

# The Effective Number of Bits (ENOB) of my R&S Digital Oscilloscope

## Technical Paper

### Products:

| R&S®RTO1012 | R&S®RTO1022  
| R&S®RTO1014 | R&S®RTO1024

This technical paper provides an introduction to the signal quality parameter "effective number of bits" (ENOB) and shows how it can be measured for the R&S®RTO Digital Oscilloscopes.

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# 1 ENOB Basics

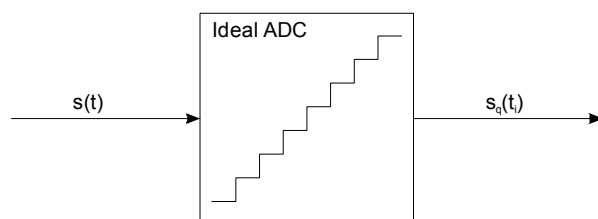
The effective number of bits (ENOB) is a way of quantifying the quality of an analog to digital conversion. A higher ENOB means that voltage levels recorded in an analog to digital conversion are more accurate.

In an oscilloscope the ENOB is not just determined by the quality of the analog to digital converter but by the instrument as a whole. This application note explains how to measure the oscilloscope ENOB and shows results for the R&S®RTO for different settings.

## 1.1 Analog-to-Digital Converters and ENOB

### 1.1.1 The Ideal Analog to Digital Converter

A simple schematic of an ideal analog to digital converter is shown in Figure 1.



**Figure 1: Schematic of an ideal analog to digital converter**

The ideal analog to digital converter has a perfectly linear characteristic and simply quantizes the incoming signal. The process of quantization introduces quantization noise. Using the signal power and the noise power, it is possible to derive a signal to noise ratio (SNR) for the signal after the analog to digital conversion. If a full-scale sine-wave is used as the input, then the SNR can be written exactly as,

$$\text{Equation 1} \quad SNR = 1.5 \times 2^{2B} .$$

The term  $B$  denotes the number of bits of the ADC. Expressing the equation in dB results in,

$$\text{Equation 2} \quad SNR_{dB} \approx 1.76 + 6.02B \text{ dB} .$$

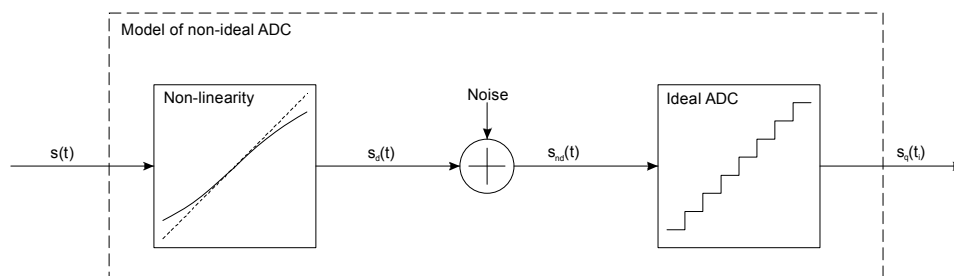
Rearranging the equation to solve for  $B$  results in,

$$\text{Equation 3} \quad B \approx \frac{SNR_{dB} - 1.76}{6.02}$$

This equations shows how the number of bits can be derived from the signal to noise ratio and provides the basis for calculating the ENOB. In the case of ideal ADCs the result for  $B$  will always be a positive real integer. In the case of non-ideal ADCs, which will be looked at in the next section, then  $B$  can be any positive real number.

### 1.1.2 Non-ideal Analog to Digital Converters

Ideal ADCs do not exist. Every ADC adds some distortions to the input signal. Typical distortions are noise, a non-linear input characteristic as well as gain and offset errors. A model for a non-ideal ADC is shown in Figure 2.



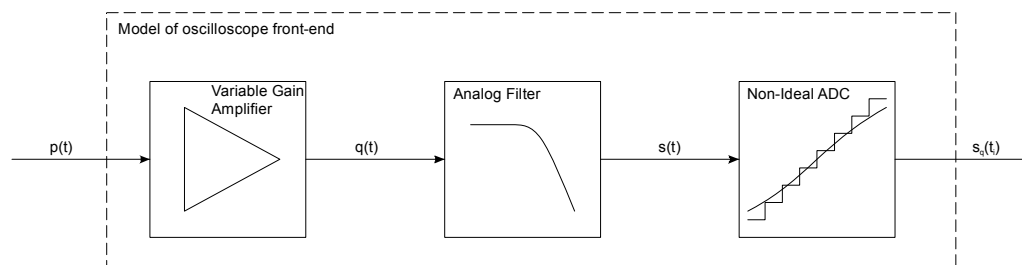
**Figure 2: A model of a non-ideal analog to digital converter**

Noise contributes directly to a degradation of the SNR of the ADC. A non-linearity results in harmonics which also reduce the achieved SNR. Thus, a 12 bit ADC might be specified with an ENOB of 10.5. This means that even though the ADC outputs 12 bits, the achieved SNR corresponds to that of an ideal ADC with 10.5 bits.

