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# Receiver Dynamics

STATUTORILY EXEMPT

Editor's Note: This paper was written before the author retired (1995).

*In K4 we use a number of HF receivers and purchase them in quantity for our systems. Because we are often in a position of deciding what is best for our particular system and application, it is good to understand the terminology used by RF engineers and receiver manufacturers in specifying the dynamics of a receiver. This technical note should help you in interpreting the manufacturer's specification when making receiver comparisons or deciding what receiver fits best in your application.*

## DYNAMIC RANGE

Dynamic range can be defined in different ways, all of which have application. Fundamentally, dynamic range is the difference in dB between the minimum discernible signal and the signal that causes a specified amount of harmonic distortion at the receiver output. This simplistic definition does not do justice to the way we use receivers in a crowded HF spectrum. Better definitions are included below. Dynamic range figures are important because they describe a very basic parameter and one with which receivers can be compared. Of course the same criteria must be used in making the comparison, and independent standard testing is the only way to be truly sure that you are comparing apples to apples. However, manufacturers' specification sheets provide a departure point for comparison. The American Radio Relay League (ARRL) performs standard and independent testing for the amateur community. The ARRL recently tested the Watkins-Johnson HF-1000, a twin sister to the WJ-8711 used by some K4 divisions, and published the results.[1] As far as I know, NSA is not now independently evaluating receivers. J42 operates an automated receiver test facility which verifies that receivers are within specification after repair. Information on actual specifications can be obtained from them for receivers currently in inventory.

## SENSITIVITY

Receiver sensitivity is a measure of a receiver's ability to detect weak signals with a prescribed signal-to-noise ratio and IF bandwidth. The value is usually in microvolts for a specified[2] signal-plus-noise-to-noise (S + N)/N ratio. In some cases the term SINAD may be used, which indicates signal-plus-noise-and-distortion-to-noise (S + N + D)/N. A variable in manufacturer sensitivity specifications is the percentage of AM modulation or FM

deviation used in the test, which may range from 30–90 percent and 3–10 kHz, respectively. Because the sensitivity test uses the audio output of the receiver, other variables can affect the specification, such as automatic gain control (AGC) threshold, demodulation mode (SSB or AM), and even the method of calibrating the generator input level. Because of this, it has become common practice to specify sensitivity in terms of noise figure (NF), which does not rely on measuring the demodulated output and uses a broadband standard noise source for input rather than a signal generator.

### *Noise Figure*

Noise figure is 10 log (noise factor). The noise factor (nf) is the input signal-to-noise divided by the output signal-to-noise.

$$NF = 10 \log (nf) = 10 \log ((Si/Ni)/(So/No)) \text{ expressed in dB}$$

A noise factor of 1, no degradation in signal to noise, produces a noise figure of 0 dB. HF receiver noise figures will range from about 10 to 20 dB. VHF and UHF receivers will often exhibit a lower noise figure, 8 to 15 dB, to take advantage of the lower atmospheric noise environment found there. The receiver noise figure is primarily a function of both the noise generated in the first stage and first stage gain. Higher gain first RF amplifiers will normally produce a lower overall receiver noise figure – one that is close to the noise figure of the first stage itself – however, high gain front ends are subject to overload by strong signals. Overloading the front end of a receiver produces spurious responses and receiver desensing or blocking that restricts dynamic range. An application requiring a very low noise figure requires the use of an external low-noise high-dynamic range amplifier at the antenna and a low-loss RF transmission line between the antenna and receiver.

### *Noise Floor*

The maximum sensitivity of a receiver is determined by the amount of noise internally generated in the receiver (primarily the first stage) and its bandwidth. It is the basic sensitivity figure, as any signal weaker than this will be masked by the noise. Another term you may encounter is minimum discernible signal (MDS) sensitivity. MDS is commonly defined in two ways. The 3dB MDS is the value of the input signal, measured in dBm or microvolts (uV) that is just perceivable at the output, that is, an input causing a signal to rise 3dB out of the device noise. MDS is also defined as the value of the noise floor and is used interchangeably with that term. Where MDS is used in this technical note, it is equal to the noise floor.

