# Receiver Specs

What does it all mean?

# Why do we care?

- Determine usability for intended purpose
- Facilitate comparison of different radio architectures
- Identify best match to buyers needs (bang for the buck)
- Set correct expectations of performance (avoid buyers remorse)
- Understand reviews in QST

# Necessary/useful background

- Decibels (dBx): x denotes reference value, if any
  - Represents power ratio expressed logarithmically (for ease in comparison and avoid use of excessively large or small numbers)
  - Defined as: $10 \log_{10} (P_{out}/P_{in})$
  - Example: an amplifier produces an output of 20 watts with an input of 10 watts. What is the gain in dB?
    - $P_{out} / P_{in} = 20/10 = 2$
    - $\log_{10} (2) = .301$
    - $10 \log_{10} (2) = 3$, therefore the gain is 3 dB

- Note that dB is a representation of a ratio and is therefore dimensionless
- Exceptions to above are dBx, with reference to some value x
- Most common x in receiver specs is dBm which represents the ratio of some power to one milliwatt
- Note that dBm is no longer dimensionless but represents a power ratio to 1 mw, which is an actual power in watts.

- dBm examples:
- 80 dBm: 100 kw, typical power output of FM broadcast transmitter
- 50 dBm: 100 w, typical HF xcvr output
- 37 dBm: 5 w, typical HT output
- 27 dBm: 500 mw, cell phone output
- 15 dBm: 32 mw, typical wireless LAN
- -60 dBm: 1 nw, earth receives about 1 nanowatt per square meter from a 3.5 magnitude star
- -73 dBm: S9 signal at antenna input, 50.12 pw (petawatt is $10^{-12}$ watt)
- -127.5 dBm: .178 fw (fw = $10^{-15}$ watt), typical received signal from GPS satellite
- -174 dBm: 4 zw (zw = $10^{-21}$ watt), thermal noise floor for 1 Hz bandwidth at room temp (20 degrees C)
- -192.5 dBm: .056 zw, thermal noise floor for 1 Hz bandwidth in outer space (4 degrees K)
- Note that dB allows you to express power ratios from the most infinitesimal to a really big number in a numeric range of less than 300

# Additional useful, but not required background

- In dynamic range discussion later on, nth order DR will be included. Where does the "order" come from and why is it called that?
- Performance of ideal amplifier can be specified as: $V_{out} = A_0 + A_1 V_{in}$, where V represents voltages (proportional to power) and A is the transfer function of the device, in an amplifier typically the gain.
- There is no such thing in the real world as an "ideal amplifier"
- The performance of a real amplifier, i.e., one with non-linearities can be represented by the power series:

  $V_{out} = A_0 + A_1 V_{in} + A_2 V_{in}^2 + A_3 V_{in}^3 + A_4 V_{in}^4 + . . .$ (etc)
- The squared term is the second order product, the cubed term is the 3rd order product which will be of the most interest. Usually the fourth order products and above are negligible and can be ignored.
- More to follow under intercept section

The **third** order term $A_3 V_{in}^{\ 3}$ determines the third order products:

$$A_3 V_{in}^3 = \frac{3A_3}{2}\left[V_1 V_2^2 + \frac{V_1^3}{2}\right]\cos(\omega_1 t) + \frac{3A_3}{2}\cos\left[V_1^2 V_2 + \frac{V_2^3}{2}\right]\cos(\omega_2 t) +$$

***Fundamental frequency terms***

$$\frac{A_3 V_1^3}{4}\cos(3\omega_1 t) + \frac{A_3 V_2^3}{4}\cos(3\omega_2 t) +$$

***3rd harmonic terms***

$$\frac{3A_3 V_1^2 V_2}{4}[\cos(2\omega_1 t + \omega_2 t) + \cos(2\omega_1 t - \omega_2 t)] + \frac{3A_3 V_1 V_2^2}{4}[\cos(2\omega_2 t + \omega_1 t) + \cos(2\omega_2 t - \omega_1 t)]$$

***3rd order IMD terms – The troublemakers***

# That was a bit of fun. Now to the specs

- For each spec:
  - What it measures/means
  - Typical values (good, better, best)
  - Impact on operator experience
  - Trade-offs, side effects
  - How test is performed

# Specs to be covered fall into three groups

- Sensitivity group:
    - Noise figure
    - Minimum discernable signal (MDS)
    - AM sensitivity
    - Spectrum scope sensitivity
- Dynamic performance group
    - Blocking gain compression
    - 2 - signal, 3rd order dynamic range
    - 2 - signal, 2nd order dynamic range
    - Reciprocal mixing dynamic range
    - Spurious, image and 1st IF rejection
- Misc group
    - IF image rejection
    - Notch filter depth

