Automotive Radar - Chirp Analysis with R&S RTP Oscilloscope
Application Note

Products:

- R&S®RTP
- R&S®VSE
- R&S®SMA100B
- R&S®VSE-K60/-K60c
- R&S®FS-Z90

FMCW radar sensors are used in vehicles for adaptive cruise control and for blind-spot, lane-change and cross traffic assistants. Radar sensors for acquisition of the surroundings are key components for future vehicles with semi-autonomous and fully autonomous driving. Autonomous driving requires radars that reliably detect objects in the surrounding area. Radar makes it possible to quickly and precisely measure the radial velocity, range and azimuth and elevation angle of multiple objects. For this reason, the automobile industry is increasingly using this technology in advanced driver assistance systems (ADAS). Rohde & Schwarz offers T&M solutions for generating, measuring and analyzing radar signals and components to ensure trouble free operation of these sensors. The high-performance oscilloscope R&S® RTP with four measurement channels is the perfect solution for multi-channel measurements on MIMO radar sensors and correlation with other signals e.g. power rails, whereas a spectrum analyzer such as the R&S® FSW85 offers highest dynamic up to 85 GHz.

This application note focuses on how to measure and analyze FMCW radar signals with up to 6 GHz bandwidth with an R&S® RTP oscilloscope. On-board analysis features for pulse and chirp analysis for single- and multi-channel measurements will be addressed as well as the combination of oscilloscope and R&S® VSE software. Measurement of an FMCW radar signal in the 77 - 81GHz band with 4 GHz bandwidth is demonstrated.

Note:

The latest version of this document is available on our homepage:
http://www.rohde-schwarz.com/appnote/GFM318

Application Note
R. Wagner

8.2019 – GFM318 0e

ROHDE&SCHWARZ

Table of Contents

In this application note, the following abbreviations are used for Rohde & Schwarz instruments:

- The R&S®RTP high-performance oscilloscope is referred to as the RTP.
- The R&S®SMA100B RF and microwave signal generator is referred to as the SMA100B.
- The R&S®FS-Z90 harmonic mixer is referred to as the FS-Z90.
- The R&S®VSE vector signal explorer software is referred to as the VSE.

1 Technical Background

Automotive radar sensors usually rely on the common principle of CW radar with each supplier adapting the transmitted waveforms and signal processing according to their research results. Specific waveforms are not mandatory or even specified. There are mainly two different types of waveforms used in today's automotive radar sensors:

1. Blind spot detection radars (BSD) often use the so called Multi-Frequency-Shift keying (MFSK) radar signal, with most of them operated in the 24 GHz range. However, there is a shift in the industry toward the 77-GHz frequency band due to emerging regulatory requirements, as well as the larger bandwidth availability, smaller sensor size and performance advantages.

2. Radars operating in the 77 GHz or 79 GHz band mainly used for adaptive cruise control (ACC) usually make use of Linear Frequency Modulated Continuous Wave (LFMCW or simply FMCW) signals or Chirp Sequence (CS) signals, which are just a special form of FMCW signals.

This application note deals with FMCW radar sensors in the 77 GHz frequency band. The chirp measurements described in Section 2 and 3 are shown on a Chirp Sequence (CS) radar signal (see section 1.3.2).

1.1 Frequency Modulated Continuous Wave Radar Signals

Continuous wave radar signals with a linear frequency modulation are applied in many radar systems. Although the FMCW technique has been in use for many years in a number of applications, the automotive radar market is nowadays perhaps the most prevalent application for the use of this radar waveform. Fast and high performance digital signal processors (DSP), field programmable gate arrays (FPGA) and direct digital synthesis (DDS) make it possible to build low-cost radar units which generate nearly arbitrary radar signals and compute the signal processing to support safer or even automated driving currently and in the future.

This signal processing includes real-time target detection, parameter estimation, target tracking and sometimes even signal classification of multi-target situations and under all weather conditions. FMCW radars have low transmit power compared to pulse radar systems. This allows the radar to be smaller in size and lower in cost. Another important feature is the zero blind range, as the transmitter and receiver are always on.

Other advantages such as direct Doppler frequency shift measurement make these radar signals very well suited in the automotive and industrial sector. Key performance indicators of radars are, among others, the resolution, ambiguity and accuracy of range and radial velocity. While the resolutions depend on signal bandwidth and length of the chirp, parameter estimation accuracy requires a high signal to noise of the radar echo signal in the first place. In addition, frequency measurement methods, windowing and the transmit signal quality have effects on these key performance indicators.

1.2 FMCW Radar Principle

Fig. 1-1 shows the principle of the Frequency Modulated Continuous Wave (FMCW) radar. For FMCW radars, a frequency modulated signal (Chirp) is transmitted. Each frequency modulated signal has a specific bandwidth B and a chirp length T_{chirp}.The transmitted radar signal follows a saw tooth waveform.

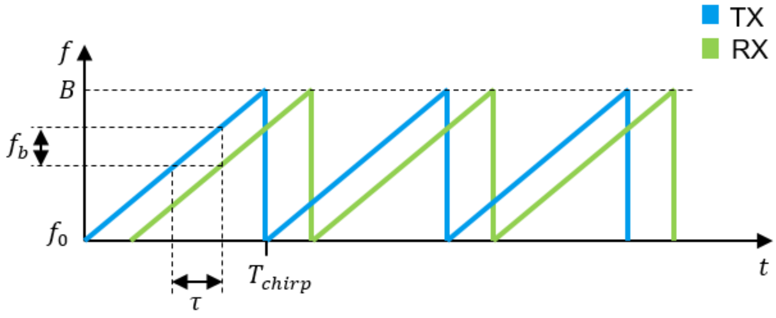


Fig. 1-1: FMCW radar principle

The saw tooth function versus time is given by:

Equation 1-1:

$$f(t) = f_0 + \frac{B}{T_{chirp}} \cdot t$$

With:

f_0: start frequency

B: Bandwidth

T_{chirp}: Chirp length

In case of a target reflecting the TX radar signal, the received signal has the same saw tooth waveform but delayed in time by the propagation time τ. The range R (distance to target) is calculated as follows:

Equation 1-2:

$$R = \frac{c}{2} \cdot \tau$$

With:

c: Speed of light

A certain frequency shift between TX and RX, called beat frequency f_b is introduced when the target reflects the radar wave. The Radar measures the beat frequency (see section 1.4). Signal propagation time τ and beat frequency f_b are equivalent and are linked together according to:

Equation 1-3:

$$\frac{\tau}{T_{chirp}} = \frac{f_b}{B}$$

With Equation 1-2 and Equation 1-3, the radar computes the range as follows:

Equation 1-4:

$$R = \frac{c}{2} \cdot \frac{T_{chirp}}{B} \cdot f_b$$

The result is only correct if the target is not moving, i.e. if the echo signal has no Doppler shift.

For a moving target, the beat frequency includes two components (see Fig: 1-2): f_τ because of the signal propagation time delay τ and the frequency shift f_D because of the Doppler effect:

Equation 1-5:

$$f_b = f_\tau + f_D = \frac{2B}{c\,T_{chirp}} R + \frac{2}{\lambda} \cdot v_r$$

With:

v_r: Radial velocity

λ: TX signal wavelength

Equation 1-5 contains two unknown variables R and v_r. That means that the measurement of the beat frequency is insufficient to determine the range and radial velocity of the target.

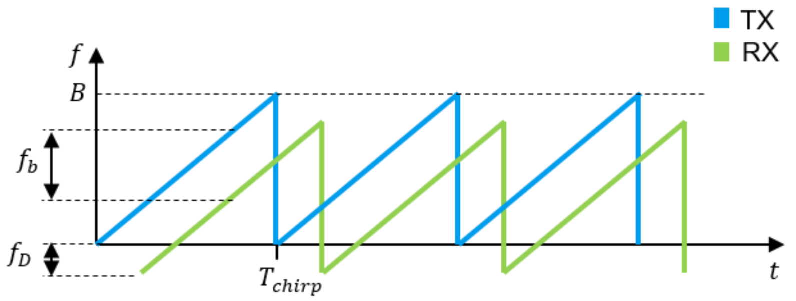


Fig: 1-2: Frequency shift in the echo radar signal due to Doppler effect and range

1.3 Typical Radar Waveforms

1.3.1 Linear FMCW radar with up-chirp and down-chirp

For solving Equation 1-5: two chirps with different slopes are used. Fig. 1-3 shows a FMCW radar signal with a positive (up-chirp) and a negative (down-chirp) slope. This yields two independent measurements of the beat frequencies f_{b1} and f_{b2}:

Equation 1-6:

$$f_{b1} = \frac{2B}{c\,T_{chirp}} R + \frac{2}{\lambda} \cdot v_r$$

Equation 1-7:

$$f_{b2} = -\frac{2B}{c\,T_{chirp}} R + \frac{2}{\lambda} \cdot v_r$$

The two equations Equation 1-6 and Equation 1-7 for f_{b1} and f_{b2} can now be solved for R and v_r. The disadvantage of this waveform is that the measurement now takes with $2 \cdot T\_chirp$ twice as long.

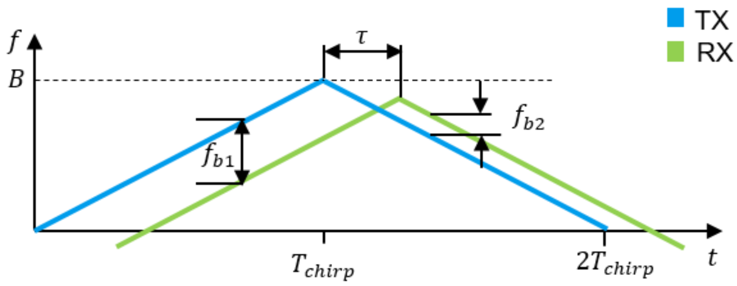


Fig. 1-3: Linear FMCW radar with up-chirp and down-chirp

The advantage of the triangular waveform is the ease of implementation and the avoidance of sharp transitions compared to e.g. saw-tooth waveforms, which are used in chirp sequences (see section 1.3.2)

For multi target situations range and radial velocity cannot be resolved unambiguously by two consecutive chirps measuring different beat frequencies. This causes ghost targets which can be resolved by additional chirps with different slopes transmitted in FMCW radar.

Typical values for automotive FMCW radar sensors are:

- T_{chirp} is designed to be in the domain of 20 ms.
- Number of Chirps for a single processing interval > 2.
- B defines the range resolution and varies between some hundred MHz up to a maximum of currently 5 GHz. In order to achieve a high range resolution the radar manufacturers are working on radar sensors with highest possible bandwidth. The RTP oscilloscope with its high bandwidth can handle radar signals from today and beyond.

1.3.2 Chirp Sequence

The other common signal waveform is a continuous wave type with very fast chirps. This waveform is called Chirp Sequence (CS) and consists out of several very short FMCW chirps each with a duration of T_{Chirp} transmitted in a block of length T_{frame} (see Fig. 1-4). Due to the fact that a single chirp is very short, the beat frequency f_{b} is mainly influenced by signal propagation time (Doppler frequency shift f_D can be neglected in the first processing step).

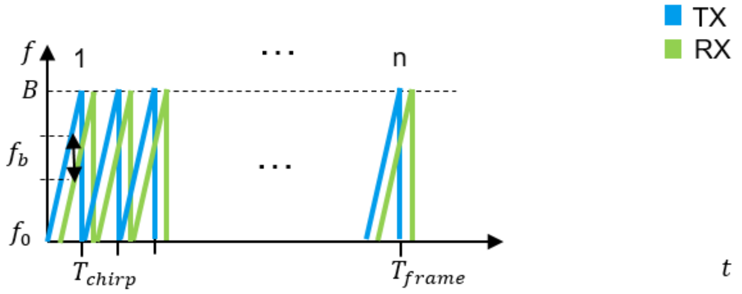


Fig. 1-4: Chirp Sequence

The signal processing follows the straight approach with an initial down conversion by instantaneous carrier frequency and Fourier transformation of each single chirp. The beat frequency is mainly determined by range. Thus under assumption of a radial velocity v_r = 0 ms, the target range R is calculated as in FMCW using

Equation 1-8:

$$f_b = \frac{2B}{c\,T_{chirp}} R$$

The radial velocity is not measured during a single chirp but instead over the block on consecutive chirps with the duration of T_{frame}. A second Fourier transformation is performed along the time axis, which will then yield Doppler frequency shift f_D.

Typical durations for CS signals:

- T_{chirp} is typically in the domain of 10µs to several hundred µs.
- Number of chirps n is typically > 100 and < 1000, depending on the frame length T_{frame} of the radar sensor.
- T_{frame} is in the domain of 20 ms and defined by the desired radial velocity resolution.
- B defines the range resolution and varies between some hundred MHz up to a maximum of currently 5 GHz. In order to achieve a high range resolution the radar manufacturers are working on radar sensors with highest possible bandwidth. The RTP oscilloscope with its high bandwidth can handle radar signals from today and beyond.

1.4 Beat Frequency Measurement

To measure the beat frequency, the receive signal is mixed with the transmit signal. This is depicted in Fig. 1-5, where the beat frequency is represented as an offset from zero, which can be measured by a Fourier transformation. A threshold for beat frequencies defines a limit above which targets are valid. All beat frequencies with an amplitude above this threshold are then detected.

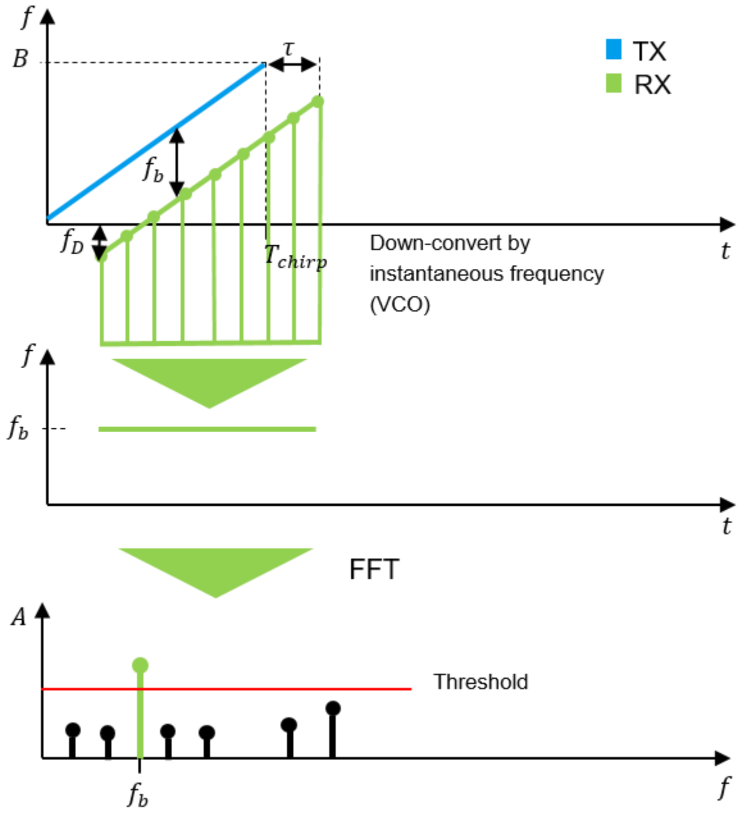


Fig. 1-5: Beat frequency measurement

1.5 Signal Linearity

Depending on the kind of signal generation there are several effects which reduce the linearity of the signal. This linearity degradation in turn reduces the radar performance. Slow frequency deviation from a perfect linear signal slope over a certain bandwidth may occur as depicted in Fig. 1-6. Due to down conversion of the receive signal with the instantaneous transmit frequency, the beat frequency will exhibit a trend. Hence, the Fourier transformed signal will result in a broader frequency peak. This decreases range and radial velocity parameter estimation accuracy and resolution, as the beat frequency measurement is less accurate. The signal linearity measurement is described in section 2.3.1.1.

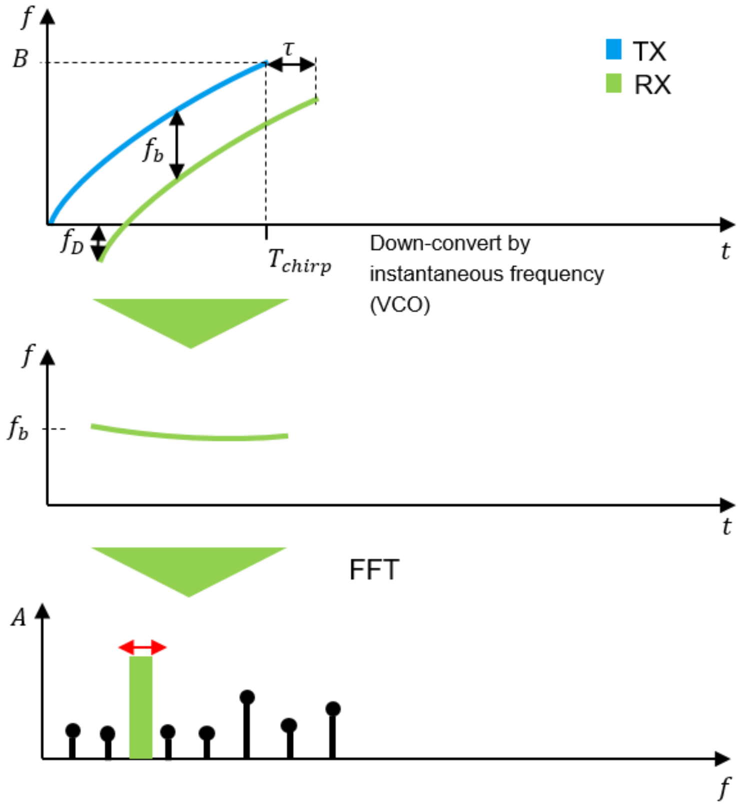


Fig. 1-6: Slow frequency deviation results in a broader frequency peak after the Fourier transformation

Another effect on transmit signals are ripples on the TX signal, as illustrated in Fig 1-7. This frequency deviation affects the accuracy of the beat frequency measurement and causes unwanted side-lobes to appear in the IF signal spectrum. The beat frequency f_b measured by down-conversion and Fourier transformation will result in a wider frequency peak in the Fourier spectrum compared to the transmission of ideal linear ramps (see Fig. 1-5). Hence resolution in both domains (range resolution, radial velocity resolution) and accuracy are degraded during the FMCW signal processing.

