Differences between analog and direct-sampling receivers

An Icom IC-7610 and Yaesu FTDX10 are similar RF transceivers in terms of outside appearance, and can be operated similarly, but internally they are completely different. The IC-7610 operates as a direct sampling SDR with an A/D converter in the RF input, whereas the FTDX10 operates as an analog receiver with an analog mixer in the RF input and a sampled IF.

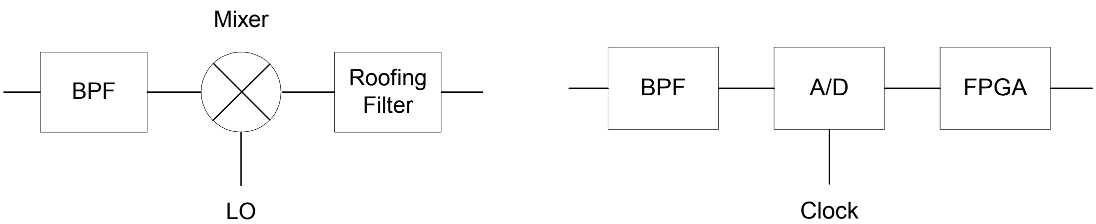

Figure 1: Principle of analog and direct-sampling receiver

In the advertisements of the FTDX10, Yaesu first lays out “magic numbers” relating to receiver performance: RMDR = 116dB, BDR = 141dB and DR3 = 109dB. By DR3 the manufacturer means the 3rd order intermodulation immunity, i.e. the distortion-free dynamic range, by BDR the maximum level that a strong signal may have next to a small received signal without blocking it, and by RMDR when a strong signal covers a small signal by sideband noise. In principle, these are the most important parameters of any analog receiver since decades ago, and should be common knowledge by now.

Figure 2: Advertising pages of the FTDX10 and IC-7610

If you look at a brochure of the IC-7610, IC-7300 or IC-705 and search for the "3rd-order IMDR", "BDR" or "Dynamic-Range", you won't find anything. The only thing you will find there is the specification of a "best in class RMDR".
What is the reason for this? Why is there neither a "3rd-order IMDR" or "BDR" nor "IP3" specified for direct-sampling receivers? How should one compare the two receivers now?

In the following, I shall try to answer these questions and to explain the essential differences between analog and direct-sampling receivers with the help of measurement examples, as well as to point out errors in publications.

Sensitivity (MDS)

The sensitivity (MDS) is an important parameter of the receiver, because it serves as a calculation basis for many other measurements. The basic noise of the receiver is defined as the measure of sensitivity for analog and direct-sampling receivers. To determine the noise level, we apply an RF signal at e.g. 14.1MHz to the input of the receiver (B=500 Hz, CW) and tunes the receiver to obtain a test tone of approx. 600Hz. Then, we reduce the RF signal until there is only a noise rise of (S+N)/N = 3dB at the AF output of the receiver (Fig. 3). If this is achieved, the level fed in corresponds to the noise floor (MDS) of the receiver, of e.g.

MDS = -130dBm/500Hz.

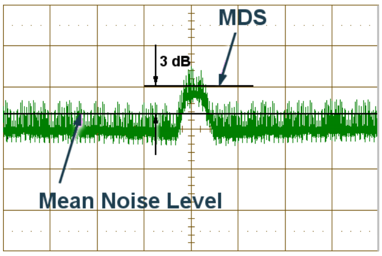

Figure 3: Measurement of the receiver noise floor (MDS) over (S+N)/N=3dB.

The noise is measured using an RMS AC voltmeter at the AF output of the receiver, where an increase of 3dB corresponds to a voltage increase by a factor of 1.414 (20lg U2/U1=3dB). The most suitable instrument for this purpose is an analog meter, if possible with a dB scale (-10 ... +20dB), which always displays the noise as a constant voltage signal due to its inertia (averaging of the pointer movement). According to the equation $P_N = kt_OB$, the noise power (P_N) at constant temperature (t_O) is directly dependent on the measurement bandwidth (B). Therefore, when specifying the MDS, the used bandwidth (more precisely noise bandwidth) of the receiver must always be specified, i.e. in dBm/Hz, in the example -130dBm/500 Hz.

Reciprocal Mixing (RMDR) and Sideband Noise (SBN)

To determine the RMDR and SBN on analog and direct-sampling receivers, the same measurement setup is used as for the sensitivity measurement and the "3dB method" is again employed. The only difference to the sensitivity measurement is that now a very low-noise test signal must be used. The sideband noise of the test signal source must be at least 10dB lower at 1...2 kHz offset than the sideband noise of the receiver to be tested, otherwise one measures the sideband noise of the test oscillator and not that of the receiver, because (unfortunately)reciprocal mixing works in both directions.

