Automotive Radar Sensors - RF Signal Analysis and Inference Tests

Application Note

Products:

- R&S®FSW
- R&S®SMW200A
- R&S®SMZ
- R&S®RTO
- R&S®FS-Z90
- R&S®HMP4040

Road safety is a global challenge at present and will be in the future. Automotive radar has become a keyword in this area and pushes again a step forward to increase driving comfort, crash prevention and even automated driving.

Driver assistance systems which are supported by radar are already common. Most assistant systems are increasing the drivers comfort by collision warning systems, blind-spot monitoring, adaptive cruise control, lane-change assistance, rear cross-traffic alerts and back-up parking assistance [1].

Today's 24 GHz, 77 GHz and 79 GHz radar sensors clearly need the capability to distinguish between different objects and offer high range resolution. That is possible with increased signal bandwidth. Furthermore, those radar systems need to cope with interference of many kinds like the one from other car's radar.

This Application Note addresses signal measurements and analysis of automotive radars that are crucial during the development and verification stages. It also shows a setup to verify the functionality of a radar in case of radio interference.

Note:

Please find the most up-to-date document on our homepage
http://www.rohde-schwarz.com/appnote/1MA267.

Application Note
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Table of Contents

1 Introduction 4

2 Theoretical Background 5

2.1 Signal Power 5

2.2 Typical radar signal waveforms 5

3 Measurement Setup for Signal Analysis 8

3.1 77 GHz / 79 GHz Radar Signal Measurements with up to 2 GHz Bandwidth 8

3.1.1 Connection Setup 9

3.1.2 Alignment 11

3.2 77 GHz Radar Chirp Measurements 14

3.2.1 Transient Analysis Setup 14

3.2.2 Chirp Measurement Results 18

3.2.3 Hop Measurement Results 20

4 Interference Test of Automotive Radar Sensors 22

4.1 Measurement Setups 22

4.2 Interference Signal Generation 24

4.2.1 Additive White Gaussian Noise 24

4.2.2 Arbitrary Interference Signals 25

4.3 Measurement Results 31

4.3.1 Interference due to AWGN 33

4.3.2 Interference due to another FMCW signal 34

4.3.3 Interference due to a CW signal 35

5 Summary 37

6 Literature 38

7 Ordering Information 39

This application note uses the following abbreviations for Rohde & Schwarz products:

- The R&S®SMW200A Vector Signal Generator is referred to as SMW
- The R&S®SMZ90 Frequency multiplier is referred to as SMZ90
- The R&S®FSWxx (xx GHz) Signal and Spectrum Analyzer is referred to as FSWxx
- The R&S®RTO Digital Oscilloscope is referred to as RTO
- The R&S®FSW-B2000 2 GHz Analysis Bandwidth is referred to as FSW-B2000
- The R&S®FSW-K60 Option Transient Analysis (Chirp and Hop) is referred to as FSW-K60C/H
- The R&S®FS-Z90 Harmonic Mixers are referred to as FS-Z90
- The R&S® Programmable Four-Channel Power Supply HMP4040 is referred as HMP

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1 Introduction

In the automotive radar market, high performance and reliability together with low-cost unit prices are mandatory. The radars shall also not interfere with each other or any other device. It follows that test and measurement of these radar sensors need to be just as fast, reliable, cost-effective and straight forward as development and production.

As a matter of the underlying physical principle, signals transmitted via radio frequency (RF) systems can be distorted by other RF systems transmitting at the same time. If such radio frequency interferences (RFI) happen, the functionality of a system can suffer severely and it may react unpredictably. The likelihood of interference depends for example on the used frequency bands of the systems (e.g. 77 GHz or 24 GHz band for automotive radar), the distance between the individual transmitters (e.g. many cars in front of each other), the waveform (chirp rate, timing, receiver bandwidth and filter stages) and the emitted power. The worst scenario of this interference would be the creation of artificial ghost targets, the malfunction of the automotive sensor or a blind automotive sensor.

This application note covers the theoretical background of automotive radar signals, the analysis of those signals and the test and measurement solutions provided by Rohde & Schwarz. Furthermore, a measurement setup is shown to also address radio interference test.

2 Theoretical 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. Every manufacturer has a slightly different approach, depending on the application and customer needs. However, the output power of automotive radar sensors is specified by the Electronic Communications Committee (ECC). On the other hand, waveforms are not specified, but there are mainly two different types of waveforms used in today's automotive radar sensors.

Blind spot detection radars (BSD) often use the so called Multi-Frequency-Shift keying radar signal, with most of them operated in the 24 GHz range. Radars operating in the 77 GHz or 79 GHz band mainly used for adaptive cruise control (ACC) typically make use of Linear Frequency Modulated Continuous Wave (FMCW) signals or Chirp Sequence (CS) signals, which are just a special form of FMCW signals.

This application note deals with both the 24 and the 77 GHz frequency band.

2.1 Signal Power

Signal power is one of the main aspects that may cause interference in automotive radar.

The ECC Decision (04) 03 entitled “The frequency band 77-81 GHz to be designated for the use of Automotive Short Range Radars” [6], which has been approved on March 19th 2004 and corrected on March 6th 2015, by the European Conference of Postal and Telecommunications Administrations (CEPT) decided,

-“that the 79 GHz frequency range (77-81 GHz) is designated for Short Range Radar (SRR) equipment on a non-interference and non-protected basis with a maximum mean power density of -3 dBm/MHz e.i.r.p. associated with a peak limit of 55 dBm e.i.r.p.” and “that the maximum mean power density outside a vehicle resulting from the operation of one SRR equipment shall not exceed -9 dBm/MHz e.i.r.p.”.

- "24 GHz SRR-equipment (within 21.65-26.65 GHz) with an e.i.r.p. mean power density of –41.3 dBm/MHz, an e.i.r.p. peak limit of 0 dBm/50 MHz;"

All standard automotive radar sensors operating in these bands have to fulfil this decision.

2.2 Typical radar signal waveforms

To our knowledge, there is no automotive radar sensor on the market making use of pulsed waveforms. All commercially available automotive radars make use of continuous waveforms.

Some of them use Frequency Modulated Continuous Wave (FMCW) signals. The radar transmits a frequency modulated signal (Chirp) with a specific frequency sweep f_{sweep} within a certain time, called coherent processing interval T_{CPI}, Figure 1 .

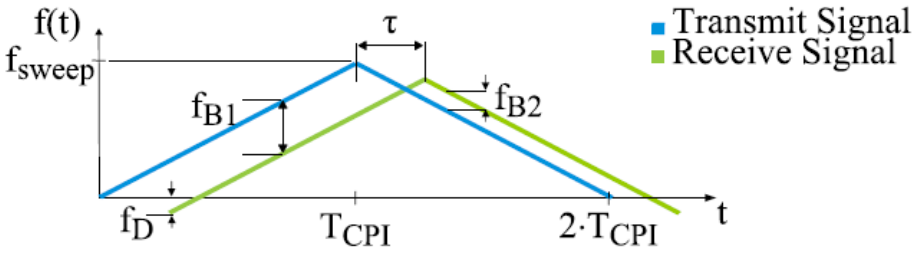


Figure 1: FMCW radar with upchirp and downchirp

Both parameters, range R and radial velocity v_r are derived from a measured beat frequency f_B.

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. For more information on this waveform, refer to the White Paper 1MA217 [5].

Typical values for automotive FMCW radar sensors are:

- T_{CPI} is typically in the domain of 20ms
- Number of Chirps for a single processing interval > 2
- f_{sweep} defines the range resolution and varies between some hundred MHz up to (probably) 4 GHz in future.

Another solution is a FMCW waveform 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_{CPI} (see Figure 2). As a single chirp is very short the beat frequency f_B is mainly influenced by signal propagation time and Doppler frequency shift f_D can be neglected in the first processing step.

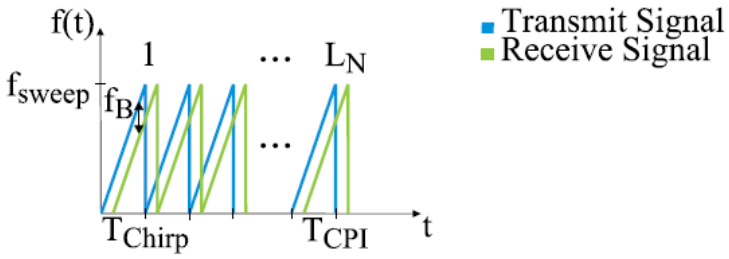


Figure 2: Chirp Sequence.

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 $v_r = 0\frac{m}{s}$ target range R is calculated as in FMCW using $f_B = \frac{2}{c}\frac{f_{sweep}}{T_{Chirp}} R$.

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

Typical durations for CS signals:

- T_{Chirp} is typically in the domain of 10µs to several hundred µs
- L_N is typically > 100 and < 1000, depending on the processing interval T_{CPI} of the sensor
- T_{CPI} is in the domain of 20ms and defined by the desired radial velocity resolution.
- f_{sweep} defines the range resolution and varies between some hundred MHz up to (probably) 4 GHz in future.

Even though the radar waveforms of the various sensors are pretty similar, there are no common parameters for automotive radar sensors, except the standardized transmission power. Each manufacturer has a slightly different waveform, with different timings, different bandwidth, etc.. As already indicated, the radio frequency interferences depend on several factors. Most critical factors are the transmitted power and a spectrum. In addition, in case the waveforms are alike or noise like there will be an impact on the down-converted signal. The timings have to match as well the receiver bandwidth and filtering need to match in order for a disturbing signal to fall into the receiver bandwidth..

This chapter explained the two main waveforms, which are used in automotive radar sensors and their signal processing. This is the basis for the following chapters, which explain measurement setups for signal analysis and radio interference test.

3 Measurement Setup for Signal Analysis

This chapter introduces measurements in order to verify the radar sensor's RF signal quality, such as for example the FM linearity, which directly influences the measurement performance of the radar sensor.

There are many different automotive radar types in the market, each using different bandwidth, radar signals and even carrier frequencies.

Rohde & Schwarz offers several methods to analyze the spectrum and signal of the FMCW automotive radar. The table below introduces different possibilities to measure and analyze automotive radar signals. The setups are described in detail in the following chapters.

For example, measuring a 77 GHz radar with a chirp bandwidth of 2 GHz could be done using a Signal and Spectrum Analyzer covering a frequency range of up to 85 GHz (FSW85) and an Oscilloscope (RTO). Alternatively one could only use the Signal and Spectrum Analyzer which operates up to 26 GHz (FSW26), a Harmonic Mixer (FS-Z90) and the Oscilloscope (RTO).

With the first setup, there would be no need for an additional Harmonic Mixer. In the case you are just looking at dedicated frequencies, a Harmonic Mixer and a Signal and Spectrum Analyzer working up to 26 GHz is sufficient. Under certain situations, a full spectrum measurement up to 85 GHz frequency range using the FSW85 may be the right choice, for example when having spurious emissions in mind. Table 3-1 summarizes the possible setups.

Signal Analysis in the 24 GHz, 77 GHz and 79 GHz range for Bandwidth up to 2 GHz			
	Radar Measurements at 24 GHz	**Radar Measurements at 77 / 79 GHz**	
Bandwidth			
<500 MHz	FSW26/50/67/85 with FSW-K60C/H	FSW26/50/67 with FSW-K60C/H	FSW85 with FSW-K60C/H
500 MHz - 2 GHz	add RTO, RTO-B4, FSW-B2000	add RTO, RTO-B4, FSW-B2000	
Harmonic Mixer	Not applicable	add FS-Z90	

Table 3-1: Possible Hardware Setups

3.1 77 GHz / 79 GHz Radar Signal Measurements with up to 2 GHz Bandwidth

This chapter describes a setup for measuring a radar under test (RUT) transmitting at 77 GHz with 2 GHz signal bandwidth using the RTO and the FSW85.

There are two methods that can be used. Either an over-the-air (OTA) setup, where there is no coaxial connection, or a wired setup, where there is a coaxial cable between the RUT and the Signal and Spectrum Analyzer.

