Benefits of the R&S®RTO Oscilloscope's Digital Trigger
Application Note

Products:

- R&S®RTO
  Digital Oscilloscope

The trigger is a key element of an oscilloscope. It captures specific signal events for detailed analysis and provides a stable view on repeating waveforms.

Since its invention in the 1940s the oscilloscope trigger has experienced continuous enhancements. The fully digital trigger of the R&S®RTO digital oscilloscopes sets an innovation milestone that brings significant advantages for the oscilloscope user in terms of measurement accuracy, acquisition density, and functionality.

This application note introduces the working principles of a conventional trigger system and explains the advantages of the real-time capable digital trigger of the RTO oscilloscopes.

<Application Note>

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ROHDE&SCHWARZ

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1 Principle of a Conventional Trigger System

1.1 Relevance of a Trigger for an Oscilloscope

The trigger of an oscilloscope has basically two main applications:

1. Ensure a stable display

   The invention of the trigger was a break-through for oscilloscopes as a debug tool for electrical and electronic design [1]. Triggering ensures a stable display of waveforms for continuous monitoring of repetitive signals.

2. Display of specific signal characteristics

   The trigger can react to dedicated events. This is useful for isolating and displaying specific signal characteristics such as logic levels that are not reached ("Runt"), signal disturbances caused by crosstalk (e.g. "Glitch"), slow edges ("Rise time") or invalid timing between channels ("Data2Clk"). The number of trigger events and the flexibility of the trigger setup has been continuously enhanced over the years.

The accuracy of a trigger system as well as its flexibility determines how well the measurement signal can be displayed and analyzed.

1.2 Implementation of a Conventional Trigger System

Today most oscilloscopes are digital meaning that the measurement signal is sampled and stored as a continuous series of digital values. However, the trigger, which is responsible for the detection of a signal event, is still an analog circuit that processes the original measurement signal. Figure 1 provides a simplified block diagram of a digital oscilloscope.

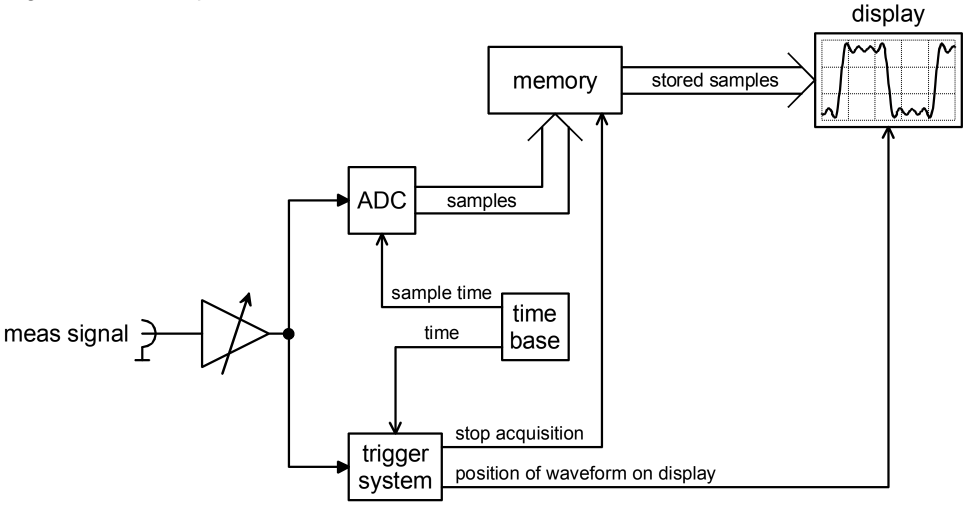

Figure 1: Simplified block diagram of a digital oscilloscope with an analog trigger unit

The input amplifier is used to condition the signal under test to match its amplitude to the operation range of the A/D converter and the display of the oscilloscope, respectively. The conditioned signal from the amplifier output is distributed in parallel to the A/D converter and the trigger system. In the one path, the A/D converter samples the measurement signal and the digitized sample values are written to the acquisition memory. In the other path, the trigger system compares the signal to valid trigger events (e.g. crossing of a trigger threshold with the "Edge" trigger).

When a valid trigger condition occurs, the recording of the A/D converter samples will be finalized, and the acquired waveform further processed and displayed. Figure 2. shows an example of an acquired and displayed waveform. The digitized sample points from the A/D conversion are marked on the signal with circles. For this example the trigger event "Edge" with positive slope is applied. The crossing of the trigger level by the measurement signal results in a valid trigger event.