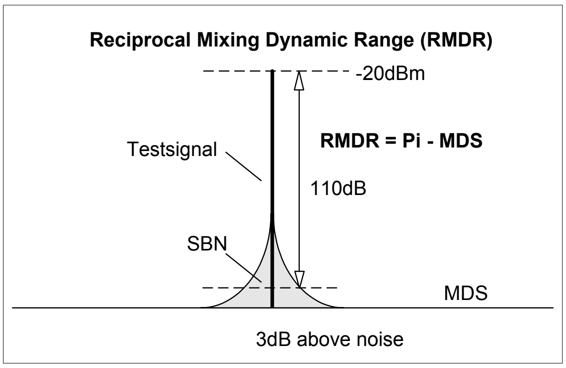

Fig. 4: Determining the RMDR with a low-noise test signal

Starting from Pi=-140s, the test signal is increased until the AF noise at the output of the receiver increases by 3dB at 1...2 kHz offset from the carrier (Fig. 4). In the example, this is done at a level of -20dBm. From this the RMDR is calculated to

RMDR = Pi - MDS = -20dBm - (-130dBm/500 Hz) = 110dB

and the sideband noise to

SBN = MDS - Pi -10logB = -130dBm - (-15dBm) - 10lg500Hz = -118dBm/Hz

Note: Strong SBN from a receiver can "mask" a small signal next to a large signal, thus desensing a sensitive receiver. The same can happen with an IMD3 measurement when an IMD3 product is covered with noise ≥ 3 dB above the IMD level at 1...2 kHz offset from the applied test signals. When this happens, the RMDR is responsible for the receiver's large-signal immunity, rather than intermodulation. However, in modern receivers, the SBN has now become so low that mostly just the 3rd order intermodulation defines the receiver's achievable dynamic range.
Under no circumstances should RMDR, BDR and DR3 be confused with each other, just because the word "Dynamic Range" appears in all abbreviations. They all describe different dynamics.

BDR (Blocking Dynamic Range) or Blocking Gain Compression
The BDR indicates how well a receiver can process small signals next to very large signals without sensitivity degradation. The maximum BDR is reached when an interfering signal (f1, P1) becomes so large that a small useful signal (f2, P2) loses 1dB of amplitude (S/N) at 2...20 kHz offset (Fig. 5). If this is achieved, the Blocking Dynamic Range is calculated to be

BDR = Blocking Level - MDS

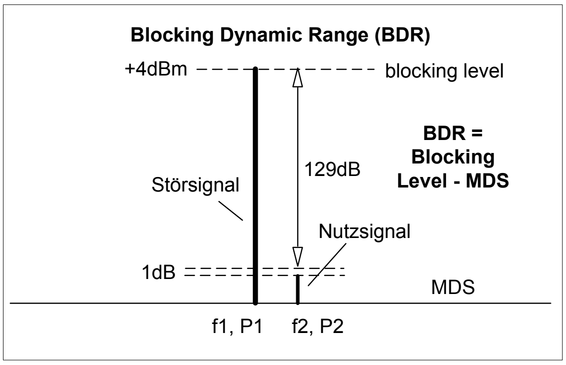

Figure 5: Blocking dynamic range of an analog receiver

Also with the BDR measurement, the SBN of the applied interfering signal must be very low. If not, the small signal will already be covered by the sideband noise of the interfering signal before the blocking of the receiver and the measurement result will be invalid (too low).

Figure 6 shows the result of a BDR measurement on an analog receiver with MDS=-125 dBm/ 500 Hz, measured by an LF analyzer at the audio output of the receiver. Only when the interfering signal has reached a level of +4 (S9+77 dB), the amplitude of the small useful signal (P2) decreases from -107 dBm to -106 dBm at 20 kHz offset. So the receiver loses sensitivity by 1dB and the resulting BDR is

BDR = Blocking Level - MDS = +4 dBm - (-125 dBm/500 Hz) = 129dB

However, BDR can ONLY be determined on analog receivers, not on direct-sampling receivers. With analog receivers, blocking occurs in the 1st mixer. An ADC (analog/digital converter) will clip (saturate) long before blocking occurs.

