# Comparing the dynamic ranges of spectrum analyzers and radio receivers—Part 1

Whether part of your instrument pool or a new acquisition, one of the main criteria by which spectrum analyzers and radio receivers are judged is their dynamic range. It plays a significant role, both in deciding what to purchase and in making error-free measurements. This Technical Note explains dynamic range for beginners and advanced users and tells you what you need to bear in mind when making comparisons.

***Figure 1: Narda SignalShark***

## Contents



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# 1 What is dynamic range?

## 1.1 Unwanted artifacts: harmonics, intermodulation, and interference lines

The following problem is not uncommon when tracking down mobile communications interference in urban areas: Reception of the interference you are looking for is very weak, so the measuring device you are using is set to high sensitivity—low reference level, low input attenuation, preamplifier on, narrow resolution bandwidth. You are trying to push the noise floor of the measuring device down far enough so that the interference is sufficiently visible. The disadvantage is that the higher sensitivity means lower immunity to stronger radio signals. Lower immunity in this context means that the instrument will be overmodulated and may as a result produce unwanted artifacts.

***An example of high system modulation and "pseudo signals"***

Let's assume that we are searching for mobile communications interference in the 1800 MHz band. Our measuring device is set to this range as shown in Figure 2 (span setting 4) and is operating at very high sensitivity. The noise floor is thus very low, but the immunity is also low.

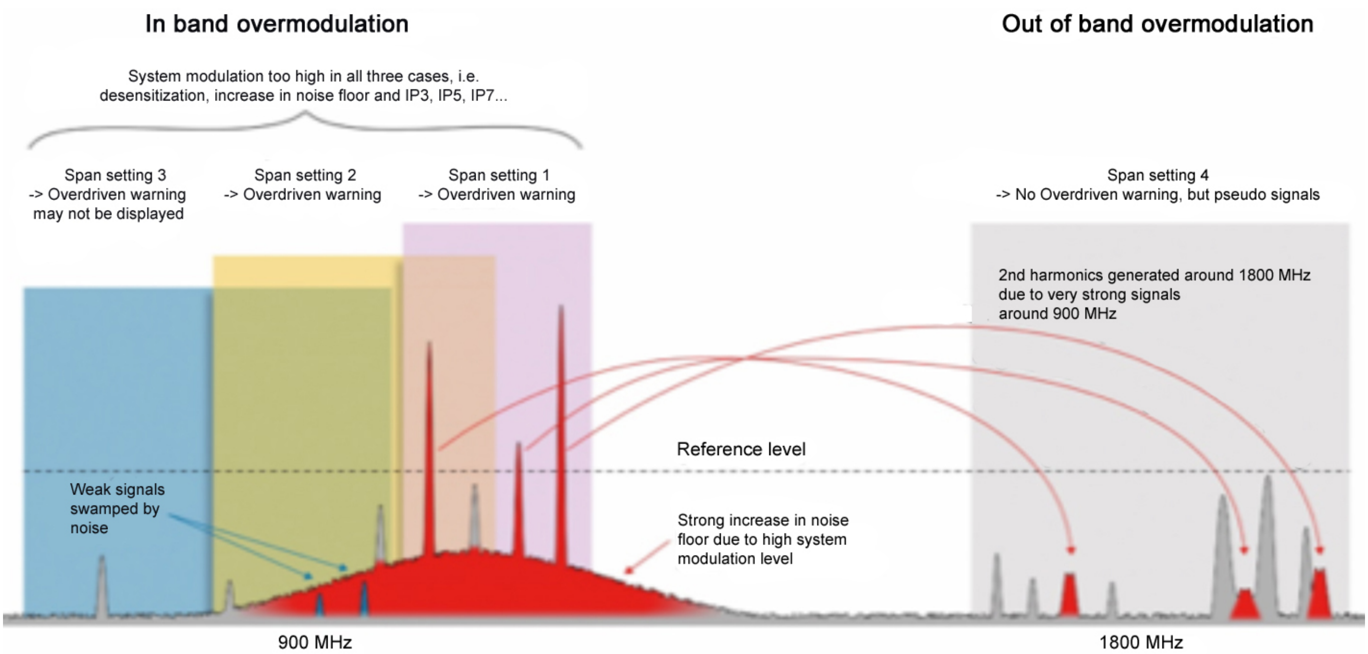


***Figure 2: Out of band overmodulation (2nd order harmonics) at 1800 MHz caused by strong RF signals at 900 MHz***

At the same time, very strong RF signals around 900 MHz are also received. These signals can overmodulate the instrument to the extent that unwanted artifacts occur—second order harmonics in this particular case.

The second order harmonic distortion (SHD) occurs at double the original signal frequency. As respects its modulation characteristics, it behaves exactly the same as the original signal, but has double the bandwidth. When viewed as a spectrum or spectrogram, it appears very similar to real signals. So, it can be easily confused with interference, or illegal or faulty transmitters on the radio network, although it is in reality the result of overmodulation of the measuring device. The aim is to reduce the risk of this happening.

### *A brief definition of dynamic range*

The scenario described here is a classic problem associated with RF signal reception that is governed by the dynamic range of the spectrum analyzer or receiver.

Put simply, the dynamic range is a relative measure of the signal intensity that can be handled by a measuring device before unwanted artifacts emerge from the noise. As a rule, the greater this difference or the smaller the level of the artifacts, the better, since the risk of confusing the artifacts with real signals becomes less likely.

It is one thing to appreciate that a large dynamic range is advantageous. But it is more important to understand that the dynamic range can change depending on the measurement settings of the device. It can assume entirely different values, depending on the reference points on which it is based. To make things clear from the outset, we need to distinguish between the following aspects of dynamic range:

- In a very general sense, the term “dynamic range” is a synonym for the level difference between signals, whether wanted or unwanted, real or unreal. Section 1.2 also often uses this interpretation.

- Among other things, the dynamic range is of interest as a measuring device specification. This is the level difference between one or more signals and the noise floor just before any unwanted artifacts appear. This is more properly described by the terms “intermodulation free dynamic range” (IMFDR) and “spurious free dynamic range” (SFDR). Unwanted artifacts in the form of intermodulation and the noise power play a part in determining the IMFDR. The second order intercept point (SOI) and third order intercept point (TOI) and the noise figure (NF) parameters are therefore closely associated with the IMFDR.

It is a good idea to take a very systematic approach to “dynamic range” in its various manifestations. We will therefore firstly take a look at the various types of unwanted artifact, i.e. harmonics and intermodulation, as well as spurious signals. These are illustrated in Figure 3 at the end of this subsection 1.1.
Subsection 1.2 describes the level behavior of harmonics and intermodulation, and explains the parameters SOI, TOI, SHI, and THI. Finally, subsection 1.3 takes a look at noise, which is the second most important factor that must be considered when dynamic range is involved.

### *N^th order harmonics*

We have already considered 2nd order harmonics in Figure 2. In that scenario, the signals at 900 MHz were so strong that they provoked copies of themselves at twice the frequency and with twice the bandwidth. 2nd and higher order harmonics occur particularly when active RF components such as amplifiers and mixers are driven beyond their linear operating range into their nonlinear range. As the input power level (to be amplified) increases further, the output power hardly changes at all. The RF module is saturated and produces a distorted, impure output signal.

