

# Measuring with oscilloscopes

## Educational note

### Products:

- R&S®RTC1000
- R&S®RTB2000

This educational note covers the theory and practice oscilloscopes based on concrete measurement examples that address authentic everyday tasks.

The theoretical portion of this paper begins with an explanation of the basic operating concepts for oscilloscopes, followed by a discussion of the most important parameters to be considered when setting up and performing the exercise measurements.

The practical portion of the educational note contains detailed measurement tasks that can be performed by small groups in the university lab. These exercises are intended to demonstrate and reinforce the knowledge gained in the theoretical portion. The exercises build upon one another and demonstrate measurement tasks that are frequently encountered by engineers in daily work.

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The following abbreviations are used in this Educational Note for Rohde & Schwarz test equipment:

- The R&S®RTC1000 Oscilloscope is referred to as the RTC1000
- The R&S®RTB2000 Oscilloscope is referred to as the RTB2000

# 1 Basics

Oscilloscopes are among the most versatile test instruments available for analyzing and testing analog and digital circuits. Because they can display and analyze a broad spectrum of electronic signals, oscilloscopes are used for a wide variety of research and development applications.

Although modern oscilloscopes support automated assignment of all parameters, it is essential for users to develop a fundamental understanding of the function and operation of the test instruments. The high degree of automation over the entire measurement process leaves many users entirely dependent on the results delivered by the instrument, while the logic behind the measurements remains a mystery to these users. Thorough practical knowledge is needed in order to assess the validity of results. The purpose of this educational note is to provide the foundation for the correct performance of typical measurement tasks.

The descriptions and exercises are applicable for modern oscilloscopes. The RTC1000 as shown in Fig.1-1 was used for all theoretical descriptions and practical exercises. For the last exercise described in chapter 8 "FMCW-Radar exercise" the RTB2000 was used.

The contents for this chapter are drawn in part from the manual for the R&S®RTO oscilloscope (1) CITATION Roh15 \l 1031 and from "Oscilloscope Fundamentals" from Rohde & Schwarz (2) CITATION Roh \l 1031.

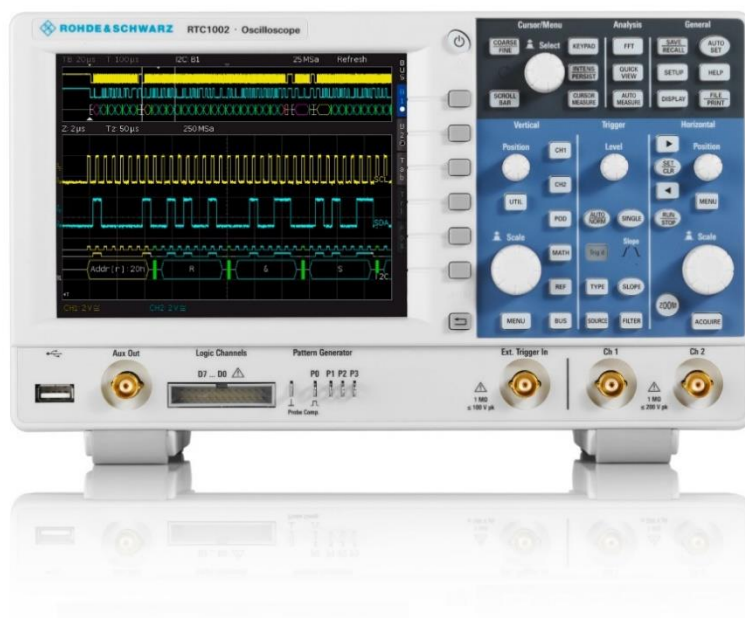


Fig.1-1: The R&S®RTC1000 oscilloscope.

## 1.1 Operation

This section introduces the most important settings for oscilloscope measurements and describes the instrument operation. The reader should also gain a feeling for the selection of both a suitable test setup and the necessary hardware for obtaining reproducible and accurate results.

### 1.1.1 Operating concept and default settings

An oscilloscope typically displays a given variable as a function of another variable. The most typical use case is the display of voltage versus time, where nearly all phenomena can be converted to electrical signals by using an appropriate converter. Oscilloscopes usually have at least two independent channels, making it possible for example to reproduce the voltage from channel 2 over the voltage from channel 1. See section 3.2 for a related use case. Either the vertical or horizontal system is used for scaling the axes in the display.

The vertical system includes all settings affecting the scaling of the amplitude or the vertical offset of the signal. The horizontal system, on the other hand, can be used to influence the temporal offset and the resolution in parts of a second.

Beyond these basic settings, the trigger system is also key. Triggers can be used to define the conditions under which the oscilloscope should start a measurement. This ensures a stable signal display that always shows the segments of interest.

All of these settings are described in more detail in the preparatory test setup sections of chapter 3.

The groupings controlling these settings can be seen based on the example of the RTC1000 (see Fig.1-1). Together with the setting options for the trigger system (see section 1.2.3), the groupings for the vertical and horizontal display take up the entire lower two-thirds of control area. The RTC1000 additionally provides buttons for system-specific settings, specialized measurement tasks and automated analysis.

The RTC1000 display is divided into 12 horizontal and 8 vertical units. This allows the user to make a quick visual assessment of the readings and to scale the axes. See Fig.1-2 for an introduction into the functionality for the horizontal and vertical systems.

The scaling for the vertical system is set using the large rotary knob labeled *VOLTS/DIV* (① Fig.1-2, right). The associated vertical scaling is displayed at the left, under the signal for each active channel. For example, 50 mV means that the height of one grid square is equal to 50 mV<sup>1</sup>. This setting then equals a vertical display over the entire range of  $50 \text{ mV} * 8 = 400 \text{ mV}$ .

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<sup>1</sup> This corresponds to 50 mV/div, where div is the abbreviation for 'division'.

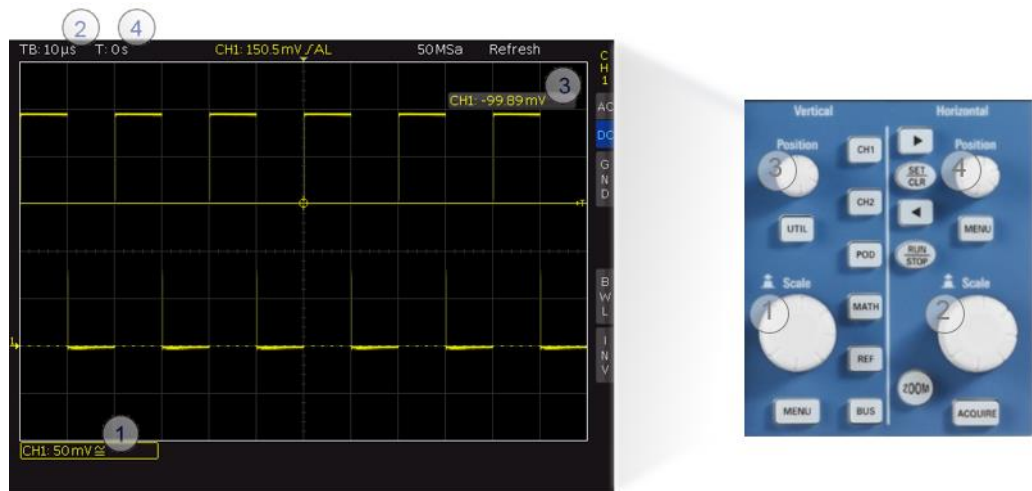


Fig.1-2: Basic settings for the horizontal and vertical systems.

The timebase is set in a similar fashion using the *TIME/DIV* rotary knob (② Fig.1-2, right). In the example provided in Fig.1-2, 10 μs is the length of one grid square. Consequently, the duration of the displayed signal is 10 μs \* 12 = 120 μs. Unlike the amplitude scaling, this setting applies to all channels. The rotary knobs labeled *POSITION* set the offsets for the vertical and horizontal systems.

For example, Fig.1-3 shows the measurement of two single-ended, square-wave signals using the RTC1000. The timebase is 10 μs. As a result, one period of the signal measured with channel 1 (yellow, top) is 20 μs in duration. This means that this is a 50 kHz signal. As mentioned above, the timebase applies to all channels. A visual analysis will therefore immediately lead to the conclusion that the signal acquired with channel 2 (blue, bottom) is at one-half the frequency. On the other hand, it can also be observed that, as a result of the different vertical scalings, there is no distinction between the two signals with respect to the maximum amplitude, even though the amplitude of the signal acquired with channel 1 could appear larger at first glance.

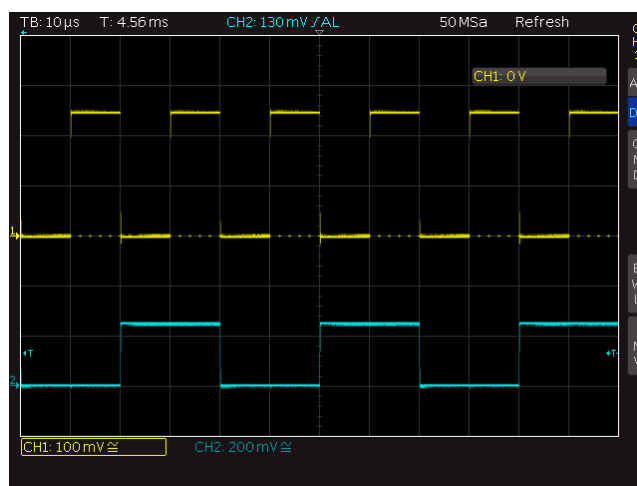


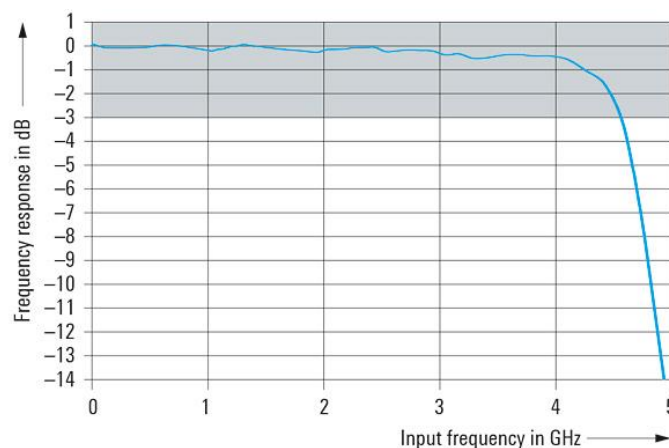
Fig.1-3: Measurement using the RTC1000.

### 1.1.2 Signals and bandwidth

Signal integrity is key to precise and reproducible measurements. Signal integrity refers to the ability of an oscilloscope to reproduce an electrical signal in its true original form. Measurements that do not provide signal integrity are essentially useless because the measured signal might not match the actual signal in either its shape or characteristics.

This is why bandwidth is one of the most important characteristics for an oscilloscope. It is only when a signal is not affected by the finite bandwidth of the test instrument that precise measurements are possible and the signal details can be displayed. However, in certain situations a test instrument's bandwidth will be reduced intentionally, for example, to minimize the effect of noise.

By definition, the bandwidth is the frequency at which a sinusoidal signal is attenuated by 3 dB (about 30 %) as compared with the original amplitude. This frequency corresponds to the  $-3$  dB point in a lowpass, which have characteristics that are essentially like those of an oscilloscope. Fig.1-4 shows the frequency response a typical 4 GHz Oscilloscopes are dimensioned for the flattest frequency response possible within the specified bandwidth, which means that the  $-3$  dB point will lie outside of the specified bandwidth. This ensures that it is still possible to analyze and measure signals near to the upper bandwidth limit. As seen in Fig.1-4, measurements above the specified bandwidth are in theory also possible with some restrictions. However, signal distortion and imprecise measurement results must be expected in this situation.



**Fig.1-4: Frequency response of a 4 GHz oscilloscope.**

Oscilloscopes are frequently used to measure digital pulses. In theory, square-wave signals have an unlimited spectrum consisting of the fundamental frequency (e.g. 1 MHz) and odd-numbered multiples of the fundamental frequency, called harmonics (e.g. 3 MHz, 5 MHz, 7 MHz, etc.).

The following rules of thumb are generally accepted for quickly estimating the required bandwidth (2).

- To preserve the integrity of digital signals, the bandwidth should be at least five times the clock frequency, which means the bandwidth permits signal components up to the 5th harmonic.
- The third harmonic is sufficient for simple decoding of signals, however.



If the required bandwidth for measuring digital signals must be defined more precisely, the rise time  $T_r$  of a pulse can be included in the calculation instead of the clock frequency. In the case of a digital signal, most of the energy is concentrated below a given frequency. Formula (1) can calculate this frequency, also known in the literature as cutoff frequency, or knee frequency  $f_{knee}$ . This shows that an electronic circuit with a flat frequency response up to  $f_{knee}$  permits a digital signal to pass with practically no distortion. The factor 0.35 is based on the rise time definition for digital signals typically used today, which looks at the rise time between 10 % and 90 % of the settled final value for the pulse.

$$f_{knee} = \frac{0.35}{T_r} \quad (1)$$

where

$T_r$  Rise time of the pulse

Depending on how much accuracy is desired,  $f_{knee}$  must then be multiplied by a constant. If an accuracy of 20 % is sufficient, then  $f_{knee}$  can be set to be equal to the oscilloscope bandwidth, while  $f_{knee}$  must be multiplied by 1.3 for an accuracy of 10 %.

(3) CITATION Joh93 \ 1031

It is also important to remember while performing measurements that the oscilloscope is not the only source of signal distortion. The probes being used can also be a possible source. This is why the bandwidth of the probes must be selected with an eye toward preserving the signal integrity of the signal under test.

The following section discusses this in more detail.

### 1.1.3 Probes

In a test setup, probes represent the connection between the signal source, i.e. the DUT, and the oscilloscope. Their primary objective is to transmit the signal to the oscilloscope in as close to its true form as possible to ensure maximum signal integrity and measurement accuracy. To meet these requirements, selection of the appropriate probe to match the measurement task and the hardware in use is essential. This section provides an overview of the most important probe parameters and characteristics.

An ideal probe would have an infinite bandwidth that would not place a load on the circuit under test during the measurement. This would make an unadulterated analysis of the circuit's behavior possible. However, this is not possible using any hardware available today. That is why a check should be made before each measurement to determine whether the expected limitations are still acceptable or whether the permissible frequency range was exceeded. A reliable assessment is possible based on the bandwidth and impedance of the probes being used.

#### Bandwidth

The combination of oscilloscope and probe creates a new system with its own bandwidth. This can be approximated as shown in (2):

$$\frac{1}{B_{system}} = \sqrt{\left(\frac{1}{B_{probe}}\right)^2 + \left(\frac{1}{B_{oscilloscope}}\right)^2} \quad (2)$$

To keep the possible measurement errors at a minimum, the selected system bandwidth should be larger than the highest frequency present in the signal.

Use the following rule to quickly estimate the required bandwidth for the probe being used (2) CITATION Roh \ 1031:

- The bandwidth of the probe should be 1.5 times the bandwidth of the oscilloscope (valid for Oscilloscopes to about 1 GHz bandwidth with a Gaussian bandlimiting).

### Impedance

In addition to the bandwidth, the probe impedance is another important characteristic for practical applications. Impedance is closely linked to the load placed on the circuit under test by the oscilloscope+probe system. As a result, a probe's resistance should be at least equal to ten times the resistance of the circuit. If it is not, the measured amplitude could be attenuated, for example. In this case, a significant portion of the current flowing through the circuit is also passed through the probe.

For this introduction into measuring with oscilloscopes, only passive probes<sup>2</sup> are of any relevance. Therefore only this type will be described here. The most important characteristic to remember for passive probes is that the impedance can change significantly versus the frequency. This effect can primarily be attributed to the various factors that contribute to loading of the circuit. At low frequencies, the resistive components are dominant. As the frequency rises, the capacitive and inductive components increase in significance:

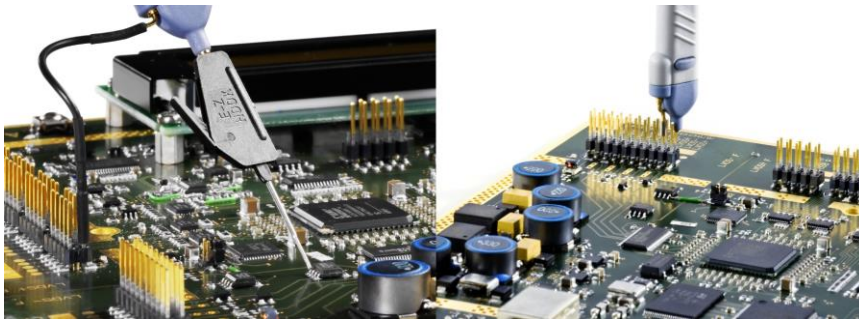
The capacitance of probes, which function as a lowpass filter at high frequencies, can greatly reduce the input impedance. This results in the loss of information present in high-frequency signal components, while the rise time and bandwidth of the system are reduced.

The loop formed from the tip of the probe to its ground wire places an inductive load on the circuit that results in distortions in the signal, in particular overshoot and undershoot. To prevent this effect, the probe's ground connection should be kept as short as possible, as should the physical distance to the device under test. Fig.1-5 on the following page shows two example measurements.

The effect can be significant enough for the measurement using the oscilloscope to damage a functioning resonant circuit.

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<sup>2</sup> Probes without any active components, such as amplifiers.