Depending on how the ADC is designed, the ENOB may also be dependent on the input frequency. High frequencies may result in worse non-linearities within the circuit thus degrading the ENOB. Thus, a detailed specification of an ADC usually includes the behavior of the ENOB with respect to the input frequency.

### 1.1.3 The Front-End

In an oscilloscope, additional elements are required in front of the ADC in order to make best use of it. These elements are shown schematically in Figure 3. The first is a variable gain amplifier (VGA), which scales the oscilloscope input signal to optimally use the dynamic range of the ADC. The second is a low pass anti-aliasing filter. Both components introduce further distortions to the input signals. The VGA consists of active components and introduces non-linearities as well as having a frequency dependent behavior. The analog filter is less critical but also has a non-ideal frequency response. A good front-end design will minimize negative impacts on the input signal.



**Figure 3: A simplified model of an oscilloscope front-end**

## 1.2 Measuring ENOB

The IEEE has defined terminology and test methods for analog to digital converters in [1]. This includes the following definition of ENOB,

$$\text{Equation 4 } \text{ENOB} = 0.5 \log_2(\text{SINAD}) - 0.5 \log_2(1.5) - \log_2\left(\frac{A}{V}\right).$$

The following definitions apply:

$V$  : full-scale range of the device under test.

$A$  : peak to peak amplitude of the sine wave fitted to the output.

SINAD : signal to noise and distortion ratio.

In this paper, SINAD is defined as

$$\text{Equation 5 } \text{SINAD} = \frac{P_S}{P_{NAD}}.$$

The following definitions apply:

$P_S$  : signal power; power in the FFT bin corresponding to the input frequency

$P_{NAD}$  : noise and distortion power; sum of powers in all other frequency bins excluding the 0 frequency bin, up to and including the bin at Nyquist frequency.

Here it is noted that SNR and SINAD, as defined in [1], are ratios of 'rms' (root mean square) values and not a ratios of power values which is for example typical for communications engineering. This paper consistently uses ratios of power values for both measures.

In [1] methods for calculating SINAD using a time domain or a frequency domain analysis are defined. For simplicity the focus of this paper is on the frequency domain analysis. The correct choice of test frequency is described in section 1.2.2. A fast Fourier transform (FFT) is then used to calculate  $P_S$  and  $P_{NAD}$  as defined above.

### 1.2.1 Choice of Amplitude

The IEEE standard does not specify a particular input amplitude for the ENOB measurement. According to [1], any input amplitude can be used, since the difference between the full-scale amplitude and the actual test amplitude is taken into account in the ENOB definition (see last term in Equation 4).

There are two possibilities for treating the amplitude.

1. The ENOB is specified for a particular input amplitude. Common specifications are ENOB at 90% full-scale or 95% full-scale. Using the definition of Equation 4, the ENOB will look better the lower the input amplitude is, because only non-linearities up to the test amplitude actually influence the measurement.

2. The amplitude normalization in Equation 4 is left out and the ENOB measurement is based purely on SINAD. Using this method, the optimal working point of the system under test can be found as the best trade-off between input power and distortion through non-linearities. Since this definition does not correspond to the official ENOB definition, it is denoted as ENOB\* in the results section.

Note that ENOB\* is the more practical measure for system design and testing. It corresponds directly to the signal quality being observed on the measuring device. The measure of ENOB provides a basis for comparing different systems but is only a useful reference when quoted together with the input amplitude at which the measurement was taken.

Results for both types of measurements are presented for different values of input amplitude in section 2.2.3. All other measurements were performed at 95% full-scale.

## 1.2.2 Choice of Frequency

The input frequency must be chosen to fit exactly onto a frequency bin of the FFT. This is equivalent to saying that the sampled sequence should include only whole periods of the test signal. This is important to exclude any windowing effects which would make the measurement unnecessarily complicated.

Further, for reliable measurements, as many phases of the input signal as possible should be sampled, and all output codes of the ADC should be activated. Using the notation of section 5.4.1 of [1], the optimal test frequencies are given by

$$\text{Equation 6 } f_{\text{opt}} = f_s \frac{J}{M},$$

where the following definitions apply:

$f_{\text{opt}}$  : a useful test frequency for calculating ENOB

$f_s$  : sampling rate of the device under test

$M$  : number of samples in the test sequence.

$J$  : number of input signal periods within the test sequence. This should be an integer which is relatively primed to  $M$ .

Being relatively primed means having no common factors. For example, 100 (factors of 2 and 5) is relatively primed to 9 (factor of 3) but not to 15 (factors of 3 and 5). In the following measurements, only frequencies which can be derived from Equation 6 are used.