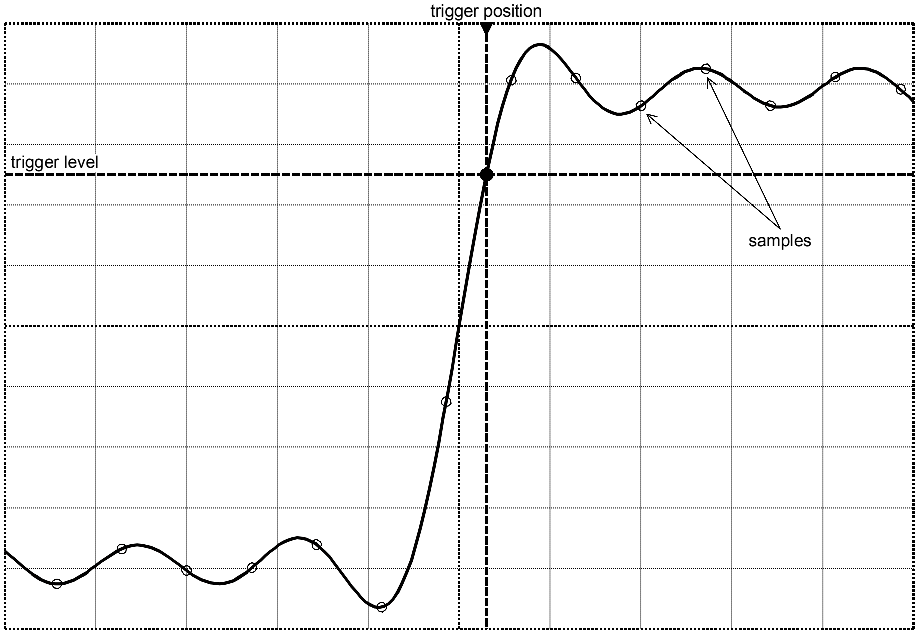

Figure 2: Example of a measurement signal with A/D converter sample and trigger point

1.3 Impairment of an Analog Trigger

For an accurate display of the signal on the oscilloscope grid, the timing of the trigger point needs to be determined precisely. If the trigger time evaluation is inaccurate the displayed waveform does not intersect the trigger point (cross point of trigger level and trigger position) in the diagram. A respective example is given in Figure 3.

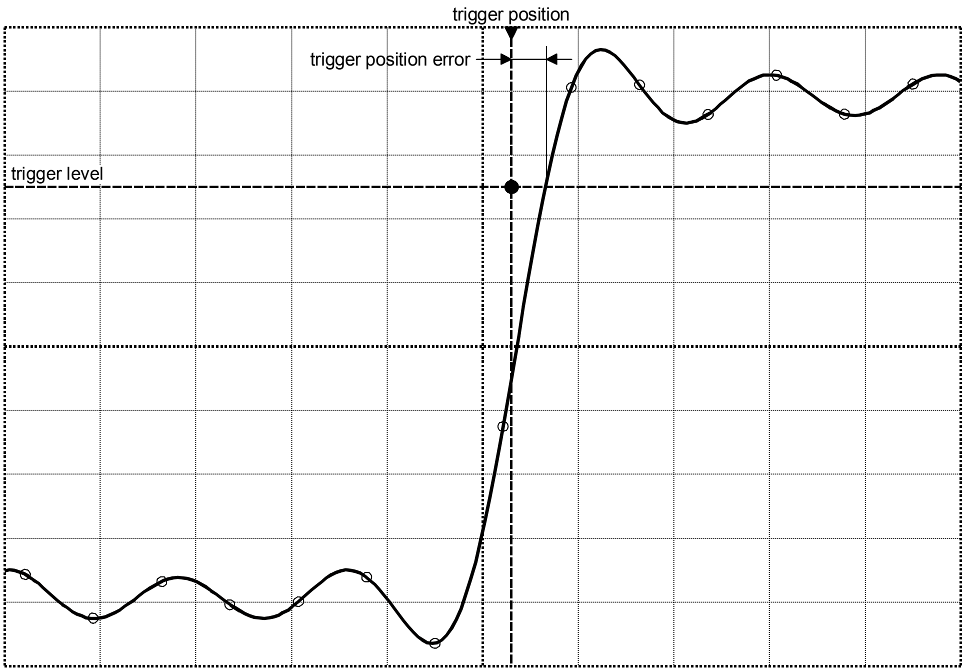

Figure 3: Example of mismatch between displayed waveform and the actual trigger point

Following reasons can cause an inaccurate trigger position:

1. Inaccurate measurement of trigger edge

In the trigger system the measurement signal is compared to a trigger threshold via a comparator. The timing of the edge at the output of the comparator needs to be measured very precisely. For this purpose a Time-to-Digital-Converter (TDC) is applied. Inaccuracy of the TDC results in an offset of individual displayed waveform to the trigger point. The random component of TDC error causes this offset to change on each trigger event which results in trigger jitter.

2. Systematic error sources in the two paths for the measurement signal

The measurement signal is processed via two different path - the acquisition path with the A/D converter, and the trigger path (Figure 1). Both paths contain different linear and non-linear distortions that cause a systematic mismatch between the displayed signal and the determined trigger point. In worst case the trigger might not react on valid trigger events though they are visible at the display, or the trigger reacts on trigger events that cannot truly be captured and displayed by the acquisition path.

3. Noise sources in the two paths for the measurement signal

The two paths to the A/D converter and to the analog trigger system include amplifiers with different noise sources. This again results in delays and amplitude variances that appear as trigger position offsets (trigger jitter) on the oscilloscope screen. The trigger jitter is displayed in the right diagram area of Figure 4 as the width and height of the superimposed signal traces. The left-hand side of Figure 4 shows that the trigger jitter appears as a random vertical and horizontal offset with respect to the ideal trigger point.