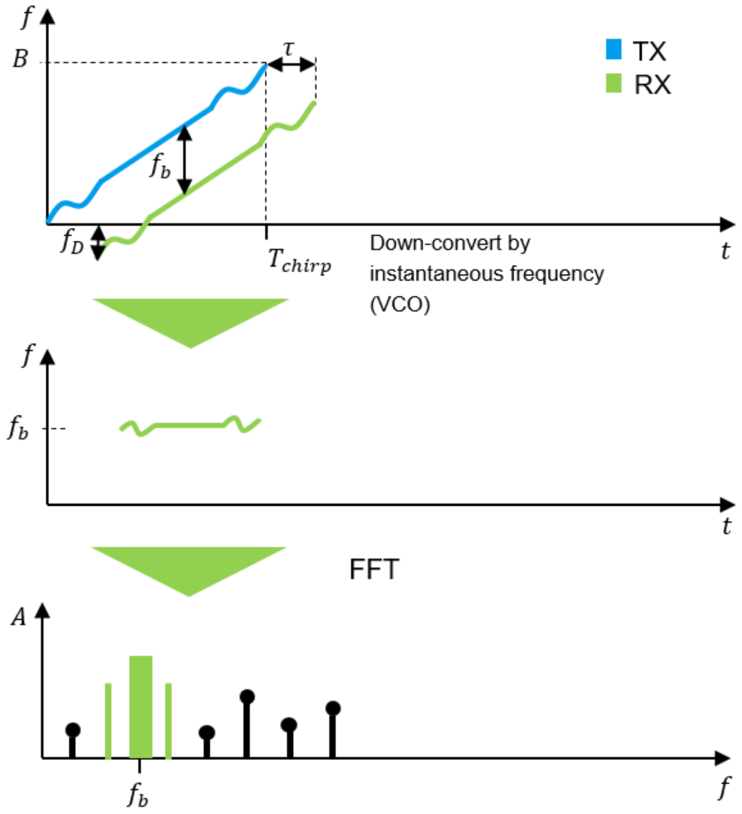


Fig 1-7: Ripple on TX signal

1.6 Range and velocity resolution

In general, the range resolution given by a radar system is determined by the bandwidth. The FMCW range resolution is given by:

Equation 1-9:

$$R_{res} = \frac{c}{2B}$$

For example, a signal bandwidth of 150 MHz determines a range resolution of 1 m, a signal bandwidth of 1.5 GHz determines a range resolution of 10 cm.

Conclusion: a better range resolution requires higher bandwidth.

The FMCW radial velocity resolution is defined by the chirp length:

Equation 1-10:

$v_{r\_res} = \frac{c}{2 f_{TX} T_{chirp}}$, or

$v_{r\_res} = \frac{c}{2 f_{TX} \cdot L \cdot T_{chirp}}$, where L denotes the amount of coherently transmitted chirp signals in case of a chirp sequence.

Equation 1-10 shows that a better speed resolution requires higher TX frequency or longer measurement time.

In automotive radar sensors the T_{chirp} is typically on the order of several milliseconds. For example a radar sensor operating at f_{TX} =77 GHz and with T_{chirp} = 10 ms has a radial velocity resolution of 0.19 m/s. This high radial velocity resolution allows distinguishing even slowly moving pedestrians from static targets.

To verify range resolution, signal bandwidth has to be measured and further signal processing steps, e.g. windowing, have to be taken into account. A corresponding measurement need also exists for the chirp length, which should be verified to guarantee the required radial velocity resolution. In practice, the achieved range and radial velocity accuracy will greatly depend on signal to noise ratio of the radar echo signal. However, the achievable performance remains bounded by the quality of the transmitted signal and its corresponding bandwidth and chirp length. Unwanted effects on the transmit signal will therefore effect the accuracy of the estimation, and in extreme cases may even be the dominating factor in determining system performance. One very important parameter of signal quality to be measured in this respect is the FM linearity (see section 1.5).

1.7 Azimuth and evaluation

Azimuth and elevation angle are measured by using several transmitting and receiving antennas. Depending on the number of antennas, resolution in azimuth and elevation is also possible. To estimate the angle, a radar generally measures the phase difference of a received signal at multiple antennas (see section 3 and 3.2.3). By increasing the number of antenna elements, azimuth resolution becomes possible and the accuracy of the angular measurement improves.

Today many automotive radars apply MIMO radar signal processing to improve angular resolution. Fig.1-8 shows a radar frontend with one TX and four RX that are spaced by $\lambda/2$. The total number of antennas, which defines the spatial resolution, is defined by $N\_TX \times M\_RX$ with proper antenna alignment. The upper case shows

$1 \times 4 = 4$ elements and the lower case $2 \times 2 = 4$ elements. Hence, the same resolution can be achieved with both arrays.

Since TX1 and TX2 are different apart from the receiver array, the phases at the receivers are different. If two transmitters are active, four phases are measured with two receiver antennas. With the Multi Channel measurement described in section 3 you can set up several receivers in different places. For example, with this setup you can check if beamforming is working properly.

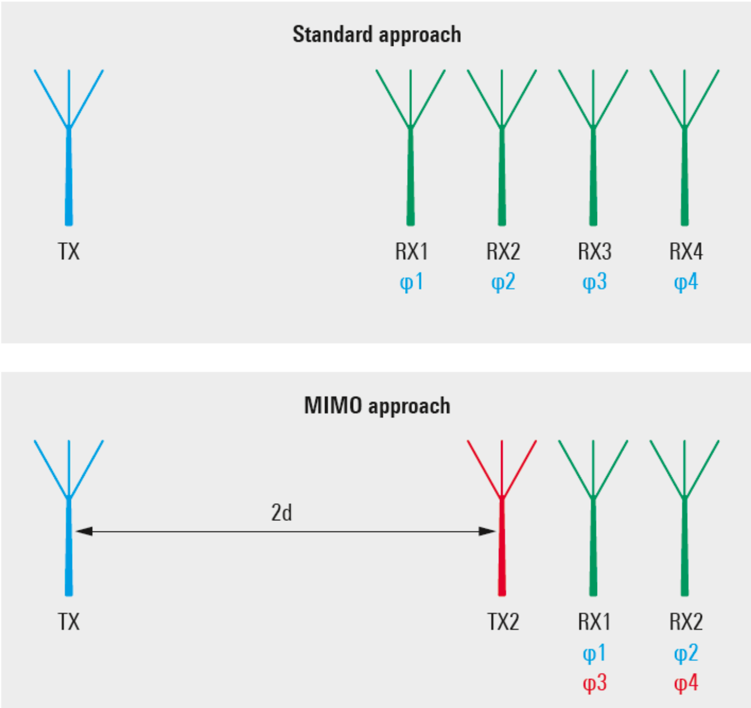


Fig.1-8: MIMO Principle

In order for the receivers to distinguish between the various transmitter signals, several different approaches like time division multiple, frequency division multiplex or code multiplex are used.

2 Chirp analysis of automotive radar sensors with RTP

For the following described chirp analysis the RTP oscilloscope is used. The RTP extends the R&S product portfolio with respect to RF pulse and chirp measurement solutions. The oscilloscope is able to perform wideband pulse and chirp measurements in time and frequency domain using on-board tools. The analysis capabilities can be further extended, by using the R&S VSE software (option).

Another powerful feature is the phase coherence of the oscilloscope. The RTP oscilloscope is a phase coherent receiver and in combination with the powerful FFT and the low noise floor of the instrument an excellent tool to address MIMO and multi-channel requirements (see chapter 3 Multi-channel measurement with oscilloscope). Furthermore, in combination with the deembedding capabilities in real time, the RTP is also capable to correct losses and mismatch in the signal path without time consuming post-processing.

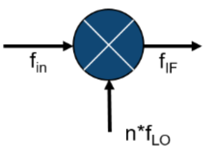
2.1 Measurement Setup

Fig. 2-1 shows the test setup for the automotive radar signal analysis. The automotive radar device is connected e.g. via USB interface with a PC. With the help of a radar control software, provided by the radar sensor manufacturer, a radar signal is generated. For receiving the radar signal over the air, a suitable horn antenna like the R&S FS-SH-90 Horn Antenna is used.

In order to extend the supported frequency range of the RTP oscilloscope, an external mixer is used. The harmonic mixer FS-Z90 performs the frequency down conversion of the radar signal. The LO frequency generated by a signal generator is output to the external mixer, where it is mixed with the RF input from the original radar input signal. In addition, the harmonics of the LO are mixed with the input signal, and converted to new intermediate frequencies. The IF from the external mixer is fed into the RTP. The frequency of the input signal can be expressed as a function of the LO frequency and the selected harmonic of the first LO as follows:

Equation 2-1:

$$f_{in} = n \cdot f_{LO} + f_{IF}$$



Where:

f_{in}: Frequency of input signal

n: Order of harmonic used for conversion

f_{LO}: Frequency LO signal

f_{IF}: Intermediate frequency

In this setup the intermediate frequency (IF) is in the range of 1 GHz to 5 GHz and the DUT operates in the range from 77 to 81 GHz. The LO harmonic number of the FS-Z90 is 6. This results in a LO-frequency of 12.66666 GHz (calculation via Equation 2-1). The LO signal is generated by the SMA100B Signal Generator and fed into the LO input of the harmonic mixer FS-Z90. By this means the connected RTP Oscilloscope is able to analyze the down converted radar signal.

For an advanced chirp analysis, the VSE Vector Signal Explorer software can be directly installed on the RTP. The VSE is able to analyze the RTP data. As an alternative, an external PC with the installed VSE software can be used. The PC and the RTP are connected via LAN. With this test setup, it is possible to analyze radar signals with up to 6 GHz signal bandwidth.

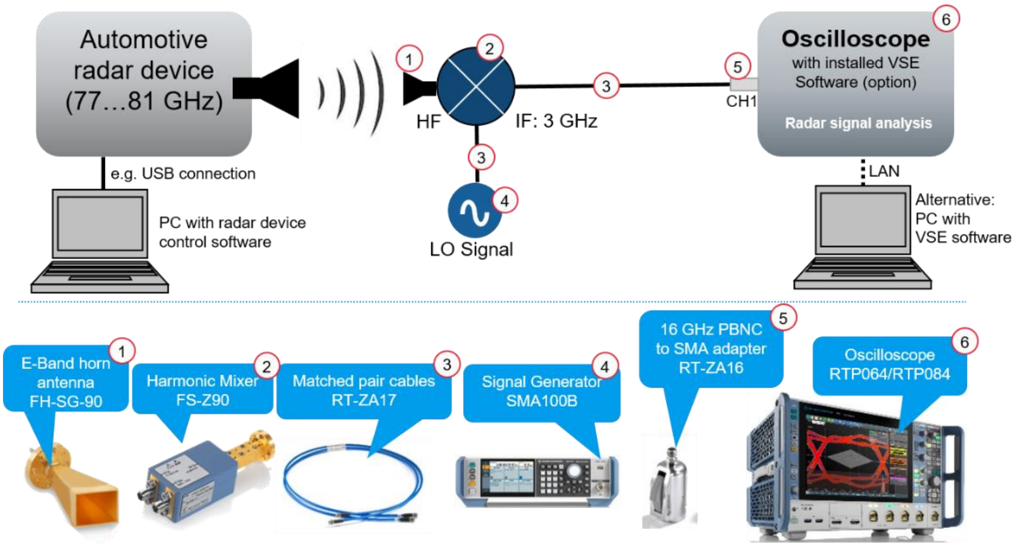


Fig. 2-1: Test setup for chirp and pulse measurement in E-band by using a harmonic mixer

2.2 Pulse and chirp analysis with RTP oscilloscope

Before you can start the measurement, perform the following basic settings:

Settings on SMA100B Signal Generator:

- Press the *PRESET* key.
- Make the settings for a CW signal with f = 12.666666 GHz, level = 17 dBm. For the multi channel measurement described in 3.2 increase the level to 20 dBm.

Settings on RTP:

- Press the *PRESET* key.
- Change the horizontal time scaling (here 400 µs/div) until some radar pulses became visible on the display (see Fig 2-2)

Settings on the radar DUT:

- Adjust the DUT settings for a specific radar signal you like to test. In the following a radar signal with f = 77 GHz with 3.9 GHz Bandwidth and a chirp duration of 400 µs is used.

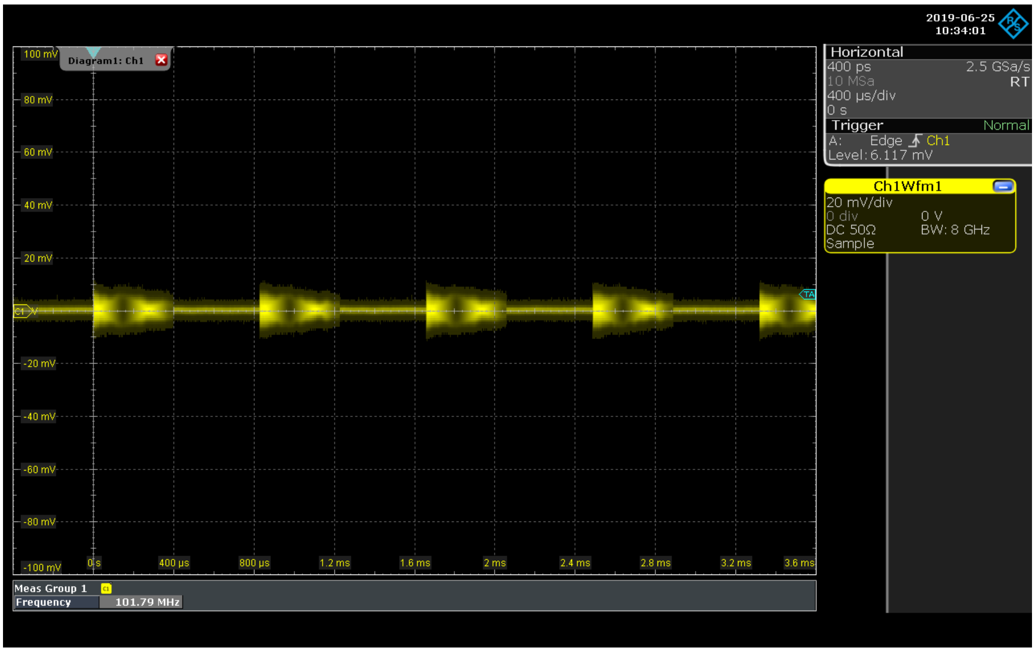


Fig 2-2: Radar Signal in time domain

- For a high horizontal resolution select the *Setup* from the *Horizontal* menu.
- Deselect the *Auto adjustment* function and set the Sample rate to 20 GSa/s:

2.2.1 Real-time deembedding of signal losses

The result on the Oscilloscope screen shows a weak signal. In order to eliminate additional signal losses caused by the mixer (conversion loss), cable and adapter (see Fig. 2-3) the RTP provides the deembedding function.

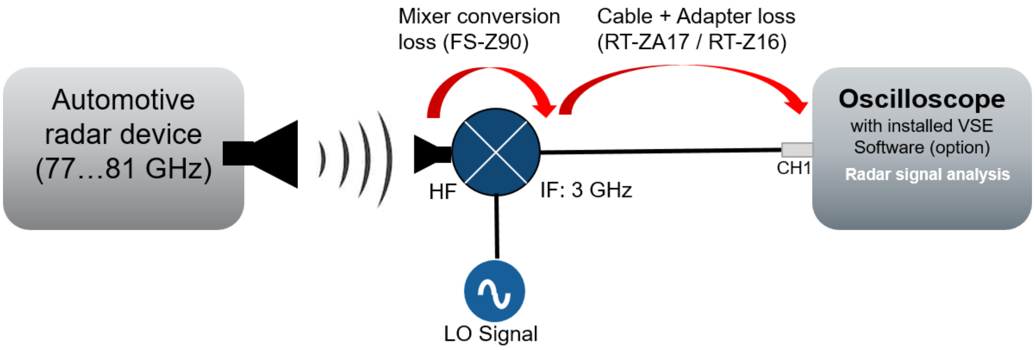


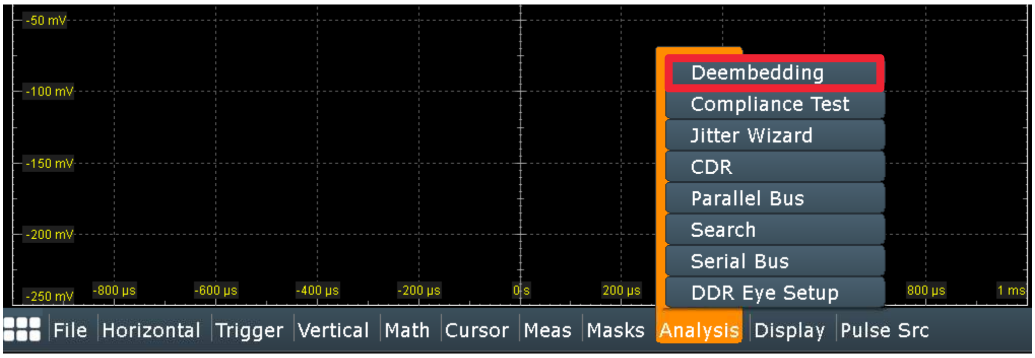
Fig. 2-3: The down converted radar signal is reduced by conversion loss, cable and adapter loss

Deembedding removes the parasitic effects of the measurement setup from the measured signal. A simple measurement setup consists of a probe only, but more complex setups include also cables, fixtures and other components. The effects of these components on the measurement are typically increasing when signal frequency increases. Thus, deembedding is useful or even necessary when measuring signals of 3 GHz frequency or higher. Furthermore, you can virtually move the measurement point to a point in a circuit that cannot be reached by probing. In this case, the effects of the components between the real and ideal probe are deembedded.