The setup described below assumes a distant radar transceiver which transmits a signal over the air (OTA) using a W-band horn antenna. The setup uses the Signal and Spectrum Analyzer FSW85 with the Transient Analysis option (FSW-K60C/H) and the Wideband Signal Analysis option (FSW-B2000). We use here the HMP programmable power supply to drive the radar under test

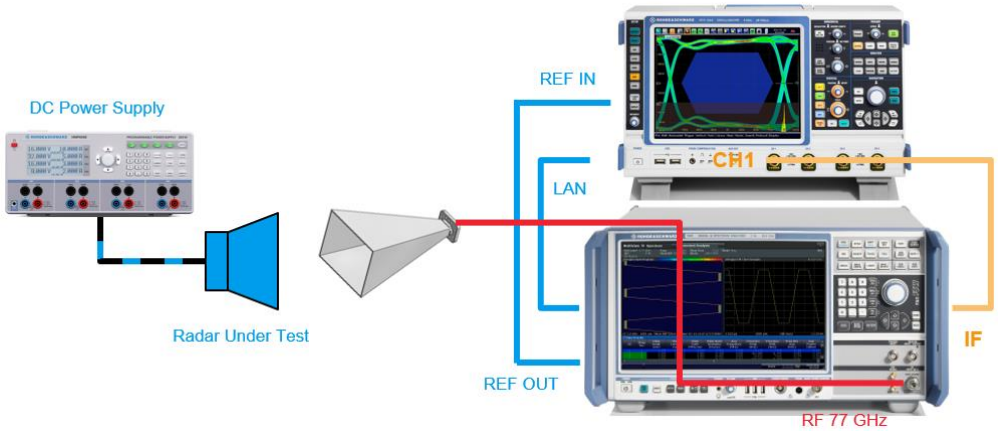


Figure 3: Measurement Setup of the 77 GHz Radar in free space (over the air)

The signal transmitted by the radar under test is received and down converted using a spectrum analyzer (FSW) with an attached horn antenna. The IF is digitized by the digital oscilloscope (RTO).

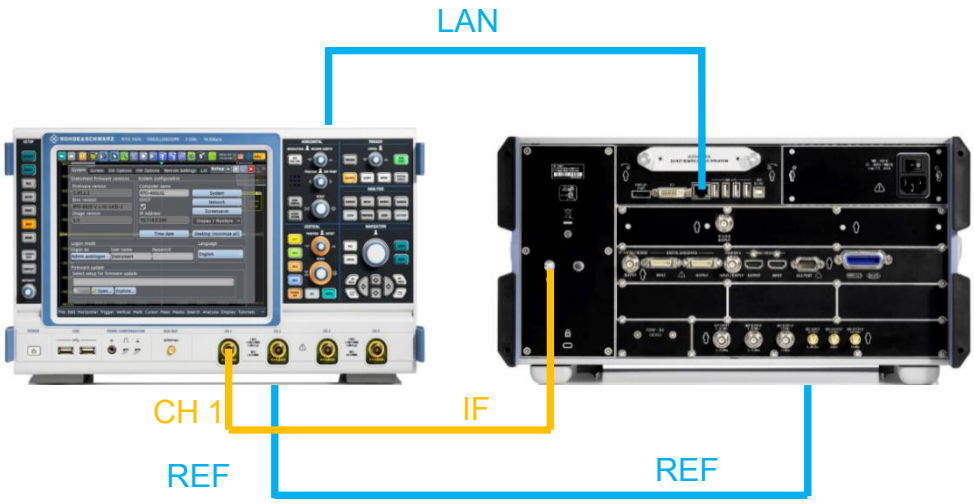


Figure 4: Measurement Setup with FSW Rear Panel (optional external Trigger in CH2)

3.1.1 Connection Setup

This section guides you through the B2000 setup and alignment.

- ► Connect both the RTO and the FSW to your local network or via direct Ethernet connection.
- ► Connect the FSW 10 MHz Reference OUT to the RTO 10 MHz Reference IN
- ► NOTE: Do not connect the FSW IF OUT to RTO before the alignment process has finished (see chapter below for the alignment procedure).

Before connecting the IF output of the FSW to the RTO Channel 1 input as depicted above, the FSW-RTO has to be configured and aligned in the software.

Therefore, note the IP address of your RTO oscilloscope by pressing “Setup”. The IP address can be found in the defined field as shown in Figure 5 below.

1. Setup: System
2. Note the RTO IP Address or Computer Name (here it is): 169.254.245.127

Figure 5: RTO Setup

Now change to the FSW Signal and Spectrum Analyzer. The wideband analysis has to be activated and setup as INPUT/OUTPUT of the FSW. It is compatible with the following options: IQ Analyzer, Pulse Measurements K6, Transient Analysis K60, and Vector Signal Analysis K70. The setup procedure outlined below applies to all options supporting B2000.

Set up the B2000 using the IQ Analyzer by pressing MODE and selecting the IQ Analyzer. Select the B2000 as an Input Source.

1. INPUT/OUTPUT: Input Source Config: B2000

Insert the IP address or name of the RTO into the TCPIP address field as depicted below. For your convenience, please select “123” in case of an IP address and “ABC” in case of a name.

2 169.254.245.127 (in this case)

Enable the B2000.

3 On

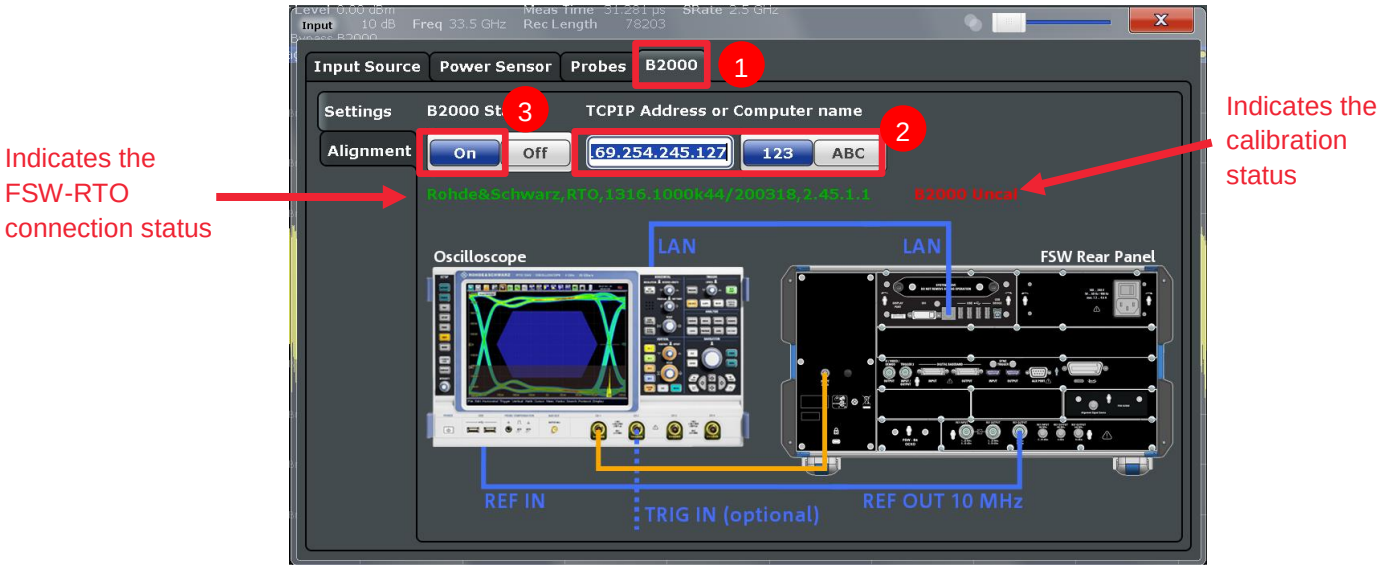


Figure 6: B2000 Input

As shown in Figure 6 the connection status and the calibration status are indicated in the B2000 settings tab. If the connection status is green it indicates a successful connection to the RTO. The calibration status is actually drawn in red and shows an uncalibrated RTO-FSW setup.

It is therefore necessary to start the alignment and calibrate the RTO-FSW connection.

3.1.2 Alignment

The alignment is done only once per RTO and takes only some seconds to finish. A wizard guides you through the entire process and stores calibration files automatically on the RTO hard disk. This enables different RTOs to be used with a single FSW.

Change to the “Alignment” tab.

1 Connect the RTO Channel 1 to the REF OUT 640 MHz connector at the rear side of the FSW as depicted in Fig.8.

2 Press “Alignment”

Figure 7: Alignment Process (1)

3 The wizard guides you through a second IF cable reconnection where you connect the RTO Channel 1 to the B2000 Alignment Signal Source.

4 Press “Continue Alignment”

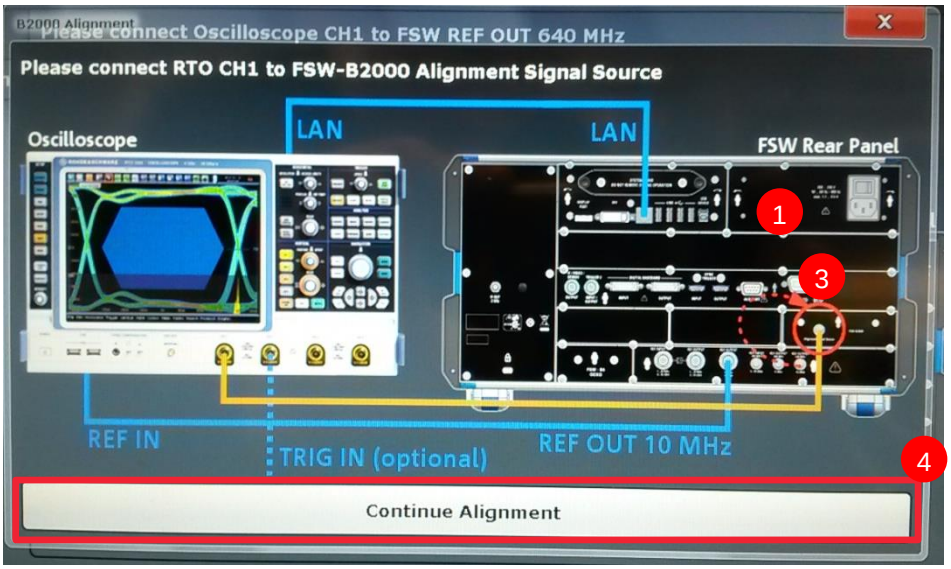


Figure 8: Alignment Process (2)

5 If the alignment succeeded and you can reconnect the RTO Channel 1 back to the IF Output.

6 Press Continue to finish the wizard.

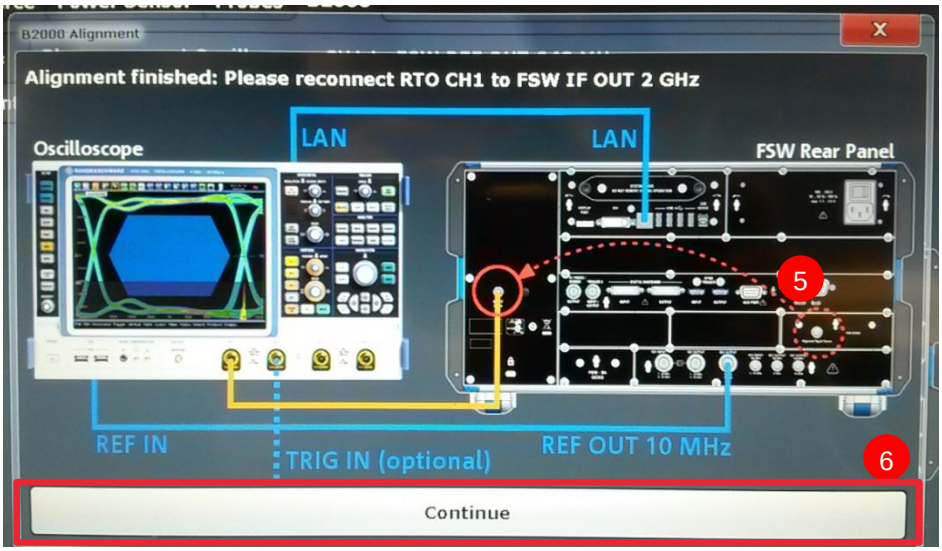
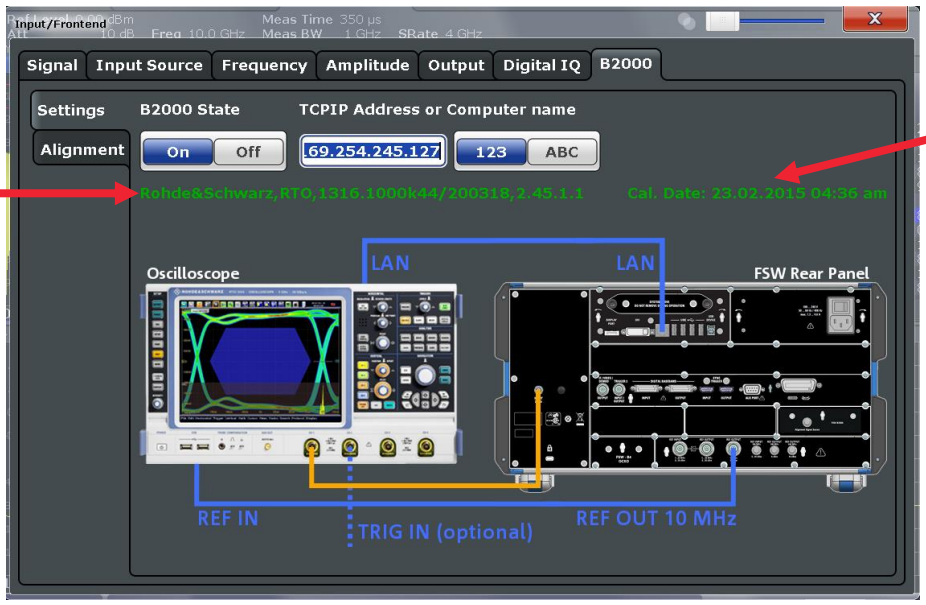


Figure 9: Alignment Process (3)

The B2000 status shows up in green color in the settings tab and calibration information and date is displayed.