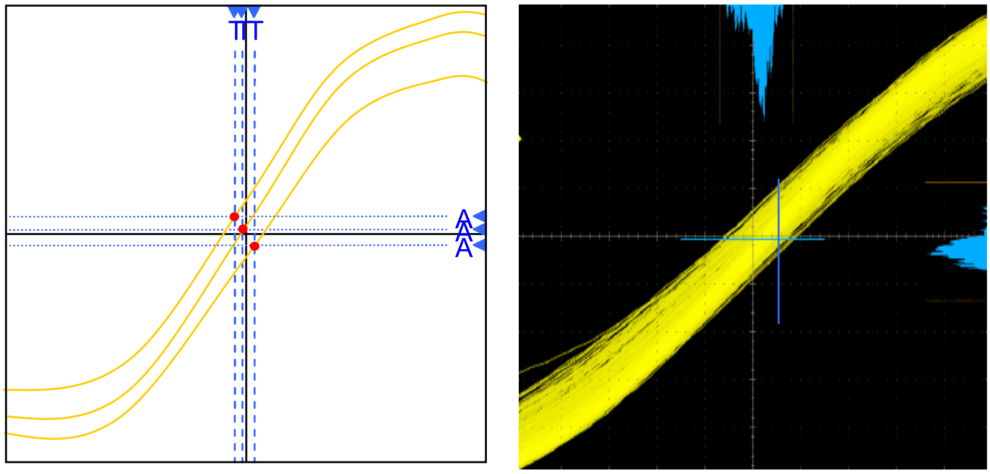

Figure 4: Trigger Jitter during the acquisition of several waveforms

In the following chapter, the implementation of a digitally implemented trigger system is introduced. A digital trigger does not include the error terms discussed above and therefore provides a more accurate approach for an oscilloscope trigger.

2 The Digital Trigger

2.1 The Concept of a Digital Trigger

Figure 5 shows the simplified block diagram of a digital oscilloscope with a digital trigger.

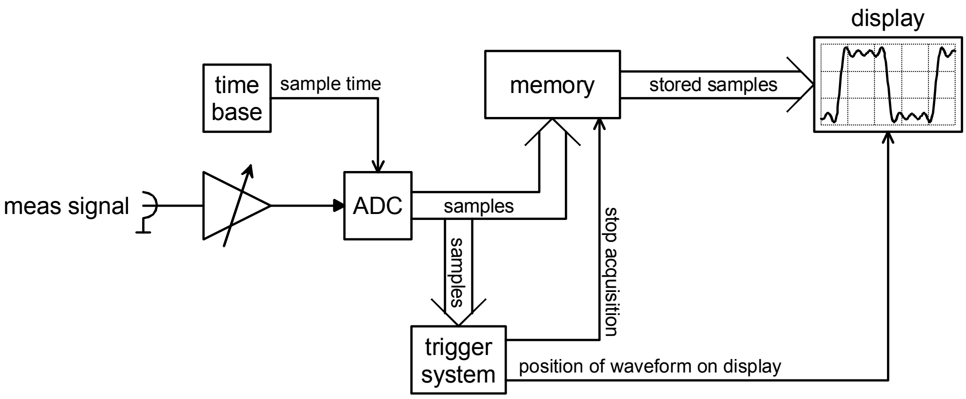

Figure 5: Block diagram of a digital oscilloscope with a digitally implemented trigger

In contrast to an analog trigger, a digital trigger system operates directly on the samples of the A/D converter. The measurement signal is not split up into two paths. Therefore, the digital trigger processes the identical signal that is acquired and displayed. The impairment of an analog trigger system discussed in chapter 1.3 are eliminated by design.

For the evaluation of the trigger point, the digital trigger applies digital signal processing methods. Precise algorithms detect valid trigger events and measure the time stamps accurately.

The challenge for a digital trigger is the real-time signal processing for seamless monitoring of the measurement signal. The R&S®RTO digital trigger operates based on the A/D converter rate of 10 Gsample/s and therefore has to process 80 Gbit/s data (8 bit A/D converter).

As the digital trigger uses the same digitized data as the acquisition unit it is important to note, that triggering only on signal events inside the ADC range is possible.

2.2 Detection of Trigger Events with a Digital Trigger

For a selected trigger event, first of all a comparator compares the measurement signal to the defined trigger threshold. For the simplest case, the "Edge" trigger, a trigger event is detected when the signal crosses the trigger threshold in the requested direction (falling or rising slope).

In a digital system the signal is represented by samples. The sampling theorem states that the sampling rate has to be at least twice as fast as the maximum frequency of the signal. Only under such conditions the complete reconstruction of the signal is possible.

