High-Resolution Measurements with R&S Oscilloscopes

Application Note

Products:

- R&S®RTO Digital Oscilloscopes
- R&S®RTE Digital Oscilloscopes
- R&S®RTO-K17 High-Definition Option
- R&S®RTE-K17 High-Definition Option

With the RTO-K17/RTE-K17 High Definition Option the user will see more signal details with up to 16 bit vertical resolution.

In combination with the superior analog front end of the RTO and RTE, the user has a versatile instrument in his hands to analyze a wide range of applications. From Switch Mode Power Supplies to Radar RF, the user can inspect all with one scope.

Application Note

Dr. Mathias Hellwig
4.2015 - 1TD06_0e

ROHDE&SCHWARZ

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1 Introduction

The introduction of high-resolution oscilloscopes is the responds to the increased necessity for more in-depth signal analysis in particular in A&D, automotive, medical and power analysis applications where it is often required to view signals with both large and small voltage details. Characterizing Switched Mode Power Supplies (SMPS) is one example. To perform accurate power measurements the oscilloscope must acquire the voltage during the off and on times within the same waveform. This requires more dynamic range than the typical 8 bit resolution can provide, since the voltage difference can be several hundreds of volts. Another example is the analysis of amplitude modulated RF signals with a small modulation index, which are found in radar applications.

When evaluating an oscilloscope for such applications, its vertical resolution is becoming more and more a key parameter to look at, besides standard parameters like bandwidth, sample rate and memory depth. The vertical resolution determines how precise signal details can be displayed on the oscilloscope and how accurate these details can be measured and analyzed.

Core component of a digital oscilloscope with regard to vertical resolution is the A/D converter. It converts the analog signal at the input channel of the oscilloscope into time and value discrete samples that can be processed and stored in the instrument's memory. The time resolution between the samples is given by the A/D converter's sample rate. The number of A/D converter bits determines the nominal vertical resolution.

Digital oscilloscopes typically use 8 bit A/D converters. Some specialized oscilloscope models however offer more than 8 bits of vertical resolution. One possibility to achieve that is to use A/D converters with more than 8 bits. Another way is to apply digital signal processing techniques in the acquisition path to gain additional resolution.

In both cases it needs to be taken into account that the number-of-bits specification of an A/D converter is a theoretical number. Its resolution, referred to as effective number of bits (ENOB) is lower than the nominal value due to error sources like noise, non-linearity as well as distortion. Furthermore, when evaluating an oscilloscope's dynamic performance the other front end components like amplifier, filter and parasitics needs to be taken into consideration, not just the A/D converter.

This application note introduces the R&S®RTO-K17 and R&S®RTE-K17 High Definition Option for the R&S®RTO and R&S®RTE Digital Oscilloscopes. It enhances the vertical resolution and trigger sensitivity of both oscilloscope families to up to 16 bit by applying digital filtering to the signal in the acquisition path. Upgrading the RTO and RTE with this option can be done on demand by software key-code, which allows for flexibility.

Section 2 of this application note explains the necessary theory and introduces the applied filtering technique. Section 3 compares different post processing methods aimed at resolution gain and shows the advantages of the R&S High Definition option. Last but not least, a few measurement examples are described in section 4.

The following abbreviations are used throughout this Application Note:

- RTO for the R&S®RTO Digital Oscilloscope, RTE for the R&S®RTE Digital Oscilloscope
- "HD-mode" for the R&S®RTO-K17/R&S®RTE-K17 High Definition Option

2 Background

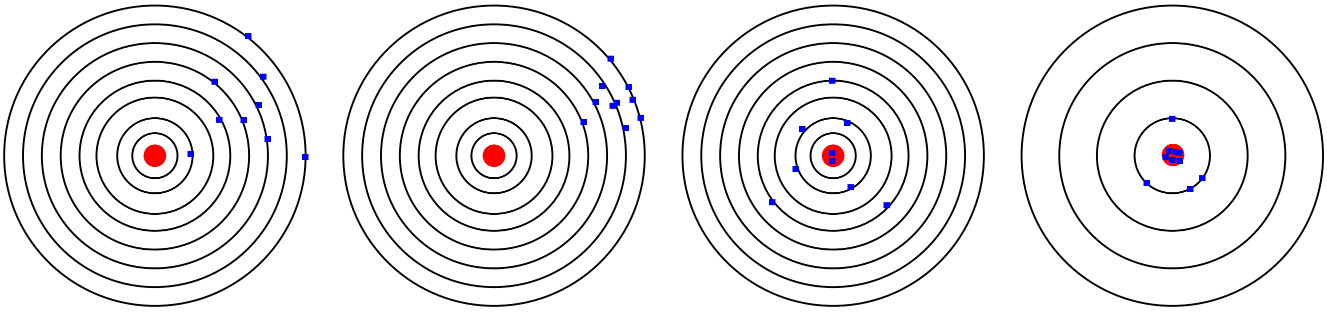
More resolution does not mean automatically more accuracy. Before looking closer to the HD-mode, it is helpful to review terms commonly used for a measurement system.

The ISO standard (1) defines most of these terms, but this document uses them with a slight change that is common for oscilloscopes. This is because the standard does not consider digitization of the measurement. But this step in the measurement cannot be neglected for the study of the HD-mode. Therefore, this document uses the term resolution where the standard uses precision. The term precision is used in the sense of a digital quantity, which is common in computer science and digital signal processing. The terms accuracy and bias are used synonymous to the ISO standard.

2.1 Definition of Measurement Terms

- Accuracy: Accuracy specifies the deviation of multiple measurements from the true value. It is based on resolution, precision and bias.
- Bias: Non-random effects, which cause the difference between the mean of the measurements and the true value.
- Resolution: The random spread of measured values around the average measured values is the resolution. The measured average is not necessary coincident with the true value and may be biased. Consequently is a high precision not necessarily a high accuracy.
- Precision: The measure of the detail, in which a numerical quantity is expressed.

Figure 2-1 depicts the terms accuracy, precision and resolution by showing four targets with a similar pattern of nine dots, spread out and biased. The figure might seem well-know, though there is a slight difference in the meaning of the concentric circles.



low accuracy
high bias
low resolution
high precision

low accuracy
high bias
high resolution
high precision

low accuracy
low bias
low resolution
high precision

high accuracy
low bias
high resolution
low precision

Figure 2-1 Comparison of Accuracy, Bias, Resolution and Precision

The concentric circles represent the analogy to the precision; the more circles the higher the precision and the more details can be expressed in the measurement results. Every measurement, indicated as a blue dot has to be located on a circle. The center of the target marked in red equals the true value. The first three targets from the left display a high precision, the right one a lower precision.

The first target from the left has a low resolution, high bias and a low accuracy. The second target shows a high resolution, but due to the bias, the accuracy is low. Next target is accurate, but lacks of resolution. The last has a high accuracy and a high resolution, even though it has a lower precision. This example clearly visualizes that a measurement done with high precision is not automatically more accurate than a measurement done with a lower precision. On the contrary, it shows that a measurement with lower precision can be the more accurate one.

For instruments such as an oscilloscope the user expects a high accuracy for all signal conditions, but the data sheet typically specifies only the accuracy of DC measurements, not the accuracy of AC conditions. Instead the data sheet typically mentions the precision or nominal vertical resolution of the A/D converter. From the Figure 2-1 above, it is obvious that it is impossible to conclude accuracy only from nominal precision.

For an oscilloscope the HW architecture determines the nominal precision. The systematic errors of the hardware implementation, like noise and dynamic non-linearity, define the resolution and the random errors of the system, like offset and static non-linearity, characterize the bias. Different components contribute to these different errors, not only the A/D converter.

Commonly oscilloscopes use A/D converters with 8 bit numerical precision; some specialized oscilloscopes use A/D converters with 10 up to 12 bit or higher nominal resolution or precision. If an oscilloscope has a good accuracy and resolution, then, and only then, an increase in precision will improve the resolution and consequently the accuracy of the measurement by a finer vertical granularity.

The next sections will show how digital signal processing can achieve an increase in resolution and precision.

2.2 Signal-to-Noise Ratio to Effective Number Of Bits (ENOB)

The data sheet of an oscilloscope does not specify accuracy and resolution for AC signals. Various errors of the A/D limit the accuracy of an oscilloscope. Therefore, it is important to understand the relation between the resolution of the oscilloscope and the precision expressed in bits.

The nominal precision of the A/D converter is not equal to the effective resolution of the oscilloscope. To characterize the effective resolution oscilloscope, the Signal-to-Noise Ratio (SNR) is measured (2). Using the SNR, the ENOB will be derived as a measure for the effective resolution.

