Application Note

UNDERSTANDING NOISE IN EMI RECEIVERS

Products:

- ► R&S®ESW
- ► R&S®ESR
- ► R&S®EPL
- ► R&S®ESRP

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https://www.rohde-schwarz.com/emc

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1 Noise Figure

Noise figure is one of the most critical parameters in the EMI measurements, directly determining the minimum detectable emission level and defining if the EMI test system is usable to test to a certain standards limit line. Noise figure quantifies how much a component degrades the signal-to-noise ratio (SNR) as a signal passes through it. Every component in a receiver (amplifiers, mixers, filters - any active or passive component) as well as the complete system (antenna, cable, external preamplifier, etc.) adds noise to the signal. Noise figure (NF) quantifies this degradation in decibels. It is defined as:

$$NF = 10 \cdot \log_{10} F \qquad F = \frac{SNR_{in}}{SNR_{out}}$$

where F is the noise factor, representing the degradation of SNR through the component. A perfect, noiseless component would have $F = 1$ (or $NF = 0\,\mathrm{dB}$), meaning the SNR remains unchanged. Any real-world component adds noise, so F is always greater than 1.

Receiver sensitivity describes the minimum signal level that can be detected as:

$$Sensitivity = -174\,dBm + 10 \cdot \log_{10}(BW) + NF$$

Here, -174 dBm/Hz represents the thermal noise floor at room temperature, BW is the system bandwidth. Noise figure directly adds to the sensitivity threshold. If a system has 6 dB NF instead of 3 dB, the sensitivity degrades by 3 dB. The required signal power is therefore twice as high to achieve the same signal-to-noise ratio. Expressed as voltage or field strength, this corresponds to a factor of $\sqrt{2}$, or approximately 1.41, because power is proportional to the square of voltage or field strength.

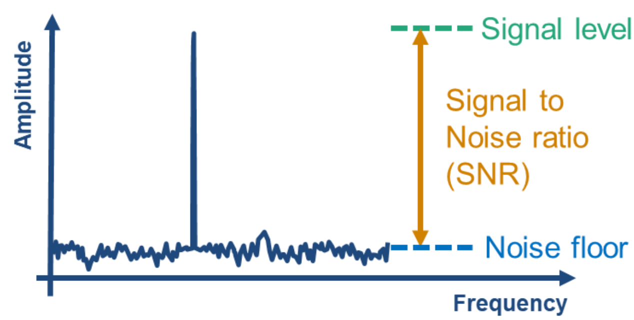

Figure 1 Noise floor and a continuous wave (CW) signal with the SNR defining the level distance in between.

1.1 Cascaded Noise: Friis Formula

In a signal path containing multiple components between antenna and the final analog-to-digital converter of the receiver, noise accumulates according to Friis' equation:

$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 \cdot G_2} + \frac{F_4 - 1}{G_1 \cdot G_2 \cdot G_3} + \cdots$$

where F_n represents the noise factor and G_n the linear power gain of the n-th component in the system. This equation clearly shows: **the first stage dominates the system noise figure**. The noise contribution of subsequent stages is divided by all the gain combined before that stage. This is why the low-noise amplifier (LNA) at the earliest possible position is critical as it significantly improves the noise performance for the entire measurement system.

1.2 Design Implications to reduce Noise Floor

This cascaded behavior sets key design decisions: maximizing gain early in the system, using the lowest-noise amplifier feasible as the first stage and recognizing that noise figure in components after significant gain has minimal impact. A filter before an LNA adds its insertion loss directly to system noise figure, while the same filter after the LNA has negligible impact.

While it is best for the preamplifier to be as close to the antenna as possible, practical considerations on overloading the preamplifier lead to restrictions. Without any filtering, wideband emission or large power signals, even outside the investigated band, can drive the preamplifier into saturation. Such overloading will result in signal distortions due to the non-linear behavior of the preamplifier. For such cases, a preamplifier situated behind the preselection filter achieves more reliable results, despite its larger noise figure.

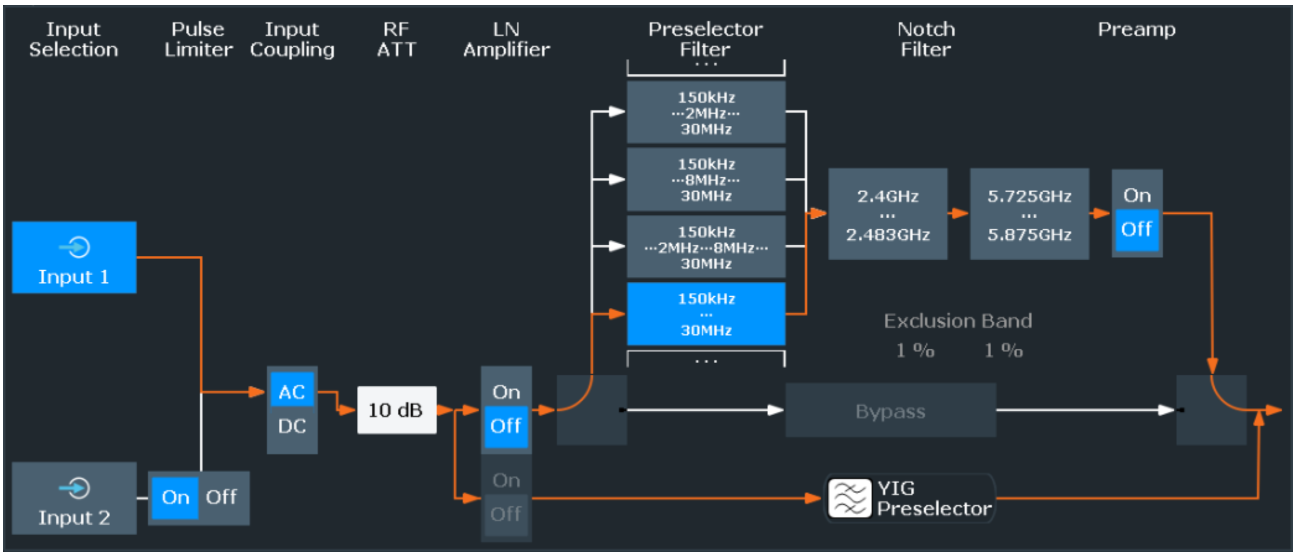

Figure 2 Input path of R&S®ESW with all user-configurable hardware components to set optimal sensitivity and dynamic range.

The Low-noise-amplifier (LNA) achieves the best sensitivity. In presence of strong signals, the Preamplifier behind the Preselection filter is a more robust alternative yet achieving less noise reduction. The R&S®ESW offers the selection between both (if equipped with R&S®ESW-B24 option) while the R&S®ESR is fixed to Preamp operation below 7 GHz and LNA above. The R&S®EPL offers a similar concept as the R&S®ESW if equipped with R&S®EPL1-B2 and R&S®EPL1-B22 option, but with less amplification.

2 Receiver settings

2.1 Resolution Bandwidth (RBW)

The receiver settings influence the displayed noise. The resolution bandwidth (RBW) is a Gaussian shaped filter with a defined bandwidth that lets voltages levels (dBμV) or power (dBm) pass within its bandwidth. The wider the RBW, the more energy of a wideband signal passes the filter. Since noise is wideband, the level reading increases with the RBW. For narrowband signals, the RBW does not have an influence if the RBW is larger than the signal. Constant waveform (CW) signals are always measured at the same level, no matter what RBW is selected (assuming the signal-to-noise ratio is sufficient).