Figures 2 and 3 show that viewing only the A/D converter samples is not sufficient to see all signal details. The same is true for a digital trigger - a trigger decision purely based on the A/D converter samples is insufficient because crossings of the trigger threshold could be missed. Therefore, the timing resolution is increased by up-sampling the signal using an interpolator to a rate of 20 Gs/s (Figure 6). Following the interpolator, the comparator compares the sample values to the defined trigger threshold. The output level of the comparator changes if a trigger event is detected.

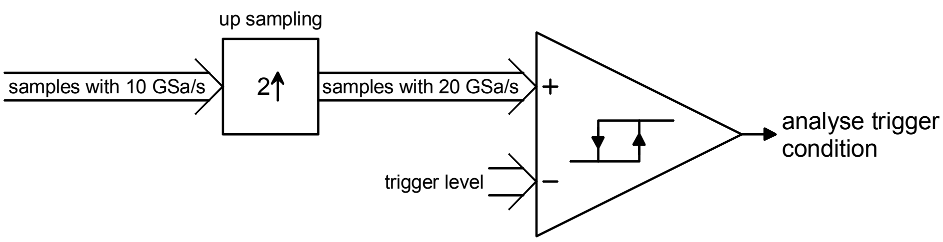

Figure 6: Enhancement of the sampling rate in the digital trigger system by "up-sampling" method

Figure 7 provides an example where the "blind" area in a signal is reduced by enhancing the sample resolution with up-sampling by a factor of two. On the left, the waveform samples do not include the overshoot in the waveform. The trigger threshold above the A/D converter samples cannot detect the overshoot. On the right, the waveform sampling rate is doubled by interpolation. Now the triggering on the overshoot is possible.

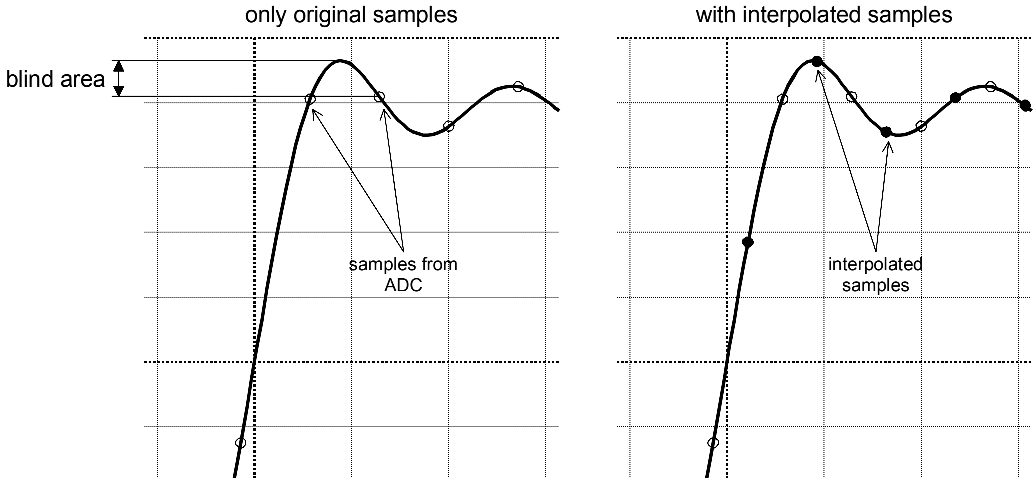

Figure 7:Example of the enhancement of the sample resolution to restrict the blind trigger area

The maximum frequency within the example waveform is 3.5 GHz. This example shows that the digital trigger system of the R&S RTO can safely detect also fast frequency components based on the A/D converter rate of 10 Gsample/s.

2.3 Determination of the Timing of the Trigger Point with a Digital Trigger System

The key requirement for a valid reconstruction of the measurement signal at an arbitrary time point is that the sampling theorem (Nyquist criteria) is fulfilled. The RTO uses poly-phase filters that can calculate the measurement signal at any timing point with a signal noise ratio (SNR) of > 90 dB. The intersection point of the measurement signal and the trigger threshold is calculated in real-time using an iterative approach with an accuracy of 250 fs.

Some trigger events such as "Glitch" or "Pulse width" are based on timing conditions. The RTO supports very precise triggering on such events as the RTO determines the intersection points at the threshold in real-time. The timing of the trigger events can be setup with a resolution of 1 ps, the minimum detectable pulse width is specified at 100 ps.

3 Advantages of the RTO's Digital Trigger

3.1 Low Trigger Jitter in Real-Time

Using the identical sample values for the acquisition and trigger processing results in a very low trigger jitter below 1 ps rms[1] for the R&S RTO. Figure 8 shows an example of the trigger jitter evaluation at the trigger point with a 10 MHz clock signal that has a rise time of 400 ps.

As discussed in Chapter 2.1 the real-time digital trigger unit of the R&S RTO is implemented in the processing path between the A/D converters and the acquisition memory. Unlike "SW enhanced" trigger systems implemented using post-processing approaches, it does not require additional blind time periods after every waveform acquisition. Lowest trigger jitter and a maximum acquisition and analysis rate of 1 million waveforms per second are part of the standard acquisition mode for the first time with the RTO.