| | |
|---|---|
| Noise Floor | = NF + 10 log BW − 174 |
| where: NF | = noise figure (ratio of input to output S/N ratio expressed as dB) |
| BW | = bandwidth in Hz |
| −174 | = noise floor (−174 dBm@290°K) |

A manufacturer's specification of sensitivity in uV or dBm at a certain signal-to-noise ratio is a different value than the noise floor. For instance, the CW sensitivity of the HF-*1000* is given by Watkins-Johnson as −116 dBm (.35uV) for 16 dB S+N/N, .3 kHz bandwidth with preamplifier off over 500 kHz to 30MHz.[3] The ARRL measured the MDS (noise floor) as −133 dBm at 14 MHz using the same filter; a 17 dB difference [calculating the noise floor using the above equation and WJ's 14 dB noise figure specification, which yields −135.3 dBm]. The difference could be in the noise figure specification, which was not measured by ARRL and is provided as a maximum value by Watkins-Johnson.

### *Blocking Dynamic Range*

Blocking dynamic range (BDR) indicates how well the receiver handles strong nearby signals before desensitization occurs. This is an important parameter when attempting to hear weak stations in the presence of strong local signals. Blocking dynamic range is referenced to the MDS and is the value of an input signal that causes the gain to drop 1 dB. Therefore, if a −25 dBm input signal causes 1 dB of gain compression for a receiver with a MDS of −135 dBm, the blocking dynamic range is 110 dB. The receiver filter bandwidth and the distance in kHz between the two signals must be specified to make this measurement meaningful. Manufacturers often use 100 kHz spacing but are not consistent.

### *Two-tone Dynamic Range*

Two-tone dynamic range, also known as intermodulation distortion (IMD) dynamic range, indicates the range of signals that can be tolerated by the receiver before an undesirable spurious response is developed. A spurious response is a distortion product that results from receiver nonlinearities. Normally, receiver filters restrict the worst case to the third order difference products. For two frequencies f1 and f2, these products are 2f1 − f2 and 2f2 − f1. The sum products (2f1 + f2 and 2f2 +1) are also produced, but are outside the receiver filter bandwidths and thus are not considered. For instance, a signal at 8030 kHz and 8050 kHz will produce the following products:

$$(\text{Spur } 1) = (2 \times 8030) - 8050 = 8010 \text{ kHz}$$
$$(\text{Spur } 2) = (2 \times 8050) - 8030 = 8070 \text{ kHz}$$

In other words, two strong signals at 8030 kHz and 8050 kHz are likely to create a signal at 8010 kHz and 8070 kHz that is receiver tunable if the third-order two-tone intermodulation distortion dynamic range (IMD3) is exceeded. If a signal of interest exists on 8010 kHz, the "intermod" could easily cover it up. The IMD3 dynamic range is defined as the input from two generators using a specified frequency separation (20 kHz) that causes a third order spurious response to appear above the noise (MDS). That is:

$$\text{Two-tone dynamic range (IMD)} = \text{MDS} - \text{IM level}$$

For instance, if a combined signal of -50 dBm causes a spurious signal to appear on 8010 kHz for a receiver with a −135 dB MDS, the IMD is −135 − (-50) or 85 dB. The receiver filter should be specified as well as the signal spacing.

### *Intercept Point (IP)*

Some years ago the concept of intercept point was introduced and has become a useful and popular specification for comparing the quality of various nonlinear electronic components (amplifiers, mixers, couplers, receivers). The intercept point is the theoretical level at which two-tone distortion products intersect the single tone transfer curve on a plot of output vs input levels. Normally the third order products are plotted; however, the intercept point can also be found for the second or other orders. To understand this concept, remember that the output of a linear device, say an amplifier, will follow the input according to the formula:

Output = A (Input)
Where A = the device gain.

Third order products (2f1 − f2) and (2f2 − f1) will follow the formula:

Output (3rd) = 3A (Input)

The third order output will have a slope that is three times that of the desired fundamental signal. By plotting the above two equations with input and output on the x and y axis, respectively, the two curves can be projected to intersect at some point on the plot; that point is known as the third order intercept point (IP3). The intercept point can be given in terms of input or output level. The output IP is the input IP times the gain of the device. Devices with higher intercept points are better than ones with lower intercept points.