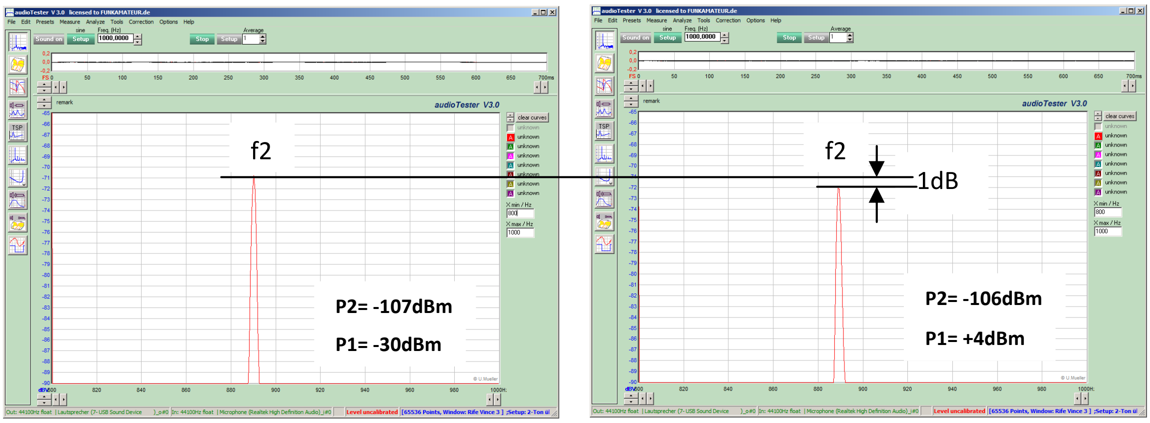

Figure 6: With an interference signal of +4 dBm (right), the receiver goes into 1dB compression.

If I try to perform the same BDR measurement with a direct-sampling receiver, no loss of dynamic range can be detected, even if the interfering signal (f1) is increased to a level just below ADC clipping of the SDR (-1 dBFS). Here, the level of the small, close-in payload signal does not decrease; it remains constant at -121 dBm (Fig. 7).

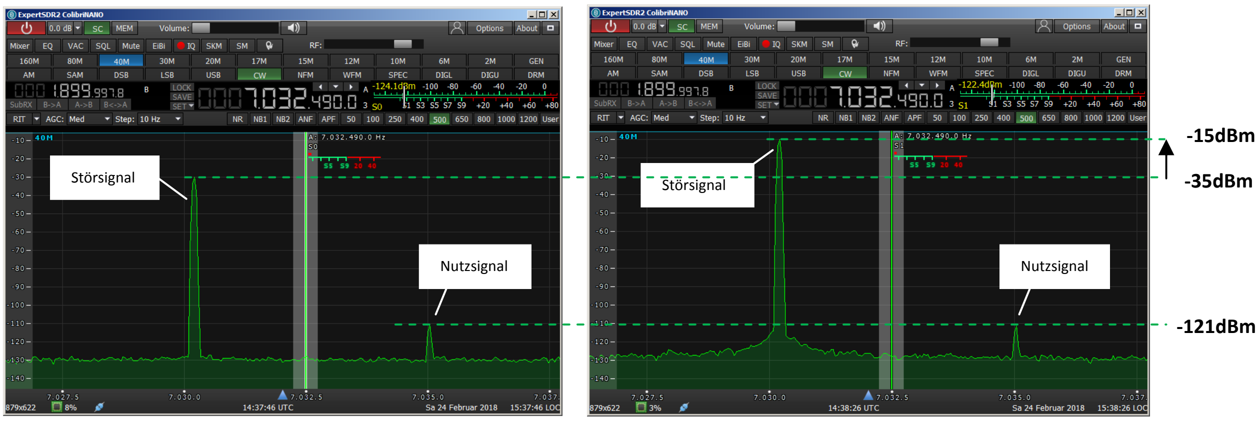

Figure 7: A direct-sampling receiver shows no blocking effect right up to its input power limit.

For this reason, in data sheets of direct-sampling receivers, such as IC-7610, IC-705 IC-7300, ANAN-7000, FlexRadio-6400, etc., you will not find any information about a "Blocking Dynamic Range".

Intermodulation 3rd order (IMD3)

Since the intermodulation behavior of analog and direct-sampling receivers is so different, I describe both measurement methods and their results separately.

Intermodulation in analog receivers

To determine the IMD3 strength of an analog receiver, a 2-tone HF test signal is used as standard (Fig. 8). Two RF signals of equal amplitude, which are close in frequency to each other, are applied to the input of the receiver and their levels are increased until the unwanted IMD3 interference at 2(f1-f2) and 2(f2-f1) reaches the noise floor of the receiver with (S+N)/N = 3dB. The difference between input level (Pi) and the noise floor (MDS) then gives the maximum IMD3-free dynamic range (DR3, Dynamic Range 3rd Order) of the receiver.

DR3 max = Pi max - MDS = -25 dBm - 130 dBm/500 Hz = 105dB

This value of e.g. 105dB is given by the manufacturers as "Dynamic Range" or "3rd IMD3" in the data sheet of the analog receiver, usually already on the first page (see figure 2).