As well as the 2nd order harmonics, higher order harmonics are also produced by the nonlinear response. These are whole number multiples (3rd, 4th, 5th, etc.). When considering dynamic range, it is not only of interest to know at which frequencies these $n^{th}$ order harmonics occur, but also to understand their level behavior. This aspect is covered specifically in section 1.2.

### *N^th order intermodulation*

The formation of intermodulation products has a similar background to that of 2nd and higher order harmonics, i.e. it occurs when RF modules are operated in a nonlinear range. Intermodulation is not just about multiples of individual frequencies, but also about frequencies formed from at least two signals. These signals mix together and generate completely different frequencies as described by the following formulas:

Second order intermodulation:

$$f_1 + f_2$$
$$f_2 - f_1$$

Third order intermodulation:

$$2 \cdot f_1 + f_2$$
$$2 \cdot f_2 + f_1$$
$$2 \cdot f_1 - f_2$$
$$2 \cdot f_2 - f_1$$

Section 1.2 discusses the level behavior of $n^{th}$ order intermodulation products in detail.

Harmonics and intermodulation are among the most important “unwanted artifacts”. However, with the increasing use of digital technology, particularly in modern analyzer / receiver designs, it is now the case that other artifacts occur, which are commonly referred to as spurious signals. There are two types of spurious signal: input related (i.e. dependent on the signal input), and residual (i.e. signals that remain or are always present regardless of the input signal). Both types are described below.

### *Input related spurious signals*

As the name implies, the level of input related spurious signals depends on the signal causing it. If this is weaker, the spurious signal will also be weaker.

### *Residual spurious signals*

Residual spurious signals are interference lines that are always present, regardless of the input signal. These spurious signals usually only show up as peaks above the noise floor when the instrument is set to very high sensitivity. Just like input related spurious signals, residual spurious signals appear as infinitely narrow lines in the spectrum.

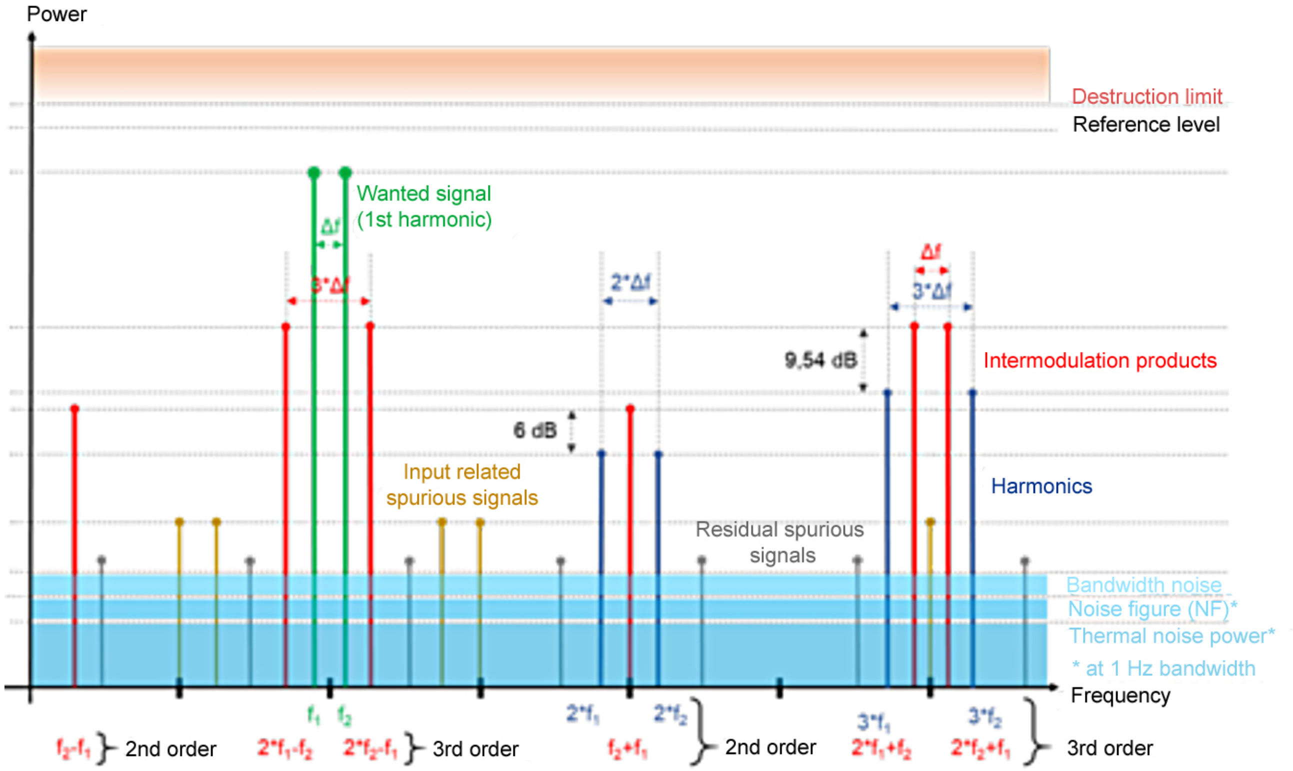


***Figure 3: Illustration of harmonics, intermodulation, input related spurious and residual spurious signals***

It is important to remember that higher order harmonics, intermodulation, and input related spurious signals can all occur at high system drive levels, not just when the system is overmodulated. The lower the reference level and input attenuation of a receiver system, the higher the probability that such artifacts will appear, and the higher the system sensitivity or the probability that weak signals will be captured.

Based on the previous explanations, Figure 3 illustrates an example of the occurrence of harmonics, intermodulation, and spurious signals to conclude this subsection. Section 1.2 takes a closer look at the interpretation of the levels of harmonics and intermodulation, and section 1.3 discusses the second important factor that determines the maximum dynamic range, the noise power.

## 1.2 Level behavior of harmonics and intermodulation and calculation of IP2/SOI, IP3/TOI, SHI, and THI

While the focus of section 1.1 was on understanding which artifacts can be formed in spectrum analyzers and RF receivers, this section concentrates on the interpretation of the levels of harmonics and intermodulation. The terms:

- IP2/SOI (second order intercept point based on intermodulation products),
- IP3/TOI (third order intercept point based on intermodulation products),
- SHI (second order intercept point based on harmonics) and
- THI (third order intercept point based on harmonics)

play an important part here and provide the lead in to section 1.3 where the intermodulation free dynamic range will be addressed specifically. The level behavior of input related spurious and residual spurious signals is not discussed further here.

The two wanted signals are shown in green in figure 3. The already mentioned unwanted artifacts are shown to the left and right of these signals along the frequency axis. If we now look at the dynamic range, that is the level difference between the wanted signals and the artifacts, we need to ask: "Which dynamic range?", since the level differences between the wanted signal and the 2$^{nd}$ / 3$^{rd}$ harmonics / intermodulation are all different. Normally it is the smallest difference or worst dynamic range that is quoted. This would be the range between the wanted and the 3$^{rd}$ order intermodulation product in figure 3. Nevertheless, it is useful to look at this in more detail because the dynamic range is variable, as already mentioned.

