Automotive Radar Sensors - Transmit Signal Analysis and Inference Tests
Application Note

Products:

- R&S®FSW
- R&S®SMW200A
- R&S®SMZ90
- R&S®RTO2000

- 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. Also these radar systems need to cope with interference of many kinds like the one from other cars radars.

This Application Note highlights signal measurements and analysis of automotive radars that are crucial during the development and verification stages. Particular emphasis is placed on 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

https://www.rohde-schwarz.com/appnote/1MA267

ROHDE & SCHWARZ

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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 FSW

◾ The R&S®RTO2064 and R&S®RTO2044 Digital Oscilloscopes are referred to as RTO

◾ The R&S®FSW-B2000 2 GHz Analysis Bandwidth is referred to as B2000

◾ The R&S®FSW-K60 Option Transient Analysis (Chirp and Hop) is referred to as K60C/H

◾ The R&S®FS-Z90 Harmonic Mixers are referred to as FS-Z90

◾ The R&S®HMP4040 Programmable Four-Channel Power Supply is referred as HMP

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1 Introduction

In the automotive radar market, high performance and reliability combined with low unit size and price are mandatory. A single car may carry in excess of ten sensors. These radars shall not interfere with each other or any other device. It follows that test and measurement of such radar sensors need to be just as fast, as reliable, cost-effective, and straight forward to use during development as well as in production.

Just like all other signal transmission via radio frequency (RF) systems, radar 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. Apart from time, the likelihood of interference depends for example on the used frequency bands of such systems (e.g. 76-81 GHz or around 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, receive bandwidth and filter stages) and the emitted power. The worst scenario for 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 for two kind of radars.

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. The output power of automotive radar sensors is specified by the Electronic Communications Committee (ECC). 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.

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 both, the 24 and the 77 GHz frequency bands.

2.1 Signal Power

Transmitted 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

There is no automotive radar sensor on the market making use of pulsed waveforms. All commercially available automotive radars seem to make use of continuous wave signals, to the author's knowledge.

For Frequency Modulated Continuous Wave (FMCW) radars, a frequency modulated signal (Chirp) is transmitted with a specific frequency sweep f_{sweep} within a certain time, called coherent processing interval T_{CPI}, see Figure 1 below.
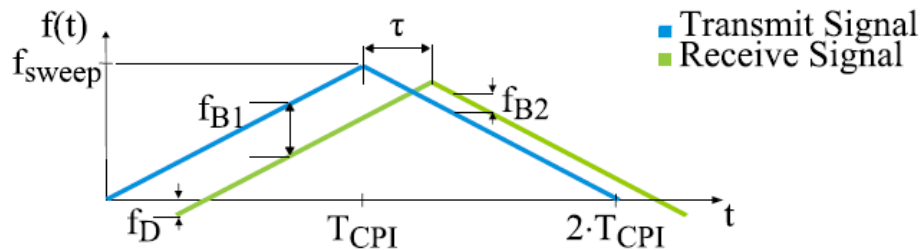
Figure 1: FMCW radar with upchirp and downchirp

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 designed to be 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 a future maximum of probably 4 GHz.

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_{CPI} (see Figure 2). Due to the fact that a single chirp is very short, the beat frequency f_B is mainly influenced by signal propagation time and Doppler frequency shift f_D, (which may be neglected in the first processing step).
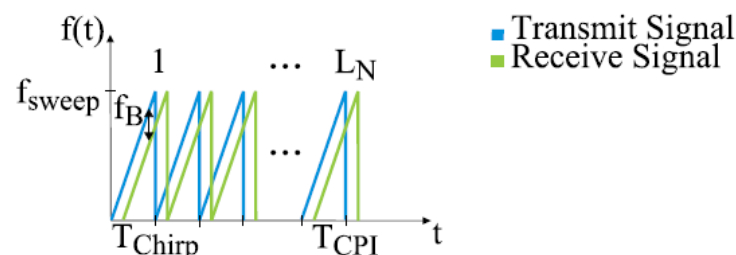

Figure 2: Chirp Sequence.

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 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

▪ 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 4 GHz (probably in the future).

Even though the radar waveforms of the various sensors may look pretty similar, there are no firm common parameters for automotive radar sensors, except the standardized transmission power. Each manufacturer has a slightly different waveform, with different chirp timings, different chirp bandwidth, etc.

If timing of an interfering signal as well the receiver timing and receiver bandwidth match, a disturbing signal will fall into the radar's receive "window" and cause a certain amount of unwanted spectrum growth. As previously indicated, the severity of radio frequency interferences depend on several further parameters. Most critical factors are the transmitted power and vicinity of the interferer frequency to the receive spectrum used. In case the interfering waveform is alike, or noise-like, there will be a larger impact on the down-converted signal in the receiver.

This section explained the two main waveforms used in automotive radar sensors today, and part of their signal processing. This is the basis for the following sections, which explain measurement setups for signal analysis and radio interference test.

3 Measurement Setup for Signal Analysis

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

Rohde & Schwarz offers several methods to analyze the spectrum and signal content of automotive radars. The table below introduces different possibilities to measure and analyze automotive radar signals. For the 77GHz range, FSW in combination with the 90 GHz harmonic mixer, or FSW85 may be used. FSW85 is the only analyzer in the market offering 85GHz bandwidth on a single, fully factory calibrated input connection.

The configurations are described in detail in the following sections, 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, FSW-B21	

Table 3-1: Possible Hardware Setups

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

This section 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. Note that for a chirp bandwidth below 500 MHz there is no need for the RTO (see Table 3-1: Possible Hardware Setups)

There are two methods that can be used. Either an over-the-air (OTA) setup, where there is no coaxial cable connection, or a wired setup, where there is a suitable coaxial cable between the RUT and the FSW 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, Chirp & Hop analysis) and the Wideband Signal Analysis option (B2000). The HMP series programmable power supply is used to DC-feed the RUT.
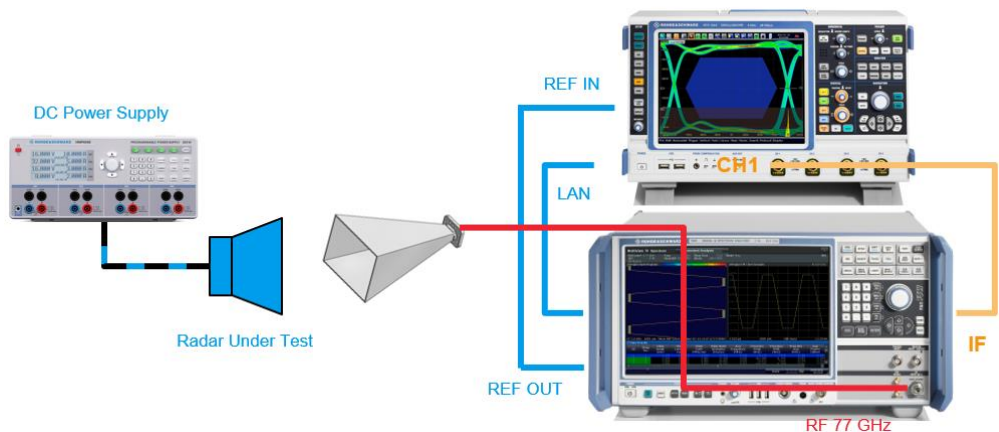
Figure 3: Measurement Setup of the 77 GHz Radar in free space (over the air)

The signal transmitted by the RUT is received and down converted using a spectrum analyzer (FSW) with an attached horn antenna. The IF is digitized by the ultra-high resolution digital oscilloscope RTO2064 (6 GHz) or RTO2044 (4GHz).
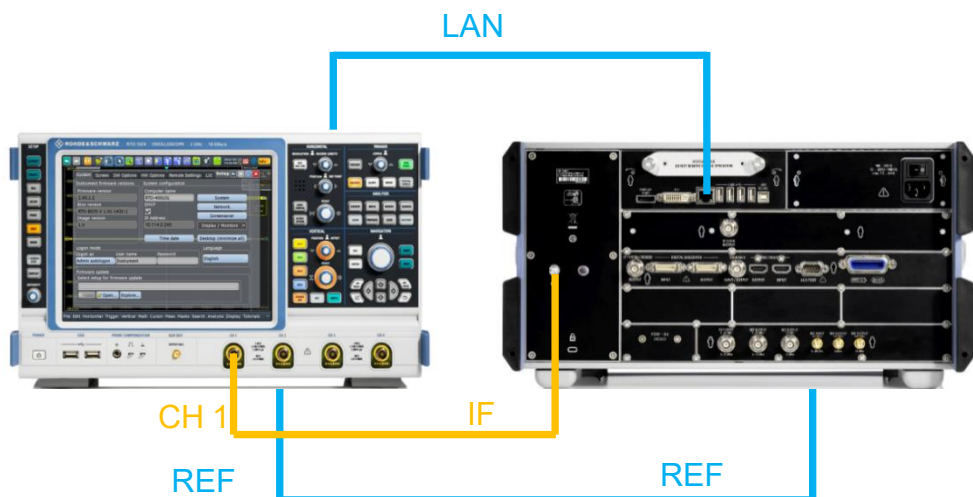

Figure 4: Measurement Setup with FSW Rear Panel (optional external Trigger in CH2)

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 section below for the alignment procedure).

Before connecting the IF output of the FSW to the RTO Channel 1 input as depicted above, the combination of FSW and RTO is 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. Wideband analysis is fully compatible with the following options: IQ Analyzer, Pulse Measurements, Transient Analysis, and Vector Signal Analysis. The setup procedure outlined below applies to all options supporting 2GHz bandwidth mode with FSW-B200 and RTO.

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 example)
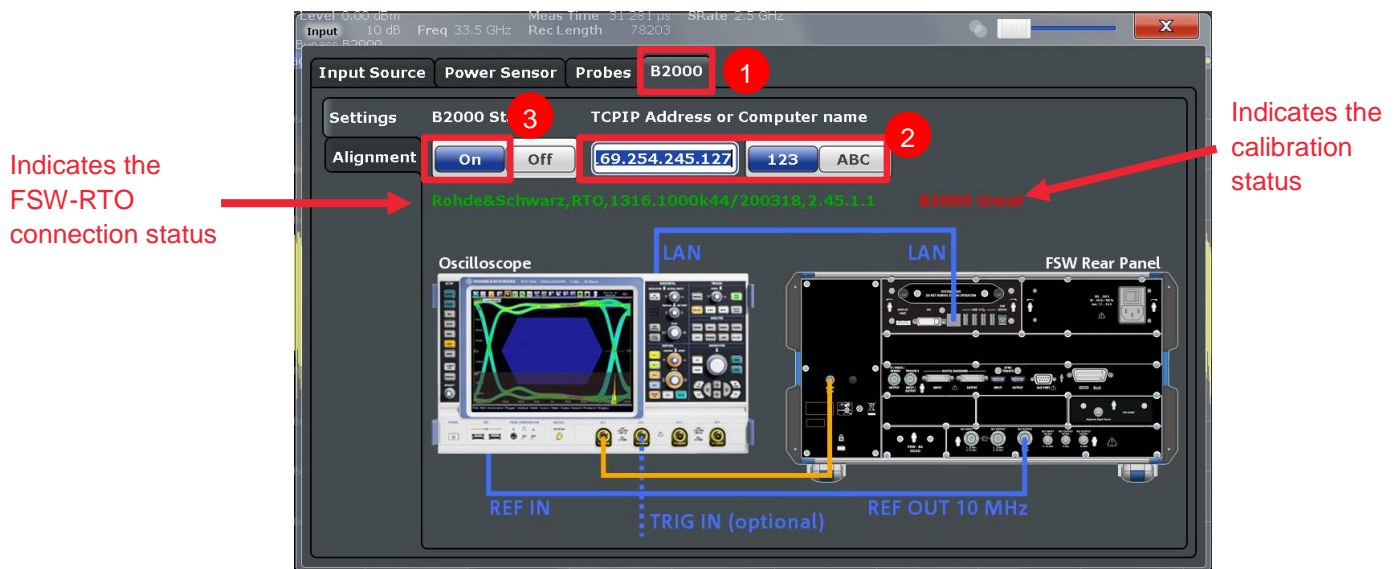
Enable the B2000.