**Fig.1-5: Measurements using a probe. Left: large loop distorting the measurement, Right: optimized setup**

The use of 10:1 probes permits the dynamic of the system and the resistive input impedance to be increased even further. This type of probe increases the input signal by a factor of 10. The advantage is that the oscilloscope can now display signals with ten times the amplitude as compared with measurements using a 1:1 probe. However, the overall system loses sensitivity, making 1:1 probes preferred over 10:1 probes for signals with amplitudes in the several millivolt range. Some probes offer selectable attenuation ratios, including the probe shown in Fig.1-6 used for these measurements, the R&S®RT-ZP03. The key point is that the attenuation ratio of the probe in use must be known to the oscilloscope to ensure that the amplitudes are displayed correctly.



**Fig.1-6: R&S®RT-ZP03 probe with 10:1 and 1:1 attenuation ratios.**

Passive probes are typically characterized by a low resistive load. For measurements in the high megahertz range, however, active probes should be used because of the increasing capacitive load.

The following factors make passive probes suitable for general measurements in a wide variety of applications:

- Favorable price
- Ability to operate without an additional power supply
- Robust design

Passive probes additionally require an adjustment before a measurement is started. The adjustment for low frequencies differs from that for high frequencies. The low-frequency adjustment matches the capacitance of the probe to the input capacitance on the oscilloscope. For example, if a 10:1 attenuation ratio is selected for the probe, the probe will have a resistance of 9 M $\Omega$ , which in combination with the 1 M $\Omega$  input resistance on the oscilloscope creates a voltage divider. The input capacitance of the

oscilloscope generates a lowpass for which the frequency response can be compensated by using a highpass with the same cutoff frequency. This is why impedance matching of the highpass must be possible using an adjustable capacitor. The impedance matching is performed by manually adjusting the probes. For measurements starting at about 50 MHz, an HF adjustment should additionally be performed.

The RTC1000 includes a special menu item that launches a wizard for performing the adjustment. Fig.1-7 shows the adjustment of a probe for low frequencies. A comparison against the image on the right shows that the probe still needs to be set in order to more closely approximate the ideal square-wave format.

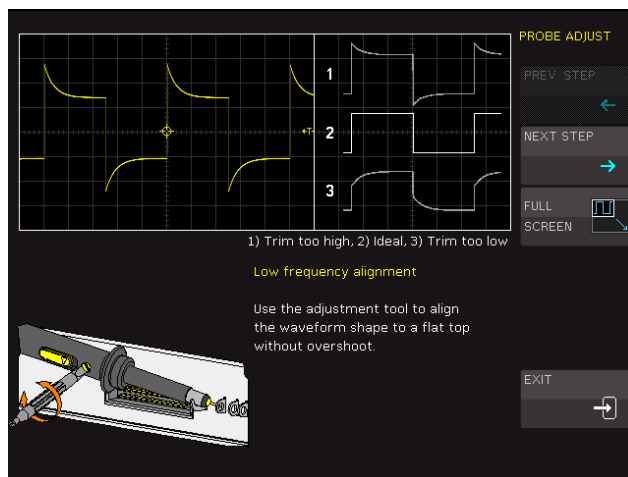


Fig.1-7: Adjusting the RT-ZP03 probe on the RTC1000.

## 1.2 Configuration

Once the appropriate setup has been selected for the measurement task, the measurement can be started. Fig.1-8 shows two possible test setups. In addition to the items discussed above, the oscilloscope must be configured to optimally meet the requirements for the measurement. This section provides the background needed to perform these steps.

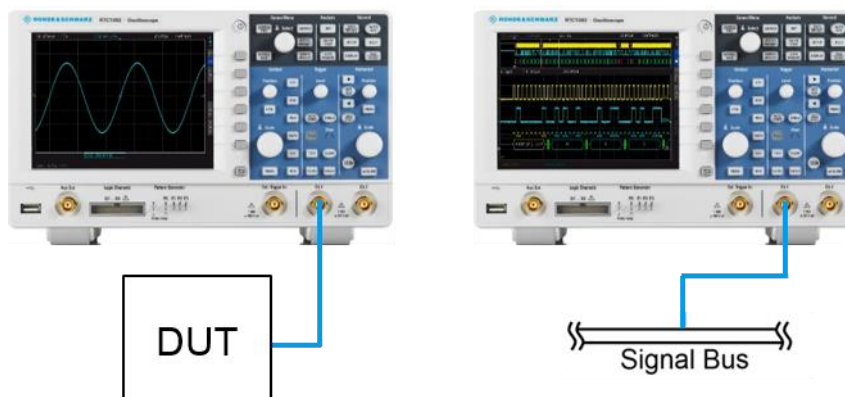


Fig.1-8 Exercise setups for oscilloscope measurements.

### 1.2.1 Vertical resolution and dynamic range

When working with the input signal, the analog-to-digital converter (ADC) is the core component of every digital oscilloscope. In the case of the RTC1000, the ADC is an 8-bit converter. The ADC converts the measured signal into  $2^8 = 256$  values. The smallest voltage difference that can be displayed, which also corresponds to the least significant bit (LSB) on the ADC, is calculated as follows:

$$U_{lsb} = \frac{\Delta U_{input}}{2^n} \quad (3)$$

where

$\Delta U_{input}$  Input voltage range

n Bit count for the ADC

The vertical scaling set by the user plays a decisive role. This scaling corresponds to the entire input voltage range, or dynamic range, for the converter. For example, if an 8-bit converter is used with a vertical resolution of 50 mV/div, the smallest increment that can be displayed is 2 mV. On the other hand, a vertical scaling of 100 mV/div doubles the minimum resolution to 4 mV.

Fig.1-9 shows these scenarios. The same signal is shown in both the right and the left images with a vertical resolution of 50 mV and 100 mV, respectively. In the image on the left, the entire dynamic range of the ADC (blue arrow) is utilized, which results in a better resolution of the measured signal. Therefore, when using oscilloscopes for measurements, always remember the following:

- For the greatest possible accuracy, the display of the input signal should utilize the entire dynamic range of the ADC.

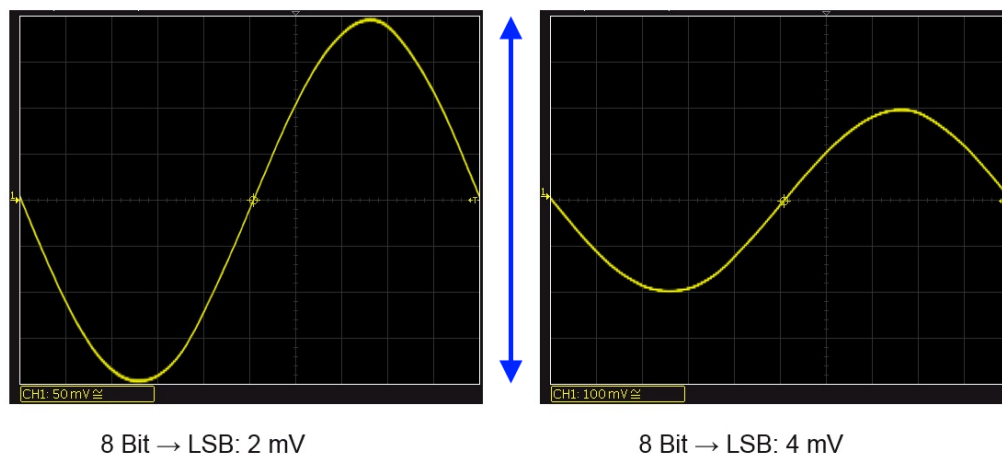


Fig.1-9: Vertical resolution at different scalings.

### 1.2.2 Signal sampling and processing

Not only the resolution of the converter, but also its speed are key factors for many measurement tasks. The ADC samples the continuous signal at regular intervals and at defined times. The obtained digitized values are known as samples. The sample

rate is equal to the number of samples the oscilloscope can take per second. In the case of the RTC1000, a maximum of 2 Gsample/s is possible for one channel and 1 Gsample/s in two-channel mode.

The sample rate must be sufficiently high in order to display the signal correctly. If the selected rate is too low, aliasing errors will occur and the signal will be displayed incorrectly. This is known as undersampling. Fig.1-10 shows how a low sample rate affects a 10 kHz input signal.

In this example, the sampling points are linked linearly; oscilloscopes typically use a  $\frac{\sin(x)}{x}$  interpolation here. The sampling rate has to be at least 2.5 times the maximum bandwidth of the oscilloscope. In summary, a high sample rate results in the following:

- More precise signal reconstruction
- Better detection of short-term anomalies (glitches). It should be noted that only the anomalies are located within the bandwidth of the oscilloscope can be detected.
- Higher sampling density requires a higher memory requirement.

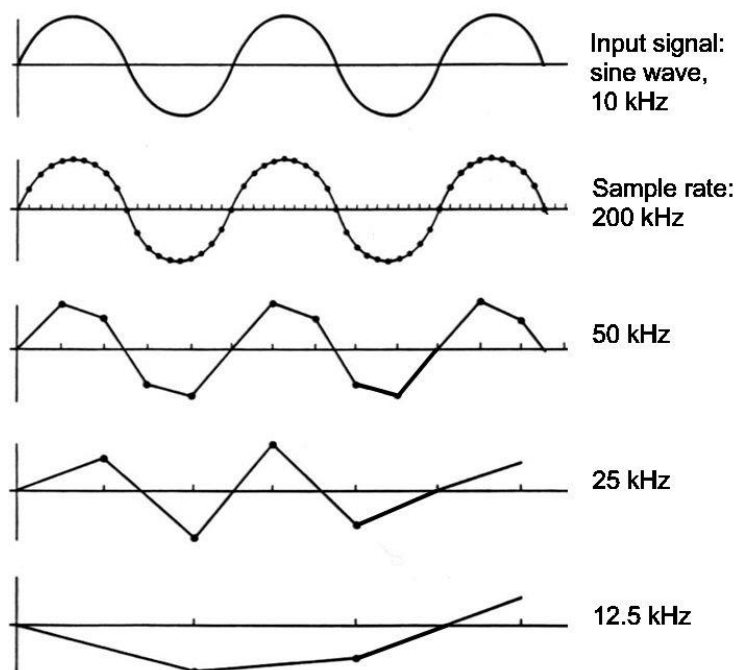


Fig.1-10: Effects of low sample rates.

Bandwidth and sample rate are key characteristics for oscilloscopes, and the highest possible values should be targeted for both. Even though the two characteristics are not physically coupled, the correct dimensioning is critical here.

To be able to faithfully reproduce measured signals the double sampling rate, ie  $2 \cdot f_{\text{signal, max}}$ , according to the Nyquist-Shannon theorem, is already sufficient. As a rule of thumb, due to the non-ideal band limitation of the oscilloscope the sample rate should correspond in practice at least 2.5 times the bandwidth of the oscilloscope.

However, it has been shown that square-wave signals, whose transitions are often very fast and which contain frequency components significantly higher than the Nyquist

frequency, require several times the bandwidth for reproducible measurements. For example, the RTC1000 is available with a maximum bandwidth of 300 MHz whereas the maximum sample rate is 2 Gsample/s.

In this context, it is important to note the following:

- A high bandwidth can be much less useful if only a low sample rate is available.

With all of the apparent advantages, it begs the question: Why not simply always use the oscilloscope with the highest sample rate? In addition to the obvious cost factor represented by the converter – a higher sample rate is obtained by using expensive, faster ADCs or multiple converters that combine the samples – this question can be answered by looking at the memory depth.

### **Memory depth**

Once the samples have been taken, the oscilloscope processes the sample values as defined by its current settings. The result is transferred to the test instrument's high-speed storage. The memory depth defines how many of these values can be saved and thus also defines the maximum acquisition period. If a large time range is to be acquired at the full sample rate, the oscilloscope must possess an appropriately large memory depth. Typically, the oscilloscope measurement speed is greatly reduced if the entire storage space is used because of the large amount of processing power required for large volumes of data. This leads to topic of blind time as described in the next section.

In summary it can be said that a high sample rate requires not only a fast analog-to-digital converter, but also sufficient memory depth on the oscilloscope for trouble-free operation. Both factors drive up the price of an instrument significantly, which is why it is advisable to be clear about the requirements before purchasing an oscilloscope.

### **Update rate and blind time**

The concept of an update rate was introduced to provide users with a convenient value that defines the frequency at which the oscilloscope can take measurements. The higher the update rate, the more acquisitions the oscilloscope can perform per second.

However, it must be remembered that an oscilloscope spends only a fraction of the time actually acquiring the signal. The rest of the time, the instrument is processing and storing the incoming data stream. For example, the RTC1000 in combination with the 8-bit ADC must process 16 Gsample/s of data to achieve the maximum sample rate (2 Gsample/s). Interpolation of the readings and the user-defined math or analysis functions additionally delay the next acquisition point. During this time, the test instrument is "blind," i.e. no new measurements can be started. As a result of this blind time, errors and deviations in the signal take longer to detect and analyze.

Fig.1-11 shows the acquisition cycle for an oscilloscope. The fixed portion of the blind time is specific to each instrument. On the other hand, the variable portion is dependent on the settings that have been defined for the acquisition and processing. In

this example, the instrument is processing data 99.999 % of the time. (4)

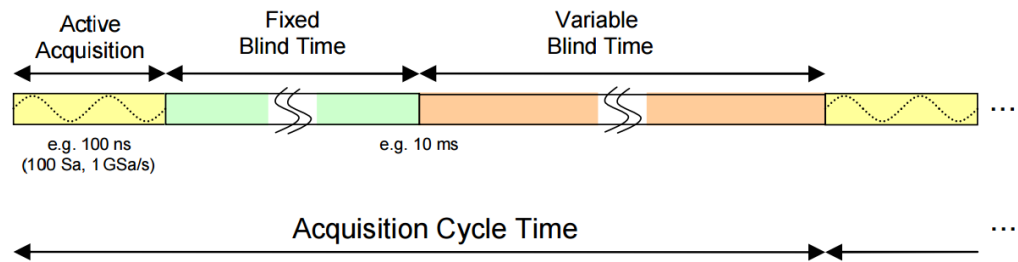


Fig.1-11 Acquisition cycle for an oscilloscope.

### Acquisition modes

Many oscilloscopes offer at least two different acquisition modes, each of which is intended for different applications.

#### *Realtime mode*

Because the analog-to-digital converter has always the same speed, the number of samples will be reduced when the measurement is performed at a slow time basis. In this case, the sampled values are used to reconstruct the signal directly. If a faster timebase is selected, the acquired points from the ADC are supplemented with interpolated values.

#### *Equivalent time mode*

This mode is used to analyze signals whose frequency is high above the sampling frequency of the converter. However, this mode requires stable, repetitive signals. An oscilloscope operating in equivalent time mode takes points from different acquisitions that were sampled at different points of the periodic signal and combines them into a single display.



### 1.2.3 Triggering basics

On oscilloscopes, the trigger is used among other things to provide a stable display of repetitive signals. Another important application is the synchronization of the acquisition to specific points in the signal that are of particular interest. When the trigger is initiated, the oscilloscope generates a snapshot at that precise moment of the current signal.

The trigger settings can be used to define the precise conditions under which a trigger should be initiated. The trigger point is set when all of the defined requirements are met by the signal at the same time. The oscilloscope has already continuously acquired data points, which are then used to fill in the pre-trigger portion of the acquisition. Once triggered, the oscilloscope acquires as many samples as required to complete the post-trigger portion, at which point the signal can be displayed on the monitor. Fig.1-12 shows a simplified version of a digital trigger. This type of trigger system works directly with the ADC samples. (5)

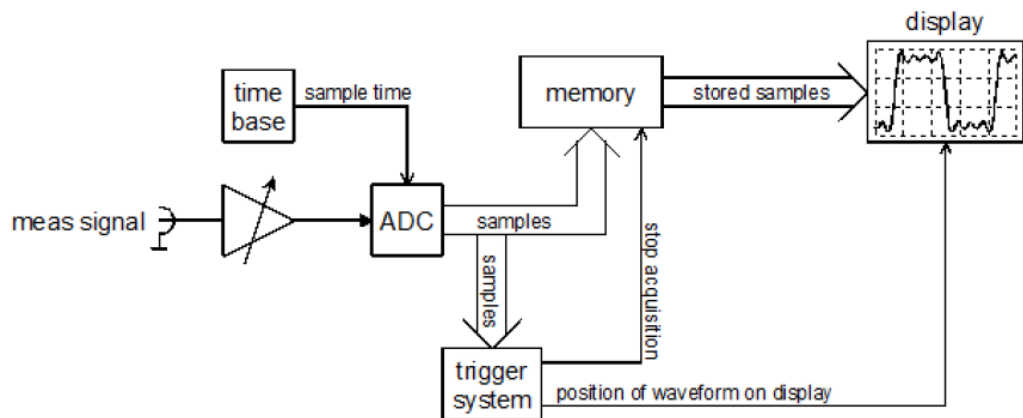


Fig.1-12: Simplified digital trigger setup.

Most oscilloscopes support, at a minimum, the following trigger conditions:

- Signal source
- Trigger type, with various settings
- Horizontal trigger position
- Mode

The RTC1000 can use channel 1, channel 2 as well as the digital channels as the signal source.

Modern oscilloscopes offer many different trigger types; this section will address only the edge triggers. This type is triggered as soon as the signal exceeds the trigger threshold (the vertical position of the trigger). The typical setting options include the threshold height and either rising or falling edge.

By saving the samples before and after the trigger time, the acquisition at various pre-trigger and post-trigger points can be analyzed later in leisure. The trigger settings can also change the trigger time by adjusting the horizontal position of the trigger.

Each oscilloscope supports two basic trigger modes. The two modes differ only in how they respond when the conditions for a trigger event are not met. The following descriptions assume that the signal does not exceed the trigger threshold.

### Auto mode

In auto mode, the oscilloscope uses first the selected trigger condition. If the trigger condition will not be fulfilled, the oscilloscope generates an asynchronous trigger that displays the signal at random times. The advantage of this mode is that a general assessment can be made as to whether a signal is present and what amplitude it has.