The noise floor increase with the RBW changing follows the simple relation:

$$\Delta\ \text{Noise floor} = 10 \cdot \log_{10}\left(\frac{RBW_{new}}{RBW_{old}}\right). \quad (1)$$

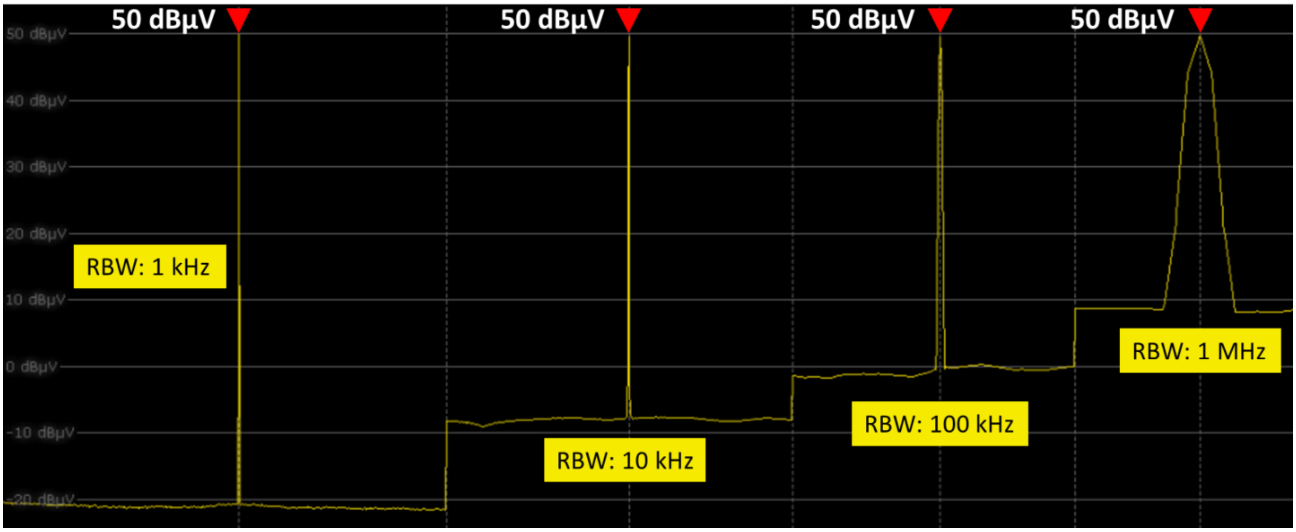

Figure 3 Continuous wave (CW) signal measured at different RBW. The signal level of the narrow band signal remains identical, while the noise floor changes its level. With wider RBW, the Gaussian filter shape gets identifiable.

As an example, for the RBW change between CISPR band A and B from 200 Hz to 9 kHz, it results in the following noise floor step by more noise energy captured by the wider filter:

$$\Delta \text{ Noise floor } (200 \text{ Hz} \rightarrow 9 \text{ kHz}) = 10 \cdot \log_{10}\left(\frac{9\ kHz}{200\ Hz}\right) \approx 16.5\ dB.$$

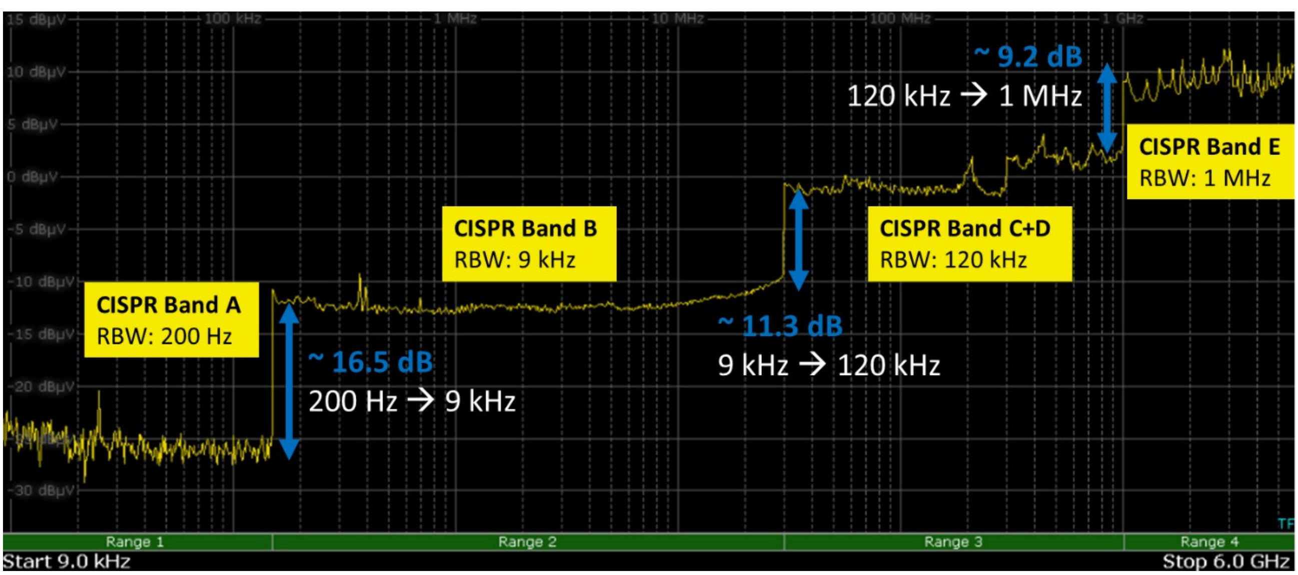

Figure 4 The noise floor increases with the resolution bandwidth (RBW). Shown are the CISPR bands with their required RBW.

2.2 Detector setting

The detector plays a significant role in weighting a signal. Over the course of the measurement time, samples are captured. Their number depends on the sampling rate of the receiver ADC. Over all these samples, the selected detector calculates the output that is shown for each individual trace point on the display.
Constant signals show the identical response with every detector as all captured samples are identical. With a time-varying signal, the detectors show different weighting behavior. Noise is a time-varying signal with its Gaussian distribution in level, resulting in different readings depending on the detector chosen.

Detectors	
Sample	The sample detector returns the first sample captured. That ignores all further samples, making it independent of the measurement time and not reliable for any changing signals.
Peak	Returns the largest peak seen over all samples during the measurement time.
Average	The average detector returns the linear average over all samples during the measurement time. The longer the measurement time, the more available samples reduce the variance.
RMS	The RMS (root mean square) detector calculates the power from all samples captured during the measurement time. The result corresponds to the signal power within the span represented by one trace point.
Quasi-peak	The quasi-peak detector is mandatory for commercial measurements to CISPR for tests below 1 GHz. It measures impulsive disturbances weighted by how annoying they sound to a human ear in an AM radio. While the peak detector immediately reacts to a spike, the quasi-peak follows with a time constant for charging. The discharge time constant is much longer and leads to a slow discharge of the quasi-peak detector reading after the pulse disappeared. With such behavior, the quasi-peak detector weights very short but strong pulses down. If they repeat before the detector has discharged, the weight increases with repetition frequency. For continuous wave (CW) signals, the quasi-peak is identical to the peak.