③ Change to: 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.
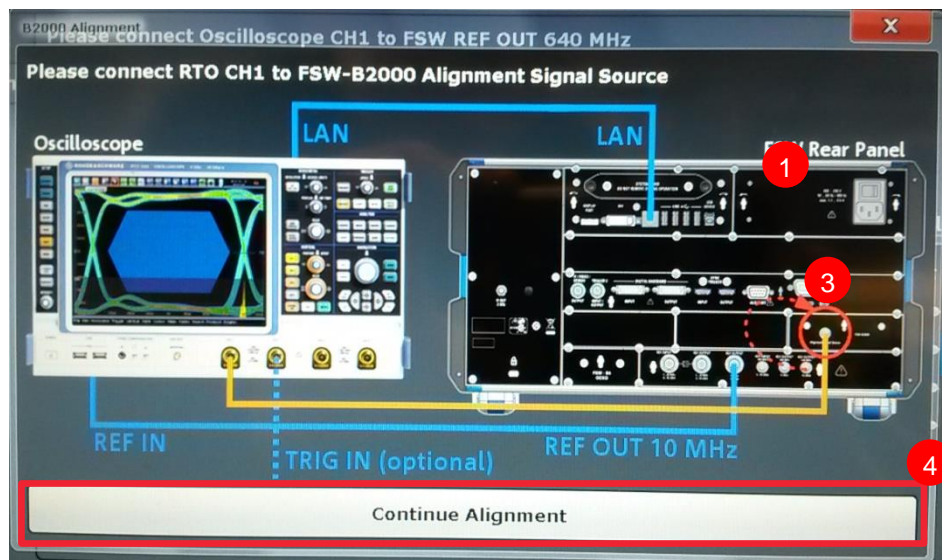
4 Press "Continue Alignment"

Figure 8: Alignment Process (2)

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

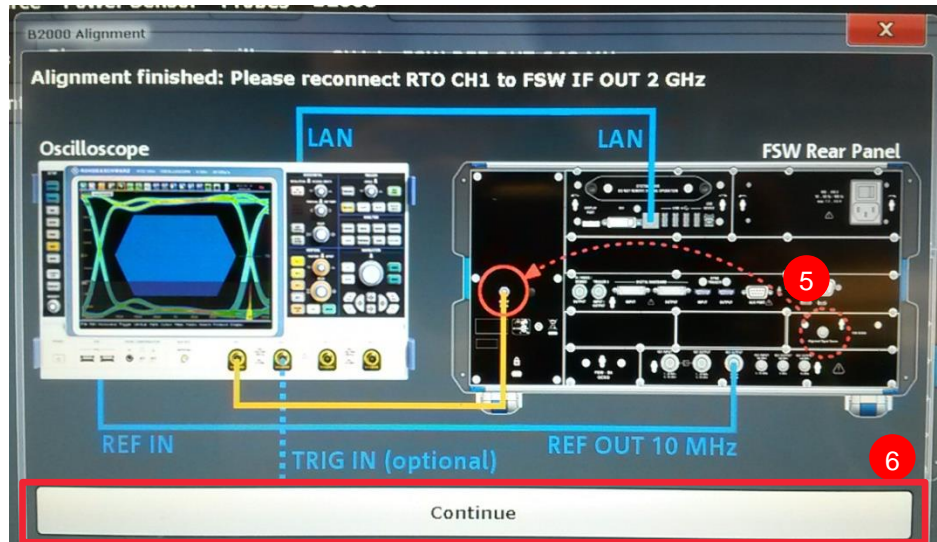**6**   Press Continue to finish the wizard.

Figure 9: Alignment Process (3)

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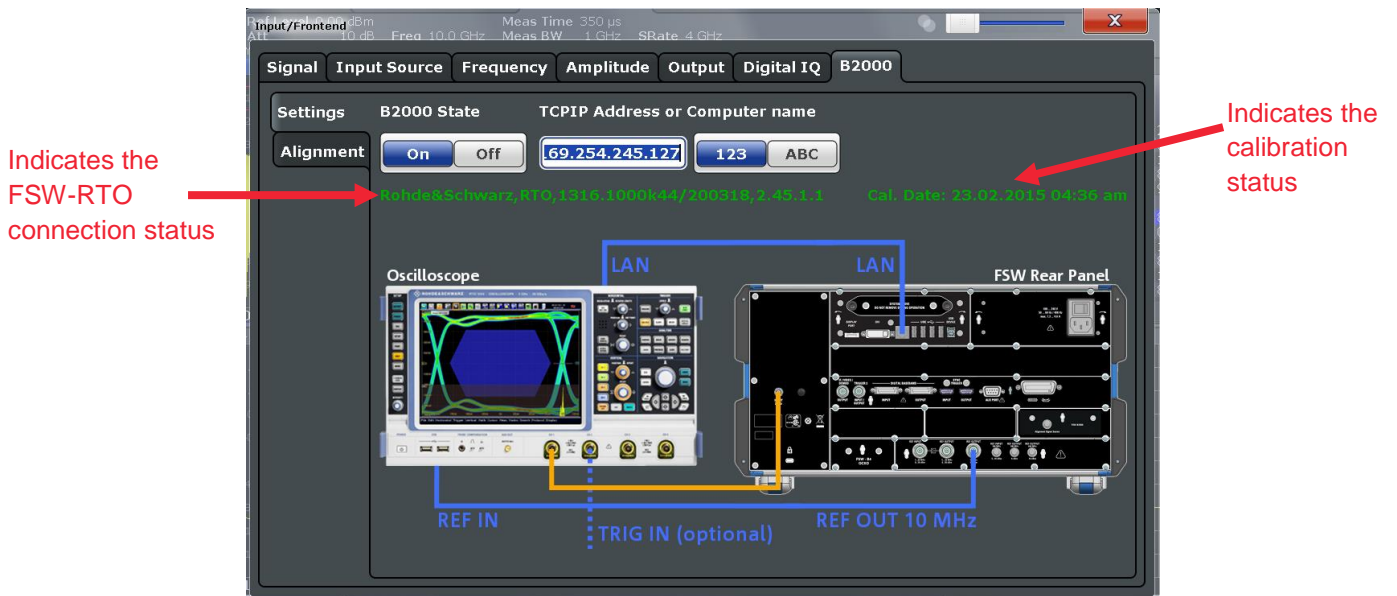

Figure 10: Alignment completed

3.2 **77 GHz Radar Chirp Measurements**

This section 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 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 B2000 has been activated as described above in section 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]**
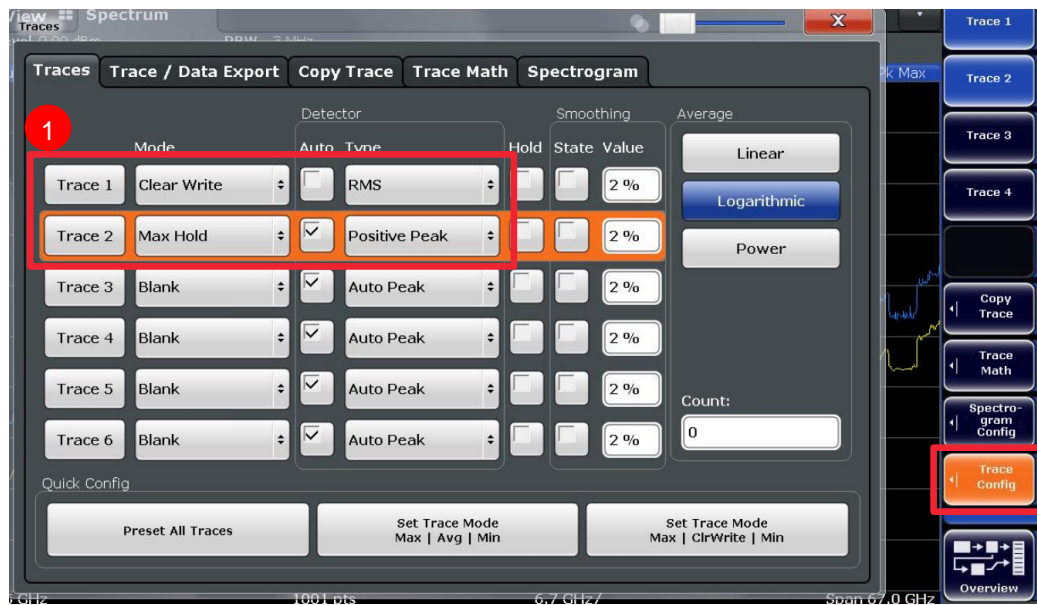
▪ Set "Trace 2" to **[Max Hold]** and **[Positive Peak]**.

Figure 11: Spectrum View Trace Configuration

After closing the traces windows you can see the spectrum of the RUT, 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.
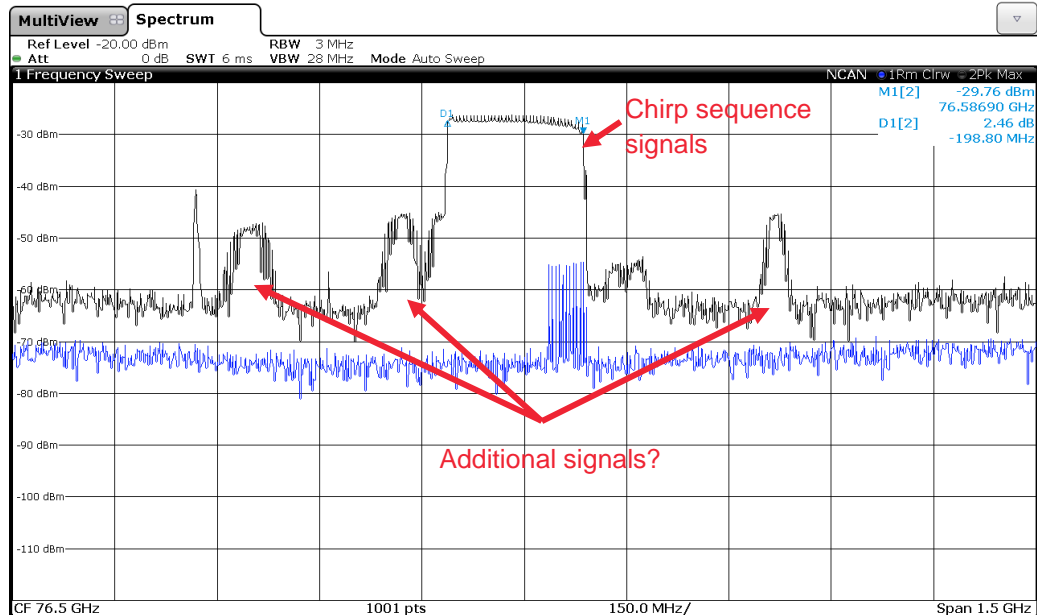

Figure 12: Spectrum View

The black trace reveals mainly two kinds of information:

3.   The 198 MHz wide signal around 76.5 GHz.

4.   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

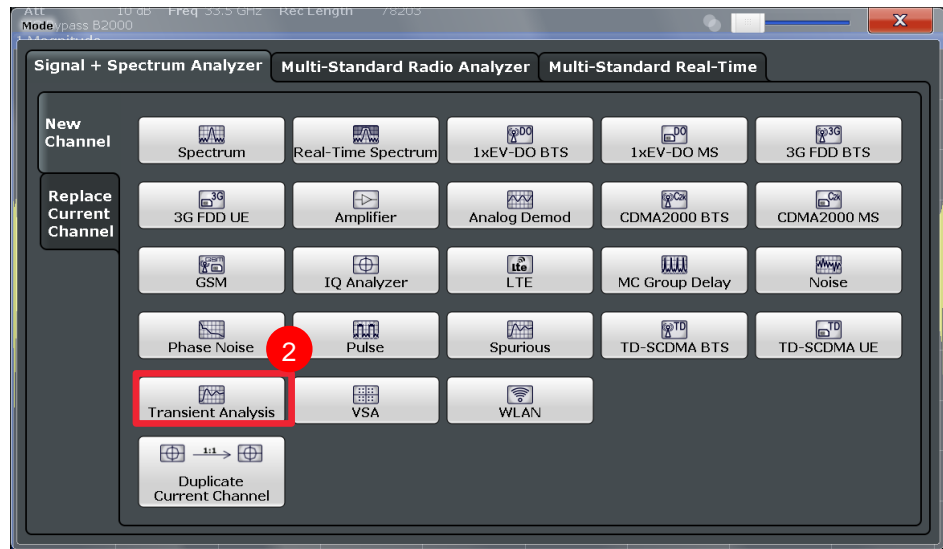**2**   **[MODE]**: Transient Analysis

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.
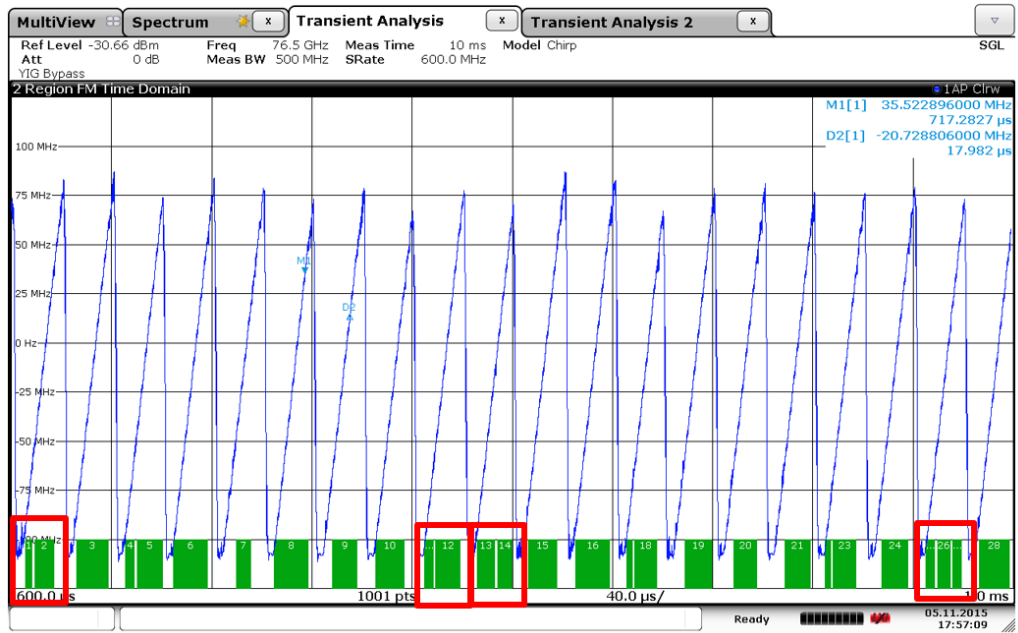
⑥   **[MEAS]**: Meas Time: 1 ms

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.
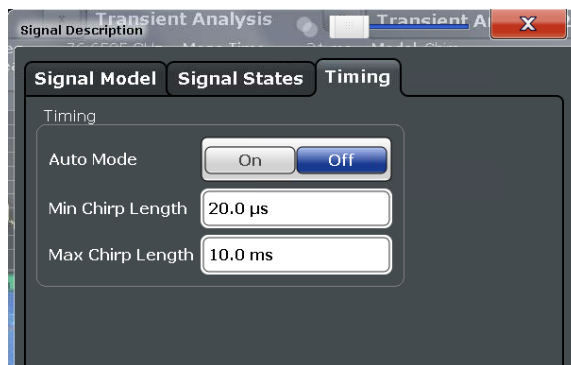
Figure 16: Signal Description window.

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 **[4 Frequency Deviation Time Domain]** window 4, Figure 17.
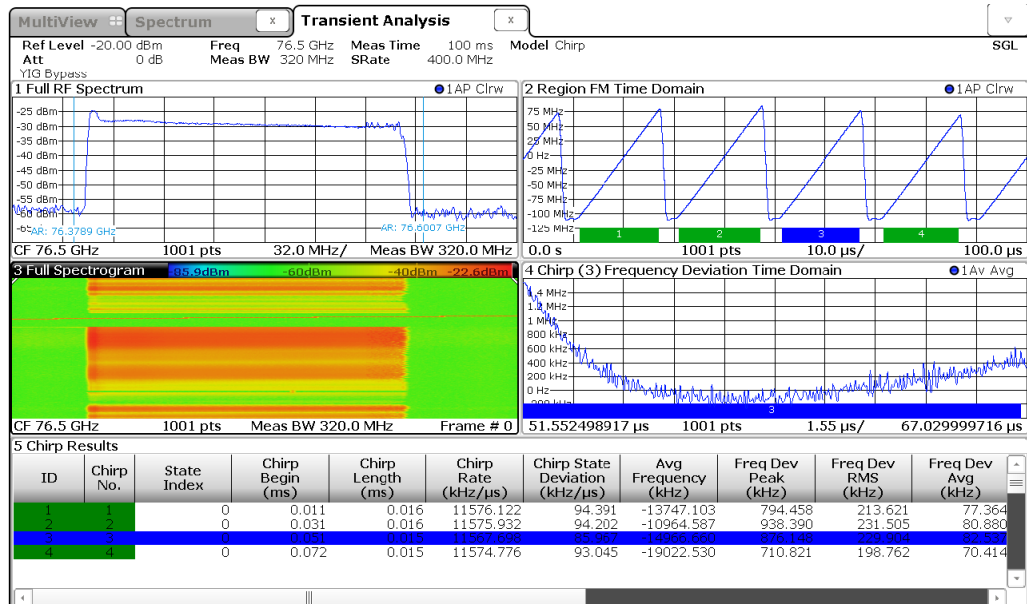

Figure 17: General Transient Analysis Window

The measurement result is depicted above. Four full chirp signals with a linearily increasing frequency modulation are captured and analyzed. The blue bar indicates the selected 3rd chirp, on which a frequency deviation over time is analyzed immediately.

The chirp results table window **[5 Chirp Results]** at the bottom, shows the entire capture of 100 us. 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, varied by color, of the received radar signals.In addition, there are signals transmitted which use much more bandwidth (frequency hopping signal?) than the chirp sequence (shown and marked in Figure 18). The next measurement investigates these signals in more detail.
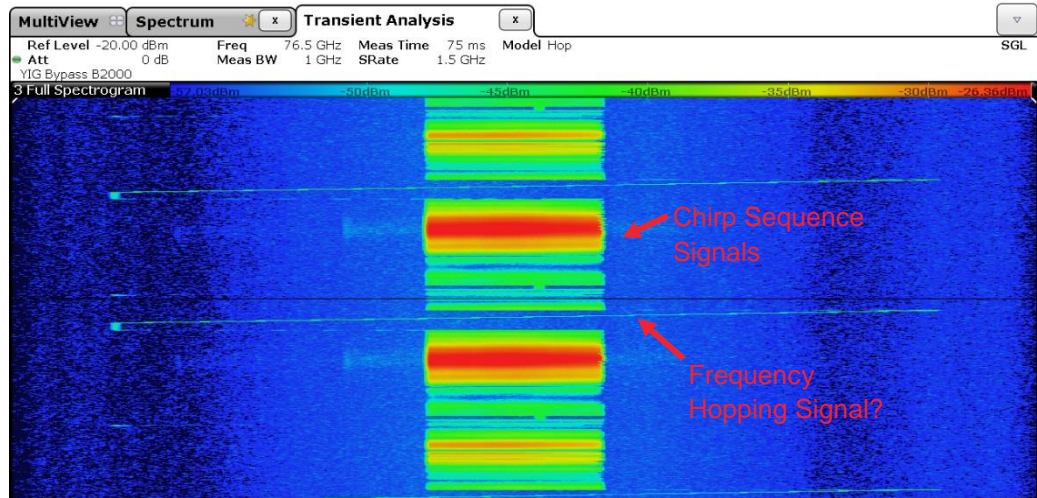
Figure 18: Full Spectrogram Window

3.2.3 Hop Measurement Results

In Figure 18 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]** is started on the Signal and Spectrum Analyzer, which now runs next to the first application view.

In the **[3 Full Spectrogram]** window, Figure 19, one can see that the radar sensor transmits a frequency stepped signal, which is selected within the **[Analysis Region]**. This may be due to measurement result ambiguities which arise in the chirp sequence signal processing of this particular chirp sequence waveform.
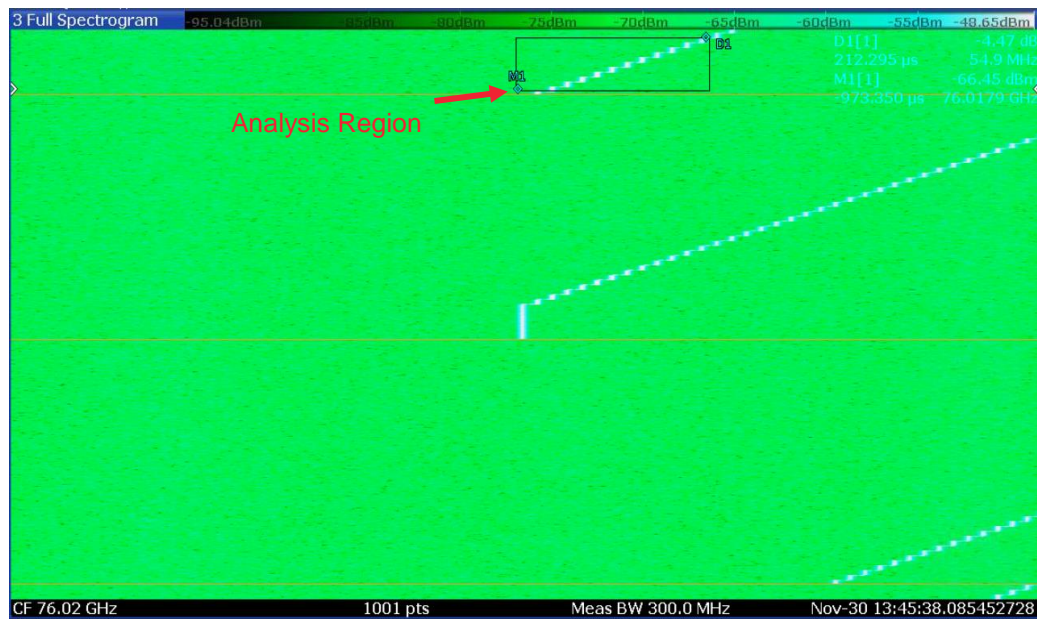

Figure 19: Transient Analysis 2, Full Spectrogram and selected Analysis Region

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

In this section, we will investigate the possibility of several automotive radar sensors interfering with each other, when operating in the same portion of the frequency band. Possible scenarios we can imagine are,

∎ to test if the RUT can be stressed enough to output artificial targets, or

∎ bring a sensor into a situation with decreased probability of detection.

A target caused by interference is called a ghost target in this application note. As the name implies, Ghost targets do not exist in reality, but appear just like real targets on the output of the radar. This may be caused by a near replica of the transmitted signal which is in fact not from the radar's own transmitter, but falls into the receive "window". For this scenario to happen, the timing, waveform and frequency between two or more radars have to match very closely and the received "apparent 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 SNR (Signal to Noise Ratio) of a target. This may cause targets with small Radar Cross Section (RCS) to disappear as the SNR of its 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.

Testing mutual interference of automotive radar sensors is even more important when these radars apply CS (Chirp Sequence, fast FMCW) waveforms. Due to the high chirp rates in CS, the resulting beat frequency of a measured target is much higher than comparable slow FMCW radars would encounter (MHz vs. kHz). This is also the reason why the sampling rates and filter bandwidth need to be increased, which in turn cause easier interference. One approach towards interference mitigation would be to combine slow FMCW and Chirp Sequence waveforms in order to measure radar echo signals even when mutual interference is present.