## 1.2.3 Choice of Number of Samples

In [1] a minimum sequence length of

$$\text{Equation 7 } M = \pi 2^b$$

is specified. For the following measurements, a round number of 10,000 was used which satisfies this condition. This condition ensures a high density of sampled phases of the test signal and thus ensures reliable results.

## 2 Test Setup and Measurement Results

The R&S RTO Oscilloscopes use an 8-bit AD converter designed by Rohde & Schwarz for high dynamic range, i.e. high ENOB values. As can be seen in [2], the ENOB of this A/D converter is above 7 for an input frequency range right up to 4 GHz. The oscilloscope's total dynamic performance additionally depends on the design of the analog front-end. This chapter describes the measurement procedure and also discusses the results.

### 2.1 Measurement Setup

#### 2.1.1 Equipment

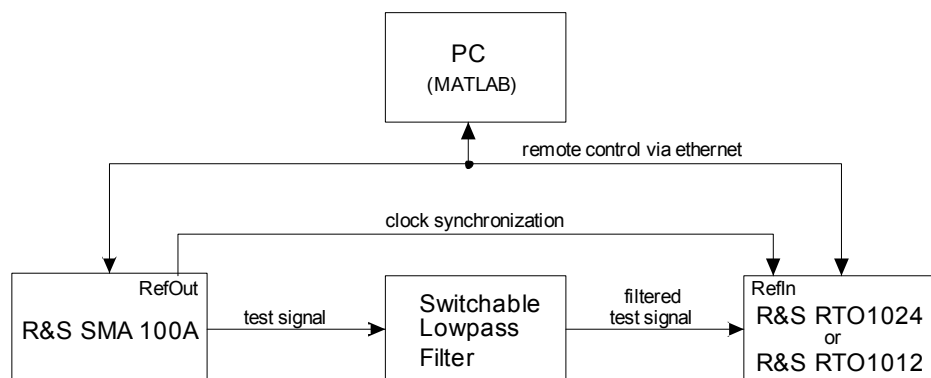
The equipment setup is shown schematically in Figure 4.

To generate the test signal the **R&S<sup>®</sup> SMA100A Signal Generator** is used. The R&S<sup>®</sup> SMA100A is specified for harmonics below 30 dBc. To mitigate the effects of these harmonics on the ENOB measurements, the R&S<sup>®</sup> SMA output is filtered with a **switchable analog lowpass filter**.

The next instrument in the measurement chain is the device under test. As an example the 2 GHz, 4 channel **R&S<sup>®</sup> RTO1024** and the 1 GHz, 2 channel **R&S<sup>®</sup> RTO1012 Digital Oscilloscopes** are tested. The **R&S<sup>®</sup> RTO1024** was fitted with an OCXO (Oven Controlled Crystal Oscillator) option, the R&S<sup>®</sup> RTO-B4. This option has a port for a reference input signal which is provided by the R&S<sup>®</sup> SMA100A. The **R&S<sup>®</sup> RTO1012** was tested without an external reference.

High quality cables were used for transmitting the signals between the instruments. Otherwise these can also be a source of distortion.

Lastly a PC with MATLAB is used to remote control the instruments and also to read and evaluate acquisition data from the R&S<sup>®</sup> RTOs.



**Figure 4: Test Equipment Setup**

### 2.1.2 R&S®RTO Settings

The R&S®RTO is set up with a sampling rate of 10 Gsample/s (no decimation or interpolation) corresponding to a resolution of 100 ps. Further a record length of 10,000 samples is used so that enough data is collected for accurate measurements (see section 1.2.3).

### 2.1.3 Remote Control with MATLAB

One very useful feature of the R&S®RTO is its support of remote control. Using this it is possible to add a high degree of automation into the measurement.

For example the ENOB at 95% of full-scale, over a range of frequencies shall be measured. The exact output level of the R&S®SMA100A depends on the output frequency. In addition, the switchable low-pass filter is not ripple free and the R&S®RTO has its own amplitude frequency response. Using remote control via a MATLAB script, the output amplitude of the R&S®SMA is adjusted to 95% of full scale at each frequency to be measured..