Based on figure 3, in each of the following illustrations two wanted signals with a specific level are defined, from which the generated harmonics and second and third order intermodulation products are determined. Both the wanted signals initially have a level of -20 dBm (figure 4). We are assuming that the measuring instrument is of acceptable quality, where the generated 2nd order intermodulation lies at -80 dBm and the 3rd order intermodulation at -110 dBm. From this, the levels of the 2nd and 3rd order harmonics are also established, since figure 3 already shows that the level difference between the harmonic and the second order intermodulation is always +6 dB, while the level difference between the harmonic and the third order intermodulation is always +9.54 dB (the mathematical proof of these relationships will not be discussed here). The 2nd order harmonics in figure 4 are therefore at -86 dBm and the 3rd order harmonics are at -119.54 dBm. Let us also assume that our measuring device is using an input attenuation (Att) of 10 dB, while the reference level (RL) is set to 0 dBm. On this basis, the assumed noise floor (shown in orange) falls to -140 dBm.

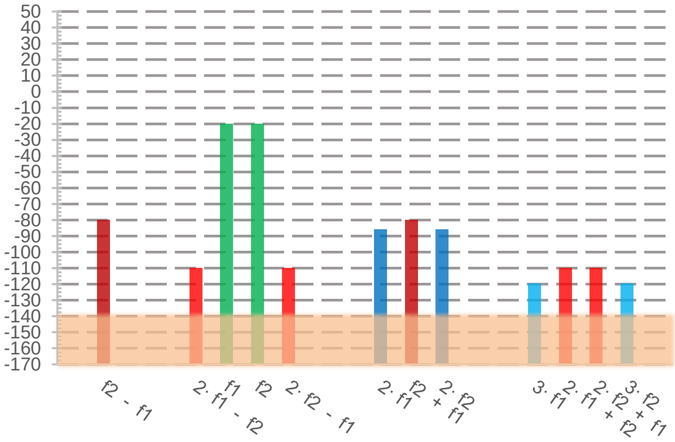


*Figure 4: Initial situation, signal -20 dBm, Att 10 dB, RL 0 dBm*

In our initial situation, then, the smallest dynamic range is 60 dB and refers to the level difference between the wanted signal and the 2nd order intermodulation. The dynamic range referred to the 2nd order harmonics is 66 dB, and it is 90 dB referred to the 3rd order intermodulation. Based on this initial situation, we will now develop new dynamic range scenarios by assuming different signal levels or system settings (input attenuation / reference level / RBW).

***When the wanted signal changes, 2nd order artifacts change by a factor of two and 3rd order artifacts by a factor of three***

Compared to figure 4, the wanted signal levels in figure 5 are increased by 10 dB to reach a level of -10 dBm. The system settings remain unchanged. It is very important to remember how this increase of 10 dB in the wanted signal affects the harmonics and intermodulation: The harmonics and the 2nd order intermodulation increase by 20 dB, i.e. twice the dB magnitude of the increase in the wanted signal. The 3rd order harmonics and

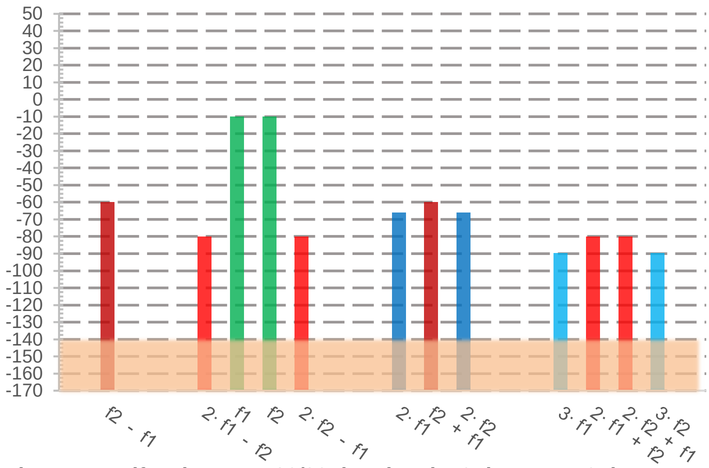


*Figure 5: Artifact increase 20/30 dB, signal -10 dBm, Att 10 dB, RL 0 dBm*

intermodulation increase by 30 dB, i.e. 3 times the dB magnitude. The dynamic relationships are now completely different: The smallest dynamic range is still the difference between the wanted signal and the 2nd order intermodulation, but it is now only 50 dB. The equivalent dynamic range referred to the harmonics is greater by 6 dB. The dynamic range for 3rd order intermodulation is now just 70 dB. Thus figure 5 shows a poorer dynamic range for our measuring device simply because the input signal is 10 dB stronger.

In figure 6, the two signals to the input of our imaginary receiver are further increased by 5 dB to -5 dBm. In total, they are now just below the reference level setting. The 2nd order harmonics and intermodulation products now increase by 10 dB and the 3rd order harmonics and intermodulation by 15 dB. The dynamic range is thus further degraded, since the 2nd order intermodulation is now only 45 dB below the wanted signal, and the 3rd order intermodulation is now only 60 dB below the wanted signal.

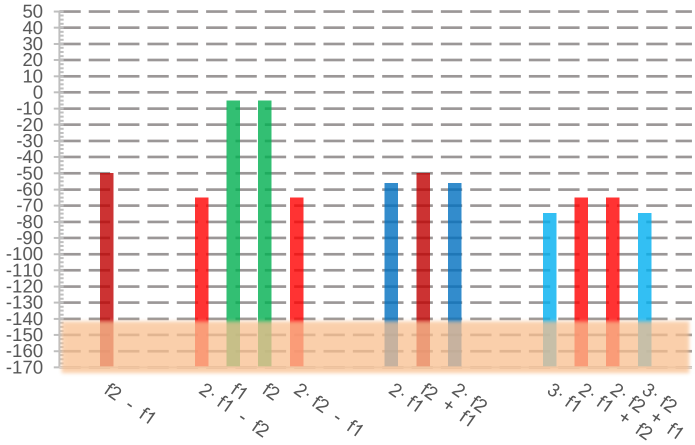


***Figure 6: Artifact increase 5/10 dB, signal -5 dBm, Att 10 dB, RL 0 dBm***

### *The "incorrect" IP3 / TOI*

Automatically, the question now arises: When will the unwanted artifacts reach the same level or even exceed the wanted signal level? It is still the case that an increase of 1 dB in the wanted signal will result in a 2 dB increase in the 2nd order artifacts, and 3 dB in the 3rd order artifacts. Starting from figure 6, we will first of all concentrate on the 3rd order intermodulation. This lies 60 dB below the wanted signal. To find the intercept point, i.e. where both "signals" are the same level, we can add exactly half the magnitude of the level difference to the wanted signal. So, we will add 30 dB to the wanted signal, bringing it up to +25 dBm. To correspond to this, 90 dB will be added to the 3rd order intermodulation so that this rises from -65 dBm to +25 dBm. The wanted signal and the intermodulation are thus both at +25 dBm. This situation is shown in figure 7, from which it is clear that the dynamic range between the wanted signal and the 3rd order intermodulation is exactly 0 dB. The dynamic range to the 3rd order harmonics is 9.54 dB, to the 2nd order intermodulation 15 dB, and to the 2nd order harmonics 21 dB.