The IP3 is related to MDS and IMD3 by IP3 = MDS + 1.5(IMD3). Most commercial manufacturers specify IP3 for their devices. For instance, the brochure on the Ten-Tec 330A receiver specifies a IP3 of +30 dBm (input IP) with preamplifier off.[4] In most cases the specification is for the input intercept point. It may be worth asking if you see an unusually high IP specification that is not designated as either input or output.

The intercept plot (see Fig. 1) shows both the input and output IP#. Note that this is not the actual transfer curve, but a knee, the point where the receiver goes into saturation stylized plot which does not show the actual transfer curve.

### *Spur-Free Dynamic Range*

Spur-free dynamic range (SFDR) is the difference between input noise level and input signal level where the IMD3 curve is equal to the noise level. Using this definition, we can see that SFDR is the distance along the x-axis between the two curves on an IP3 plot that is extended to the noise floor. The SFDR is shown on the IP3 plot above. SFDR is defined as

$$\text{SFDR (dB)} = 2/3\,(\text{IP3} - \text{NF} - 10\log\text{BW} + 174)$$

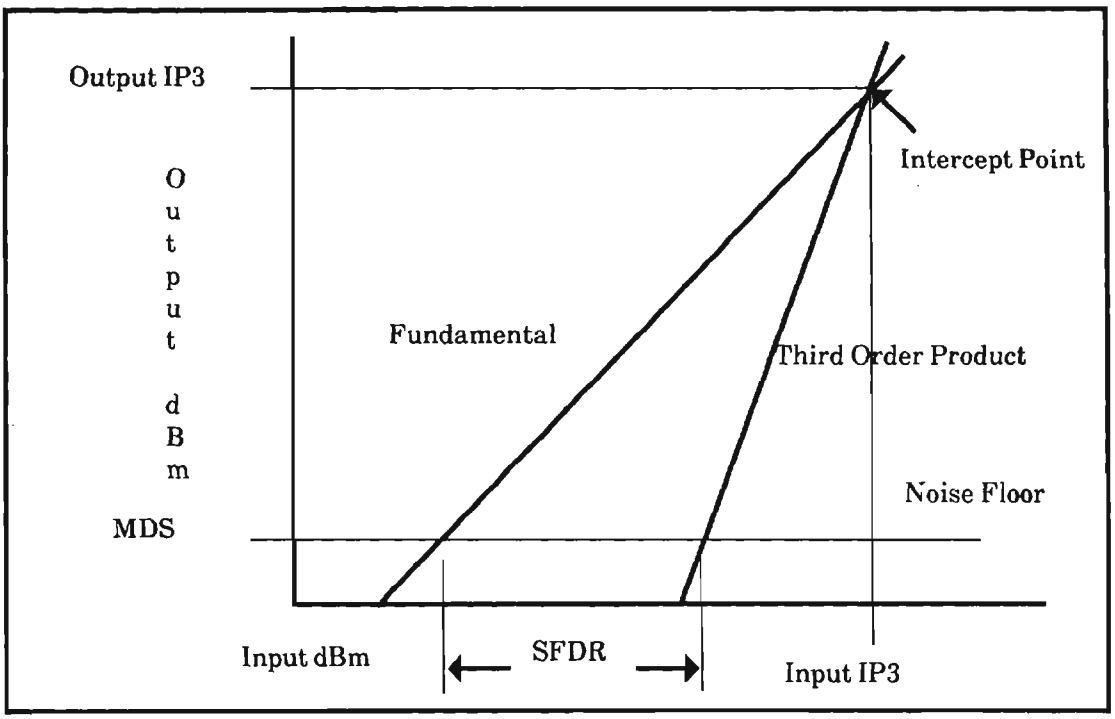


**Fig. 1. Third order intecept point plot**

With a little thought, you will recognize this as just a restatement of the IP3 equation above, and SFDR is equal to IMD3. These two terms are used interchangeably.

| Radio (BW = 3kHZ) | NF dB | IP3 dBm | SFDR dB |
|---|---|---|---|
| Racal 2174[5] | 13 | +20 | 88 |
| WJ-8711A | 14 | +30 | 104 |
| Ten-Tec 330A | 20 | +30 | 100 |

**Fig. 2. SFDR derived from receiver specification sheets**

Since most manufacturers provide noise figure and IP3 specifications, the SFDR number can be derived and used for comparison purposes across a number of similar radios.