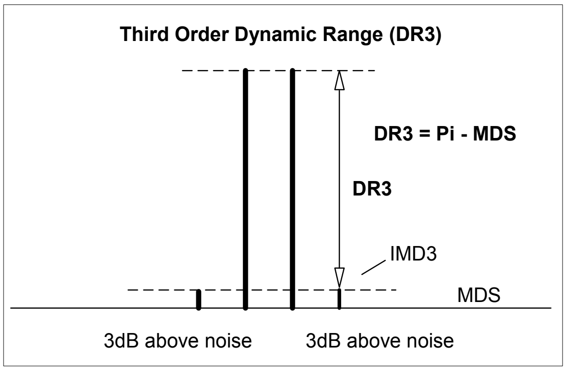

Figure 8: Measurement of intermodulation with a 2-tone signal

The intermodulation curve of an analog receiver is shown in Fig. 9, over a level range from -130 to +30 dBm. The x-axis shows the 2-tone signal power and on the y-axis the IMD3 product amplitude. The maximum dynamic range of the receiver occurs when the IMD3 reaches the noise floor of the receiver (red dot), at Pi=-25 dBm and is calculated at this point as DR3 = Pi - MDS = 105dB. If you increase or decrease the gain, the receiver loses dynamic range in both cases. I mention this so explicitly because direct-sampling receivers behave in a completely different manner here, as will be shown.

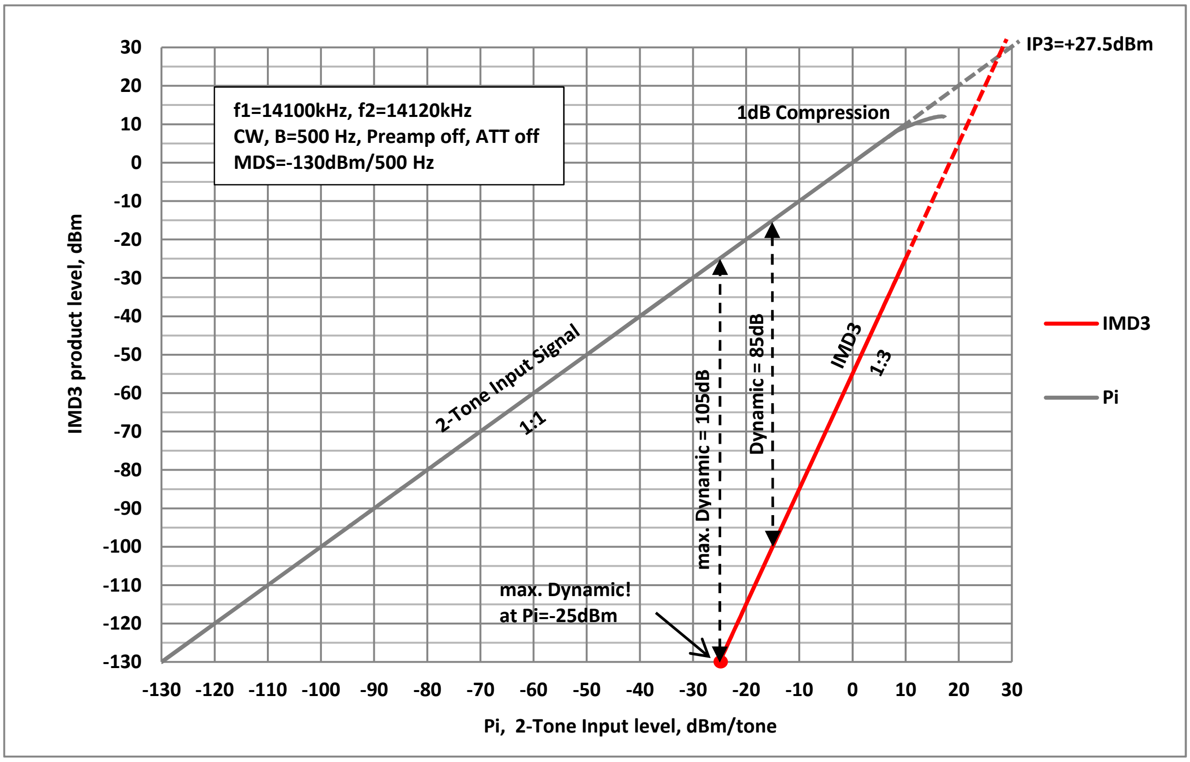

Fig. 9: IMD3 curve of an analog receiver.

For example, if the signal is increased by 10dB, the intermodulation products increase by 30dB, from -130 dBm to -100 dBm and the dynamic range decreases by 20dB from 105dB to 85dB. Accordingly, the IM3 products grow three times as fast as the input signals and theoretically meet at an intercept point called the "3rd Order Intercept-Point " (IP3). If an IP3 is achieved, as in the example of +27.5 dBm, this is a very good value and the user knows that he has a receiver with fairly large signal immunity.