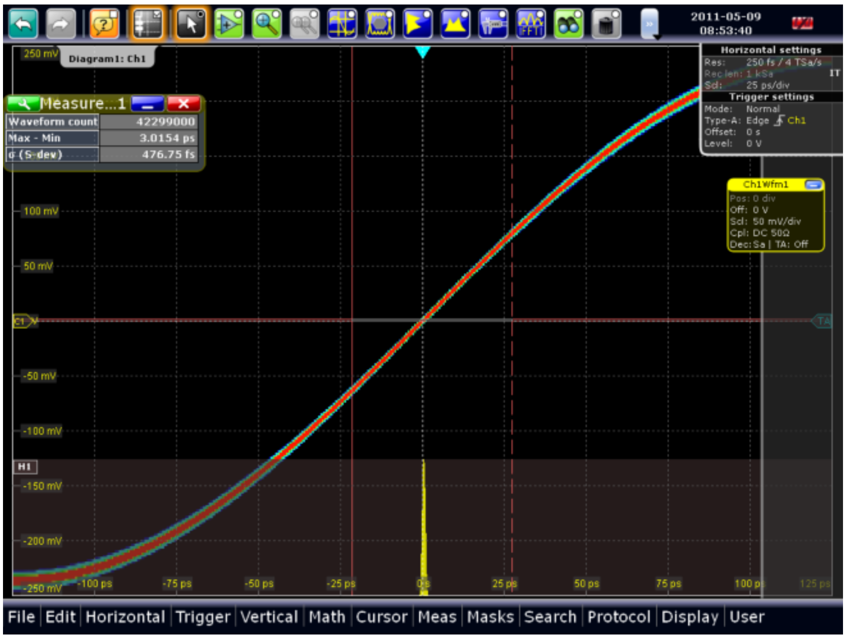

Figure 8: Intrinsic trigger jitter evaluated with a 2 GHz sine wave signal with 500 mV Amplitude peak-peak

Application Hint

The OCXO option available for the R&S RTO oscilloscope improves the time base accuracy to ±0.2 ppm. This is especially useful for deep memory acquisition, for acquisitions with high trigger offset, or for applications where the time relation between rare trigger events is of interest.

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[1] The trigger jitter measured in the trigger point depends on the rise time of the measurement signal. Slow signal edges result in larger displayed trigger jitter.

3.2 Optimized Trigger Sensitivity

There are two contradicting requirements for the trigger sensitivity. For stable triggering on noisy signals a trigger system requires a certain hysteresis around the trigger threshold (see Figure 9). A wide hysteresis on the other hand limits the sensitivity of the trigger system for small amplitude signals.

The trigger sensitivity of conventional oscilloscopes is typically limited to greater than one vertical division. Additionally, a larger hysteresis can be selected with the "Noise Reject" mode for stable triggering on noisy signals.

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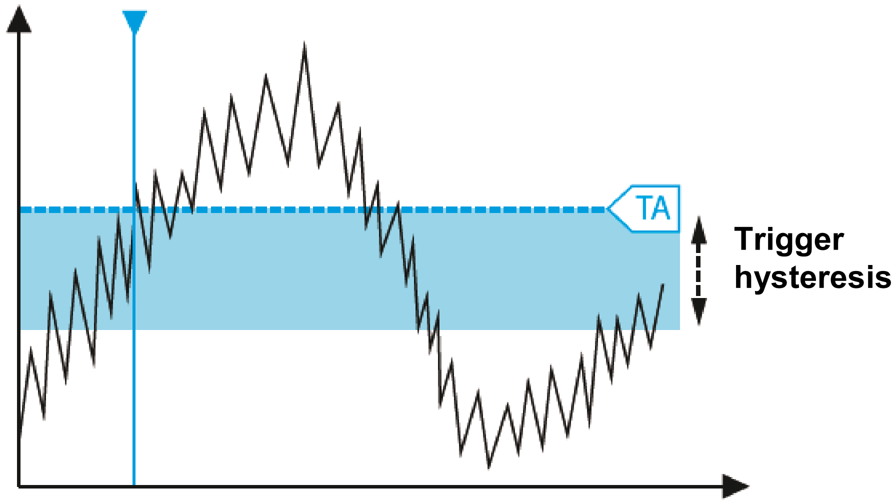

Figure 9: The hysteresis of the trigger level enables stable triggering on noisy signals

The digital trigger system of the R&S RTO allows an individual setting of the trigger hysteresis from 0 to 5 div to optimize the trigger sensitivity for the respective signal characteristic, Figure 10.

- With the "Auto" hysteresis mode the R&S RTO firmware uses a vertical scale dependent hysteresis.
- The hysteresis can be manually increased in the "Manual" hysteresis mode to enable stable triggering on signals with high noise level (Figure 9).
- The hysteresis set to zero provides the highest trigger sensitivity for signals with fast edges.

Another advantage of the R&S RTO that should be mentioned in the context of trigger sensitivity is that the low-noise front end allows precise triggering down to 1 mV/div with no bandwidth limitation.

Figure 10: The hysteresis of the RTO trigger threshold is freely programmable. Set to zero for highest sensitivity.