### *LO Phase Noise*

The receiver local oscillator exhibits short-term instability in the form of phase and frequency modulation. The effect of the FM is to widen the LO to include frequencies above and below the carrier in the form of FM noise. In the mixing process, this noise is transferred to the signals in the passband of the receiver. As the distance from the LO frequency increases, this noise is reduced. A typical specification is in dB below the carrier (-dBc) in a one hertz bandwidth at some offset from the carrier. The specification for the

WJ-8711 is -110 dBc/Hz at 1 kHz offset, typical.[6] The lower this number the better, and lower numbers measured closer to the carrier are better than those measured farther away. The transfer of local oscillator phase noise to signals in the mixer during the frequency conversion process is called *reciprocal mixing*. Phase noise will tend to mask weak signals in the presence of strong signals as the phase noise on the strong signal may be larger than the weak signal.

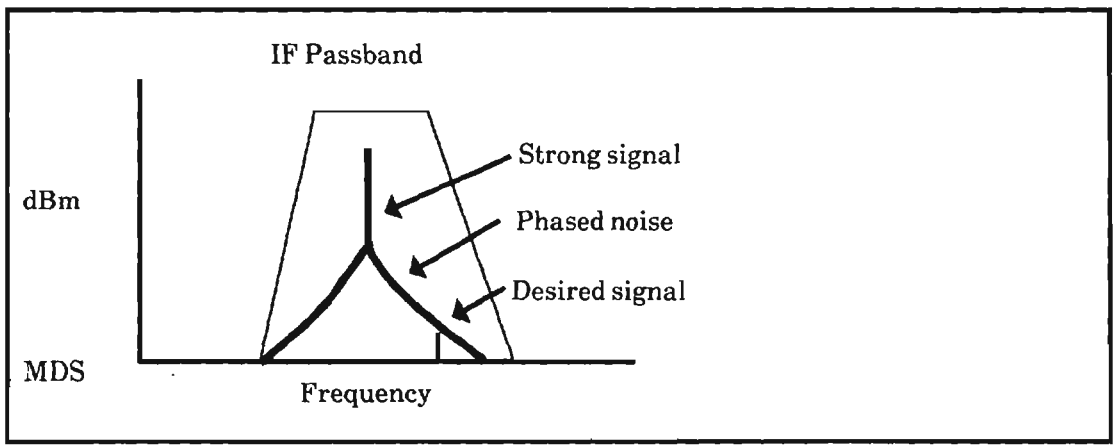


**Fig. 3. Weak signal masked by strong signal phase noise**

Receivers using phase locked loop techniques tend to exhibit more phase noise than those using crystal oscillators or direct digital synthesis (DDS) techniques. Not all manufacturers specify reciprocal mixing.

### *LO Spurs*

The local oscillator may produce spurious signals (spurs) resulting from the process used in synthesis of the oscillator signal. Spurs that rise above the noise can be detected by terminating the receiver input and tuning through the receiver through its range while listening for signals. Spurs should be few and weak, barely rising above the noise. Spurious responses are specified by the maximum value of their amplitude and number.

### *Cross Modulation*

Cross modulation (CM) is the ability of a receiver to reject modulation of a signal in its passband by a strong signal outside the passband. The undesired signal must be of sufficient amplitude to drive one of the receiver stages into nonlinear operation. It is usually given in terms of a percentage of CM – in other words, the amount of modulation the undesired signal imposes on the desired signal. The desired and undesired signal amplitudes, modulation percentage, and frequency separation are also parameters of the specification. Because of the variables and lack of standards, CM, although important, is not particularly useful for receiver comparison purposes.