Because Pi and IMD3 are in a fixed ratio of 1:3 to each other, the most important characteristics of the receiver can be calculated from this, such as

- IP3 = DR3/2 + Pi = 107dB/2 - 23 dBm = +27,5 dBm
- Pimax = 1/3 x (2 x IP3 + MDS) = 1/3 (55 - 130) = -25 dBm
- DR3max = Pi - MDS = -25 dBm - (-130 dBm) = 105dB
- MDS = 3xPi -2xIP3 = -75 dBm -55 dBm = -130 dBm

A signal limitation occurs relatively late and slowly, at perhaps +10 dBm. Before that, the receiver already generates strong intermodulation, but is still usable until shortly before its limitation. If there are bandpass filters and/or preamplifiers before the 1st mixer, these can negatively influence the IMD3 course, which must be considered.

Note on the 2-tone generator: Similar to the RMDR and BDR measurement, the SBN of both generators must be very small, so that IMD3 signals with only 3dB above noise are not covered by the SBN of the generators. At 20 kHz spacing the SBN often does not matter yet, but at 2 kHz it does. Furthermore, the intrinsic IMD3 of the 2-tone generator must be no worse than -110 dBc (for example, at a -20 dBm/tone, the intrinsic IMD3 product amplitude must not exceed -130 dBm). If the intrinsic IMD product level is excessive, there is a risk that we are measuring the IMD of the test signal source rather than that of the DUT, thereby corrupting the measurements.

Intermodulation in direct-sampling receivers

The IMD3 of a direct-sampling SDR receiver differs completely from that of an analog receiver. A 2-tone signal is also used for testing. An ideal ADC at the input of a receiver theoretically generates no intermodulation at all up to its saturation. In fact, however, a “real-world” ADC does generate intermodulation, which can be more or less severe due to its quantization errors. Figure 10 shows the different IMD3 curves of three direct-sampling receivers, the IC-705 (red), IC-7300 (blue) and ColibriNANO (green), together with the IMD3 curve of an analog receiver, on a common chart.

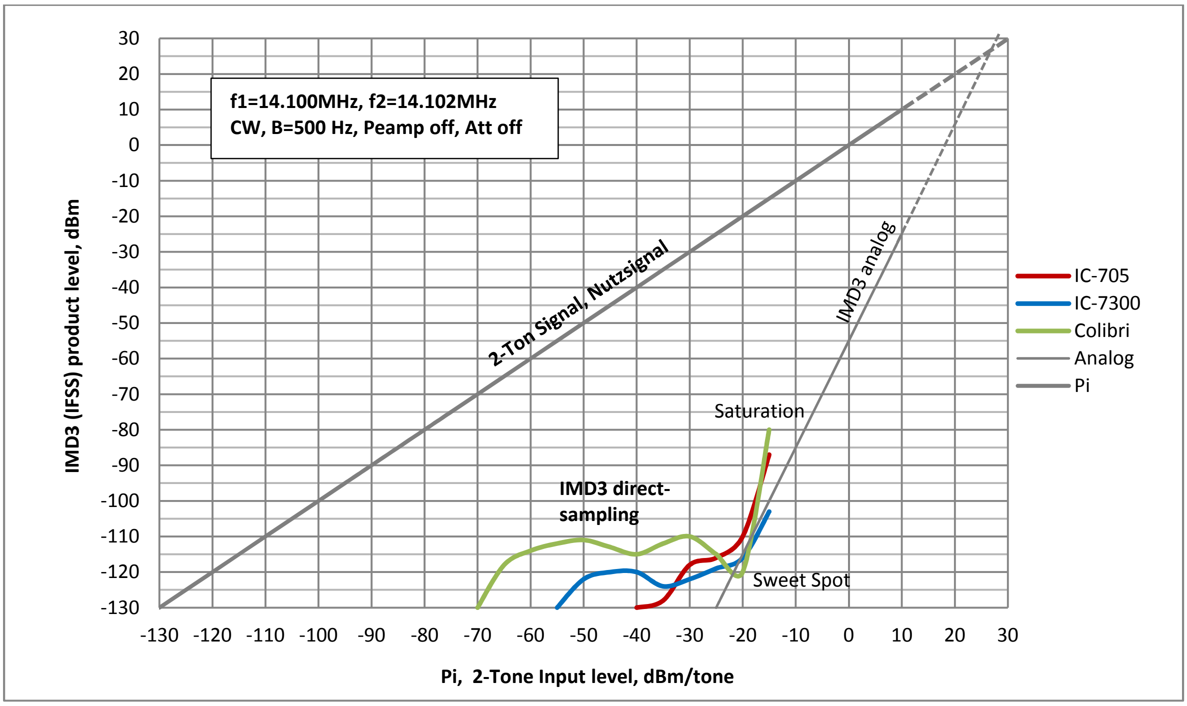

Fig. 10: IMD3 curve of direct-sampling receivers (green, red, blue).