### Normal mode

In normal mode, on the other hand, the oscilloscope does not refresh the monitor until the trigger conditions have been met again. This mode is preferred if the trigger event occurs only very infrequently.

Fig.1-13 lists several settings for the edge trigger on the RTC1000 and their effects. The arrows along the edges of the images show the horizontal and vertical position of the trigger, which is indicated by a red circle.

In image ①, the trigger system is not yet set correctly. The selected trigger level is too high, which is why a valid trigger event is not present. This setting will not generate a stable image. The oscilloscope is apparently in auto mode, as it is displaying the asynchronously triggered signal. In image ②, the trigger was set to rising edge with 0 V. In image ③, the trigger was changed to falling edge, but the selected horizontal offset ( $-10\ \mu\text{s}$  in this example) is such that at first glance, it appears to be the same as image ②. The final image shows that the display can also combine rising edge and falling edge triggers. This is useful for assessing the symmetry of a signal, for example.

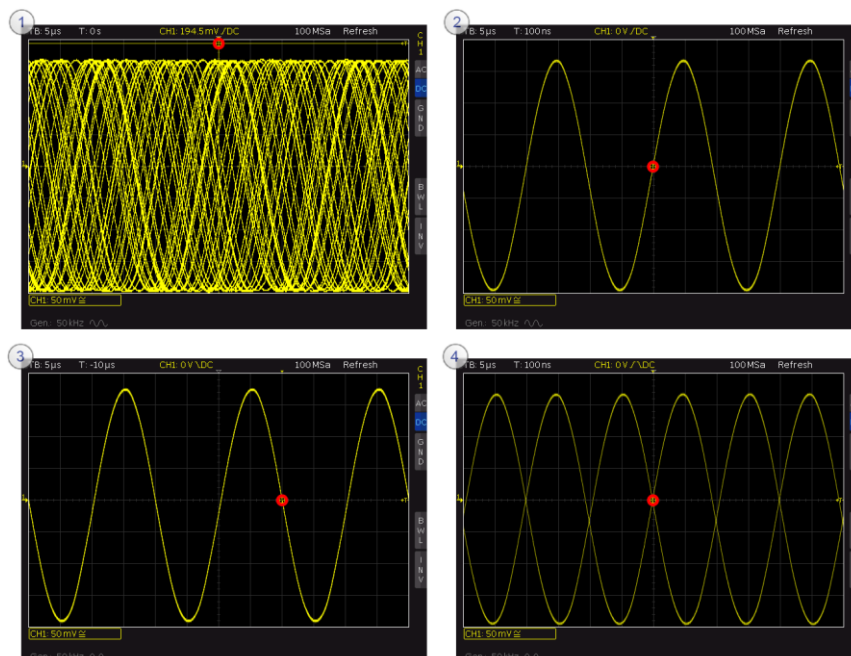


Fig.1-13: Effects of various trigger settings.

## 2 Preparing for the measurement exercises

This chapter begins the practical portion of the educational note. The following chapters deepen the reader's understanding with typical measurement tasks used in the analysis and verification of electronic circuitry.

Before starting with the actual measurements, however, a few points should be mentioned about using oscilloscopes.

### When using passive probes, always measure against ground!

Even though an oscilloscope measures voltages like a multimeter, it cannot be used in the same way in the test setup. The ground clip for a probe must always be connected to ground to prevent a short circuit of the circuit nodes. Fig.2-1 shows what happens when a measurement is performed incorrectly. The red arrow corresponds to the tip of the probe and the gray arrow to the ground clip. As seen in the image on the right, the circuit is set completely out of operation. This setup will not produce any useful measurements! In a worst-case scenario, the short circuit can cause serious damage.

Specialized differential probes can be used for differential measurements.

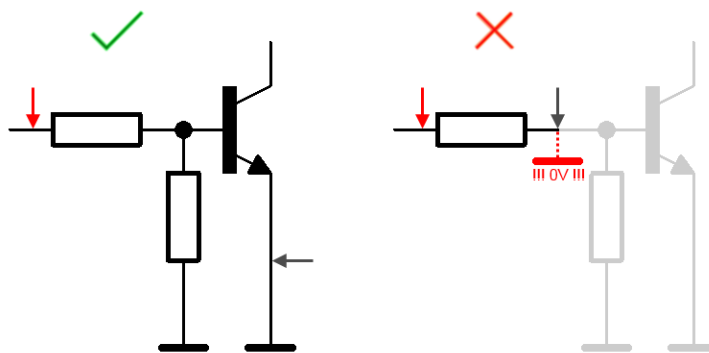
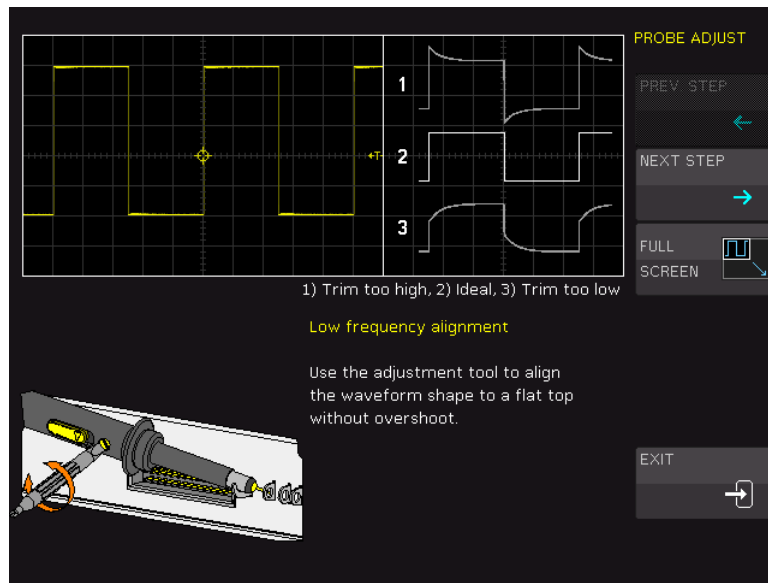


Fig.2-1: Correct use of an oscilloscope for measurements.

### Passive probes require adjustment, and the attenuation ratio must be known in the oscilloscope!

As described in section 1.1.3, all probes must be adjusted before being used in the measurements. On the RTC1000, this is done by pressing the *Setup* button in the *General* grouping. In the submenu, use *PROBE ADJUST* to open the adjustment wizard. Once a probe is connected as described on the monitor, the appropriate channel must be selected. Fig.2-2 shows an LF adjustment on channel 1. To perform the HF adjustment, select *NEXT STEP*.

- ▶ Perform the adjustment on both channels.



**Fig.2-2: Performing the probe adjustment.**

Once the adjustments have been successfully completed, a check must be made to ensure that the correct attenuation ratio for the probes is known in the oscilloscope. First check that the switch is set to 10:1 (x10) on both probes. In the grouping for the vertical system, use the *MENU* key and select *PROBE* on the monitor (page 2) to set the attenuation ratio. The channel can be changed by pressing the *CH1 / CH2* key.

**After every preset, the duty cycle must be set again!**

Note: higher class Oscilloscopes, such as R&S®RTM3000 or R&S® RTO offer with suitable probes an automatic recognition of the division ratio.

Almost every modern oscilloscope offers an autoseg function that automatically performs all necessary settings on the instrument to optimally display the signal. While this function can be very convenient for daily measurement tasks, to increase the educational value of these exercises it is better not to use it here. Once you are sufficiently comfortable working with oscilloscopes, you can use autoseg to get an initial overview of the measured signal. The RTC1000 offers an education mode that deactivates the autoseg function along with all automated measurements. If necessary this mode can be password-protected.

► Use *SETUP* → *EDUCATION MODE* (page 3) to enter education mode.

**Perform all exercises in education mode!**

Press the  $\frac{SAVE}{RECALL}$  button and select *DEVICE SETTINGS* → *DEFAULT SETT.* to reset the oscilloscope to the default settings.

**By performing a Preset, the instrument should be reset to the default settings before every exercise!**

Throughout the exercises, you will find thought-provoking questions that will lead to a better understanding of the exercise. The questions are in italics and indicated by the symbol *?*. Most of the questions can also be answered beforehand in order to prepare for the exercises.

## 3 Basic measurements

In spite of all the automation of measurements, manual setup and estimation of measurement results are still an important part of an engineer's everyday life. This chapter provides a practical introduction into the operation of a modern oscilloscope and the completion of basic measurement and display procedures.

### 3.1 Exercise setup

The setup in Fig.3-1 is provided as a general overview and will be worked through step-by-step in the exercise.

The training board in Appendix A.1 will not be used until later in the exercise.

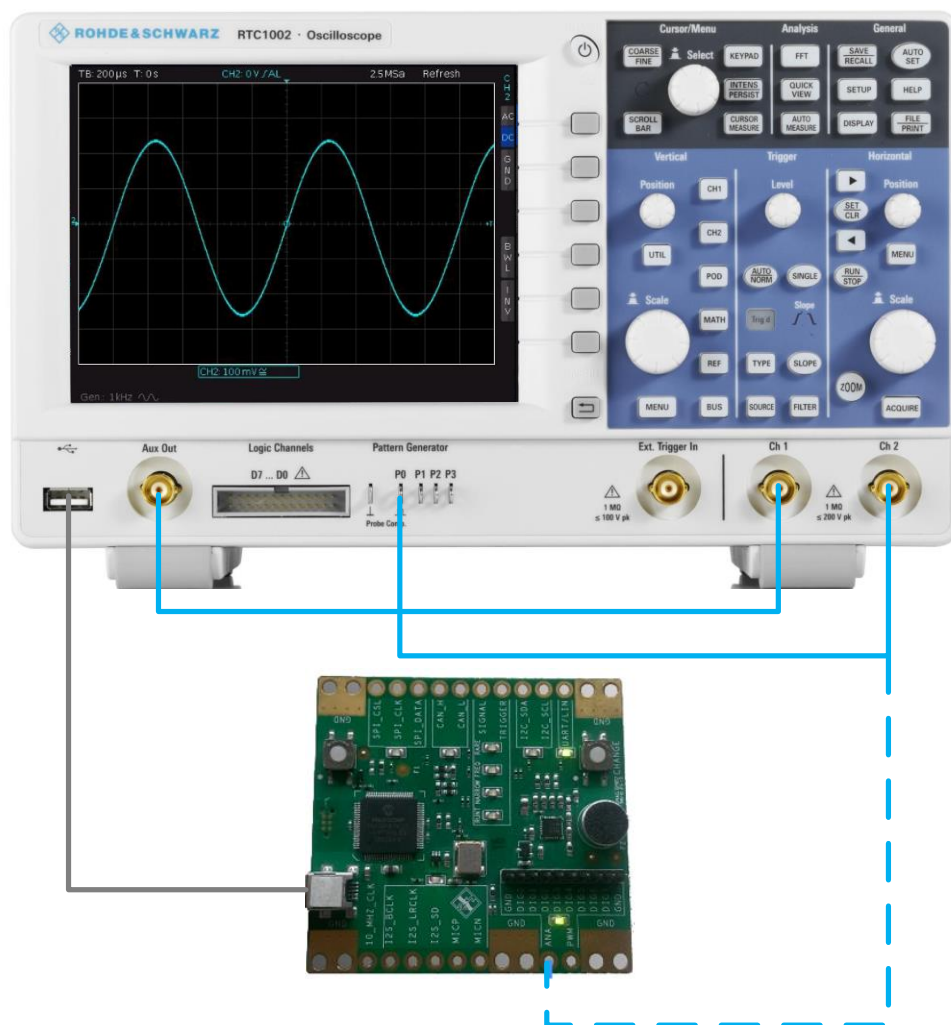


Fig.3-1: Test setup for manual measurements.

## 3.2 Exercise

- ▶ Set the oscilloscope to the default state (*PRESET*).
- ▶ Set the probe attenuation factor for channel 1 to 1:1 and for channel 2 to 10:1; see also chapter 2.

The RTC1000 has both an integrated function generator and a test pattern generator. The function generator whose output signal can be tapped on BNC jack *AUX OUT* is used for the initial measurements.

- ▶ Connect a BNC cable from the function generator to the input for channel 1.

To switch on the generator, press the *UTIL* button in the *VERTICAL* grouping and then select *FUNCTION GEN.* on the monitor.

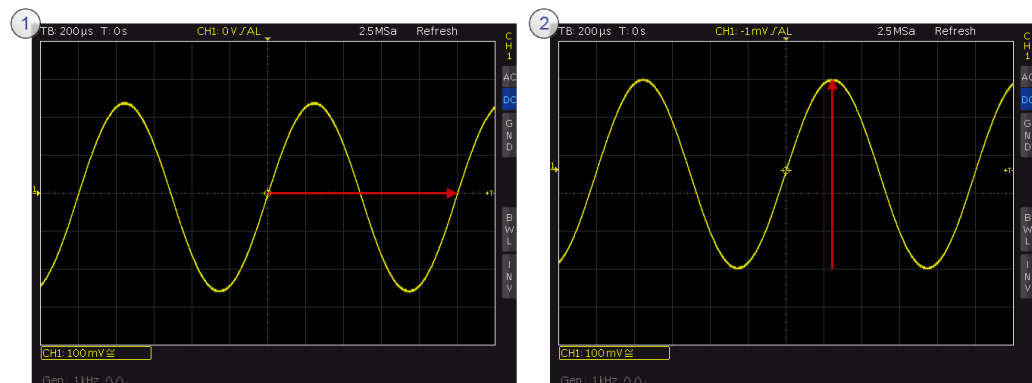
- ▶ Switch on the function generator and then use the  $\leftarrow$  key to exit the menu.

The function generator generates a 1 kHz sine-wave signal with a peak-to-peak voltage of 500 mV.

The crosshair in the center of the screen, in combination with the arrows at the left and upper edges of the monitor, indicates the current trigger position.

- ▶ Set the horizontal and vertical scaling and the trigger threshold to generate a stable image similar to Fig.3-2 ① on the oscilloscope.

The display of the second channel can be removed by pressing the *CH2* key twice.



**Fig.3-2: Measuring the period and the peak-to-peak voltage of a sine-wave signal.**

- ▶ Read the frequency of the sine-wave signal by counting off the grid squares multiplied by the horizontal scaling. (Do this even if you already know it!)

By varying the vertical offset, you can obtain a display as shown in Fig.3-2 ②, which makes it possible to read the amplitude of the signal more precisely.

- ▶ Determine the peak-to-peak voltage of the sine-wave signal and compare your results against the settings in the function generator.

The method used above does not provide exact measurement results. While a visual analysis is suitable for quick estimations, cursor measurements deliver significantly more accurate results.

After it is reset to its default settings, the oscilloscope will automatically use the edge trigger. As you have seen, when working with sine-wave signals it is useful to trigger

on the falling or rising edge. This type of trigger is suitable for square-wave signals as well.

► Set the function generator to a pulse signal at a frequency of 10 kHz and leave the other parameters unchanged. Use the *KEYPAD* button to set the frequency.

This signal is triggered correctly with the current settings, as well.

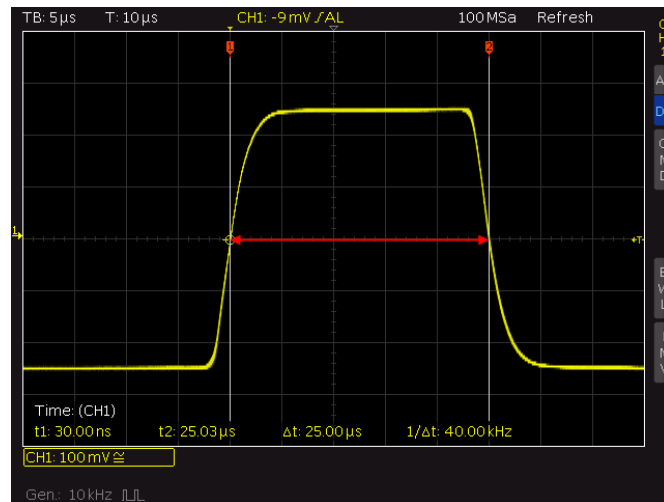
► Adjust the horizontal scaling for optimal measurement of one pulse width.

In the *CURSOR/MENU* grouping, locate the *CURSOR MEASURE* button.

► Open the cursor menu and select the time measurement.

You can show shift the displayed markers horizontally using the *SELECT* rotary knob. The  $\frac{COARSE}{FINE}$  key must be pressed for fine adjustments. Pressing the *SELECT* rotary knob switches between active cursors.

► Measure the pulse width; see Fig.3-3 for an example. The pulse width is measured at 50 % of the amplitude in the steady state.



**Fig.3-3: Cursor measurement of a pulse width.**

► Measure the duty cycle for the signal.

Fig.3-3 shows the finite rise time for the pulse. Depending on the bus specifications, the 10 % to 90 % definition (for example TTL) or the 20 % to 80 % definition (for fast buses based on LVDS) is used to measure the rise time. In this definition, the rise time is the time required for the amplitude to rise from 20 % to 80 % of the final settled value.

► Set the oscilloscope so that the rise time can be properly measured.

Fig.3-4 provides an example of a correct RTC1000 display configuration for measuring the rise time  $t_A$ . The important thing to note is that the steady state is assumed for 0 % and 100 %.