### *Image Rejection*

In a superhertrodyne receiver there exists an image frequency which when mixed with the LO will produce a signal in the IF bandpass along with the signal of interest. For a receiver with an LO higher than the tuned frequency, the image is 2IF + f, where IF is the IF frequency and f is the tuned frequency. For instance, for a receiver tuned to 500 kHz with an IF of 1100 kHz, an LO of 1600 kHz, the image is 2700 kHz.[7] This means that a signal at 2700 kHz could be present in the IF along with the desired 500 kHz signals if image rejection is not high. Images can be identified in the IF passband because they tune backwards. Image rejection should be high, >75 dB, meaning that the image is more than 75 dB down from the signal of interest in the IF passband. Normally image rejection is given for the first IF. Image rejection can be improved by converting the tuned signal up in frequency, as was done in the case above. Most modern HF receiver systems convert the RF input signal to a high first IF in the low VHF range, which causes the image to be well out of the passband of the receiver and thus improves the image rejection specification. This also improves the rejection of signals at the IF (IF rejection) by putting them well out of the receiver tuning range. IF rejection specifications should be greater than 80 dB in a modern communications receiver.

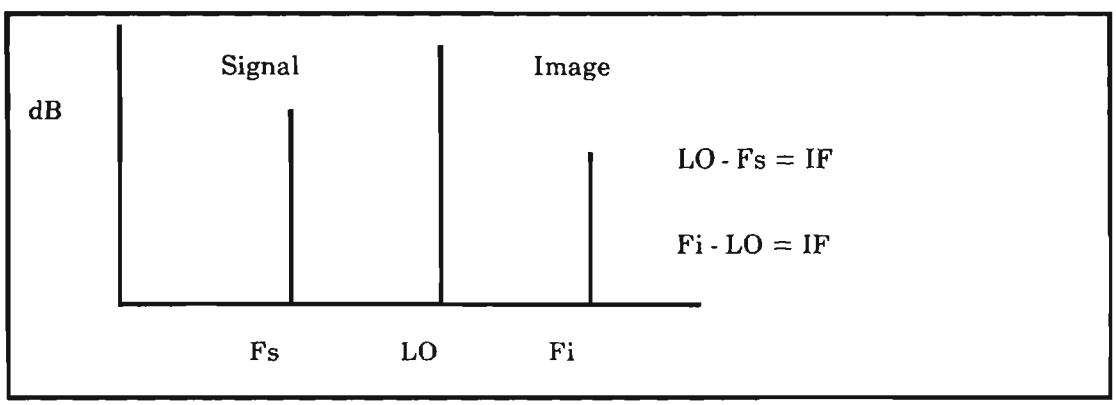


**Fig. 4. Image signal relationship to LO and tuned signal, Fs**

Manufacturers often use microvolts (uV) and decibels referenced to one milliwatt (dBm) interchangeably throughout their specification sheets. To convert uV to dBm, the impedance (Z) must be known. In most cases this is 50 or 75 ohms. Using the fact that power, $p = e^2/r$, converted by

$$dBm = 10 \log (uV^2/Z)(10^3)$$

Need more information? K4 has several experts in the receiver dynamics area who would be willing to interpret specification sheets and answer detailed questions. Your system engineer can lead you to these people.

DOCID: 3928940



## Notes

1. David Newkirk, Product Review – Watkins-Johnson HF-1000 General Coverage Receiver, QST December 1994, ARRL Newington, CT, 76–79.

2. The specified S+N/N depends on the demodulation selection, with 10 dB, 16 dB, and 17 dB being used by Watkins-Johnson for AM/SSB, CW and FM, respectively. This is not consistent across manufacturers.

3. Watkins-Johnson HF-1000 specification sheet, October 1993.

4. Ten-Tec RX-330A specification sheet, September 1994.

5. Technical Manual T.O. 31R2-2URR-251 (Racal 2174) 1–8.

6. Watkins-Johnson WJ-8711 specification sheet, April 1994.

7. Keith Henny, *Radio Engineering Handbook*, New York: McGraw Hill,1959, 19–35.

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Hayward, W. *Introduction to Radio Frequency Design*, Prentice Hall, 1982.

Rhode, U., and T. Bucher. *Communications Receivers Principles and Designs*, McGraw Hill, 1987.