# Sensitivity group: Noise Figure

- Noise factor of a system, F, is defined as: $F = SNR_{in} / SNR_{out}$
- Noise figure is F in dB: $NF = 10 \log_{10} (F)$
- Formula only valid when input termination is at $T_0 = 290$ K (room temp +/-)
- To use the "Gain Method" to measure the noise figure, the gain of the DUT needs to be pre-determined. Then the input of the DUT is terminated with the characteristic impedance (50Ω for most RF applications. Then the output noise power density is measured with a spectrum analyzer.
- Typical NF values are in the range of 10 - 15 dB
- On most modern receivers the noise figure is less than the ambient band noise (below 21 MHz)
- The better the NF, the better the “weak ones” can be heard (up to a point)

# Sensitivity group: Minimum Discernable Signal (MDS)

- Defined as input power (in dBm) required to raise noise floor by 3 dB (bandwidth dependent, usually measured at 500 Hz)
- Typical values in the -130 to -135 dBm range.
- Lower is better
- BUT! With pre-amps on, strong nearby signals can cause IMD which actually reduces sensitivity

# Sensitivity group: AM sensitivity

- Input necessary to produce specified level at output
- Typically defined as voltage at input to generate a 10 dB value of (S+N) / N
- In testing usually measured using a signal modulated at 30% with a 1 kHz tone and 6 kHz filter
- Acceptable values run from 1 to 2.5 microvolts, with better numbers at lower frequencies

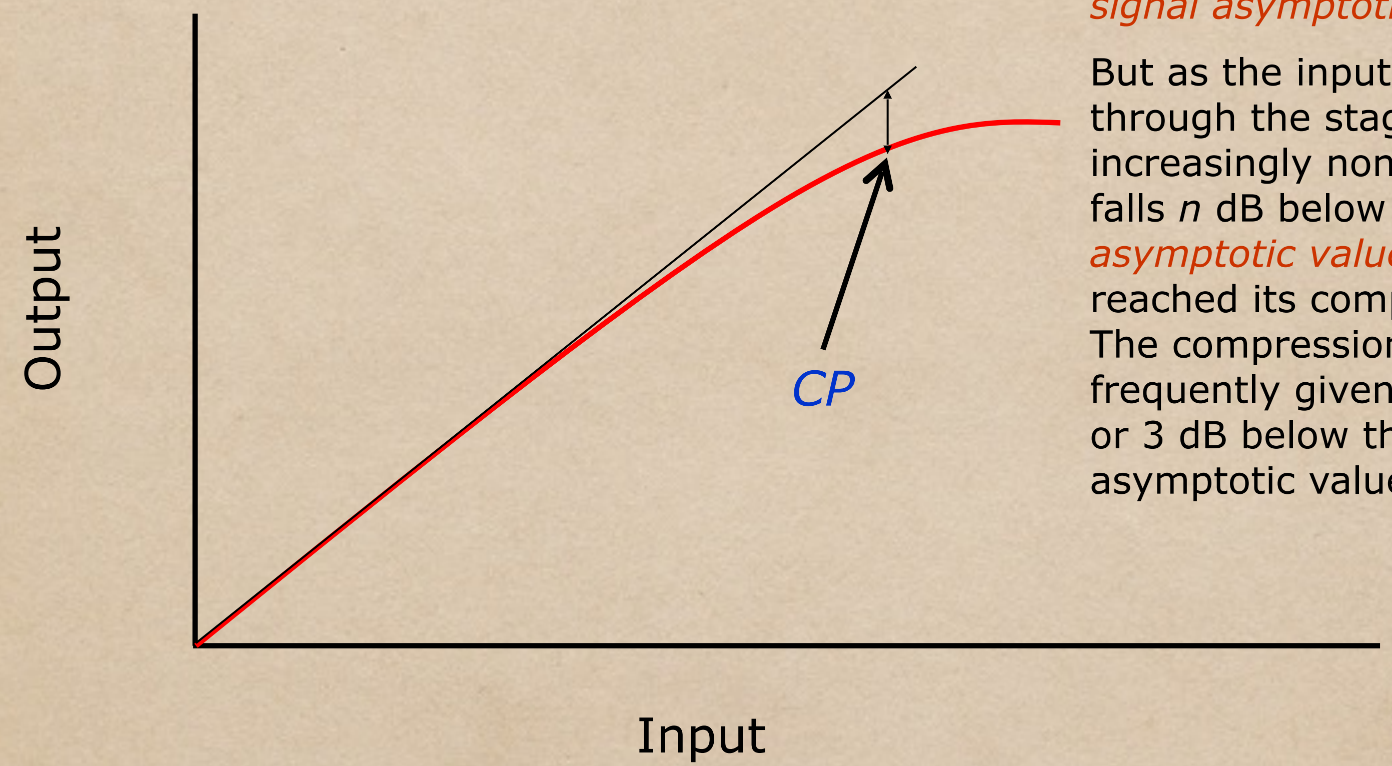
# Sensitivity group: spectrum scope sensitivity