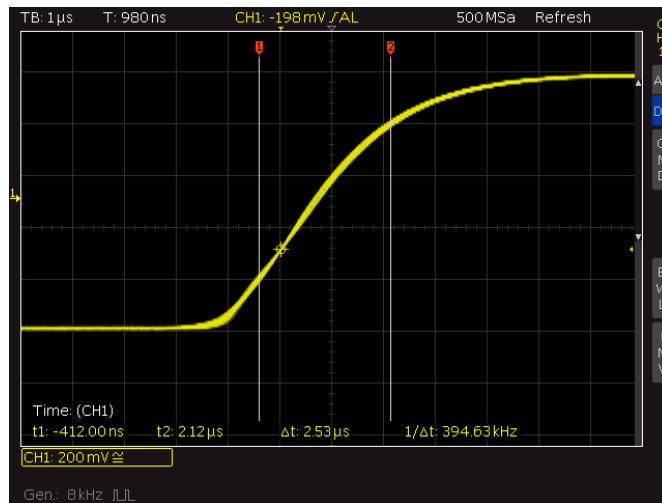


Fig.3-4: Measuring the rise time of a pulse.

? What is the minimum bandwidth an oscilloscope must have in order to measure the signal from Fig.3-4 with 10 % accuracy? Use formula (1) to calculate.

► Measure the rise time for the pulse and calculate the required oscilloscope bandwidth.

The *MEASURE TYPE* menu also offers a number of automated measurements.

► Select *Rise Time 80%* and set the cursor so that the rise and fall times can be measured simultaneously; see Fig.3-5.

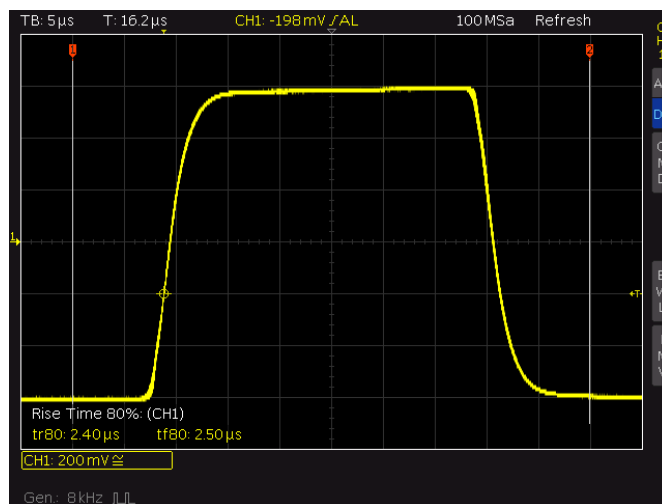


Fig.3-5: Automated cursor measurement.

► Compare the results.



The automated measurements are suitable for quick analyses. As you have seen here, however, the user has very little influence on these measurements. It must therefore always be remembered for these types of measurements that even if the measurement is automated, the plausibility of the results must be manually checked at the very least!

It can sometimes be useful to measure two signals simultaneously. The RTC1000 has two independent inputs for this purpose.

► As shown in Fig.3-1, connect channel 2 to the output *S0*. Always remember to connect the probe ground wire.

Press the *CH2* key to select channel 2. Repeated pressing of the *CH1* or *CH2* key displays or hides the respective channel.

► Display channel 2 and hide channel 1.

The signal under test is present on channel 2. The oscilloscope must therefore know to apply the trigger to this channel.

► Under the *TRIGGER* grouping, use the *SOURCE* button to select *CHANNEL 2*.

The test pattern generator is used as the signal source for channel 2. This is designed for higher frequencies than the signal generator on the RTC1000. As a result, the signal edges are significantly steeper.

Like the signal generator, the test pattern generator is selected using the *UTIL* button.

► Switch on the *PATTERN GENERATOR* and select *SQUARE WAVE*. Accept the remaining settings without modification.

► Perform another rise time measurement on this signal and calculate the required oscilloscope bandwidth for 10 % accuracy.

? *Is the RTC1000 reliable enough to perform precise time measurements on this signal?*

Next, the effect of smaller bandwidths on the measured signal will be explored.

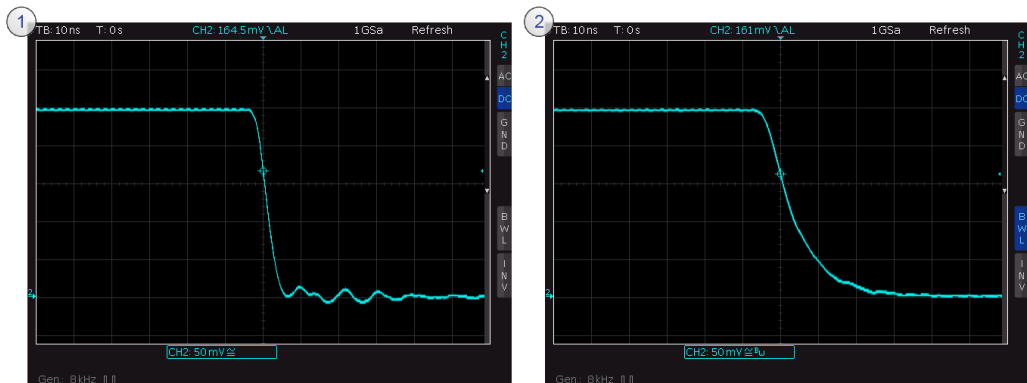
► Set the test pattern generator to the highest possible frequency and zoom in on a falling edge via the scaling function. (Set the trigger to falling edge.)

Press the *MENU* key and reduce the channel bandwidth to 20 MHz.

► Observe how the signal display changes.

? *What advantages might bandwidth limitation have for measurements?  
What is causing the ripple in the unfiltered signal (see Fig.3-6)?*

► Switch off the bandwidth limiting.



**Fig.3-6: Comparing measurements with full bandwidth and limited bandwidth.**

- ▶ Turn on both channels.
- ▶ Set the following parameters for the pulse and square-wave signal sequence on the signal generator and test pattern generator:

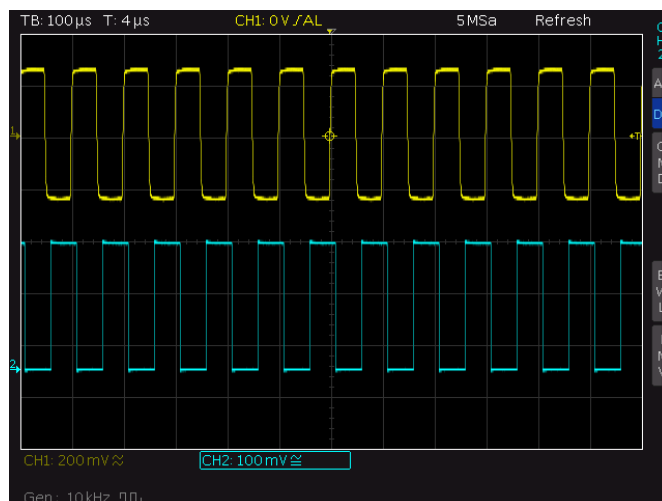
FREQUENCY	10 kHz
DUTY CYCLE	50 %

Display both channel 1 and channel 2 on the monitor; see Fig.3-7.

Many signals possess both DC and AC components. Sometimes only the AC components are of interest. In this case, it makes sense to use AC coupling. When AC coupling is being used, an upstream 2 Hz input filter is used to suppress the DC components.

? *What is the expected result when the DC is suppressed for these signals (Fig.3-7)?*

- ▶ Press the *MENU* key and use *COUPLING* to select the *AC* option for both channels. Check the result against your expectations.



**Fig.3-7: Displaying both channels simultaneously with DC coupling.**

DC coupling is more commonly used for measurements.

- ▶ Select DC coupling to make all signal components visible again.

The final step in this exercise presents a new display mode, the XY display.

As you learned in section 1.1.1, an oscilloscope displays a variable as the function of another variable. The voltage versus time display is most commonly used, but in some cases it can be very useful to display both of the oscilloscope's independent channels as X and Y axis. This makes it possible to display diode characteristics, for example.

► Connect the training board from Appendix 55A.1 to the USB port as shown in Fig.3-1.

The training board must be configured so that a sine-wave signal can be tapped at the ANA output.

► Use the two keys to switch to state ② as defined in Table 2.

► Use the probe connected to channel 2 to tap into the signal at the ANA output.

► Perform a cursor measurement to determine the frequency and amplitude of the sine-wave signal being measured on channel 2.

XY mode is not only very practical for measuring component characteristics but can also be used to determine the phase difference between two signals.

You have already learned about the integrated signal generator on the oscilloscope.

► Configure the signal generator so that channel 1 has a signal that approximates the sine-wave signal just measured on channel 2 as closely as possible.

An oval figure is displayed after switching to XY display mode. The phase angle of the two signals can be identified based on the shape and position of the displayed figure; see Fig.3-8.

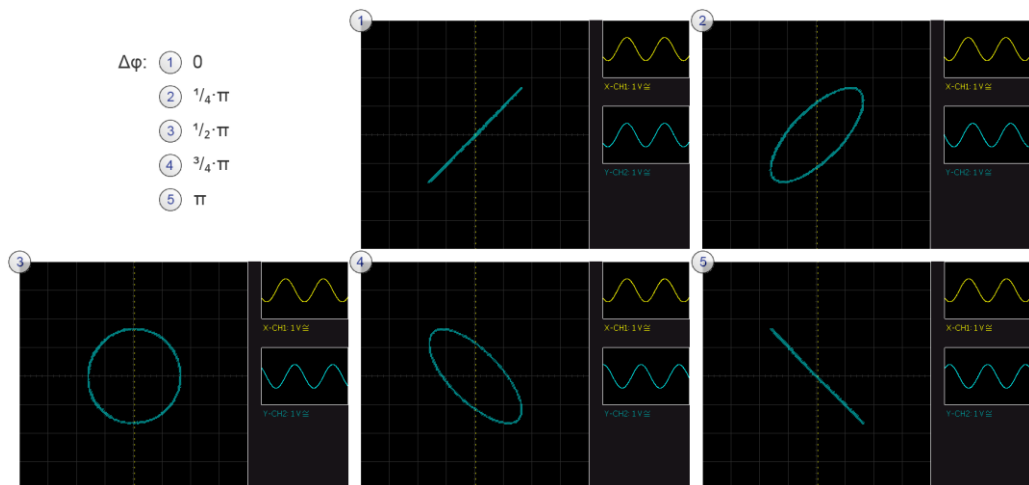


Fig.3-8: Display of frequency ratio 1:1 in XY mode.

On the RTC1000, use the *UTIL* key and select *XY* to change to XY mode.

► What is the phase angle for the signals on your monitor?

► Change the frequency on the signal generator in small increments. What do you see in the standard display and in XY mode?

The images generated in XY mode are called Lissajous figures.

► Set frequency ratio 3:1 and watch the resulting changes.

## 4 Documentation and storage

This chapter provides a practical introduction into the documentation of oscilloscope measurements. Especially when sharing test instruments, as is typically the case in a university environment, it can be practical to save all settings and measurement data to a personal storage medium for later use.

You should have a USB flash drive handy to perform this exercise.

The RTC1000 can save different types of information in order to document measurements or save current settings:

- Device setup
  - Device setup for later import. Data can be stored locally or externally.
- References
  - Data records consisting of the device setup and the ADC data. Data can be stored locally or externally.
- Traces
  - Measurement results consisting of only the ADC data and which can be stored only externally.
- Screenshots
  - Image files showing what is displayed on the monitor at a given point in time.

### 4.1 Exercise setup

The setup for this exercise (see Fig.4-1) is identical to the exercise setup in section 3.1.

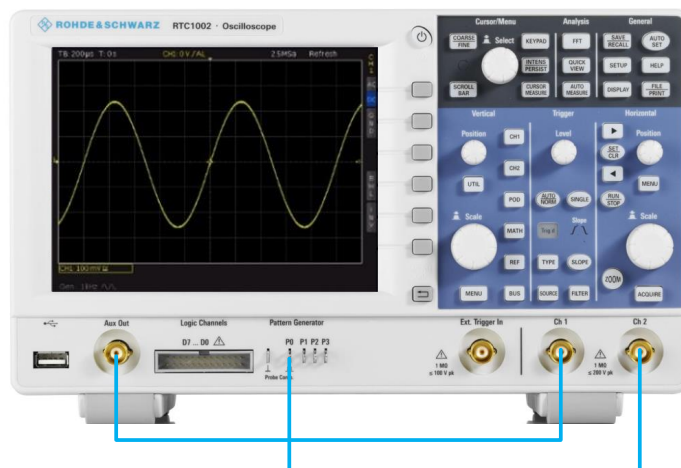


Fig.4-1: Test setup for documentation and storage.

## 4.2 Exercise

### Storing a reference signal:

- ▶ Set the oscilloscope to the default state (*PRESET*). Don't forget to set the correct probe attenuation factor!
- ▶ Configure the test pattern generator so that a 100 kHz square-wave signal is generated with a duty cycle of 50 %.
- ▶ Set several periods of this signal on the monitor with channel 2.

In practice, a generated signal – and in particular its edges – might not meet the requirements for a product. One possible correction might be to use different filters. References are a convenient way to compare the signals acquired using different filters.

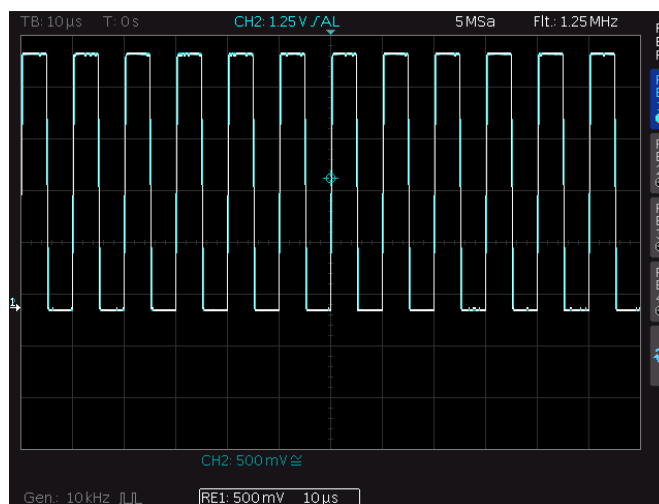
The menu for references is opened using the *REF* button in the *VERTICAL* subgroup.

- ▶ Open the reference signal menu and select *RE1*.
- ▶ Use *SAVE* to save the signal and the following parameter configuration:

TRACE	CH2
STORAGE	INTERNAL

Go up one level in the *REFERENCES* menu and select *DISPLAY* to make the reference signal visible.

The display should now look something like Fig.4-2. The white signal is the saved reference.



**Fig.4-2: Saved reference signal.**

The oscilloscope's integrated lowpass filter is useful for simulating a filter being switched out.

The cutoff frequency for the filter can be set based on the current sample frequency. To make the cutoff frequency as low as possible, the oscilloscope sample speed must be reduced.

- ▶ In the *HORIZONTAL* grouping, press the *ACQUIRE* button and select the option *RECORD MODE* → *MAX. WFM. RATE*.

This setting will reduce the sample rate to obtain the maximum trigger repetition rate.

- ▶ In the *ACQUIRE* menu, select the option *ARITHMETIC* → *FILTER*.

Use the *SELECT* rotary knob to set the cutoff frequency within the range defined by the sample frequency.

The current display (see Fig.4-3) can now be used to visually compare the two signals.

- ▶ Experiment with the settings to find out at which harmonics of the fundamental frequency the square-wave signal is displayed satisfactorily.

- ▶ Use *ACQUIRE* to return the acquisition options to the default:

<i>ARITHMETIC</i>	<i>REFRESH</i>
<i>RECORD MODE</i>	<i>AUTOMATIC</i>

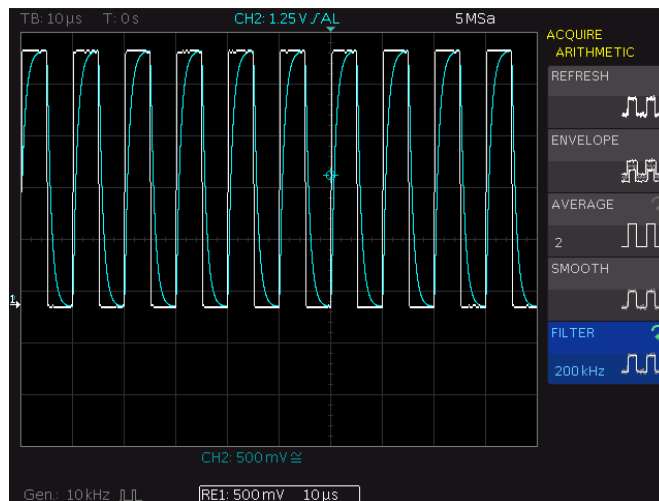


Fig.4-3: Comparing a signal against the reference.

#### Saving a trace for external analysis:

For many applications, an analysis on the oscilloscope monitor is not sufficient. The data must often be analyzed and processed in more detail on a computer. This is why it is possible to load the values acquired via the ADC directly onto a USB flash drive.

- ▶ Connect the USB stick to the front jack.
- ▶ Turn off the display of the reference signal by tapping the *REF* key twice on the GUI.
- ▶ Configure the signal generator so that the following signal is generated:

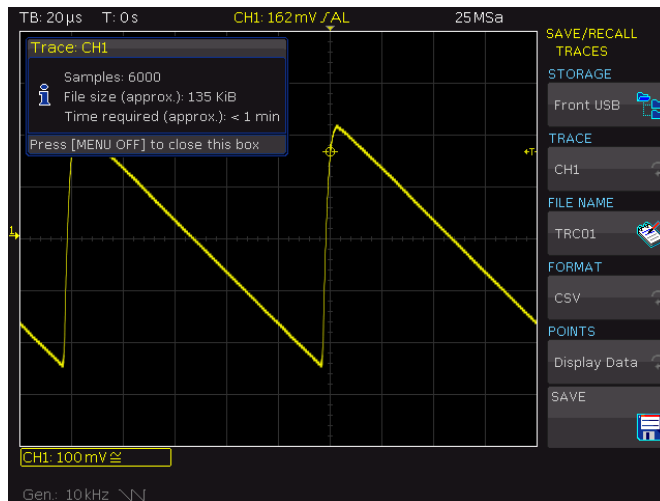
FUNCTION	RAMP
FREQUENCY	10 kHz
AMPLITUDE	500 mV (Vpp)

- ▶ Display the signal on channel 1.