For an ideal A/D converter the relation between the calculated SNR (SNR_{dB}) and the resolution is given in several references (3) and presented in equation (2-1).

$$SNR_{dB} = 6.02 \cdot N + 1.76 \tag{2-1}$$

An oscilloscope with a real world A/D converter has the impairments as aforementioned noise, non-linearity and distortion. To relate the real world A/D converter with the ideal A/D converter, the rms quantization error of an ideal A/D converter is set equal to the rms noise (and distortion) of the oscilloscope. Using the measured SNR (SNR_{Meas}), the effective resolution in bits can be calculated. Equation (2-2) shows the result. The resolution is expressed as bits of an ideal A/D converter, which is not necessarily an integer, and is called effective number of bits (ENOB).

$$ENOB = \frac{SNR_{Meas} - 1.76}{6.02} \tag{2-2}$$

For oscilloscopes with real A/D converters the ENOB will be lower than the precision expressed in number of bits due to noise and distortion. The RTO and the RTE have a superior noise performance in the analog front end. The deployed A/D converter has numerical resolution of 8 bit and an ENOB of more than 7 bit up to 4 GHz.

2.3 Noise Reduction with Filtering

The previous chapter showed the relation between precision, bias, resolution and SNR. This chapter examines now the spectral properties of the signal and noise and presents the gain in resolution if a filter is applied. This discussion neglects distortion effects, which is a good assumption for the linearity of the analog frontend of the RTO and RTE.

Trends in the area of A/D converter development (4) show, that the sample rate of new A/D converter designs strongly increases over time, whereas the resolution of the A/D converter designs are relatively constant. With this trend in mind, techniques have been developed, which can improve the resolution of an A/D converter in the digital domain, like the one presented in this section. These techniques interchange sample rate with vertical resolution for oversampled signals. A common example is the 1 bit sigma-delta A/D converter in 24 bit audio applications.

The noise of an ideal A/D converter as well as an equivalent, high quality real A/D converter can be regarded as pure white noise (3). White noise is evenly distributed in the spectrum, means that in the interval $[-f_a/2 \leq f \leq f_a/2]$ the noise spectral density $p_N(f)$ is constant. The magnitude of the noise spectral density in this case equals the total rms noise power P_N divided by the sampling frequency f_a.

In case of oversampling, means the bandwidth of the signal $S(f)$ is much smaller than the sampling frequency f_a, the bandwidth of the sample signal can be reduced by a filter without changing the signal $S(f)$. For the sake of simplicity, this section assumes a rectangular filter $X(f)$ with a cut-off frequency f_B. This is shown in Figure 2-2. From the figure, it becomes obvious that the total noise power is reduced by the ratio of sampling frequency f_a to cut-off frequency f_B. The gain in decibels is expressed in equation (2-4)

$$p_N(f) = \frac{P_N}{f_a} \tag{2-3}$$

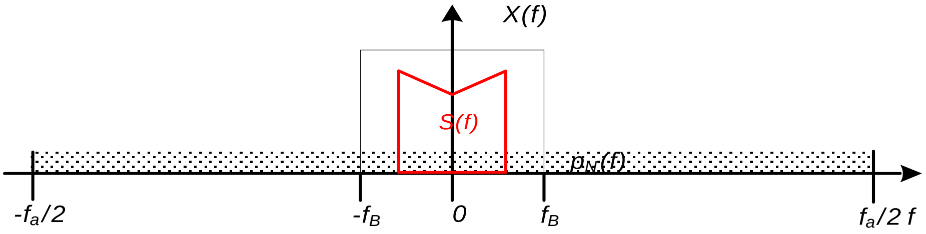


Figure 2-2 Reduction of noise Power by filtering.

$$SNR_{gain} = 10\log\left(\frac{f_a}{2 \cdot f_B}\right) \tag{2-4}$$

Proakis (3) showed that doubling the sampling frequency f_a, while maintaining the filter bandwidth, reduces the power of the noise and consequently the SNR by a factor of $\sqrt{2}$ or 3 dB equals ½ bit. This result is true for any quantizer. If the sample rate is increased by a factor of 4 or 6 dB, the gain in resolution equals 1 bit, according to equation (2-2).

2.4 Filter for Noise Reduction

The previous chapters showed the dependencies of accuracy and resolution, and how the resolution can be improved by a low pass filter (LPF). This chapter will prove how the filter will limit the bandwidth and increase the precision, so that the gain in resolution can be displayed with sufficient precision.

Several types of LPF are available to limit the bandwidth, but in this chapter the focus is on a moving average filter (MAV) to simplify the discussion. A MAV filter calculates the arithmetic average for every output value y_n out the most recent M samples $x_n \dots x_{n-M+1}$. In this context the parameter M is called the filter length. For the arithmetic average, the mathematical definition requires a division by the filter length M, which ensures that the average signal power of the filter output is the same as of the original input signal. Equation (2-5) gives the exact definition. For the next paragraph a simple example assumes the filter length of 2 and an input sequence x_n with signed integers of 8 bit precision.

Under the assumption above, the MAV filter sums up the two most recent samples and divides these by two, $y_n = (x_n + x_{n-1})/2$. The result of the sum $(x_n + x_{n-1})$ for this 8 bit example is in the range of $-256 \dots 254$, because the input values are in the range of $-128 \dots 127$. Using fixed point arithmetic, the result of the sum requires 9 bit precision $\left(\cong ld(511)\right)$ to display the 511 possible output values. Effectively there is a gain in precision of 1 bit compared to the 8 bit input values and with the fixed point arithmetic this gain can be preserved also after the following division, in this example by 2.

This example can be generalized to any filter length M using fixed point arithmetic, with M being a positive integer number. For an arbitrary filter length, the gain in precision is the logarithm to the basis 2 of the filter length of the MAV filter. In case the filter length equals the power of two $(2,4,8,16,\ldots)$ the gain is an integer number $(1,2,3,4\ldots)$. For all other filter lengths, the gain in precision is a fractional number, and the fixed point arithmetic will truncate the result to the hardware precision. In case of RTO and RTE the hardware precision is 16 bit. The introduced error due to truncation is negligible.

$$y_n = \frac{1}{M}\sum_{i=0}^{M-1} x_{n-i} \tag{2-5}$$

The reason to introduce also a filter length other than powers of two, becomes obvious, when the associated bandwidth of the filter is considered. The last chapter 2.3 examined the noise reduction in relation to the applied filter bandwidth. This chapter explained so far the increase in precision. Now the link between precision, filter bandwidth and ultimately the resolution is given.

The pulse response y_n of a moving average filter is a time discrete rectangular-function (see Figure 2-3). The transfer function $H(f)$ in the frequency domain of this filter is the time discrete Fourier-transform of this pulse response.

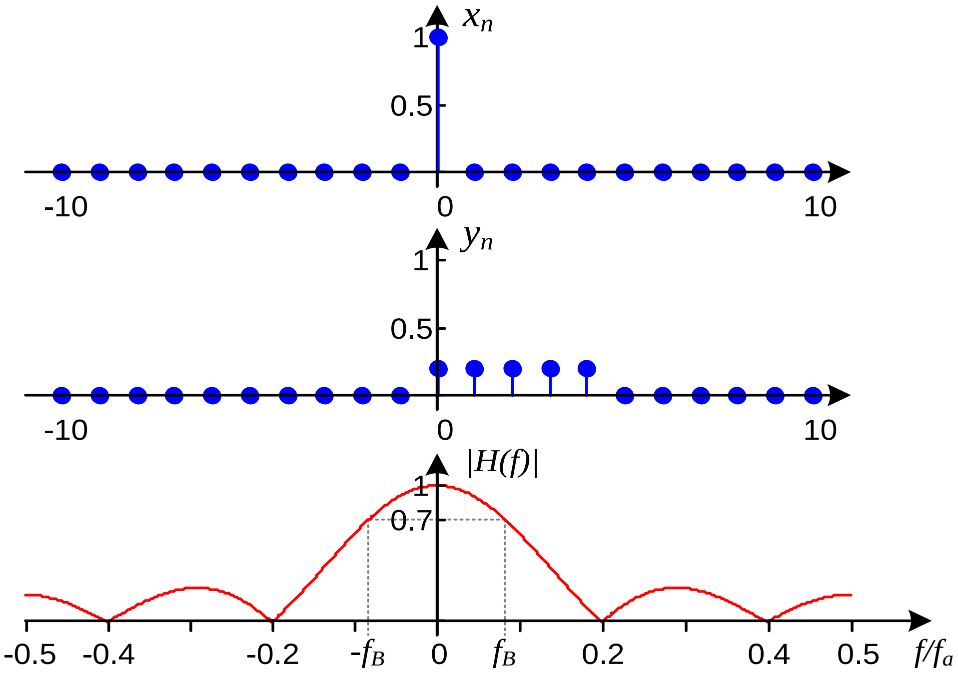


Figure 2-3 Filter pulse response and filter bandwidth of a MAV filter with a filter length of M=5

Based on the pulse response, equation (2-6) presents the magnitude of the transfer function $|H(f)|$ in the frequency domain for a moving average filter. Proakis (3) gives more details on the derivation of the transfer function. The frequency f is scaled to the sampling frequency f_a and exists in the range of $-0.5 \ldots 0.5$. The filter cut-off frequency f_B, which is the frequency at which the signal is attenuated of -3 dB or 0.7 relative to the pass band, depends on the filter length M. It is not possible to derive the cut-off frequency in a closed form.

$$|H(f)| = \frac{\sin(\pi \cdot M \cdot f)}{M \cdot \sin(\pi \cdot f)} \qquad \textbf{(2-6)}$$

Using the example of an MAV filter of the filter length M=5, the 3 dB bandwidth is at $0.09 \cdot f_a$, the gain in precision is $2.3 \cong ld(5)$ and the gain in SNR is 7.4 dB according to equation (2-4).