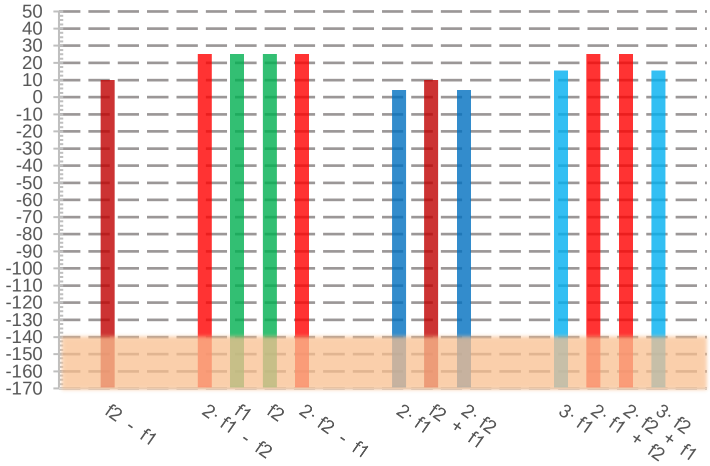


***Figure 7: "Incorrect" IP3, signal 25 dBm, Att 10 dB, RL 0 dBm***

We should, of course, at this point realize that the measuring device could already be operating in its destruction range when it is being driven by two signals each having a level of +25 dBm (totaling +28 dBm). This consideration is therefore more hypothetical than real, and should not be reproduced in practice with such high signal levels. It is nevertheless relevant. The intercept of the wanted signal and the 3rd order intermodulation is the so called IP3 or TOI value. The "intercept point of 3rd order intermodulation products" or "third order intermodulation intercept point" is at +25 dBm in figure 7, and specifies the theoretical level at which both the "signals" under consideration are equally high. Later in this article, we will make a similar consideration of the 3rd order harmonics and the 2nd order harmonics and intermodulation. Before that, though, we need to reconsider the system settings we have at the moment.

### *The effect of input attenuation on the dynamic range and the intercept points*

In all the dynamic range examples considered so far (figures 4 through 7), our measuring device was set to an input attenuation (Att) of 10 dB. In fact, this setting plays an extremely important role in our determination of the intercept points. In order to be able to compare the specifications given in data sheets correctly, it is necessary to check the system settings used to specify a particular dynamic range or intercept point. It is usual to specify the IP3 / TOI for an input attenuation of 0 dB. This section and figure 8 looks at this situation. Based on figure 7, the input attenuation of 10 dB is set to 0 dB and both the signal levels are reduced to +15 dB in figure 8. The fact that the noise power is reduced by 10 dB when the Att setting is reduced by 10 dB will be looked at in more detail in section 1.3, but it is shown correctly in figure 8.

#### *The "correct" IP3 / TOI*

The IP3 / TOI of our imaginary measuring device was determined as +25 dBm according to figure 7. Let us now determine the new IP3 / TOI in figure 8 by adjusting the wanted signals again until the levels are the same as the 3rd order intermodulation. A wanted signal of +15 dBm gives the same relationships between the levels as in figure 7.

Consequently, the IP3 / TOI of our measuring device is not +25 dBm, but +15 dBm. The fact that an input attenuation of 10 dB was used in figures 4 through 7 resulted in an increase of 10 dB in the IP3

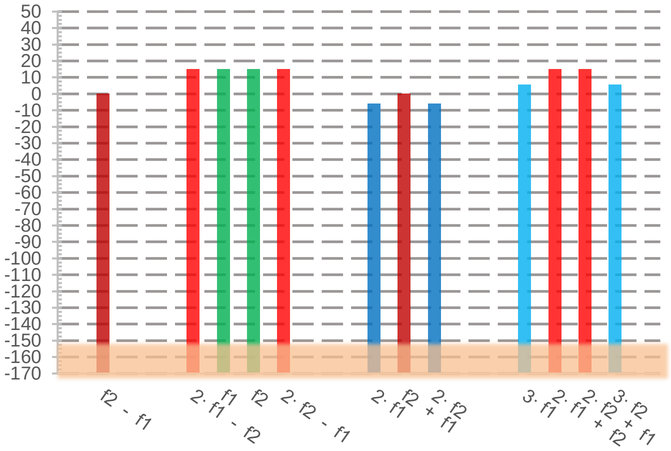


***Figure 8: "Correct" IP3, signal 15 dBm, Att 0 dB, RL -10 dBm***

value. We therefore need to stress at this point that all intercept points, regardless of whether they refer to 2nd / 3rd harmonics / intermodulation, are always dependent on the selected system settings. It is thus fundamentally important to pay attention to these parameters when comparing instruments.
Data sheets usually quote the intercept points on the basis of the highest system sensitivity, i.e. the lowest settings for input attenuation and reference level.

### *The THI*

Let us now determine all the other intercept points for our imaginary spectrum analyzer or receiver. First of all, we will look at the third order harmonic intercept point, or THI. In figure 8, the 3rd order harmonics lie at +5.46 dBm, i.e. 9.54 dB below the 3rd order intermodulation or the TOI (15 dBm). To find the intercept point between the 3rd order harmonics and the wanted signal, we add 4.77 dB to the TOI. The wanted signal rises to 19.77 dBm and the 3rd order harmonics rise by 14.31 dB to 19.77 dBm as well. This is illustrated in figure 9, which also shows that the 3rd order intermodulation is now higher. For this reason, the THI is less important than the IP3 / TOI in many cases.

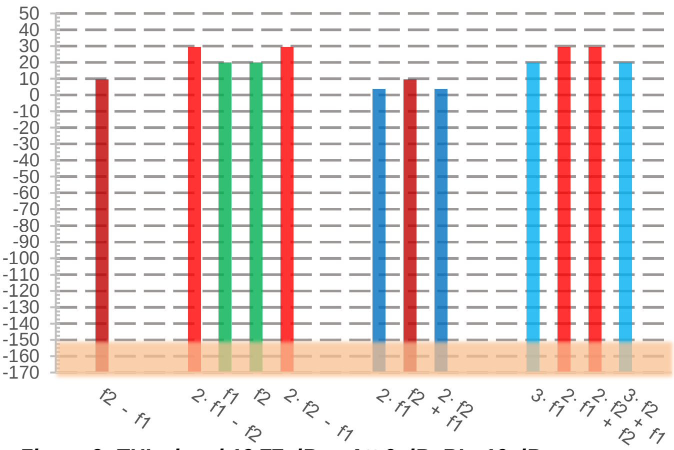


***Figure 9: THI, signal 19.77 dBm, Att 0 dB, RL -10 dBm***

### *The IP2 / SOI*

Let us now look at the 2nd order intermodulation products. These are found at 9.54 dBm in figure 9, accompanied by the 2nd order harmonics, which are 6 dB lower. The dynamic range between the wanted signal and the 2nd order intermodulation products is 19.77 dBm – 9.54 dBm = 10.23 dB. If we now increase our hypothetical wanted signal by exactly this amount, so that it has a new level of 30 dBm, the 2nd order artifacts will correspondingly increase by double this amount, i.e. by 20.46 dB. The 2nd order intermodulation products thus also rise to 30 dBm. This new dynamic situation is shown in figure 10 (the Y-axis scale has to be increased to a maximum of 80 dB here in order to be able to show all the other artifacts fully). The intercept point thus determined is