This section explained how RF signals that allow test of unwanted behavior should look like in respect to desired signal content, bandwidth and frequency. How these signals are created and then used to stimulate an operating automotive radar sensor. Is shown in the following sections. 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 three different measurement setups introduced, one can be used for radars operating up to 26.5 or 40 GHz covering 24 GHz automotive radar sensors, and two which can be used up to W-band frequencies (i.e. 77 and 79 GHz band automotive

radar sensors). For the W-Band frequencies, there are an 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.
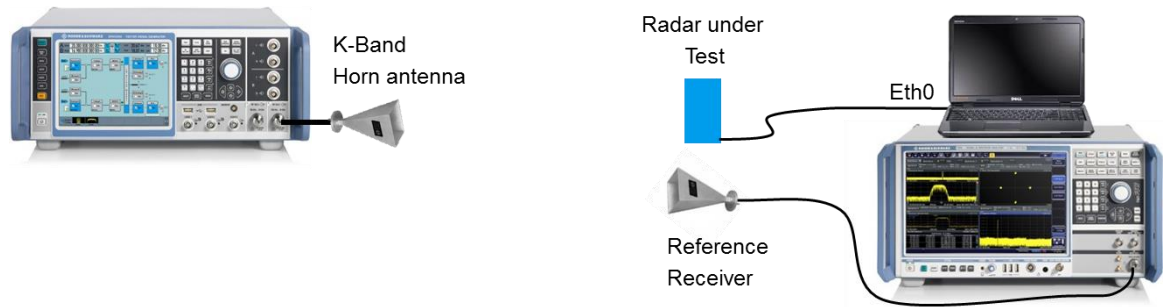

Figure 21: Setup for stimulating 24 GHz Automotive Radar Sensors

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

Signal generators cannot provide W-Band signals using a single commercial off the shelf (COTS) instrument as of today. Therefore, a lab setup providing a wideband chirped signal at 79 GHz is instead composed of a wideband baseband source, a signal generator with analog baseband inputs, an external harmonic mixer and a second generator as local oscillator for the mixer, Figure 22.
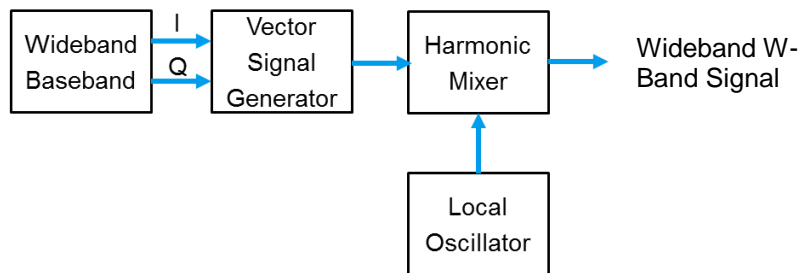

Figure 22: Setup for generating Wideband Modulated signals at 79 GHz

A second possibility is shown in Figure 23. The vector signal generator SMW can be configured for 160 MHz bandwidth and seamlessly integrates the external frequency multiplier SMZ90 which multiplies the instantaneous frequency by a factor of six. As an example, a 160 MHz wide chirp at 12.75 GHz can thus be converted to 76.5 GHz with 960 MHz bandwidth. While the frequency is multiplied, the phase is kept. This setup can therefore be used for generating frequency or phase modulated signals (no AM).

Figure 23: Simplified setup for generating wideband modulated signals at 79 GHz range, 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.
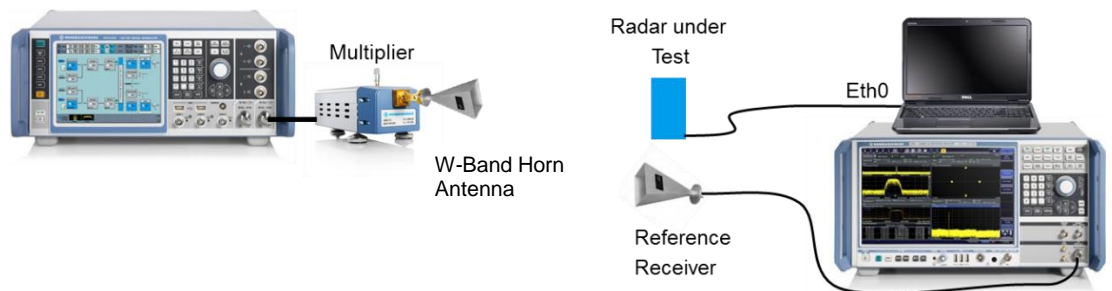
Figure 24: Setup for 77/79 GHz Automotive Radar Sensors

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 section describes the signals used as interferer and their setup. The Vector Signal Generator SMW is used to generate different kinds of interference signals. In combination with the SMZ90 frequency multiplier, the narrow bandwidth is then multiplied to the desired bandwidth at the carrier frequency above 50 GHz.

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

  b) 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, 77 GHz and 79 GHz radars).

  c) Continuous wave signals at different frequencies

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 RUT, verify your carrier frequency and level of the output signal (see Figure 25).This scenario is possible for a 24 GHz radar with SMW models providing a frequency range up to 31.8 GHz or to 40 GHz.

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".
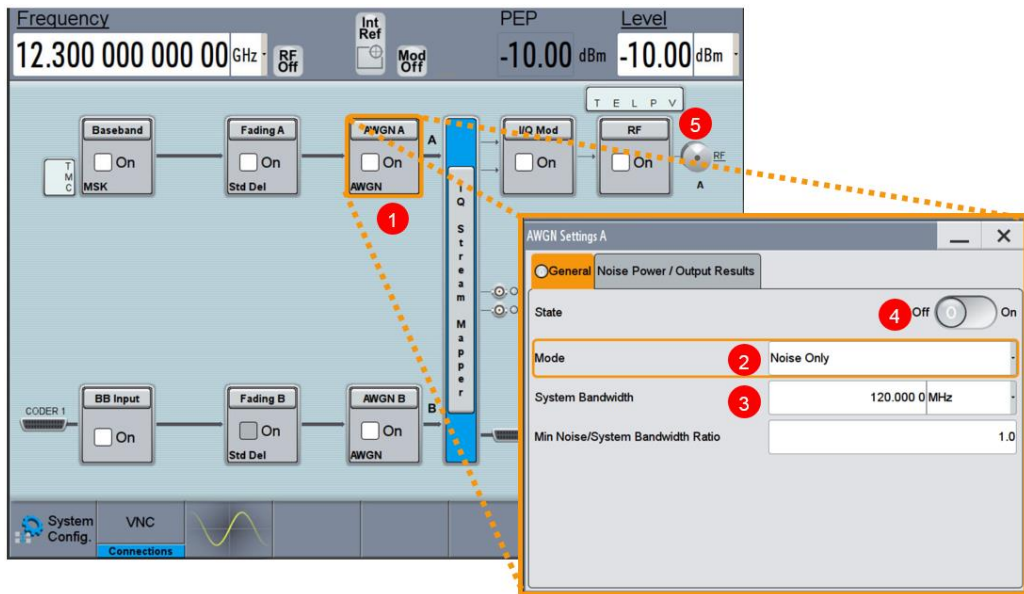
The blocks that are on/enabled turn blue.

Figure 25: SMW AWGN configuration

4.2.2 Arbitrary Interference Signals

The Rohde & Schwarz Pulse Sequencer software is a versatile tool to generate sophisticated pulse/interference signal scenarios simulating real life conditions and allows to create a controlled, cost-effective and reproducible test bed with many variable parameters. The Pulse Sequencer software allows to create RF signal environments, like those from the field, into the laboratory. It uses 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:
https://www.rohde-schwarz.com/software/smw200a/

4.2.2.1 Pulse Sequencer Workspace

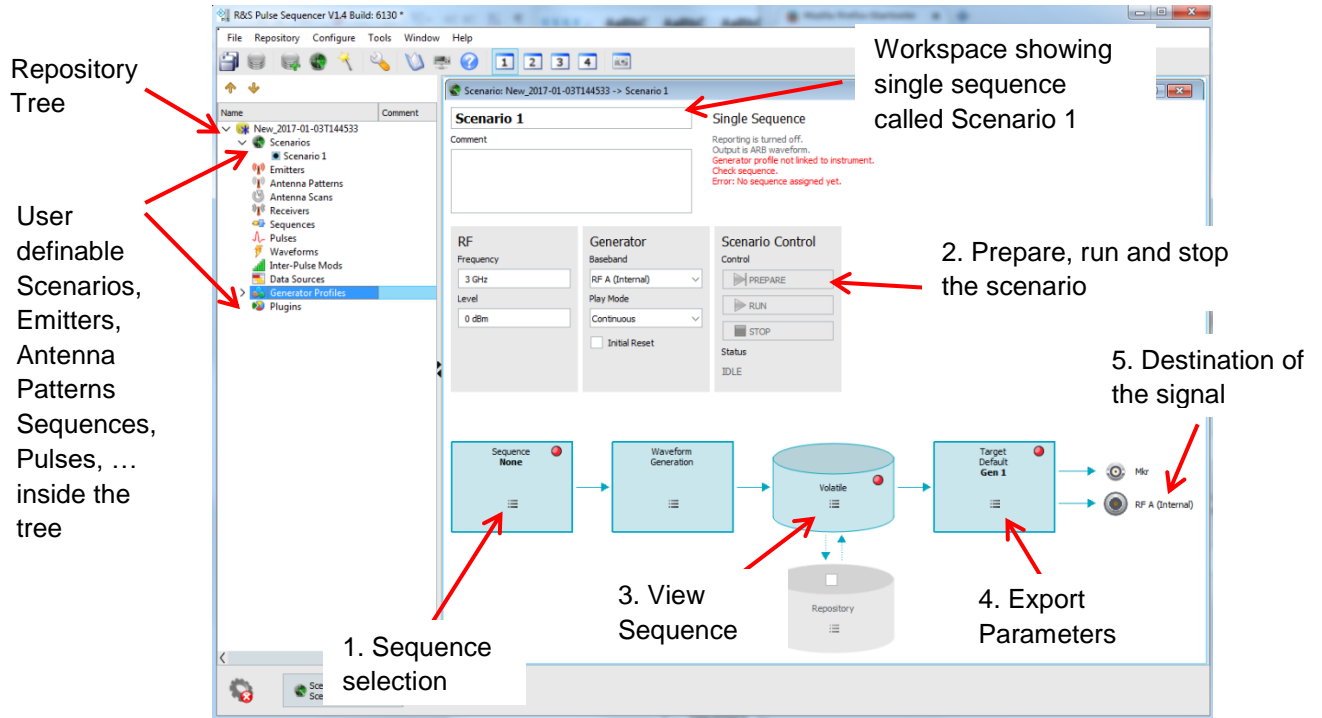The following section explains the default workspace

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
- Receivers
- 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 section shows how to generate an FMCW chirp signal (similar to the one used by our RUT, with 459.6 MHz signal bandwidth, 2.1 ms duration). 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 a new repository]** then press **[Next]**

3   Chose **[Simple Pulse/Pulse Sequence]** then press **[Next]**.

4   Define the length of your pulse under **[Width]** (in here 2.1 ms), mark **[Modulation]** then press **[Next]**.

5   By default it is a Linear Chirp. We require 459.6 MHz signal bandwidth (as the signal bandwidth is multiplied by a factor of 6, and the deviation is half of the signal bandwidth (before multiplication) we need to set this to 38.6 MHz (multiplied by 2, then multiplied by 6 using the SMZ90 = 459.6 MHz). Then press **[Next]**.