3.3 Minimum Detectable Pulse Width

A further key parameter of a trigger system is the minimum detectable pulse width. It corresponds to the narrowest pulse that the oscilloscope can detect and trigger on. The R&S RTO family supports stable triggering on pulse, glitches, intervals, and rise / fall time down to 50 ps.

An example of stable triggering on a pulse width set to shorter than 50 ps is shown in Figure 11. In this example a TTL signal of 3.5 V amplitude with a steep overshoot at the rising edge is used to demonstrate the R&S RTO trigger sensitivity.

Important for this particular example is that the trigger hysteresis needs to be set to zero to achieve the highest trigger sensitivity.

In the zoom diagram it can be seen that all acquired waveforms fulfill the trigger condition of a pulse width shorter than 50 ps.

Figure 11: RTO1044 (4 GHz model) triggering with a pulse width trigger set to shorter than 50 ps

3.4 No Masking of Trigger Event

An analog trigger requires some time after a trigger decision to rearm the trigger circuitry before they can trigger again. During this rearm time, the oscilloscopes cannot respond to new trigger events - trigger events occurring during the rearm time are masked.

In contrast the digital trigger system of the R&S RTO oscilloscopes can evaluate individual trigger events with the Time-to-Digital-Converters (TDC) within 400 ps intervals (Figure 12) with a resolution of 250 fs. This is important for the applications with sophisticated trigger conditions such as counted event hold-off, or A-B trigger sequences where for several B events are needed before triggering.

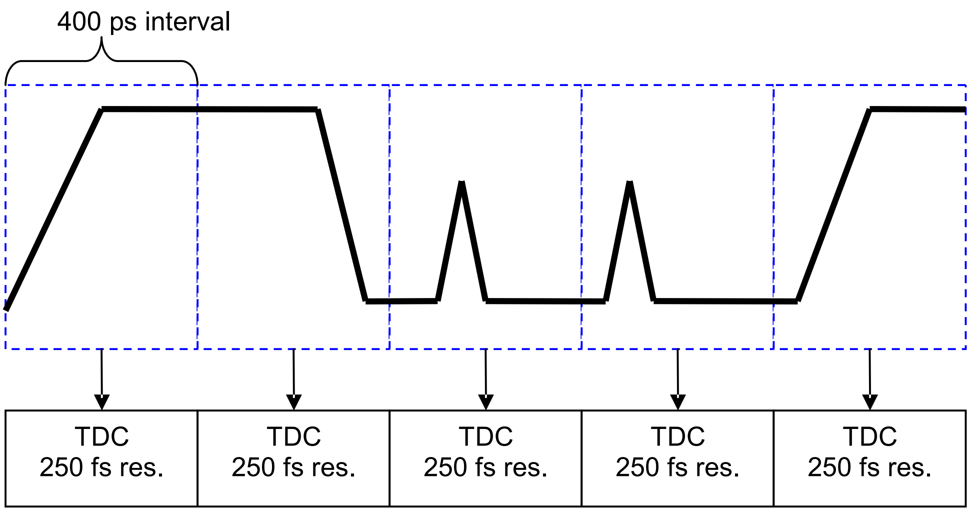

Figure 12: The RTO trigger system can detect trigger events within 400 ps intervals with 250 fs resolution.

Application Hint

The ultra-segmented mode with a minimum blind time of 300 ns supports the acquisition of fast repeating trigger events.

3.5 Flexible Filtering of Trigger Signals

The acquisition and trigger ASIC in the R&S®RTO oscilloscopes supports the flexible programming of the cut-off frequency of a digital low-pass filter in the real-time path. The same filter settings can be used for either or both the trigger signal and the measurement signal (Figure 13). Low-pass filtering on the trigger signal only suppresses high-frequency noise for triggering purposes while at the same time capturing and displaying the unfiltered measurement signal.