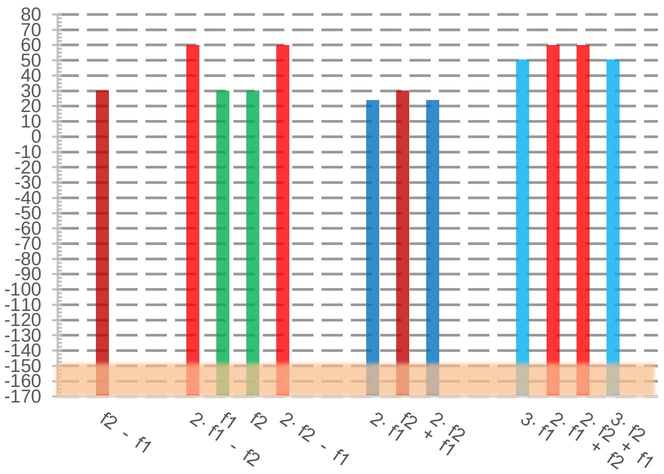


***Figure 10: IP2, signal 30 dBm, Att 0 dB, RL -10 dBm***

the IP2 or SOI, i.e. the intercept point of 2nd order intermodulation products, or the second order intermodulation intercept point. It is virtually obligatory to quote this figure along with the IP3 in device data sheets.

### *The SHI*

Finally, let us look at the 2nd harmonic intercept point, or SHI, to complete the determinations. From figure 10 we can see that our wanted signal intercepts the 2nd order intermodulation (IP2 / SOI) at 30 dBm. The 2nd order harmonics are 6 dB below this. To identify the SHI, we will increase the wanted signal by 6 dB to reach a value of 36 dBm. The 2nd order harmonics correspondingly increase by double this amount, i.e. by 12 dBm, also to 36 dBm (see figure 11).

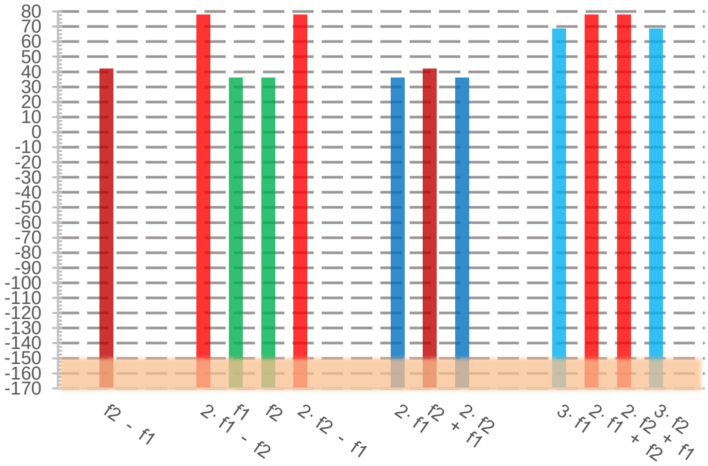


***Figure 11: SHI, signal 36 dBm, Att 0 dB, RL -10 dBm***

### *Single tone and dual tone scenarios*

The SHI may not appear to be particularly important in the scenario depicted in figure 11, since in our system the problems caused by stronger 2nd order intermodulation and 3rd order artifacts would occur before this point is reached. Nevertheless, the SHI is very important in the situation where the device is driven by a single tone. In the previously considered scenarios, we have assumed that two signals (or tones) have driven our device into saturation. Each of these two signals provoke both harmonics and intermodulation. If we now overmodulate our device with just one signal (tone) instead of two, there will be no intermodulation, but there will still be harmonics. Based on figure 11, the SHI is shown again in figure 12 with just one signal ($f_1$) present. The SHI and also the THI of a measuring device remain unchanged when driven by a single tone.

We should remember that precisely this scenario is of particular importance in measurement practice. It can happen, particularly when “interference hunting”, that a high sensitivity measurement is made at a particular frequency while a strong signal at half this frequency is causing harmonics to be generated in the measuring device. This particular situation was highlighted in figure 2 on page 2.

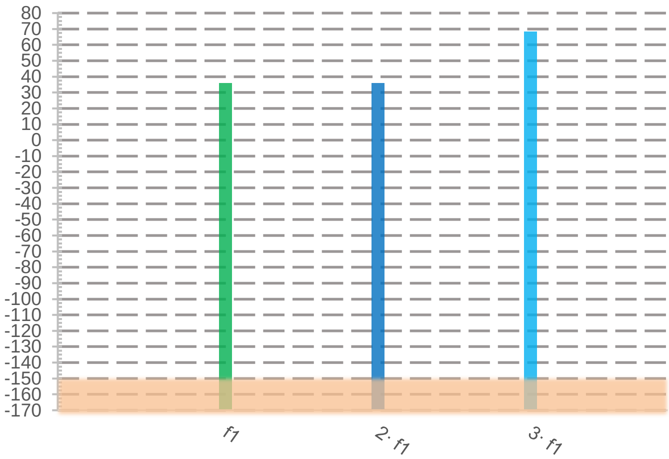


***Figure 12: Single tone SHI, signal 36 dBm, Att 0 dB, RL -10 dBm***

*Summary of intercept points*

We have now identified some but not all of the important dynamic range parameters of our imaginary measuring device. They are summarized in Table 1, which also reminds us that the intercept points for both the second and third order artifacts will change if input attenuation is active.

| Intercept point | | | Level | Reference |
|---|---|---|---|---|
| **IP3 / TOI** | for | Att = 10 dB | 25 dBm | Figure 7 |
| **IP3 / TOI** | for | Att = 0 dB | 15 dBm | Figure 8 |
| **THI** | for | Att = 0 dB | 19.77 dBm | Figure 9 |
| **IP2 / SOI** | for | Att = 0 dB | 30 dBm | Figure 10 |
| **SHI** | for | Att = 0 dB | 36 dBm | Figure 11 |

***Table 1: Intercept points of the imaginary device described in section 1.2***

Table 1 shows that IP2/SOI and SHI are exactly 6 dB apart. This concurs with the illustration in figure 3, which clearly shows that the 2nd order intermodulation and harmonics are always separated by 6 dB. It is different for IP3/TOI and THI (with Att = 0 dB): Figure 3 shows that the 3rd order intermodulation and harmonics are separated by 9.54 dB, but this is not the case with the 3rd order intercept points. These are separated by just half this amount, i.e. 4.77 dB.