6   Leave the PRI here as is, since this is modified later on. Then press **[Finish]**. The left display window has been populated by the [Startup Assistant]
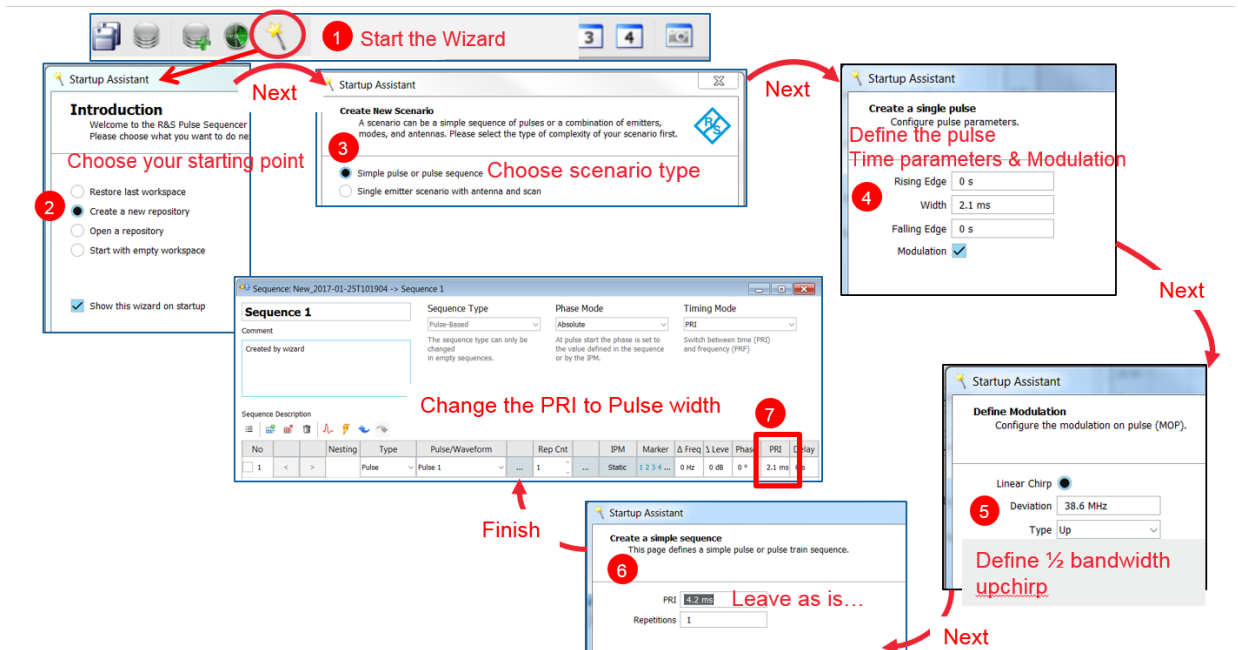

Figure 27: Pulse Sequencer Startup Assistant

7   The window **[Sequence: New_YYYY-MM-DD_x]** appears on front, type in **[PRI]** column the value of the pulse width from point 4, to get an FMCW signal (in here 2.1 ms)

8. Press **[Scenario1]** to be displayed in front.

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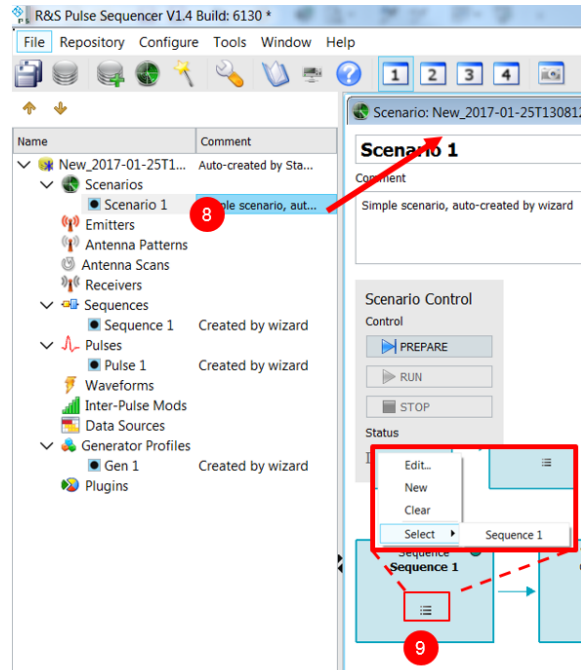

Figure 28: Select Sequence into scenario

By Pressing **[PREPARE]**, a waveform file (*.wv) is calculated and stored on the local PC.

4.2.2.3   Transferring the FMCW waveform to SMW

At this point the SMW is connected via LAN to the PC where Pulse Sequencer is operated. The IP Address of the SMW is known (in here 10.85.0.94).

Note: A VISA library must be installed If not already on your PC. Download from http://www.rohde-schwarz.com/appnote/1DC02

1. On the menu toolbar click **[Configure/Hardware Management…]**, a new window appears with empty list.

2. Click on **[Add]** to open a request for a manual IP address input (here, 10.85.0.12). Then click **[OK]**. A [Generator Configuration] should appear on the left side of this window, which indicates the option and RF frequency capability of the connected SMW (in here SMW200A s/n: 102716).

③ Press the **3 hexagon icon […]** to create a generator profile from a connected generator. Verify that the right lower side of this window is populated with the same values of its left counterpart.

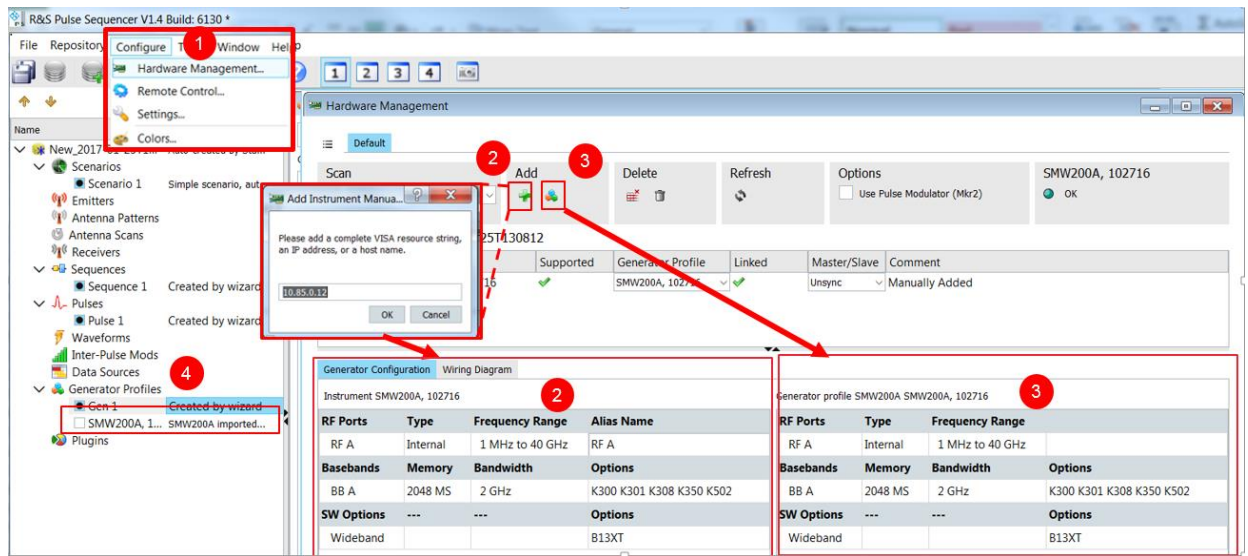④ Verify that the connected instrument has been added in the tree under **[Generator Profiles]**

Figure 29: Creating a Generator Profile

⑤ Click on the last **[Scenario1]** so the window **[Scenario: New_YYYY-MM-DD_x]** comes to the front.

⑥ Click on the last block, chose **[Target]** then select [**Generator].**

⑦ Press again on 6 and press **[Select]** generator profile that you have just created (in here SMW200A). Verify the green LED on that block.

⑧ Set the **[Frequency]** and Level of the SMW. (here 12.705 GHz, multiplied by 6 results in a carrier frequency of 76.23 GHz) and **[Level]** (here 5 dBm)

⑨ Press **[PREPARE]**. A waveform file (*.wv) is generated, locally.

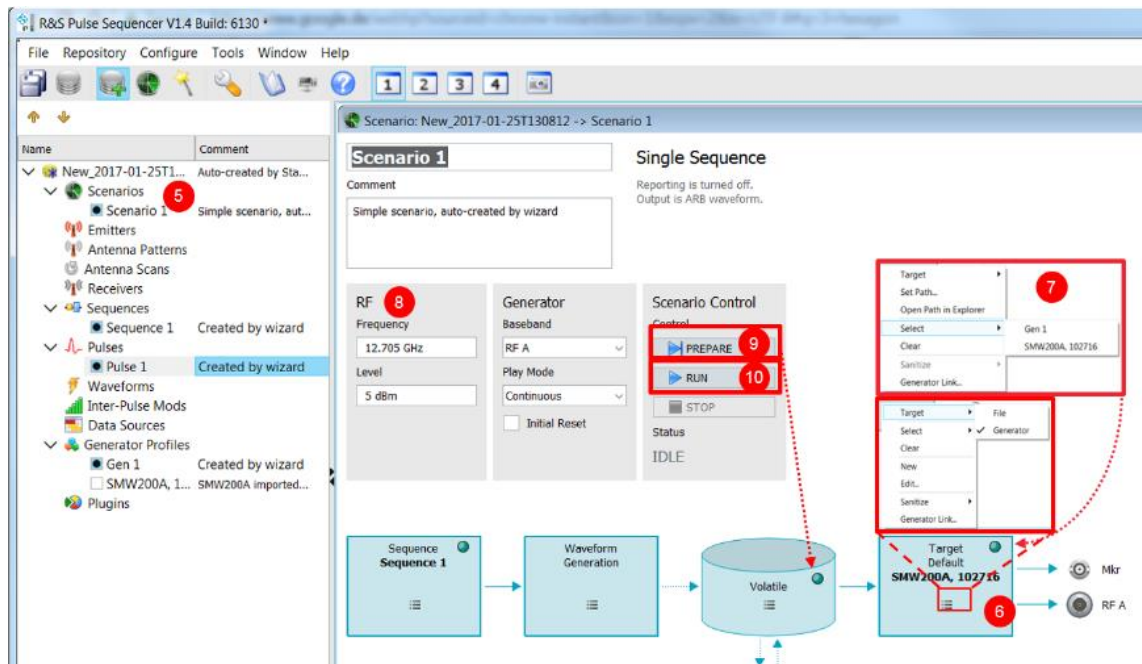⑩ Press **[RUN]** to upload the waveform to the SMW and replay it at the defined frequency and level from point 8.

Figure 30: Uploading a waveform file to SMW

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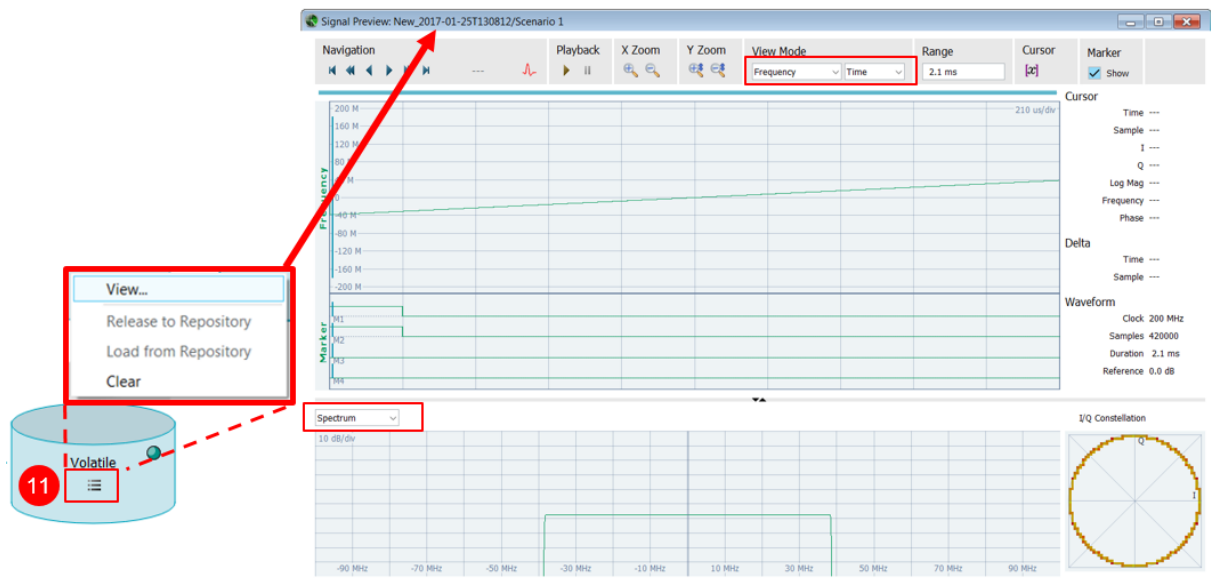

Figure 31: Pulse Sequencer, waveform view (here chirp bandwidth 77.2 MHz)

4.3 Measurement results of a 24 GHz radar

This section describes measurements taken on a 24 GHz IMST RADAR SR-1200 [7] in presence of interference signals as generated by a one-path SMW up to 40 GHz.