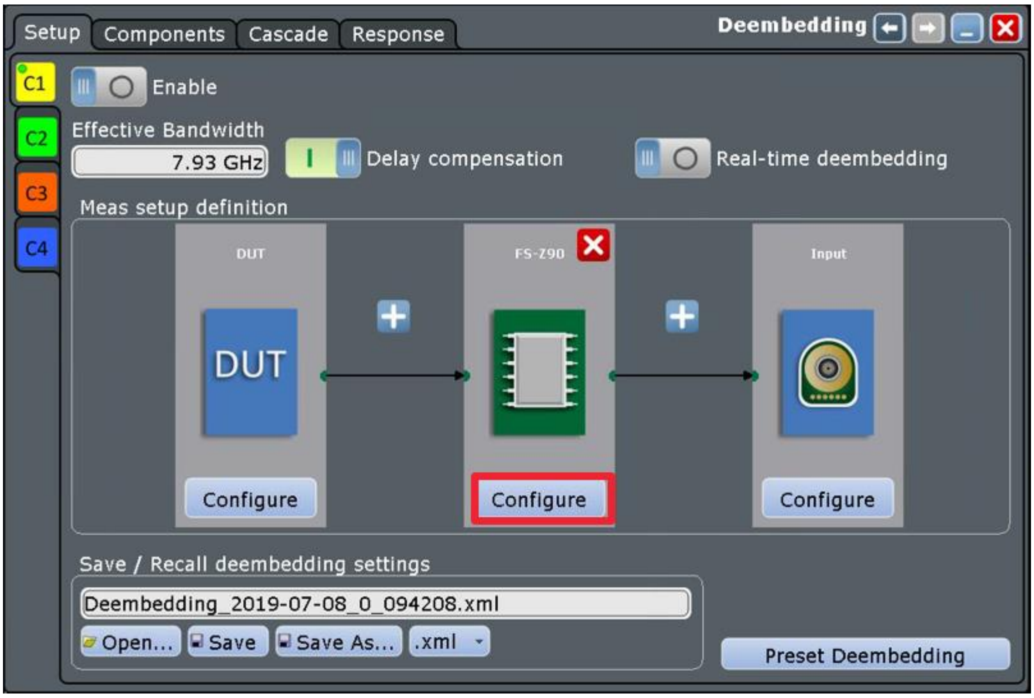
The components of a measurement setup are usually multi-ports, and each multiport can be described by a scattering matrix. The elements of a scattering matrix are the S-parameters. The S-parameters of a multiport are usually measured using vector network analyzers (VNA), and they are saved in Touchstone files. From the S-parameters of the measurement components, the deembedding option determines the transfer function for the measurement setup. Based on the transfer function, filter coefficients are calculated, and the filter is applied to the measured signal. Option R&S RTP-K121 realizes the deembedding process in software. As the process requires some time, triggering on the corrected signal is not possible, and the acquisition rate decreases. Option R&S RTP-K122 realizes the deembedding process in hardware. This process is fast, so you can trigger on the corrected signal, and the acquisition rate remains unchanged.

For the deembedding of the shown losses in Fig. 2-3 proceed as follows:

- Select the *Deeembedding* function from the *Analysis* Menu:



- In order to add the FS-Z90 RF-characteristic press *Configure* of the custom icon:



The following settings are shown in Fig. 2-4:

- Enter a name for the deembedding device, here "FS-Z90".
- With *Open,* load the S-Parameter file for the FS-Z90 mixer. The conversion loss of the mixer in the down converted frequency range is shown in Fig. 2-4 .
- Activate the *Enable* field.

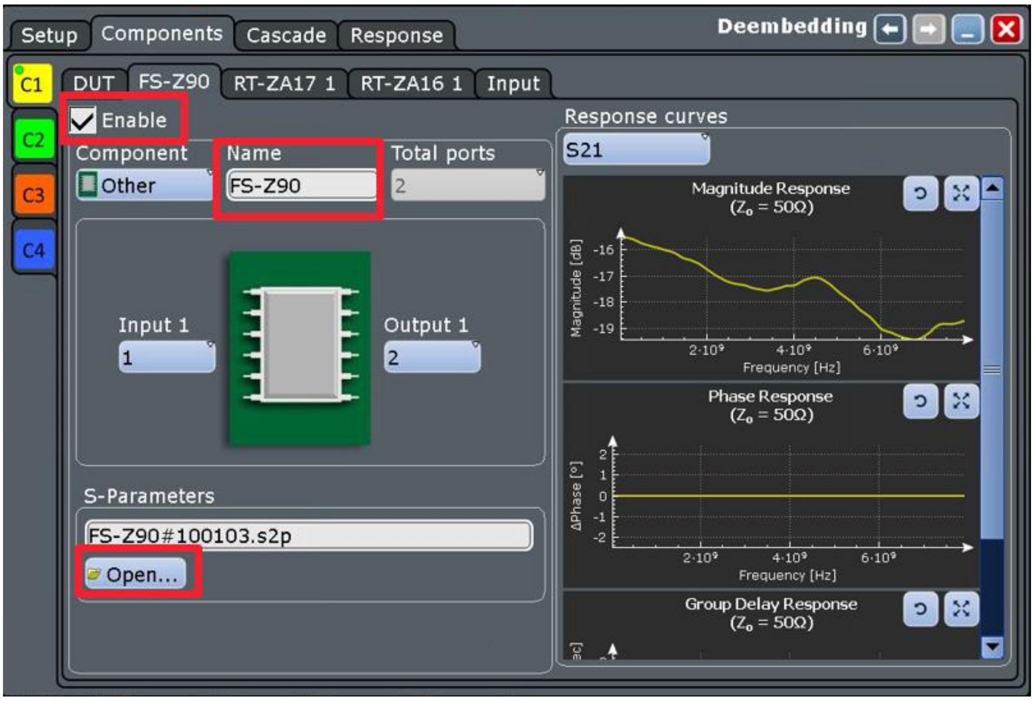
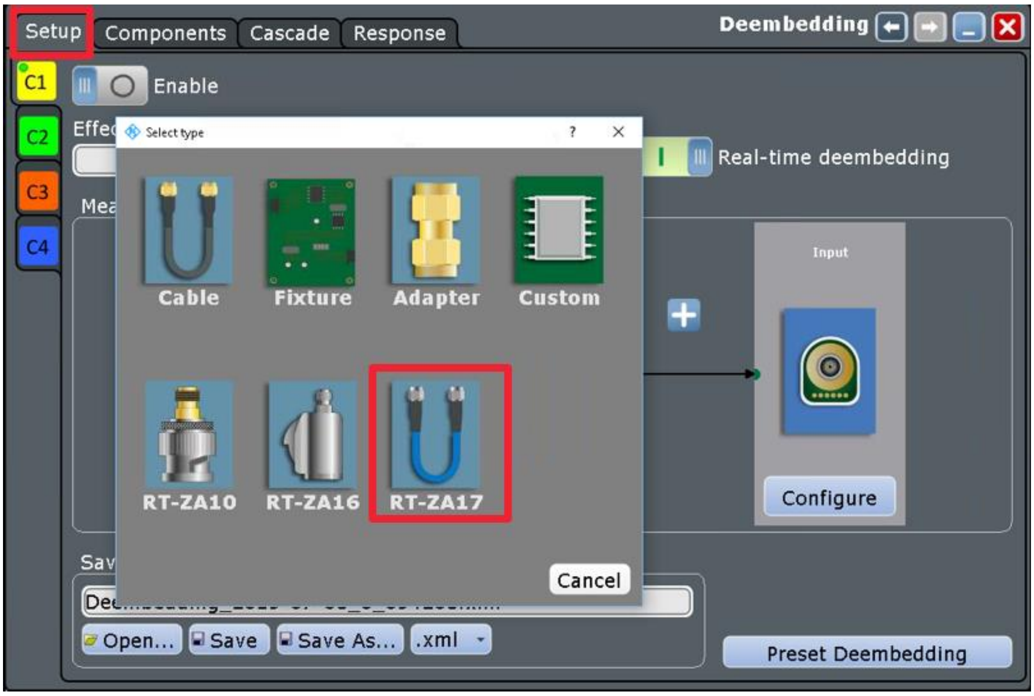


Fig. 2-4: Deembedding settings for FS-Z90

Add the SMA RF-Cable:

- Select the *Setup* tab and add (press the + sign) a new deembedding component.
- Choose the predefined RT-ZA17.



☞ Hint: Instead of using the default values of the RT-Z17 cable you can determine the S-Parameters with a VNA. Then select the *Cable* icon and load the S-Parameter file as it is described above for the mixer. This can increase the measuring accuracy even more.

- Press the *Configure* button of the RT-ZA17 icon and activate the *Enable* box.
- Add the RT-ZA16 in the same way like for the RT-ZA-17.

Finally, the deembedding setup looks like in Fig. 2-5.

- Activate the *Real-time deembedding* and *Enable* the Deembedding function.

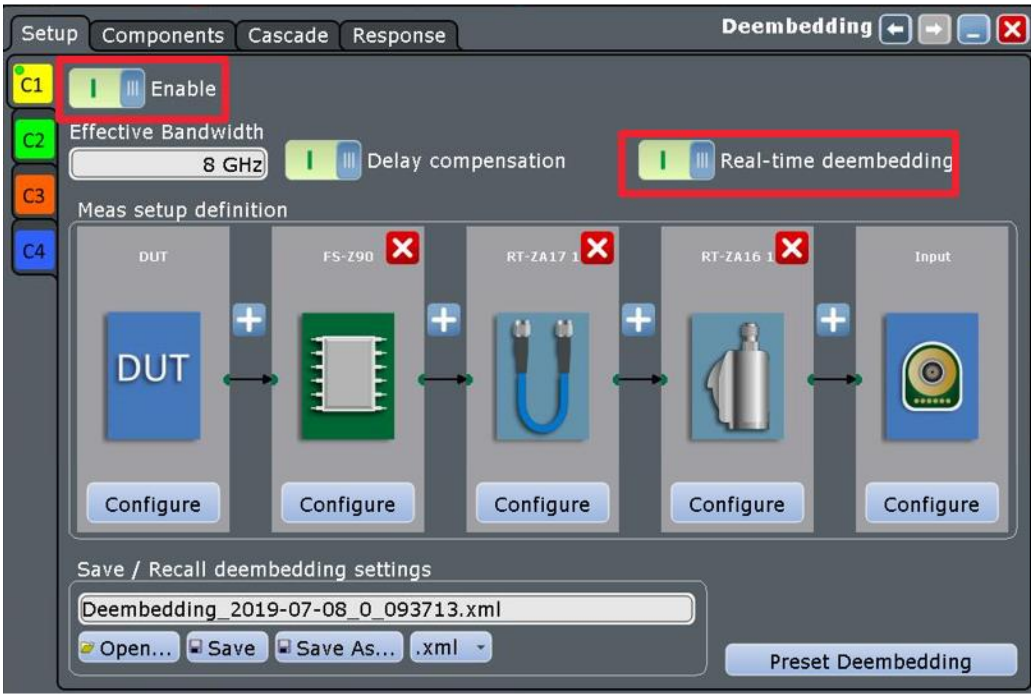


Fig. 2-5: Deembedding setup

After the Deembedding function is activated, the mentioned losses of the used components are removed and the signal amplitude of the radar signal is increased (Fig. 2-6):

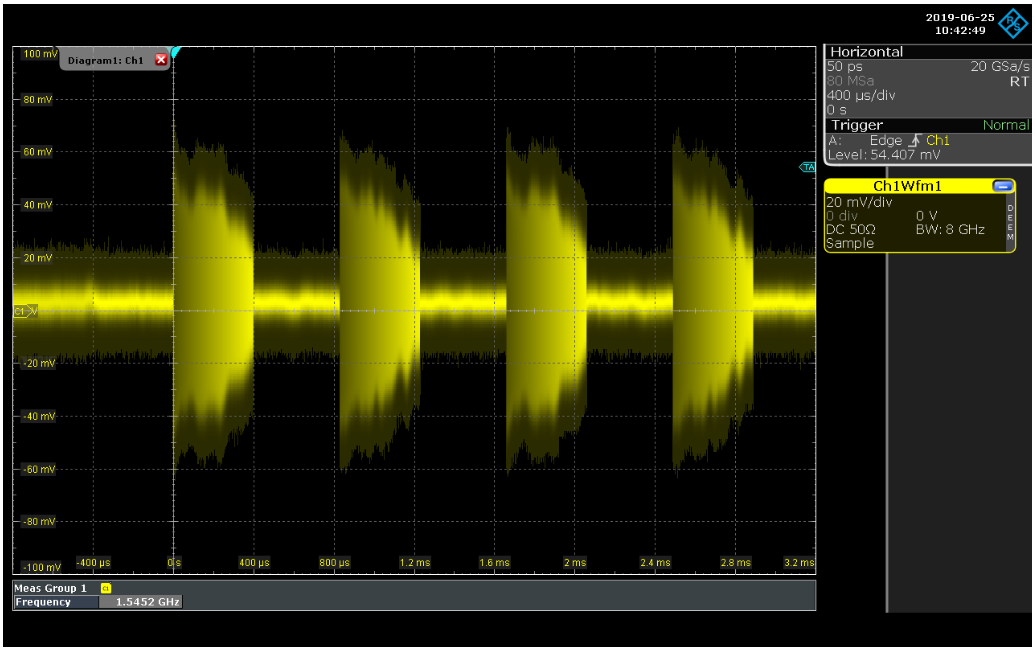


Fig. 2-6: Rader signal with increased signal amplitude after the Deembedding of losses

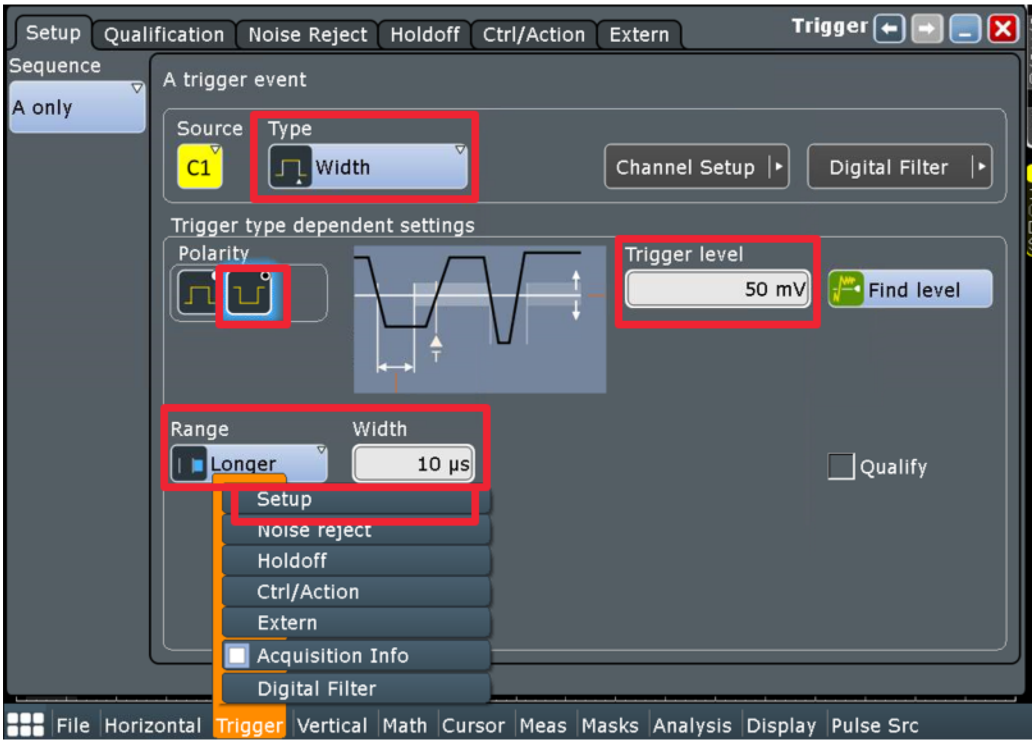
2.2.2 Precise triggering on pulsed signal

The activated Real-Time Deembedding (option R&S RTP-K122) realizes the deembedding process in hardware and allows the triggering on the corrected signal. The width trigger detects positive and/or negative pulses of a pulse width (duration) inside or outside of a defined time limit. It can trigger on a single digital channel or a logical combination of digital channels. The instrument triggers at the beginning of the detected pulse[1].