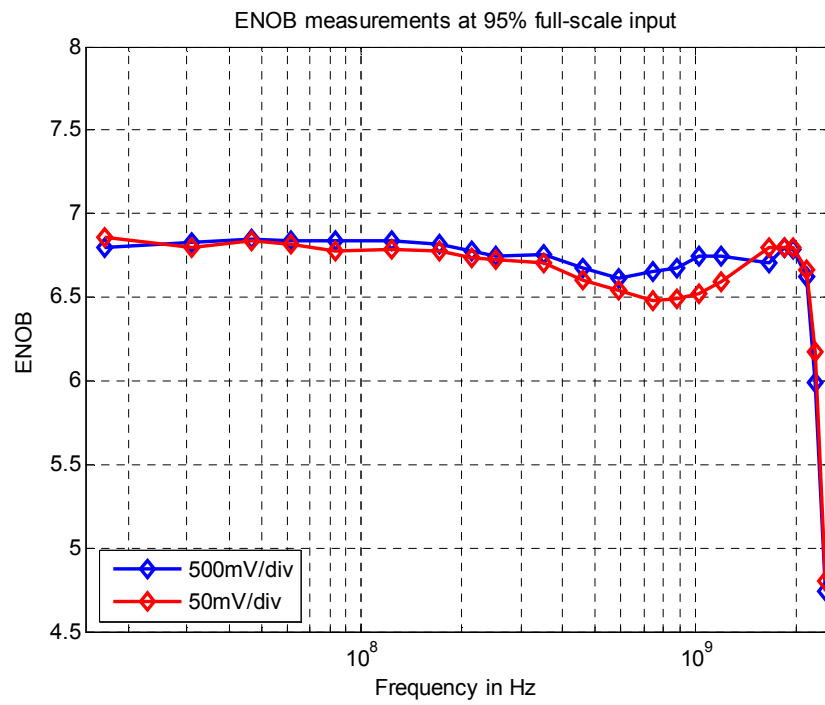
For more information on remote control of the R&S®RTO refer to [3].



## 2.2 Results

Unless otherwise stated, all results were obtained using the OCXO Option to frequency synchronize the R&S®RTO with the R&S®SMA.

### 2.2.1 R&S®RTO1024 at 50 mV/div and 500 mV/div and 95% Full-Scale



## 2.2.2 R&S® RTO1024 at 50 mV/div with and without R&S® OCXO Option

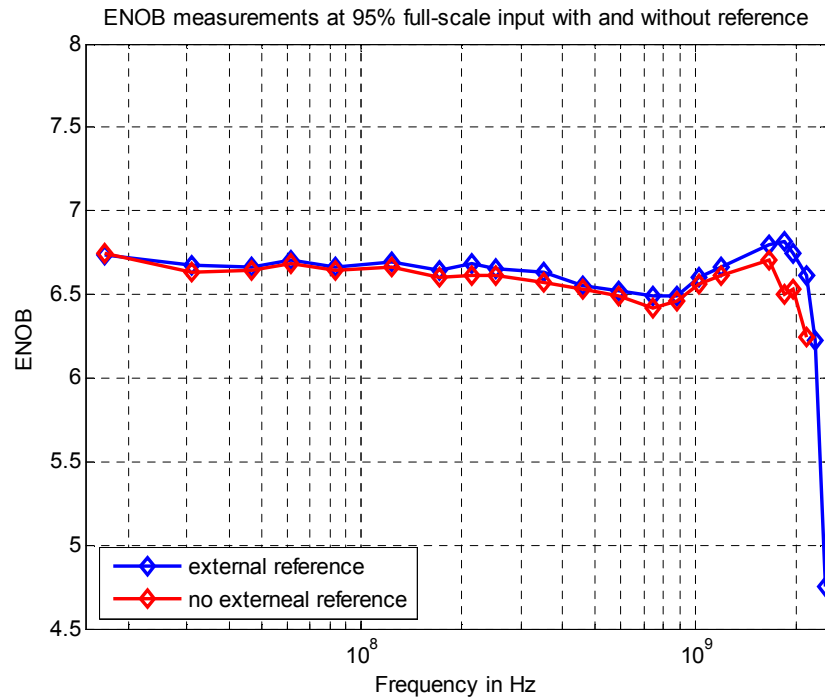
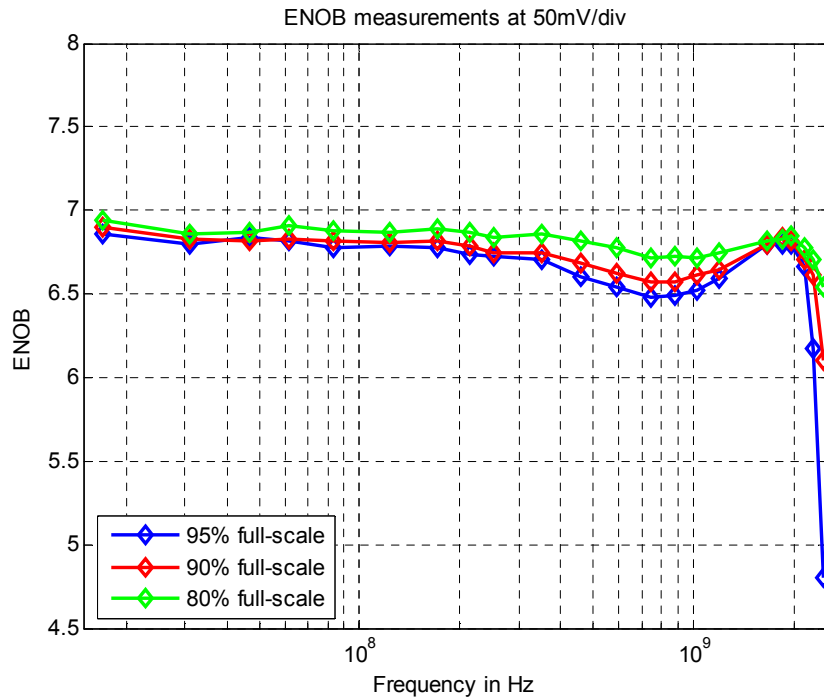