- Defined as power input in dBm necessary to produce minimum visible spike on display (above noise floor)
- Typically around -125 dBm (pre-amp on)
- Lower is better
- Allows operator maximum visibility into the display range

# Dynamic range group

- General definition: Dynamic range is the difference in dB between the MDS and a signal that causes a specified amount of harmonic distortion at the receiver output.
- Recall that MDS is defined as:
  $MDS = NF + 10 \log_{10} BW - 171$, where:
    - NF = noise figure
    - BW = band width
    - -171 = 3 dB above noise floor (-174 dBm @ 290 degrees K)

# Gain and the Compression Point




At low input levels, receiver RF and IF stage gain will be generally linear—approaching a level called the *small-signal asymptotic value.*

But as the input level increases, gain through the stage becomes increasingly nonlinear.  When the gain falls *n* dB below the *small-signal asymptotic value*, it has said to have reached its compression point (*CP*). The compression point, stated in dB, is frequently given as either 1 dB or 3 dB below the small-signal asymptotic value.

# Nonlinearity and Intermodulation Distortion

- Nonlinearity in RF and IF circuits leads to two undesirable outcomes: harmonics and intermodulation distortion.
- Harmonics in and of themselves are not particularly troublesome.
- For example, if we are listening to a QSO on 7.230 MHz, the second harmonic, 14.460 MHz is well outside the RF passband.
- However, when the harmonics mix with each other and other signals in the circuit, undesirable and troublesome intermodulation products can occur.

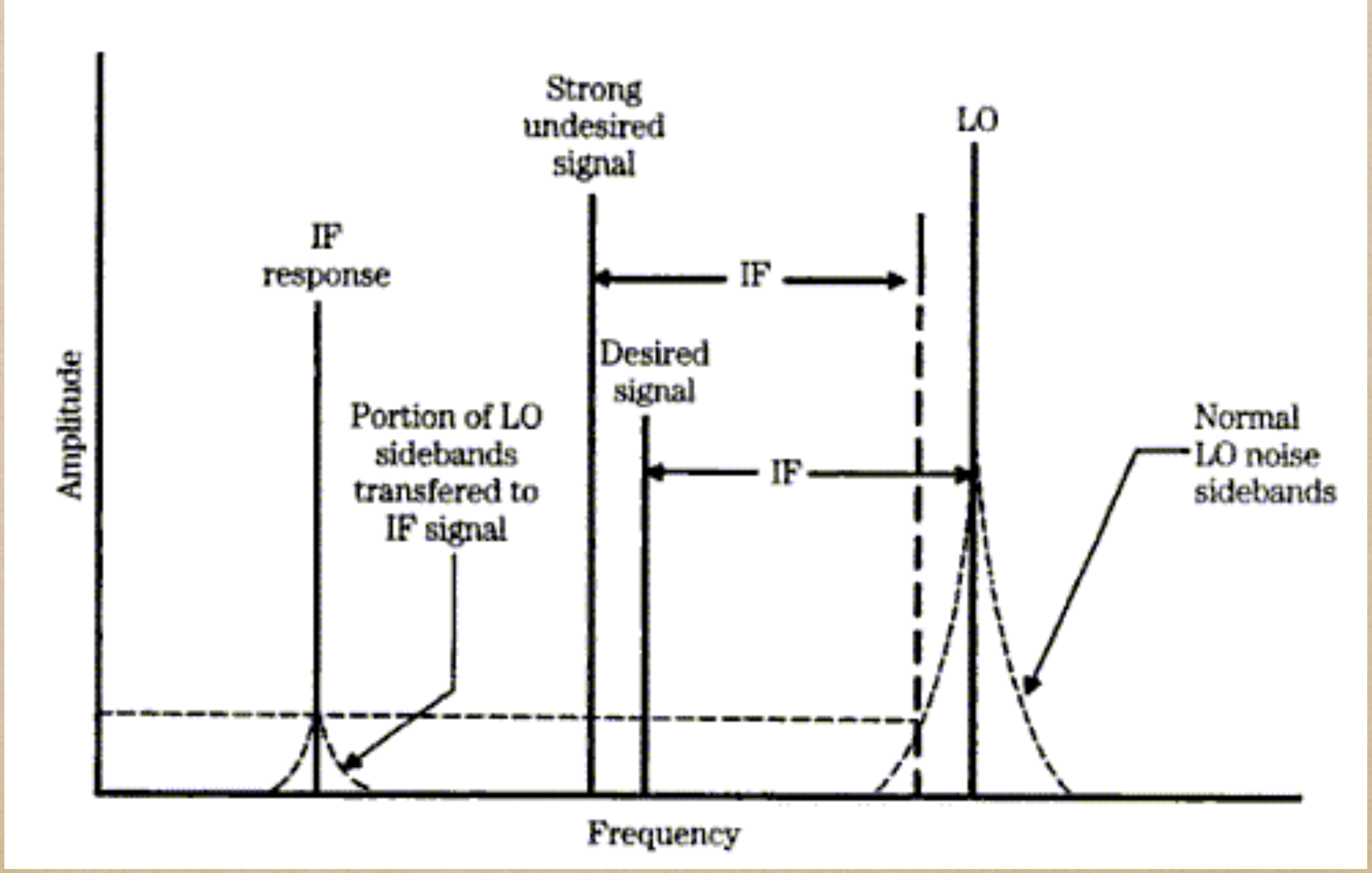
# Dynamic range group: Blocking gain compression dynamic range (BDR)