At this point it should be quite clear that the development of the 2nd and 3rd order harmonics and intermodulation relative to the wanted signal is always governed by factors of two and three, respectively. It depends on the initial situation, the wanted signal level, and the system settings as to whether it is the 2nd or the 3rd order intermodulation that is higher for a particular measurement. A further important factor is that the dynamics between the wanted signals and the unwanted artifacts are also affected by the system settings (input attenuation and reference level). You should also now understand how we arrive at the parameters IP3/TOI, THI, IP2/SOI, and SHI, and that these parameters also change with the input attenuation. Additionally, these intercept points are one of two factors that are important in determining the intermodulation free dynamic range. We are reminded that the IMFDR of the system is what needs to be maximized, as mentioned in section 1.1. We will therefore look at the second of these two factors that determine the IMFDR, the noise power, in the next section, 1.3.

## 1.3 Intermodulation free dynamic range / dynamic range referred to noise

In the previous section, we looked at the dynamic range in the presence of harmonics and intermodulation. The level of the intrinsic noise floor was basically ignored. Not really a problem, since the generated artifacts were always well above this. In this subsection, we will reduce the wanted signals until the unwanted artifacts disappear below the noise floor. Along with this, we will see how the input attenuation as well as the reference level and the resolution bandwidth (RBW) affect the noise floor, so that we will be able to define the intermodulation free dynamic range or IMFDR.

Figure 13 basically shows the same dynamic scenario as figure 4. Our wanted signals were at -20 dBm, while the measuring device used an input attenuation of 10 dB. The noise floor in this situation was at -140 dBm. However, we did not specify the RBW in section 1.2 or figure 4. The RBW does have a considerable effect on the level of the noise floor, and hence also on the dynamic range. We will assume a setting of 20 Hz for the RBW from figure 14 onwards.

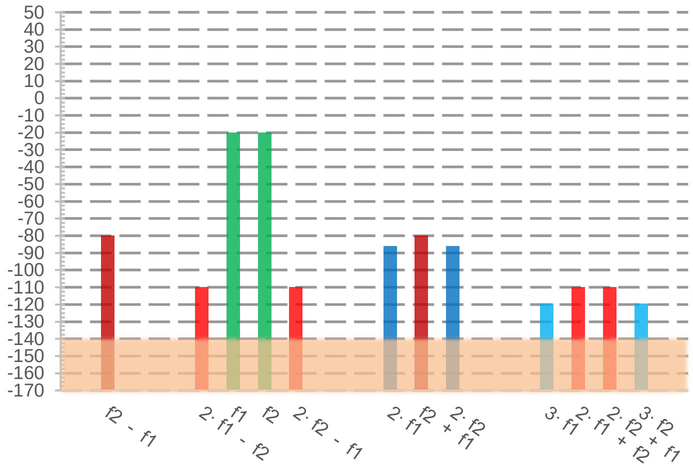


*Figure 13: Starting situation, signal -20 dBm, Att 10 dB, RL 0 dBm, RBW 20 Hz*

### *Reducing the input attenuation / reference level*

So that we can “measure” things correctly from the start, we will reduce the input attenuation from 10 dB (figure 13) to 0 dB. This gives the dynamic scenario shown in figure 14, where the Y-axis scaling has again been adjusted. The wanted signals here are still at -20 dBm, but the 2nd order artifacts have increased by 10 dB and the 3rd order artifacts by 20 dB. We already observed this effect when correctly determining the IP3 in section 1.2.

While the input attenuation is reduced by 10 dB, the noise floor also drops by 10 dB. In other words, the

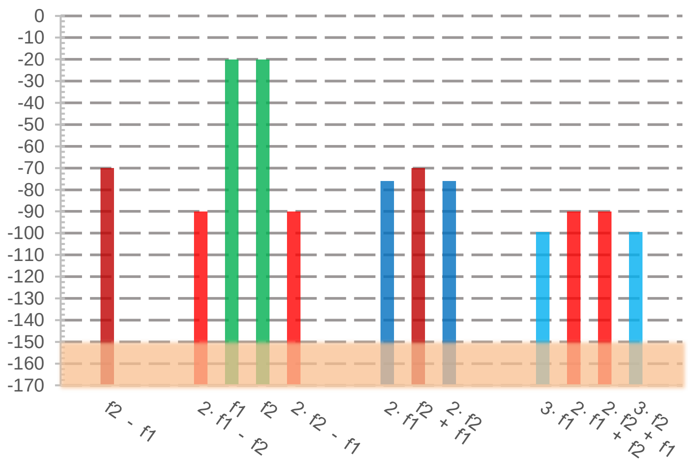


*Figure 14: After Att adjustment, signal -20 dBm, Att 0 dB, RL -10 dBm, RBW 20 Hz*

sensitivity of our system has increased. We will next reduce the wanted signal to the point where firstly the 3rd order artifacts disappear into the intrinsic noise floor. This happens at a wanted signal level of -40 dBm. The wanted signals have now been reduced by 20 dB, so the 3rd order artifacts must correspondingly drop by 60 dB. This is shown in figure 15. (We will continue to concentrate on the harmonics and intermodulation in this discussion and will for the moment ignore the possible effects of spurious signals that might reduce the dynamic range.)

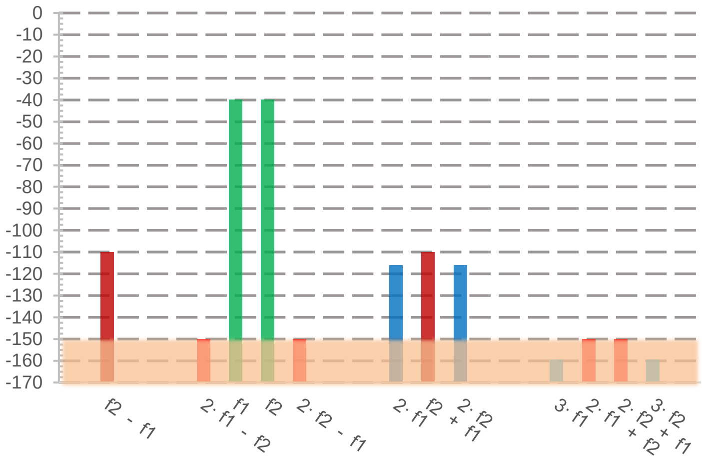


***Figure 15: No 3rd order artifacts, signal -40 dBm, Att 0 dB, RL -10 dBm, RBW 20 Hz***

In the next step, we will further reduce the wanted signal level until the 2nd order artifacts also disappear into the intrinsic noise floor. As shown in figure 16, this happens when the wanted signal level is -60 dBm. The wanted signal has been reduced by 20 dB, so the 2nd order harmonics are reduced by 40 dB to the level of the noise floor at -150 dBm.

Let us now look at the dynamic range of our hypothetical measuring device again. In figure 16, the dynamic range is 90 dB, which is given by the difference between the wanted signal level and the average noise power level.