Figure 6: ENOB results for 95% full-scale input at 50 mV/div with and without an external reference

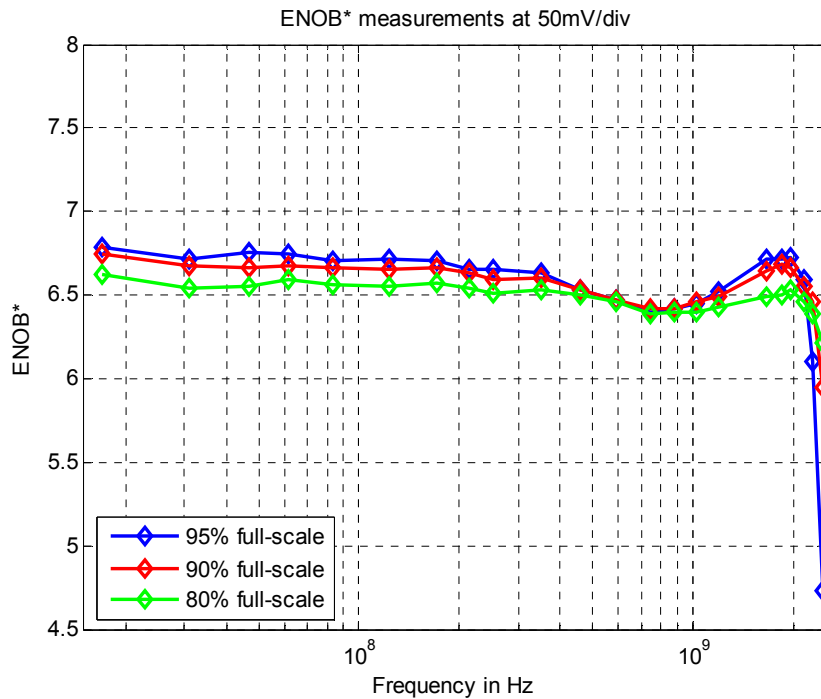
## 2.2.3 R&S® RTO1024 at 50 mV/div with Different Full-Scale Values

Figure 7 shows ENOB measurements for different full-scale values. As expected, the results as calculated with Equation 4 show better ENOB values for lower input amplitudes. This is because less of the non-linearities in the system are tested due to the smaller input amplitude.

Leaving out the normalization gives the results for ENOB\* which are shown in Figure 8. These results are purely dependent on the SINAD.



**Figure 7:** ENOB results for 50 mV/div with different full-scale values. The amplitude differences are compensated in the calculation of the ENOB value, resulting in better results for the lower input amplitudes. This is because the input signal is affected by less of the system nonlinearities.



**Figure 8:** ENOB\* results for 50 mV/div with different full-scale values. The ENOB\* value does not compensate for the difference in input amplitude and is purely dependent on the SINAD.

## 2.2.4 R&S®RTO1012 at 50 mV/div

Measurements for the R&S®RTO1012 were made at 95% full-scale without the R&S®OCXO Option. Note that the R&S®RTO1012 has a bandwidth of 1 GHz and has 2 input channels.

