Advanced methods for analyzing ultra wide automotive radar signals

White paper

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Automotive FMCW radars typically operate between 76 GHz and 77 GHz. In some countries, the frequency range between 77 GHz and 81 GHz has become available for automotive radar applications. The distance resolution of an FMCW radar is proportional to its signal bandwidth. Therefore, automotive radar manufacturers are already developing FMCW radars with bandwidths of several GHz to get the most out of the available frequency range.

In addition to signal frequency and bandwidth, the signal linearity and chirp duration determine radar performance. It is therefore important to analyze automotive radar signal parameters such as chirp length, chirp rate and frequency deviation.

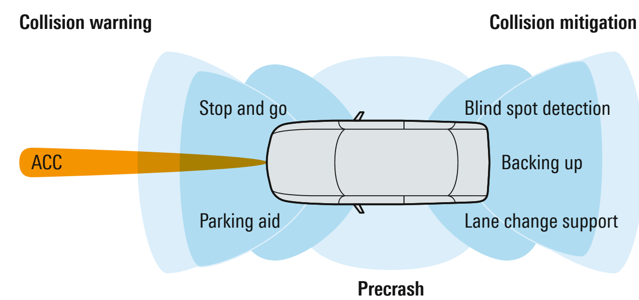
This paper will review different ways to overcome the challenges of RF measurements in the E band for ultra wide signals. It will look at the demodulation and analysis of a wideband automotive radar signal and discuss the results and main performance parameters.

Introduction

Radar makes it possible to quickly and precisely determine the velocity, distance and azimuth angle of multiple objects.

Automobiles advanced driver assistance systems (ADAS) are increasingly being equipped with radar sensors to support drivers in critical situations and help reduce the number of accidents.

Fig. 1: Vehicles are increasingly equipped with radar sensors



In addition to the 77 GHz band (76 GHz to 77 GHz), the 79 GHz band (77 GHz to 81 GHz) has become available in some countries for automotive radar. Therefore, the automotive industry is already developing radar sensors operating in the E band with signals several GHz wide.

The distance resolution of a radar sensor is proportional to its signal bandwidth, i.e. the wider the bandwidth, the better the radar sensor's ability to distinguish between different targets that are close to each other.

Signal bandwidth alone is not enough to ensure the distance resolution or radar performance. Other signal parameters such as frequency, power, frequency deviation from linear FM chirp, signal to interference ratio, chirp rate and chirp duration need to be thoroughly tested during development and verification of radar components.

Analyzing 5 GHz wide automotive signals in the E band represents a challenge for traditional test and measurement equipment. In this paper, we show how a high-performance signal and spectrum analyzer combined with an oscilloscope helps automotive radar manufacturers overcome this challenge.

RF measurements in the E band (60 GHz to 90 GHz): spectrum analyzer versus external harmonic mixers, aspects to consider

Spectrum analyzers are a common tool for evaluating RF parameters such as frequency, EIRP, occupied bandwidth and out-of-band emissions during development, production and verification of radar sensors. High-performance spectrum analyzers operating up to 90 GHz are available today to measure RF signals transmitted by radars operating between 76 GHz and 81 GHz directly. If a spectrum analyzer does not support such high frequencies, its frequency range can be extended using external harmonic mixers. This section points out the main aspects to consider when using these different approaches.

Measurements in the E band with external harmonic mixers

Most spectrum analyzers do not directly support frequencies as high as 79 GHz. In this case, the frequency range of the analyzer can be extended with external harmonic mixers. A harmonic of the LO signal produced in the mixer is used to convert the input signal to the spectrum analyzer IF frequency.

Fig. 2: The R&S®FSW26 (up to 26.5 GHz) can be used with the R&S®FS-Z90 external harmonic mixers (60 GHz to 90 GHz) to measure RF signals in the E band.

The frequency conversion done by the mixer can be expressed with the following equation:

$$\left| m \cdot f_{LO} \pm n \cdot f_{RF} \right| = f_{IF}$$

Where:

m is the order of the harmonic of the LO signal (m = 1, 2, 3 ...)
n is the order of the harmonic of the microwave input signal (n = 1, 2, 3...)
f_{LO} is the frequency of the local oscillator
f_{RF} is the frequency of the input signal
f_{IF} is the intermediate frequency

Looking at the formula above, one can deduce that in addition to the input signal at the wanted receive frequency, there are also a number of unwanted images and mixing products. External harmonic mixers do not have a preselection filter and do not provide image rejection. Therefore, unwanted mixing products will be present in the spectrum as shown in Fig. 3.