First of all, it can be seen that in a direct-sampling receiver the first IMD3 products above the noise floor appear relatively early, at -70 dBm (ColibriNANO), -55 dBm (IC-7300) and -40 dBm (IC-705). If the input power is increased further, the IMD3 curves do not increase by a factor of 1:3, but are relatively flat and wavy in form until they are limited (clipped) at approx. -20 dBm.

Since the IMD3 curves obviously no longer follow any law, legacy calculations (e.g. maximum distortion-free dynamic range or maximum input power for highest dynamic range) are invalid. IP3 also becomes meaningless, as the transfer and IMD lines never converge, but diverge indefinitely.

In contrast to analog receivers, direct-sampling receivers achieve the greatest dynamic range only at their maximum input level, in the “sweet spot” shortly before ADC clipping (-1 dBFS, or 1 dB below full scale). For quality assessment of direct-sampling receivers, the following applies: The later the first IMD3 product appears in the receiver noise, and the deeper and flatter the IMD3 curve as it approaches clipping, the better the receiver!

For clarification, Figure 11 shows the dynamic range curve of the IC-7300, but now with a higher resolution. I calculated the dynamic range along the IMD3 curve in 10dB intervals (DR3=Pi-IMD3) and added red numbers. Only now can we clearly see to what extent the dynamic range of the IC-7300 increases with increasing level, starting at 74 dB with the first IMD3 product with 3 dB above the noise, increasing to 94dB shortly before clipping.

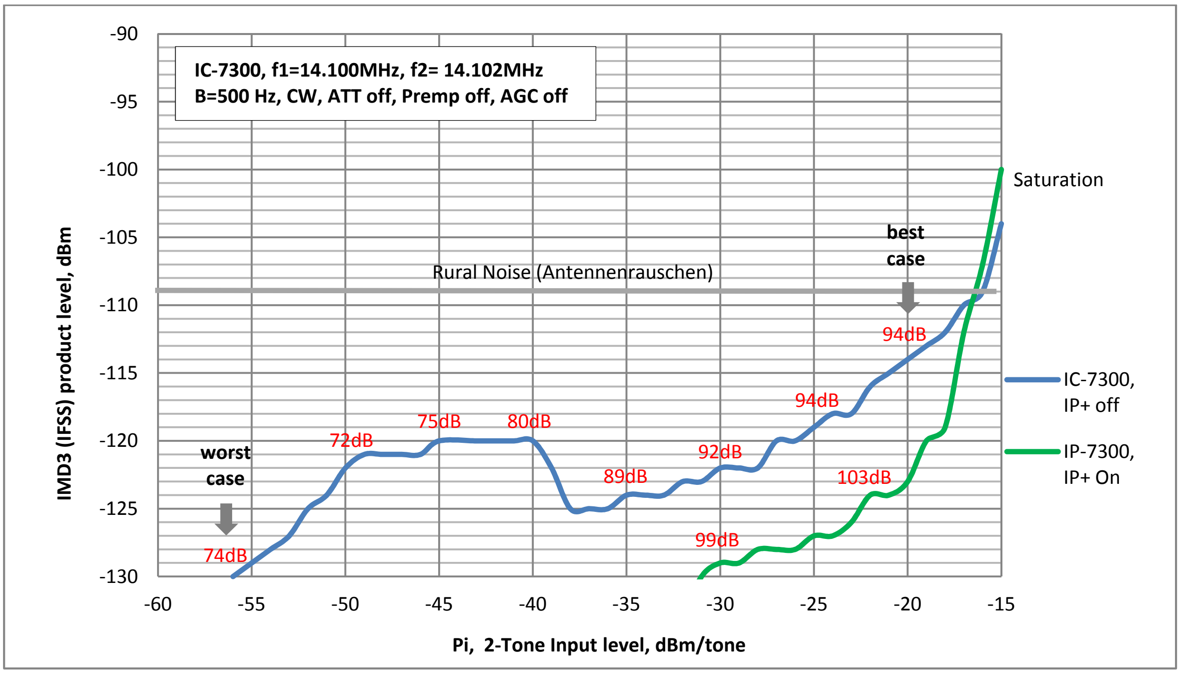

Figure 11: Intermodulation curve of the IC-7300

If the "dither function" (IP+) of the IC-7300 is activated (green curve), almost all IMD3 interference products are suppressed and the distortion-free dynamic range is now up to 103 dB. Adding white