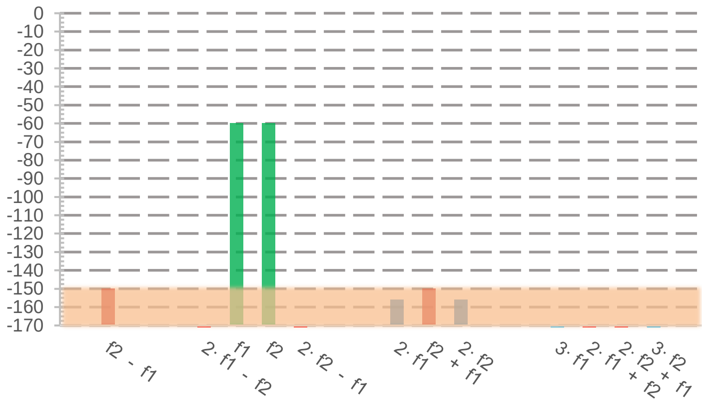


***Figure 16: No 2nd order artifacts, signal -60 dBm, Att 0 dB, RL -10 dBm, RBW 20 Hz***

### *Reducing the RBW*

We still need to be careful, though. At the start of this subsection, we stated that our system was currently still operating with an RBW of 20 Hz. Now, we do not want to determine some random dynamic range; rather, we are interested in finding out the dynamic range when our measuring device is at its most sensitive settings. We therefore have to reduce the RBW as far as possible. The typical minimum RBW setting for a spectrum analyzer is 1 Hz. A reduction in the RBW from 20 Hz to 1 Hz causes the noise floor to drop by 13 dB to -163 dBm. This situation is shown in figure 17, which also shows that the 2nd order harmonics and intermodulation have reappeared above the noise floor. So, before we can determine the dynamic range, we need to ensure that these artifacts are reduced to the extent that they again disappear below the noise floor by reducing the level of our wanted signals. This

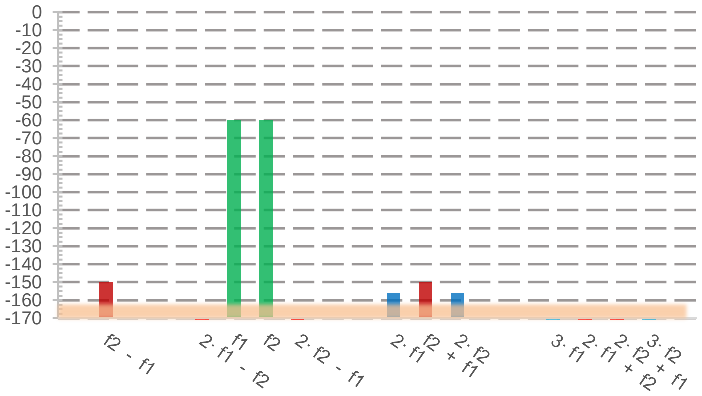


***Figure 17: RBW reduced to 1 Hz, signal -60 dBm, Att 0 dB, RL -10 dBm, RBW 1 Hz***

happens when the wanted signal is -66.5 dBm, i.e. when the level is reduced by 6.5 dB. The 2nd order intermodulation is then the same as the noise power level at -163 dBm, while the 2nd order harmonics are practically invisible at a level of -169 dBm.

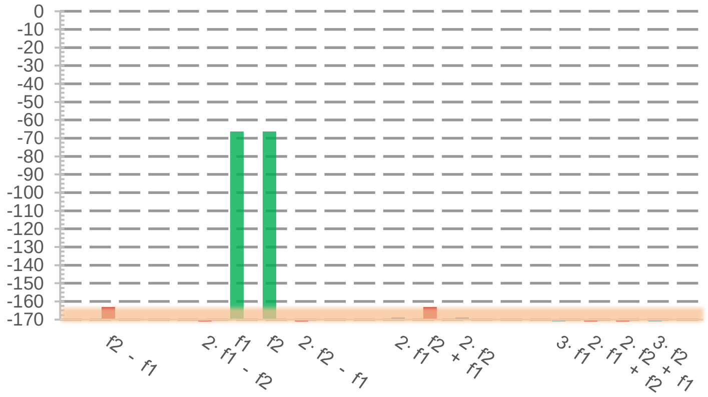


***Figure 18: No 2nd order artifacts, signal -66.5 dBm, Att 0 dB, RL -10 dBm, RBW 1 Hz***

### *Expressing the IMFDR$_{2/3}$*

Let us go back and look at the dynamic range again: The noise floor is at -163 dBm in figure 18, and the wanted signal is at -66.5 dBm. This gives us a dynamic range of 96.5 dB. Compared to the scenario depicted in figure 16, which is based on an RBW of 20 Hz instead of 1 Hz, the dynamic range has increased by a useful 6.5 dB.

We can now properly speak of this as the intermodulation free dynamic range (IMFDR). This is defined as the maximum dynamic range before 2nd or 3rd order intermodulation rises above the noise floor of a measuring device. Based on the 2nd order intermodulation products, the IMFDR$_2$ is 96.5 dB as already mentioned, and as shown in figure 18. Without going into detail, the IMFDR$_3$, which is based on the 3rd order intermodulation products, is 118.67 dB.

As an alternative, the two equations below can be used to calculate the intermodulation free dynamic range (2nd / 3rd).

***Equation 1:***

$$IMFDR_2 = \frac{1}{2}\,(IP2 - DANL)$$

***Equation 2:***

$$IMFDR_3 = \frac{2}{3}\,(IP3 - DANL)$$

All the parameters in equations 1 and 2 are stated in dBm. The noise power, i.e. the level of the noise floor, is referred to as the displayed average noise level, or DANL. The DANL is given by the RBW setting, the system sensitivity or noise figure (NF), and the thermal noise. We will look at this further later on.
Equations 1 and 2 thus again make it clear that the intermodulation free dynamic range is defined on the one hand by the intercept points IP2/SOI and IP3/TOI, and on the other hand by the noise power that is dependent on the RBW and the NF.

### *Expressing the $HFDR_{2/3}$*

Let us remind ourselves of the fact that our consideration thus far has been based on a dual tone scenario. This situation results in the formation of both intermodulation products and harmonics. In terms of levels, however, the harmonics are less than the corresponding intermodulation products. It was therefore sensible to talk about the IMFDR to be on the safe side, as this is always less than the dynamic range referred to the point where the harmonics are swamped by the noise floor.

If we now consider a single tone rather than the dual tone scenario, the IMFDR becomes meaningless because intermodulation does not occur in this situation. Nevertheless, the harmonics are still present, and these now become important in our consideration of the dynamic range.

From the previous sections we have seen that there is a specific relationship between the intermodulation and harmonics of the same order in two tone scenarios. The $2^{nd}$ order harmonics are always 6 dB below the $2^{nd}$ order intermodulation products, and the $3^{rd}$ order harmonics are 9.54 dB below the corresponding intermodulation products.

It is not too difficult to reimagine figure 18 as a single tone scenario. The wanted signal level was -66.5 dBm and the $2^{nd}$ order harmonic level was -169 dBm, while the noise power was -163 dBm. To achieve the best dynamic range between the wanted signal and the $2^{nd}$ order harmonics, we need to increase the wanted signal by 3 dB. The $2^{nd}$ order harmonics then rise by 6 dB to the same level as the noise floor. This results in a harmonic free dynamic range of 99.5 dB for the $2^{nd}$ harmonics. The term harmonic free dynamic range, or HFDR, is not commonly used; we use it here to make the terminology easier to understand.

Compared with the $IMFDR_2$ determined earlier, it is easy to see that the $HFDR_2$ is 3 dB higher. This is due to the 6 dB difference in level between the $2^{nd}$ order harmonics and intermodulation, as expected.