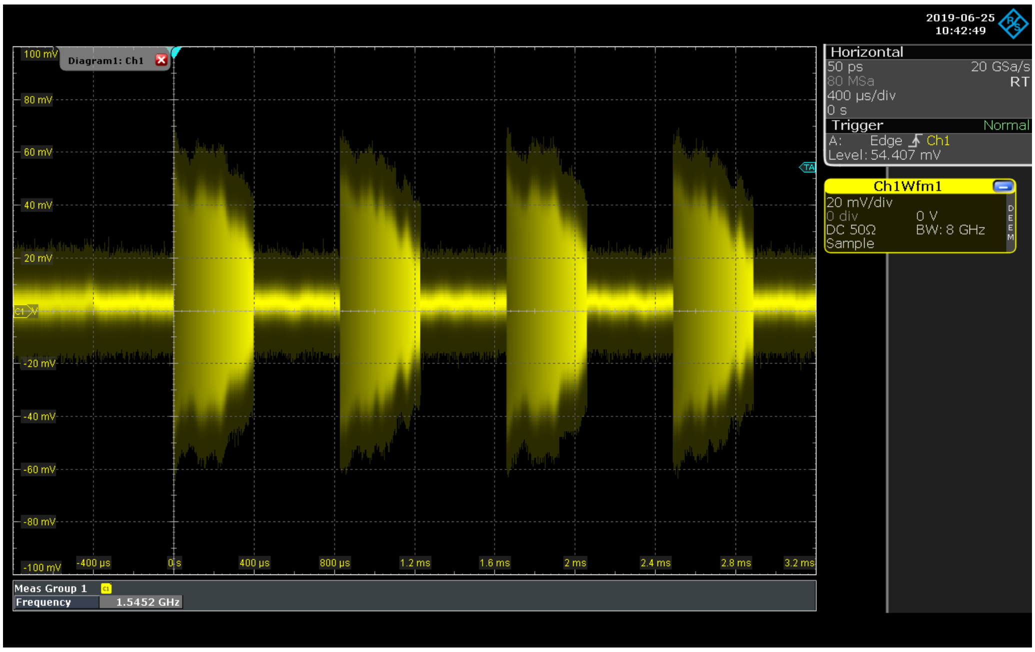
- Select the *Width Trigger* in the *Trigger Setup* window.
- In the trigger *Type* settings make the following settings to account for the pulse of-time:
  - Trigger Pulse Polarity: off-time
  - Off-time range *longer* than 10µs
  - *Trigger Level* 50 mV

  (Please note: the values can be the different for other radar waveforms.)

[1] Advanced trigger capabilities, e.g. selective trigger on certain pulse durations, are described in a separate application card: Trigger on radar RF pulses with an oscilloscope



- After closing the *Trigger Setup* window, there are stable pulses on the screen:



2.2.3 Pulse Envelope measurement

In order to create the pulse envelope it is necessary to filter out the RF carrier. The *Advanced Math* function of the RTP allows to do this with the help of some mathematical functions.

- For the pulse envelope measurement, select the *Math Setup* function within the *Math* menu.
- Select the *Advanced* tab and enter the in Fig. 2-7 shown formula.

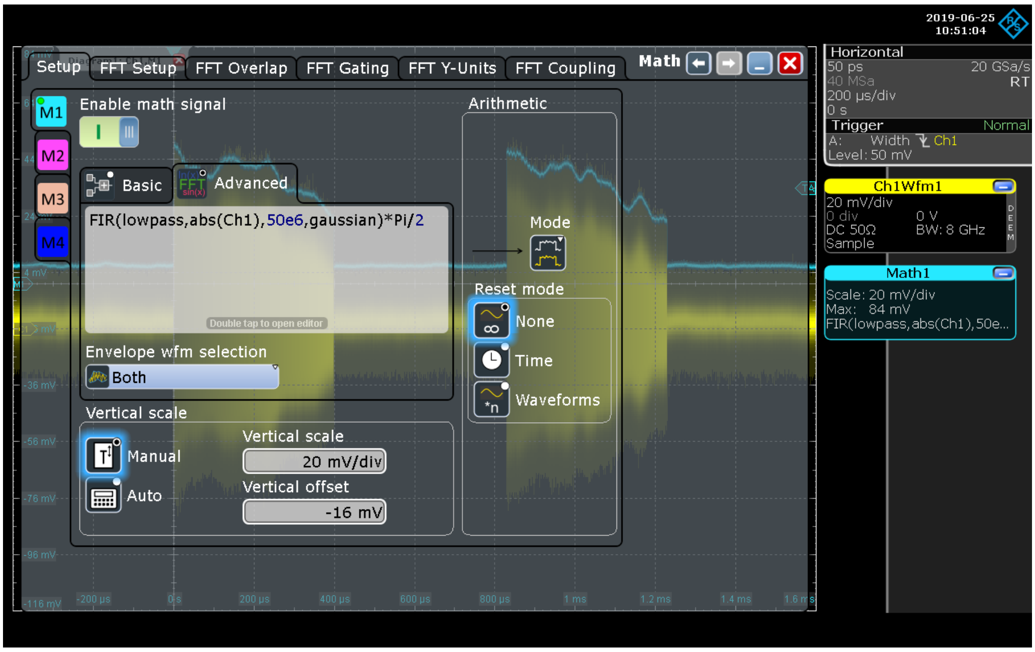


Fig. 2-7: Settings for the pulse envelope measurement

- For entering the formula, the RTP offers a powerful formula editor. The formula shown in Fig. 2-8 creates a Gaussian low pass filter with 100 MHz cutoff frequency and applies to the absolute value of channel [2]. Depending on the chosen cut-off frequency the math channel follows closely the RF signal or smooth out the ripple.

[2] For more detailed information please see the application card: Analyzing RF radar pulses with an oscilloscope

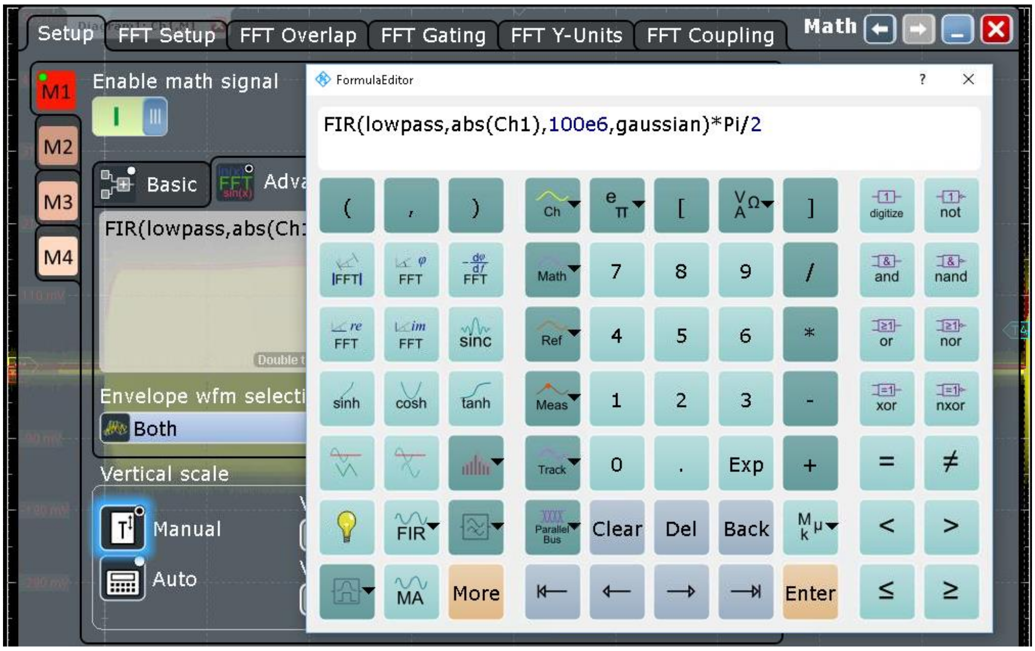


Fig. 2-8: This low pass filter formula removes the RF carrier and creates the pulse envelope

- *Enable* the Math signal as shown in Fig. 2-7. The result is shown in Fig: 2-9 :

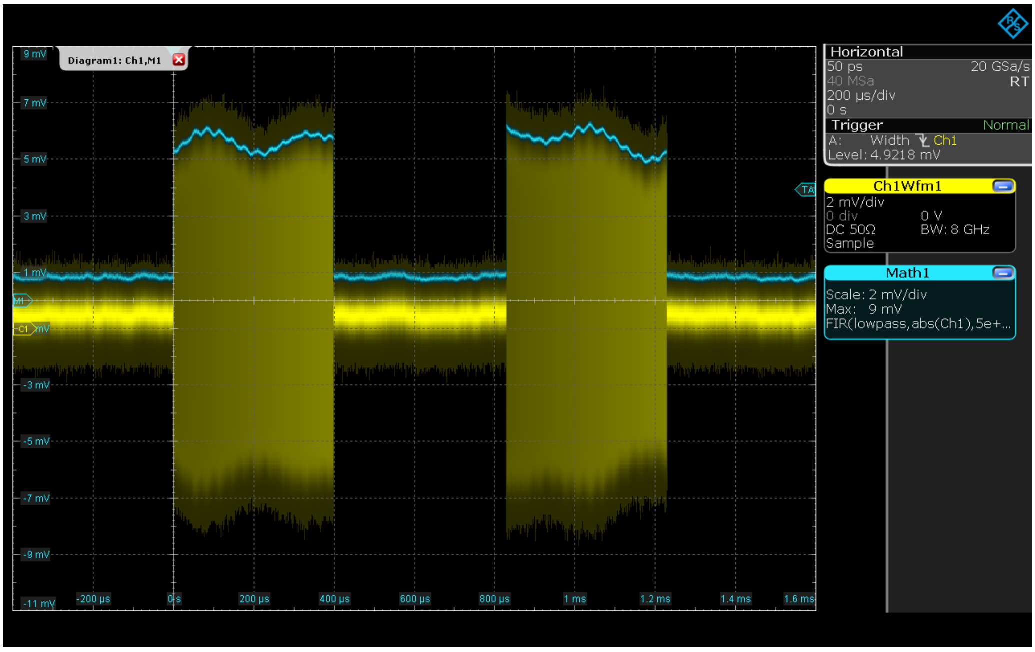
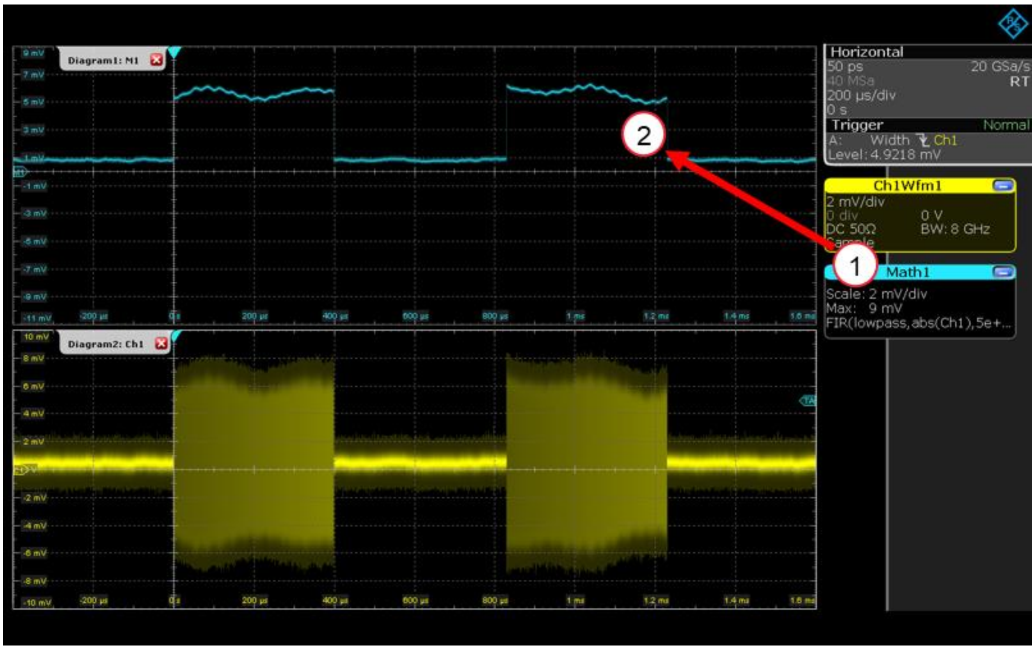


Fig: 2-9: The blue trace represents the pulse envelope. Few, fast transitions are ignored by the filter due to its cut-off frequency.

- In order to separate the pulse envelope from the signal pulse move the *Math1* Field from the right side to the left measurement display (1->2):



To measure important parameters of the pulse envelop make the following settings (see also Fig 2-10):

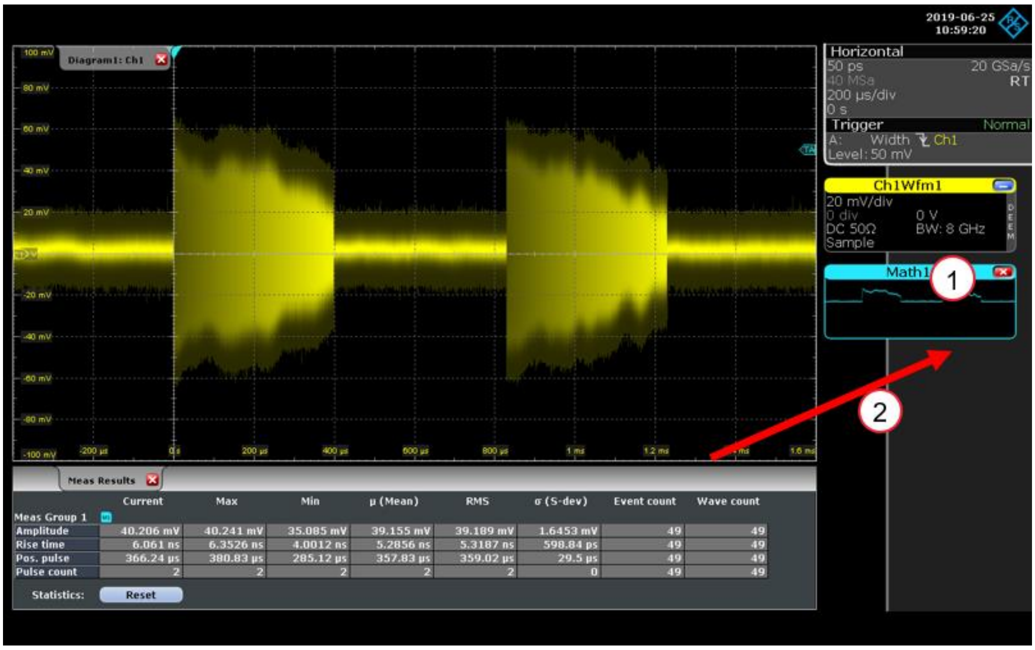
- Press the measurement icon on the tool bar (1).
- Within the side bar select the measurement function in the tab *Amp/Time* for parameters you like to measure (2). In this example, it is *Amplitude*, *Rise time, Pulse Width* and *Pulse* count.
- For additional statistic information over time like max value, min value, standard deviation etc., switch the *Statistics* button *on* (3).
- Apply the selected measurements on the envelope trace M1 (4). The numerical results of all measurements are displayed in a table (5).

Fig 2-10: Measurement settings and results for certain pulse envelope parameters

2.2.4 Demodulation of chirp in time domain

The following steps describe how the automotive radar signal can be demodulated in time domain by the RTP.

- Minimize the pulse envelope measurement screen (1) and move the result table to the right area (2) so that only the pulse signal is visible on the screen:



Create a new measurement group (Fig. 2-11):

- Select *Meas Group* from the *Meas* menu. Choose the tab MG1.
- *Set Category* to *Amp/Time* and *Source* to *C1*
- Select Add/Remove Measurements

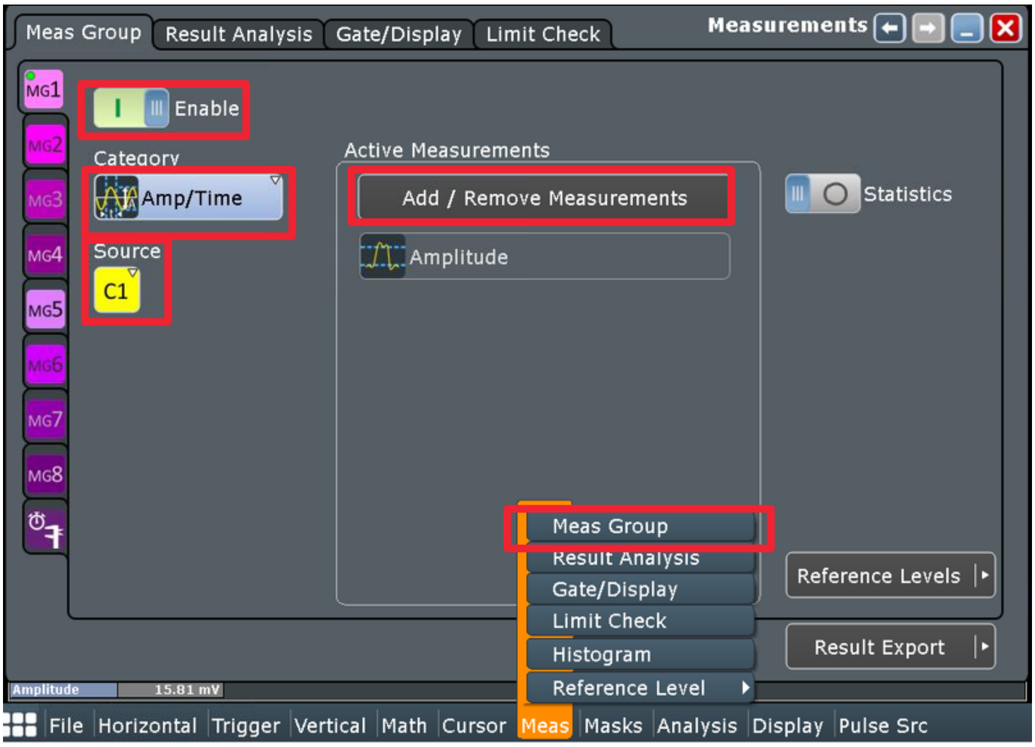


Fig. 2-11: New measurement group for chirp demodulation

- Make sure that only the *Frequency* measurement function is selected and press *Ok*:

- Select the tab *Result Analysis* (Fig. 2-12).
- In order to display the chirp enable the Track function

The track is a waveform that shows measurement values in time-correlation to the measured signal. It is the graphical interpretation of all measurement values of a single acquisition.