- Indicates how well receiver handles strong nearby signals before desensitization occurs
- References to MDS and defined as value of input signal that causes gain to drop 1 dB
- Example: if a -25 dBm causes a 1 dB gain drop in a receiver with a -135 dB MDS, blocking dynamic range is 110 dB
- The higher the BDR the better, allowing operator to make QSOs in the presence of strong nearby signals

# Dynamic range group: reciprocal mixing dynamic range

- Reciprocal mixing noise: Excessive local-oscillator phase noise will mix with strong unwanted signals to yield noise at IF, masking a weak signal.
- Modern transceivers with Direct Digital Synthesis have much lower reciprocal mixing noise. Direct-sampling SDR has virtually eliminated this problem.
- At 2 kHz spacing: Acceptable: 78 to 80 dB. Excellent: > 90 dB. Superb: > 100 dB.

# Impact of reciprocal mixing noise on a weak signal



# Dynamic range group: 2 signal 3rd order IMD dynamic range

- Also known as two tone IMD dynamic range
- For every 1 dB increase in the power of input tones, the 3rd order product will increase 3 dB
- Indicates  range of signals that can be tolerated before spurious responses develop
- Receiver filters restrict worst case to third order difference products
- Result of IMD is that 2 signals outside passband can produce strong signal within passband masking desired signal

# 3 rd order IMD DR (cont'd)

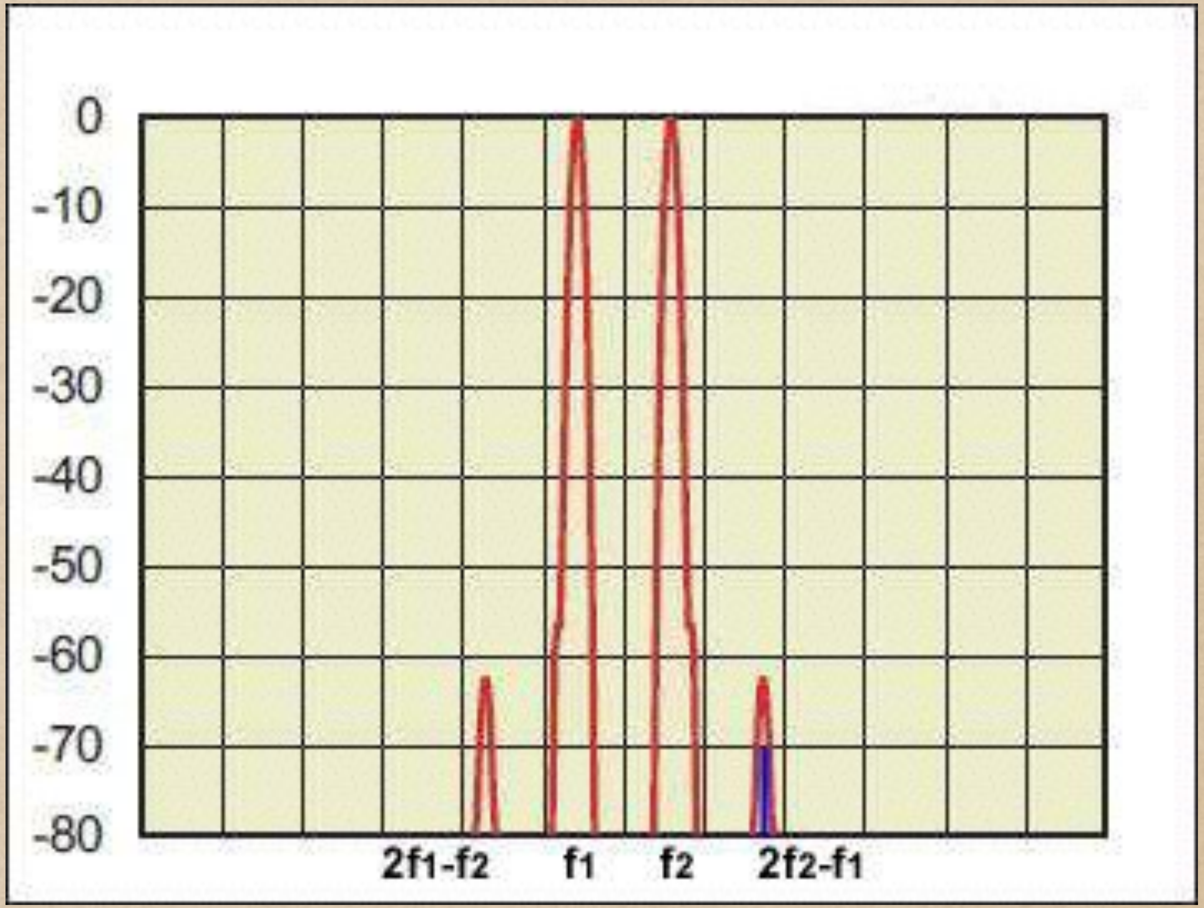
- Example:
  - 2 strong signals "near" but not in passband at $f_1$ and $f_2$ produce four products:
  - $2f_1 - f_2$, $2f_2 - f_1$, $2f_1 + f_2$, $2f_1 + f_2$
  - Also $3f_1$ and $3f_2$ which are so far outside the passband as to be of no interest
  - If signals are present at 7030 and 7050 kHz they produce the following products:
    - Spur 1 = (2 x 7030) - 7050 = 7010 kHz
    - Spur 2 = (2 x 7050) - 7030 = 7070 kHz
  - If there is a juicy DX signal at 7010 kHz the intermod would more than likely cover it up