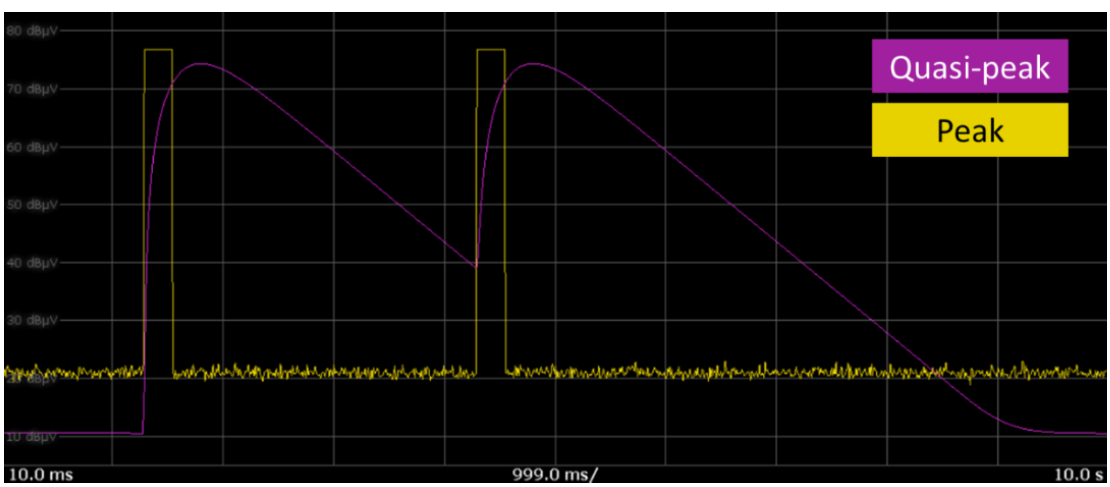

Figure 5 The quasi-peak detector follows the short pulses, charges with the pulse present and discharges slowly after the pulse disappeared. The quasi-peak weights the emission depending on intensity and periodicity of the occurrence.

CISPR-Average

The CISPR average detector is optimized to measure narrowband signals, recovering their true level despite modulation content or surrounding broadband noise. After the envelope detector, the signal passes a meter simulation network with a defined time constant. The displayed value is the maximum reading of this slow meter output. Because the meter responds slowly, short or infrequent pulses are weighted down far more than by the quasi-peak detector. As the pulse repetition frequency increases, the reading rises toward the peak value, and for continuous wave signals the CISPR average equals the peak. In contrast to the quasi-peak detector, which emphasizes disturbances according to their repetition rate to model how annoying they sound, the CISPR average reveals the underlying continuous level beneath impulsive noise.
Since the CISPR average is governed by the fixed meter time constant, the number of pulses within a measurement interval affects the reading far less than for the linear average, whose reading shifts with every additional pulse in the window. Across the chosen measurement time, the CISPR-average shows the maximum of this reading.

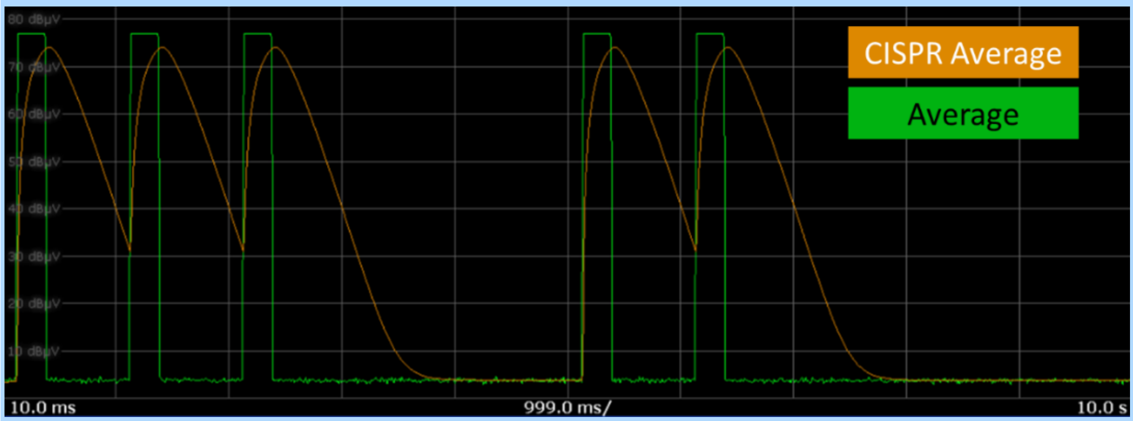

Figure 6 CISPR-Average detector follows the pulsed signal with its meter time constants compared to the linear average detector that immediately follows, averaging only over the measurement time (here: 10 ms).

2.3 Detectors for Noise Floor measurement

For each measurement time interval, the receiver calculates a new detector value from the available samples. The samples shown in below Figure 7 are voltage or power levels measured by one RBW (one trace point) over time. Each detector returns one scalar number that is then drawn onto the trace for all frequency points across the measured span for the spectrum display or, as in the above visualization of the quasi-peak and CISPR-Average, in a time series in Zero Span.

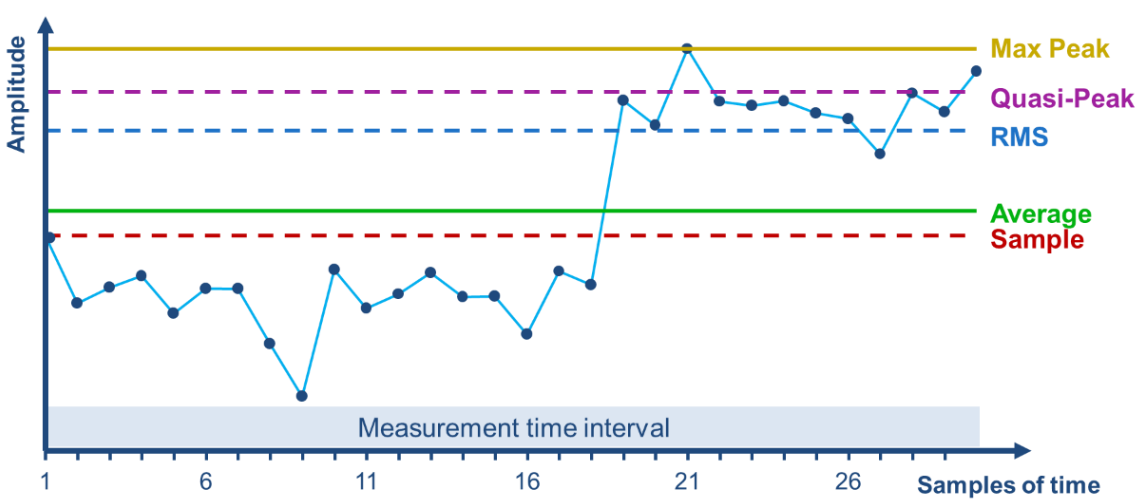

Figure 7 Comparison of detectors calculated from the captured samples within the measurement time interval.

For noise floor measurements, the Average detector shows comparable results with true mean (average) value. A common misunderstanding is noise measurements using peak detector, which always returns the highest available sample raising in level with the measurement time and not representing the statistical behavior of the underlying noise distribution (see also the graph in section 2.4 and section 5.1 on noise verification measurements).

2.4 Measurement time on Noise Floor measurements

The noise figure typically follows a Gaussian distribution. At infinite number of samples, the exact Gaussian shape is reached when drawing the probability of occurrence of all measured amplitudes over the amplitude itself in a graph as in below Figure 8.