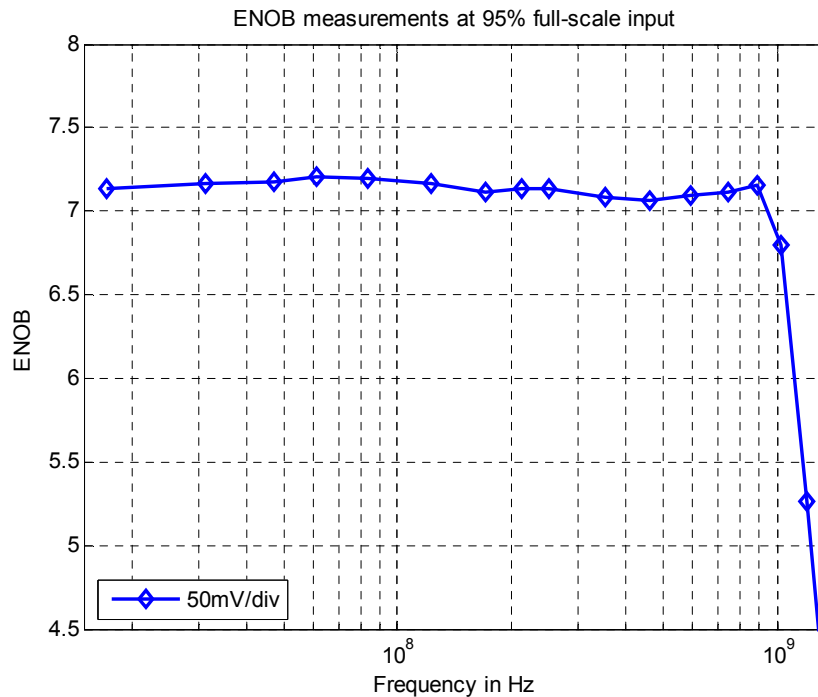


Figure 9: ENOB results for the R&S®RTO1012 (1 GHz bandwidth, 2 channels)

## 2.2.5 Fast Results Directly on the R&S®RTO

Approximate ENOB results can also be obtained directly on the R&S®RTO using the FFT feature.

In the following example a test frequency of 107 MHz was used with a sample rate of 10 Gsample/s and a record length of 10,000 samples.

In the screenshot of Figure 10, the following can be seen:

- Diagram 1 shows the acquired signal.
- Measurement 1 confirms that the input signal is slightly more than 95% of full scale. In this case full scale is 500 mV and 95% of full scale is 475 mV.
- Diagram 2 shows the FFT of the input signal in the frequency range of 0 Hz to 5 GHz.
- Measurement 2 shows the signal power within the range of 120 MHz to 5 GHz, which is equal to approximately -45.4 dBm.
- Measurement 3 shows the signal power within the range of 90 MHz to 120 MHz which is equal to approximately -2.45 dBm.

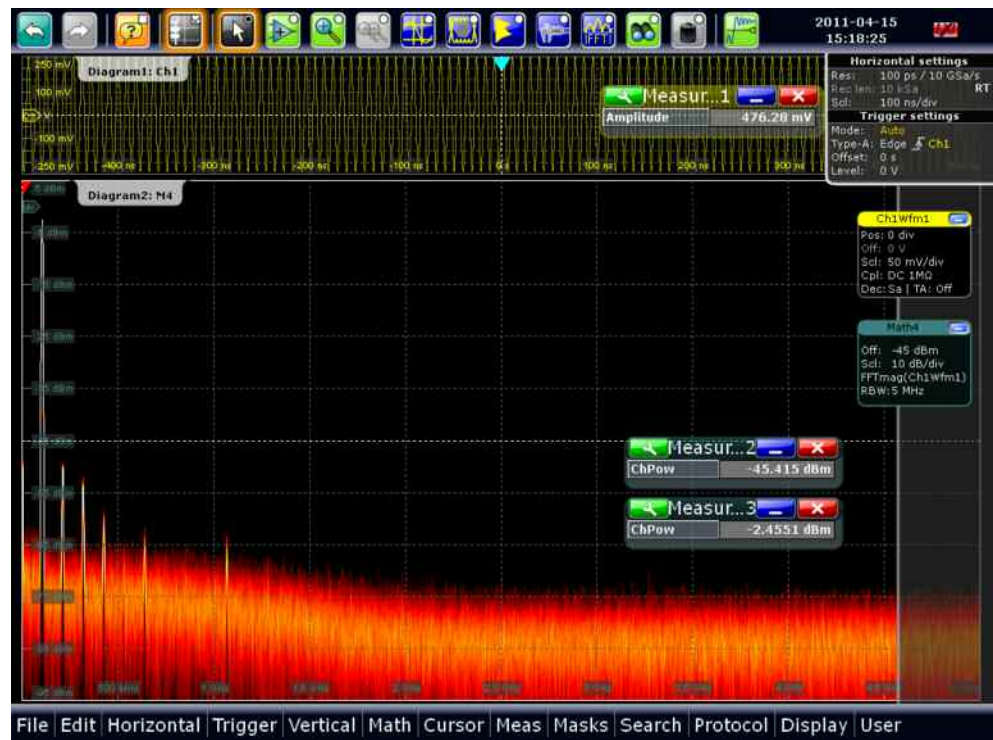


Figure 10: Screenshot for ENOB measurement directly on the RTO.

Using Equation 4, results in

$$\begin{aligned} \text{ENOB} &= 0.5 \log_2 \left( 10^{\frac{-2.45 - (-45.4)}{10}} \right) - 0.5 \log_2(1.5) - \log_2(0.95) \\ &= 7.13 - 0.29 - (-0.074) \end{aligned}$$

which gives an ENOB of approximately 6.9.