The  $\frac{SAVE}{RECALL}$  button opens a menu that permits configuration of the  $\frac{FILE}{PRINT}$  button.

- Under TRACES, accept the settings from Fig.4-4:

STORAGE	FRONT USB
TRACE	CH1
FORMAT	CSV



**Fig.4-4: Saving an acquired signal.**

Before saving the signal, the acquisition should be stopped so that the maximum number of values is used.

- Use the  $\frac{RUN}{STOP}$  button to stop the acquisition.
- Return to the main menu and then under the option *KEY*, select *TRACES*.

The  $\frac{FILE}{PRINT}$  button is now configured so that when it is pressed, the current ADC values are automatically saved to the USB flash drive.

- Use the  $\frac{FILE}{PRINT}$  button to save the signal trace.

The ADC values are now available in an Excel-readable .csv format on your USB stick.

If you have a computer available to perform the assessment, you can open the file in Excel and generate a chart using the data as shown in Fig.4-5.

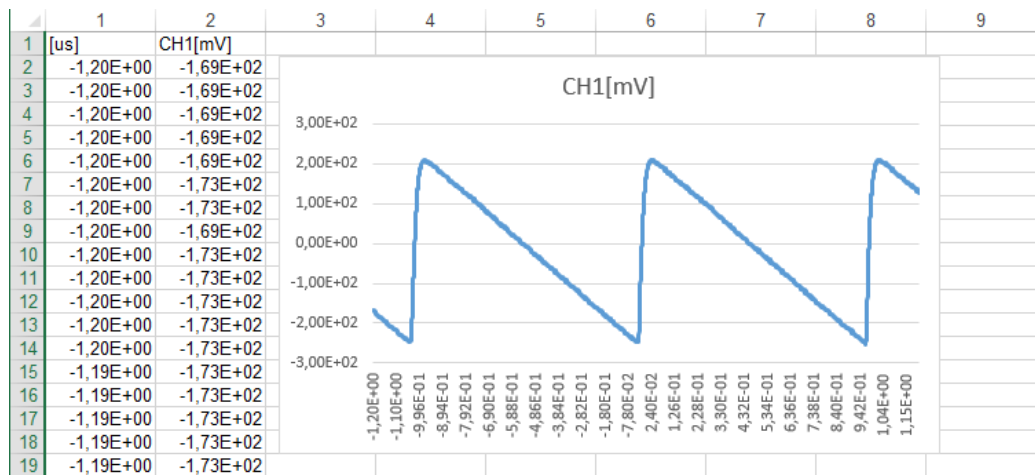


Fig.4-5: Importing the data into Excel.

### Saving screenshot:

Even though screenshots cannot be loaded back into the instruments like the other formats described above, they are still a very good format for documenting measurements.

The easiest method is to configure the  $\frac{FILE}{PRINT}$  button so that it saves a screenshot to the USB stick. The behavior of the button can be configured in the *KEY* submenu of the  $\frac{SAVE}{RECALL}$  button.

- Configure the  $\frac{FILE}{PRINT}$  button as described and save a screenshot to the USB flash drive, similar to the example in Fig.4-4.



## 5 Advanced trigger settings

The objective of this chapter is to build on the fundamentals in section 1.2.3 and to discuss advanced trigger system applications. The exercise shows the correct method to select and configure appropriate triggers for more complex measurement tasks.

### 5.1 Exercise setup

For the exercise setup, the internal signal generator of the oscilloscope is connected to channel 1 and the training board from Appendix A.1 is connected to channel 2 and supplied with power via the USB port. Fig.5-1 shows this setup in its entirety. The probe connected to channel 2 is first connected to the *UART/LIN* output on the circuit board and then later during the exercise to the *SIGNAL* output.

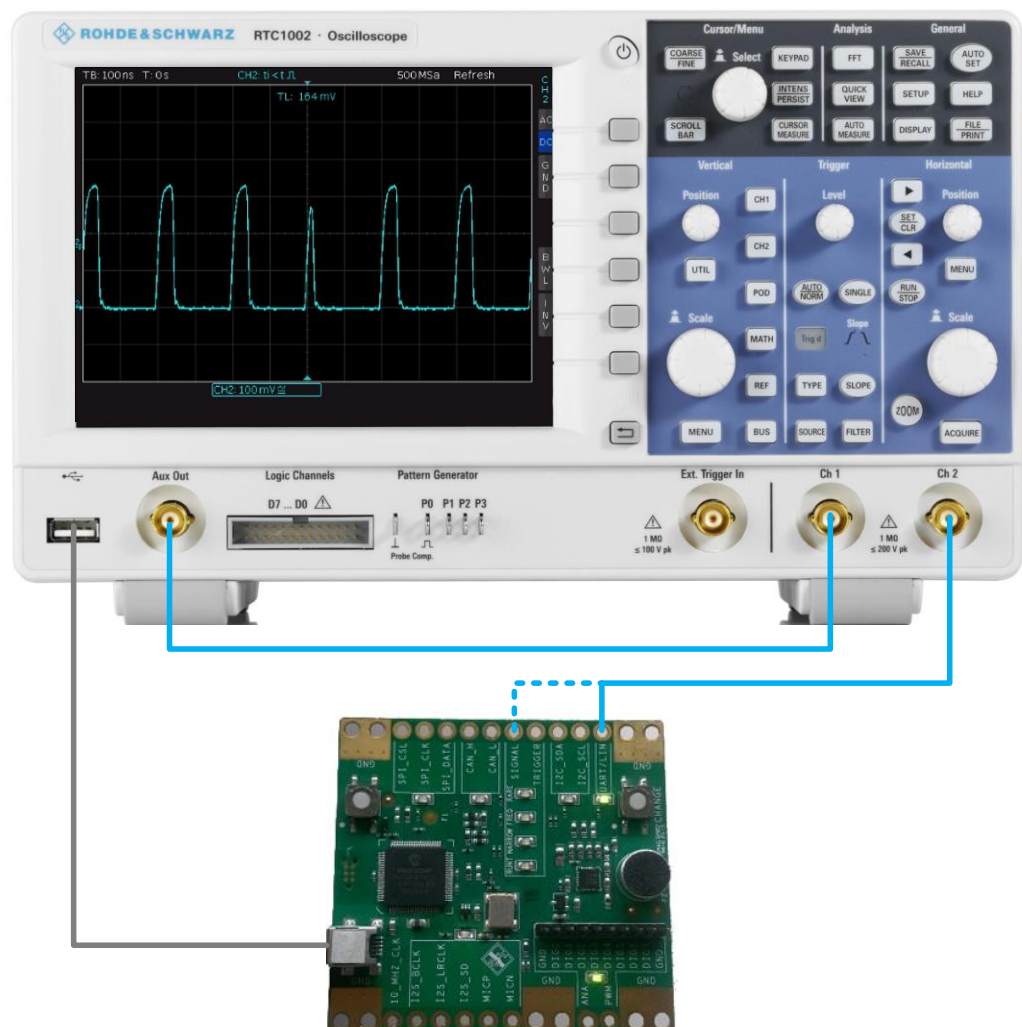


Fig.5-1: Test setup for advanced trigger settings.

## 5.2 Exercise

- ▶ Set the oscilloscope to the default state (*PRESET*). Don't forget to set the correct probe attenuation factor!

You already learned about the simplest and most frequently used trigger, and you have used it in the exercises in section 1.2.3. The additional setting options for the edge trigger are briefly discussed here before the other trigger types are introduced.

- ▶ Configure the signal generator so that the following signal is generated:

FUNCTION	SINUS
FREQUENCY	1 kHz
AMPLITUDE	500 mV
OFFSET	400 mV

- ▶ Display the signal on the monitor.

### Triggerfilter:

- ▶ Use the *FILTER* button to open the setup menu for the edge trigger and then select option *AC*.

The display should resemble that in Fig.5-2. In this mode, the DC component can be changed at will. The AC filtering ensures that the threshold value for the trigger remains constant and the signal appears to be triggered correctly. In addition, in auto mode the threshold value is limited within the signal automatically, which results in a stable display of the signal even though the trigger level actually does not appear to be set correctly as shown in Fig.5-2. In normal mode, the trigger level can be shifted above the peak values for the signal.

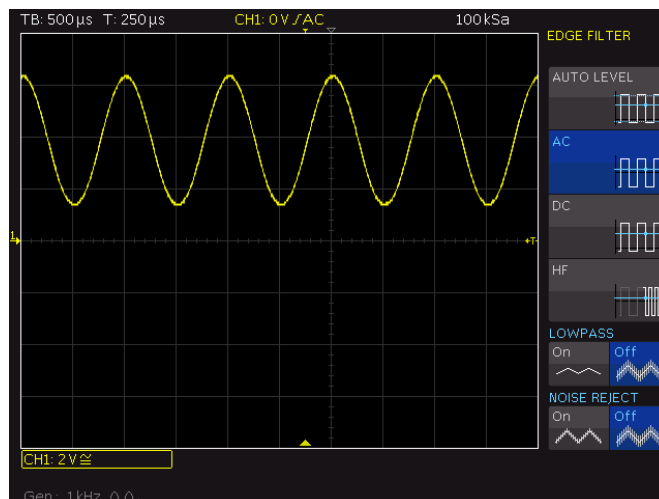


Fig.5-2: Triggering with an AC filter.

- ▶ Set the *AUTO LEVEL* option.

As shown in Fig.5-2, it is also possible to add in a lowpass that filters the trigger signal with an upper cutoff frequency of 5 kHz. The measured signal is not affected by this.

In cases of strong noise, the edge trigger can interpret signal transitions that are generated by noise components as actual signal edges. To prevent this, the noise

suppression can be switched on, in which case a 100 MHz lowpass filter is inserted before the trigger signal.

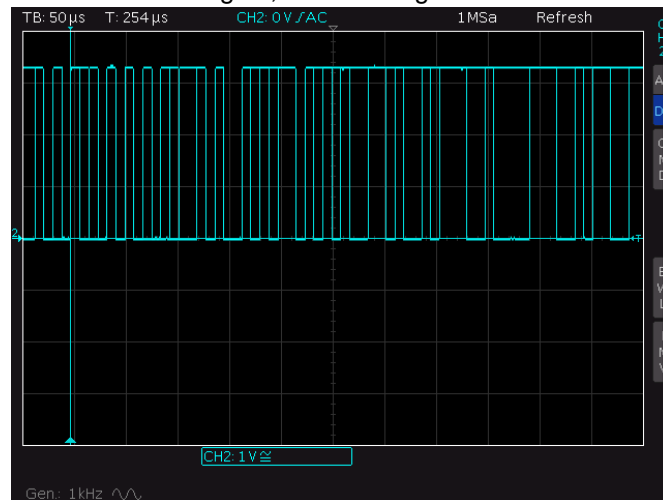
#### Triggering of data bursts:

► Hide the display of channel 1 and change the training board state to ① as defined in Table 2 in Appendix A.1.

The board will generate a UART signal at 115.2 kbaud.

► Use the probe connected to channel 2 to tap into the output signal at the *UART/LIN* output.

► Set the oscilloscope so that you can clearly identify the individual bit lengths of a burst in the bus signal; see also Fig.5-3.



**Fig.5-3: Display of a bus signal with random trigger points.**

Although the individual bit lengths are easily recognized in the above screenshot, this type of display cannot be used to decode the information contained in the transmission. This is because the oscilloscope triggers on random edges within the burst. You could either press the *SINGLE* key in the *TRIGGER* grouping to initiate a single acquisition and then use the oscilloscope memory for analysis or you could set a hold-off time.

The hold-off setting permits the trigger to initiate only after a defined time period. This ensures that the oscilloscope always triggers on the first falling edge (the start bit) of the entire burst. In the example of the bus transmission, a time period should be defined that lies between the length of a burst and the timespan between two bursts.

► Set the horizontal scaling to permit you to estimate the length of a burst and the timespan between the bursts.

Use the *TYPE* key to set the trigger type and the hold-off time.

► Set the hold-off value to be a time lying between your two estimated values.

The bus transmission is now displayed with the correct triggering and you should also be able to see the differences between individual bursts in the form of alternating bits. The transmission acquired with a hold-off time is shown in Fig.5-4.

► Turn off the hold-off time.

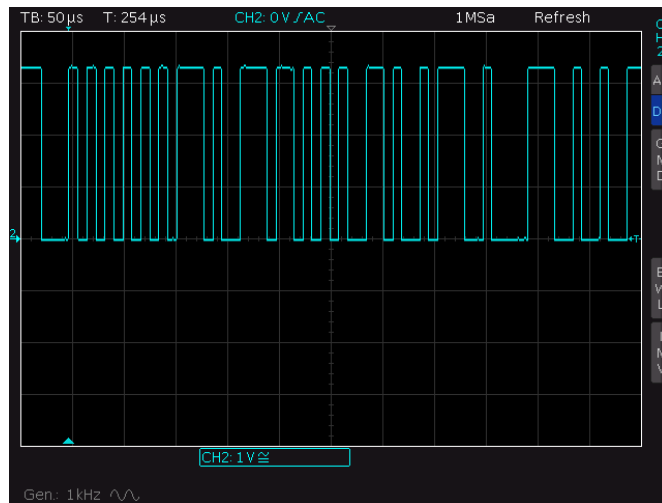


Fig.5-4: Display of the bus signal with hold-off triggering.

Another trigger form that can now be introduced is the pulse trigger.

This trigger is especially suited to square-wave signals. The many possibilities for configuring this trigger make it possible to trigger on specific ranges within a transmission.

The training board can simulate several bus standards as well as different types of signal errors.

Complex digital circuits are prone to glitches. Glitches cause momentary false interpretation in logic circuits and a temporary distortion of a Boolean function. They arise because the signal transient times in the individual logic gates are never completely equal or by crosstalk. ► Switch the board to state ④ as shown in Table 2 in Appendix A.1 and use the probe to tap into the signal at the *SIGNAL* output.

► Use the edge trigger to set the oscilloscope so that several pulses are displayed.

The glitch cannot be detected with these settings even though it appears 100 times per second. If a glitch is suspected in a signal, the sample rate should be reduced in order to achieve the highest possible rate of trigger events. This reduces the dead time<sup>3</sup> between the measurements and increases the odds of acquiring even rare signal errors. As described in section 4.2, the RTC1000 offers *MAX. WFM. RATE* mode.

► Switch to this mode for the maximum signal repetition rate.

The signal errors cannot be detected with the naked eye because of their very short duration, even with this setting. The RTC1000 offers the option of continuing to display signals on the monitor for a defined time after the trigger event. In this case, the display is not updated with the latest acquisition after every trigger event. Instead, a static image consisting of many acquisitions is displayed.

This mode is called *PERSISTENCE* and can be called using the  $\frac{INTENS}{PERSIST}$  button.

<sup>3</sup> See section 1.2.2.

- ▶ Make the following settings under *SETTINGS*:

MANUAL            INFINITE (maximum value)  
BACKGROUND    ON

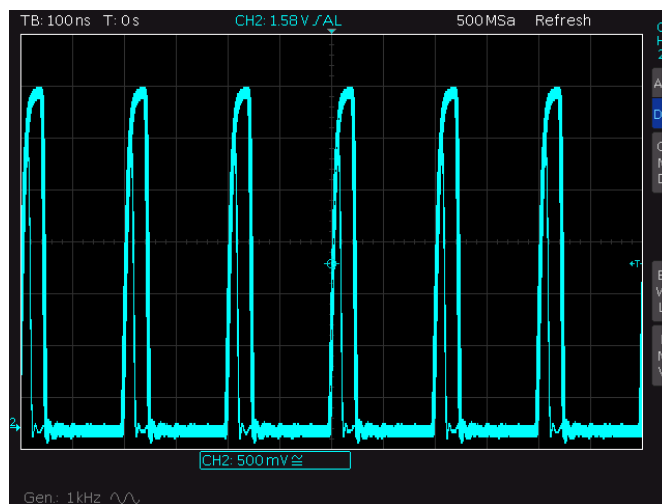
The background option continues to display the existing lines on the monitor for an unlimited length of time.

To better detect measured glitches, the display intensity should be increased by using the *SELECT* rotary knob.

- ▶ Set the following on the oscilloscope:

INTENSITY        100 %

This setting makes it possible to detect short pulses occurring at irregular intervals. In Fig.5-5, an acquired glitch can be seen within each regular pulse.



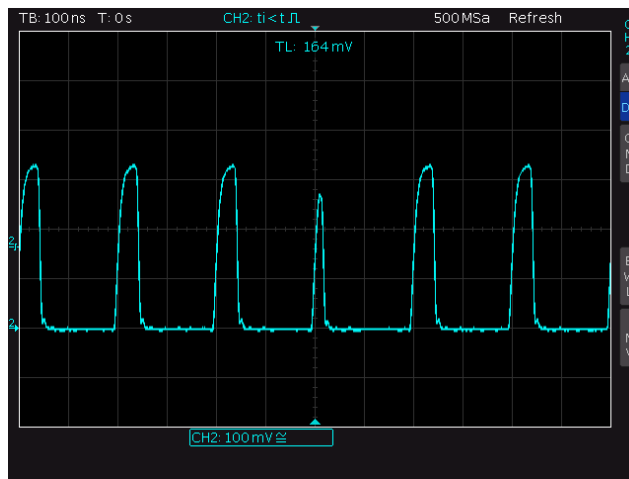
**Fig.5-5: Pulse packet with a glitch.**

This makes it possible to identify the shape of a glitch. With this information, the pulse trigger can be configured so that it reliably triggers on the transmission error.