Three different interference scenarios have been tested.

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 and slow FMCW with chirp duration of 20 ms.

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

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

Equation 4-1: Free Space Loss

The TX antenna gain G_{tx} of the pyramidal horn antenna is approximated using the aperture (A) and the aperture efficiency (eA):

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 in 24 GHz range, the RUT will receive a power of -40 dBm.

There are additional gains and losses at the RUT due to its antenna structures and LNAs. Measurement was done indoors to better approximate a dense environment.
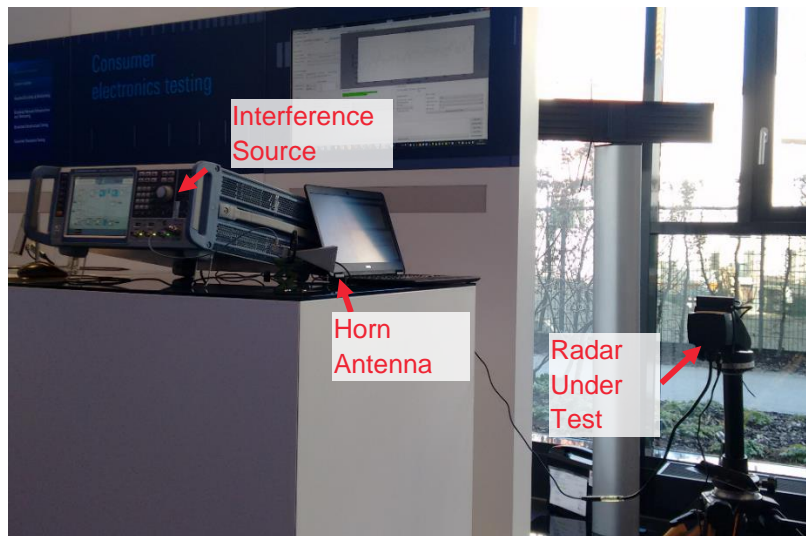
Figure 32: Measurement setup using a 24 GHz Radar and SMW as Interference Source

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.
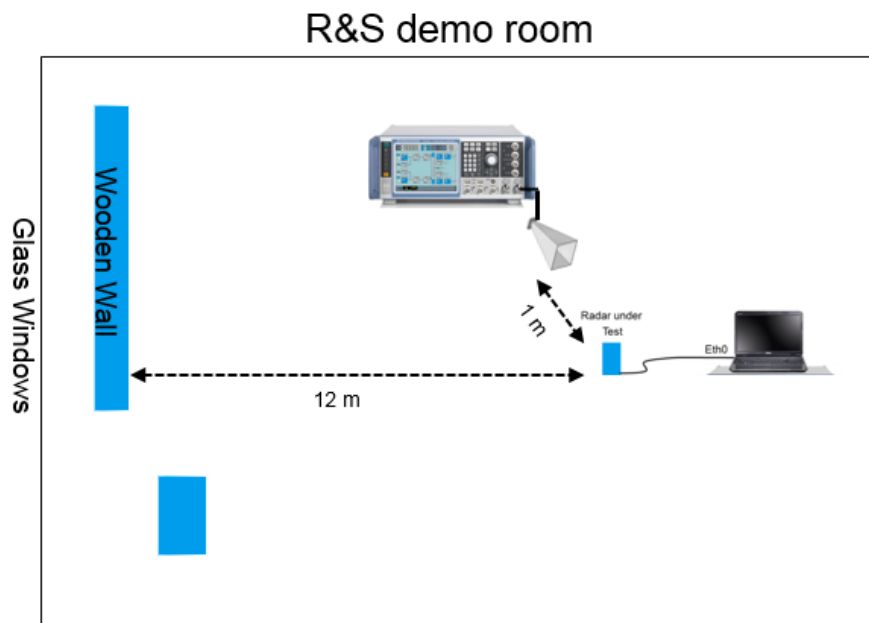

Figure 33: simplified sketch of the demo room

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 RUT)

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

Please note: There is no detailed analysis given, the setup and measurement results should only present the approach to interference testing. There is no triggering or any time correlation between the interfering signal and the RUT. Interference signal power and content has not been matched to the RUT, except for the carrier frequency.

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 34.

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).
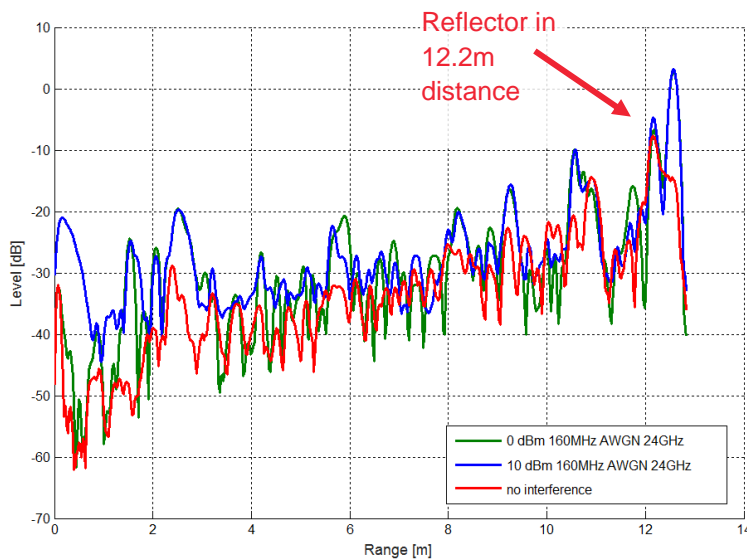

Figure 34: Scenario 1, AWGN interferer

4.3.2 Interference due to another FMCW signal

In here we compare the FMCW generated by the SMW and the Pulse Sequencer software as the interferer to the RUT 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 RUT 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
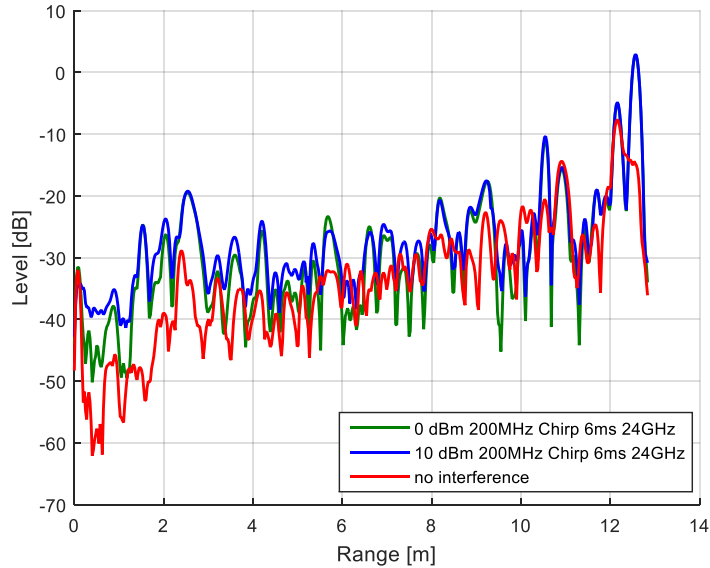

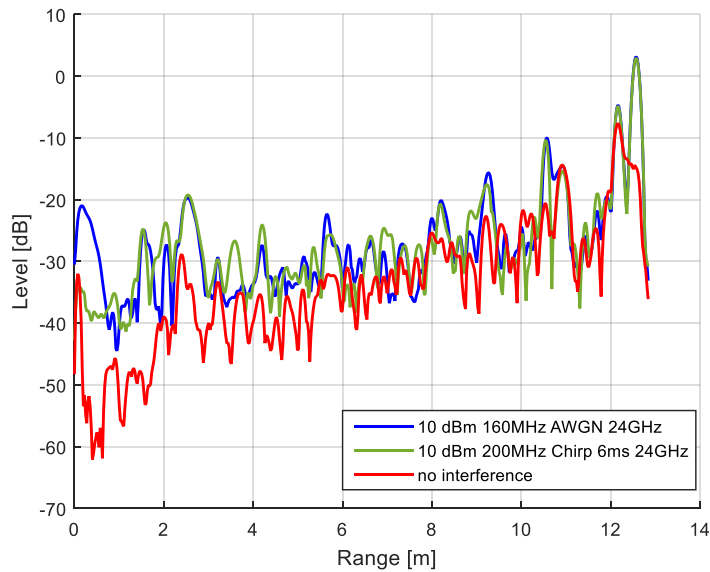**Figure 35: Scenario 2, FMCW interferer**

Figure 36: 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 RUT operates 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 37. This high signal power (blue trace at 0.2m range) could be interpreted as a target.
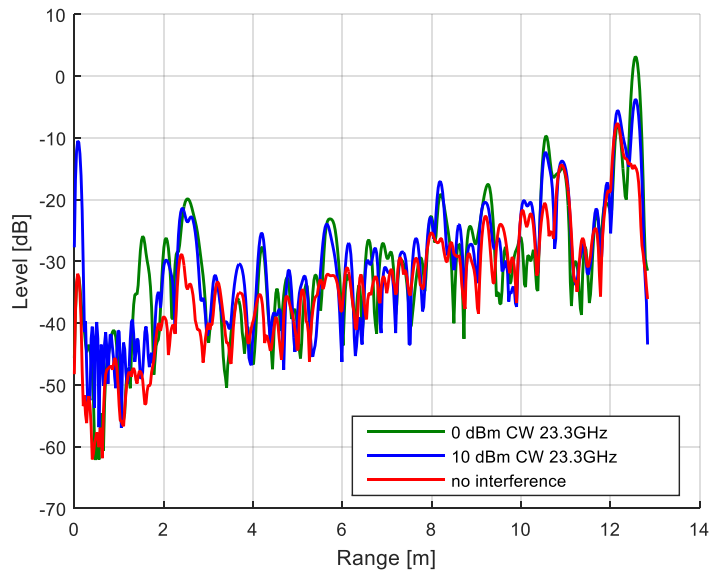
Figure 37: Scenario 3

4.4 **Measurement results of a 76 GHz radar**

This section describes the measurement results from a 76 GHz INRAS Radarbook [8] in presence of interference. The interference signals were generated by a single path SMW vector signal generator (up to 20 GHz) in combination with the SMZ90 frequency multiplier as explained earlier in this application note. Three different interference scenarios are generated using the Pulse Sequencer Software as described in section 4.2.

1.   Upchirp. The upchirp interferer occupies a similar bandwidth and chirprate compared to the radarsignal.

2.   Downchirp. The downchirp interferer occupies the same bandwith as the upchirp but with negative chirprate compared to the radarsignal.