Indicates the FSW-RTO connection status

Indicates the calibration status

Figure 10: Alignment completed

3.2 77 GHz Radar Chirp Measurements

This chapter describes the software setup and results. For analysis and verification of continuous wave radar signals, the Transient Analysis FSW-K60C/H has been developed. For a detailed description of this option, refer to application note 1EF88 [2].

This option makes it possible to characterize chirp or hopping 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.

For this purpose a commercially available automotive radar sensor is used and referred as the radar under test (RUT).

3.2.1 Transient Analysis Setup

According specification, the signal descriptions are the following,

- Measurement cycle
  - 35 ms for Far Range Scan (FRS)
  - 16 ms for Near Range Scan (NRS)
  - Chirp Sequence

The FSW-B2000 has been activated as described above in chapter 3.1.1 . Start the spectrum application (which is by default the initially started application by the FSW). To have a look at the radar signal spectrum set the center frequency and select a trace, see Figure 11.

- Set the **[Center frequency]** to 76.5 GHz

1 Under **[TRACE]/[Trace Config]** set the "Trace 1" to **[Clear Write]** and its Detector to **[RMS]**

- Set "Trace 2" to **[Max Hold]** and **[Positive Peak]**.

Figure 11: Spectrum View Trace Configuration

After closing the traces windows you can see the spectrum of the radar under test, Figure 12. Trace 2 is drawn in black color, trace 1 is drawn in blue color. The 198 MHz wide chirp signal is clearly visible in the center. In addition, there are some other signals present after every radar signal sweep, which are visible in the black trace and approximately 375 MHz apart from the center frequency.

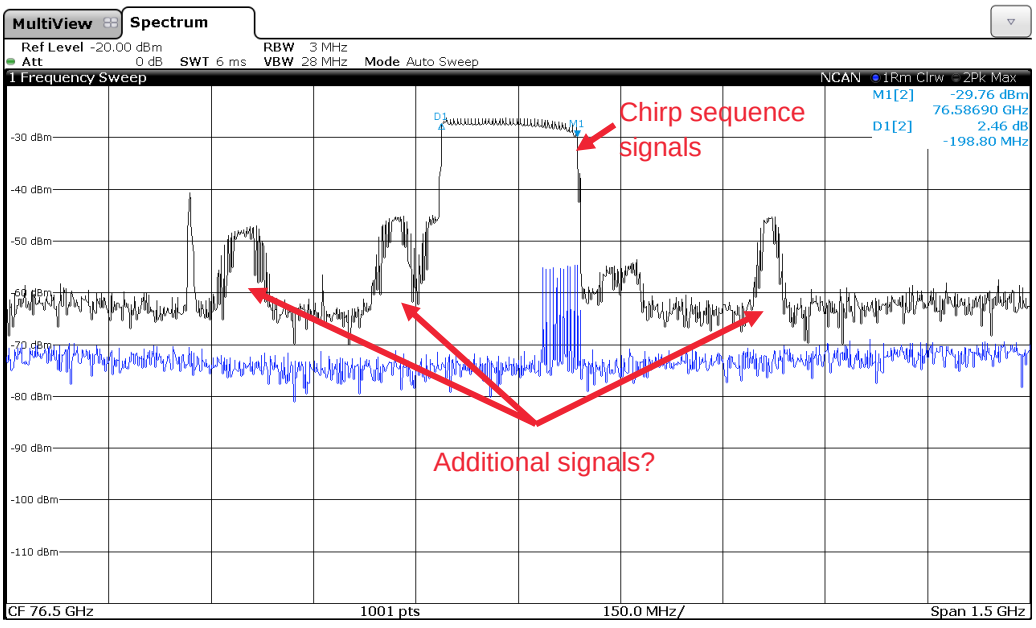


Figure 12: Spectrum View

The black trace reveals mainly two kinds of information:

1. The 198 MHz wide signal around 76.5 GHz.

2. There are several other signals measured occasionally.

In order to analyze these signals you need to go to the **[Transient Analysis]** option, Figure 13. The transient analysis is started and configured to 76.5 GHz with the FSW default bandwidth (40/80/160/320/500 MHz). The next steps define the 2 GHz bandwidth demodulation procedure

2 **[MODE]**: Transient Analysis

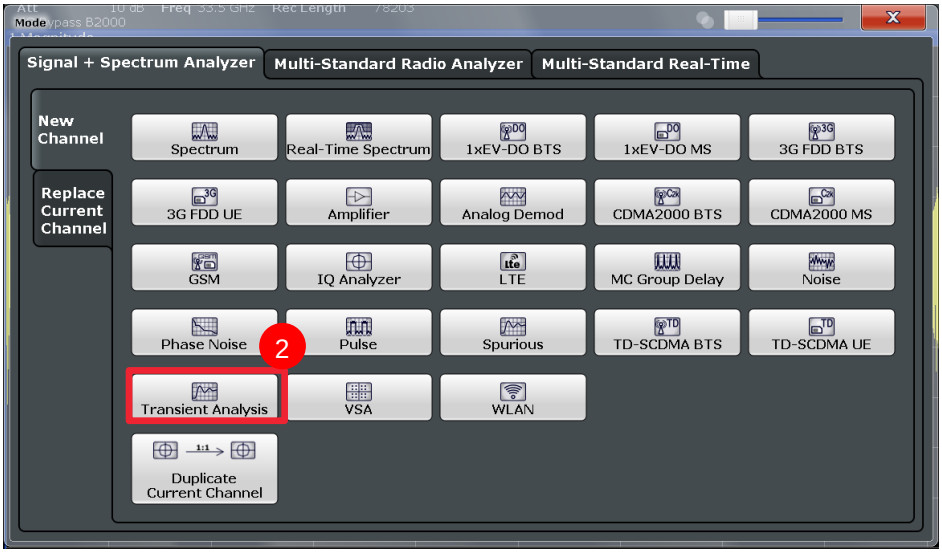


Figure 13: Transient Analysis

Select the signal model according to the radar signal. In this case, the radar transmits a chirp signal, so the signal model needs to be set to "Chirp". This is necessary to use the automatic detection build in the software

3 **[Signal Description]/Signal Model/ Chirp**

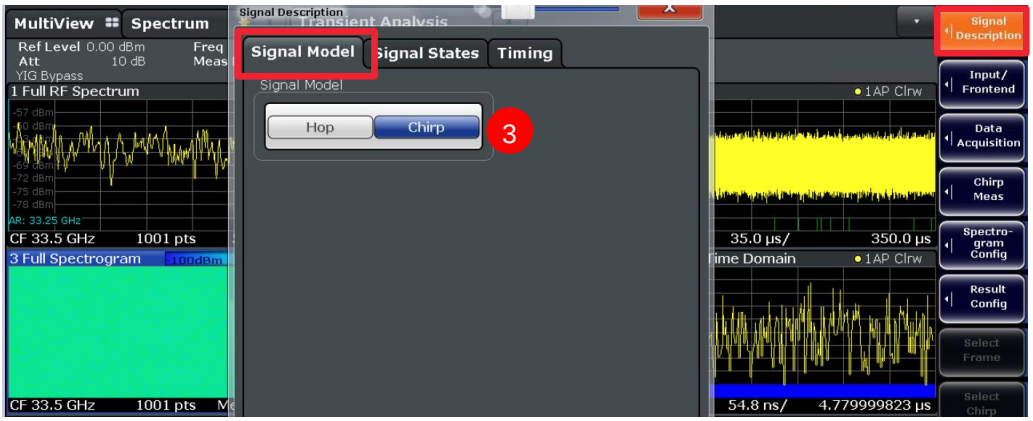


Figure 14: Signal Model Configuration

Select the bandwidth and measurement time according to the expected signal values.

4 **[INPUT]:** B2000 on (see Figure 10: Alignment completed)

5 **[BW]**: 500 MHz

The measurement duration is set to 1 ms to capture at least several consecutive chirp signals.

6 **[MEAS]**: Meas Time: 1 ms

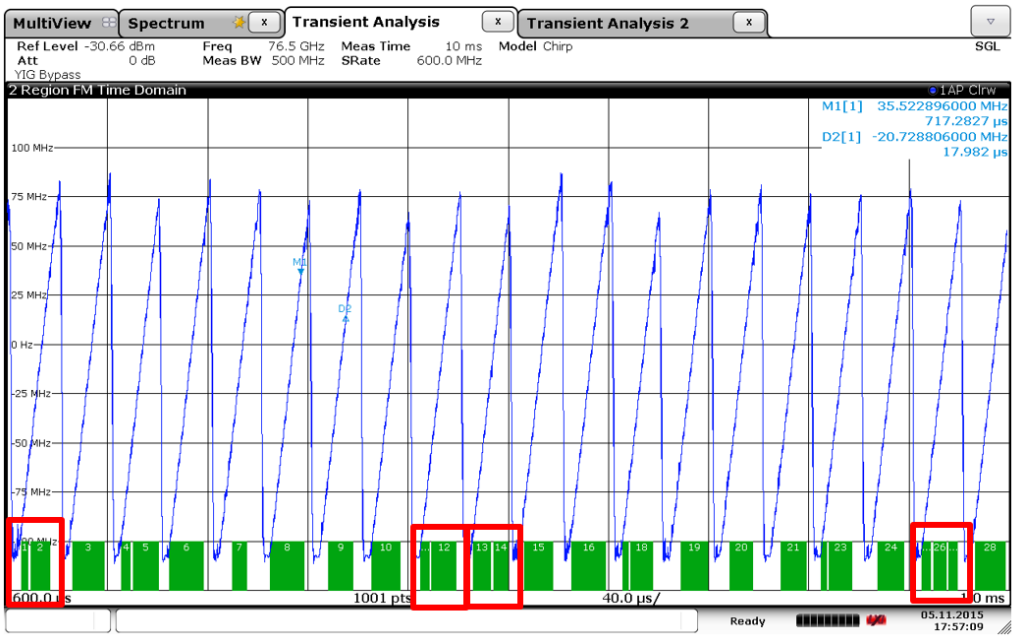


Figure 15: FM time domain measurement window

Sometimes it might be useful to select **[AUTO SET]** then the **[Auto Level]** to align the reference level and attenuation according to the signal level.

The window **[Region FM Time Domain]** shows a 1 ms long measurement. All chirp signals that have been identified as chirps are being demodulated and marked by a green bar at the bottom of the window. Some of these chirps are marked by two or even more green bars (see red squares in Figure 15). This is mostly due to noise or non-linearity in the received signal. For a less stringent "filter" you can customize the signal description **- [Signal Description]/[Timing]** window, Figure 16

Besides the signal model, which has already been set to "Chirp", one can define the "Signal States" and the "Timing". The measured signal is filtered according to the values set in this signal description.