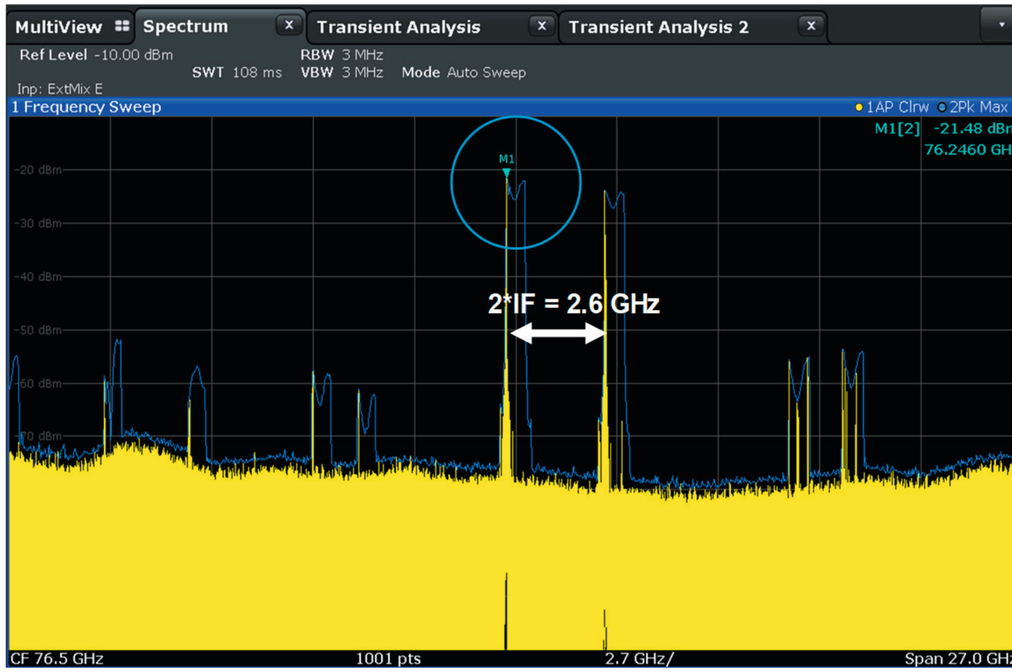


Fig. 3: Spectrum from 60 GHz to 90 GHz measured with the R&S®FS-Z90 external harmonic mixer connected to the R&S®FSW43. The wanted signal at 76 GHz is 500 MHz wide. The closest image is located at twice the spectrum analyzer intermediate frequency from the signal. Other unwanted mixing products and their images are also present.

The delta between the wanted signal and its image is twice the spectrum analyzer intermediate frequency $(2 \cdot f_{IF})$. If the signal bandwidth is wider than $(2 \cdot f_{IF})$, the wanted signal and its image will overlap in spectrum.

The R&S®FSW has an intermediate frequency (IF) of 1.3 GHz, so it provides an image-free frequency range of 2.6 GHz for spectrum analysis with external harmonic mixers.

To ensure unambiguous spectrum measurements, it is necessary to filter out unwanted image frequencies.

Software algorithms using double sweep techniques can identify and suppress unwanted mixing products. These algorithms work well with static signals, but reach their limitations when working with pulsed or transient signals, which are usual in radar applications.

Measurements in the E band with a signal and spectrum analyzer (2 Hz to 90 GHz)

The R&S®FSW85 high-performance signal and spectrum analyzer covers frequencies between 2 Hz and 85 GHz or optionally 90 GHz.

For frequencies between 8 GHz and 85 GHz, the analyzer features hardware preselection to reject unwanted image frequencies. The frontend is equipped with a narrow bandpass filter implemented with YIG technology. The center frequency of the YIG filter corresponds to the input signal, and its narrow band allows the unwanted image frequencies to be filtered out.

After the YIG filter, the mixer converts the input RF signal to an IF of 1.3 GHz. In Fig. 4 you can see an image-free, 500 MHz wide signal at 76 GHz.

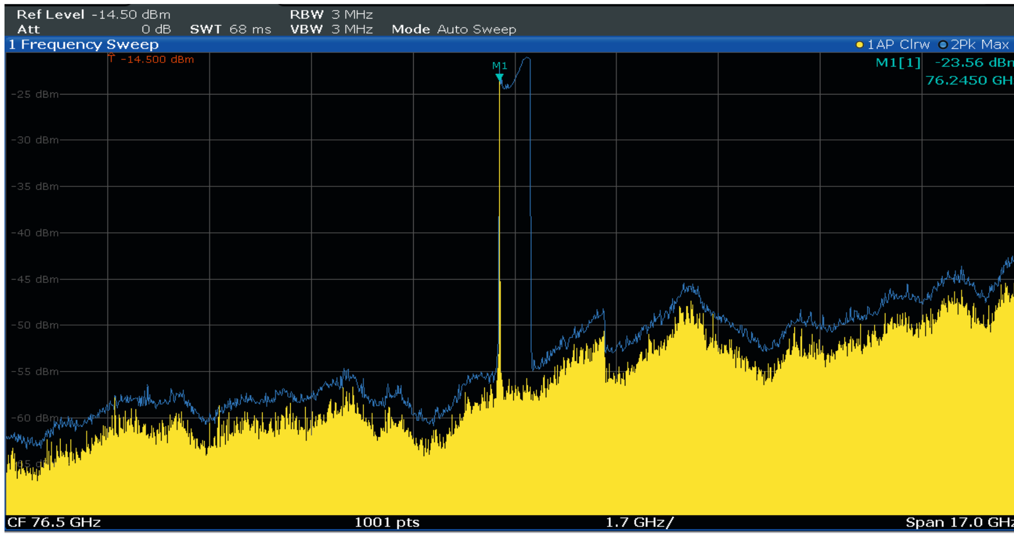


Fig: 4. Spectrum of a 500 MHz bandwidth FMCW radar signal at 76 GHz, measured with an R&S®FSW85