2.5 Limitations of discussed Noise Reduction

There are limitations for this method that the user should pay attention to. The most significant limitation of noise reduction is distortion caused by linearity errors in the A/D converter and analog front end, which cannot be reduced. Testing these errors with a sine wave, the Spurious Free Dynamic Range (SFDR) is a measure for the distortion (5). It is measured in dB and the larger the SFDR the lower the distortion. The previous sections have so far neglected the distortion due to the assumption of an ideal A/D converter, but the SFDR will limit the gain of resolution for a small filter bandwidth.

The IEEE standard (5) is more specific and distinguishes between noise and distortion and introduces therefore the signal-to-noise-and-distortion ratio (SINAD). For a large bandwidth the noise typically dominates the SINAD. Reducing the noise by filtering, the distortion becomes more relevant and starts to dominate the SINAD.

Comparing the measured SFDR of a 4GHz / 8 bit A/D converter RTO with a specialized high resolution oscilloscope with higher precision than 8 bit ADC, it turns out that the minimum SFDR numbers are comparable (see Figure 2-4). Also for the so called high resolution oscilloscope the SFDR is the limiting factor, showing a minimum of 46 dB.

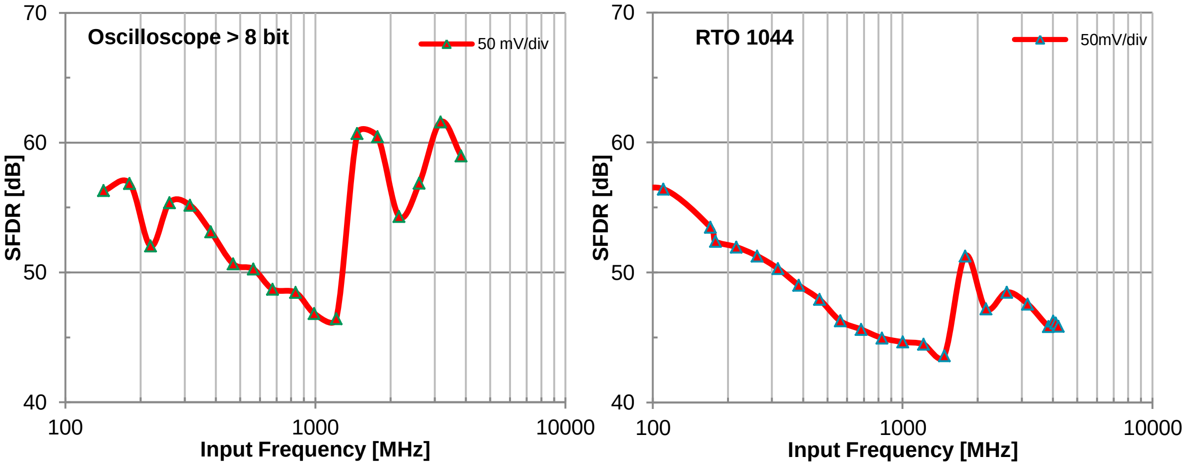


Figure 2-4 SFDR of a high resolution oscilloscope and the RTO1044.

Another limitation is the width of the data path to process the samples. The hardware precision must be sufficient to represent the gain in resolution. For the RTO and RTE the width of the data path in HD-mode is 16 bits, which is a unique feature for oscilloscopes.

Last but not least, the previous discussion used the basic assumption that the noise floor is evenly distributed. Though this is a fairly good assumption, it may not hold true for a high ratio of sampling frequency to cut-off frequency of the digital filter. In this case the influence of the $1/f$ noise is not negligible anymore and the equation (2-4) is not valid. This will reduce the expected gain in SNR.

3 Resolution Enhancement with RTO & RTE

The RTO and RTE have several ways to reduce the noise by applying filter techniques. Chapter 2.3 explained already the underlying theory, so that this section focuses on the benefits on the individual filter methods.

3.1 Resolution gain through different noise reduction techniques

3.1.1 16 bit High Definition Option (HD-mode)

The HD-mode implements a digital filter in the acquisition path of the oscilloscope, see Figure 3-4. The filter architecture has a linear phase response, no ringing and is alias-free. This gives the user a high degree of signal fidelity under all possible filter settings. If the signal contains frequency components, higher than the filter cut-off frequency, the filter will suppress these components. The RTO for example samples the signal with a constant sampling rate of 5 Gsample/s. Additionally decimation is possible by selecting a lower sample rate. Unlike for the "High res" mode, decimation is implicit. For the HD-mode, further decimation allows an economic use of the acquisition memory.

Table 1 lists the precision or vertical resolution dependent on the filter bandwidth of the HD-mode. This filter bandwidth equals the cut-off frequency of the LPF. Depending on the oscilloscope model, filter bandwidth starts at 1 GHz and can go down to 10 kHz.

Table 1 - Vertical Resolution vs. Bandwidth Limit

Bandwidth [MHz]	Resolution [b]		Bandwidth [MHz]	Resolution [b]	
	RTE	RTO		RTE	RTO
0.1	16	16	20	16	16
0.2	16	16	30	16	16
0.3	16	16	50	14	16
0.5	16	16	100	13	14
1	16	16	200	12	13
2	16	16	300	11[1]	12
3	16	16	500	10[2]	12
5	16	16	1000	--	10[3]
10	16	16			

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[1] Not for RTE102x

[2] Not for RTE102x and RTE103x

[3] Not for RTO100x

The benefit of the introduced noise reduction for the user is a better signal resolution and improved trigger sensitivity, which chapter 3.3 will highlight. The HD-mode brings high flexibility to the RTO and RTE oscilloscope. Based on his application the user can decide to use it as a high bandwidth, mid resolution oscilloscope or as a high resolution, lower-bandwidth oscilloscope with one instrument. Figure 4-2 shows the configuration dialog for setting the bandwidth.

3.1.2 "High res" Decimation

The "High res" decimator is a processing block in the acquisition path of the oscilloscope. It consists out of a MAV filter followed by a decimator, so that the filter length equals the decimation factor (N) of the decimator (see Figure 3-1). The decimation factor is the ratio between the A/D converter sample rate of 10 Gsample/s (RTO) and the configured sample rate.

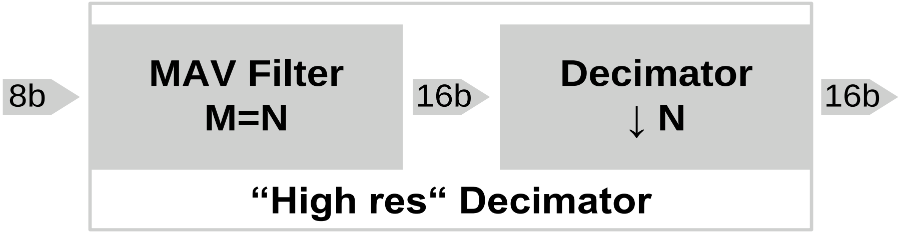


Figure 3-1 Building Blocks of the "High res" Decimator

Chapter 2.4 already discusses the MAV filter, which limits the bandwidth and increases the precision. But the relative flat roll-off of the filter (see Figure 2-3) together with the following decimation impacts the signal fidelity. The next section will examine this in further detail.

According to the sampling theorem, a signal can be reconstructed using the samples if the signal is band limited so that the maximal frequency f_S is lower than half the sampling frequency $f_a/2$. This sampled signal has a spectrum, which replicates the spectrum of the original signal by multiple ($m = [-\infty, \infty]$) of the sampling frequency $m \cdot f_a$. The decimation by the factor of N changes the replication of the spectrum of the original signal to $f_a \cdot m/N$ (3).

Figure 3-2 shows the spectrum $|H(f)|$ before (top) and after decimation (bottom) by a factor of 5. The decimation step creates five times more replicas, which are shown in a blue graded color. In the decimated spectrum an overlay of the original spectrum is observed and marked with a shaded triangle. This aliasing impacts the signal fidelity unfavorably and the original signal cannot be reconstructed anymore. Chapter 3.2 compares the "High res" option and the HD-mode and presents a real world example.