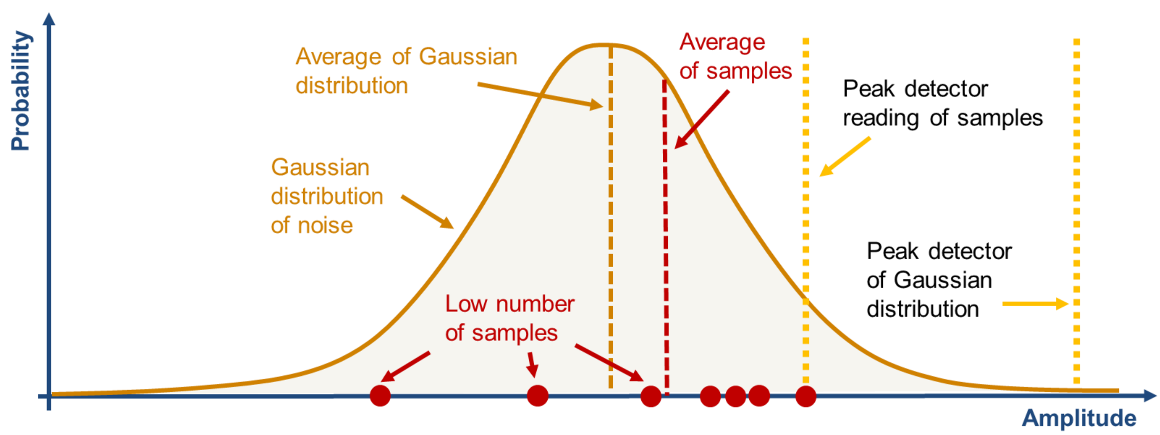

Figure 8 Gaussian distribution of noise floor amplitudes with its mean (average). At long measurements times with large number of samples, the Gaussian shape is reached. With a low number of samples (red), the average might differ from the mean (average) value of the underlying distribution.

Short measurement (dwell) times result in lower number of samples that reduce the statistical relevance and might result in a deviation of the noise distribution and its mean (average). The red samples define a small set of samples with low statistical relevance, giving a deviation in the mean. The lower the number of samples, the more variance the average detector will show.
For comparable results, a measurement time of > 100 ms is recommended as a practical guideline.

2.5 Level unit dBµV

For EMI measurements, signal levels are expressed in dBµV (decibels relative to one microvolt). This logarithmic unit provides a way to represent the wide dynamic range of voltages encountered in EMI measurements. EMI related limits by the various standards are given in dBµV. The conversion from voltage levels measured by the receiver to dBµV is defined as:

$$V_{dB\mu V} = 20 \cdot \log_{10}({}^{V}/_{1\ \mu V})$$

where V is the measured voltage. The factor of 20 (rather than 10 for power units, e.g. dBm) is used because voltage relates to power proportionally to its square.
Beside the unit dBµV, in spectrum analysis dBm appears throughout component datasheets — noise figures, phase noise, and amplifier specifications are almost universally expressed in unit dBm.
With $P = {}^{V^2}/_{R}$ it follows for a 50 Ω system for a simple conversion by:

$$dB\mu V = dBm + 10 \cdot log_{10}(50\Omega \cdot 10^9) \approx dBm + 107$$

2.6 Noise influence on level readings

At low voltage levels, particularly near the noise floor, small absolute voltage changes produce disproportionately large changes in dBμV readings. For example, a change from 1 μV to 2 μV represents a 6 dB increase, while changing from 100 μV to 101 μV yields only 0.09 dB. This logarithmic characteristic means that measurement uncertainty and noise have a much greater relative impact on dB readings when measuring small signals.

The following table illustrates the relationship between dBμV readings, absolute voltage levels, and measurement sensitivity. It demonstrates how small voltage changes impact dB readings differently across the measurement range.

Level (dBμV)	**Voltage** (μV)	ΔdB for +1μV change	**Noise influence** (dB) to signal reading, assumed noise N = 0 dBμV
0	1.00	+6.02	3.01
3	1.41	+4.44	1.76
6	2.00	+3.52	0.97
10	3.16	+2.75	0.41
20	10.0	+0.83	0.04
30	31.6	+0.27	0.00

CISPR standard defines that the influence of noise on the signal reading must be lower than 1 dB (CISPR 16-4-2 Annex 2). This defines how small a signal can be to be correctly evaluated below a limit line. With the assumption in the above table of a noise floor of 0 dBμV, the level is equivalent with the SNR for each row. The right-most column shows that a 6 dB SNR is required to keep the noise-induced level error below 1 dB.

The influence of noise to the emission level reading sets the 6 dB margin below every EMI limit line towards the noise floor, the minimum requirement for every EMI measurement to be compliant.

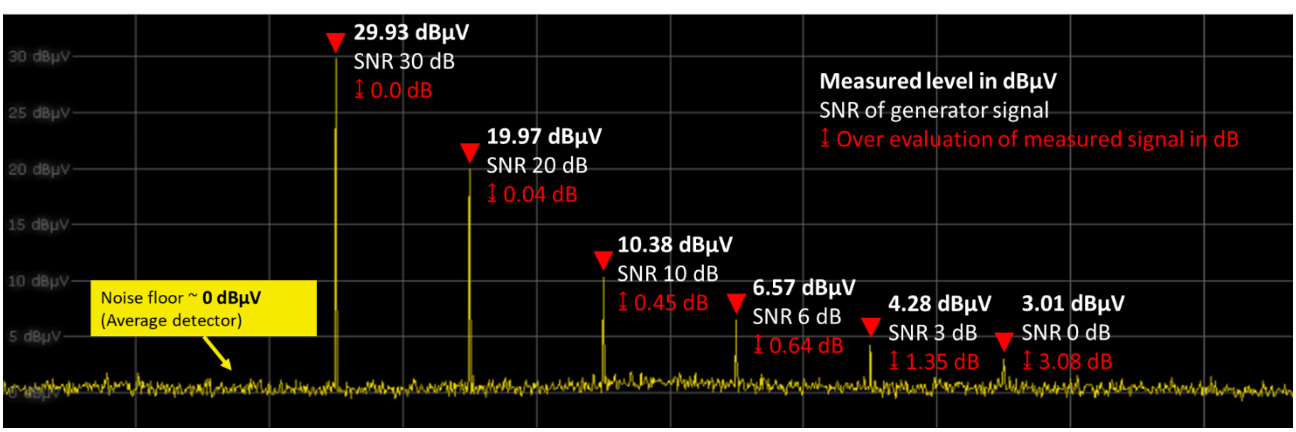

Figure 9 Measurement of CW signals at a defined signal-to-noise ratio (SNR). At low SNR, the over evaluation of signal readings due to noise influence rises and compares to the theoretical table above with the consideration of measurement uncertainty.

3 Noise and Dynamic Range

The dynamic range is the level range in which signals can be detected. It spans between the noise floor at the low end and the 1 dB compression point at the top. The attenuator and preamplifier shift the entire measurement window up or down in level without changing its width.

Adding attenuation pushes the window upward: strong signals move away from the compression point, but weak signals sink into the noise and become unreadable.

Switching on the preamplifier pulls the window downward: weak signals emerge from the noise, but the compression point drops simultaneously, so strong signals now risk overloading the input.

The correct setting is whichever combination places the signal of interest inside the window with a sufficient margin towards the compression point. If the instrument offers enough dynamic range, the noise floor is such low it offers at least 6 dB margin to the selected limit line. Although it is desirable to work with the lowest possible attenuation, in case of sufficient margin (> 20 dB) between noise floor and limit line, more attenuation helps to protect the instrument and make the measurement more robust and reliable.