Analyzing the spectrum with a single instrument that supports the required frequency has several advantages over external harmonic mixers:

- Gapless spectrum from DC to 85/90 GHz
- Inherent image suppression with preselection/YIG filter in spectrum analyzer mode
- Better level adjustment: internal adjustment of attenuators, etc.
- Less cabling
- Higher dynamic range for SEM measurements

An optional external preamplifier up to 85 GHz improves the spectrum analyzer’s noise floor. This is especially useful when measuring radar signals over the air.

Fig. 5: R&S®FSW85 signal and spectrum analyzer with the R&S®HA-Z24E external preamplifier (1 GHz to 85 GHz)

Ultra wideband measurements with spectrum analyzers

The demand for analysis bandwidth is continuously increasing, driven by industry demands for aerospace and defense, wireless and automotive applications. Consequently, signal and spectrum analyzers with an internal demodulation bandwidth of up to 2 GHz are commercially available today. The R&S®FSW signal and spectrum analyzer with internal bandwidth options executes wideband measurements up to 2 GHz bandwidth with more than 60 dBc spurious free dynamic range (SFDR).

To demodulate and analyze automotive radar signals, especially in R&D labs, demodulation bandwidths of up to 5 GHz are required. For this purpose, it is possible to combine a high-performance signal and spectrum analyzer with an oscilloscope as an external A/D converter.

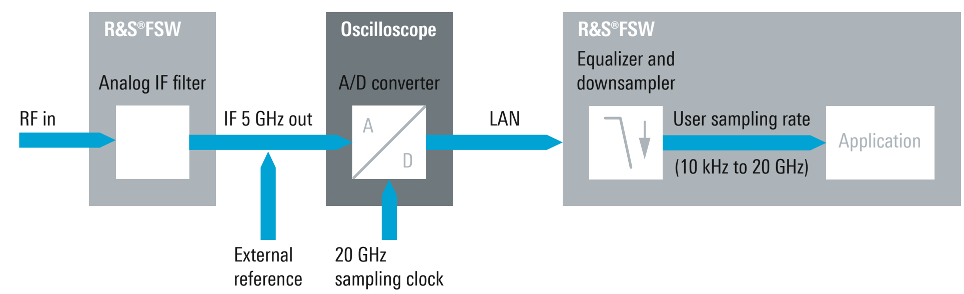
Fig. 6: The R&S®FSW85 signal and spectrum analyzer equipped with the R&S®FSW-B5000 hardware option used together with an R&S®RTO2064 oscilloscope as an external digitizer provides an equalized 5 GHz signal analysis bandwidth.

Depending on the measurement bandwidth set by the user, the analyzer downconverts the signal to an intermediate frequency of 2.8 GHz or 3.5 GHz. The oscilloscope digitizes the signal and transfers the digitized data back to the analyzer via LAN. Fig. 7 shows a block diagram of the signal processing.

The entire signal path from the spectrum analyzer's RF input to the oscilloscope's A/D converter is characterized with respect to amplitude and phase response. The digital data from the oscilloscope is mixed to the digital baseband and the measurement applications receive equalized I/Q samples.

The connection between the oscilloscope and the analyzer is completely transparent to the user. The signal analyzer fully controls the oscilloscope, transferring, processing and equalizing the digital data.

Fig. 7: Signal processing block diagram to achieve 5 GHz demodulation bandwidth with the R&S®FSW, the R&S®FSW-B5000 option and the R&S®RTO2064



The R&S®FSW downconverts the signal to an intermediate frequency of 2.8 GHz or 3.5 GHz. The R&S®RTO2064 then digitizes the signal with a sampling rate of 20 GHz and transfers it back to the R&S®FSW via LAN. Various R&S®FSW measurement applications can analyze the resulting I/Q data.

Maximum measurement time with activated 5 GHz I/Q bandwidth extension

The 5 GHz bandwidth extension makes it possible to capture ultra wide chirp sequences without missing any data. In each sweep or I/Q data acquisition, the analyzer captures a certain amount of gapless data.

The longest gapless sequence the analyzer can capture with 5 GHz bandwidth depends on the data rate that the oscilloscope processes and on the installed memory updates.