3.   CW signal at a carrier frequency of 76.225 GHz (center frequency of the RUT).

In contrary to the measurement of a 24 GHz radar at section 4.3, the test equipment receives a trigger from the RUT to correlate the interference scenario. In a real life scenario this might not often be the case, but satisfies the means to investigate the radar signal processing in such an occasion. The SMW-B9 baseband wideband option was used to receive the trigger and to initiate the interference. The setup is shown in Figure 38. The FSW Signal and Spectrum Analyzer is only used for verifying the RUT transmission. The trigger signal from the RUT is connected to the SMW Vector Signal Generator.
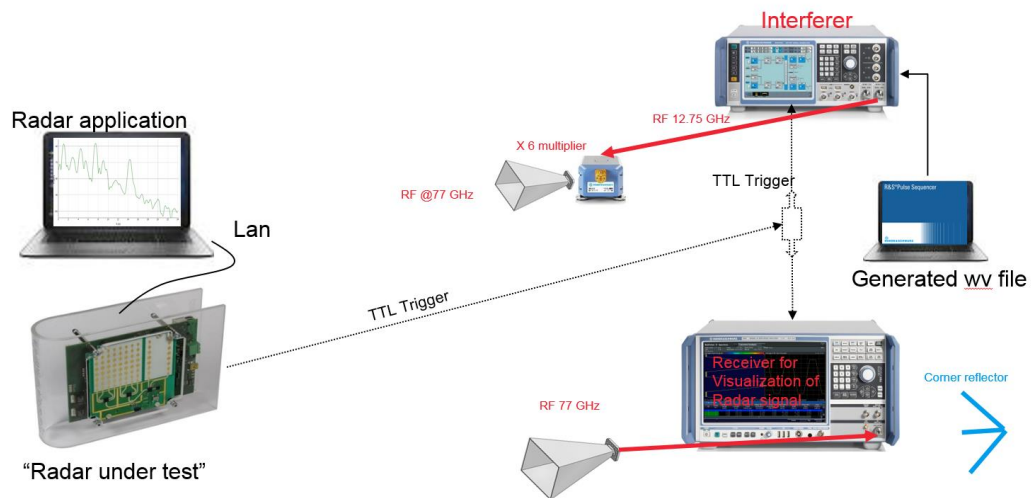

Figure 38: Measurement setup using a 77 GHz Radar and SMW+SMZ90 as Interference Source

As it can be seen in Figure 39 the RUT applies an FMCW up-/ downchirp signal with 450 MHz signal bandwidth, the upchirp has a chirprate of ~900 kHz/us and length of 500 µs and downchirp ~-14062 kHz/us and ~26 µs.

Chirp Sequence waveforms usually have chirp length of 10-50 µs. However, compared to the 24 GHz radar mentioned above, which uses a 20 ms chirp duration, 500 µs is already short enough.
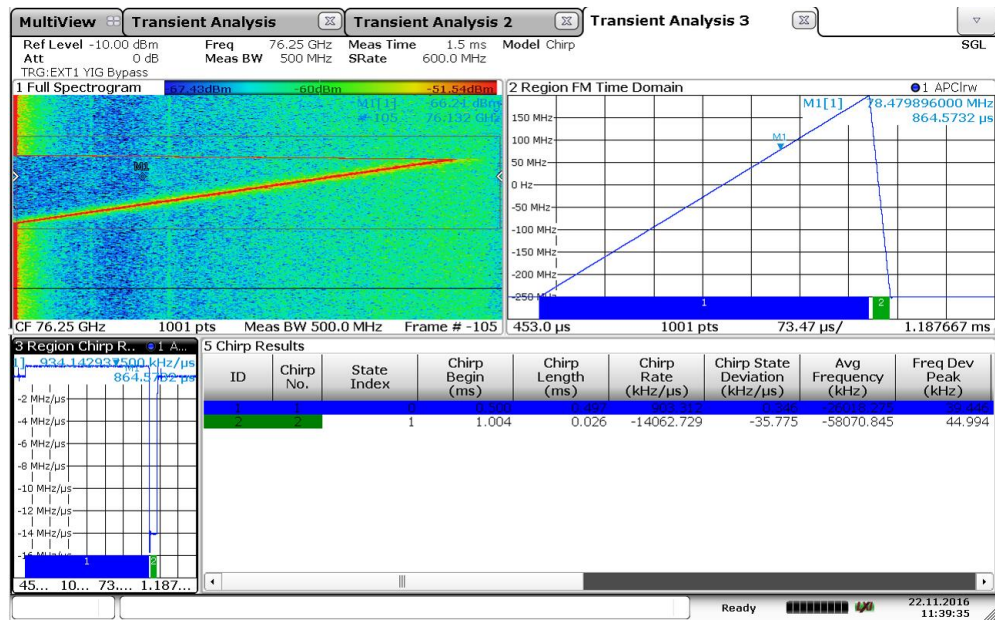
Figure 39: Signals emitted from the Inras [8] RUT

The distance from the SMZ90 interfering source to the radar sensor is 1 m. The level stated in the measurements below is the SMZ90 RF output power for CW signal. To get the expected receive power you have to calculate the free space path loss L, for 1 m distance at the corresponding frequencies:

$$L = 20\ log_{10}(distance) + 20\ log_{10}(frequency) + 20\ log_{10}\left(\frac{4\pi}{c}\right) = 70{,}1\ dB\ at\ 76.5\ GHz$$

Equation 4-3: Free Space Loss

The TX antenna gain G_t of the pyramidal horn antenna is specified with 25 dBi at 76 GHz

The SMZ90 has an output power Ptx of 2.8 dBm at 76.3 GHz (measured with an input power of 6.4 dBm from the SMW for a CW signal).

This yields to the absolute receiving power Prx at the radar of -42.3 dBm for a CW signal.

$$Prx = Ptx\ (SMW/SMZ90) + Gt - \text{L}(1\text{m}) \approx 2.8\ dBm + 25\ dB - 70.1\ dB \approx -42.3\ dBm$$

There are additional gains and losses at the RUT due to its antenna structure and LNAs.

The radar was pointing into the office room with a reflector in 6 m distance and an office wall at 14 m distance. There are also other objects in this room which are detected by the radar.

10 measurement cycles (FFT captures) have been performed and the mean values have been calculated by the INRAS radar software. Each mean FFT spectrum is compared to the mean spectrum of a "no interference" situation.

4.4.1 No interference

As a reference a "no interference" mean spectrum is introduced in all measurement results. Three main obstacles can clearly be seen in Figure 40. The test rack on which the SMW and the FSW are location in front of the radar, the corner reflector at 6 m and the office wall at approx. 14 m range. There are also several other reflections.
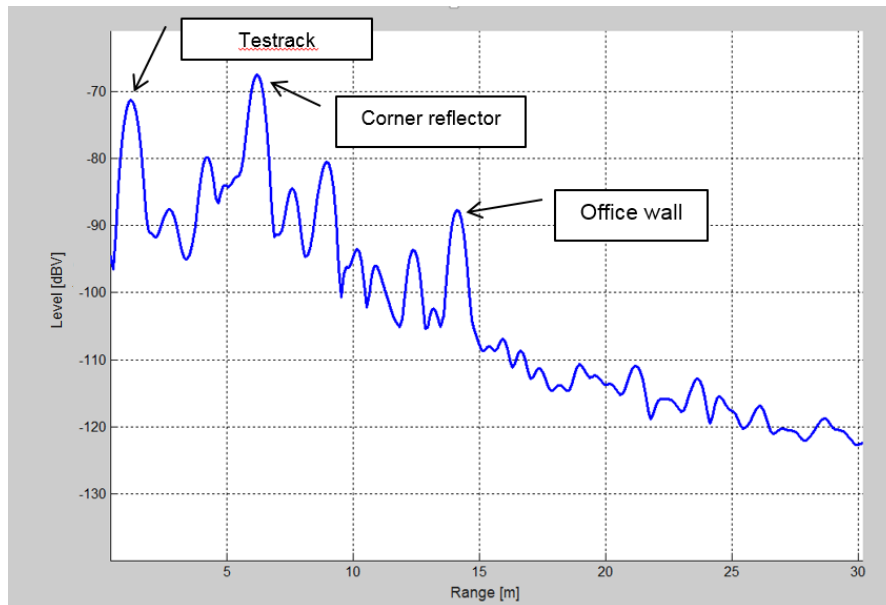

Figure 40: Spectrum of a "no interference" scenario

4.4.2 Interference caused by a time aligned upchirp signal

In this section we compare the RUT behavior on an FMCW interferer signal, generated by SMW and Pulse Sequencer Software, to the RUT's "no interference" situation. The mean spectrum of both scenarios taken from the RUT are compared.

To visualize the interferer in comparison to the transmitted radar signal, the SMZ90 was put to transmit in the same direction as the radar, so both could be measured by the FSW with K60C and displayed on a spectrogram window as shown in Figure 41 and the following FSW-K60C figures.
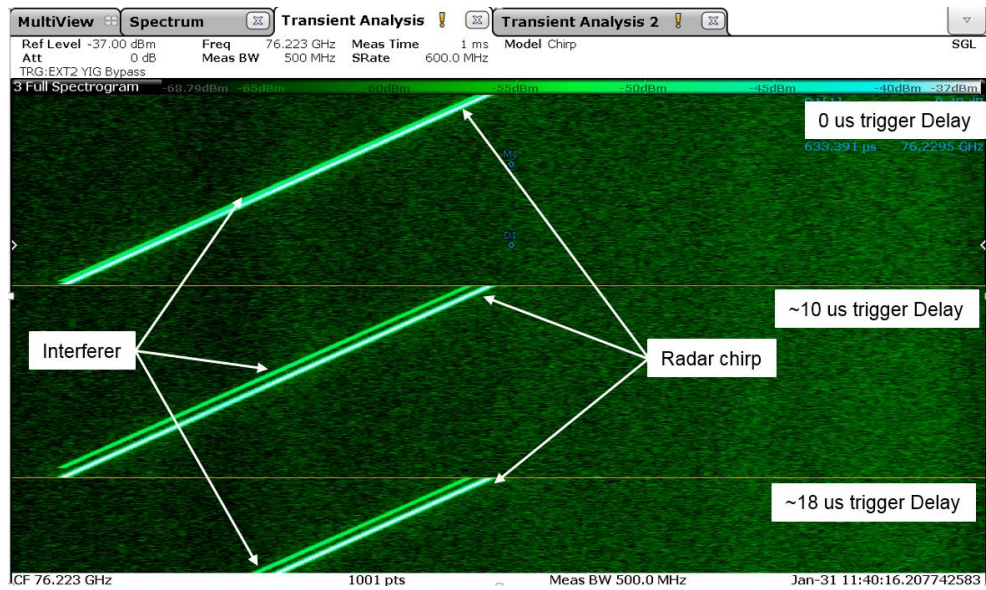
Figure 41: FSW-K60C Spectrogram time aligned triggered interferer (3 triggered delays)

The contribution of the interference signal is drawn as a pink curve in Figure 42. It can be seen that the "office wall" in 14 m range disappeared due to the increased noise level. Also the echo signal power of the close target in 1 m range has decreased by 9 dB.
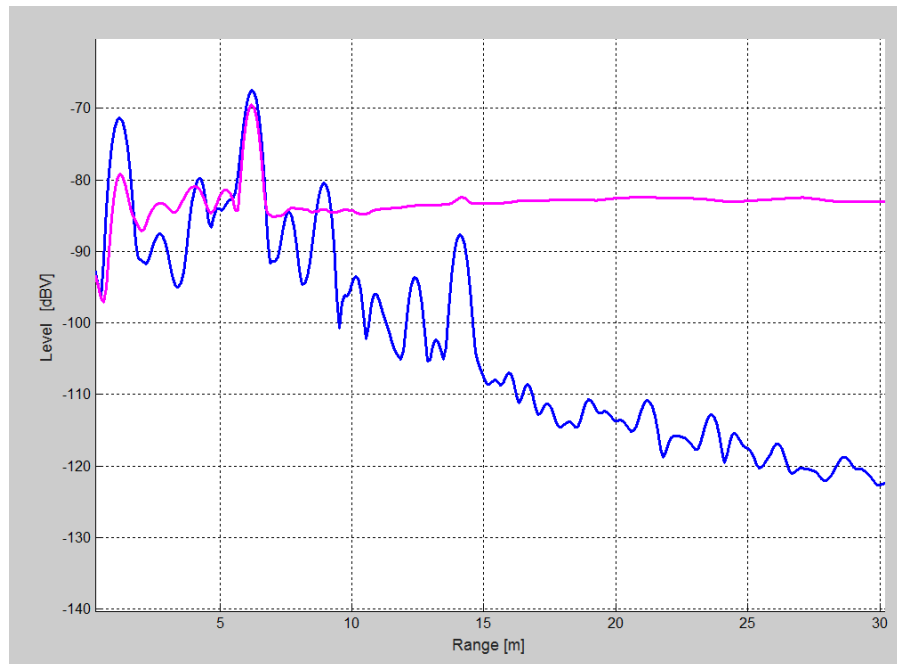