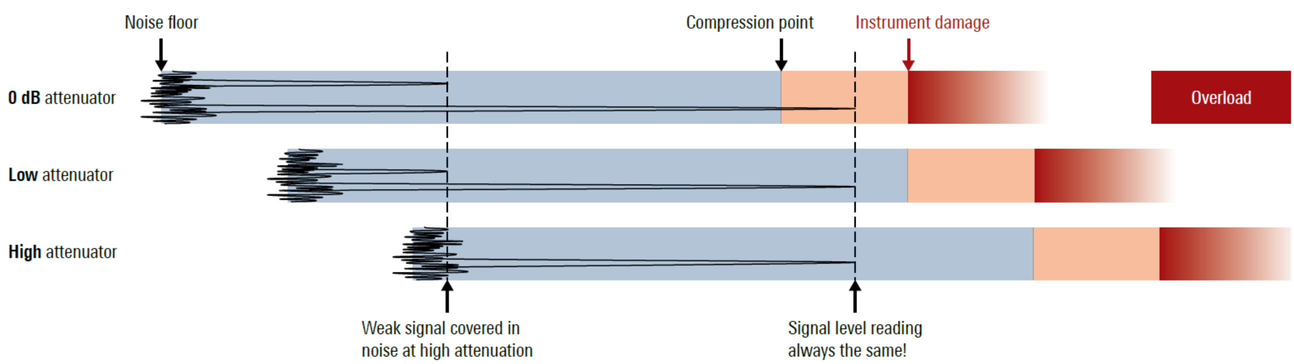

Figure 10 Input leveling for maximizing the dynamic range using the instruments internal attenuator.

For best sensitivity, all cables should be shortest possible, with highest importance on the one between antenna and preamplifier. The higher the frequency measured, the more important the cable loss is, requiring shorter and lower loss cables.

The preamplifier should be situated as close as possible to the antenna to optimize the system noise figure according to the Friis formula presented in section 1. A larger gain will offer more amplification but also comes with compromises. The gain in sensitivity is less than the signal-level gain because the preamplifier also adds its own noise. In addition, intermodulation products and harmonics are more pronounced with larger amplification. A common practical recommendation is a maximum preamplifier gain of 30 dB. Additionally, the higher the preamplifier gain is, the more likely it will overload.
Despite overload detection is implemented in the receivers input hardware, not every non-linearity is detected if the signal level gets very close to the compression point. A manual verification of linearity is easily done by adding attenuation. If the level reading remains identical with more attenuation added within the receiver, the compression point is not yet reached and measurements are done within the linear range. If external attenuation pads are used, the level should drop with the specified attenuation.

3.1 Preselection Filter

The preselection filter is the key hardware differentiation between a spectrum analyzer and an EMI test receiver. By narrowing the frequency span the instrument is sensitive for, less power reaches the sensitive input stage. This allows for better dynamic range leveling - as explained above - with less attenuation needed, reducing the noise floor for higher usable dynamic range.
Due to the wideband characteristics of EMI testing antennas, the receiver may capture emissions far outside the specific frequency range of interest. Without preselection filters, more power over the full RF bandwidth reaches the receiver, requiring more attenuation to avoid overloading of the instrument.
Without preselection filters, the RF bandwidth is defined by the overall frequency range of the instrument. More attenuation results in a reduced dynamic range by raising the noise floor in the same number as the attenuation added.
Preselection reduces the RF bandwidth to the bandwidth of the preselection filter used for each particular measurement. A larger number of analog filters as part of the preselection filter bank are switched depending on the current measurement frequency.

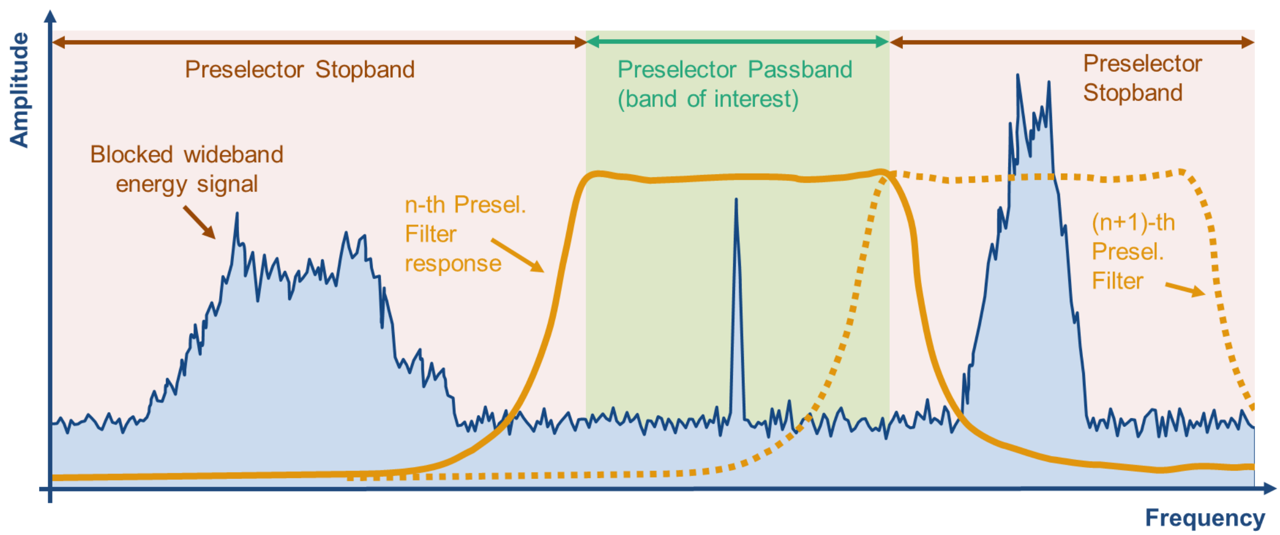

Figure 11 The preselection filter reduces the input power seen by the instrument by limiting the RF bandwidth. The receiver automatically switches through a filter bank while scanning to always only see the current band of interest (green marked passband), blocking all other out-of-band emission in the stopbands.

Spectrum Analyzers use the term Preselection when referring to the suppression of image products or harmonics of mixing products. Spectrum Analyzers allow bypassing image filtering in certain cases to increase the analysis bandwidth. This is acceptable for a known spectral distribution of the input signal, but not for EMI testing with unknown DUT emission characteristics. EMI receivers are free of image products and harmonics even with the dedicated EMI preselection filter turned off (only available in the EMI receiver's Spectrum Mode).

The EMI receiver's preselection filter comes in addition, defining the most relevant hardware difference between EMI receivers and Spectrum Analyzers to reduce the RF bandwidth of the instrument to optimize for noise reduction and dynamic range. Spectrum Analyzers have a different focus on widest bandwidth and fastest possible sweep times with compromises on dynamic range.

4 Instrument Calibration and Alignment

The following terms are relevant when it comes to a correctly calibrated instrument: Accredited calibration, manufacturer calibration, adjustment and self-alignment. While the first 3 are done by the manufacturer or an accredited 3rd party calibration laboratory, the self-alignment can be done by the user on a regular basis.

Self-alignment is an internal adjustment routine the instrument performs on itself, either automatically by schedule (e.g. every morning at 7 am) or started by the user. The instrument uses its own built-in reference sources to compensate for short-term drifts caused by temperature changes or short-time aging. It computes correction data and stores it in user correction tables on the disc. Self-alignment does not conform to standards and doesn't offer traceability or certifications. **It should be run at least every month, ideally once a week or after temperature changes or after movement of the instrument.**

Accredited Calibration is the formal, external process of comparing the instruments reading against traceable reference standard in an accredited calibration laboratory (accredited to DAkkS in Germany, UKAS in the UK, A2LA or NVLAP in the US, etc.). The instrument is characterized using testing equipment whose values are traceable through an unbroken chain to national metrology institutes. The result is a calibration certificate stating the measured deviations, measurement uncertainties, and whether the instrument meets its specifications. Depending on the outcome, adjustment may follow. Accredited Calibration intervals are typically 24 months and are mandatory for accredited EMC test labs under ISO/IEC 17025.