If the oscilloscope uses a sampling rate of 20 GHz and has a memory depth of 2000 Msample, the maximum record length that can be achieved for a measurement bandwidth of 5 GHz is calculated as:

$$\left(\left(2000 \text{ Msample} \cdot 6.25 \text{ GHz}\right)/20 \text{ GHz}\right) - 100 = 624.999900 \text{ Msample},$$

where 6.25 GHz is the sampling rate used by the analyzer for 5 GHz analysis bandwidth. The maximum measurement time can be calculated as:

$$MaxMeas\_time(s) = \frac{MaxRecordLength\_analyzer(Msample)}{Sampling\_Rate_{Analyzer}(GHz)} = \frac{624.99}{6.25} \cong 100 \text{ ms}$$

The formula indicates that an R&S®FSW equipped with the 5 GHz analysis bandwidth extension and used with an R&S®RTO2064 oscilloscope is able to capture up to 100 ms of gapless I/Q data in a single acquisition. Different measurement applications allow in-depth analysis of the captured I/Q data. The section below shows an example of wideband analysis of an FMCW chirp signal with a bandwidth close to 5 GHz at 77 GHz, similar to the signals used in automotive radar applications.

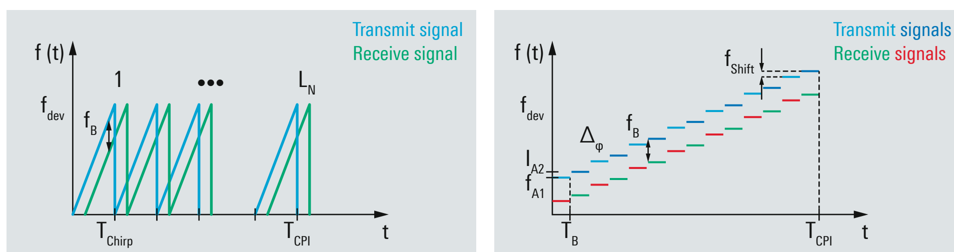
Analysis of an FMCW signal in the E band: measurement approaches and performance parameters

The most common waveforms used in automotive radar are typically chirped or hopped continuous wave (CW) signals. There is not a common waveform standard. Waveforms are specific to each radar manufacturer and belong to their intellectual property.

CW radars have low transmit power compared to pulsed radar systems. This allows the radar to be compact in size and economical. Other advantages such as zero blind range, direct measurement of Doppler frequency shift and the possibility to measure static targets make CW signals very well suited for the automotive and industrial sector.

The first automotive radars used hopped signals like MFSK. Nowadays, an increasing number of automotive radars generate frequency modulated chirp waveforms, e.g. slow LFMCW or fast FMCW waveforms.

Fig. 8: Frequency modulated continuous wave (FMCW) chirp waveforms (left) versus multiple frequency shift keying (MFSK) waveforms (right)

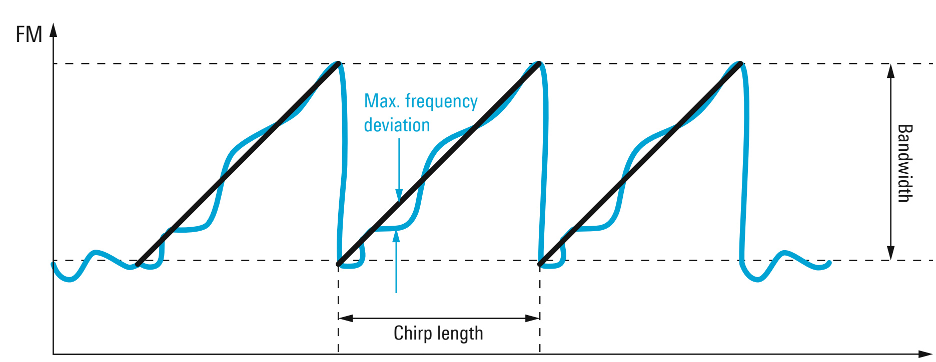


Most automotive radars use chirp sequences consisting of several very short linear frequency modulated continuous wave (LFMCW) chirps, each with a duration of T_{Chirp} transmitted in a block of length T_{CPI}.

Parameters such as signal bandwidth, chirp duration and chirp rate have a direct influence on the radar's distance and velocity resolution.

The achieved range and radial velocity resolution also depends on the signal linearity. Unwanted effects in the radar signal will affect the estimation accuracy and radar system performance.

Fig. 9: Linearity parameters for chirped signals



For the analysis of continuous wave radar signals, a dedicated measurement application is available. It supports the analysis of chirped signals. The measurement application detects the beginning and end of individual chirps within I/Q data captured by the signal analyzer. It calculates all performance parameters within a user-defined analysis range, i.e. a measurement bandwidth and acquisition time.