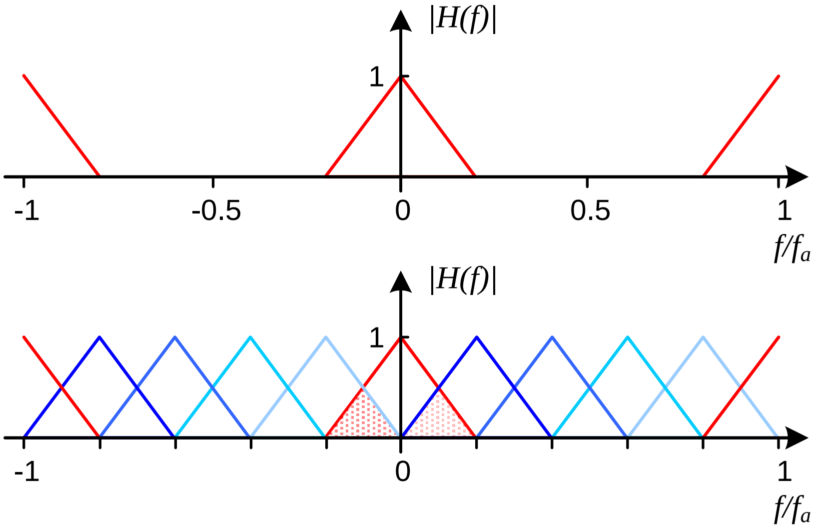


Figure 3-2 "High res" spectrum without and with decimation

3.1.3 Waveform Averaging

Waveform averaging reduces noise by averaging every sample of consecutive acquisitions. It is a common noise reduction technique building an ensemble average with a configurable number of acquisitions. This method has a few limitations. First it only works for periodic signals, like sinusoidal signals or clock signals, which limit the applicability for this method.

Second the accumulation of the average over several waveforms requires a digital signal processing post the acquisition memory, usually in software though RTO and RTE support this in HW. The accumulation limits the performance in terms of acquisition rate as a stable output is only available after the completed accumulation.

3.2 Comparison of HD-mode versus "High res"-mode

In order to demonstrate the differences in signal fidelity between the "High res" decimation and the HD-mode, which were already discussed in theory, a 10 MHz digital clock signal is analyzed to show the advantages of the HD-mode.

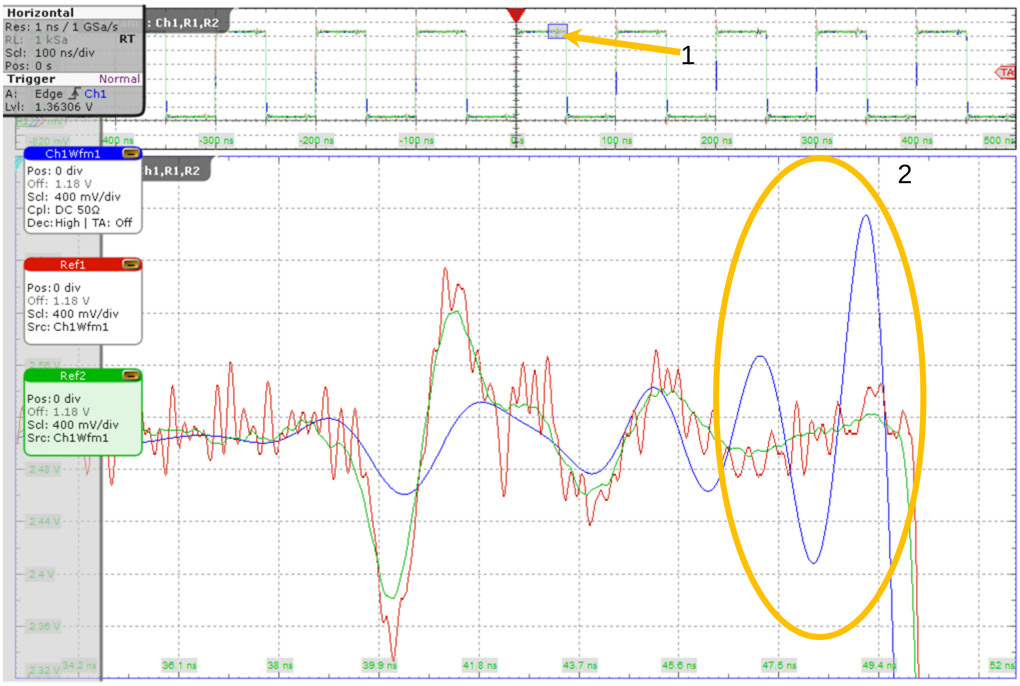
Figure 3-3 displays three waveforms all taken from the same clock signal captured with a 2 GHz RTO and a 3 GHz active probe (RT-ZS30). This bandwidth is more than sufficient for this signal with a relatively low period of 100 ns and a rise time of about 800 ps.

The blue waveform is a "High res" decimated acquisition of the clock signal with a decimation rate of 1:10. The red waveform is the original waveform without digital signal processing and 8 bit vertical resolution that shows significant amount of noise. The green waveform is the original waveform applied to digital signal processing of the HD-mode using a comparable noise bandwidth (500 MHz) as the one of the "High res" decimation.

The top graph displays all three waveforms and the waveforms seem to match pretty well. A zooms is applied, the zoom window is marked "1" in Figure 3-3, and displayed in the second graph. From the zoom graph, the reader can make a few important observations. Both methods, the "High res" decimation (blue) and the HD-mode (green), noticeably reduce the noise of the original waveform (red) shown in the left side of the zoom graph.

The difference between "High res" decimation and the HD-mode becomes apparent by looking at mark "2" in Figure 3-3. The mark shows a significant ringing of the "High res" decimated waveform, which is in contrast to the original waveform and the waveform processed with the HD-mode. This artifact reveals a significant flaw in the "High res" decimation as already discussed in chapter 0.

The applied zoom interpolates the waveform under the assumption of an alias free signal. However, this does not hold true for the "High res" decimation. In signal areas with high frequency components, like the falling edge in the clock signal, the aliasing in the "High res" decimated signal causes some kind of ringing and a loss in signal fidelity. The HD-mode does not show such a behavior and this is a clear advantage.



Horizontal
Res: 1 ns / 1 GSa/s
RL: 1 kSa RT
Scl: 100 ns/div
Pos: 0 s
Trigger Normal
A: Edge Ch1
Lvl: 1.36306 V

Ch1Wfm1
Pos: 0 div
Off: 1.18 V
Scl: 400 mV/div
Cpl: DC 50Ω
Dec:High | TA: Off

Ref1
Pos:0 div
Off: 1.18 V
Scl: 400 mV/div
Src: Ch1Wfm1

Ref2
Pos:0 div
Off: 1.18 V
Scl: 400 mV/div
Src: Ch1Wfm1

Figure 3-3 Comparison of noise reduction techniques (green: HD-mode; blue: "High res"; red: original)

3.3 Benefit of the HD-mode on the Trigger System

The discussion about high resolution oscilloscopes has not touched yet the important fact, that an increase in resolution for the displayed waveform will likewise require an improvement in the trigger system for an adequate and consistent analysis.

A measure for the precision of the trigger is the trigger sensitivity, which expresses the necessary vertical signal change to start an acquisition. Typically data sheets express the trigger sensitivity in units of vertical divisions. For most of the high-resolution oscilloscopes, the trigger sensitivity is not sufficiently increased to cope with the increase in resolution.

As a result, the A/D converter captures more signal details, but the oscilloscope cannot display these details in a stable mode, because the trigger is lacking sensitivity. Chapter 4.3 will present an example for this behavior.

To understand the issue, a closer look into the oscilloscope system is helpful. Figure 3-4 shows a schematic view of an oscilloscope with the analog frontend, the A/D converter, the acquisition processing and memory. The precision of acquisition path is indicated between the building blocks. In addition to these blocks, there is a (post)processing, for math and measurement functions and a display to examine the waveforms.

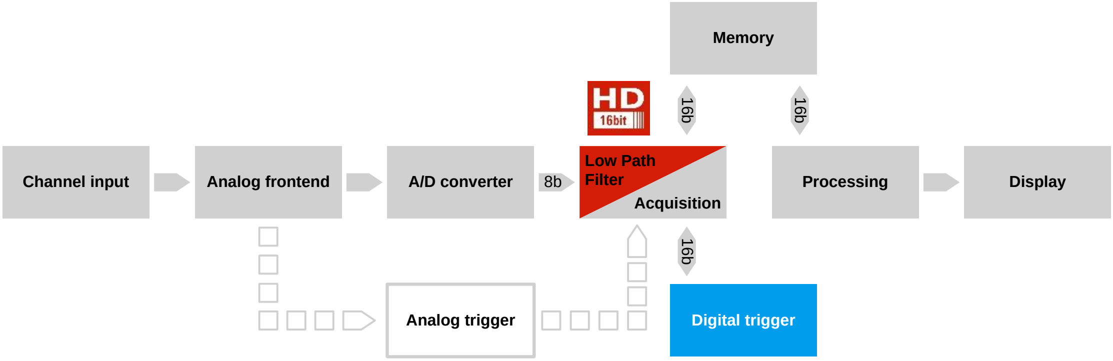


Figure 3-4 Conceptual view of an Oscilloscope

Conventional oscilloscopes implement the trigger as an analog trigger shown in Figure 3-4 as an outlined block. This trigger type uses the same input signal as the A/D converter, but opens a different signal path parallel to the A/D converter. This path difference cannot be compensated under all operating points and conditions, so that the result is an increase in trigger jitter visible in a mismatch between the displayed waveform and the trigger point. Moreover increasing the resolution of the A/D converter does not improve the analog trigger block and the trigger sensitivity.