Although these results correspond to the measurements made using MATLAB, care should still be taken for the following reasons:

- Firstly, the most accurate ENOB results are obtained when the FFT length is exactly equal to the record length and this is most easily done in MATLAB. In this measurement scenario, directly on the R&S® RTO, this is not the case. This is because the FFT function of the R&S® RTO is optimized for speed and not for an arbitrary setting of the FFT length. This also explains why signal power was measured over a frequency range corresponding to the main signal lobe from 90 MHz to 120 MHz.
- Secondly, as the focus was on obtaining fast results, a measurement of the noise power from DC to 90 MHz was omitted. Including this measurement would result in a marginally worse value for ENOB.

Figure 11 and Figure 12 show the setup screens for the power measurement results of Measurements 2 and 3.

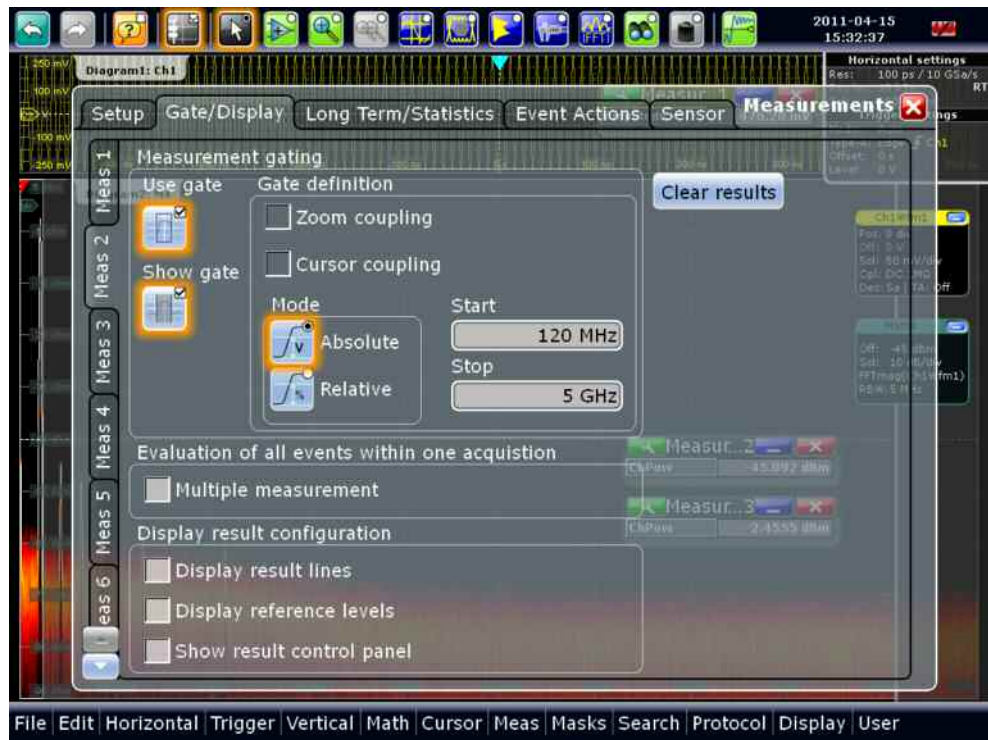


Figure 11: Setup screen for gated measurement of noise and distortion power (Measurement 2).