- In order to display the demodulated chirp for the complete pulse, increase the Limit under *Measure all events in each acquisition* to the maximum possible value (Fig. 2-12).

Fig. 2-12: Settings for the chirp measurement (frequency versus time)

To demodulate the radar signal only within the radar pulse the gating function can be used:

- Select *Meas Group* from the *Meas* menu. Choose the Gate/Display tab.
- Enter the absolute values for the gate start and gate stop
- Select Add/Remove Measurements

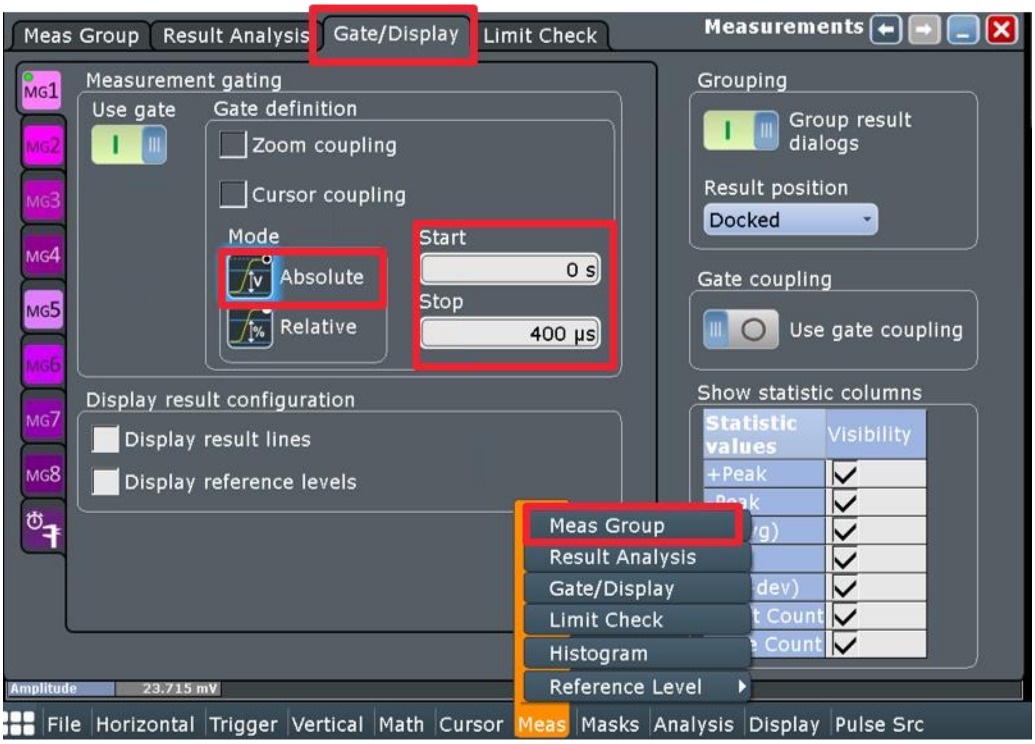


Fig. 2-13 shows that the demodulation was removed outside the chirp with the help of the gate:

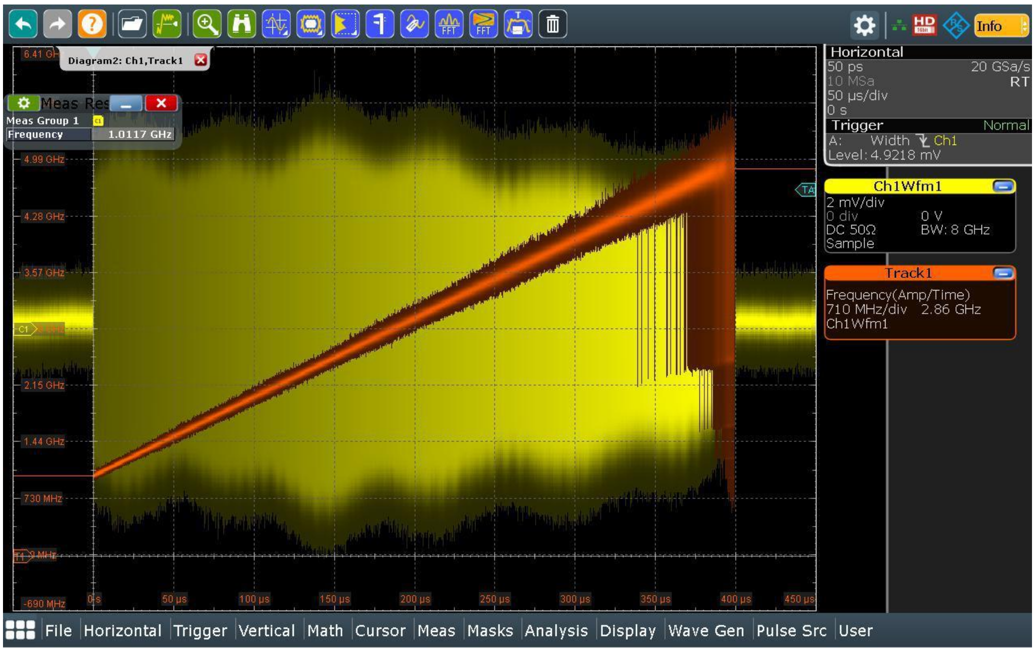


Fig. 2-13: Demodulated Chirp signal in time domain with active gating

For reducing the noise on the chirp signal, the signal will be filtered by low pass. In order to represent the demodulated chirp not in the IF range but in the original radar frequency range, a rescaling of the result was additionally performed (Fig. 2-15). For the filtering and rescaling, follow the following steps:

- Select the *Math Setup* function within the *Math* menu.

Select the *Advanced* tab and enter the in Fig. 2-14 shown formula. The cascaded Math function includes the rescale function ax+b and the Gaussian low pass filter function with a 40 MHz cutoff frequency.

For the scaling of x the formula editor expression rescale(x,a,b) defines the values for the rescale function (ax+b).

- "x" is the signal source, in this case it is the low pass filtered Track1
- "a" is the factor the signal source is multiplied with, in this case a = 1 because the gradient should not be changed
- "b" is the offset of the signal source on the y-axis, in this case b = 76 GHz

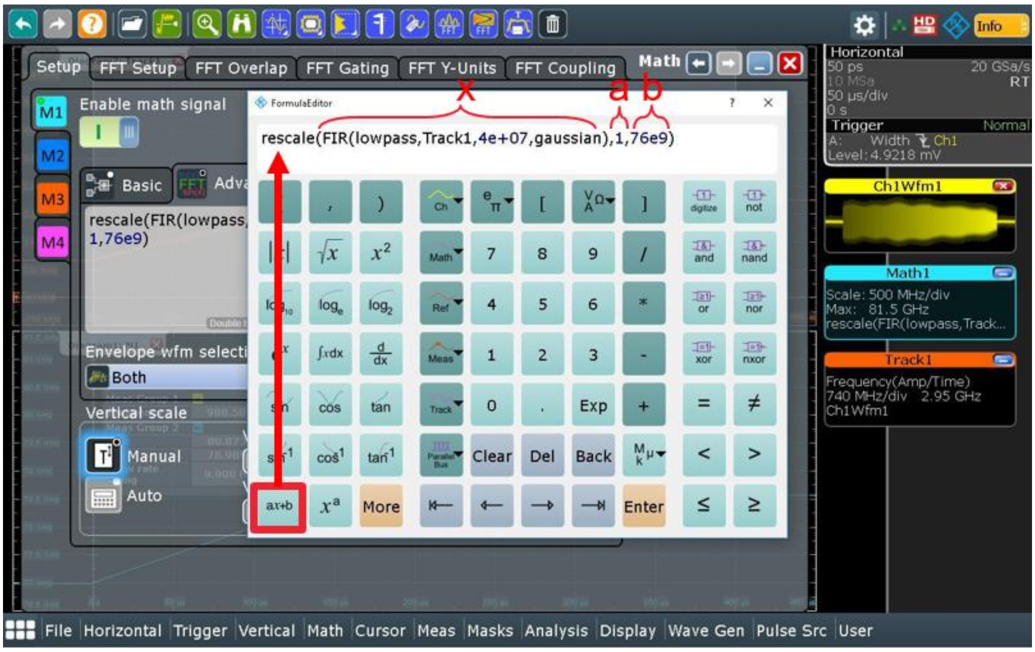


Fig. 2-14: Noise reduction via low pass filter and frequency range rescaling

- Choose a meaningful scaling for the vertical scale:

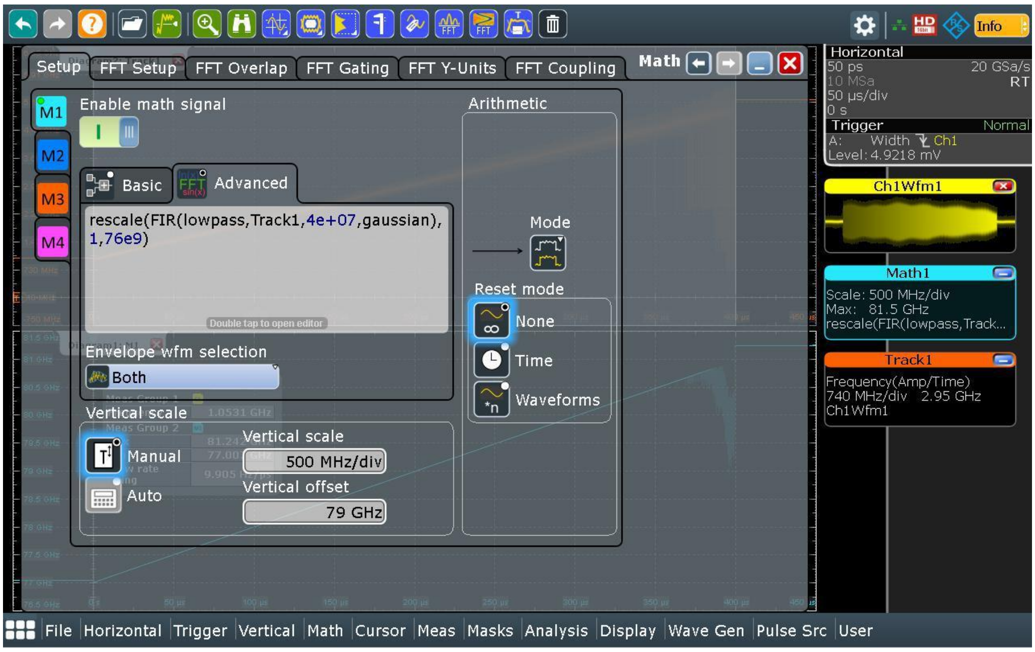


Diagram1 in Fig. 2-15 shows the result of the chirp analysis in time domain after the filtering. The chirp bandwidth is 3.9 GHz.

Fig. 2-15: Diagram1 (blue trace) shows the low pass filtered demodulated chirp signal in time domain beginning at 77 GHz

2.2.5 Demodulation of chirp in frequency domain

The following steps describe how the automotive radar signal can be analyzed in frequency domain by the RTP.

- Minimize Track 2
- Select the *FFT icon* in the tool bar
- For the spectrum analysis enter the settings in the side bar window as shown in Fig 2-16. The Center frequency corresponds to the IF frequency of the measurement setup, here 3 GHz. The setting for *Frequency span* should be higher than the expected chirp bandwidth.
- In order to measure the frequency spectrum of a single pulse, mark the pulse of interest with a rectangular window.

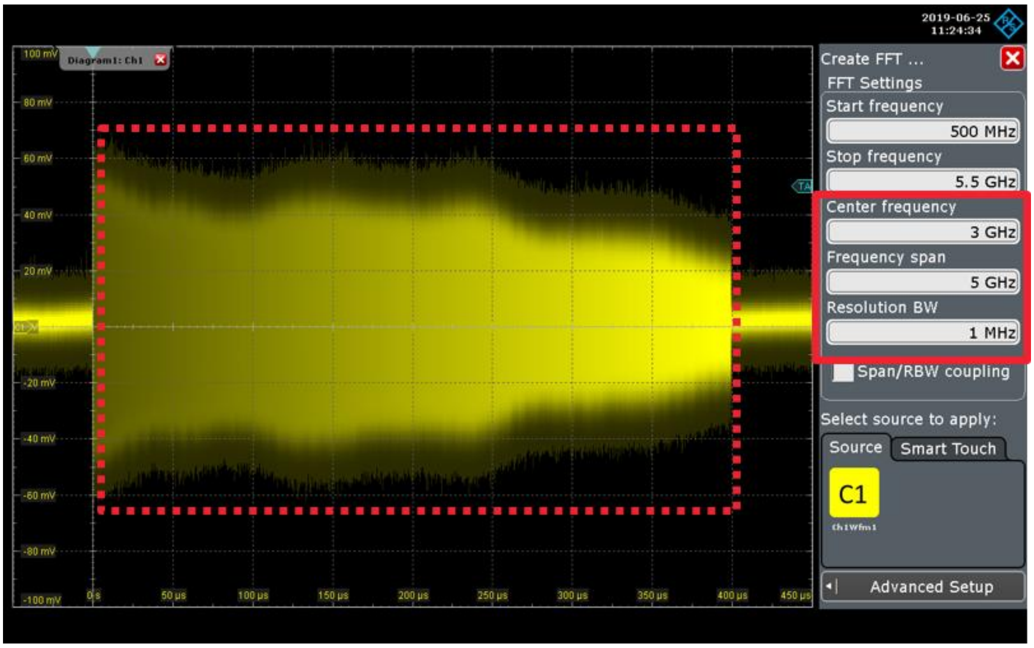


Fig 2-16: Settings for the frequency domain measurement via FFT on a certain radar pulse

Diagram2 in Fig. 2-17 shows now the frequency spectrum from 500 MHz to 5 GHz of the selected pulse.

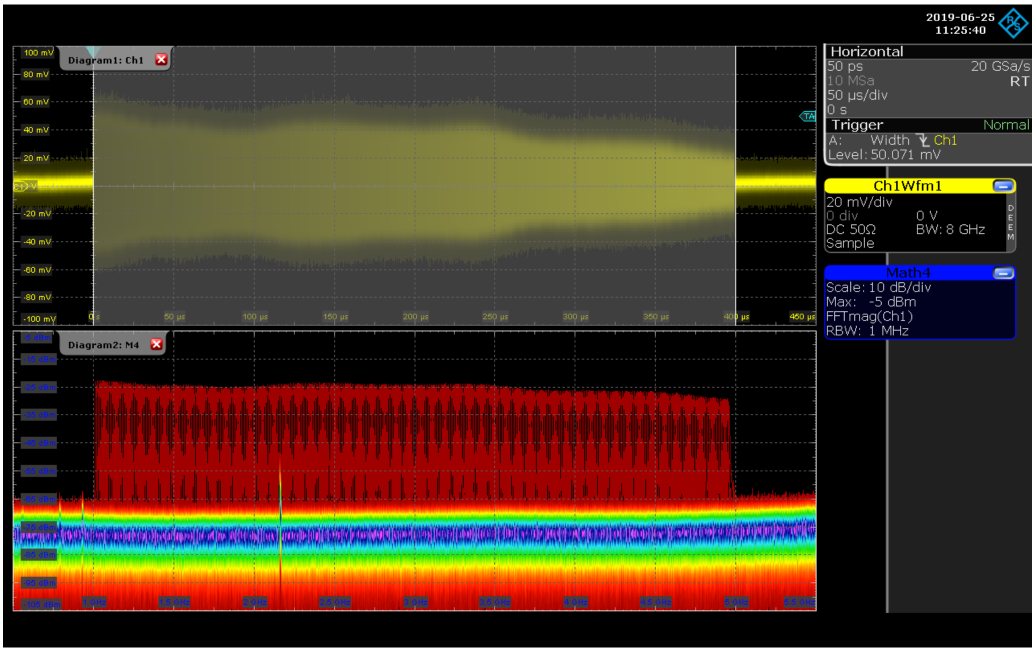


Fig. 2-17: Frequency spectrum of a single radar pulse in diagram 2

- In order to measure the frequency spectrum versus time select the *Advanced Setup* within the *Create FFT…* window.
- Enable the *Spectrogram* under the *FFT Setup* Tab. For the representation of several radar chirps versus time, enter a suitable value for the resolution bandwidth, in this case 200 kHz.

The spectrogram in the middle of the RTP screen of Fig 2-18 shows now the frequency spectrum versus time of the chirp. As the spectrogram “flows” upwards earlier signals are on top, thus the figure shows up chirps.