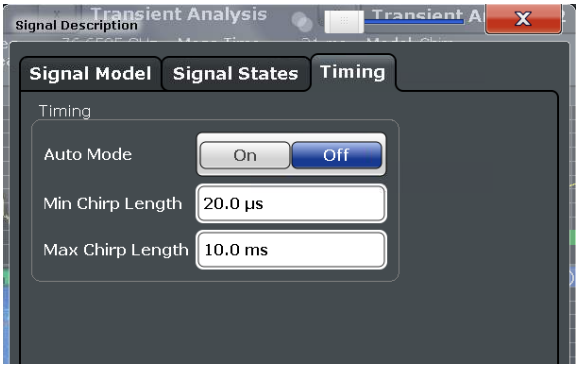


Figure 16: Signal Description window.

3.2.2 Chirp Measurement Results

There are several measurement windows shown by the FSW-K60C/H option. Each measurement window can be configured on its own, replaced by others or defined to show a specific portion of the capture.

When looking at the Transient Analysis (FSW-K60C) option as depicted in Figure 17 one can see

1. "**Full RF Spectrum**", which describes the measured power levels for the detected hops/chirps. The displayed data corresponds to one particular frame in the spectrogram;

2. "**Region FM Time Domain**", which describes the 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. "**Full Spectrogram**", as a waterfall diagram, frequency over time with color coded amplitude;

4. "**Chirp (3) Frequency Deviation Time Domain**", which shows the frequency deviation of the selected chirp (in this case chirp number (3), see the blue bar in the second window "region FM time domain") compared to a linear slope.

5. "**Chirp Results**", which derives a table from the detected and analyzed chirp signal parameters.

Please note that there are three different capture portions, which can be defined - **Full**, **Region** and **Chirp**. While **Full** shows the entire capture in time and frequency, the **Region** is a selection of this data and **Chirp** is the automatically detected signal within the region.

If there are no chirps detected in your measurement, you can reduce the FM Video BW.

1. Click on the window 2 "Region FM Time domain", under **[BW]/[FM Video BW]** Set **FM 5%**.

And/or select a trace:

1. Set **[TRACE]/[Trace1]** detector type to Average

Now the chirps should be demodulated. The linearity of the chirp is measured by subtracting if from the ideal chirp trajectory. The results are shown in the "Frequency Deviation Time Domain" window 4, Figure 17.

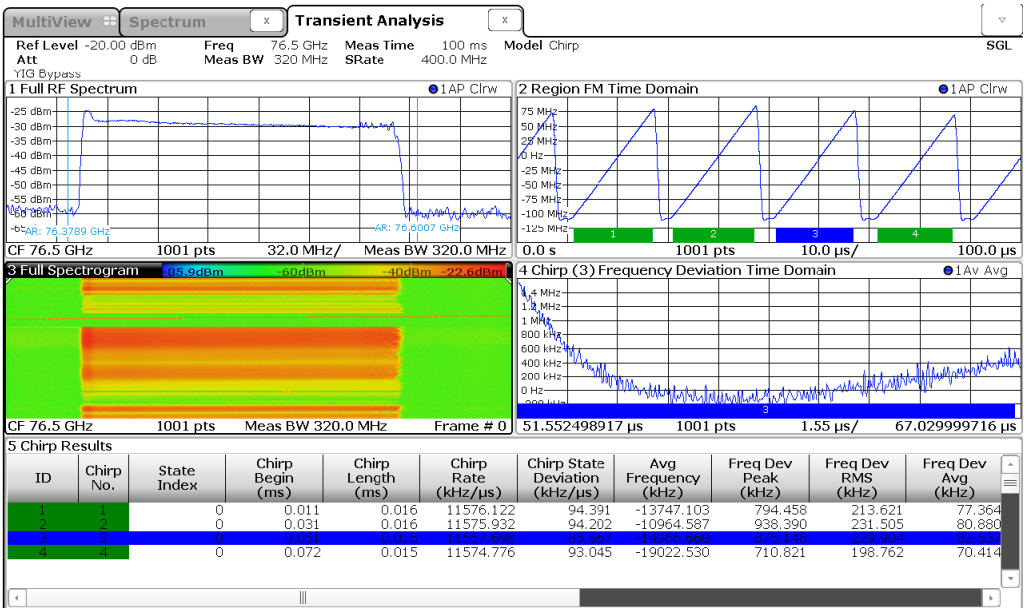


Figure 17: General Transient Analysis Window

The measurement result is depicted above. Four full chirp signals with linear increasing frequency modulation are captured and analyzed. The blue bar indicates the selected third chirp, which “frequency deviation” over time is analyzed automatically.

The chirp results table of the entire capture of 100 us is displayed at the bottom. It can be seen from the chirp rate (kHz/µs) and chirp length (ms), that this chirp has a signal bandwidth of 173.5 MHz and a duration of 15 µs.

Furthermore one can see that the "3 Full Spectrogram" window shows several different amplitudes of the received radar signals.

In addition, there are signals transmitted which use much more bandwidth (frequency hopping signal?) than the chirp sequence (marked in Figure 18). The next measurement investigates these signals in more detail.

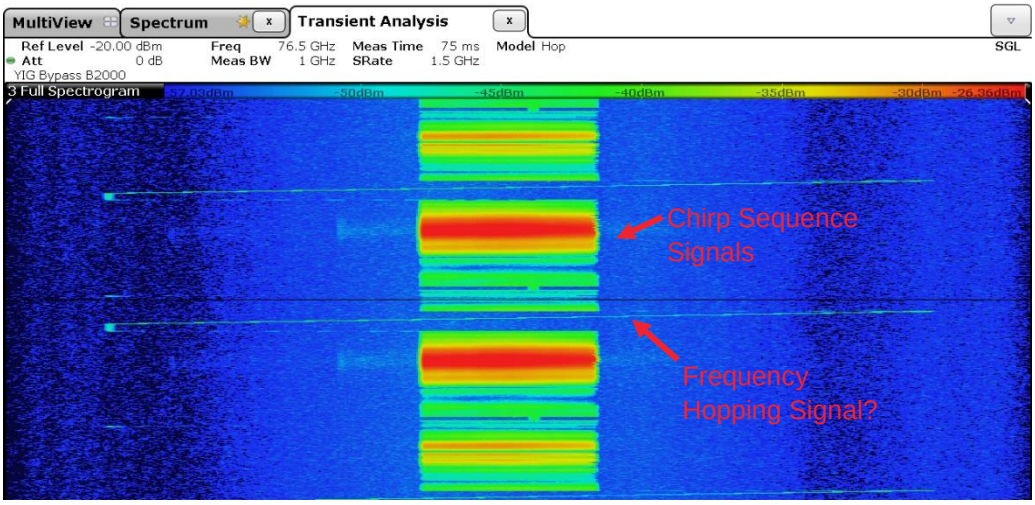


Figure 18: Full Spectrogram Window

3.2.3 Hop Measurement Results

In Figure 19 one could already see that there is, besides the chirp sequence signal, an additional signal transmitted by the radar. To analyze this signal in detail, a second "Transient Analysis" option is started on the Signal and Spectrum Analyzer, which now runs in next to the first application.

In the "Full Spectrogram", Figure 20, one can see that the radar sensor transmits a frequency stepped signal. This may be due to measurement result ambiguities which arise in the chirp sequence signal processing of this particular chirp sequence waveform.

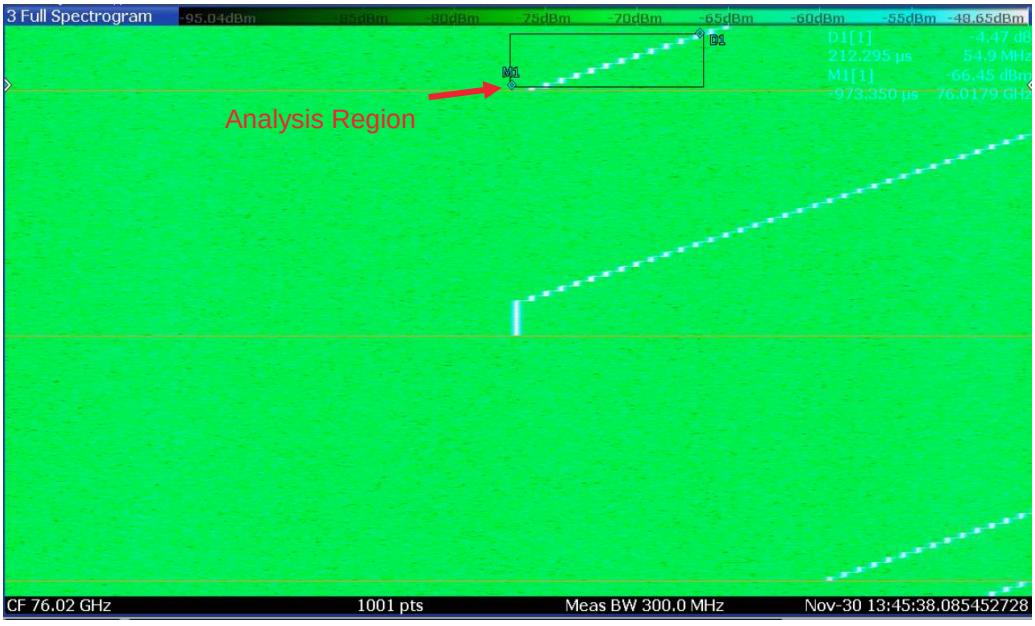


Figure 19: Transient Analysis 2, Full Spectrogram and selected Analysis Region

As already explained and shown in Figure 14, the signal model needs to be adapted to "Hop" in order to automatically detect the radar signal for further analysis.

Therefore, select the signal model "Hop" in the **[Signal Description]/Signal Model/ Hop**.

To reduce the data, set the Analysis Region **[MEAS CONFIG]/[Data Acquisition]** so that you can verify the most strong signal within 10 ms and within the bandwidth. In Figure 19 Marker M1 and Marker D1 indicate the selected analysis region as a gray box.

When switching back from the full screen window to the measurement display with all windows, the frequency steps are depicted more clearly, Figure 20.

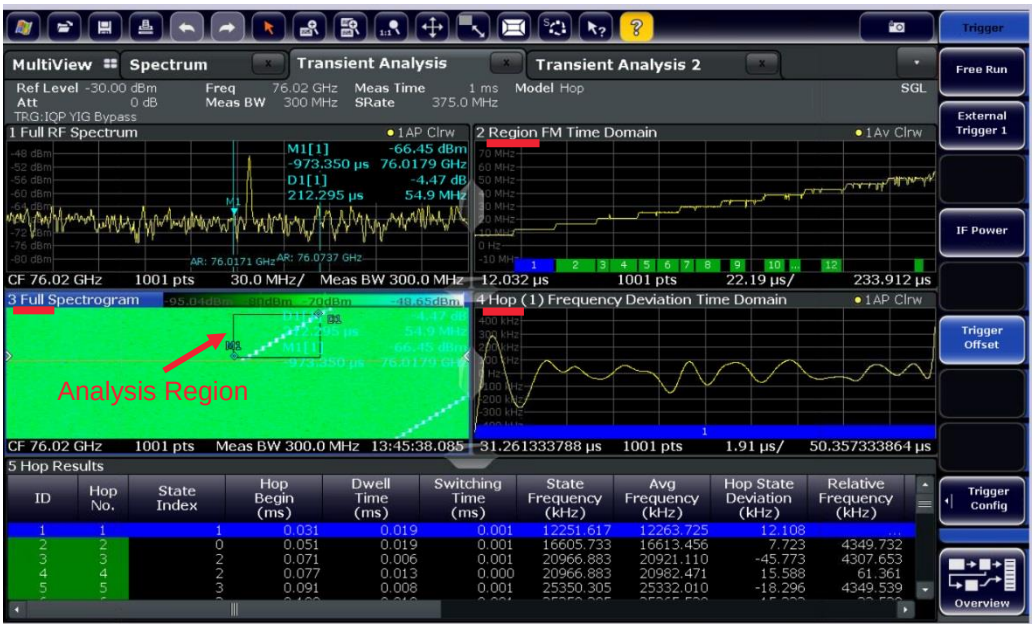


Figure 20: Hop Analysis

The green bars in the "Region FM Time Domain", the filled "Hop Results" table and also the "Hop (1) Frequency Deviation Time Domain" windows verify that several frequency hops have been detected and automatically analyzed.