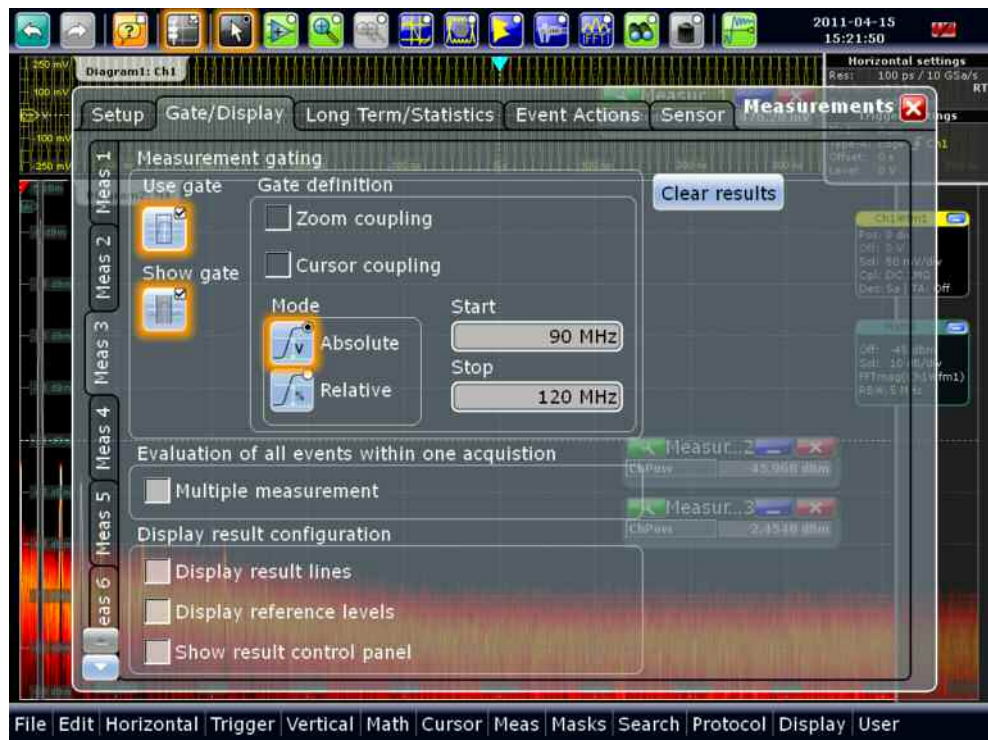


Figure 12: Setup screen for gated measurement of signal power (Measurement 3).

## 2.3 Discussion of Results

The results show that the R&S®RTO1024 has an ENOB well above 6.4 over the whole instrument bandwidth of 2 GHz. The R&S®RTO1012 has an ENOB above 6.7 over the whole instrument bandwidth of 1GHz and an ENOB of 7.1 right up to approximately 900 MHz. These experiments have shown some interesting effects which should be explained.

### 2.3.1 What Causes the ENOB Dip Between 400MHz and 1GHz?

In each of the measurements in the figures above, there is a dip in the ENOB values between 400 MHz and 1 GHz. The reason for this is that the VGA produces stronger harmonics with higher input frequencies. The ENOB climbs again for input signals above 1 GHz because the harmonics of these signals are attenuated by the lowpass filter in the R&S®RTO front end. Thus the ENOB gets better again.

### 2.3.2 What Happens to the ENOB after the Specified Bandwidth?

The R&S®RTO1024 is specified up to 2 GHz and the R&S®RTO1012 is specified up to 1 GHz. Above the specified frequency, input signals are attenuated by lowpass filters in the front end. Achieving 95% full scale on the oscilloscope display means overloading the VGA with the input signal, which results in particularly significant harmonic components, thus quickly degrading the ENOB.

### 2.3.3 Is the Use of the R&S®OCXO Option Really Necessary?

For the most reliable results, it is necessary to use the external reference of the R&S®OCXO option. However good approximate results can also be obtained without it as shown in Figure 6 (only 0.05 bits difference).

### 2.3.4 Effect of Input Signal Amplitude

Figure 5 shows that there is less of an ENOB dip between 400 MHz and 1 GHz for a vertical scale of 500 mV/div than for 50mV/div. This is due to the VGA having to amplify less for a large input signal. This results in less harmonics, thus producing a better ENOB value.

### 2.3.5 ENOB > 7 for the R&S®RTO1012!

Figure 9 shows that the R&S®RTO1012 (which is specified to 1 GHz) has an ENOB of approximately 7.1 right up to around 900 MHz. It dips slightly to 6.75 at 1 GHz. Why is this result better than the R&S®RTO1024? Both instruments sample at 10 Gsample/s but the difference is in the bandwidth. In its smaller bandwidth of 1 GHz (the R&S®RTO1024 has a bandwidth of 2 GHz), the R&S®RTO1012 effectively samples less noise and less harmonics leading to a better value for the ENOB.

## 3 Literature

[1] IEEE Standard for Terminology and Test Methods for Analog-to-Digital Converters, IEEE Standard 1241-2010

[2] R&S®RTO Digital Oscilloscopes, Scope of the Art, Product Brochure

[3] R&S®RTO Digital Oscilloscopes, Remote Commands Reference

## 4 Additional Information

This Application Note is subject to improvements and extensions. Please visit [our website](#) in order to download new versions. Please send any comments or suggestions about this Application Note to [TM-Applications@rohde-schwarz.com](mailto:TM-Applications@rohde-schwarz.com).

## 5 Ordering Information

Naming	Type	Order number
<b>Base unit</b> (included accessories: per channel: 500 MHz passive voltage probe (10:1), accessory pouch, Quick-start manual, CD with manual, power cord)		
<b>Digital Oscilloscopes</b>		
1 GHz, 10 Gsample/s, 20/40 Msample, 2 channels	R&S®RTO1012	1316.1000.12
1 GHz, 10 Gsample/s, 20/80 Msample, 4 channels	R&S®RTO1014	1316.1000.14
2 GHz, 10 Gsample/s, 20/40 Msample, 2 channels	R&S®RTO1022	1316.1000.22
2 GHz, 10 Gsample/s, 20/80 Msample, 4 channels	R&S®RTO1024	1316.1000.24

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