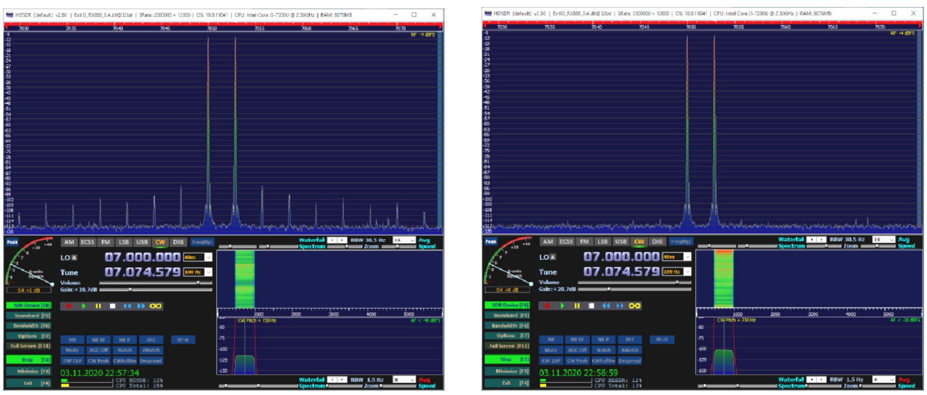

Figure 12: 2-tone signal without (left) and with dither (IP+) (right)

noise to the input of the A/D converter "blurs" its quantization errors and the dynamic range results become like those of the large signal handling capability of analog receivers (Fig. 12).

What "dynamic range" should now be stated in a test report? 74dB, 72dB, 75dB, 80dB, 89dB, 92dB or 94/103dB? Nothing of the sort! As clearly shown in Figure 11, the dynamics of direct-sampling receivers - in contrast to analog receivers - cannot be named with a single "dB value". Possibly one could specify the "worst case" of 74dB or the "best case" of 94dB/103dB or any value in between, but that would confuse more than help. Result: A fixed dynamic range, as with analog receivers, does not exist. For this reason the data sheets of direct-sampling receivers like IC-7300, IC-705, Perseus, ANAN7000 and FlexRadio6600 do not present any information about a "dynamic range" or "DR3"; Only RMDR is stated, and that not in every case. When evaluating a direct-sampling receiver, only a careful study of the IFSS curve will yield a true picture of the ADC’s IMD behavior.

The only way to convey the large signal strength of direct-sampling receivers is to publish their IFSS (Interference-Free Signal Strength curves (Figure 11), as Adam Farson has been doing for years in his "Receiver Test Reports" (https://www.ab4oj.com/test/reports.html).

Another way to classify the dynamics of receivers is the NPR (Noise Power Ratio) method, where instead of two sinusoidal signals, a white noise band is fed into the receiver and a notch filter is used to determine the maximum output level of the receiver. This method can be used with all receivers, whether analog, hybrid or direct-sampling. In principle, this would be the only procedure that could be used to create a realistic receiver comparison list with regard to dynamics. However, the NPR test procedure is technically complex and requires specialized test equipment, so that it will very probably not become established (https://www.ab4oj.com/test/docs/npr_test.pdf).

The main differences summarized

	analog receiver	**direct-sampling receiver**
IP3	yes	no
IP2	yes	yes
BDR	yes	no
RMDR/SBN	yes	yes
Fixed dynamic range	yes	no
Highest Dynamic Range	with small signals	with large signals
Improvement of the dynamics	with higher LO-Signal power and better mixer	with higher-resolution ADC (14 or 16 Bit) with on-chip Dither & Randomization
Saturation, Compression	slowly, at -1dB compression	very fast, at > 0dBFS (clipping)
best RMDR	with lower LO phase noise	with low-jitter clock source

Table 1: Comparison of important properties of analog and direct-sampling receivers

Faulty measurements

As shown in Table 1, analog and direct-sampling receivers cannot be directly compared with in all cases. For direct-sampling receivers, for example, there is no IP3 and no fixed dynamic range. The dynamic range of a direct-sampling receiver increases or decreases with each dB of change in input level and therefore - in contrast to analog receivers - cannot be designated by a single value in dB (see Figs. 10 and 11). If these differences are not taken into account, measurement errors will occur. An example is the "Receiver Comparison List" (http://www.sherweng.com/table.html) by Rob Sherwood. In this list direct-sampling receivers like IC-7300, IC-705, FlexRadio7400 etc. are all declared with a fixed "Dynamic Range", which is not tenable. This works only with analog receivers

(Fig. 9), where its specifications are also correct.
If you want to compare analog and direct-sampling receivers in a list, there should be no dB value at all for direct-sampling receivers, like the IC-705 in Figure 13. Conclusion: The dynamic range values of direct-sampling receivers (direct sampling SDRs) in the list are not relevant and should in no case be compared with the results of other receivers - especially analog receivers.


