high phase-noise is shown in Figure 7. The particular response is due to conversion of FM noise to AM noise on the sides of the IF filter. The noise cancels in the center because the lower slope converts to the opposite polarity of the upper slope. The AM detector sees both positive- and negative-going noise and produces the sum of the signals.

FM signal-to-noise is tested in a similar manner. The signal generator is adjusted for a low repetition of 66% of the narrowest IF bandwidth. The signal level is about -50 dBm, which eliminates front-end noise contribution. The FM output is monitored with a RMS responding voltmeter. The deviation is turned off and the voltmeter will read the residual noise. The S/N ratio should be at least 40 dB. Ultimate signal-to-noise ratio can also be converted to incidental FM by the formula:

$$\text{IPM (RMS)} = \frac{\text{peak deviation x .707}}{\text{20 antilog (S/N) in dB)}}$$

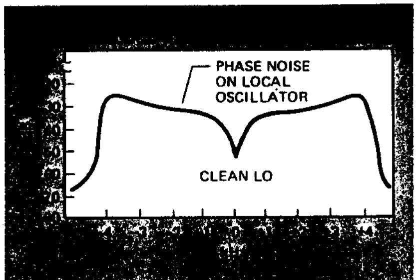

Figure 7. Ultimate S/N ratio.

The test for out-of-bandwidth phase-noise degradation, i.e., the reciprocal mix test, will show the degradation of IF selectivity due to translation of phase noise from the LO to the large incoming signal.

Specification Glossary for Digitally Controlled Receivers

A digitally controlled VHF/UHF receiver must conform to certain specifications to avoid poor performance or high cost due to improper synthesizer design parameters. In the past, certain specifications have been used incorrectly, resulting in a receiver that was either too high in cost or poor in quality. The glossary at the end of this article delineates some of the important terms necessary to the determination of specifications required for high-quality receiver design.

Conclusion

Digitally controlled receiver design is very different from its manual counterpart. The product evaluation by the end user requires a different set of test specifications to make cost/performance buying decisions. The local oscillator spectrum that is now synthesized dominates good receiver performance. A review of receiver specification for IF bandwidth, selectivity and dynamic range can qualify the required purity of the LO spectrum.

* * *

Specification Glossary

Reciprocal Mixing — A specification that determines how much noise is transferred from the LO to the translated RF signal through reciprocal mixing. In general, it is determined by the amount of signal-to-noise degradation allowed when a large signal of specified amplitude above the desired signal is brought to within a specified frequency away. The small signal is placed at least 30 dB above the front-end noise, and the signal-to-noise is then allowed to degrade to 20 dB. A good interfering level would be 80 dB greater than 35 kHz away in a 10 kHz bandwidth.

Desensitization — This specification also involves a small signal being degraded by the presence of a large signal. The cause will be quite different. Poor desensitization can be either from poor receiver signal handling ability or from a synthesized LO with spurious sidebands. A typical specification requires monitoring the demodulated small signal while noting changes in level when a large unmodulated signal is brought close in frequency.

Incidental FM — The synthesized local oscillators contribute mostly to this specification. Incidental FM is a measurement of the FM noise within the IF Bandwidth and is directly related to the phase noise close to the carrier of the LO. The measurement is made by monitoring the FM output while the deviation is turned on and off on an FM signal generator. VHF/UHF receivers should have an IFM of less than 100 Hz rms.

Phase Noise — An expression for the noise that frequency-modulates the local oscillators. It can be directly measured on a spectrum analyzer or indirectly using the receiver itself. A good specification for phase noise on the LO of a VHF/UHF receiver is: greater than 95-dB down in a 1-Hz bandwidth 10 kHz from the carrier.

Ultimate S/N Ratio — A test for residual noise on signals that occur within the IF Bandwidth when the receiver is tuned to a high level unmodulated signal. The signal-to-noise ratio is determined by measuring the modulation at the video output and again with the modulation off. This ratio should be 40-50 dB. The cause of a poor ratio is usually high close-in phase noise or spurious signals close-in on the LO spectrum.

Phase Jitter — Associated with the frequency standard for the synthesizer and is useful as a measurement of low frequency phase noise. It is expressed as the phase difference between several readings of the IF output frequency on a frequency counter with the receiver tuned to a standard crystal source.

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Mr. Dexter is a member of the Watkins-Johnson CEI Division technical staff and is Head of Developmental Engineering, Receiver Department. The WJ-8617A VHF/UHF Digitally controlled Receiver was designed under his leadership.

He was the program manager for the WJ-8718 HF Receiver, which is a high-volume, low-cost HF Receiver. Previously, Chuck was a member of the CEI Advanced Development Section, where his responsibilities included development of frequency synthesizer techniques designed to improve spectral purity and the production of more effective synthesizers.

Before joining the Advanced Development Section, Mr. Dexter was Head of the Frequency Counter and Synthesizer Group and was responsible for the design of frequency counters, frequency extenders, and communications receiving systems. Major design activities were directed toward designing frequency synthesizers and digital control of the WJ-8888 HF Receiver and frequency synthesizers for the WJ-9085 Tuner and the WJ-8950 EMI measuring system. The frequency range of these synthesized receivers ranges from 0.5 to 1000 MHz. Major products developed by Mr. Dexter's group include the DRO-280A and the DRO-309A Frequency Counters.

Mr. Dexter holds a B.S.E.T. degree in Applied Science from Capital Institute of Technology.