Manufacturer Calibration is performed by the instrument manufacturer after production. The references used are traceable, but the calibration is not independently accredited. The result is a manufacturer's calibration certificate confirming that the instrument meets its published specifications, listing measured values and deviations in a calibration report.

Adjustment is the adjustment of readings in such a way that the calibration is successful by applying correction values. These values are stored in the internal storage of the instrument and are independent of changes of the hard drive. Despite the accredited calibration can be done by 3rd party calibration laboratories, a potentially required alignment can only be done by Rohde & Schwarz.

4.1 Instrument warm-up

The instrument calibration (both manufacturer and accredited calibration) is only valid at a stable temperature in the specified range. To keep the measurement results as stable as possible and to align with the calibration, the instrument needs to warm up before it can correctly be used.
After turning on the instrument, it will show a notification that it is warming up. Once the instrument aligns with the calibration temperature, this message disappears and calibrated measurements can be performed. The warmup takes about 30 min, depending on environmental conditions. Until then, the instrument is fully functional, but additional uncertainties must be considered.

5 Understanding Datasheet Values

Instrument specifications follow a **Gaussian (normal) distribution** across production units and operating conditions. Understanding the terminology is key for comparing datasheet values between instruments.

- **Typical** values represent the mean (μ) of the distribution. With the Gaussian distribution assumed 50% of units perform better, 50% worse. If the distribution is not symmetrical as the Gaussian distribution, the mean might not represent the center which is defined by the term median. Typical values look impressive but offer no guarantee.
- **95% confidence / 95th percentile** values correspond to approximately ±2σ (two standard deviations) of the Gaussian distribution. This means 95.4% of all units under specified conditions will meet this value. This is the only trustworthy specification for system design.
- **Nominal/Defined** values are exact by design or definition as a guaranteed value. All instruments delivered fulfill these definitions. Instruments not meeting these values are refined or replaced in the factory. Nominal values are usually identical in the probability distribution to the 95% confidence.

σ (sigma) describes the spread of the distribution. A tighter σ means more consistent production; ±σ covers ~68% and ±2σ ~95% of units.

Example: Displayed Average Noise Level (DANL)

Given is a specification at a frequency range and settings defining: –166 dBm, typ. –169 dBm

From that specification, the typical (mean) is read at -169 dBm. The definition is -166 dBm, so that all instruments are better than -166 dBm with the ±2σ range from -172 dBm to -166 dBm as depicted in below graph.

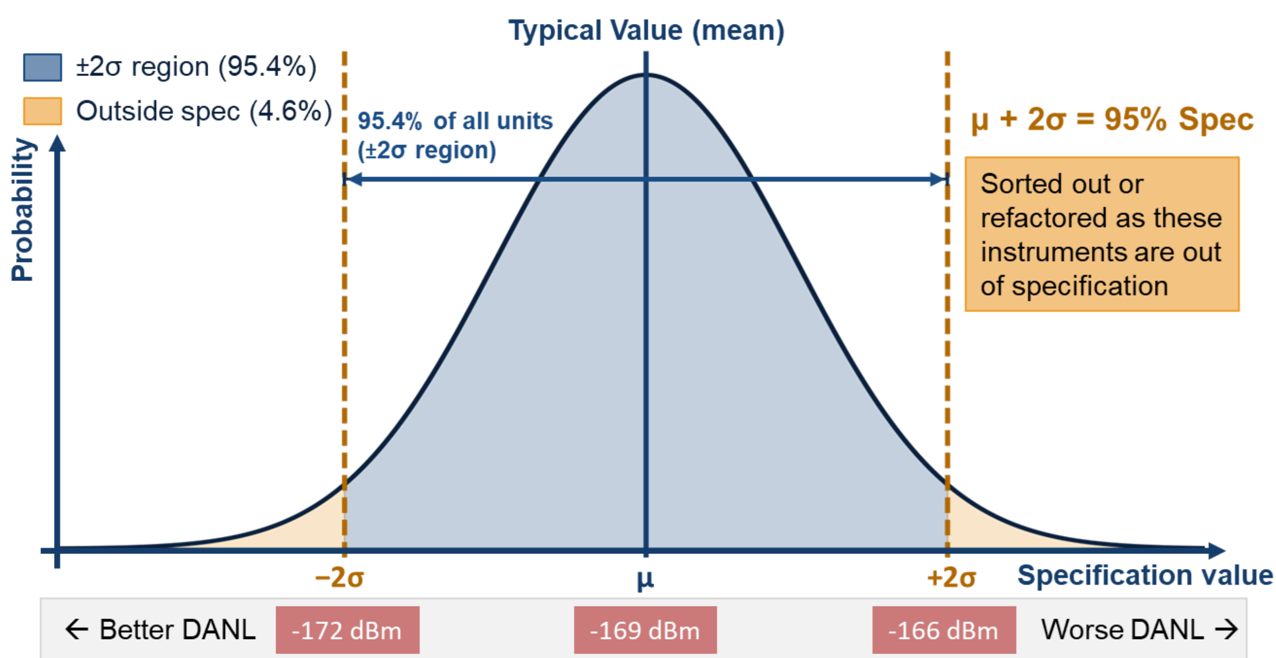

Figure 12 Specification interval of a Gaussian distributed DANL. Shown is the mean value in the center of the acceptable range (blue) with its boundary towards the lowest acceptable value (guaranteed value).

5.1 DANL and Indicated Noise Verification

The noise floor is typically stated as Displayed Average Noise Level (DANL) in the datasheet across various settings, modes and configurations of the instrument. The following states the configuration of the highest sensitivity from the R&S®ESW datasheet:

> Preselection off/on, preamplifier off, LNA on, RF attenuation = 0 dB, termination = 50 Ω, log. scaling, normalized to 1 Hz RBW, RBW = 1 kHz, VBW = 1 Hz, +5 °C to +40 °C

The lowest noise floor or highest sensitivity is achieved at 0 dB attenuation and the Low-noise-Amplifier turned on, that has the best combination of highest gain and lowest noise figure. Values are normalized to 1 Hz RBW (see section 2.1) but measured at 1 kHz RBW to reduce the testing time. The video bandwidth (VBW) is reduced to a minimum, achieving averaging over time, an alternative method. Instead, use the average detector at a long measurement time (>> 100 ms) as described in sections 2.3 and 2.4. To avoid any influence from outside, the input is terminated with 50 Ω. The temperature interval is given as the range in which these datasheet values are guaranteed (see section 4.1).

With the measurement performed at 1 kHz RBW, a normalization to 1 Hz corrects for the too large RBW. The choice of 1 kHz RBW is the tradeoff between accuracy and testing speed. Following equation 1 in section 2.1, it follows for the correction:

$$\text{1 Hz Normalization} = 10 \cdot \log_{10}\left(\frac{1\ \text{Hz}}{1\ \text{kHz}}\right) = -30\ \text{dB}$$

With the correction factor applied to the level reading, we can now directly compare the measured values with those stated in the datasheet.

An easier and more practical method is the indicated noise shown in receiver datasheets, particularly tailored to the requirements on EMI tests against the common standards (CISPR, MIL-STD, etc.). It uses the required RBW (e.g. 120 kHz for CISPR between 30 MHz and 1 GHz or 1 MHz above 1 GHz for both CISPR and MIL-STD), so that the measured numbers for each band are directly comparable to the datasheet.