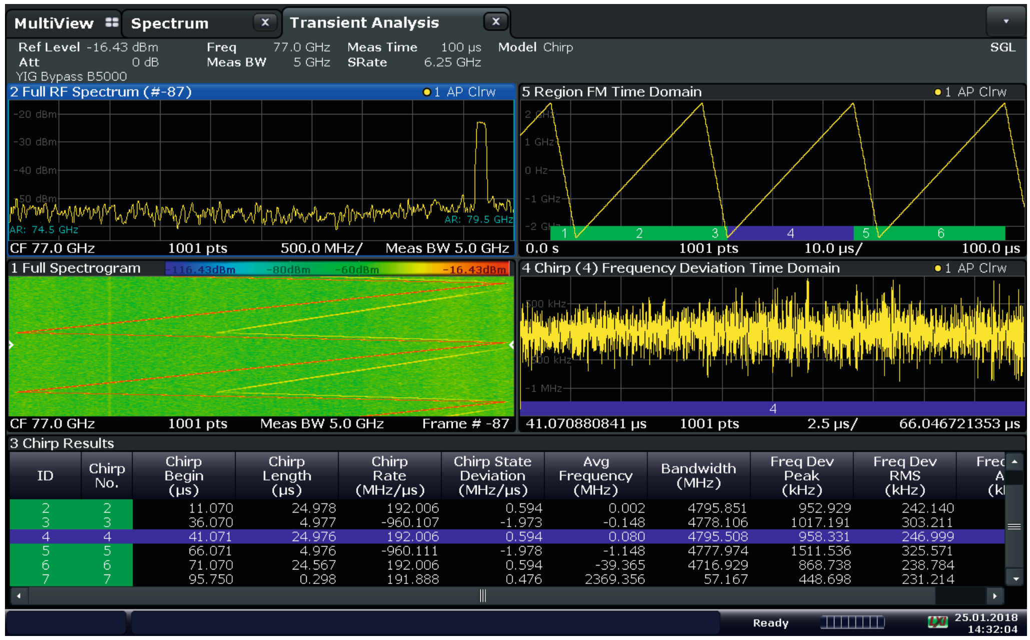


Fig. 10: R&S®FSW-K60c transient measurement application

The figure above shows a screenshot of the chirp measurement application:

- The "Full Spectrogram" graph shows the full I/Q capture buffer in the time (vertically upwards) and frequency (horizontal) domain. The color indicates the power level.
- In this example, the measurement time has been set to 100 µs; six frequency chirps with a bandwidth close to 5 GHz have been captured.
- The "Full RF Spectrum" graph represents an FFT of a part (frame) of the capture buffer. Here it is the last frame – the upper line in the spectrogram. The main carrier is visible.
- The "Region FM Time Domain" displays the frequency modulation (FM) of the signal versus time; a blue or green color bar underlines the 6 detected chirps. A video filter of 1 % of the demodulation bandwidth (i.e. 50 MHz) filters out unwanted signals and noise before the peak detector.
- The "Chirp Frequency Deviation Time Domain" displays the frequency error of the demodulated FM signal versus time for one of the detected chirps.
- The "Chirp Results" table displays all parameters of interest for all detected chirps.
- In the example, the application detects the chirps automatically and calculates the frequency deviation assuming a best fit linear chirp as a reference.

The next section explains chirp detection and linearity measurements in detail.

Chirp detection

By default, the analysis application automatically detects the so-called chirp states: the different nominal chirp rates in MHz/µs and a tolerance span to compensate for settling effects. As long as the chirp rate deviation remains within the tolerance above or below the nominal frequency, the chirp is detected.

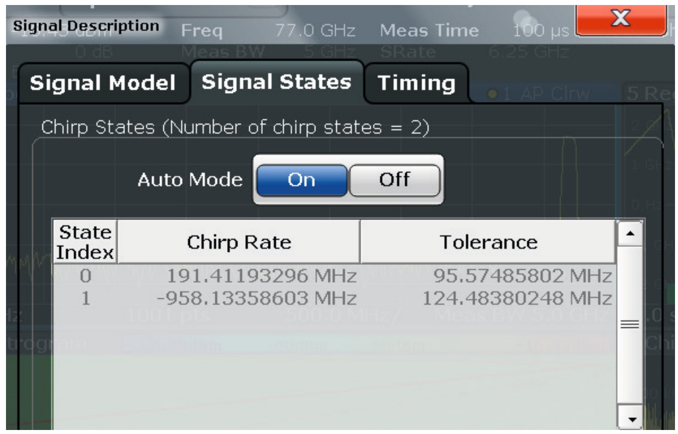


Fig. 11: Signal description table in the R&S®FSW-K60C application, chirps are detected automatically (auto mode: on)

In the default automatic mode, the application calculates the nominal chirp rate and the tolerance from the chirp rate time domain trace (Fig. 12). The application calculates the distribution of the measured chirp rate and detects those parts of the signal with a relatively constant chirp rate.

The nominal chirp rates in the signal description table are those chirp rates that occur more often. The tolerance value increases if the signal noise increases and the chirp rate is not constant.