- ▶ Make a note of the pulse width of a glitch at the height of the trigger threshold.
- ▶ Return all *PERSISTENCE* settings to their original values.
- ▶ Make the following settings for the trigger:

TYPE	PULSE	
FILTER	POLARITY	POSITIVE
	COMPARISON	$t_i < t$
	TIME $t$	Width of the glitch $< t <$ pulse width

The trigger will now search for a pulse that has a duration shorter than the specified timespan. Because only the searched glitch matches this condition, the oscilloscope reliably triggers on the interference, as seen in Fig.5-6.



**Fig.5-6: Triggering on a glitch using the pulse trigger.**

In the case of digital signals, runts can occur in addition to glitches. These are normally shaped pulses that do not have the necessary amplitude. Runts can cause logical 1 not to be recognized correctly, leading to incorrect processing of a data message.

Because the signal errors occur only rarely, a maximum update rate should be used once more.

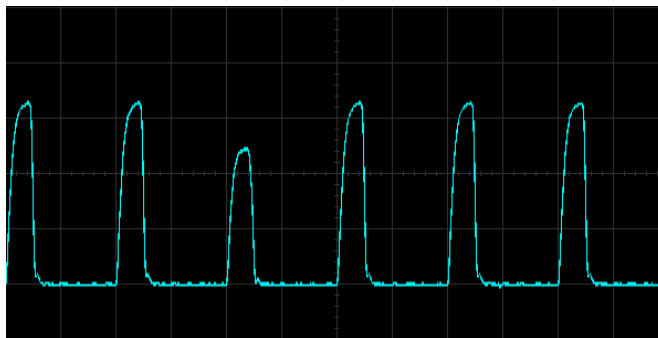
- ▶ Switch the board to state ⑥ as shown in Table 2 in Appendix A.1.
- ▶ Repeat the glitch analysis steps in order to get an idea of the error properties.

After you have an idea of the shape of the faulty pulse, the trigger must be set so that the oscilloscope will reliably trigger on the runts.

Some oscilloscopes offer a special runt trigger for this situation, although this is not offered by the RTC1000. The properties of runts make the procedure used for triggering on glitches ineffective for runts. Runt triggers analyze the height of a pulse in order to correctly initiate the trigger.

The following procedure can be used for the pulse trigger in this situation: If the trigger threshold is set high enough, i.e. over the maximum amplitude of a runt pulse and under the amplitude of the other pulses, then an unusually long time will pass without a pulse. The trigger system evaluates this time period as a segment with negative polarity.

- ▶ Turn off the *PERSISTENCE* settings and configure the pulse trigger so that a stable image similar to that in Fig.5-7 is generated.



**Fig.5-7: Triggering a runt pulse.**

## 6 Signal analysis using FFT

Even if it initially seems unusual, many digital oscilloscopes offer a simple form of spectrum analysis that uses Fast Fourier transformations. This chapter provides a practical introduction into the analysis of signals in the frequency domain using an oscilloscope.

### 6.1 Exercise setup

The exercise setup consists of the oscilloscope and the training board from Appendix A.1, which is supplied with power via the USB port. Fig.6-1 shows this setup in its entirety. The oscilloscope's integrated signal generator is first connected to channel 1. A probe is then connected that will measure the signal that is output at the `10_MHZ_CLK` output. Channel 2 on the oscilloscope is connected to the `MICP` output of the circuit board via a probe.

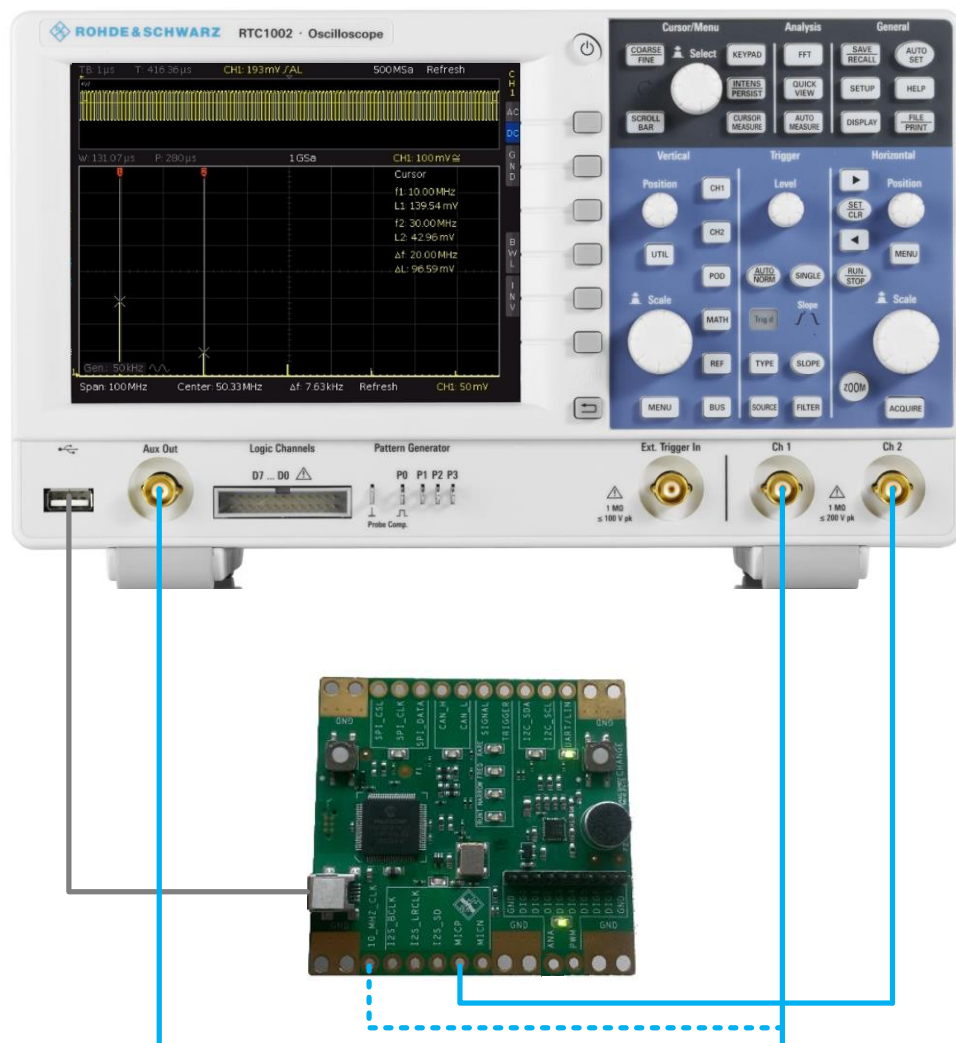


Fig.6-1: Test setup for signal analysis using FFT.

## 6.2 Exercise

- ▶ Set the oscilloscope to the default state (*PRESET*). Don't forget to set the correct probe attenuation factor!

Before beginning the exercise, configure the oscilloscope to use the maximum sample rate.

- ▶ Switch the oscilloscope to *MAX. SA. RATE* mode.
- ▶ Press the *FFT* button under the *ANALYZE* grouping.

The screen is split into two panes; see Fig.6-2. The upper pane (①) displays the previously defined voltage-time trace for the measured signal and the settings for the horizontal system.

The zoom and position information is displayed in between the two panes (②). Only the signal segment that is displayed on the monitor and bound by the two vertical white lines is used for the FFT.

? *What does the frequency spectrum for a sine-wave signal look like if its maximum amplitude lies far above the displayed range as a result of the vertical system being set incorrectly?*

The lower pane (③) shows the result of the FFT analysis and the associated settings:

*Span* shows the size of the currently displayed frequency range. The *span*, timebase and selected segment are directly linked to one another. As the selection for the timebase and the range in the time domain displayed between the two vertical lines increases, so too decreases the frequency band that can be set.

*Center* defines the frequency at the center of the segment displayed on the monitor.

The minimum step size  $\Delta f$  can be set indirectly via the number of points.

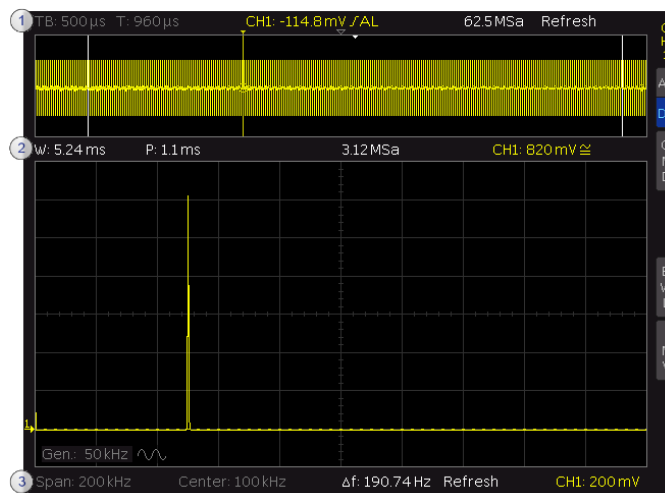


Fig.6-2: Setup of FFT mode.



Press the *TIME/DIV* rotary knob to switch between the panes. The currently active pane (time domain, selected signal segment for the FFT or frequency domain) is boxed in white. The rotary knobs are assigned different tasks depending on the currently active pane:

MODE \ KNOB	<i>VOLTS/DIV</i> + <i>Offset</i>	<i>TIME/DIV</i> + <i>Offset</i>
<i>Time domain</i>	Voltage range (total) of the signal segment	Timebase (s/div)+Position
<i>Signal segment</i>	Voltage range (total) of the signal segment	Width of the signal segment for the FFT (ms)
<i>Frequency domain</i>	Voltage scaling (V/div) in the spectral display	Frequency band (Hz)

**Table 1: Controls in FFT mode**

A sine-wave signal is initially measured as an output signal from the signal generator.

- ▶ Set the following on the function generator:

FUNCTION	Sinusoid
FREQUENCY	50 kHz
AMPLITUDE	350 mV (Vpp)

- ▶ Set the timebase for the oscilloscope to 500  $\mu$ s and select a maximum signal segment for the FFT.

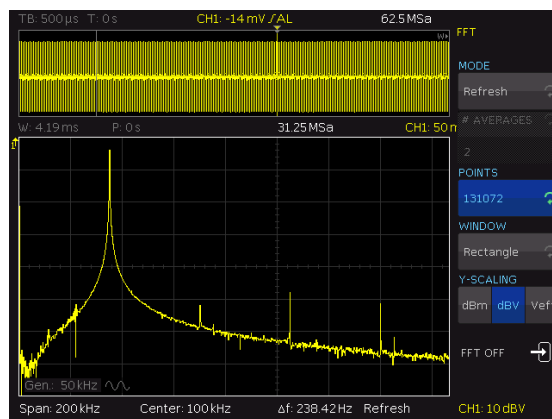
- ▶ Select the minimum frequency band for these settings and verify that the spectrum of the sinusoidal signal is displayed correctly.

Press the *FFT* button to open the menu again.

- ▶ Display the result in dBV; see Fig.6-3.

The RTC1000 offers four different window functions.

- ▶ Explain why the window functions are needed, and explain the differences between the various functions. (For detailed information please see the RTC1000 manual)
- ▶ Compare how each of the window functions affects the spectrum.



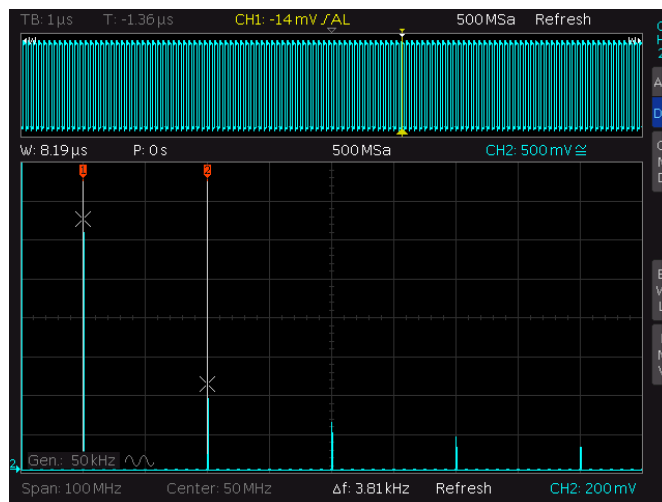
**Fig.6-3: Measuring a sine-wave signal using the rectangle window.**

**Clocksignal:**

The training board provides a 10 MHz clock in all operating modes. Use a probe to tap into this clock pulse.

► Accept the following settings:

TIME BASE	1 $\mu$ s
VOLT RANGE	500mV
SPAN	100 MHz
POINTS	131072



**Fig.6-4: FFT analysis of a square-wave signal.**

As can be assumed for a square-wave signal, only odd harmonics of the fundamental frequency are present.

? *What is the rule that says that the amplitudes decrease for a square-wave signal?*

As seen in Fig.6-4, FFT mode also supports cursor measurements.

► Measure the amplitudes of the harmonics and verify your assumptions.

The signal has a DC component that can be filtered.

? *How does the DC component affect the FFT?*

**MIC-Signal:**

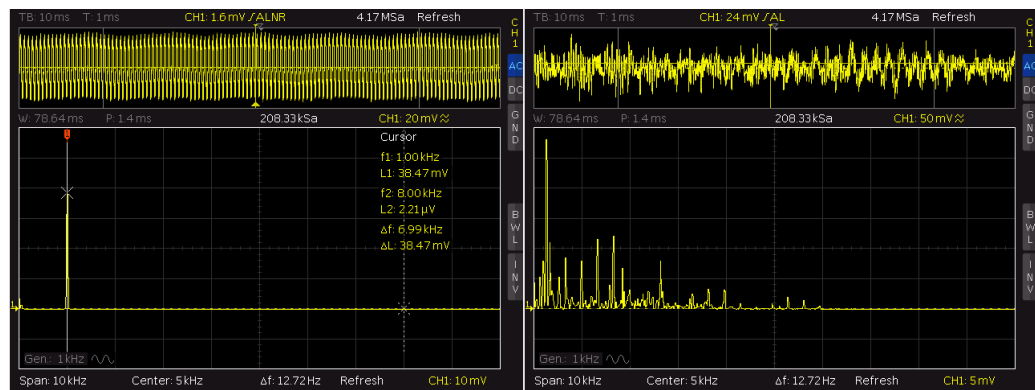
The training board is equipped with a microphone. This hardware can be used to make acoustical signals visible on the oscilloscope and available for analysis using the FFT function.

The output signal from the microphone is differential. Two outputs, *MICP* and *MICN*, are therefore available. In the next chapter, you will learn how to measure these signals differentially using the oscilloscope. For this exercise, it is sufficient to tap into the *MICP* signal.

- Switch the board to state ③ as shown in Table 2 in Appendix A.1.

The image at the left of Fig.6-5 shows the measurement of a 1 kHz sine-wave signal generated by a smartphone. The screenshot in the right half of the figure was acquired during playback of an .mp3 file. In this image, the attenuation of the higher frequencies by the format is visible.

If the source is located directly at the microphone, the volume can be set very low.



**Fig.6-5: Measuring different signals using the training board microphone.**

The optimum settings depend on the signal source. For the measurements in Fig.6-5, the following configuration was used:

TIME BASE	10 ms
WINDOW WIDTH	78.64 ms
SPAN	50 kHz
CENTER	5 kHz

- Using an appropriate device (such as a smartphone), generate a variety of signals and analyze them using the oscilloscope's FFT function.

## 7 Analysis of protocol-based bus signals

Signal buses play an important role in electronic systems, ensuring error-free and rapid communication between all system components. Modern oscilloscopes are able to decode bus signals. Therefore they are perfectly suited for the important task of screening all bus functions. This chapter provides a look into the various bus systems and analysis methods using an oscilloscope.

IMPORTANT NOTE: A portion of this exercise requires the RTC-K3 option.

### 7.1 Test setup

For the test setup, the training board from Appendix A.1 is connected to both channels and supplied with power via the USB port. Fig.7-1 shows this setup in its entirety. The probe connected to channel 1 is first connected to the *UART/LIN* output on the circuit board and then later during the exercise to the *CAN\_H* output. The signal is applied to channel 2 from the *CAN\_L* output.