6 Noise Floor Characteristics

The noise floor of an instrument or any other component is never perfectly flat but shows characteristics that not only vary between components but even among individual production samples, ageing or temperature deviations. Most effects are visible only on highly sensitive instruments with a noise floor close to the technical limit that is set by the thermal noise. Adding any signal hides the effects as shown in section 6.4.

Consider Transducer Factors added to the signal reading. For evaluations of the instrument's noise floor, Transducer Factors must be turned off to avoid affecting the measurement result. When measuring with an antenna connected, they are required to compensate for the Antenna Factor. When measuring across definition ranges of Transducer Factors, these might create jumps in noise floor.

6.1 FFT Ripple

When using the FFT-based Time Domain Scan in an EMI test receiver, the instrument scans across the span of interest with steps sized by the FFT bandwidth. For each step, the receiver tunes to a new frequency that is mixed down to the IF stage before sampling the signal in time and calculating the spectral components using the FFT. Figure 13 illustrates this simplified hardware path.

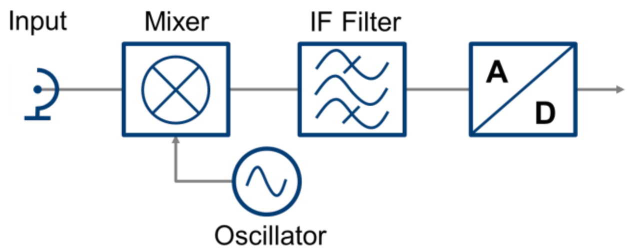

Figure 13 Simplified block diagram of the receiver IF path.

The bandwidth of the IF filter, as well as all other components in the signal path, need to be at least as wide as the FFT bandwidth to allow broadband measurements using the FFT. This filter has a specific frequency response, that influences the level reading in a repetitive pattern for each step of FFT scan.

Despite the frequency response being corrected by the refinement as part of the instrument production, due to temperature drift or aging, the effect will always be visible in a small scale on a sensitive instrument (see section 2.6 for more details about the influence on noise behavior by low SNR signals).

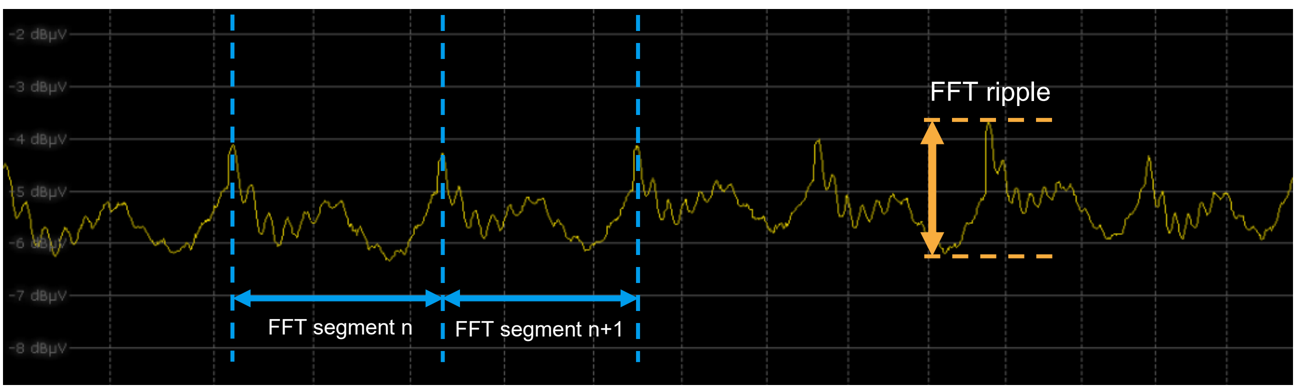

Figure 14 FFT ripple in a Time Domain Scan measurement with repetitive noise characteristics in the segment size of the FFT bandwidth. The effect is normal and accepted behavior if the ripple excursion is low.

This FFT ripple typically has a "sawtooth" pattern and is a normal noise behavior if the span between maximum and minimum level is less than 3 to 4 dB.
With the temperature drift being the most relevant reason for the effect, a self-alignment (see section 4) can reduce the effect to the lowest possible level.
The effect is only visible on very sensitive and low noise instruments. As soon as any signal is added, this signal will cover the effect in the spectrum display. Even the added noise figure from an activated preamplifier or LNA will lead to a flat noise floor with the effect hidden behind the amplifiers added noise figure.

The FFT ripple does not influence the level reading of a real signal to be measured beyond the instruments measurement uncertainty if the signal has at least a few dB SNR, or in other words is visible in the spectrum display just above the noise floor.

6.2 Spurious Responses

Spurious responses are narrowband emissions visible in the noise floor of the instrument. These emissions can interfere with the emission measurement as the spurs might not be distinguishable from input signals. Spurs originate from LO harmonics, internal reference leakage, IF crosstalk among many other effects. While these responses cannot be eliminated entirely, careful design and shielding during the development of the instrument minimize their amplitude.

Each unit undergoes individual spurious characterization in manufacturing and service to meet the specified datasheet limits. These limits are guaranteed and if exceeded, the instrument is repaired or refined in the service department within the warranty period. To test the amplitude of spurious responses, investigate the noise floor as described in section 5.1.

As spurious responses are narrowband signals, the RBW does not change their amplitude. It requires measurements at small RBW to keep the noise floor low to unveil the spurious responses. At a raised noise floor due to higher attenuation or larger RBW, the spurious responses are typically not visible.

To verify if a narrowband emission is an internal spurious response or an outside signal, swap the antenna with a 50 Ω termination. If the emission persists, it is generated internally but must stay below the datasheet specification.

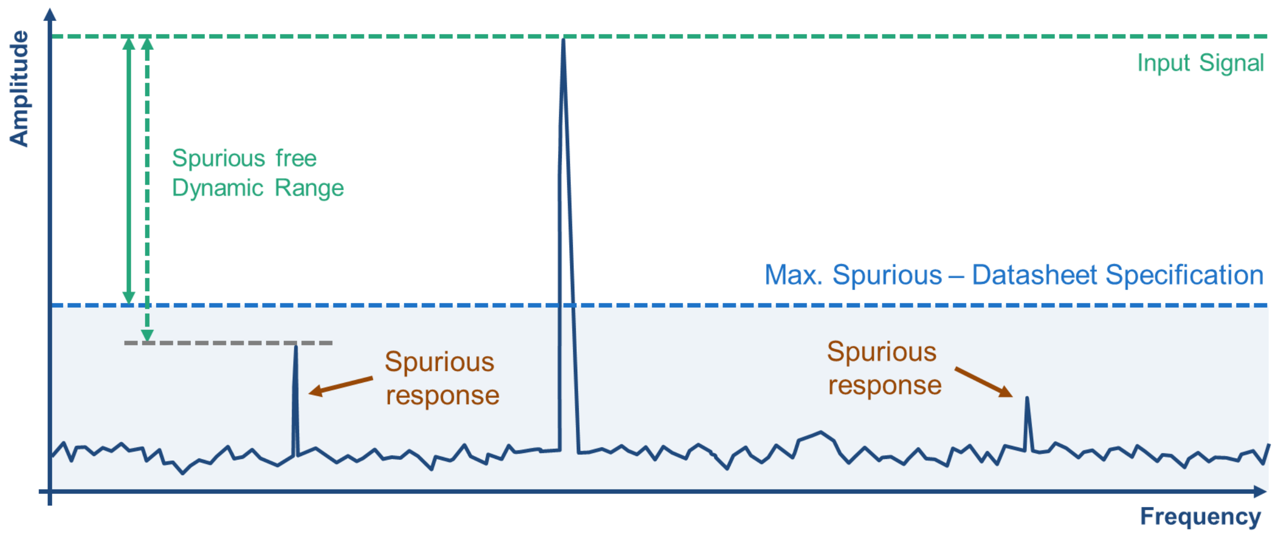

Figure 15 Spurious responses are narrowband signals internally created by the instruments. These signals are unavoidable to see with the noise floor very low but must stay below the datasheet specification.