It is similar for the $HFDR_3$, which is always 3.18 dB more than the $IMFDR_3$. The difference of 3.18 dB is one third of 9.54 dB. Put simply, the $3^{rd}$ order harmonics and intermodulation products in a dual tone scenario are separated by 9.54 dB. Converting the dual tone $IMFDR_3$ to the single tone $HFDR_3$ involves raising the level of the harmonics by 9.54 dB so that they are at the same level as the intermodulation in the dual tone scenario. This is achieved by raising the level of the wanted signal by 3.18 dB.

### *The effect of the RBW on the noise power*

Let us come back from considering the HFDR to concentrate on the noise power of our hypothetical measuring device. The noise sets the lower limit of measurement for our system. Automatically, the lower the noise floor, the greater the dynamic range. This is demonstrated particularly by the development in dynamic range shown in figures 16 through 18, where we reduced the RBW from 20 Hz to 1 Hz and the noise floor correspondingly dropped by 13 dB. We then adjusted the wanted signal level until the biggest artifacts matched the noise floor again. A low noise floor is an advantage in achieving a high dynamic range. The noise floor (or DANL) depends on the RBW setting and on the system sensitivity. Table 2 initially examines only the effect of the RBW. We must, however, understand that the RBW always has a relative effect on the noise floor. We can state what the change in the noise floor will be for a given change in the RBW but cannot state the absolute noise power that will result from the change. Information about the system sensitivity is also required in order to make an absolute statement.

Table 2 uses a few examples to show the effect on the noise floor of raising the RBW.

| RBW | Level change, logarithmic [dB] | Level change, linear with respect to power |
|---|---|---|
| **1 Hz (starting point)** | 0 dB (no increase) | X 1 (no increase) |
| **2 Hz** | 3 dB | X 2 |
| **3 Hz** | 4.77 dB | X 3 |
| **5 Hz** | 7 dB | X 5 |
| **10 Hz** | 10 dB | X 10 |
| **20 Hz** | 13 dB | X 20 |
| **50 Hz** | 17 dB | X 50 |
| **100 Hz** | 20 dB | X 100 |
| **1 kHz** | 30 dB | X 1000 |

***Table 2: Effect of the RBW on increase or decrease in the noise floor***

Table 2 is based on equation 3. This enables you in relative terms to calculate the logarithmic change in the noise power as a function of the change in the RBW.

$$Change\ in\ noise\ power_{dB} \quad = \quad 10 \cdot log_{10}\left({RBW_{Hz}^{new}}\middle/{RBW_{Hz}^{old}}\right)$$

***Equation 3: Relative calculation of the change in noise power (in dB) as a function of the RBW***

### *What is noise power?*

Of course, you can also determine the noise power in absolute terms. This calculation is based on the so-called Nyquist equation. This assumes white noise (i.e. uncorrelated noise) and takes the noise temperature and sensitivity of the measuring device (noise factor [logarithmic] or noise figure, NF [linear]) into account as well as the measurement bandwidth (RBW):

$$\begin{aligned} Noise\ power\ [dBm] &= 10 \cdot log_{10}(k \cdot T) + 10 \cdot log_{10}(RBW_{Hz}) + NF_{dB} \\ &= -174\ dBm + 10 \cdot log_{10}(RBW_{Hz}) + NF_{dB} \end{aligned}$$

*where:* *Boltzmann constant* $k = 1.3806505\ 10^{-20}\ mJ/K$

*Noise temperature* $T = 300\ K\ (\sim 26.85\ °C)$

***Equation 4: Absolute calculation of noise power (in dB) using the Nyquist equation***

The value of -174 dBm is considered as the lower limit of noise power for commercial spectrum analyzers / receivers. If, for example, absolute sensitivity figures are stated in a data sheet, then the bandwidth dimension and the noise factor must both be added to exactly this value. At the same time, equation 4 also makes it clear that this lower limit can be further reduced if the temperature coefficient is smaller. Such significantly undercooled or cryogenic receiver systems are beyond the scope of this discussion.

We can now use equation 4 to work out the sensitivity of our hypothetical measuring device. We saw in figure 18 that the noise floor was at -163 dBm. This value was based on an RBW of 1 Hz. Consequently, if we now take the difference between -163 dBm and the “thermal noise” (-174 dBm), we get a value for the noise figure NF = 11 dB. This low noise figure is realistic, but also quite agile, and can often be matched or even beaten by additional preamplification, particularly in compact systems.

Finally, we have also established that the noise floor drops and the measurement sensitivity rises at lower RBW values. The measurement speed also drops at lower RBW values, and the level of certain signals, particularly wideband or pulsed signals, will be underestimated. However, the RBW has no effect on the level of intermodulation or harmonics, in contrast with the input attenuation or reference level settings.

The RBW is of only limited use for an accurate determination of the noise. The noise bandwidth gives a more correct value. The noise bandwidth of the digital gaussian filters that are commonly used in modern spectrum analyzers is 1.055 times larger than the RBW.

The detector used in many spectrum analyzers also plays an important role in the determination of the correct noise level. If the DANL is displayed using a video filter and then taking the logarithm of the level and not the power, the RMS value of the noise will be higher by 2.5 dB. Some data sheets indicate that this correction between the DANL and RMS noise value is necessary by means of a footnote specifying “average of logs detection”. The SignalShark displays the correct RMS value, so no correction of 2.5 dB is needed.

At the conclusion of Part 1, then, we have therefore worked out the two major factors that govern the dynamic range of a spectrum analyzer or receiver. These are on the one hand the intercept points, which are a measure of the upper measurement limit, and on the other hand the lowest noise level as a measure of the lowest measurement limit. We have established that the measurement settings of our system play a part in determining the intercept points, and we have learned to distinguish between single tone and dual tone scenarios. We have also established that the noise power of a measuring device systematically increases with increasing RBW, and that it can be calculated using the Nyquist equation as long as we know what the system noise factor is. Armed with this knowledge, we can now confidently approach the task of comparing dynamic ranges in Part 2.

## References

Based on this Guide, readers should also refer to the following documents, which can be found on our Internet site under the product “Interference and Direction Analyzer IDA 2” and “Product literature”:

- Technical Note 110: “Using external filters to maintain measurement sensitivity in highly dynamic measurement environments”
- Technical Note 104: “Maximizing dynamic range by optimizing the input attenuator setting”

Also take a look at our product pages on the Internet:

Monitoring Receiver and Real Time Handheld Analyzer SignalShark:
https://www.narda-sts.com/de/signalshark/
Interference and Direction Analyzer IDA 2:
https://www.narda-sts.com/de/spektrum-und-real-time-spektrum-analyzer/ida-2/
Narda Remote Spectrum Analyzer & Monitoring Receiver NRA 6000 RX:
https://www.narda-sts.com/de/monitoring-receiver/nra-6000-rx/
External filters (data sheet):
https://www.narda-sts.com/de/spektrum-und-real-time-spektrum-analyzer/ida-2/?eID=mpNardaProducts_Downloads&tx_mpnardaproducts_download%5BcontentElement%5D=12560&tx_mpnardaproducts_download%5BfileReference%5D=2507&cHash=faa1d20d1ea349d1187bfc79ecd21e86

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