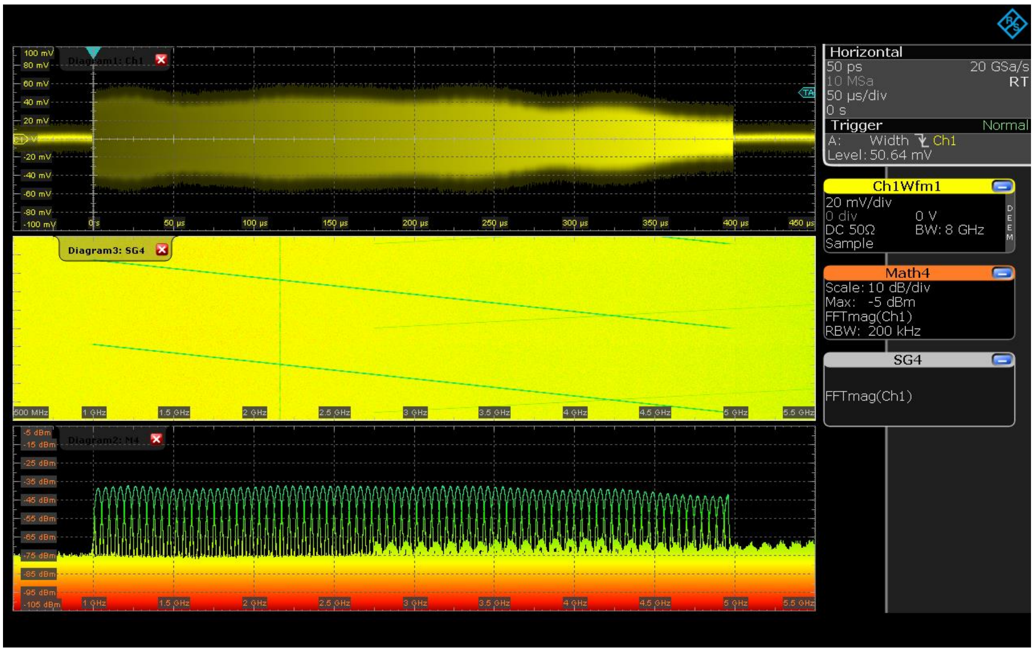


Fig 2-18: Spectrogram of a single radar pulse in diagram 3

2.3 Advanced pulse and chirp analysis with VSE-K60

The VSE vector signal explorer software was developed to bring the power of the signal and spectrum analyzers R&S®FSW signal processing to the engineer’s PC. It analyzes signals from a wide range of instruments like the RTP as well as files originating from simulations or recorded measurements. On instruments like the RTP the VSE software can also be installed directly without the need of an extra PC.

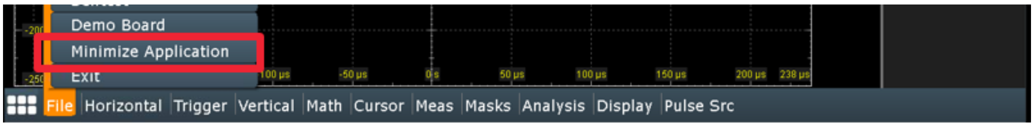
This section describes the VSE software setup and results. For analysis and verification of continuous wave radar signals, the VSE options Transient Analysis VSE-K60 and the Transient Chirp Analysis VSE-K60c has been developed.

These options make it possible to characterize chirp signals (with their linear frequency ramps and large bandwidths) considering important parameters such as chirp rate, chirp length and chirp rate deviation. Results are displayed in various charts and a straightforward table. Additional statistical evaluations make it easier to conduct extended period signal stability measurements and to detect outliers.

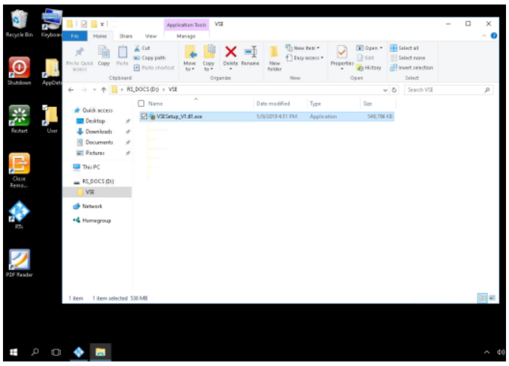
2.3.1 VSE & Measurement configuration using an RTP oscilloscope

For using the VSE software on the RTP perform the following installation steps:

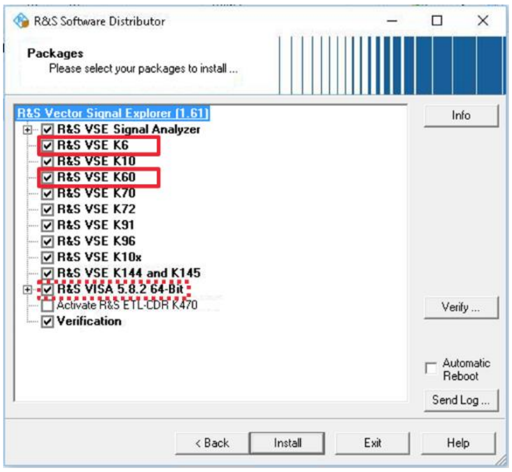
- *Select File* and *Minimize Application*



- Start the VSESetup.exe file from a certain location:

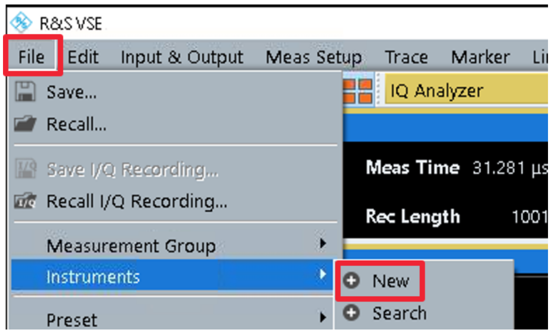


- Follow the instruction of the installation procedure. Select at least the red marked software package in the figure below, i.e. K6 for general pulse analysis and K60 for transient analysis. It is recommended to install the R&S Visa also:

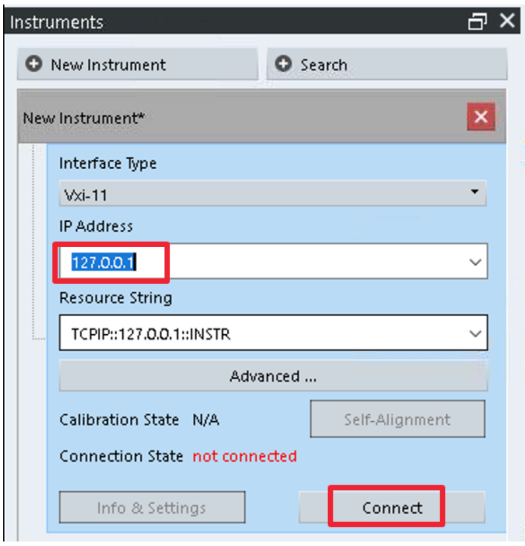


- Make sure that the USB License Dongle R&S® FSPC is plugged into one of the USB ports on the RTP. How to enter the license key for a certain VSE software package is described in the VSE manual.
- Press the key. This opens the *App Cockpit*. Start the VSE software from under the *R&S Apps* tab:

- Connect the RTP with the VSE with: File -> Instruments -> New:



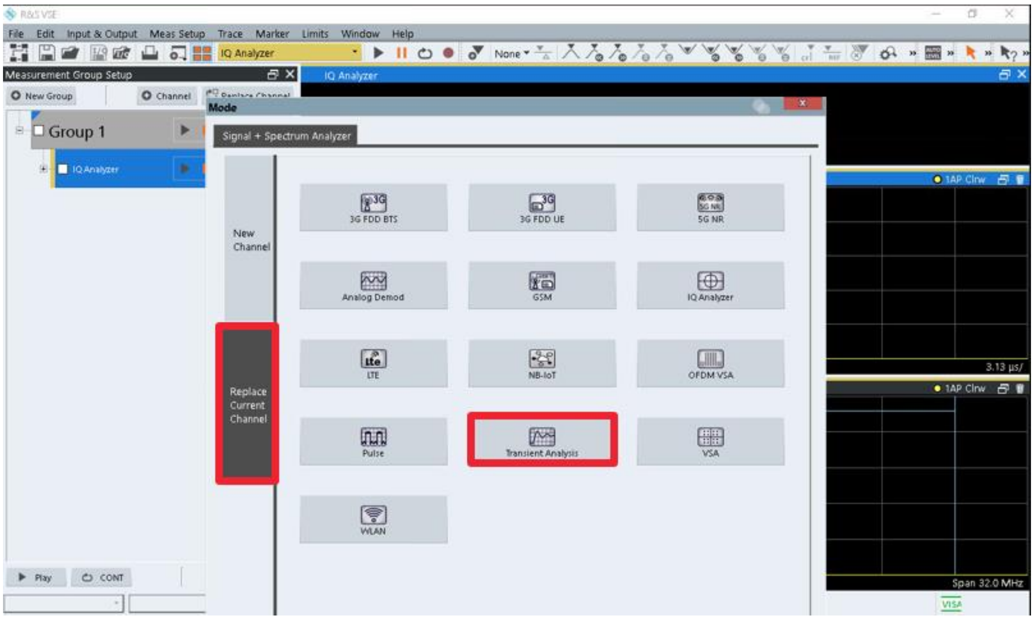
- Enter the *IP Address 127.0.0.1* and press *Connect:*



The VSE software is now ready for use. As an alternative, the VSE software can also be installed on a PC and the RTP measurement data can be transmitted via LAN. Please see the VSE manual for more information.

Before you can perform a measurement with VSE software it is necessary to create a measurement channel. At the beginning it is meaningful to perform a Preset.

- Select File -> Preset -> All
- Select *File* from the tool bar -> *measurement Group* -> *+New Measurement* Channel
- In the *Mode* window choose the *Replace Current Channel* and select *Transient Analysis*:



- In order to enter the necessary measurement parameters, open the *Overview* window for the Transient Analysis with the overview icon from the toolbar (Fig. 2-19)

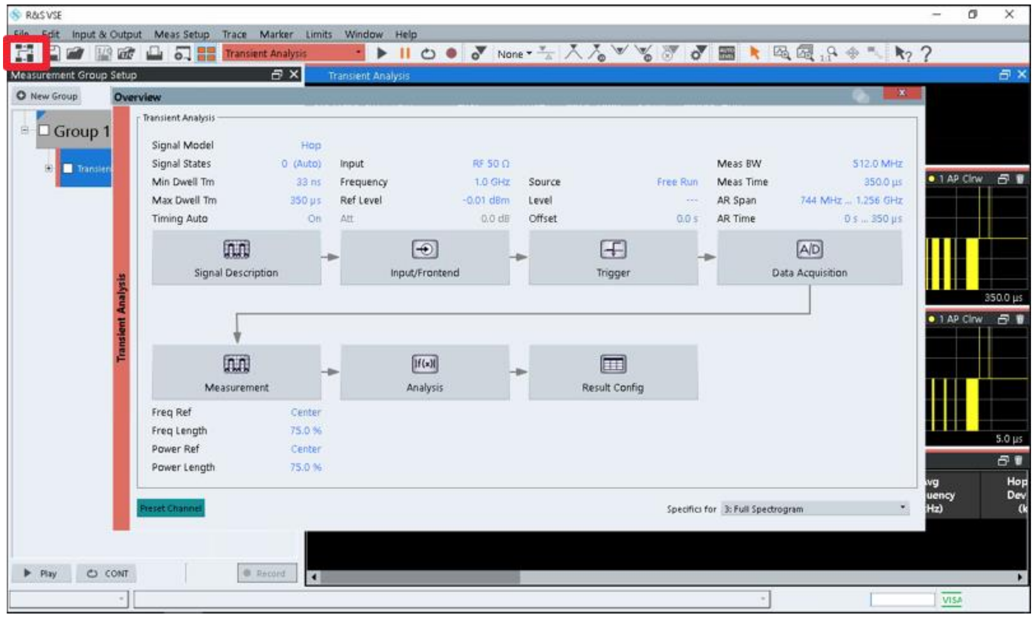
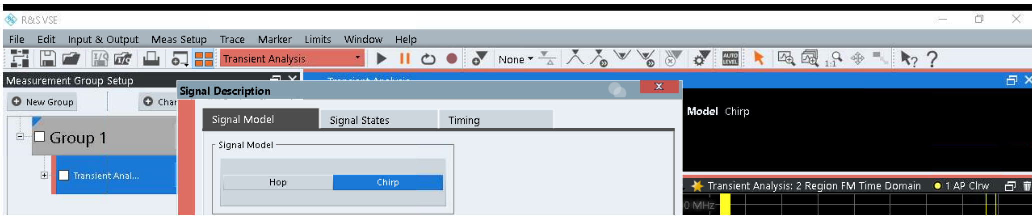
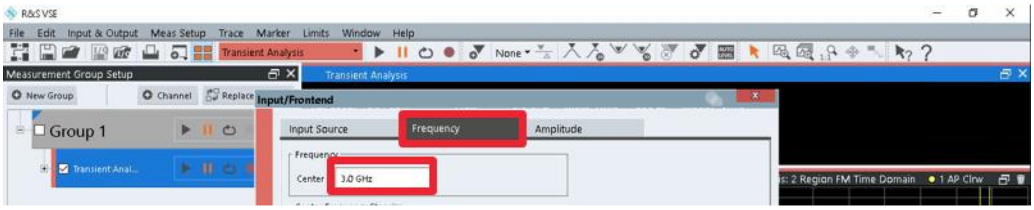


Fig. 2-19: Float chart for the configuration of the Transient Analysis measurement.

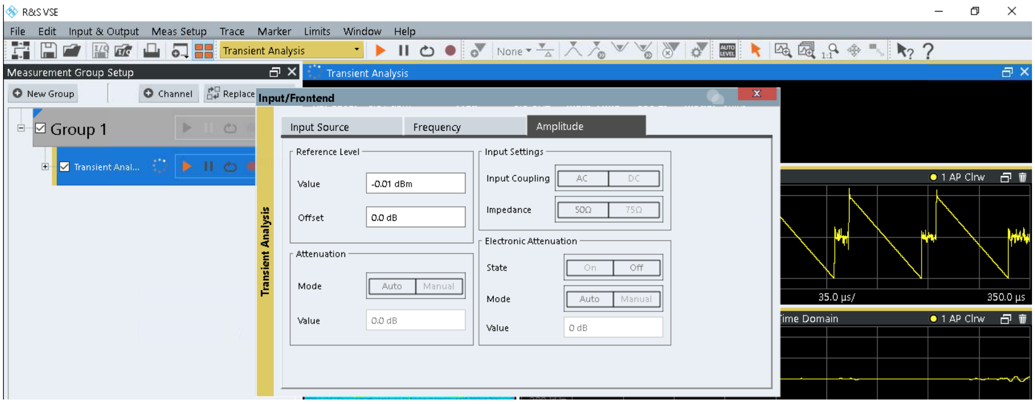
- Select *Signal Description* from the float chart (Fig. 2-19) and choose *Chirp* under the tab *Signal Mode*.
- Select the *Auto Mode* under the tabs *Signal States* and Timing and close the *Signal Description* Window.



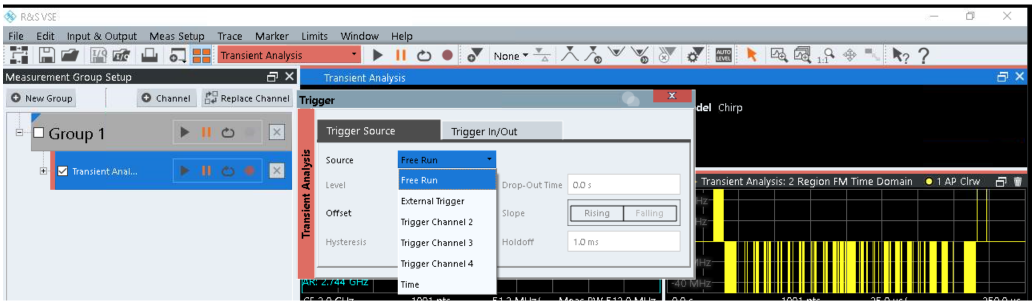
- Select *Input/Frontend* from the float chart (Fig. 2-19) and enter the IF Frequency, here 3 GHz, of the test setup from Fig. 2-1:



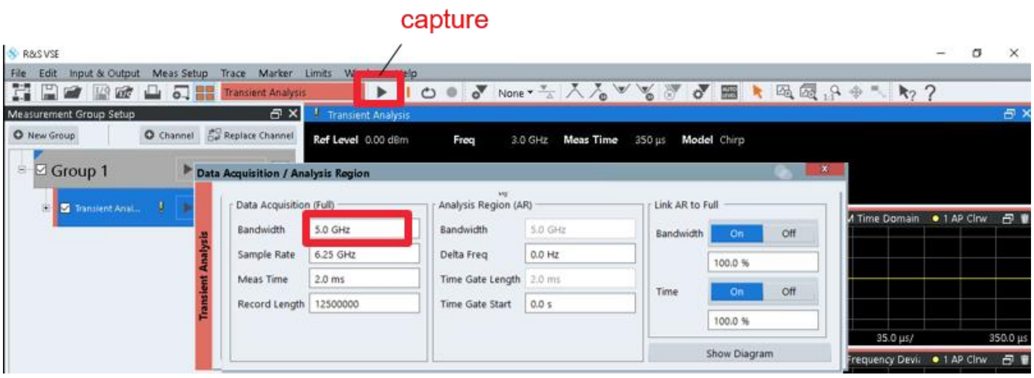
- Sometimes it might be useful to align the reference level and attenuation according to the signal level. This can be done und the tab *Amplitude*:



- Select *Trigger* from the float chart (Fig. 2-19) and choose the right trigger. Here the *Free Run* trigger is used:

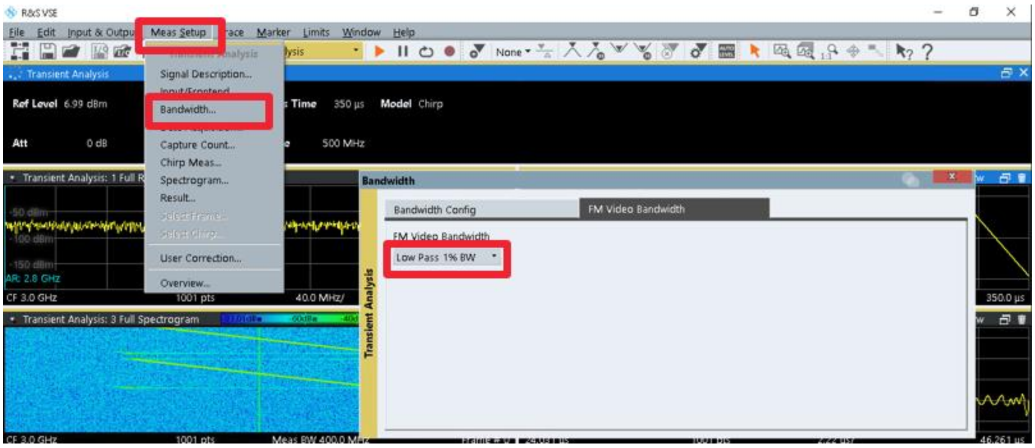


- Select *Data Acquisition* from the float chart (Fig. 2-19) and enter the *Bandwidth* of the radar signal and start the measurement with the *Capture* button :



With the setting of the Video Bandwidth you can smooth the measurement curve if necessary:

- Choose *Bandwidth…* in the *Meas Setup* menu and select a suitable value for the *FM Video Bandwidth*:



2.3.1.1 Chirp Measurement Results

There are several measurement windows shown by the VSE software. Each measurement window can be configured on its own, replaced by others or defined to show a specific portion of the capture. Fig. 2-20 shows the result of the Transient Analysis (requires VSE-K60 and VSE-K60c). It contains the following measurements, each displayed in a separate window:

1. The window **Full RF Power Power Time Domain** (1) shows the measured power levels versus time for the detected chirps. The displayed data corresponds to one particular frame in the spectrogram.