# 3 rd order IMD DR (cont'd)

IMD products are: 2f1 – f2
2f2–f1

Example:

f1 = 14050 kHz
f2 = 14052 kHz
IMD products: 14048, 14054 kHz
IMD product masks weak signal at 14054 kHz



# 3 rd order IMD DR (cont'd)

- Definition: 2 tone DR (IMD) = MDS - IM level
- Example: if a combined signal of -50 dBm causes a spurious signal to appear on 7010 kHz in a receiver with a -135 dBm MDS the IMD is -135 - (-50) = -85 dBm
- For the result to be meaningful, the separation of the two signals and the filter width must be specified
- IMD DR is then calculated as: | measured IMD level - measured input level |
- Example from recent QST review: For 20 kHz spacing, with 400 Hz BW and 400 Hz roofing filter, at 3.5 MHz, measured levels were IMD: -135 dBm; input -30 dBm, therefore IMD DR is | -135 - (-30) | = 105 dB
- Larger numbers are better; IMD DR in range of 90 dB + are acceptable
- IMD is not an issue in SDR receivers where signal from antenna is fed directly into an ADC

# Intercept point

- IP is a theoretical number.  It is never reached in practice because amplifier would be totally saturated (or blow up) well  before it is reached
- It represents the point on a plot of output vs. input where the n-order two tone distortion products intersect the single tone transfer curve (i.e., the theoretical level at which first and third order products are equal in power)
- As a general rule, n-order products grow n times faster than first order products
- Following slide shows binomial expansion of the earlier formula for power response for two signals with frequencies w1 and w2.
- Its a very nasty formula for very nasty effects.

An input signal with two frequencies may be represented: $V_{in} = V_1 \cos(\omega_1 t) + V_2 \cos(\omega_2 t)$

The **first** order term $A_0 + A_1 V_{in}$ gives the fundamental products $V_{out} = A_0 + A_1 V_1 \cos(\omega_1 t) + A_1 V_2 \cos(\omega_2 t)$

The **second** order term determines the second order products:

$$A_2 V_{in}^2 = \frac{A_2 V_1^2}{2} + \frac{A_2 V_2^2}{2} + \frac{A_2 V_1^2}{2}\cos(2\omega_1 t) + \frac{A_2 V_2^2}{2}\cos(2\omega_2 t) + \frac{A_2 V_1 V_2}{2}[\cos(\omega_1 t + \omega_2 t) + \cos(\omega_1 t - \omega_2 t)]$$