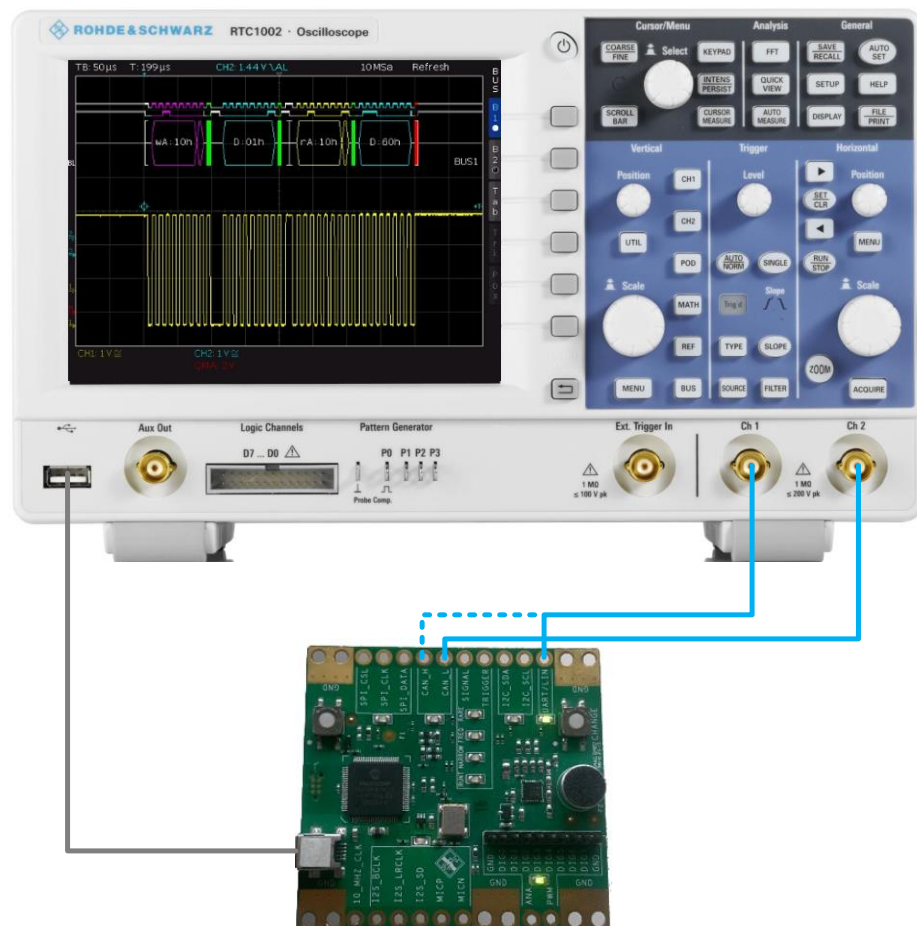


Fig.7-1: Test setup for analysis of bus signals.

## 7.2 Exercise

- ▶ Set the oscilloscope to the default state (*PRESET*). Don't forget to set the correct probe attenuation factor!

### UART-Bus:

As an example for a simple bus transmission, let us take a closer look at the UART signal from section 5.2. The following values are defined for the transmission:

THRESHOLD	1.65V
BIT RATE	115.2Kbps
STOP BITS	1
DATA BITS	8
PARITY	None
BIT ORDER	LSB First
POLARITY	Idle High

? What defines the *THRESHOLD* value?

- ▶ Switch the training board to state ① as shown in Table 2 in Appendix A.1.
- ▶ Use a pulse trigger as described in section 5.2 to generate a stable display of the channel 1 signal.
- ▶ Use a marker measurement to check the bit rate.

In Fig.7-2, a data byte is marked within a UART transmission. Note that the transmission begins with the least significant bit (LSB) and ends with the most significant bit (MSB). A start bit (logical 0) is inserted before and a stop bit (logical 1) after every transmitted byte. The bytes to be transmitted are arranged sequentially following these rules. The resulting byte sequence is combined into packets. Individual packets are separated by idle time. The *Idle High* setting is interpreted by the bus as logical 1 during this time.

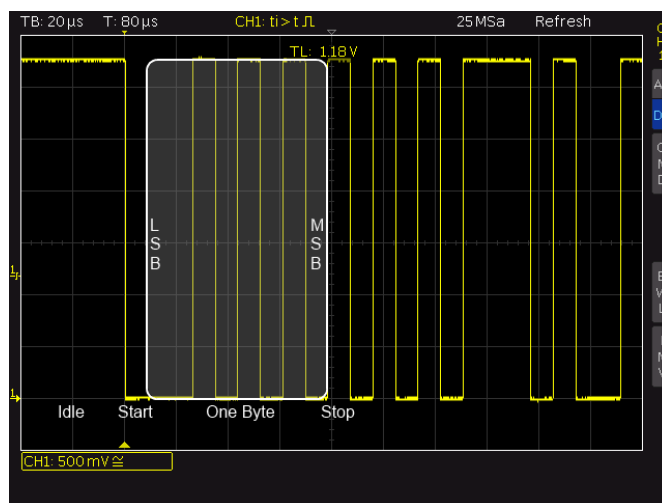


Fig.7-2: Setup of a data byte within a UART transmission.

The marked byte in Fig.7-2 transmits the value:  $0101\ 0100_b$ .

In this example, an entire packet consists of a 12-byte ASCII string.

- ▶ Read the first four bytes of the string as ASCII characters.

You can likely now explain why several of the middle bits in the transmission continually alternate. You will soon be able to decode the entire data message using the automated tools on the RTC1000.

Before moving on to the measurement of other bus systems, it is important to understand a peculiarity of UART transmissions:

A UART transmission is started asynchronously. This means that the transmitter can start transmitting the data at any time. In addition, no clock signal is needed because the accuracy of the local oscillator synchronized to the frame is sufficient for the short packets within the transmission.

One of the most widely used UART buses is the RS232 interface.

During the manual analysis of the UART transmission, you probably noticed how time consuming and error prone the manual analysis of a bus transmission can be. The RTC1000 offers automated analysis programs for a variety of buses. The oscilloscope must first be used to decode the entire content of the UART transmission.

- ▶ Switch the training board to state ① as shown in Table 2 in Appendix A.1.

Use the *BUS* button under the *VERTICAL* grouping to turn on the bus analysis.

- ▶ Set the oscilloscope to *BUS* mode and open the settings using the *MENU* key.
- ▶ Select *UART* as the *BUS TYPE* and set the parameters listed at the start of the chapter under *CONFIGURATION*.

To get a display as shown in Fig.7-3, the vertical scaling must be adjusted and the data decoded as ASCII characters.

- ▶ Set the scaling to 500 mV/div and then set *DISPLAY SETUP* to *ASCII* to display the transmission in plain text.

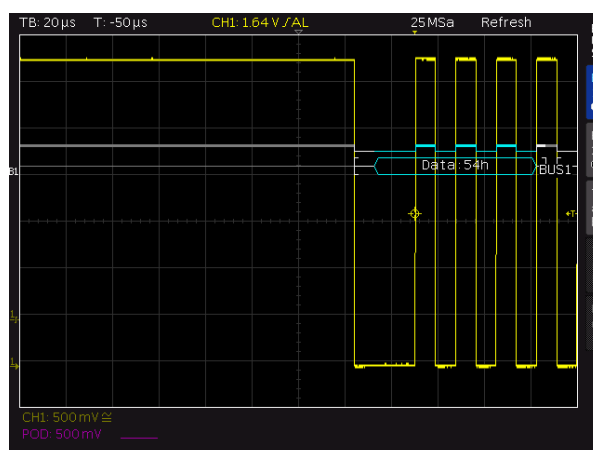


Fig.7-3: Automated analysis of a UART transmission.

### CAN-Bus decoding and triggering:

The CAN bus standard was developed in large part for use in the automotive arena. For this application, immunity to noise is very important. Therefore, systems like the RS232 interface are not possible here.

In the CAN bus, differential signals are used to suppress common-mode disturbances. Even if the passive probes are designed only for measurements relative to the ground potential, they can still be used to measure differential signals. Basically, when a differential signal is received, the negative component is subtracted from the positive component. This task can be undertaken using the oscilloscope test setup shown in Fig.7-1.

- ▶ Switch the training board to state ⑧ as shown in Table 2 in Appendix A.1.
- ▶ Use channel 1 to measure the CAN\_H signal and channel 2 to measure CAN\_L. Superimpose the two signal components on the oscilloscope display over the length of the packet.

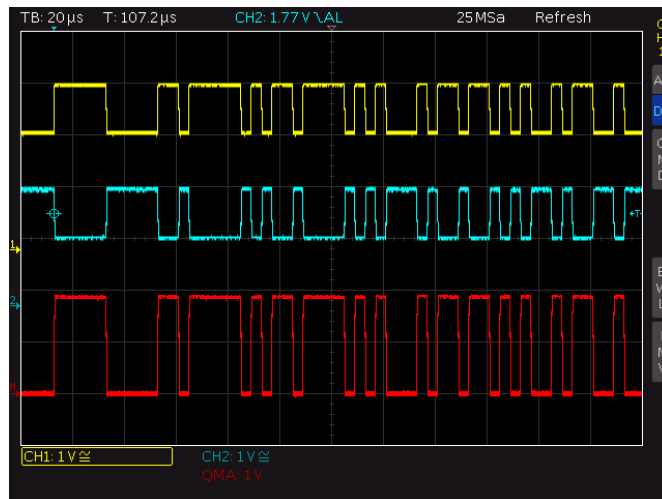


Fig.7-4: Measuring differential signals.

- ▶ Press the *MATH* key under the *VERTICAL* grouping on the edge of the monitor and select *SUB* instead of *ADD* in the menu.

With these settings, the signal measured with channel 2 is subtracted from channel 1 and the actual bit sequence is displayed as a red signal; see Fig.7-4.

? *What other advantages of differential transmission can be seen in Fig.7-4?*

- ▶ Calculate the bit rate for the transmission.

CAN bus signals also do not require a separate clock signal. Multiple nodes are connected to the bus simultaneously. A wired AND connection makes it possible for these nodes to detect conflicts and respond appropriately.

You can then analyze the previously analyzed CAN bus signals similar to the UART transmission using the RTC1000.

- ▶ Set up an automated CAN bus measurement for the current signal on the oscilloscope. Use your previously calculated bit rate for the configuration.

The current trigger settings will not permit a stable display of the CAN signal. However, by using the automated bus measurements, a new trigger type is available:

- ▶ Under *TYPE*, select the option *SERIAL BUS*.

The *FILTER* key can be used to set the various trigger conditions.

- ▶ Select *START OF FRAME*.

The various segments of a CAN transmission are now visible on the oscilloscope monitor; see Fig.7-5.

The structure of a CAN frame is briefly described here based on Fig.7-5.

A single, dominant bit indicates the start of a frame.

This is followed by the identifier (dID), which displays the content of the data message. The identifier does not provide the destination; instead the receivers decide whether the data message is relevant for them.

The identifier is followed by the control field, which specifies the number of bytes in the current frame. In the example, the receiver is expecting two bytes of information that the oscilloscope has identified as data.

Finally, a CRC code is sent for error detection. (6) CITATION Rob91 \l 1031

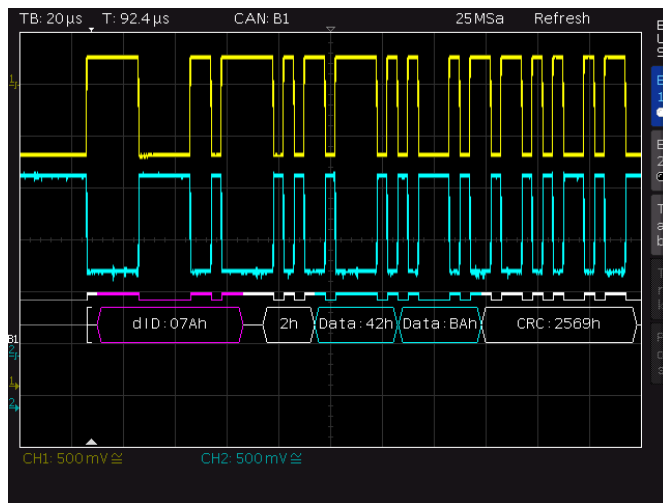


Fig.7-5: Automated analysis of a CAN bus transmission.



During the analysis of a bus transmission, faulty data packets are of particular interest. The manual analysis of all received transmissions is not practicable in this case. The RTC1000 offers special trigger settings for this purpose that permit reliable and rapid detection of various types of errors.

- ▶ Set the oscilloscope up with the optimal trigger and acquisition mode to detect rare events with the highest level of probability.
- ▶ Under *FILTER*, select the following for the current trigger type:

*ERROR*                      *CRC*

If you shift the horizontal trigger position slightly, you will get a display as shown in Fig.7-6. With these settings, the oscilloscope reliably detects the faulty CRC sequence received every three seconds.

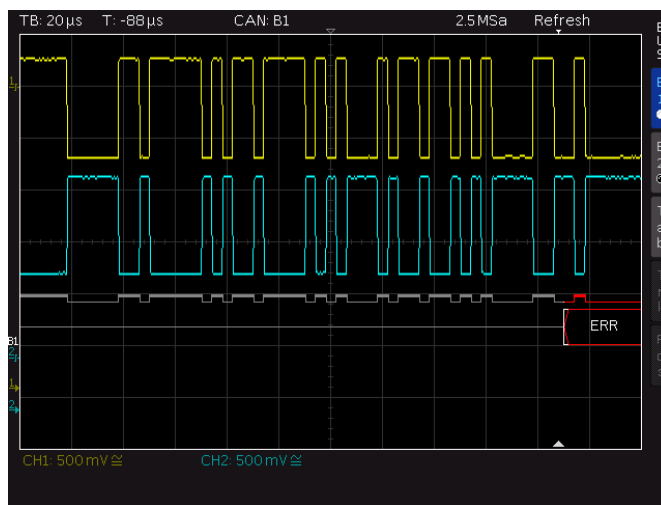


Fig.7-6: Triggering on a CRC error.

## 8 FMCW-Radar exercise

Although an oscilloscope are used to measure voltage vs. time, many digital oscilloscopes can be used as analog to digital (A/D) converters, thus providing the possibility to allow signal post processing, for example on an external PC connected through a LAN. In our exercise, binary samples are streamed into the PC running MATLAB and analyzed there. This chapter provides a practical introduction into the radar world in form of a FMCW radar application for range measurements. Range is the term used for distance in Radar applications. This exercise consist of HW and MATLAB script which remotely controls the oscilloscope.

See the Appendix A.4 for the RF components needed for this exercise. The assembly of the RF components is described in Appendix A.3.

### 8.1 Exercise setup

The exercise setup consists of the oscilloscope and the RF components (refer to Appendix A.2)

A DC power supply delivers the 5 V (up to 150 mA) for the RF components. The antennas are part of the bill of material (BOM) shown in Appendix A.4.

The oscilloscope used here has an integrated signal generator which is connected to Channel 3 input and to the VCO tune pin divided by a BNC-T connector. The IF path from the RF components is then connected to Channel 1 input connector of the oscilloscope using a cable with BNC connectors.

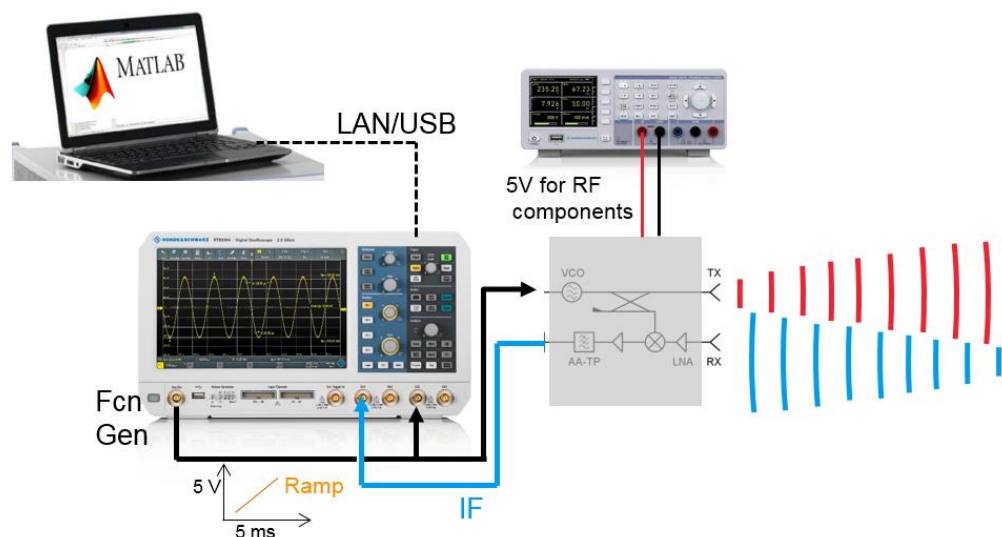



Fig. 8-1: Test setup FMCW Radar generation.

RF components are fed from a DC source of +5.0 V referred to ground. Please wire accordingly, for details, see Appendix A.3.

Mount the two antennas to a fixture.

## 8.2 Exercise

- ▶ Set the oscilloscope to the default state (*PRESET*). Don't forget to set the correct probe attenuation factor! We would like to have at least 1 cycles on the display (3 x 5 ms of ramp  $\geq$  15 ms)
- ▶ Connect the RTB2000 via LAN cable to the controlling PC (or via HUB). Verify the  IP address under [icon ] on the RTB2000. In the MATLAB code, apply this IP address.
- ▶ Set the Generator of the oscilloscope to generate a ramp up signal between 0-5 V within 5 ms. Verify the ramp operation in channel 3.