Receiver Test Data
Nicht sicher | sherweng.com/table.html

Updated 3/21/17 FlexRadio Systems 6300 Second Sample Preamp Updated	-117 -136[b2]	3.0 1.0[b2]	Var	125 preamp Off	2.1 0.23[b2]	143 148	10 50	D High & Low Pass	110	89	20&2	89[ai]	20&2
Added 11/07/20 Icom IC-705 S/N 12003232	-127 -137[b] -139[b1]	4.2 1.50[b] 0.87[b1]	3	122	0.67 0.20[b] 0.16[10]	138 142	10 50	C 0.8 Octave	100	89	20	88	2
Added 12/30/10 Kenwood TS-590S on 20 meters Down-conversion Mode For Up-Converson see Narrow Spaced at 76 dB	-128 -137[b]	1.8 0.5[b]	3	144[s]	0.43 0.15[b]	140	10	B Band Pass	92[f]	104	20	88[f]	2
Device Under Test	**Noise Floor (dBm)**	**AGC Thrshld (uV)**	**dB**	**100kHz Blocking (dB)**	**Sensitivity (uV)**	**LO Noise Spacing (dBc/Hz)**	**kHz**	**Front End Selectivity**	**Filter Ultimate (dB)**	**Dynamic Range Wide Spaced (dB)**	**kHz**	**Dynamic Range Narrow Spaced (dB)**	**kHz**
Added 02/26/11	-112to-116 -120to-	3.1			2.8								

Figure 13: Excerpt from the receiver comparison list by Rob Sherwood. The direct-sampling IC-705 is named with a fixed dynamic range of 88/89dB.

Figure 14 shows the rising and falling IMD product amplitude (from which DR3 can derive over 75 - 98dB range) of the IC-705. Unlike the case of an analog receiver, classic fixed single-point DR3 figure cannot be specified.

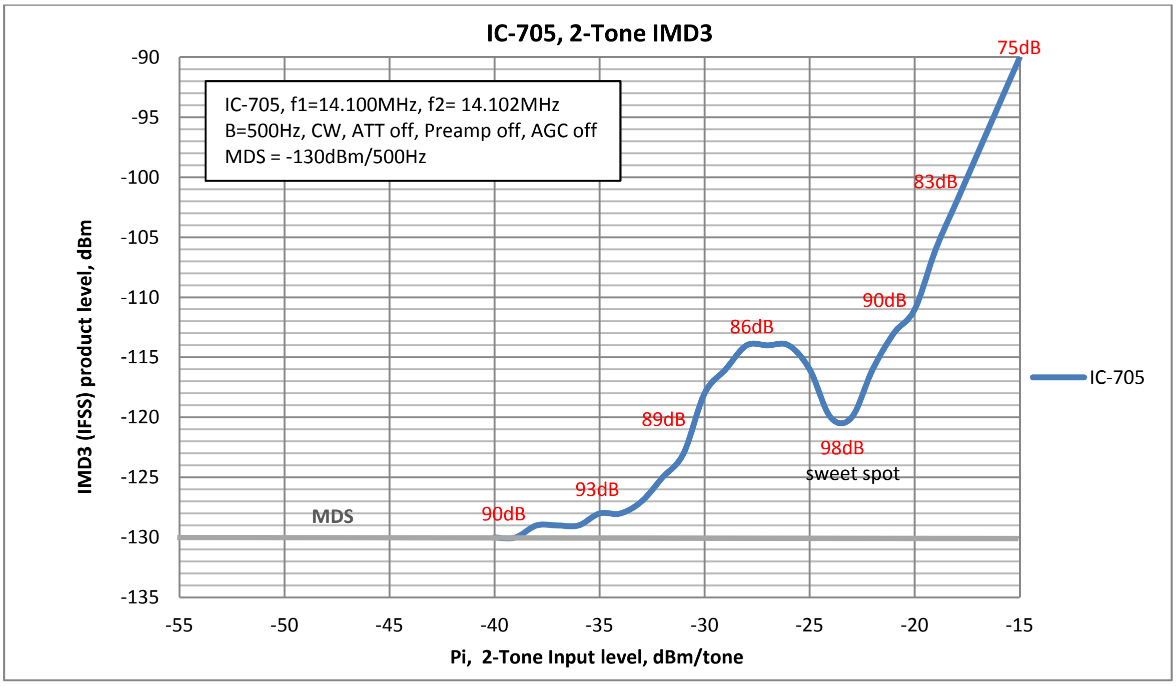

Figure 14: IFSS (Interference-Free Signal Strength) curve for the IC-705, showing a "DR3 maximum" of 98 dB at the "sweet spot".

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