Figure 42: Spectra of the RUT with interferer (time aligned chirp in pink) and without interference (blue)

4.4.3 Interference caused by a downchirp signal

In this section a downchirp signal interference is triggered while the RUT is transmitting its upchirp as shown in Figure 43.
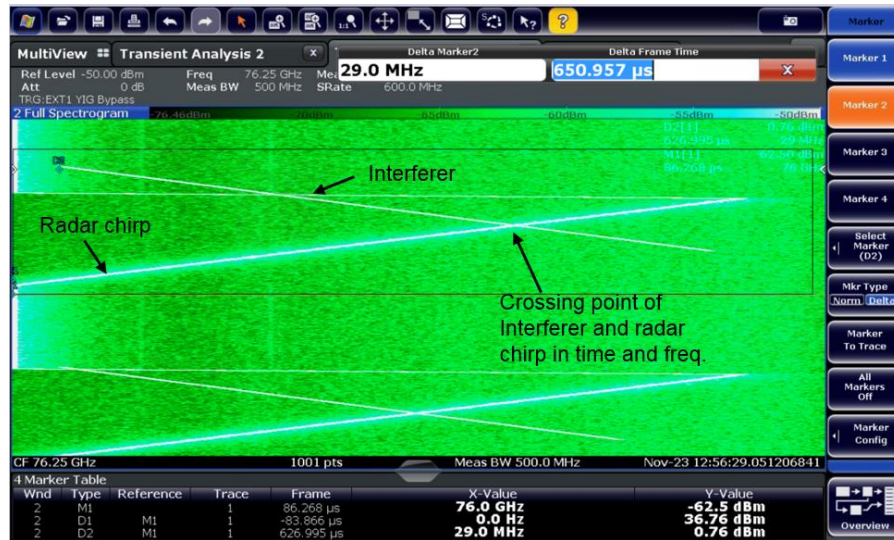

Figure 43: FSW-K60C Spectrogram downchirp interferer

The contribution of this interferer to the RUT is shown in Figure 44. In comparison to the time aligned upchirp, the downchirp has a different impact. The "office wall" at 14 m range can still be detected, but with less SNR.
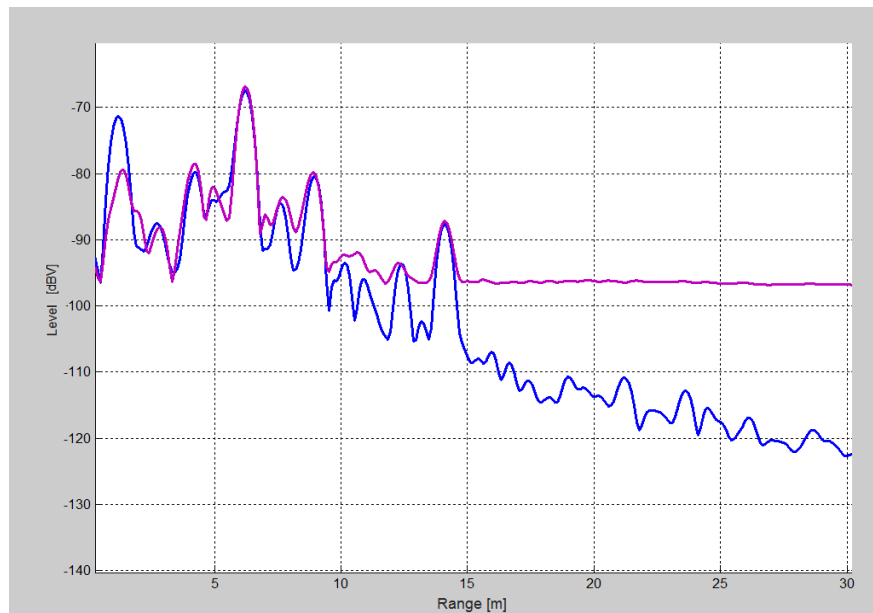

Figure 44: Spectra of the RUT with inverted chirp interferer (pink) vs. no interference (blue)

4.4.4 CW Interference

In a third test we make use of a CW signal, which is present at the center frequency of the RUT (76.23 GHz) as shown in Figure 45.
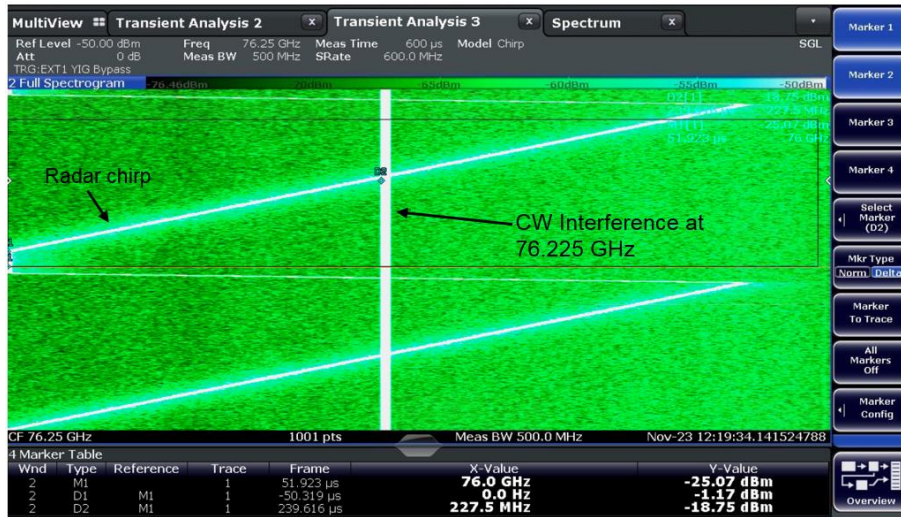
Figure 45: FSW-K60C Spectrogram, CW Interferer at the center frequency of the RUT

The impact is shown in Figure 46. Similar to the other results, the noise floor of the spectrum rises.

Figure 46: Spectra of the RUT with CW interferer (red) vs. no interference (blue)

The comparison of all three interference scenarios is shown in Figure 47 for a radar range up to 100 m. These measurements verify that the noise floor rises depending on the interference signal. Some targets cannot be detected anymore.

Figure 47: Spectra of the RUT with all Scenarios vs. No Interference (blue)

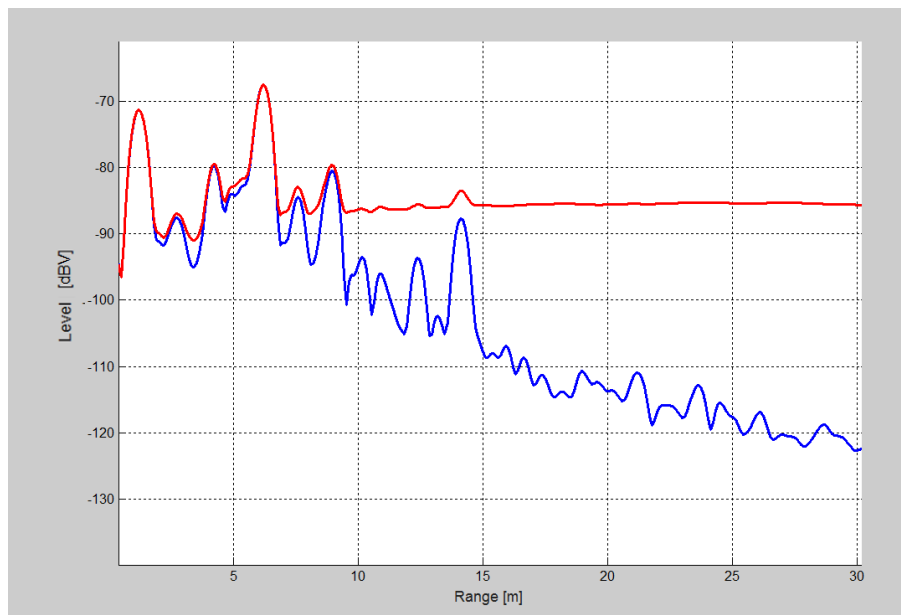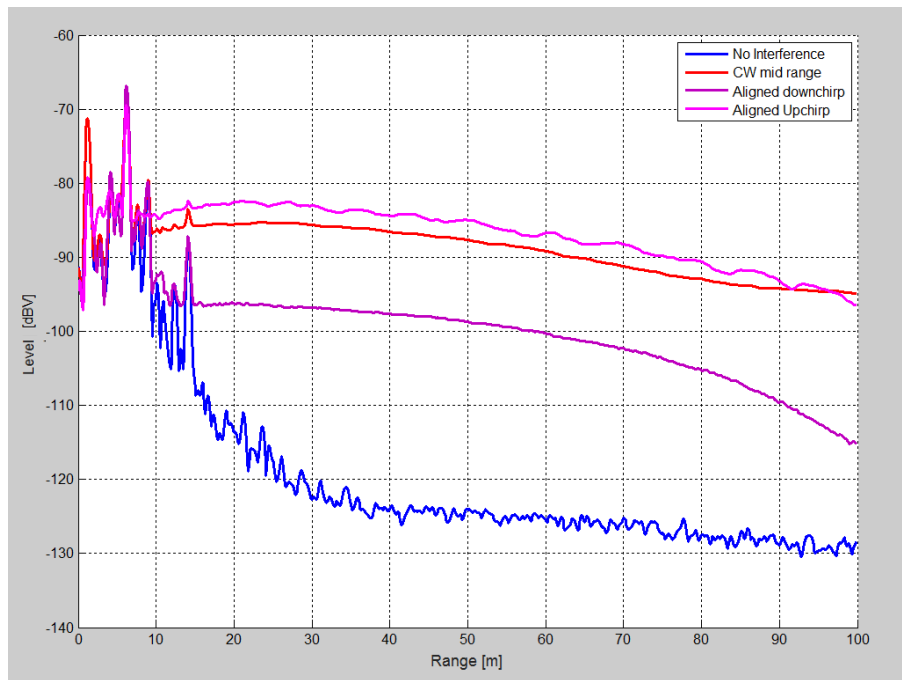# 5 Summary

Automotive radar sensors already allow increased driving comfort. In combination with additional sensor systems, like cameras and/or lidar (light detecting and ranging), they will pave the way for autonomous driving in the future. One advantage of automotive radar sensors is, that they deliver essential environment information under all weather conditions and under any driving conditions (as long as the radar is not covered by snow or any other highly reflective obstacle)

Verification according to standards relevant for the radar signals is important. These standards deal with the emitted power and spectral emissions. Transmit signals can be arbitrary and are not defined by a standard. When considering spectral masks and frequency occupation this may not only reduce the radars own performance, but may also interfere with other radars nearby. Even radars from the same manufacturer and type may interfere with each other under certain conditions.

With a steadily increasing number of automotive radar sensors on the streets, mutual interference needs to be considered. Depending on the applied radar waveform, sampling rates and filter bandwidth interference might cause the radar to be blind.

This application note presented Test & Measurement setup to measure and analyze high frequency and large bandwidth continuous wave radar signals. It introduced an approach to test interference scenarios using commercial off-the-shelf test and measurement equipment. It could be seen that other radar's signals cause the noise floor of a RUT to rise strongly. Targets with small radar cross section could not be detected reliably anymore in all cases.

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/

[8]   Inras GmbH radar evaluation board http://www.inras.at/en/products/radarbook.html

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
Wideband Baseband Generator with ARB (256 Msample), 500 MHz RF bandwidth	R&S®SMW-B9	1413.7350.02
Baseband Extension to 2000 MHz RF bandwidth	R&S®SMW-K526	1413.9318.02
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
ARB Memory Extension to 2 Gsample	R&S®SMW-K515	1413.9360.02
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).5) 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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