With a signal at the input to be measured, the spurious free dynamic range is derived as the amplitude margin the signal has towards the highest spurious within range. With typically the instrument spurs being much lower than the datasheet specification, the instrument specific spurious free dynamic range offers even more margin.

6.3 Input Impedance Mismatching

On an open transmission line, a standing wave is formed if the line end is open or closed (shortened). With the reflection coefficient $\Gamma = 1$ for the open line, all waves are reflected and add up constructively to a standing wave. The voltage standing wave ratio (VSWR) derives from the reflection coefficient and becomes infinite for $\Gamma = 1$ and this case of a mismatching. In the ideal case of a 50 Ω termination, the VSWR equals 1 or a perfect matching without any reflections.

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

As no real antenna achieves the ideal $VSWR = 1$, there might be a standing wave visible in the receiver's noise floor. With the preamplifier or LNA activated, their produced output noise travels towards the antenna and gets reflected due to the mismatch. These traveling waves create a standing wave.

Figure 16 shows a measurement at an open 1.5 m long cable connected to the receiver's input. Without any amplifier turned on, the noise floor doesn't change. With the activated preamplifier adding noise figure that acts as a signal travelling onto the cable, a standing wave forms. The preamplifiers noise is reflected at the open cable end.

This example shows the worst case with an open cable. However, some broadband antennas or other transducers can have poor VSWR especially in their frequency specification edges, leading to the identical effect.

A simple method to reduce the effect is adding attenuation. With just a small attenuator pad of e.g. 2 dB, the effect gets significantly smaller by this forced matching. Since the preamplifiers signal passes the attenuator twice (towards the cable and in return), the better matching is still advantageous even though the noise floor is slightly raised due to the added attenuation.

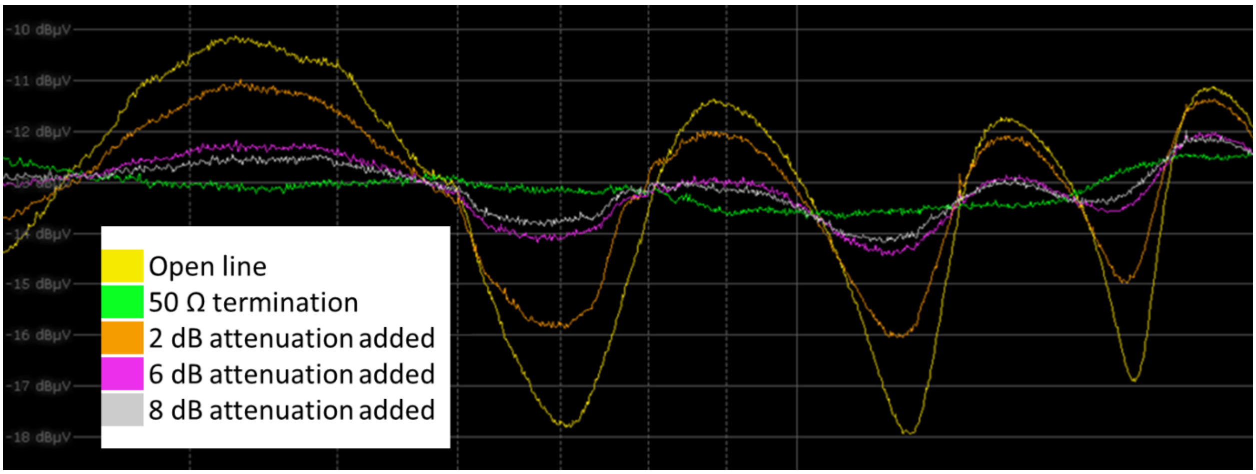

Figure 16 Standing wave from the receivers preamplifier noise figure reflected at the open end of a 1.5 m long cable. The reflected waves added up constructively and shaped the receivers noise floor by the resulting standing wave.

6.4 Noise floor inconsistencies

Sensitive instruments achieve a low noise floor close to the limit of the thermal noise. With such low internal noise, not only artefacts as described in the above sections become visible but also changes in the input hardware are identifiable. At different frequency ranges, the input hardware changes its configuration, filters, IF stages, etc. Even if two hardware stages use identical physical components, both have their own specific noise specifications. This results in noise floor changes particularly at frequencies where the input hardware changes.

Component variation affects the comparability between two instruments of the same kind or even with the same instrument after it has aged. Small artefacts in the low noise floor require only minimal variation of the components as the influence on such small signals is significant (see also section 2.6).

All those effects are visible only due to the high sensitivity of the instruments. The influence on level readings from outside signals is limited to the effect of noise on low-SNR signals described in section 2.6. The noise floor can be flattened by adding any noise signal. With the preamplifier or LNA turned on, the amplifier adds a broadband noise signal that covers up the effects as shown in Figure 17.

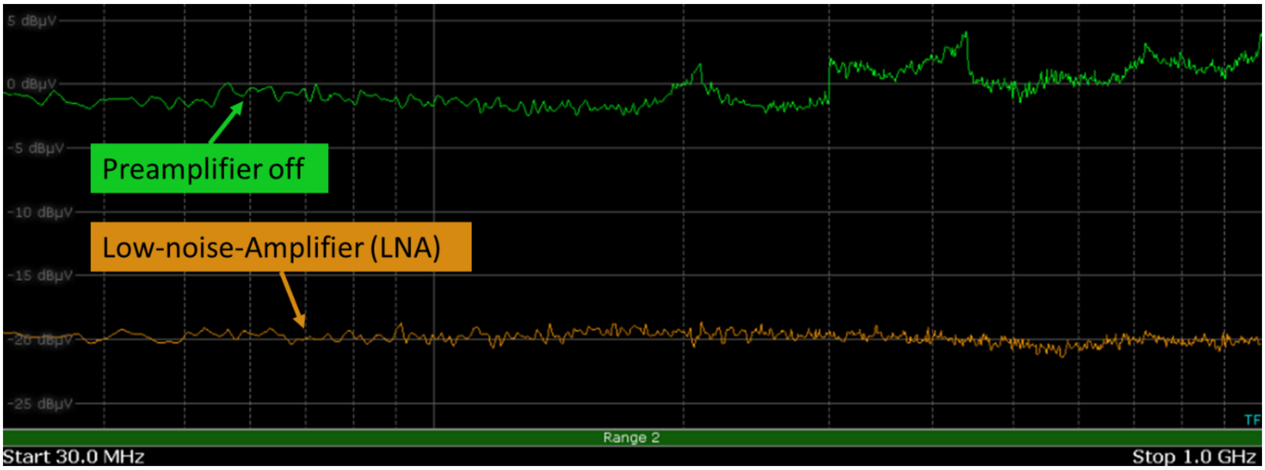

Figure 17 Noise artefacts are covered by the added broadband noise of the low-noise-amplifier (LNA) to achieve a flat but slightly elevated noise response. The sensitivity improvement is the LNA gain minus the noise it adds results in the improvement in system noise figure.

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