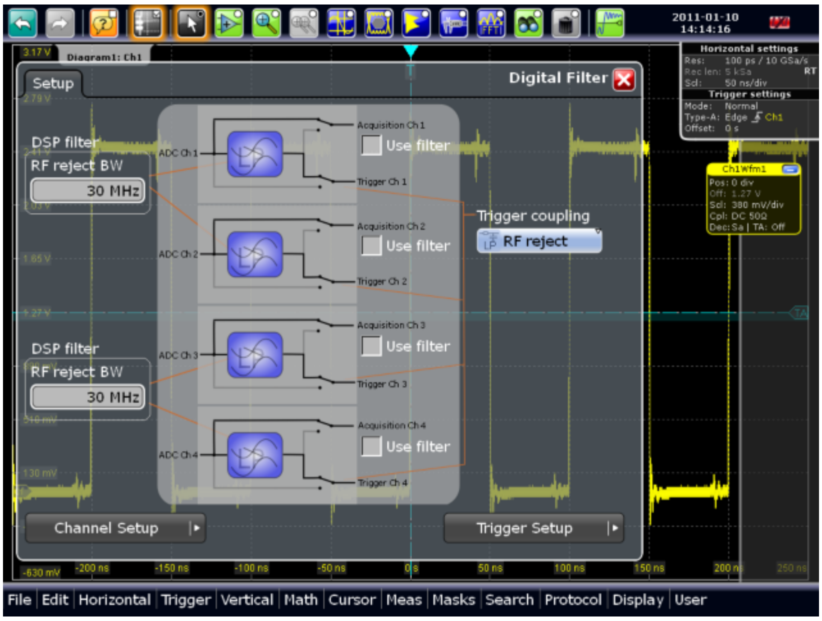

Figure 13: Flexible filter definition for acquisition and trigger signal

A related application example is shown in Figure 14. Here the user applies a Runt trigger to catch data pulses that do not reach the logic one level. The setup of the Runt trigger thresholds turns out to be difficult because of a of the high leading overshoot that crosses the runt window. The solution is to apply the low-pass filter to the trigger signal only. Now the analysis of the original and unmodified measurement signal is possible.

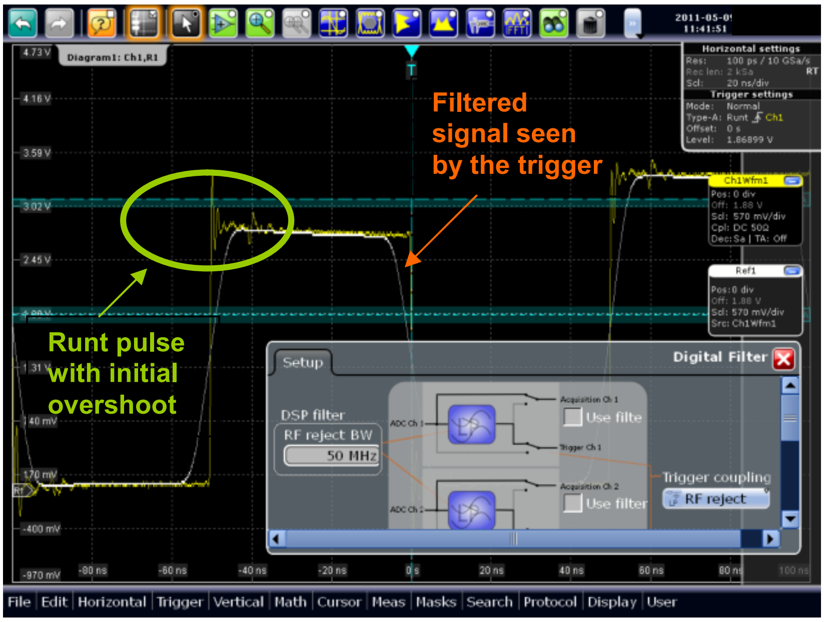

Figure 14: Triggering on a runt pulse where a fast leading overshoot is suppressed by a low pass filter on the trigger signal

3.6 Recognition of Channel De-skew by the Trigger Unit

The timing relationship between oscilloscope input channels (skew) is important for measurements and trigger conditions between two or more signals. Different length of cables, probes, or probe point positions cause also skew between channels.. Standard digital oscilloscopes provide a signal de-skew feature to compensate for delays on different inputs. The de-skew is typically processed in the acquisition path after the A/D converter and therefore can not be seen by a standard analog trigger. This leads to inconsistent signals displayed at the screen and evaluated by the trigger system.

With the R&S®RTO digital oscilloscope the acquisition unit and trigger unit use identical digitized and processed data (Figure 15). Therefore, the waveforms seen at the display and the signal processed by the trigger unit are consistent even when channel de-skew is applied. Since the RTO uses digital delay filters, it is possible to set the de-skew in 1 ps steps.

Examples for inter channels trigger conditions include triggering on qualification of trigger events on one channel (e.g. "Edge") and certain level combinations ("high" or "low" state) on other channels.