2. The window **Region FM Time Domain** (2) shows the demodulated RF signal over time including the indication if a defined signal has been detected as such (indicated by a green bar) and a signal has been selected (indicated by a blue bar).

3. The window **Chirp Rate Time Domain** (3) shows the changing chirp rate from the selected chirp versus time.

4. The window **Full Spectrogram** (4) shows a waterfall diagram, frequency over time with color-coded amplitude.

5. The window **Chirp Results** (5) derives a table from the detected and analyzed chirp signal parameters.

6. The window **Chirp Frequency Deviation Time Domain** (6) shows the frequency deviation of the selected chirp (in this case chirp number 1, see the blue bar in the second window "region FM time domain" (2) compared to a linear slope. The linearity of the chirp is measured by subtracting if from the ideal chirp trajectory. As shown in section 1.5, the chirp linearity is of great importance for radar parameter estimation accuracy and resolution.

Fig. 2-20: Chirp analysis with the VSE software

3 Multi-channel measurement with oscilloscope

In order to increase the detection range of the radar sensor, state of the art radar sensors perform beamforming or other changes in the antenna pattern. For doing that the sensors include several TX- and RX-antennas. The beamforming is realized by changing the signal phase usually in 5 degree steps. In order to verify the mentioned change in phase a multi-channel measurement setup as shown in Fig. 3-1 is necessary.

3.1 Measurement Setup

Fig. 3-1 shows the test setup for the automotive radar multi-channel analysis. The test setup is similar to test setup 2.1 but incudes an additional receiver RX 2. RX 2 includes the same components as RX 1. For beamforming measurement, a phase coherent measurement setup must be used. In order to achieve this, both receivers are operated by one LO signal source. All inputs of an oscilloscope are phase coherent by design.

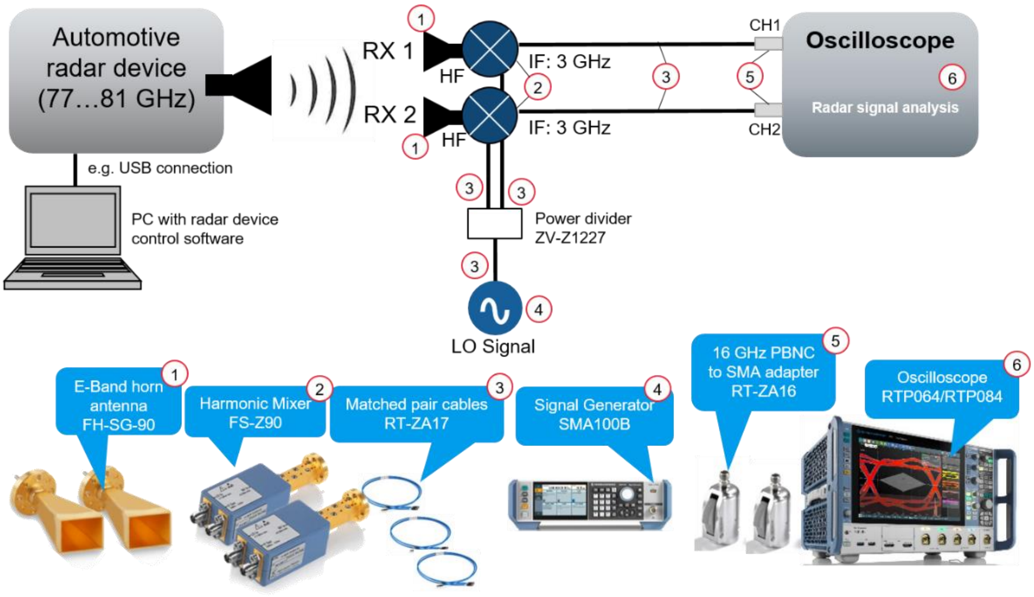


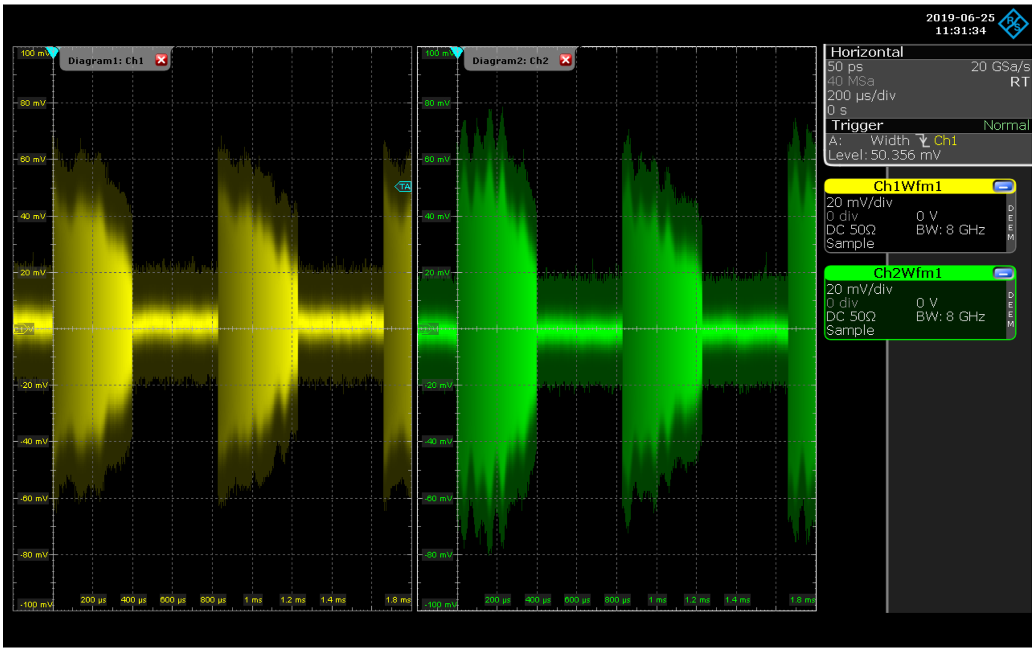
Fig. 3-1: Test setup for measuring the phase difference between two receivers

3.2 Multichannel Measurements

3.2.1 Basic Setup

- Perform the Basic settings similar like it is described in section 2.2. In addition, activate a second channel CH2 for RX 2 with the same settings like CH1.

- Perform the Deembedding as described section 2.2.1 for CH1 and CH2. Make sure to use the appropriate *.sp2 file for the two Harmonic Mixers.
- Arrange Diagram1 for Channel 1 and Diagram2 for Channel 2 as shown below:



- Perform a FFT spectrum measurement for RX 1 and RX 2 similar to section 2.2.5 . Select at least one pulse (here two pulses are used) for the FFT calculation.
- The result of a ~4GHz bandwidth signal is shown in Fig. 3-2.

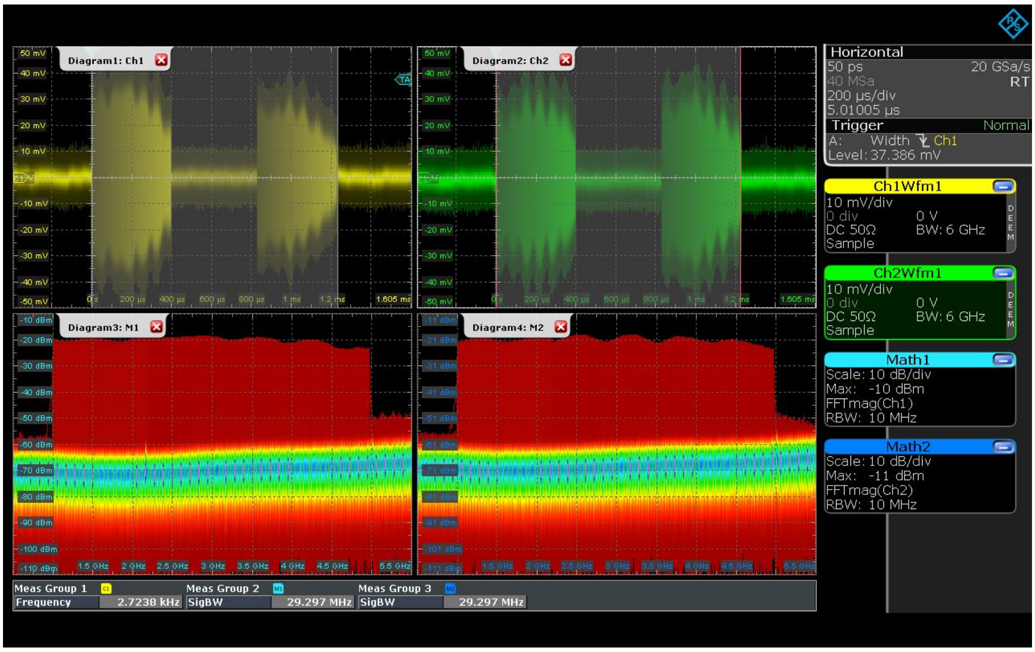


Fig. 3-2: Frequency domain measurement for RX 1 and RX 2 (Diagram3 and 4)

3.2.2 Amplitude Difference

Follow these steps to determine the amplitude difference between RX 1 and RX 2:

- In order to measure the spectrum envelope (Fig. 3-5) of the radar signal activate the *Math signal* and select the *Setup* tab. Choose *Max Hold* under *Arithmetic Mode* for the FFT signals, i.e. Math1 (CH1) (Fig. 3-3) and Math2 (CH2) (Fig. 3-4):

Fig. 3-3: Setup Math Signal M1

Fig. 3-4: Setup Math Signal M2

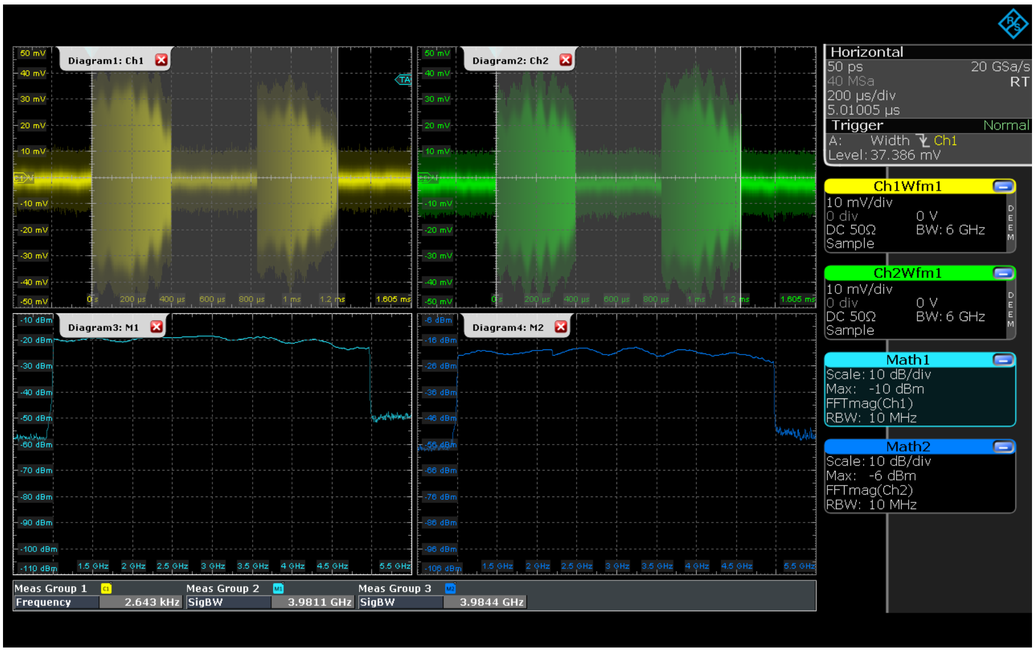
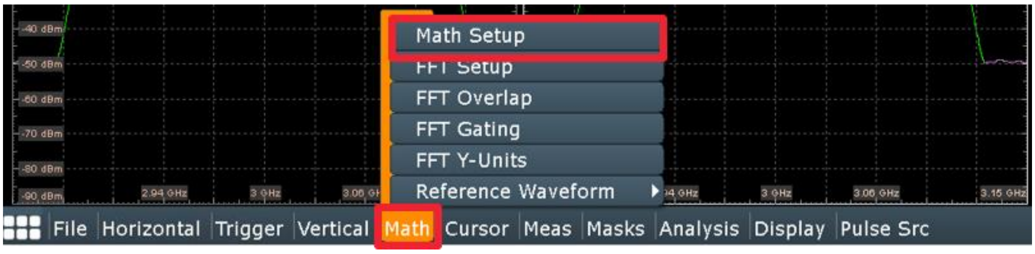


Fig. 3-5: Frequency spectrum envelope for RX 1 (Diagram3) and RX 2 (Diagram4)

- In order to measure the magnitude difference of RX 1 and RX 2 select *Math Setup* in the *Math* menu select the Math Signal *M3* under the tab *Setup*:



- Create the formula[3] (amplitude difference RX 1 – RX 2) with the *Formula Editor* under the *Advanced* tab as shown in Fig. 3-6 .
- Enable the *Math Signal*.

[3] Spectrum values are stored internally in linear format. Therefore, first the ratio of the two spectra needs to be calculated and then expressed in logarithmic values.

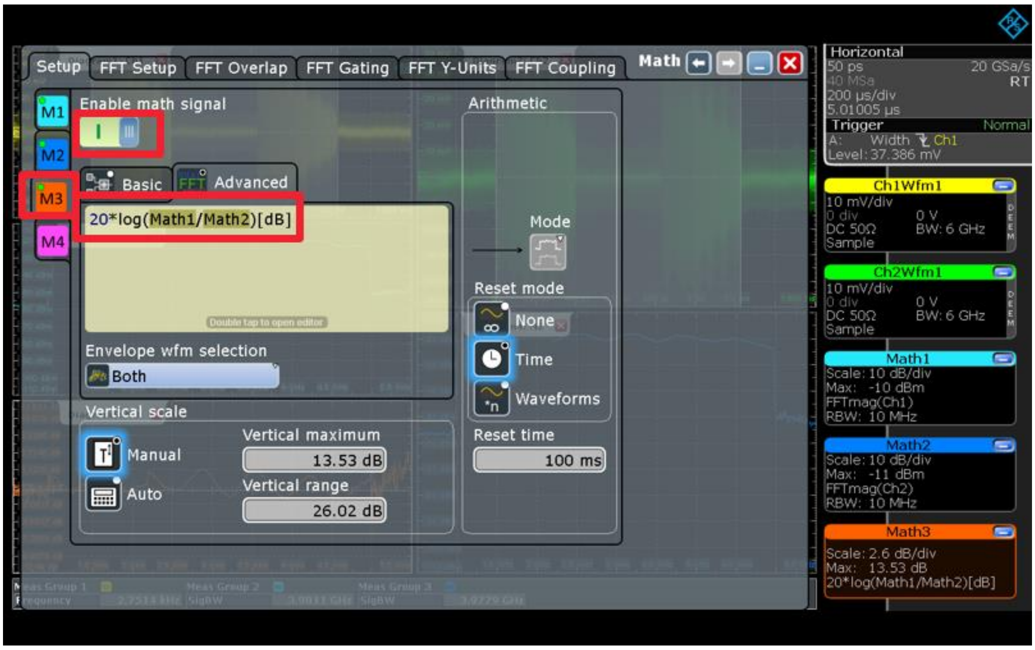


Fig. 3-6: Formula for the amplitude difference of RX 1 and RX 2

The magnitude difference of RX 1 and RX 2 of the Math Signal M3 (Diagram5) is shown in Fig 3-7. As can be seen, the ripples from the second receiver (Math2) are clearly visible in the amplitude difference.