In this window configuration one can now also see the difference between a "Full", a "Region" and "Hop" visualization. While there is a **regional** visualization of the FM Time Domain plotted in window 2, there is a **full** Spectrogram plot shown in window 3. A single **hop** is visualized in window 4, where the blue marker and the number 1 in this marker indicates that this is the first hop. All data analyzed and plotted is a portion of the full time domain measurement as indicated by the gray box shown in the third window.

This way, one can reduce a full capture to a certain analysis region in which an automatic detection process finds all chirps or hops. For the detected hops and chirps further analysis (e.g. statistical evaluation) is automatically done.

4 Interference Test of Automotive Radar Sensors

The possibility of several automotive radar sensors interfering each other, when operating in the same portion of the frequency band is now investigated. Possible scenario one can imagine are the creation of artificial ghost targets (malfunction of the automotive sensor) or a sensor with decreased probability of detection (due to increased noise floor).

A target caused by interference is called a ghost target in this application note. Ghost targets do not exist in reality, but appear as real targets to the radar sensor. This may be caused by a copy of the transmitted signal which is originally not from the own transmitter, but falls into the receiver bandwidth. For this scenario to happen, timing, waveform and frequency between two or more radars have to match perfectly and the echo power has to exceed a certain limit.

High power broadband CW signals, or broadband CW noise like signals with certain power that fall into the receiver bandwidth may increase the noise floor of the radar and reduce the amount of Signal-to-Noise ratio of a target. This may cause targets with small Radar Cross Section (RCS) to disappear as the Signal-to-Noise ratio of the echoes is reduced. For this scenario to happen, a continuous broadband noise like signal, or any other signal which spreads over all frequencies after the FFT signal processing and high signal power, has to be transmitted.

This chapter initially explains how to generate RF signals with the desired signal content, bandwidth and frequency. These signals are then used to stimulate an operating automotive radar sensor. As a key performance indicator, the FFT spectra of the radar sensor are compared with and without additional interference signals.

4.1 Measurement Setups

There are two different measurement setups introduced, one can be used for radars operating up to 40 GHz (i.e. 24 GHz automotive radar sensors), another can be used up to W-band frequencies (i.e. 77 and 79 GHz automotive radar sensors). For the W-Band frequencies, there are additional two different signal generation possibilities, depending on your interference signal needs.

To analyze the behavior of the automotive radar sensor in presence of interfering signals a test setup allows to generate arbitrary RF signals on the desired frequency. For the K-Band (24 GHz radar sensors) the vector signal generator SMW can be equipped with an RF frontend for frequencies up to 40 GHz without the necessity of any further mixing or multiplying, see Figure 21.

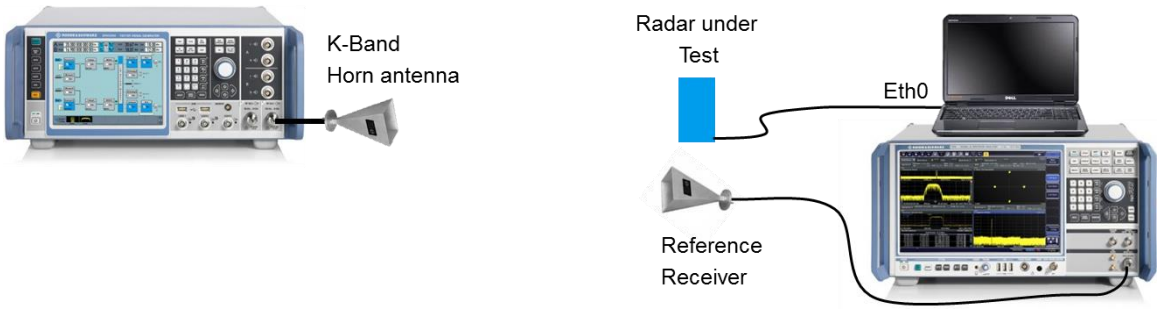


Figure 21: Setup for stimulating 24 GHz Automotive Radar Sensors

To generate signals in the W-band, i.e. signals at frequencies at 77 and 79 GHz, two different approaches are used:

Vector signal generators provide signals up to 40 GHz using a single commercial off the shelf (COTS) instrument as of today. Therefore, a laboratory setup providing a wideband chirped signal at 79 GHz is setup by a wideband baseband source, a signal generator with analog baseband inputs, an external harmonic mixer and a second generator as local oscillator for the external harmonic mixer, Figure 22.

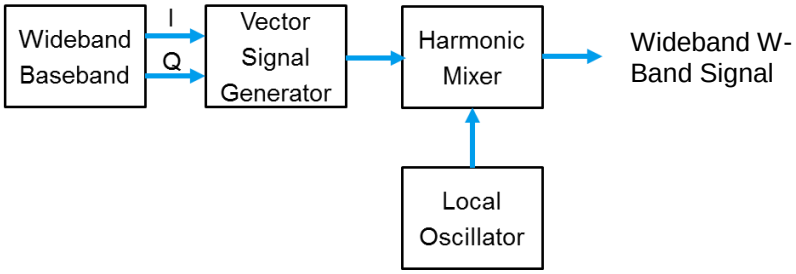


Figure 22: Setup for generating Wideband Modulated signals at 79 GHz

A second possibility is shown in Figure 23. The vector signal generator SMW with 160 MHz bandwidth and the frequency multiplier SMZ90 which multiplies the instantaneous frequency by a factor of six. A chirped signal with 160 MHz bandwidth at 13.1666 GHz is converted to 79 GHz with 960 MHz bandwidth. While the frequency is multiplied, the phase is kept. This setup can therefore be perfectly used for generating frequency or phase modulated signals (no AM).

Figure 23: Simplified setup for generating wideband modulated signals at 79 GHz, using a frequency multiplier

The final test setup for W-band signals is comparable to the 24 GHz test setup, but requires an additional frequency multiplier, Figure 24.

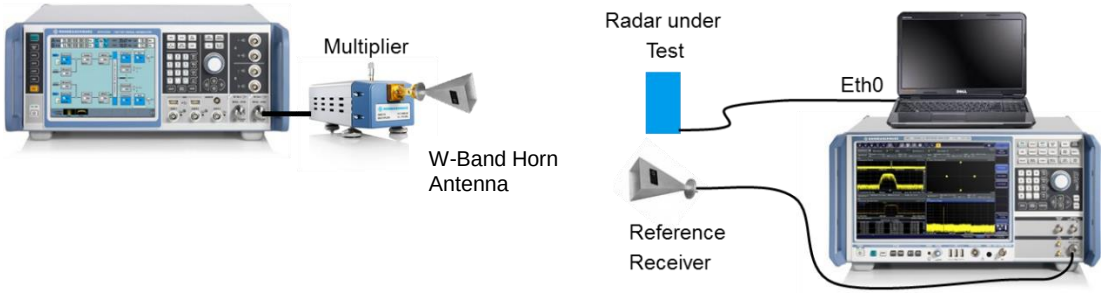


Figure 24: Setup for 77/79 GHz Automotive Radar Sensors

Depending on your interference signal definition there might be a need of the setup depicted in Figure 22 using an additional LO and mixer. For example, in case there is an amplitude modulated signal (like e.g. QAM) one needs an LO plus an additional mixer.

4.2 Interference Signal Generation

This chapter describes the signals used as interferer and their setup. The Vector Signal Generator SMW is used to generate different kinds of interference signals.

a) 160 MHz wide Additive White Gaussian Noise (AWGN) signal, which can be generated by the SMW itself (for 24 GHz radars).

b) 160 MHz wide chirp signals that are generated in the Pulse Sequencer Software SMW-K300 and then uploaded to the arbitrary waveform generator of the SMW (for 24 GHz and 77 GHz radars).

c) 960 MHz (160 MHz x 6 with frequency multiplier) wide chirp signals that are generated in the SMW-K300 software and then uploaded to the baseband of the SMW. This setup operates in combination with the SMZ frequency multiplier and covers a frequency range depending on the multiplier model from 50 GHz - 170 GHz (for 77 GHz radars).

4.2.1 Additive White Gaussian Noise

The AWGN option SMW-K62 allows the Vector Signal Generator to generate AWGN signals. To apply such a signal to the radar under test, verify your carrier frequency and level of the output signal (see Figure 25).This scenario is possible for a 24 GHz radar only with a SMW higher in frequency range namely 31.8 GHz or 40 GHz.

Then configure the AWGN block in the signal processing chain of the SMW:

1. Open the AWGN Block
2. Define **[Noise Only]**
3. Set the desired BW of the Noise (this example shows 120 MHz)
4. Set the AWGN State to **[On]**

5 Toggle/Match/Turn RF Block "On".

The blocks that are on/enabled turn blue.

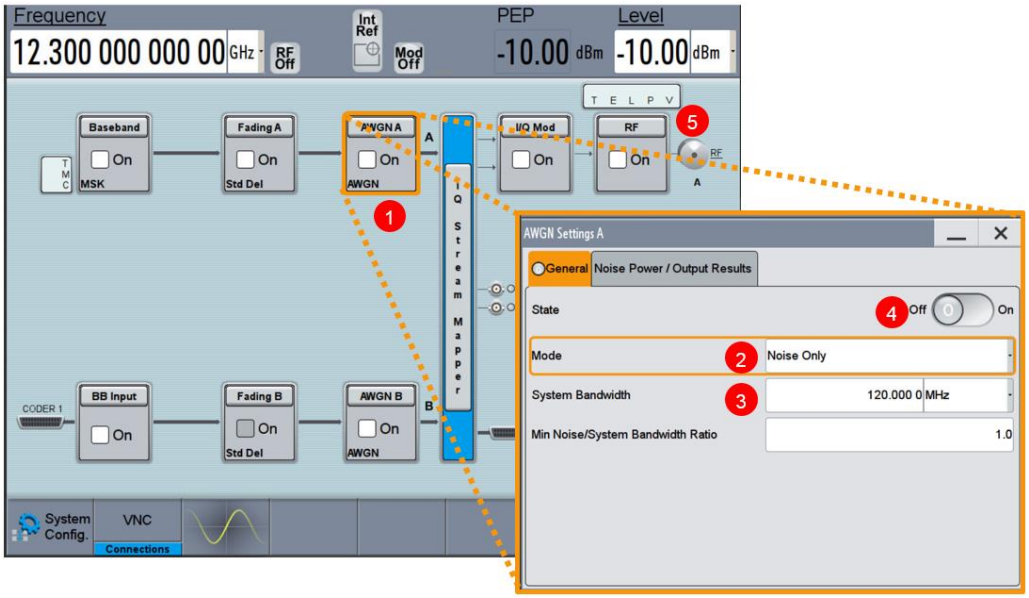


Figure 25: SMW AWGN configuration

4.2.2 Arbitrary Interference Signals

The Rohde & Schwarz Pulse Sequencer software brings the RF signal environment from the field into the laboratory, where a controlled, cost-effective and reproducible environment applies with many variable parameters. The Pulse Sequencer software is a versatile tool to generate sophisticated pulse/interference signal scenarios simulating real life conditions. It is using predefined, configurable test scenarios with different complexity. You can simulate signals of different emitter and receiver configurations, including antenna and scan types. The signal can be processed by the Rohde & Schwarz test and measurement instruments, limited only on the samples created and the memory size in the SMW.

The Pulse Sequencer Software can be downloaded free of charge from the Rohde & Schwarz website under: https://www.rohde-schwarz.com/software/smw200a/

4.2.2.1 Pulse Sequencer

Before going into detail how to setup an arbitrary waveform signal using Pulse Sequencer Software the default workspace (when starting the software) is explained.