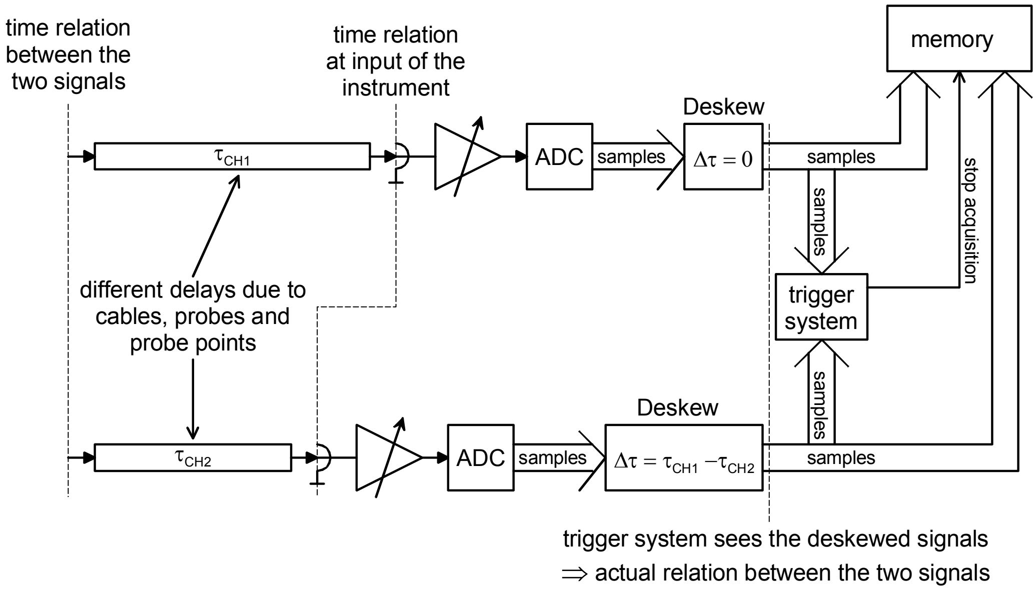

Figure 15: The digital trigger of the R&S®RTO can use the channel deskew for appropriate triggering on channel combinations

3.7 History View Function with Timestamps

In many cases the actual cause of an error cannot be pinpointed until looking back on a signal acquisition's history. The R&S®RTO oscilloscopes always provide access to prior acquired waveforms. Regardless of the function from which the measurement was stopped, the waveform data stored in memory is immediately available for analysis. Additionally, every waveform has an individual timestamp to clearly identify when the trigger events took place. Depending on the memory option, extensive data for efficient debugging is available to the user.

The history viewing tool controls the replay of the waveforms, Figure 15. The timestamps can be displayed as absolute time with respect to the system clock or relative to the last triggered waveform. The timestamp time resolution in the latter mode is one picosecond. Applications requiring a long-term stable timing reference will benefit from the high time base accuracy of the optional oven oscillator (hardware option R&S®RTO-B4).

Application Hint

All processing and analysis tools such as math test, measurement functions, mask test or histogram tool can be applied during the replay of the waveform data.

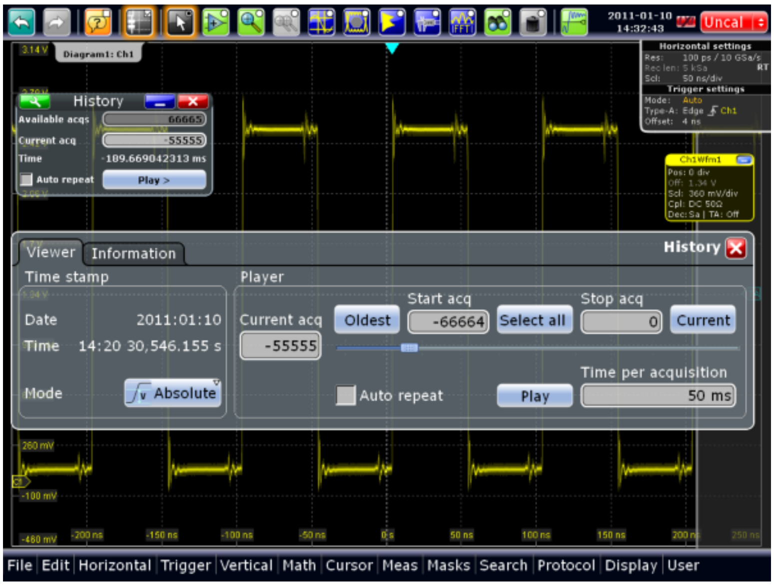

Figure 16: The history view tool provides access to all waveforms in the acquisition memory

4 Conclusions

This application note discussed the advantages of a digital trigger compared to a traditional analog trigger. A digital trigger operates directly on the A/D converter samples. This architecture provides a consistent timing for the acquisition and the trigger data, which results in more precise measurement results.

The R&S®RTO Digital Oscilloscope features a real-time digital trigger. It yields very low trigger jitter combined with a very high waveform acquisition and analysis rates.

The R&S RTO's digital trigger enables precise measurements thanks to the high trigger sensitivity at full bandwidth and the adjustable digital filter for the trigger signal.

These advantages combined with other features like high dynamic range (ENOB) of the front end, high acquisition and analysis rate, and the intuitive user interface turn the RTO oscilloscope into a powerful debug and analysis tool.

5 Literature

[1] Hickmann, I.: Digital Oscilloscopes, Newnes, 2001
[2] R&S application note, "The Impact of Digital Oscilloscope Blind Time on Your Measurements"
[3] R&S product brochure, "R&S®RTO Digital Oscilloscopes"
[4] R&S user manual, "R&S®RTO Digital Oscilloscopes - Getting Started"

6 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.

7 Ordering Information

Naming	Type	Order number
Base unit (included accessories: per channel: 500 MHz passive voltage probe (10:1), accessory pouch, Quick-start manual, CD with manual, power cord)		
Digital Oscilloscopes		
600 MHz, 10 GSample/s, 20/40 MSample, 2 channels	R&S®RTO1002	1316.1000.02
600 MHz, 10 GSample/s, 20/80 MSample, 4 channels	R&S®RTO1004	1316.1000.04
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
4 GHz, 20 GSample/s, 20/80 MSample, 4 channels	R&S®RTO1044	1316.1000.44

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