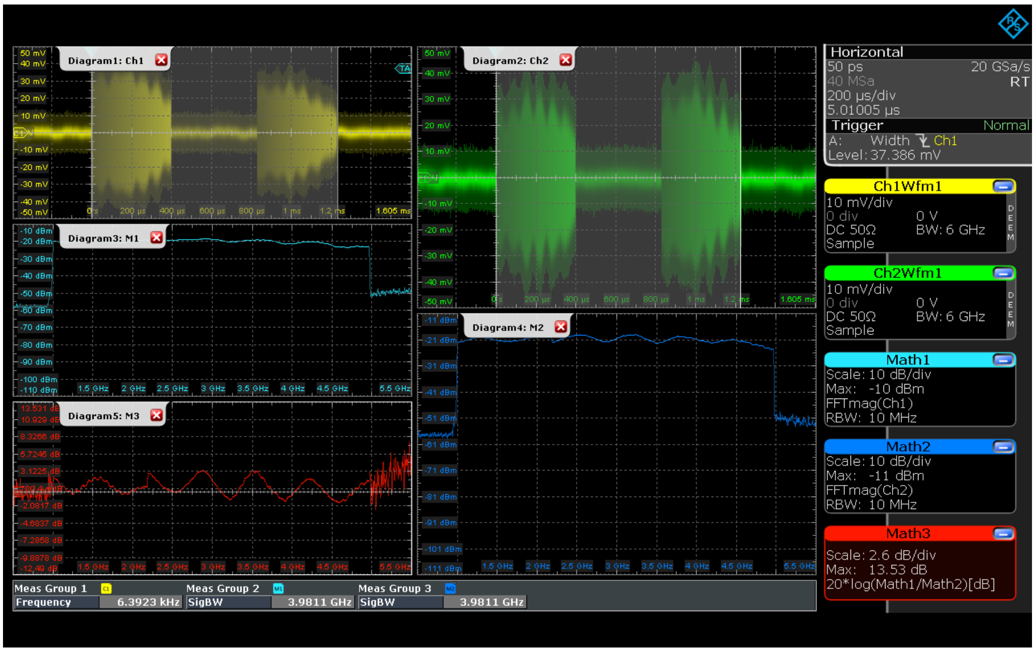
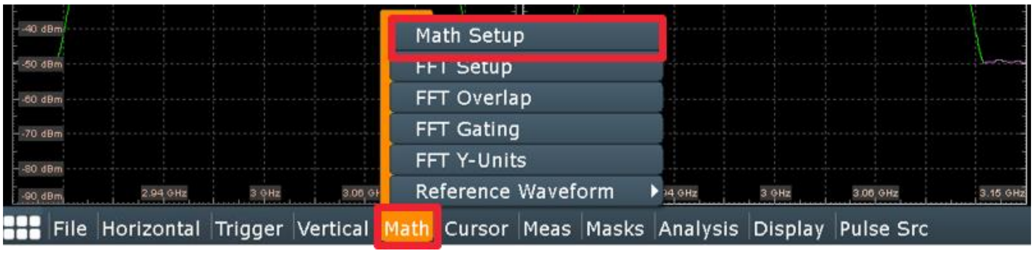


Fig 3-7: The Math signal in diagram 5 shows the magnitude difference of RX 1 and RX 2

3.2.3 Phase Difference

Follow these steps to determine the phase difference between RX 1 and RX 2:

- In order to measure the phase difference of RX 1 and RX 2 select *Math Setup* in the *Math* menu:



- Select *M4* under the tab *Setup*.
- Create the formula (phase difference of FFT Channel 1 and FFT Channel 2) with the *Formula Editor* under the *Advanced* tab as shown in Fig. 3-8.
- Enable the *Math Signal*.

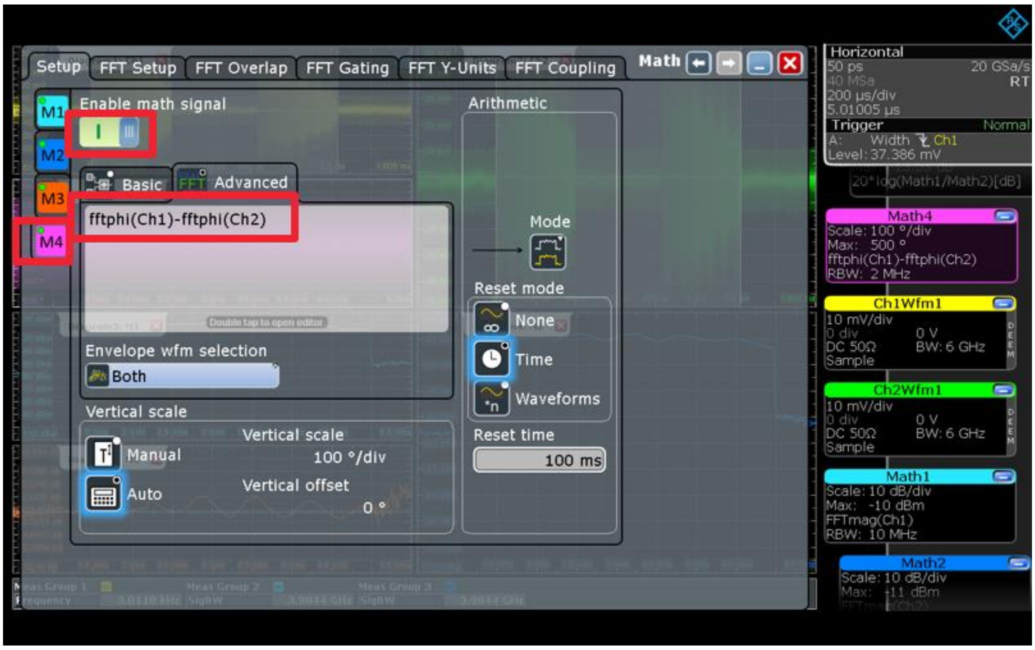


Fig. 3-8: Formula for the phase difference of RX 1 and RX 2

- Select the *FFT Overlap* Tab
- Under *Max FFTs/ Acquisition* set the amount of frames = 1.

The phase measurement must not start in a noise region. In order to avoid this, the FFT gating will be used. A further advantage is that, since only 1 segment is used, the FFT corresponds to a certain (now well-defined) point in time.

- Select the *FFT Gating* Tab
- Adjust the *Start* time in the way that no noise is included at the beginning of FFT gate.

Fig. 3-9: Settings for the FFT Gating

- Select the FFT Y-Units tab.
- In order to ensure that only valid signals are used check the *Suppression* checkbox. Enter a meaningful value into for the threshold. The information can be inferred from the previous FFT measurement, e.g. Math1 and Math2.
- Because a wrapped phase can cause signal jumps, check the *Unwrap* checkbox.
- Enter useful values for *Vertical maximum and Vertical range*.

The phase difference of RX 1 and RX 2 is now displayed in an additional diagram of (see Diagram 6 of Fig. 3-10).

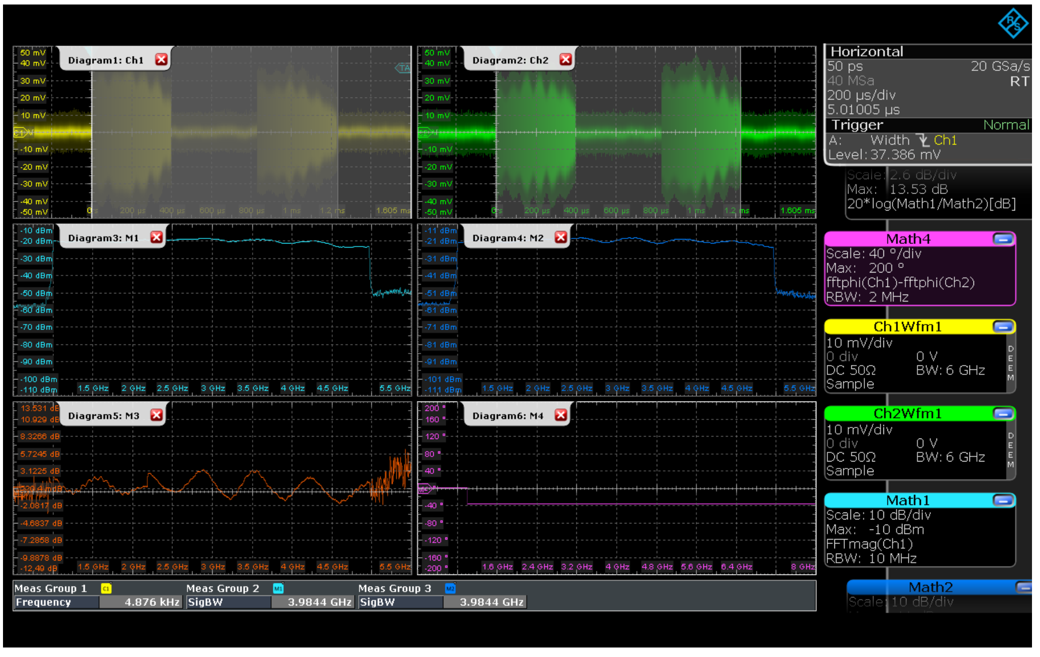


Fig. 3-10: Result of the multichannel measurement

If you zoom in the radar chirp pulse of RX 1 and RX 2, the phase difference between RX 1 and RX 2 can be investigated more in detail. In this example, the phase difference is 180° (Fig. 3-11).

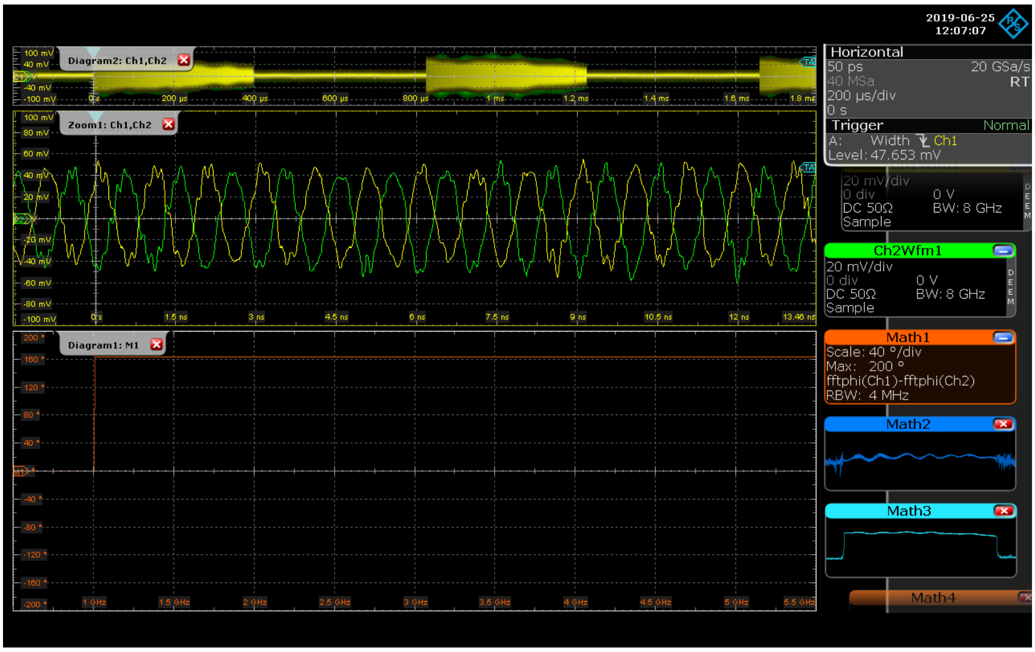


Fig. 3-11: Detailed analysis of the phase difference RX 1 vs. RX 2

The original signal increases frequency with time. As the two receivers are geometrically apart from each other the measured phase difference will change with time as well. In order to investigate the phase difference at another point in time, the start value of the gate (see Fig. 3-9) needs to be adapted.

3.2.4 Labeling Diagrams

If desired, each diagram in Fig. 3-10 can be labeled with a name:

- Select *Labels* under the menu *Display:*

- Choose the right diagram with *Source* (Fig. 3-12).
- Create a new label with the *Add* button and enter the name of the label in the new visable text field.
- Activate the Label with *Show labels*.

- Position the text by entering the right values for the *Relative X position* and *Relative Y position*, or drag and drop the text field.

Fig. 3-12: Creating a label for a certain diagram

Fig. 3-13 shows the result with activated diagram lables.

Fig. 3-13: Results with labels for a certain diagrams

4 Summary

To ensure proper functionality of radar system, one requires both effective signal processing and very good RF performance. In FMCW radar signals, as they are applied for automotive radar sensors, signal linearity is one of the most important parameter to be verified.

This application note explained the basics of FMCW radar systems and indicated the impact of non-linear effects in the transmit signal. It described single-channel and multi-channel measurements step by step performed on a 77 GHz radar with a chirp sequence signal with 4 GHz bandwidth, using an RTP Oscilloscope and Transient Measurement Application (VSE-K60/K60c).

5 Literaturverzeichnis

[1] **2017.** Analyzing RF Radar Pulses with an Oscilloscope. *Application Card.* s.l. : Rohde & Schwarz, 2017. PD 5215.4781.92.

[2] **Heuel, Dr. Steffen. 2014.** Automated Measurements of 77 GHz FMCW Radar Signals. *Application Note.* s.l. : Rohde & Schwarz, 2014. 1EF88.

[3] **Heuel, Dr. Steffen. 20018.** Automotive Radar Technology, Market and Test Requirements. *White Paper.* s.l. : Rohde & Schwarz, 20018. PD 5216.2930.52.

[4] **Heuel, Dr. Steffen. 2015.** Radar Waveforms for A&D and Automotive Radar. *White Paper.* s.l. : Rohde & Schwarz, 2015. 1MA239.

[5] **2019.** Trigger on Radar RF Pulses with an Oscilloscope. *Application Card.* s.l. : Rohde & Schwarz, 2019. PD 3609.2000.92.

6 Ordering Information

Digital oscilloscope and accessories		
Designation	Type	Order No.
High-performance oscilloscope, 6 GHz, 50 Msample memory or higher 1)	R&S®RTP064	1320.5007.06
High-performance oscilloscope, 8 GHz, 50 Msample memory 1)	R&S®RTP084	1320.5007.08
Memory upgrade, 1 Gsample per channel	R&S®RTP-B110	1337.9530.02
Deembedding base option	R&S®RTP-K121	1326.3064.02
Realtime deembedding extention option RTP-K121	R&S®RTP-K122	1326.3070.02
Spectrogram	R&S®RTP-K37	1338.1110.02
Matched pair SMA Cable	R&S®RT-ZA17	1337.8991.02
16 GHz PBNC to SMA adapter	R&S®RT-ZA16	1320.7074.02

Vector signal analysis		
Designation	Type	Order No.
Vector signal explorer software, basic edition1)	R&S®VSE	1320.7500.02
License dongle	R&S®FSPC	1310.0002.03
Transient measurements	R&S®VSE-K60	1320.7868.06
Transient chirp measurements (requires VSE-K60)	R&S®VSE-K60c	1320.7874.06
User defined frequency response correction by SnP file	R&S®VSE-K544	1309.9580.06

Signal generators		
Designation	Type	Order No.
Signal generator base unit[1)]	R&S®SMA100B	1419.8888.02
RF frequency range 8 kHz to 20 GHz	R&S®SMA-B120	1420.8788.02
High output power for 12.75 GHz / 20 GHz (+20 dBm @ 20 GHz)	R&S®SMA-K33	1420.7300.02

1) Further equipment options can be found at www.rohde-schwarz.com or contact your local Rohde & Schwarz representative.

Harmonic Mixer / Antennas /Power Devider		
Designation	Type	Order No.
Harmonic Mixer 60 GHz to 90 GHz	R&S®FS-90	3638.2270.02
Standard Gain Horn Antenna 20 dB gain, 60 GHz - 90 GHz (E-band)	R&S®FH-SG-90	3629.2464.02
2-Way Power Divider, 4GHz to 27 GHz	R&S®ZV-Z1227	1307.0886.02

Rohde & Schwarz

The Rohde & Schwarz electronics group offers innovative solutions in the following business fields: test and measurement, broadcast and media, secure communications, cybersecurity, monitoring and network testing. Founded more than 80 years ago, this independent company has an extensive sales and service network with locations in more than 70 countries.

The electronics group ranks among the world market leaders in its established business fields. The company is headquartered in Munich, Germany. It also has regional headquarters in Singapore and Columbia, Maryland, USA, to manage its operations in these regions.

Regional contact

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

North America
1 888 TEST RSA (1 888 837 87 72)
customer.support@rsa.rohde-schwarz.com

Latin America
+1 410 910 79 88
customersupport.la@rohde-schwarz.com

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

China
+86 800 810 82 28 |+86 400 650 58 96
customersupport.china@rohde-schwarz.com

Sustainable product design

- Environmental compatibility and eco-footprint
- Energy efficiency and low emissions
- Longevity and optimized total cost of ownership

Certified Quality Management ISO 9001

Certified Environmental Management ISO 14001

Rohde & Schwarz GmbH & Co. KG
Mühldorfstrasse 15 | D - 81671 München, Germany
Phone + 49 89 4129 - 0 | Fax + 49 89 4129 – 13777

www.rohde-schwarz.com