The RTO and RTE do not share the concept of an analog trigger, rather implement a digital trigger (6), which determines the trigger events based on A/D converter samples without post processing, shown in Figure 3-4 in the blue block. The noise reduction of the HD-mode happens in the acquisition block, so that the digital trigger benefits from the noise reduction of the HD-mode on top of the already excellent trigger sensitivity. Additionally, this enhancement is not only available for the simple edge trigger rather it applies for complete set of trigger types of the RTO and RTE.

Table 2 compares the trigger sensitivity of traditional oscilloscope architectures with various resolutions and the digital trigger based on RTO and RTE architecture. It shows the characteristics of the oscilloscope in terms of channel bandwidth with nominal resolution and the trigger bandwidth with the trigger sensitivity. In order to relate the trigger sensitivity to the nominal resolution, the bottom row calculates the trigger sensitivity in units of LSB instead of div.

Table 2 - Trigger sensitivity

	RTO/RTE	Traditional oscilloscope architectures		
Nominal resolution # bits	8	8	10	12
Channel BW [GHz]	4.0/2.0	4.0	6.0	1.0
Trigger BW [GHz]	4.0/2.0	4.0	3.0	1.0
Sensitivity [div]@Channel BW	0.04	1.0	0.4	2.0
Sensitivity [LSB]	1[4]	32	51[5]	512

This table clearly shows the benefit of the digital trigger, as oscilloscopes with this architecture have a sensitivity of 1 LSB, whereas the traditional oscilloscope architecture shows significant lower trigger sensitivity. High resolution oscilloscopes do not adequately scale the sensitivity with the resolution rather decrease the sensitivity or limited the trigger bandwidth.

An important notice, unlike the HD-mode the "High res" mode does not improve trigger sensitivity.

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[4] This specifies the trigger sensitivity without HD-mode

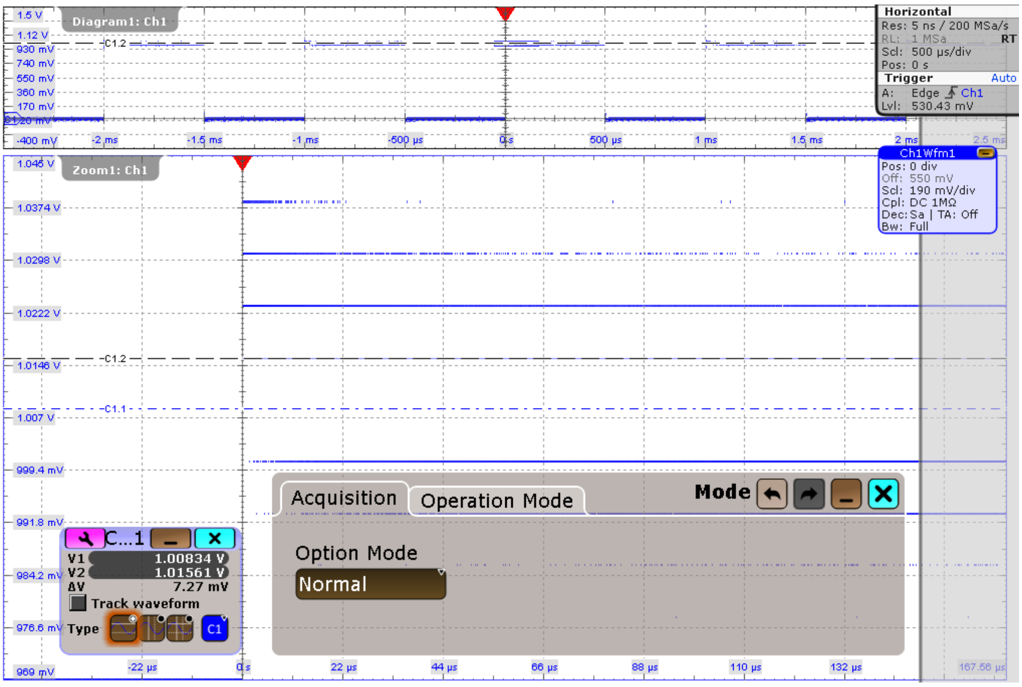
[5] The bandwidth of the trigger path is significantly limited compared to the channel bandwidth

4 HD-mode Measurement Examples

4.1 Visualization of the Gain in Vertical Resolution

The RTO and RTE can easily illustrate the gain in vertical resolution or precision with the HD-mode. The Figure 4-1 gives a simple example, which displays the waveform and the zoom of the 1 kHz probe calibration signal with a 4 GHz RTO.

Setting the display to dots mode and enabling the sample&hold interpolation reveals the quantization levels of the 8 bit ADC. The quantization level can be measured for example with a horizontal cursor in this case to 7.3 mV. This corresponds well to the expected value: 190 mV/div * 10 div / 2^8.



Horizontal
Res: 5 ns / 200 MSa/s
RL: 1 MSa
Scl: 500 µs/div
Pos: 0 s

Trigger Auto
A: Edge Ch1
Lvl: 530.43 mV

Ch1Wfm1
Pos: 0 div
Off: 550 mV
Scl: 190 mV/div
Cpl: DC 1MΩ
Dec: Sa | TA: Off
Bw: Full

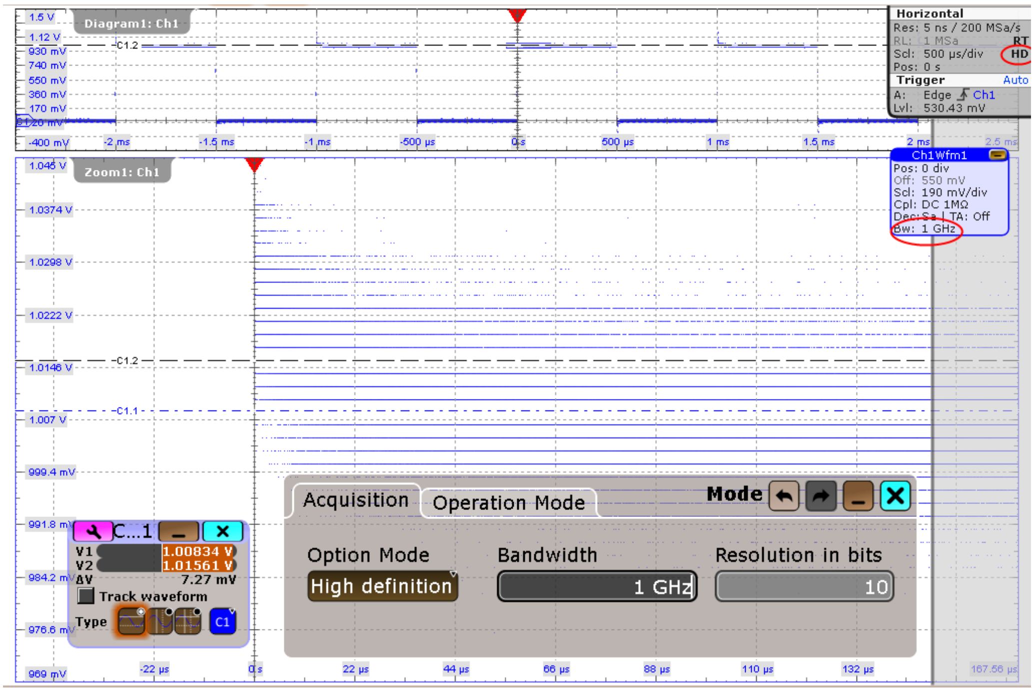
C...1
V1 1.00834 V
V2 1.01561 V
ΔV 7.27 mV
☐ Track waveform
Type

Option Mode: Normal

Figure 4-1 Quantization levels "Normal Mode"

This was the default acquisition mode, for the RTO/RTE. In a next step the HD-mode is applied. In the Mode menu the Option Mode is changed from "Normal" to "High definition" and a filter of 1 GHz bandwidth is selected. Figure 4-2 exposes the difference. Between the cursor lines, the four additional quantization levels have appeared which matches the difference in vertical resolution from 8 bit in Normal mode to 10 bit in High definition mode at 1 GHz bandwidth.

The RTO and RTE indicate this mode by HD in the signal bar and the RTO also displays the configured bandwidth in the respective signal icon. Both indications are encircled in red in Figure 4-2.