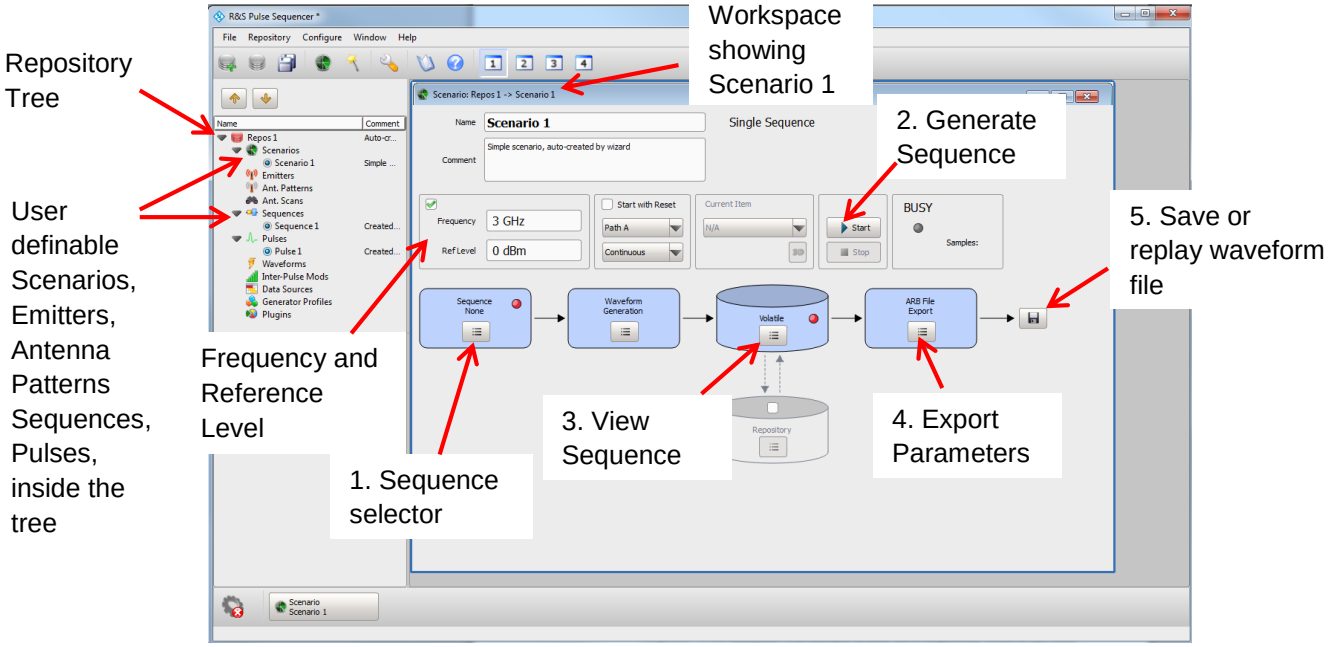


Figure 26: Screen after running the Startup Assistant

The repository tree depicted on the left side in Figure 26 holds the user definable

- Scenarios
- Emitters
- Antenna Patterns
- Antenna Scans
- Sequences
- Pulses
- Waveforms
- Inter-Pulse Mods
- Data Sources
- Generator Profiles and
- Plugins.

Each module holds user defined content. The "Scenario 1" depicted in Figure 26 for example is built out of "Sequence 1", which in turn is built out of "Pulse 1". Due to this modular approach, the user is able to generate arbitrary building blocks in order to rebuild the scenario of interest.

4.2.2.2 Waveform Generation

This paragraph shows how to generate an FMCW wide chirp waveform signal. After installation and first start, the R&S Pulse Sequencer opens a startup assistant which supports to restore a workspace, create a new repository, open a repository or start with an empty workspace.

1 Start the wizard on the menu bar.

2. Chose **[Create new Scenario]** then press **[Next]**
3. Chose Simple Pulse/Pulse Sequence or complex scenarios with emitters, modes and antennas

   Please note that you need to set the pulse width equal to the pulse repetition time (PRI). This way, you can generate a CW signal
4. Define the length of your pulse under **[Width]**
5. Chose the tab **[MOP]** (Modulation on pulse), enable the MOP.
6. Chose **[Linear Chirp]** according to your bandwidth (here: 200 MHz)

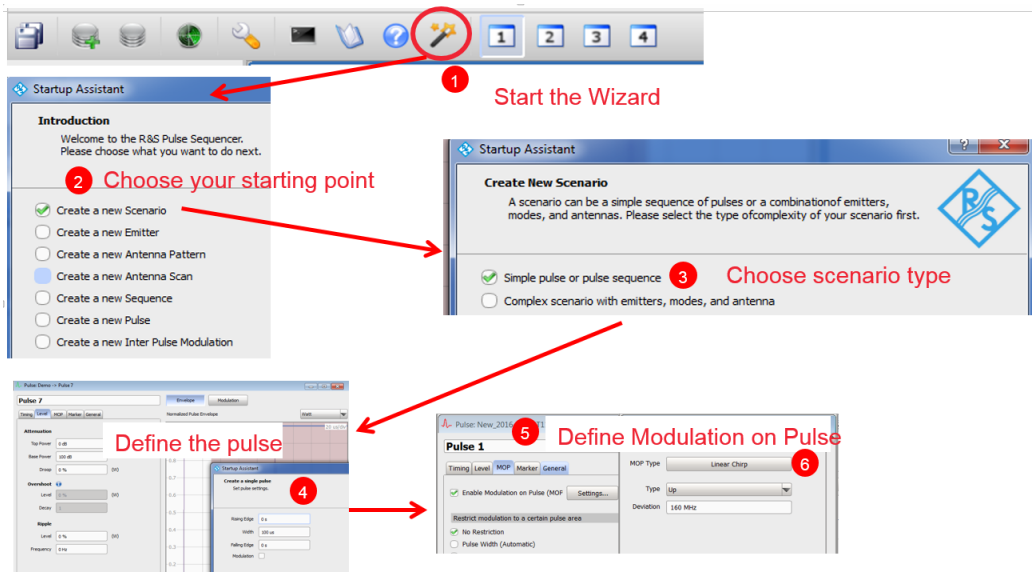


Figure 27: Pulse Sequencer Startup and Pulse Definition

7. Go to **[Sequences]** right-mouse-click and choose **[New]**
8. Press the button to add a new Pulse
9. Fill in the values as seen in the figure below, make sure the PRI value equals the pulse width as mentioned in 3.

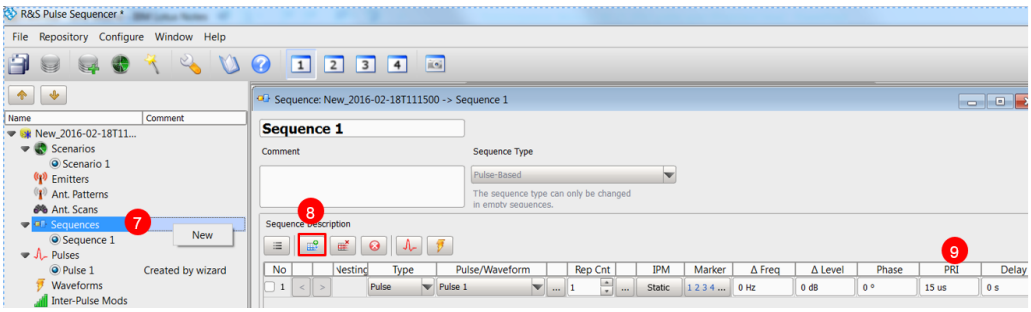


Figure 28: Pulse Sequencer, Sequence Definition

10 Go to **[Scenario]** right-mouse-click and choose **[New]**. A new window appears. Chose the **[Single Sequence]** then press **[Create]**

11 Click the **[Sequence]** block and choose from there the **[Sequence]** you named in point 7.-9. The block should indicate a green LED.

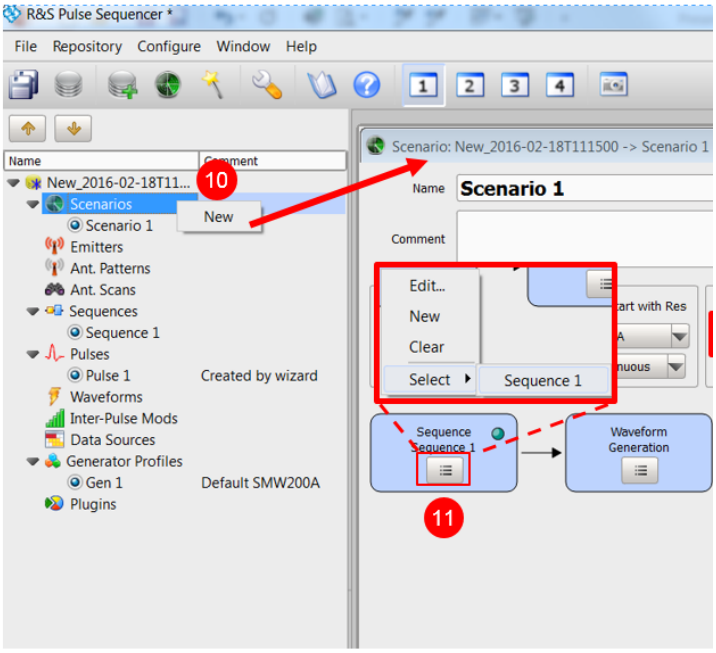


Figure 29: Select Sequence into scenario

At this point the SMW is connected via LAN to Pulse Sequencer pc and its ip-address is known (in here 10.85.0.94)

Note: A functioning VISA library must be in the controlling pc, otherwise you can download it here: http://www.rohde-schwarz.com/appnote/1DC02.

12 Click on the wizard icon on the toolbar.

13 Startup Assistant windows opens, chose there the last possibility **[create and validate a new generator profile].** Press **[Next].**

14 Startup assistant II: Chose Profile Type **[Connected],** press **[Next].**

15 Startup assistant III: type in the IP address of your SMW (in this example it is 10.85.0.97), press **[Connect]** then **[Next].** On the SMW you can find the ip-address under **[System Config]/[Remote Access]/[Network]**

16 Startup assistant IV: press **[Map]**, verify it says "Mapping successful" and it indicates a green LED. Press **[Next]**.

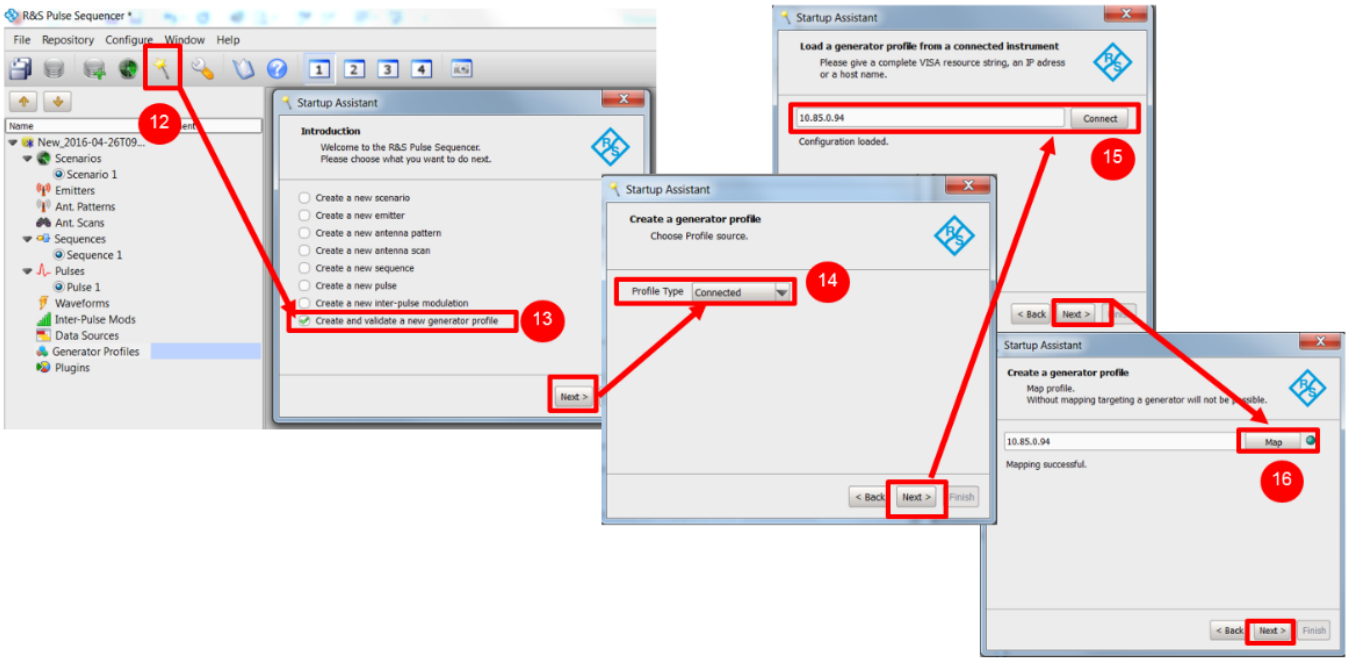


Figure 30: Startup assistant for Generator profile

17 Startup assistant V: Press **[Finish]**. One can see that there is a new Generator Profile called "Gen 1", it is "mapped" indicated by a green LED and is also in the tree pane.