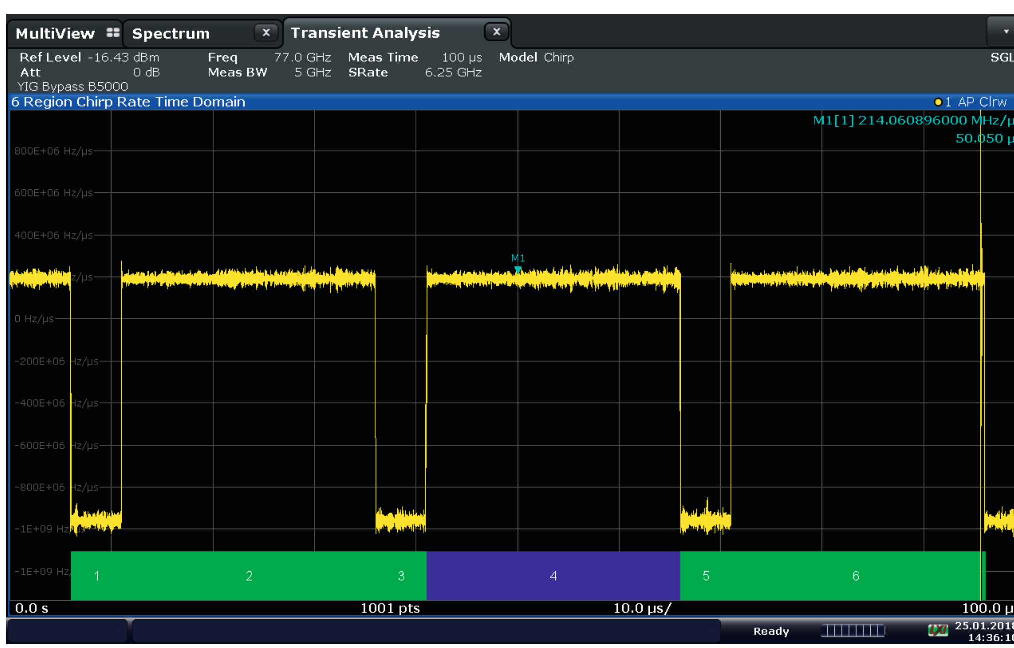


Fig. 12: Chirp rate measurement in the time domain used as a base for chirp detection

For an initial overview of the signal, the default automatic detection is usually sufficient. If you know the signal's nominal frequency or chirp rate values, you can enter those manually in the signal states table (Fig. 11) and turn auto mode off. The application will then detect the chirps that meet the user-defined chirp rate and tolerance values.

Chirp linearity measurement: best fit versus user defined

For radar systems using chirped frequency modulated (FM) signals, FM linearity is an important measurement. The FM and the frequency deviation in time domain measurements are key when measuring linearity.

The frequency deviation in the time domain is calculated with respect to a certain FM reference signal.

By default, the FM reference signal is calculated directly from the average measured chirp rate (Fig. 12). Any deviation from the measured average chirp state is compensated for.

The default setting is recommended if you want to see the smallest deviation from a best fit of the model parameters In this case, the compensate chirp state deviation checkbox is activated (Fig. 13).

Fig. 14 shows an example of a linearity measurement using the best fit approach focusing on one chirp. A marker has been set to highlight the peak frequency deviation in the time domain.

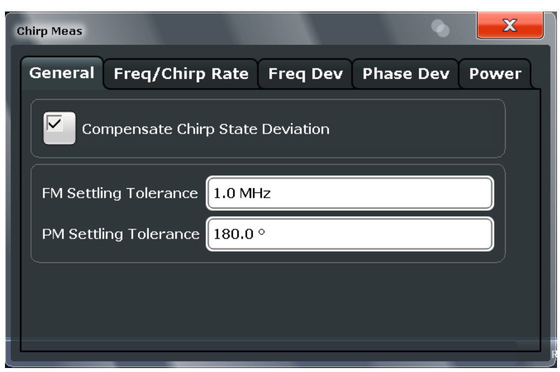


Fig. 13: By default, the measured chirp rate is used to perform the chirp linearity measurement and any deviation to the average chirp state is compensated for.