Horizontal
Res: 5 ns / 200 MSa/s
RL: 1 MSa
Scl: 500 µs/div
Pos: 0 s

Trigger: Auto
A: Edge Ch1
Lvl: 530.43 mV

Ch1Wfm1
Pos: 0 div
Off: 550 mV
Scl: 190 mV/div
Cpl: DC 1MΩ
Dec: Sa | TA: Off
Bw: 1 GHz

C...1
V1 1.00834 V
V2 1.01561 V
ΔV 7.27 mV
☐ Track waveform

Mode
Option Mode: High definition
Bandwidth: 1 GHz
Resolution in bits: 10

Figure 4-2 Quantization levels "HD-mode"

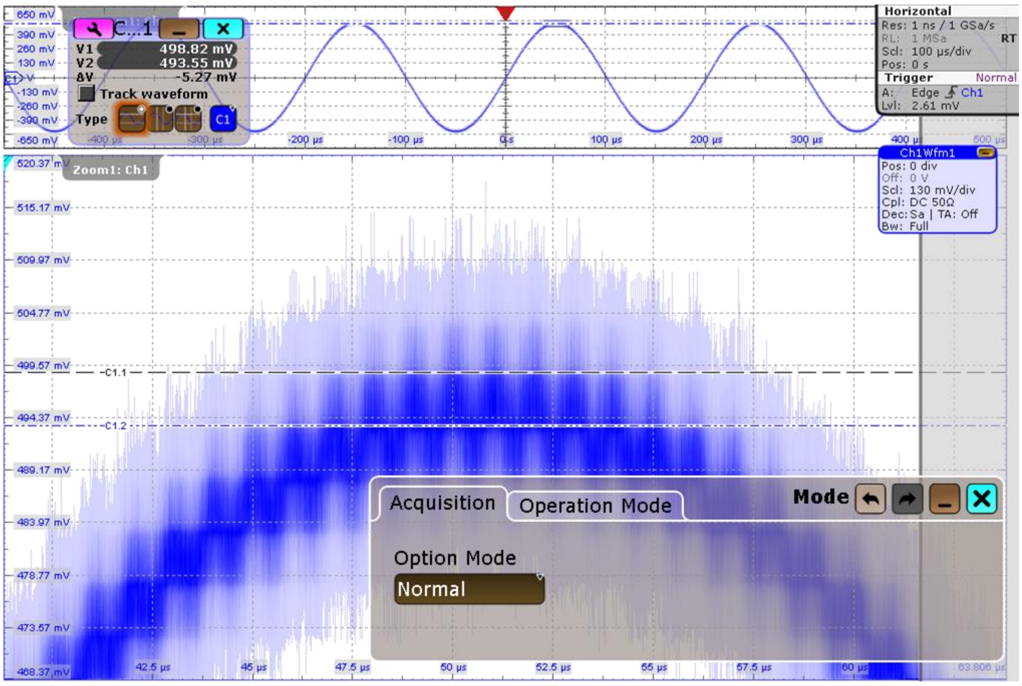
4.2 Detection of Small Signals

The previous section was a specific example to show the gain in vertical resolution. A more real-world scenario is the analysis of a large signal with a small disturbance. This is the case when high resolution becomes very useful, because decreasing the vertical scale to analyze the disturbance will not work. The large signal would drive the oscilloscope out of range into an overload condition and void the measurement.

Figure 4-3 shows a 5 kHz, 1 V amplitude sinusoidal signal and a zoom to the maximum of the signal. From the screenshot, there seems to be a lot of noise added to the signal, and a disturbance is vaguely visible. At the most, the quantization levels of 5.1 mV can be measured with the cursor.

In this case the HD-mode lets the user see more signal details (see Figure 4-4). The mode is enabled via the mode menu and the bandwidth field in the menu is decreased step-by-step as the improvement in the graph is observed. At a bandwidth of around 30 MHz, the zoom graph clearly reveals the disturbance.

Now the HD-mode allows not only to detect a small sinusoidal disturbance, but also to analyze it. Using the cursor, the user measures a frequency of 1.02 MHz and amplitude of 4.9 mV for the disturbance. Both values matches well the parameters used for the generation of this compound signal. This amplitude is even lower than the nominal ADC resolution of 8 bit with a LSB of 5.08 mV(130 mV/div * 10 div / 2^{8})!



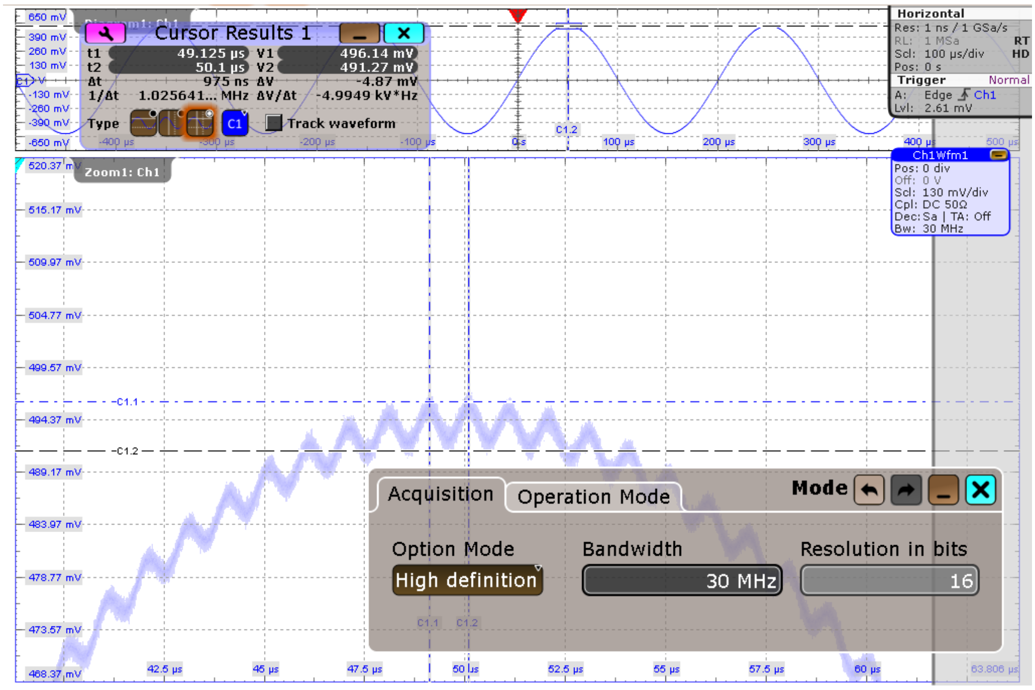
C...1
V1 498.82 mV
V2 493.55 mV
ΔV -5.27 mV
☐ Track waveform

Horizontal
Res: 1 ns / 1 GSa/s
RL: 1 MSa
RT
Scl: 100 µs/div
Pos: 0 s
Trigger Normal
A: Edge Ch1
Lvl: 2.61 mV

Ch1Wfm1
Pos: 0 div
Off: 0 V
Scl: 130 mV/div
Cpl: DC 50Ω
Dec: Sa | TA: Off
Bw: Full

Option Mode
Normal

Figure 4-3 Signal Analysis with 8 bit vertical resolution



Cursor Results 1
t1 49.125 µs V1 496.14 mV
t2 50.1 µs V2 491.27 mV
Δt 975 ns ΔV -4.87 mV
1/Δt 1.025641... MHz ΔV/Δt -4.9949 kV*Hz
☐ Track waveform

Horizontal
Res: 1 ns / 1 GSa/s
RL: 1 MSa
RT
HD
Scl: 100 µs/div
Pos: 0 s
Trigger Normal
A: Edge Ch1
Lvl: 2.61 mV

Ch1Wfm1
Pos: 0 div
Off: 0 V
Scl: 130 mV/div
Cpl: DC 50Ω
Dec: Sa | TA: Off
Bw: 30 MHz