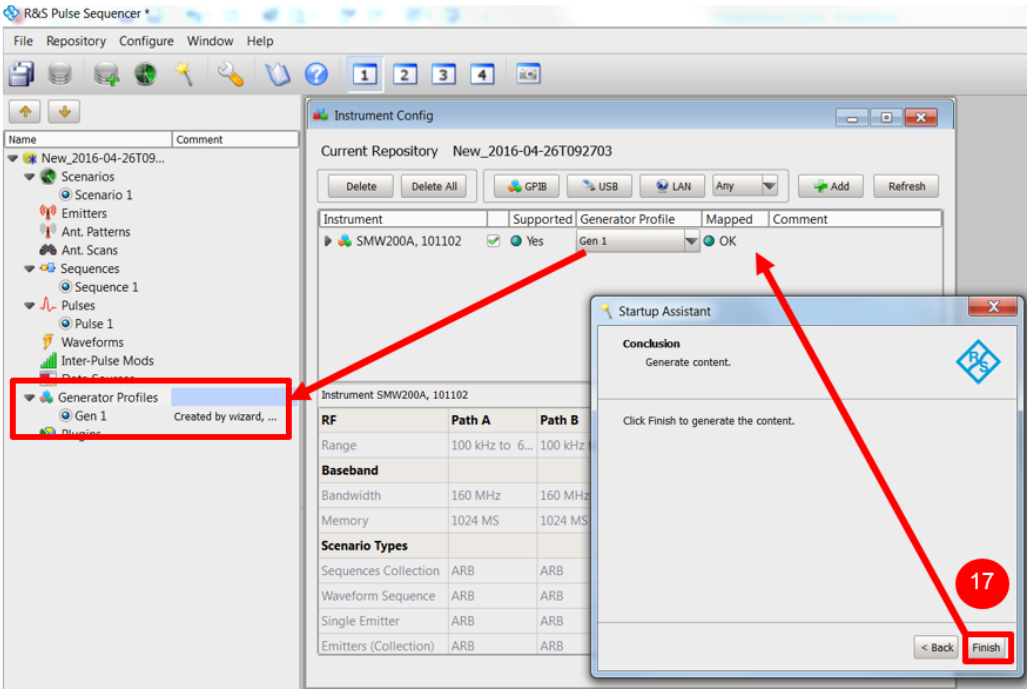


Figure 31: Finalize Generator profile

18 Click on the last block, chose **[Target]** then select [**Generator].**

19 Press again on 18 and press **[Select]** generator profile called **["Gen 1"]**

20 Set the Frequency and Level of the SMW.

21 Press **[Start]**. A waveform file (*.wv) is generated, uploaded to the SMW and replayed at the defined frequency and level at point 20.

22 By pressing the **[Volatile]** button and **[View]** you can verify your chirp as a file.

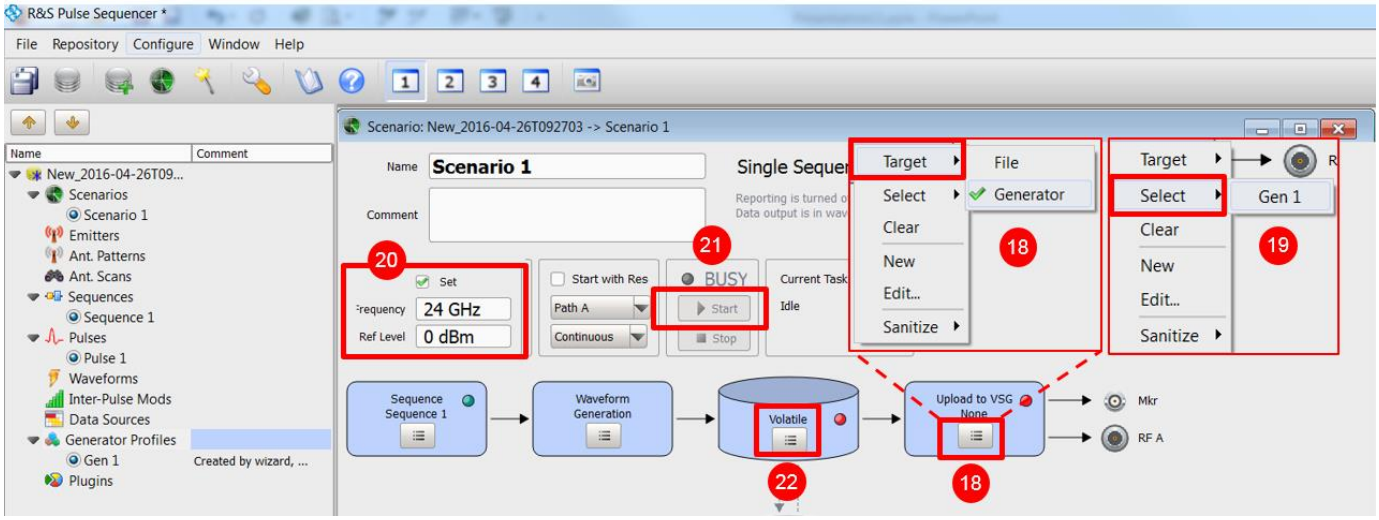


Figure 32: Pulse Sequencer, scenario definition and waveform generation

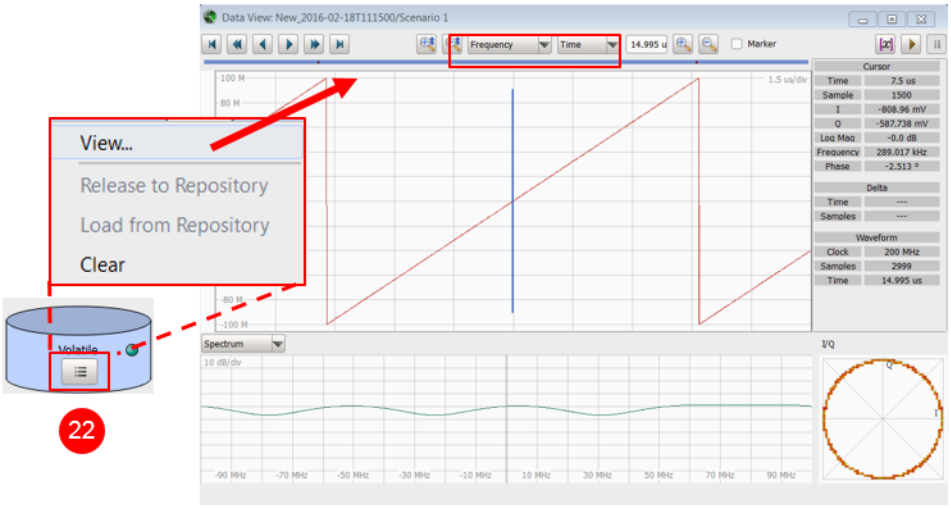


Figure 33: Pulse Sequencer, waveform verification (here PRI 9us and chirp bandwidth 200MHz)

4.3 Measurement Results

This chapter describes the measurement results gathered from a 24 GHz IMST RADAR SR-1200 [7] in presence of interference signals generated by a one path SMW up to 40 GHz. Three different interference scenarios have been generated.

1. Chirp sequence as described above using the Pulse Sequencer software,
2. Broadband AWGN,
3. CW signal.

The radar applies an FMCW signal with 1.5 GHz signal bandwidth.

The measurement setup is shown below. The distance from the SMW interfering signal to the radar sensor was approximately 1 meter. The level stated in the measurements below is the SMW RF output power. To get a feeling about the expected receive power you have to calculate the free space path loss L, which is:

$$L = 20\,log_{10}(distance) + 20\,log_{10}(frequency) + \ 20\,log_{10}\left(\frac{4\pi}{c}\right) = 60{,}1\ dB\ for\ 24\ GHz$$

Equation 4-1: Free Space Loss

The TX antenna gain G_{tx} of the pyramidal horn antenna is calculated via its aperture (A) and the aperture efficiency (eA) and is a figure between 0 and 1 yields approximately:

f = 24.25 GHz, d1 = 6cm, d2 = 4.5 cm (where d1 and d2 are the dimensions of the antenna horn)

$$G_{tx} = \frac{4\pi A}{\lambda^2}\ e_A \qquad G_{tx}[dBi] = \ 10 * \log\left(\frac{4\pi A}{\lambda^2}\ e_A\right)\ [dBi] \approx 20\ dBi$$

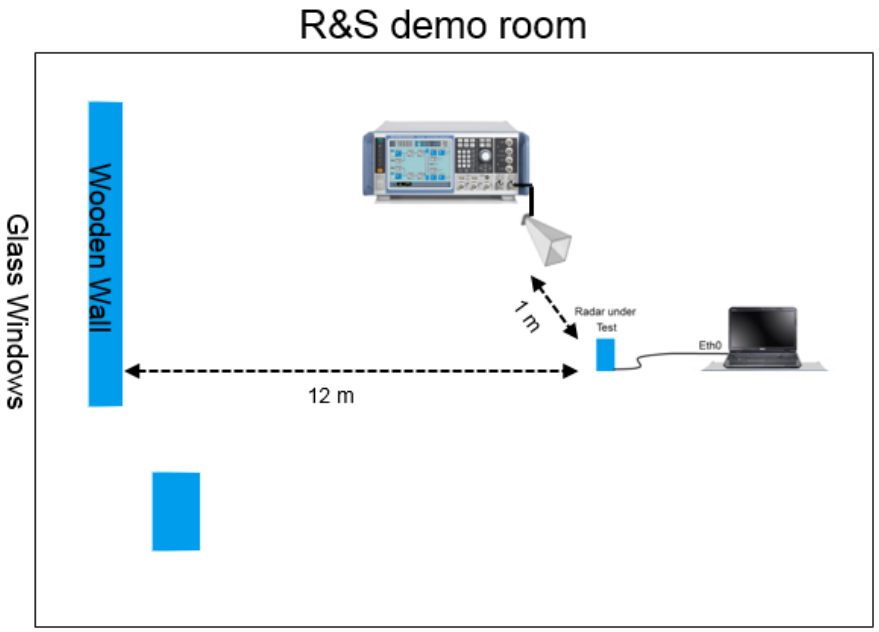
Equation 4-2: Gain calculation of rectangular horn antenna

By leveling 0 dBm at the RF output of the SMW at 24 GHz range, the radar under test will receive a power of -40 dBm.

There are additional gains and losses at the radar under test due to its antenna structures and LNAs.

Figure 34: Measurement setup using a 24 GHz Radar and SMW as Interference Source

The radar was pointing into the room with a reflector in approximately 12.2m distance. There are also other objects in this room which are detected.



The mentioned three scenarios are in detail the following interference signal conditions:

1. 0 dBm and 10 dBm AWGN with 160 MHz bandwidth
2. 0 dBm and 10 dBm FMCW signal with 200 MHz bandwidth and 6ms duration
3. 0 dBm and 10 dBm CW signal at 23.3 GHz (lowest frequency of the radar under test)

50 measurement cycles (FFT captures) have been performed and the mean values have been calculated by the IMST radar software. Each time the mean FFT spectra calculated by the radar under test is compared to a "no interference" situation.

Please note: There is no detailed analysis given, the setup and measurement results should only present an approach, how interference test could be performed. There is no triggering or any time correlation between the interference signal and the radar under test. Interference signal power and content has not been matched to the radar under test, except for the carrier frequency.

Figure 35: simplified scetch of the demo room

4.3.1 Interference due to AWGN

There are two different AWGN signals present which differ in TX power only. Each of the signals is compared to the "no interference" FFT depicted in Figure 36.

It can be seen that the spreading of the noise signal contributes to the entire spectrum as expected. The noise is increased at certain FFT bins by more than 10 dB (see range bins between 0m to 2m).