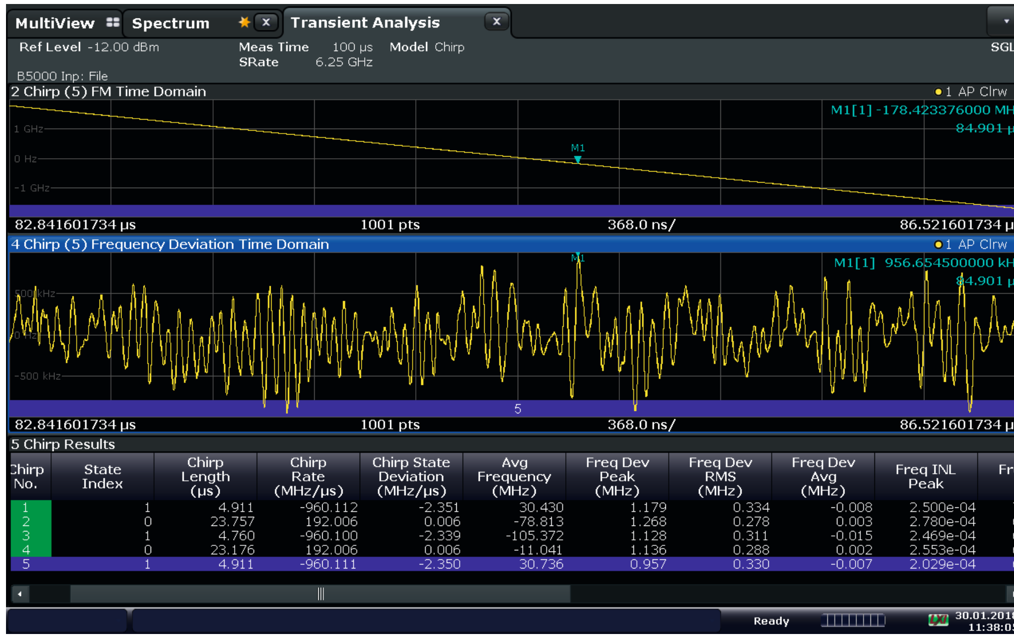


Fig. 14: Example linearity measurement with best fit measurement approach. Focus on chirp 5; FM time domain and frequency deviation time domain parameters

In practice, it is often required to measure the FM deviation trace with respect to a known, user-defined nominal chirp rate in order to verify that the radar signal meets the specified chirp rate and tolerance.

In this case, you can turn auto mode off and enter the specified chirp rate and tolerance values in the signal description table (Fig. 11) and measure the deviation between the measured and specified values. For this measurement, the user must turn off auto mode and deactivate the "Compensate Chirp State Deviation" checkbox.