***DC terms*** ***2nd harmonic terms*** ***2nd order IMD terms***

The **third** order term $A_3 V_{in}^{3}$ determines the third order products:

$$A_3 V_{in}^3 = \frac{3A_3}{2}\left[V_1 V_2^2 + \frac{V_1^3}{2}\right]\cos(\omega_1 t) + \frac{3A_3}{2}\cos\left[V_1^2 V_2 + \frac{V_2^3}{2}\right]\cos(\omega_2 t) +$$

***Fundamental frequency terms***

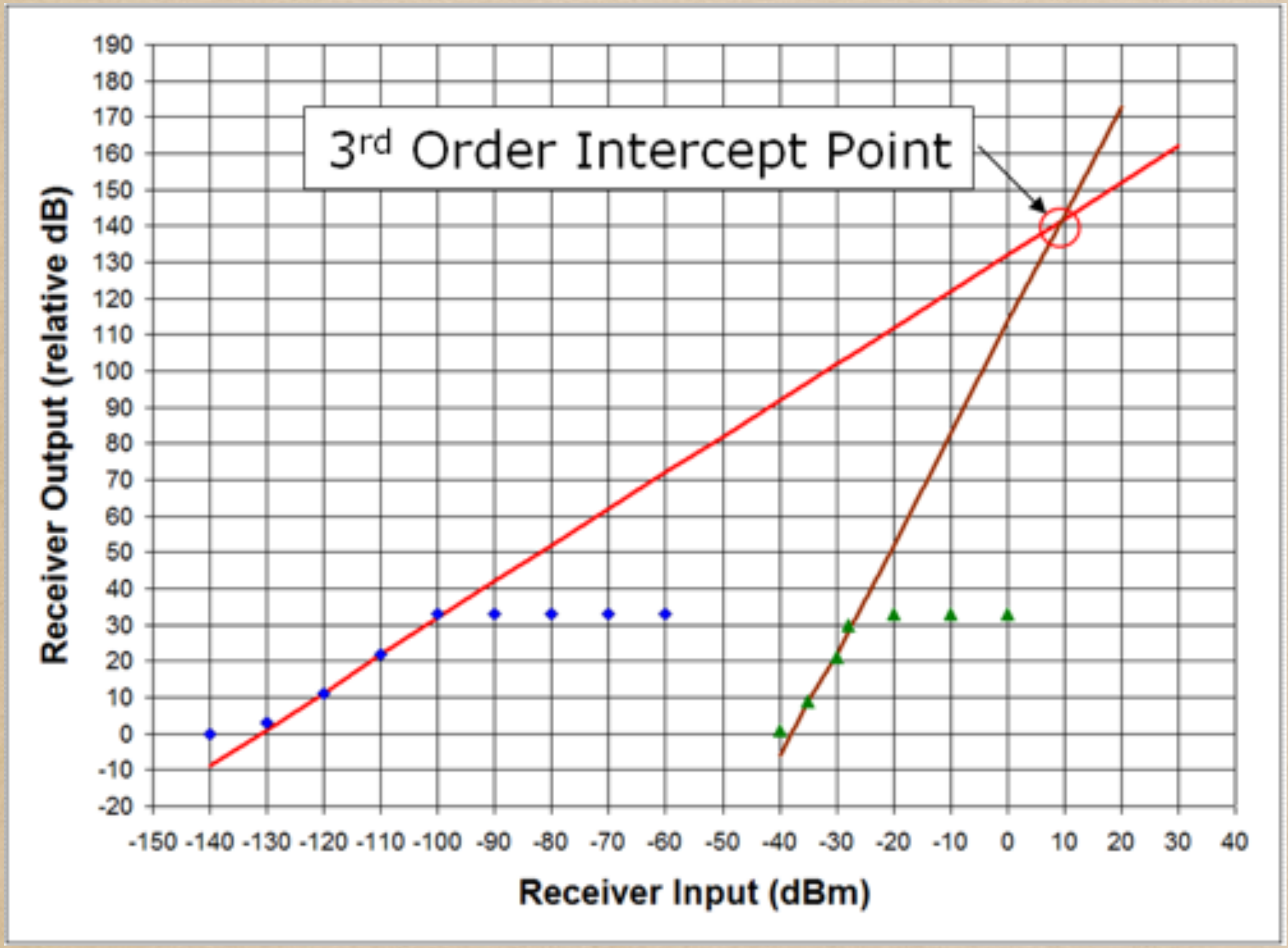
$$\frac{A_3 V_1^3}{4}\cos(3\omega_1 t) + \frac{A_3 V_2^3}{4}\cos(3\omega_2 t) +$$