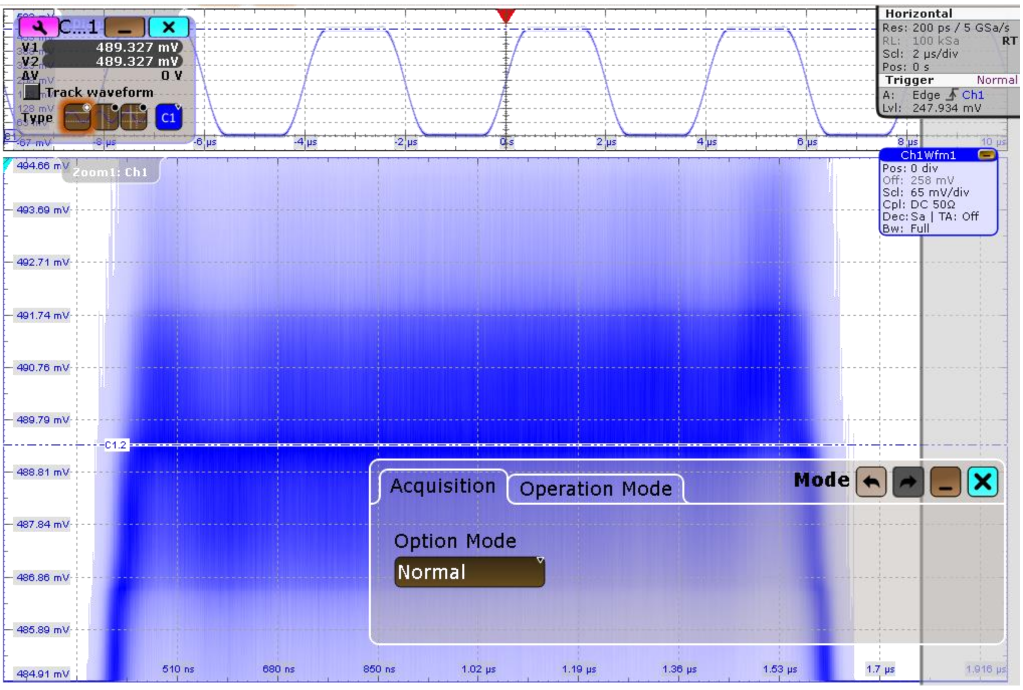
Option Mode: High definition
Bandwidth: 30 MHz
Resolution in bits: 16

Figure 4-4 Signal Analysis with HD-mode

4.3 Improvement in Trigger Sensitivity

Chapter 3.3 pointed out the improvement in trigger sensitivity by the HD-mode. In this section an example will highlight this unique feature of the HD-mode for RTO and RTE.

Figure 4-5 shows a 250 kHz, 500 mV clock signal with a relative slow rise time of about 500 ns in the top graph. The large graph of the screen shot displays a Zoom into the waveform on the high level around the trigger point. The Zoom window has a very small vertical range so that the alleged noise does not fit completely into the zoom window.



V1 489.327 mV
V2 489.327 mV
ΔV 0 V
☐ Track waveform

Horizontal
Res: 200 ps / 5 GSa/s
RL: 100 kSa
Scl: 2 µs/div
Pos: 0 s

Trigger Normal
A: Edge Ch1
Lvl: 247.934 mV

Ch1Wfm1
Pos: 0 div
Off: 258 mV
Scl: 65 mV/div
Cpl: DC 50Ω
Dec: Sa | TA: Off
Bw: Full

Option Mode: Normal

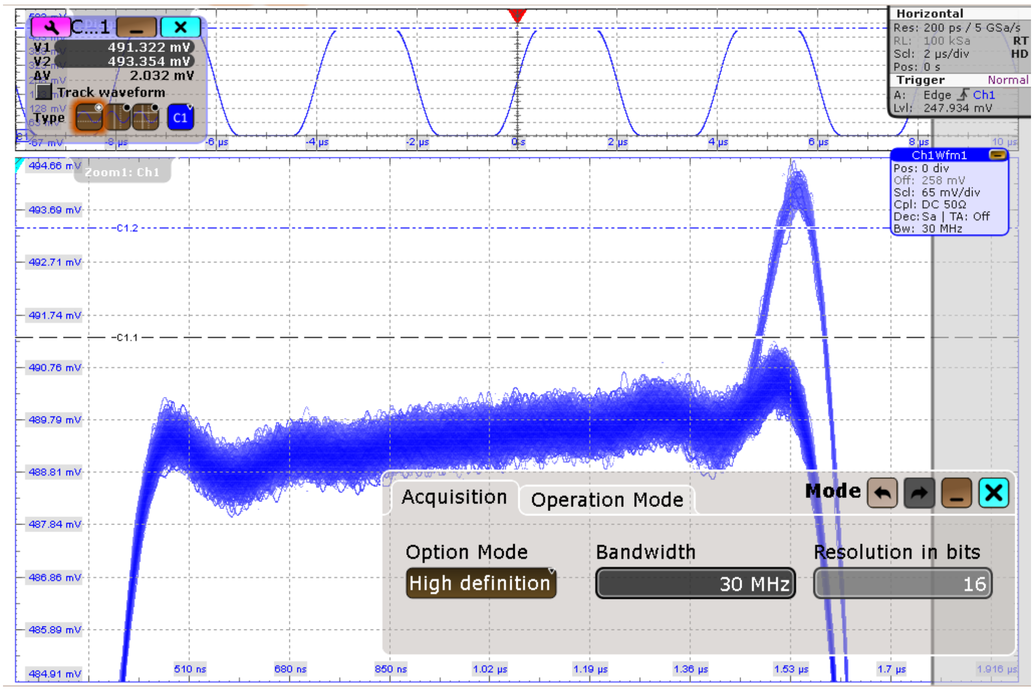
Figure 4-5 Signal Analysis of a 250 kHz clock signal

The HD-mode can again display more signal details. Keeping the display settings, the HD-mode is invoked by the mode menu. A glitch on top of the high level of the clock signal becomes apparent if the bandwidth is successively reduced.

Figure 4-6 shows the applied HD-mode with the configured 30 MHz bandwidth in the signal bar. While the waveform in the top graph does not show any difference to the top graph in the previous screen shot, the Zoom shows a 2 mV glitch on top of the high level measured by a cursor.

It appears that the glitch occurs only occasionally, because the zoom shows the overlay of bits with and without glitches with the persistence. Up to this point a high resolution oscilloscope might display a similar result.

However, in order to understand the timing behavior of this glitch, it is necessary to resolve the glitch signal in time and to trigger on the signal detail. The difficulty is that the required sensitivity is very small. It is defined by the difference between the maximum high level of a bit without a glitch and the minimum peak value of a glitch. The measured 2.0 mV is less than an LSB of the 8 bit A/D converter with 2.5 mV (65 mV/div * 10 div / 2^8).



V1 491.322 mV
V2 493.354 mV
ΔV 2.032 mV

Horizontal
Res: 200 ps / 5 GSa/s
RL: 100 kSa RT
Scl: 2 µs/div HD
Pos: 0 s

Trigger Normal
A: Edge Ch1
Lvl: 247.934 mV

Ch1Wfm1
Pos: 0 div
Off: 258 mV
Scl: 65 mV/div
Cpl: DC 50Ω
Dec: Sa | TA: Off
Bw: 30 MHz

Option Mode: High definition
Bandwidth: 30 MHz
Resolution in bits: 16

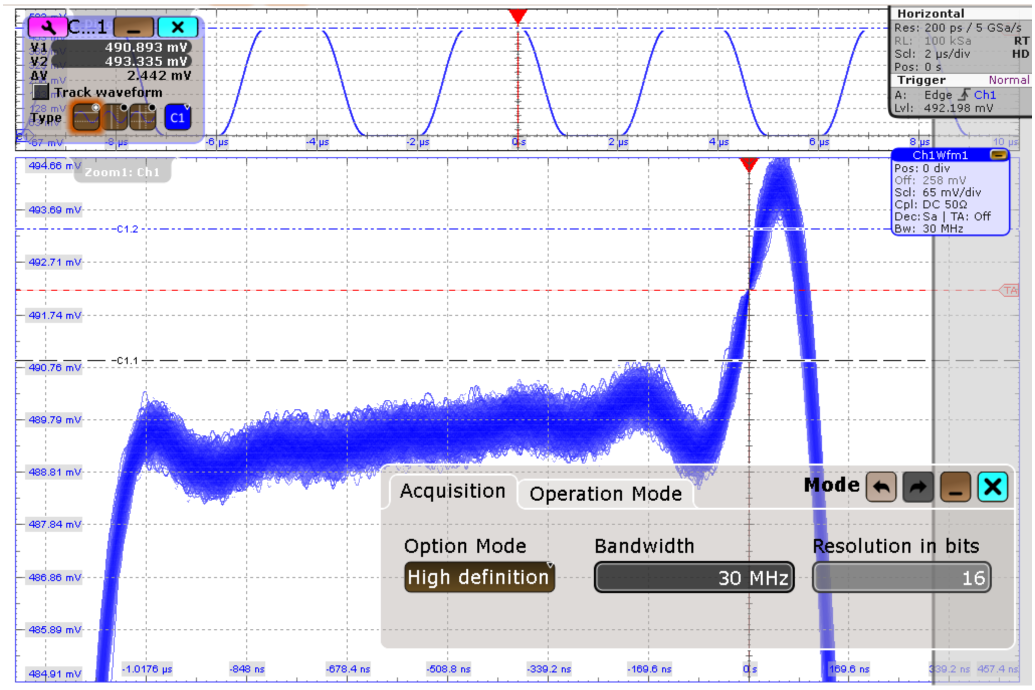
Figure 4-6 Signal Analysis of a 250 kHz clock signal with HD-mode

The digital trigger of the RTO and RTE exploits the gain in resolution of the HD-mode unlike conventional high resolution mode oscilloscopes. Using this example of the clock signal, the digital trigger of RTO and RTE can isolate the glitch from the remaining bits, and show a waveform without overlaying different bits.