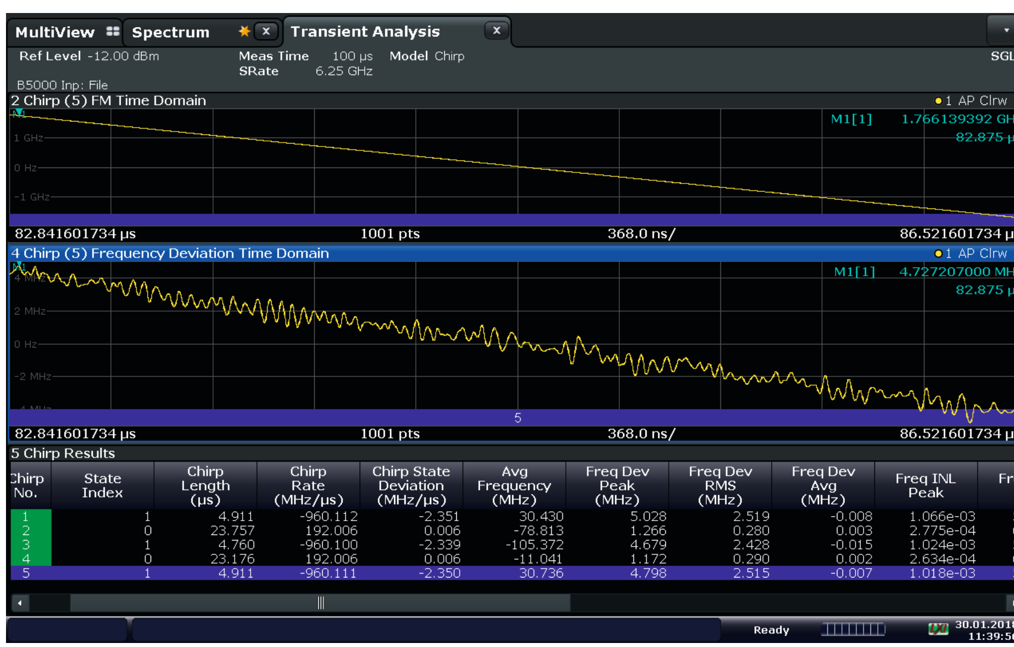


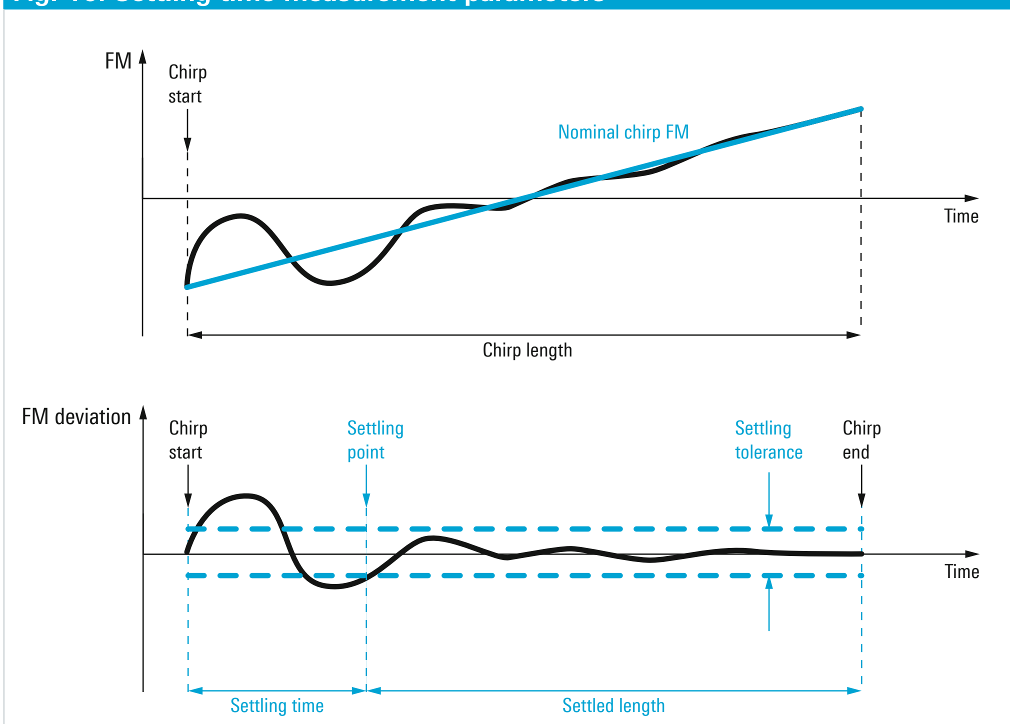
Fig. 15: Frequency deviation calculated using the nominal chirp rate values in the signal description table as a reference instead of the measured average chirp rate (best fit)

Measurement of chirp settling time

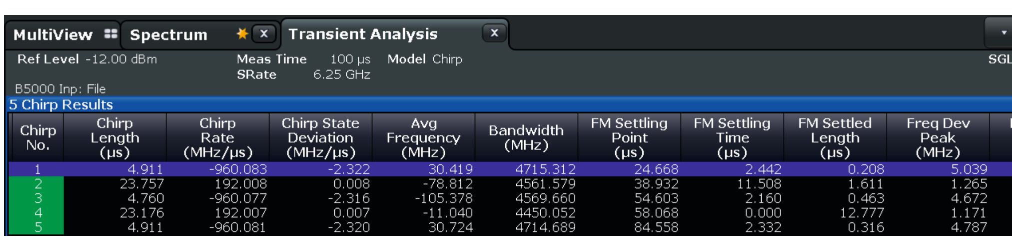
In order to more accurately calculate frequency, phase or power results for chirped signals, you can define a measurement range and take only a certain portion of the chirp into consideration, to eliminate settling effects for instance.

It is also important to measure the chirp settling time, which is the time it takes the FM signal to remain within a specified tolerance around the nominal frequency. Settling parameters such as chirp settling time, settling point and settled length are calculated from the FM deviation taking into consideration the user-defined FM settling tolerance as shown in Fig. 16.

Fig. 16: Settling time measurement parameters



The screenshot below shows the settling time and settling point measurement results for the example signal in Fig. 10, where the FM settling tolerance has been set to 1 MHz around the nominal frequency.



Chirp No.	Chirp Length (µs)	Chirp Rate (MHz/µs)	Chirp State Deviation (MHz/µs)	Avg Frequency (MHz)	Bandwidth (MHz)	FM Settling Point (µs)	FM Settling Time (µs)	FM Settled Length (µs)	Freq Dev Peak (MHz)
1	4.911	-960.083	-2.322	30.419	4715.312	24.668	2.442	0.208	5.039
2	23.757	192.008	0.008	-78.812	4561.579	38.932	11.508	1.611	1.265
3	4.760	-960.077	-2.316	-105.378	4569.660	54.603	2.160	0.463	4.672
4	23.176	192.007	0.007	-11.040	4450.052	58.068	0.000	12.777	1.171
5	4.911	-960.081	-2.320	30.724	4714.689	84.558	2.332	0.316	4.787

Fig. 17: Measurement results for 1 MHz FM settling tolerance

Summary

Rohde & Schwarz offers a flexible, fully integrated and user-friendly solution to overcome the challenges of analyzing ultra wide automotive radar signals in the E band. The R&S®FSW85 makes it possible to measure a gapless spectrum from 2 Hz to 85 GHz or 90 GHz with a single instrument. A built-in YIG filter ensures an image-free spectrum up to 85 GHz.

The R&S®FSW-B5000 5 GHz bandwidth extension combined with an R&S®RTO oscilloscope as an external digitizer offers an equalized and fully characterized signal path. The signal analyzer controls the oscilloscope so that the complete operation is performed through the R&S®FSW user interface.

The transient analysis application running on the R&S®FSW provides flexible and in-depth analysis of signals transmitted by radar chips, sensors and components. It measures the main signal parameters such as signal linearity either automatically or manually depending on the user's needs.

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[5]	R&S®FSW-K60 Transient Measurements User Manual, Rohde & Schwarz, Munich

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