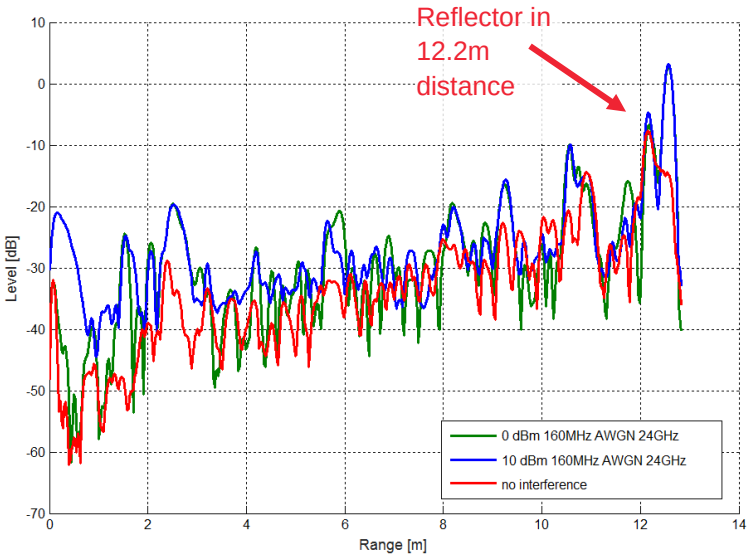


Figure 36: Scenario 1, AWGN interferer

4.3.2 Interference due to another FMCW signal

In here we compare the FMCW generated by the SMW and the pulse sequencer sw as the interferer to the radar under test with the no interference scenario. The FFT spectra are compared.

In comparison to the AWGN, the FMCW signal contributes less to the entire FFT spectrum, depending on timing and frequency match and the receiver bandwidth. There was no timing alignment or any signal match to the radar under test foreseen. In case signal and timing match, the FFT spectrum could look different. The contribution to the spectrum is visible, especially in the lower FFT bin between 0 - 2m

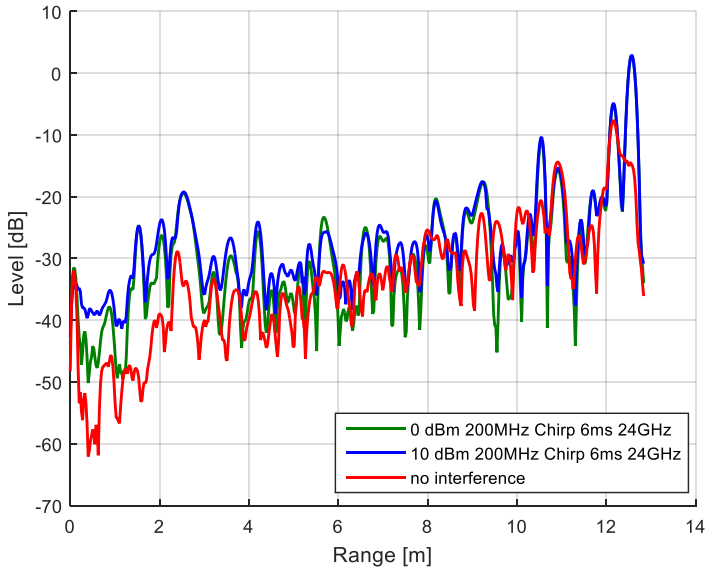


Figure 37: Scenario 2 FMCW interferer

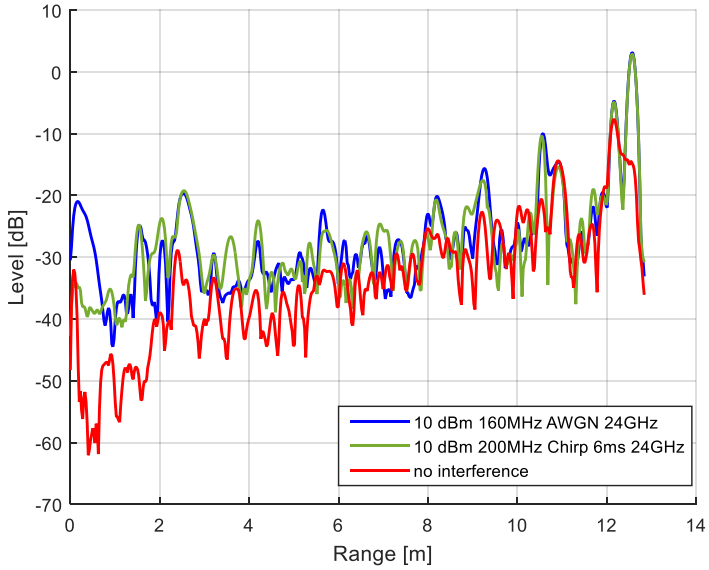


Figure 38: Comparison AWGN and FMCW interferer

4.3.3 Interference due to a CW signal

The last example is a CW signal, which is present at the lower bound (23.3 GHz) of the radar spectrum. The radar under test is still operating with 1.5 GHz signal bandwidth. While all other signals had less impact on the range bins in close range, the CW signal contributes with a highly increased signal power at close range bins, see Figure 39. This high signal power (blue trace at 0.2m range) could be interpreted as a target.

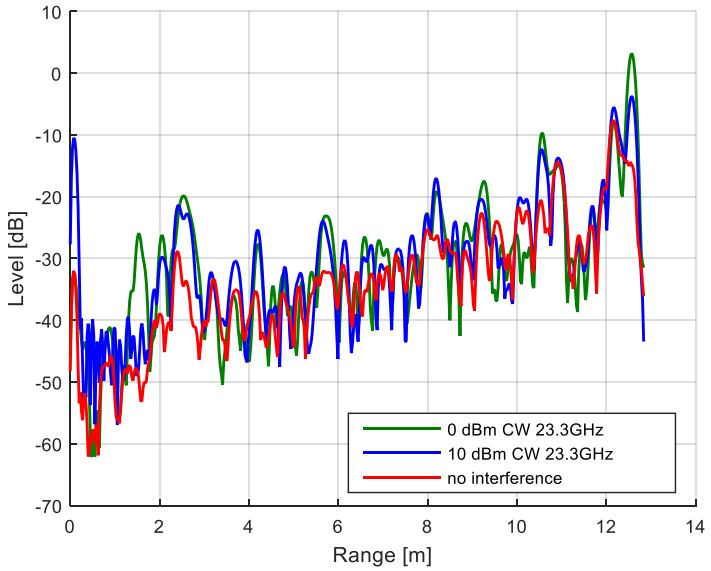


Figure 39: Scenario 3

5 Summary

Automotive radar sensors supporting already an increasing driving comfort. In case of sensor fusion with additional sensor systems, like cameras or lidars (light detecting and ranging), automotive radars will pave the way for autonomous driving in the future. One advantage of automotive radar sensors is, that they deliver an essential and very important piece of environment information under all weather conditions and under any driving conditions (in case the radar is not covered by snow or any other high reflective obstacle)

Test, measurement and verification according to standards of the radar signals is important as introduced in section 2.1. This standard deals only with the power emitted.

Having the knowledge of the accuracy of the transmitted signals, one can derive also radar range, Doppler and azimuth measurement accuracy and the impact on resolution. Transmit signal which are not according to standards, when considering spectral masks or power emission, may not only reduce the own radars performance, but may also interfere with other radars nearby. However, also radars from the same manufacturer and type may interfere with each other under certain conditions.

This application note presented a setup how to measure and analyze high frequency and large bandwidth continuous wave radar signals in detail and introduced an approach how to test interference scenarios using commercial off-the-shelf test and measurement equipment.

6 Literature

[1] H. Winner, S.Hakuli, G. Wolf, "Handbuch Fahrerassistenzsysteme", Viewig+Teubner, ISN 978-38348-0287-3

[2] S. Heuel, Application Note 1EF88 "Automated Measurements of 77 GHz FMCW Radar Signals"

[3] S. Heuel, S. Michael, M. Kottkamp, Application Note 1EF92 "Wideband Signal Analysis"

[4] Committee on Radio Astronomy Frequencies, ITU-R Footnote 5.340, retrieved from www.craf.eu/s5_340.htm, April 22nd, 2014

[5] S. Heuel, White Paper 1MA239, "Radar Waveforms for A&D and Automotive Radar"

[6] ECC Decision (04)03, " The frequency band 77 - 81 GHz to be designated for the use of Automotive Short Range Radars", March 2004, retrieved from http://www.erodocdb.dk/docs/doc98/official/pdf/ECCDec0403.pdf, Feb, 25th, 2016

[7] IMST Small and Flexible 24 GHz radar modules: http://www.radar-sensor.com/products/radar-modules/sr-1200/

7 Ordering Information

Designation	Type	Order No.
Signal Generator	R&S®SMW200A	1412.0000.02
100 kHz to 40 GHz	R&S®SMW-B140	1413.0604.02
100 kHz to 31.8 GHz	R&S®SMW-B131	1413.8605.02
100 kHz to 20 GHz	R&S®SMW-B120	1413.0404.02
100 kHz to 12.75 GHz	R&S®SMW-B112	1413.0204.03
100 kHz to 6 GHz	R&S®SMW-B106	1413.0104.02
Baseband generator with ARB (64 MS/120 MHz)	R&S®SMW-B10	1413.1200.02
ARB memory Extension to 512 Msample	R&S®SMW-K511	1413.6860.02
ARB memory Extension to 1 Gsample	R&S®SMW-K512	1413.6919.02
Baseband Extension to 160 MHz RF bandwidth	R&S®SMW-K522	1413.6960.02
Signal routing and baseband main module, one I/Q path to RF	R&S®SMW-B13	1413.2807.02
Pulse Sequencing SW	R&S®SMW-K300	1413.8805.02
Additive White Gaussian Noise (AWGN)	R&S®SMW-K62	1413.3484.02
Frequency Multiplier 60 GHz to 90 GHz	R&S®SMZ90	1417.4504K02
Signal and Spectrum Analyzer, 2 Hz to 26.5 GHz	R&S®FSW26	1312.8000K26
Signal and Spectrum Analyzer, 2 Hz to 85 GHz	R&S®FSW85	1312.8000K85
512 MHz Analysis BW (1,4)	R&S FSW-B512	1313.4296.04
Real-Time Analyzer 512 MHz (2)	R&S FSW-B512R	1313.4296.06
Upgrade to 512 MHz (3,4)	R&S FSW-U512R	1321.6320.06
Upgrade to 512 MHz Real-Time (2,3)	R&S FSW-U512R	1321.6320.06
Upgrade 500 MHz to 512 MHz (3)	R&S FSW-U512A	1321.6320.14
2 GHz Analysis Bandwidth	R&S®FSW-B2000	1325.4750.02

Transient Measurement Application	R&S®FSW-K60	1313.7495.02
Transient Chirp Measurement (precondition FSW-K60)	R&S®FSW-K60C	1322.9745.02
Transient Hop Measurement (precondition FSW-K60)	R&S®FSW-K60H	1322.9916.02
Digital oscilloscope 4 GHz, 4 channels2 GHz Analysis Bandwidth	R&S®RTO1044R&S®FSW-B2000	1316.1000.441325.4750.02 *)
OCXO 10 MHz Digital oscilloscope 4 GHz, 4 channels	R&S®RTO-B4R&S®RTO1044	304.8305.021316.1000.44
OCXO 10 MHz	R&S®RTO-B4	304.8305.02
Optional		
Memory upgrade 100MSa per channel (Optional)	R&S®RTO-B102	1304.8434.02
Memory upgrade 200MSa per channel Memory upgrade 100MSa per channel	R&S®RTO-B103R&S®RTO-B102	1304.8440.021304.8434.02
Memory upgrade 400MSa per channel Memory upgrade 200MSa per channel	R&S®RTO-B104R&S®RTO-B103	1304.8457.021304.8440.02
Memory upgrade 400MSa per channel	R&S®RTO-B104	1304.8457.02
Programmable Four-Channel Power Supply	R&S®HMP4040	3622.2023.02

1) An upgrade from option FSW-B512 to B512R is not possible.

2) R&S FSW-B512R and FSW-U512R is export restricted

3) Depending on hardware status of the instrument the upgrade costs can vary

4) The option FSW-B512 (1313.4296.04) replaces option FSW-B500 (1313.4296.02).
The option FSW-U512 (1321.6320.04) replaces option FSW-U500 (1321.6320.02).

Rohde & Schwarz

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

The electronics group is 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.

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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

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