To display solely the glitch, the trigger level, which was before in the middle of the signal at 248 mV is shifted now to 492 mV, right in the middle of the glitch between the two cursors (see red dashed line in Figure 4-7). Furthermore the trigger hysteresis is reduced to zero to trigger reliably on the glitch. Both measures, the arbitrary configuration of the trigger hysteresis and the sensitivity below one LSB of the A/D converter, are only possible with a digital trigger and unique for RTO and RTE.

Figure 4-7 exhibits the result. With this superior sensitivity, the RTO and RTE reliably trigger on the small glitch, but for example not on the overshoot of high level at -85 ns, which would result in a skewed overlaid waveform in the top graph. The oscilloscope also does not miss waveforms, because the waveform update rate is in the same range as for the previous setting with a trigger level of 248 mV.

With the history mode or a second zoom window (see Figure 4-8) the user can observe this disturbance only every 17th pulse. The period of the occurrences is marked with a red arrow in the Figure 4-8. Further analysis is possible based on this finding to relate this behavior to other components of the circuit.



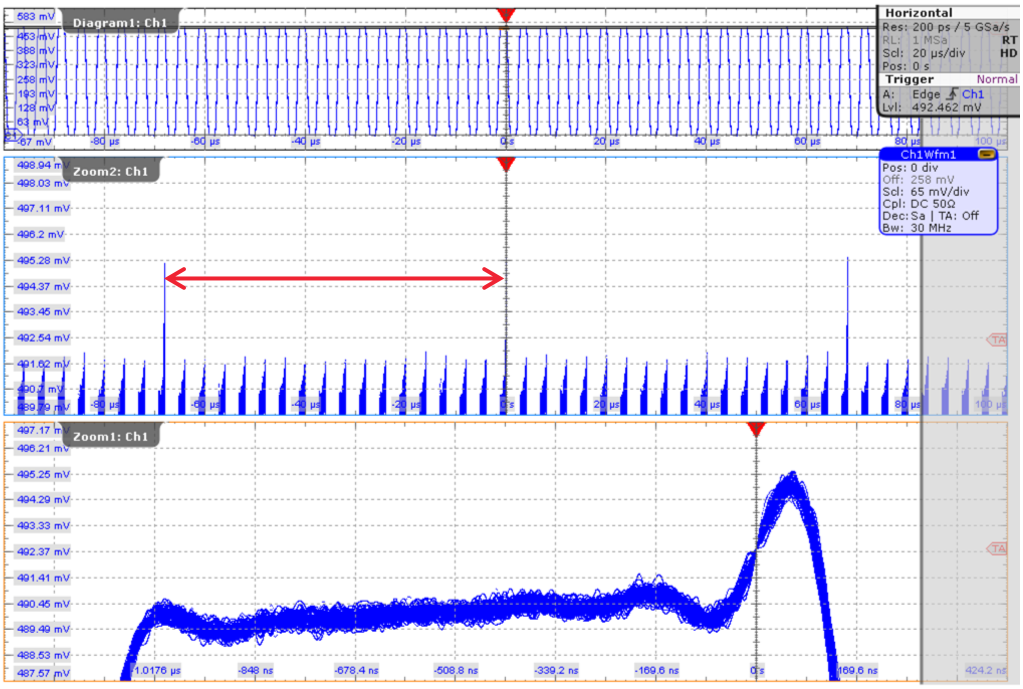
V1 490.893 mV
V2 493.335 mV
ΔV 2.442 mV

Horizontal
Res: 200 ps / 5 GSa/s
RL: 100 kSa RT
Scl: 2 µs/div HD
Pos: 0 s
Trigger Normal
A: Edge Ch1
Lvl: 492.198 mV

Ch1Wfm1
Pos: 0 div
Off: 258 mV
Scl: 65 mV/div
Cpl: DC 50Ω
Dec: Sa | TA: Off
Bw: 30 MHz

Option Mode: High definition
Bandwidth: 30 MHz
Resolution in bits: 16

Figure 4-7 Signal Analysis with a trigger on a signal detail



Horizontal
Res: 200 ps / 5 GSa/s
RL: 1 MSa RT
Scl: 20 µs/div HD
Pos: 0 s
Trigger Normal
A: Edge Ch1
Lvl: 492.462 mV

Ch1Wfm1
Pos: 0 div
Off: 258 mV
Scl: 65 mV/div
Cpl: DC 50Ω
Dec: Sa | TA: Off
Bw: 30 MHz

Figure 4-8 Signal Analysis showing the repeated disturbance

5 Conclusion

The K17 High Definition Option for RTO and RTE is an excellent tool that enhances the vertical resolution of the oscilloscope up to 16 bit. With this option, the user can analyze applications like Switch Mode Power Supplies (7), amplitude modulated RF signals or jitter analysis. These applications require high speed, mid-resolution oscilloscopes, like jitter analysis, as well as high resolution, medium speed oscilloscopes. All applications can be analyzed with one scope.

The resolution gain achieved by digital signal processing requires a superior analog front end together with an A/D converter that has an ENOB number close to its nominal resolution, like RTO and RTE provide. This is important, because the resolution gain will add to the ENOB, not on the nominal resolution of the A/D converter.

There are more benefits from the HD-mode than just the gain in vertical resolution. With the digital trigger, the RTO and RTE are able to take advantage of the resolution gain and trigger stable on small signal details as opposed to oscilloscopes with traditional architectures. In addition, this option maintains a high sampling rate, shows no aliasing and contrary does not inhibit further decimation for an economic use of the acquisition memory and a long acquisition time.

The RTO and RTE in combination with the K17 High Definition Option can be the better choice for the user than conventional high resolution oscilloscopes, as it is a versatile instrument for a wide range of applications.

6 Bibliography

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7 Ordering Information

Naming	Type	Order number
Digital Oscilloscopes		
600 MHz, 2 channels 10 Gsample/s, 20/40 Msample	R&S®RTO1002	1316.1000.02
600 MHz, 4 channels 10 Gsample/s, 20/40 Msample	R&S®RTO1004	1316.1000.04
1 GHz, 2 channels 10 Gsample/s, 20/40 Msample	R&S®RTO1012	1316.1000.12
1 GHz, 4 channels 10 Gsample/s, 20/80 Msample	R&S®RTO1014	1316.1000.14
2 GHz, 2 channels 10 Gsample/s, 20/40 Msample	R&S®RTO1022	1316.1000.22
2 GHz, 4 channels 10 Gsample/s, 20/80 Msample	R&S®RTO1024	1316.1000.24
4 GHz, 4 channels 20 Gsample/s, 20/80 Msample	R&S®RTO1044	1316.1000.44
200 MHz, 2 channels 5 Gsample/s, 10/20 Msample	R&S®RTE1022	1326.2000.22
200 MHz, 4 channels 5 Gsample/s, 10/40 Msample	R&S®RTE1024	1326.2000.24
350 MHz, 2 channels 5 Gsample/s, 10/20 Msample	R&S®RTE1032	1326.2000.32
350 MHz, 4 channels 5 Gsample/s, 10/40 Msample	R&S®RTE1034	1326.2000.34
500 MHz, 2 channels 5 Gsample/s, 10/20 Msample	R&S®RTE1052	1326.2000.52
500 MHz, 4 channels 5 Gsample/s, 10/40 Msample	R&S®RTE1054	1326.2000.54
1 GHz, 2 channels 5 Gsample/s, 10/20 Msample	R&S®RTE1102	1326.2000.52
1 GHz, 4 channels 5 Gsample/s, 10/40 Msample	R&S®RTE1104	1326.2000.64
1.5 GHz, 2 channels 5 Gsample/s, 10/20 Msample	R&S®RTE1152	1326.2000.72
1.5 GHz, 4 channels 5 Gsample/s, 10/40 Msample	R&S®RTE1154	1326.2000.74
2 GHz, 2 channels 5 Gsample/s, 10/20 Msample	R&S®RTE1202	1326.2000.82
2 GHz, 4 channels 5 Gsample/s, 10/40 Msample	R&S®RTE1204	1326.2000.84
Software Options		
High Definition Option	R&S®RTO-K17	1326.0536.02
High Definition Option	R&S®RTE-K17	1326.0542.02

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Regional contact

Europe, Africa, Middle East
+49 89 4129 12345
customersupport@rohde-schwarz.com

North America
1-888-TEST-RSA (1-888-837-8772)
customer.support@rsa.rohde-schwarz.com

Latin America
+1-410-910-7988
customersupport.la@rohde-schwarz.com

Asia/Pacific
+65 65 13 04 88
customersupport.asia@rohde-schwarz.com

China
+86-800-810-8228 /+86-400-650-5896
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Rohde & Schwarz GmbH & Co. KG
Mühldorfstraße 15 | D - 81671 München
Phone + 49 89 4129 - 0 | Fax + 49 89 4129 – 13777

www.rohde-schwarz.com