***3rd harmonic terms***

$$\frac{3A_3 V_1^2 V_2}{4}[\cos(2\omega_1 t + \omega_2 t) + \cos(2\omega_1 t - \omega_2 t)] + \frac{3A_3 V_1 V_2^2}{4}[\cos(2\omega_2 t + \omega_1 t) + \cos(2\omega_2 t - \omega_1 t)]$$

***3rd order IMD terms – The troublemakers***

An input signal with two frequencies $\omega_1$ and $\omega_2$ may be shown as:

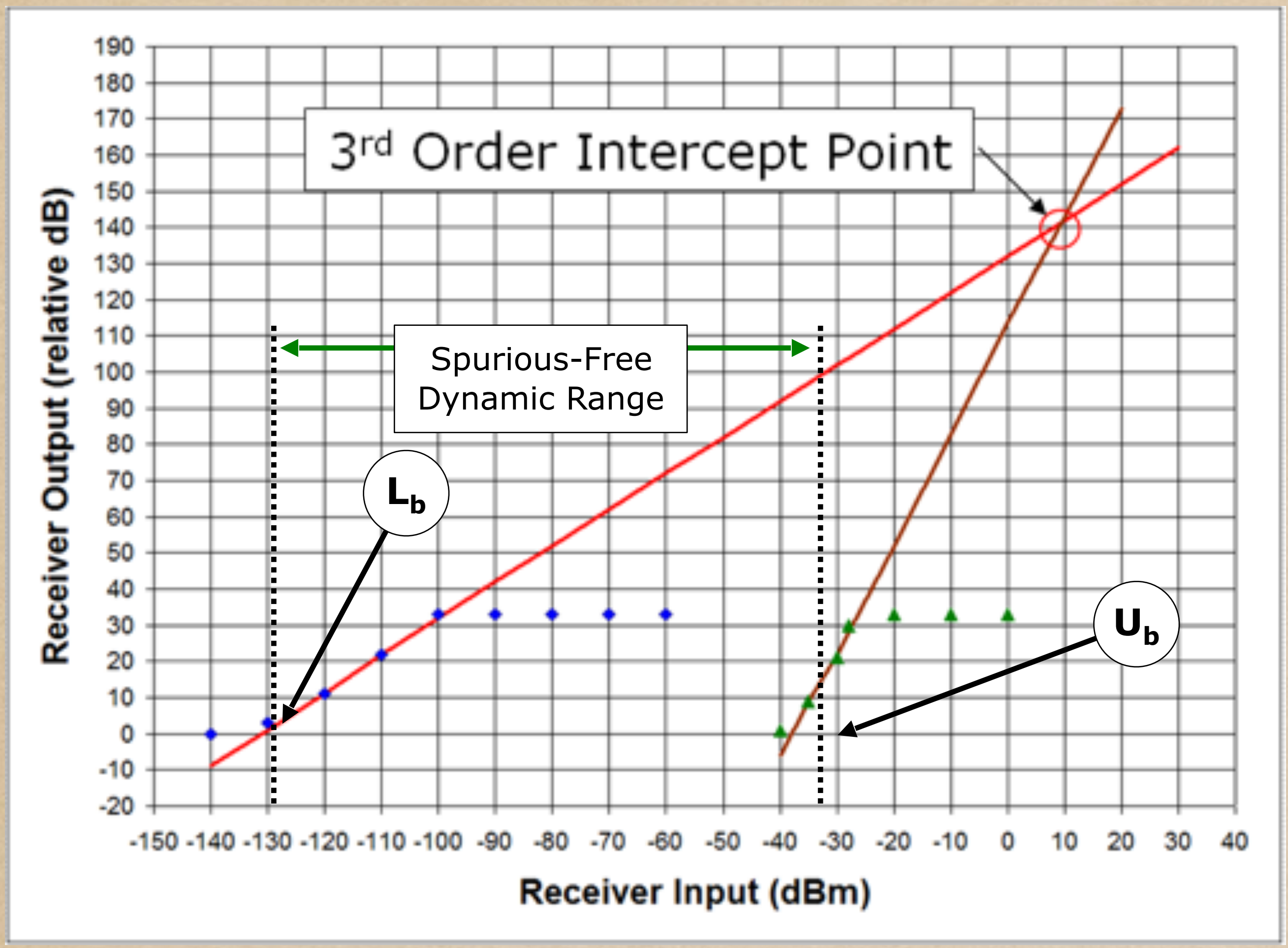



Our graph illustrates that the 3rd order intercept point is defined by the intersection of two hypothetical lines. Each line is an extension of a linear gain figure: first of the signal of interest; and second, of the 3rd order intermodulation distortion product—from which IP3 gets its name.

You will note that the larger the value of IP3, the less likely the receiver will be adversely affected by 3rd order intermodulation products. More on this later.