Configure the signal generator so that the following signal is generated:

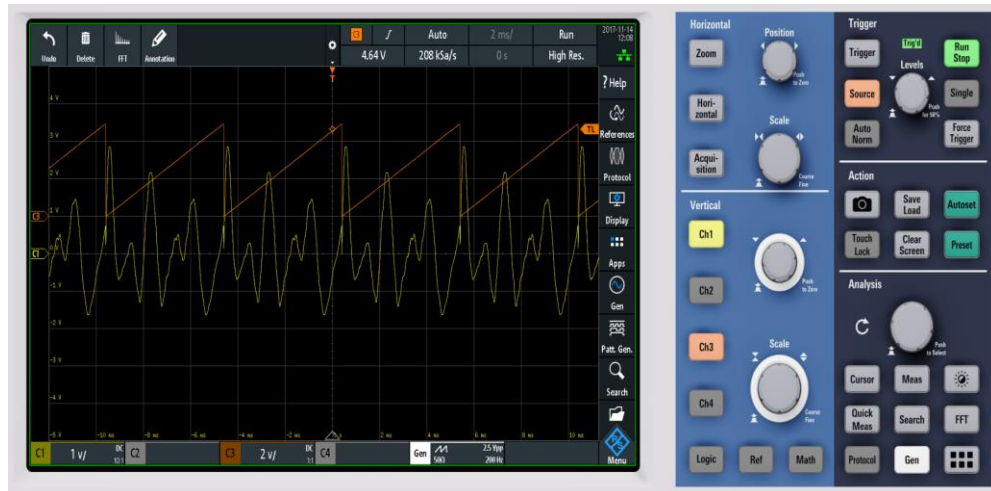
FUNCTION	Ramp (Polarity up)
FREQUENCY	200 Hz
AMPLITUDE	2.5 Vpp
OFFSET	1.25 V

(switch it ON)

- ▶ Display the signal on the monitor.
- ▶ Set the Channel 1 (IF signal) to trigger at Ch3 at  $> 0V$  to verify a steady Signal.
- ▶ Set the [Acquire] values of the scope as follows,
 

RECORD LENGTH	20 MSa (highest) will set the sample rate to 305 kSa/s
ACQUIRE MODE	High Resolution
NX SINGLE	1
INTERPOLATION	Sin(x)/x
- ▶ Set the Horizontal scale of Ch1 (IF Signal) so it won't clip

The Signal should now look like this:



### 8.3 Equations used in Matlab Code

The Matlab code consists of several functions, which are explained in the comments. The Matlab code processes the time signals of CH1 (IF Signal) and CH3 (ramp signal) retrieved from RTB2000 through its LAN connection.

The IF signal (CH1) is undergoing a FFT to display a power vs. frequency bin, which is translated to range in [m] according to the following formula

$$\frac{\text{speed of light}}{2 \times \text{Bandwidth chirp}} = \frac{c [m/s]}{2 * bw[Hz]} = \frac{2.98 \text{ m/s}}{2 * 343 \text{ MHz}} = 0.45 \text{ m per FFT bin}$$

This is also called the “range resolution”, that means in here, 2 obstacles with 30 cm distance cannot be distinguished.

The beat frequency (is the difference between the received echo signal to the transmitted signal), defines the target reflection at a specific range according to the following formula,

$$f_B = \frac{2 \times \text{Bandwidth chirp}}{\text{speed of ligh} \times \text{Time}_{\text{chirp}}} * \text{Range [m]}$$

$$= \frac{2 \times BW}{c \times T_{\text{chirp}}} * R$$

For example, with a known chirp bandwidth a reflecting obstacle at 10 m would generate a beat frequency  $f_B$  at 2.23 kHz,

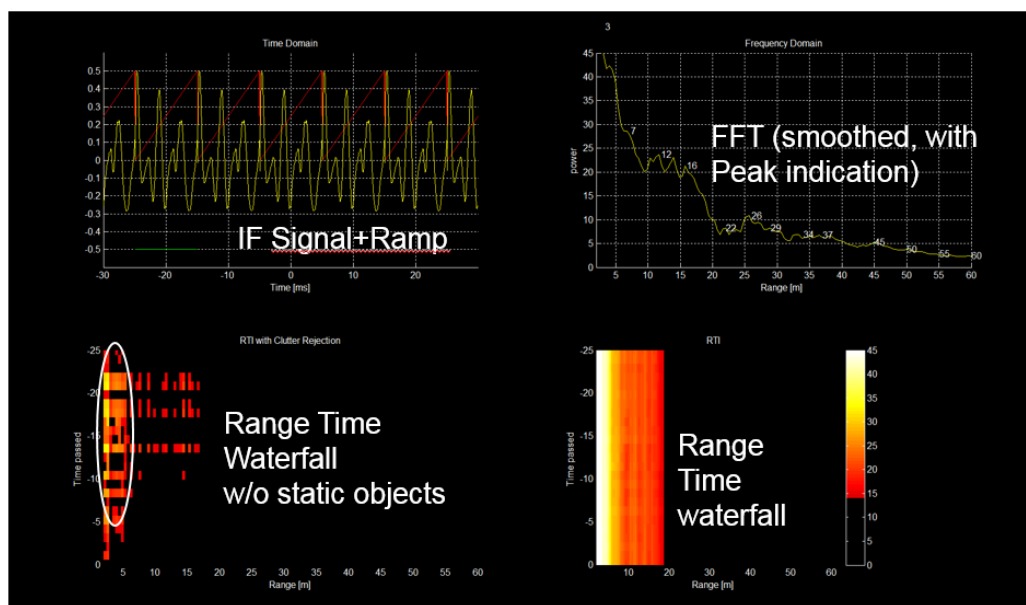
$$f_B = \frac{2 \times 343 \text{ } 10^6 \text{ Hz}}{2.98 \times 10^9 \text{ m/s} * 0.1 \text{ s}} * 10 \text{ m} = 2.23 \text{ kHz}$$

Note that the bandwidth used here refers to the specific VCO described in the appendix.

The generator signal (CH3) is used to synchronize the FFT-time window, since the RTB2000 has not a gated trigger capability.

The following outputs are plotted in Matlab and described in 4 windows

- Top left "Time Domain": fetched CH1 and CH3 time signals
- Top right "Frequency Domain": FFT from the CH1 (IF) (windowed by green bar top left display)
- Bottom right "RTI": "waterfall Spectrum" with history. Changes of peak values can be identified.
- Bottom left "RTI with Clutter rejection": Static object are not displayed, only moving objects.



► Change the ramp peak to 0-2.5 V. The ramp drives the VCO frequency

*How does the DC ramp change affect the bandwidth of the chirp?*

? *What is the resulting range resolution?*

► Change Generator's ramp from 5 ms duration to 10 ms.

? *How does the cycle time affects FFT diagram?*

► Let a student run towards the radar

? *How does this affects the RTI with clutter rejection diagram*

## 9 Reference

- [1] 1. **Rohde & Schwarz GmbH & Co. KG.** *R&S@RTO Digital Oscilloscope - User Manual.* [Manual] München : s.n., 2015.
- [2] 2. —. *Oscilloscope Fundamentals - Primer.* Columbia : s.n.
- [3] 3. **Johnson, Dr. Howard W. and Graham, Dr. Martin.** *High-speed Digital Design – A Handbook of Black Magic.* s.l. : Pearson Education, 1993.
- [4] 4. **Rohde & Schwarz GmbH & Co. KG.** *The Impact of Digital Oscilloscope Blind Time on Your Measurements.* München : Rohde & Schwarz GmbH & Co. KG, 2011.
- [5] 5. —. Benefits of the R&S@RTO Oscilloscope's Digital Trigger. 2012.
- [6] 6. **Robert Bosch GmbH.** *CAN Specification Version 2.0.* Stuttgart : s.n., 1991.

# Appendix

## A.1 The training board

Fig.9-1 shows the training board used in sections 3.2, 5.2, 6.2 and 7.2. The items used in those sections are boxed in red and the used outputs (as well as the microphone input) are identified on the board. To acquire the "Demo Board Time Domain Measurements" (Service Part No. PW0002.9763.00), please contact the local Rohde & Schwarz sales representative or service center.

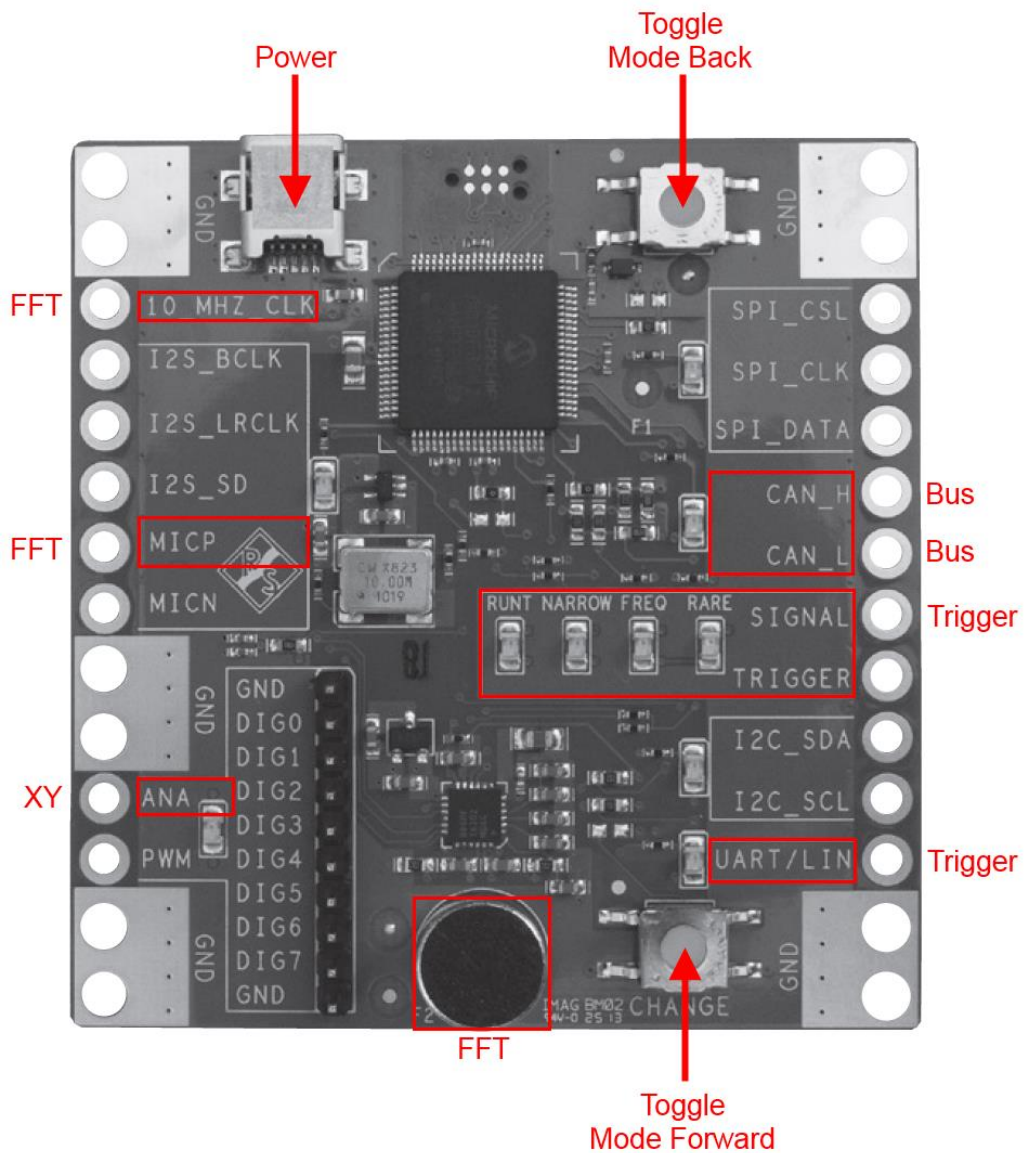


Fig.9-1: The training board.

Table 2 lists the various modes for the board. The two keys can be used to switch between the modes. The LEDs indicate the current operating state.

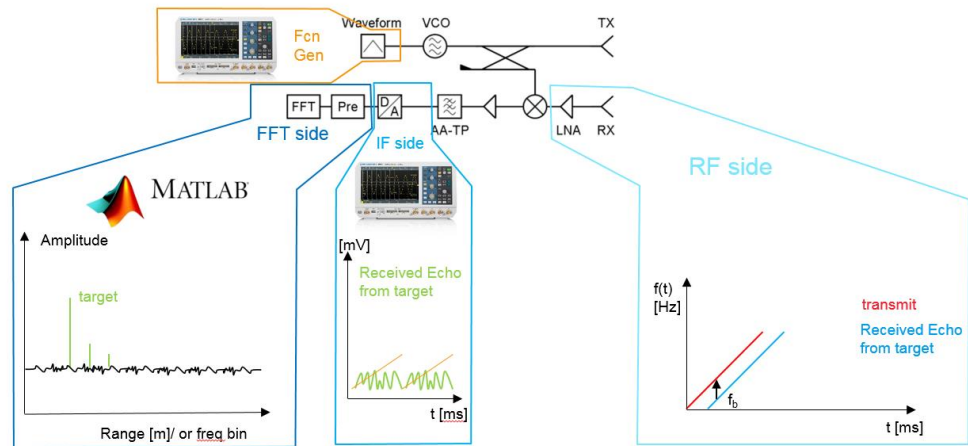
**Signal Configuration Modes**

Mode / LED Config	Audio Block	Digital Logic/ PWM/ ANA	UART/ LIN Signal	I2C Bus	SPI Signals	Rare Events Block	CAN Bus
1	Shows AGC turned on thus the result is amplified	Distorted Sine Wave	115.2kbaud UART Signal	Continuous Readback of ACG (Auto Gain Control)	ASCII Freq. Switch Synthesis		
2		Sine Wave	19.2kbaud LIN Frame with Checksum Errors				
3	Normal Mic Signal	Sawtooth Digital Counting Pattern		Setup of Audio Chip Without AGC		Pulse With No Error	
4						Pulse With Narrow Glitch 100/s	
5						Pulse With Narrow Glitch 1/s	
6						Pulse With Runt 100/s	
7						Pulse With Runt 1/s	
8							250kbps CAN Frame With CRC Error
9		Simulated Power Supply Ripple (mV)					

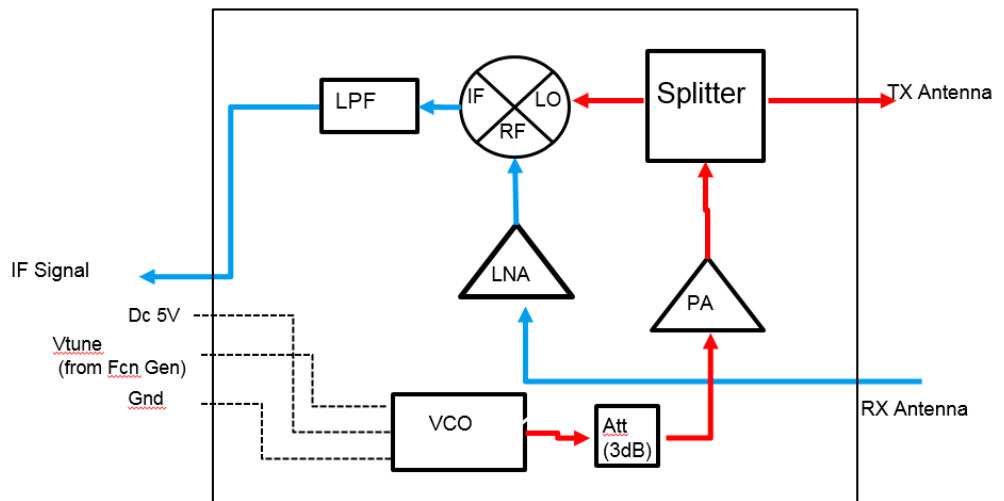
**Table 2: The different training board modes**

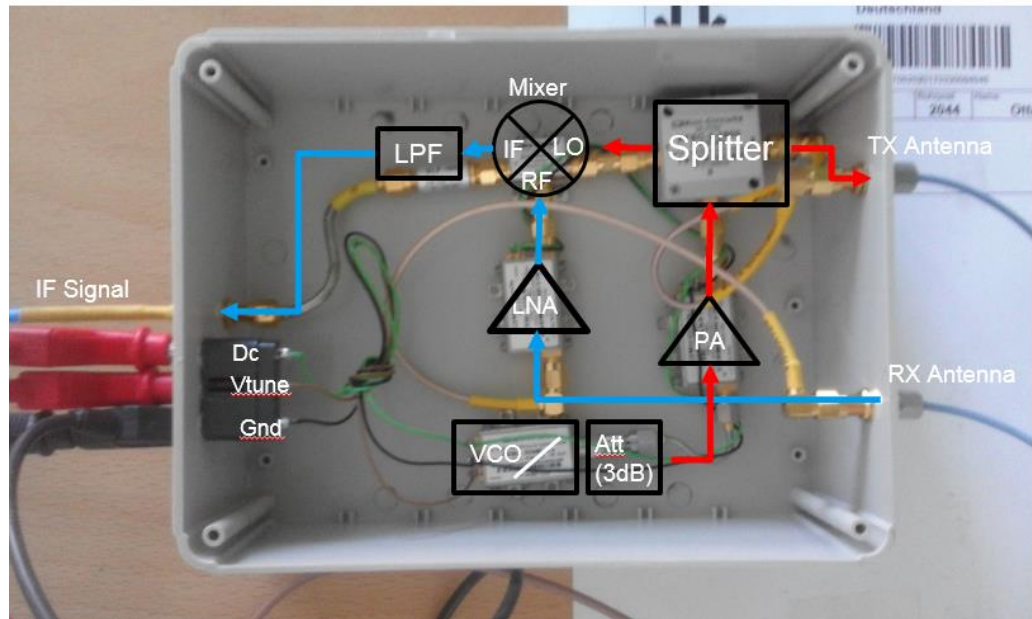


## A.2 Radar experiment: from idea to design



## A.3 Radar experiment: RF components assembly scheme





#### A.4 Radar experiment: List of components

Name	Quantity	Supplier	Part no
VCO	1	Mini-Circuits	ZX95-2536C+
PA/LNA	2	Mini-Circuits	ZX60-272LN-S+
Mixer	1	Mini-Circuits	ZX05-43MH-S+
LPF	1	Mini-Circuits	VLF-1000
Att	1	Mini-Circuits	VAT-3+
Splitter	1	Mini-Circuits	ZX1002042+
SMA connector male-male	3	Mini-Circuits	SM-SM50+
Cable accessories	3	Any company	3.5 mm male to male, coaxial 50 Ohm, max 50 cm long
Antenna	2	ebay/Any company	Can be any 2.4 GHz antenna

Link to [MIT coffee can antenna design instructions](#)

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## Sustainable product design

- Environmental compatibility and eco-footprint
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- Longevity and optimized total cost of ownership



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