# Intercept point, again
## Stuff to note about the graph

- Since dB is a logarithmic quantity, and the axes of the graph are in dB, terms of power n are represented by straight lines of slope n which makes the whole process easier
- As the $IIP_n$ moves right, the intercept point moves up meaning that it takes a stronger spurious signal before linear performance is affected (i.e., IMD DR improves)
- Both lines on the graph are generated by measurements within the linear range (i.e., before compression or distortion) and then extrapolated to the IP
- Example in following graph:




$L_b$ Lower bound

The lower bound is defined as a signal of interest 3 dB greater than the noise floor.

$U_b$ Upper bound

The upper bound is set by the 3rd order IMD equal to the MDS.

In graph an input signal of -110 dBm will produce 20 dB of output in signal of interest. To achieve 20 dB of output in the 3rd order product, the off channel signals must be 80 dB (110 dBm - 30 dBm) greater than signal of interest, an unlikely occurrence.

# Second order intercept point

- As with 3rd order intercept, a theoretical point, but in this case its where the 2nd order curve (slope of 2) intersects the first order curve
- Two signals outside a ham band can mix to drop a signal onto a weak signal within a ham band
- Example: two strong signals at 6 and 8 MHz can generate a product on 14 MHz
- A preselector will greatly improve IP2
- Acceptable range for IP2 is 65 - 70 dB; good is 80 dB +, and excellent is anything over 95 dB

# IF and image rejection

- Images will cause false signals to appear in the IF which are carried through the rest of the IF chain and ultimately end up in the audio output
- Signals can appear at $f_0$ +/- 2 * IF
- Example: If $f_0$ = 10455 kHz, and IF is 455 kHz, images will appear at 10000 and 10910 kHz
- IF images are not a problem in receivers whose 1st IF is above the highest operating frequency
- For IF image rejection values: acceptable > 70 dB; good 80 - 90 dB; excellent > 95 dB

# Notch filter depth

- Band-stop filter is a filter that passes most frequencies unaltered, but attenuates those in a specific range to very low levels
- Notch filter is a band-stop filter with a very narrow stopband
- A notch filter, usually a simple LC circuit, is used to remove a specific interfering frequency
- Key notch filter specs are bandwidth (in Hz) and depth (in dB)
- Bandwidth is sometimes adjustable by operator
- Notch depth is usually a fixed value, the higher the better
- Typical ranges of notch filter depth are 55 dB and up

# Squelch Sensitivity

- Squelch circuit is noise operated. It uses a high pass filter to remove voice component from received signal
- Resulting signal is rectified. The DC output of the rectifier turns off the receiver audio
- Appearance of a signal causes noise derived voltage to drop, unmuting the receiver audio.
- Squelch sensitivity allows adjustment of level of signal necessary to "break squelch", i.e., unmute audio
- Range of adjustment is usually from tens of microvolts to a couple hundred millivolts
- Larger ranges are better. E.g., recent product review in QST showed a range of .11 microvolts (at 29 MHz) to 316 millivolts (at 52 MHz)

# FM Sensitivity

- Input signal required (in microvolts) to produce a specified SINAD.
- SINAD = 10 log ( (signal+noise+distortion) / (noise + distortion) )
- Roofing filter used and frequency are also usually part of this spec
- SINAD value used is usually 12 dB which corresponds to a distortion value of 25%
- Also for this test a 1 kHz tone is used to modulate the carrier, and deviation is set to 12.5% of channel spacing.
- Spec usually also shows values for pre-amp off and on
- Good range is ~ .20 to .65 microvolts (pre-amp off)
- Lower is better

# FM Adjacent Channel Rejection

- Ability to reject signals on adjacent frequencies
- Initial SINAD measurement is made at some arbitrary level to establish a reference sensitivity. Level is then raised 3 dB.
- Second signal, modulated with 400 Hz tone is then added at a specified offset from the original carrier frequency
- The level of the second signal is raised until the 400 Hz tone appears in the receiver output. That is the initial point.
- Signal level is raised further until SINAD is degraded to the original reference value. The difference in levels between this point and the initial point (in dB) is the adjacent channel rejection.
- Bigger is better
- Acceptable values range from 80 dB upwards

# S-meter Sensitivity

- Standard is S 9 equals a 50 microvolt signal (at 50 ohms) at the antenna jack (equivalent to -73 dBm)
- Actual receiver tests show readings all over the map, some off by as much as 10 dB in either direction
- Unless you calibrate your S meter using reliable signal sources, your S meter readings are only somewhat blind relative indicators
- Some rigs have user adjustable S meter sensitivity. Not terribly useful unless you have access to accurate signal sources to use in the adjustment

# Thanks
# for
# Watching