Application Note

VCO MEASUREMENTS WITH R&S FSPN PHASE NOISE ANALYZER

Products:

- R&S® FSPN

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Contents

1 Overview

Next generation technologies in radar and satellite communication with high data rates call for innovative testing solutions to develop and manufacture RF components like voltage controlled oscillators (VCO). The R&S®FSPN phase noise analyzer increases efficiency and reproducibility of VCO characterization and phase noise measurements from lab to production.

Voltage controlled oscillators are oscillators whose output frequency is controlled by means of an external tuning voltage, and they are used in a wide variety of electronic and RF applications like function generators, phase-locked loops including frequency synthesizers used in communication equipment. Different VCO design approaches yield different parameters and performance, and therefore it is important to measure or characterize VCOs under different conditions. This application note provides a short technical introduction to voltage controlled oscillators and explains the most common and the most important measurements made during the VCO characterization process.

2 Oscillator Basics

An oscillator is an electronic device that produces a repeating signal or waveform. In most cases, the output of an oscillator is a sinusoidal signal (harmonic oscillator), although some oscillators are designed to produce sawtooth or triangular waveforms (relaxation oscillator). The primary characteristic of any type of oscillator is the frequency of the signal that it generates, but the stability or spectral purity of the oscillator is also a key performance parameter. It is often important to know how much the output frequency and/or output power change as a function of time, or whether significant harmonics or spurious signals are present at the RF output of the oscillator. Because oscillators are often one of the core components of electronic and RF devices, the quality of an oscillator's output can have a significant impact on the function or behavior of the overall system. Good engineering practice therefore calls for accurate measurement or “characterization” of oscillators during design, debug, production, and/or integration.

Many oscillators have an output frequency that is constant or fixed. In these cases, the oscillator output frequency depends on the design of the oscillator or on the components in the oscillator's feedback network. In other cases, the output frequency of the oscillator may be variable, with the frequency of the oscillator dynamically changing based on some external input or control.

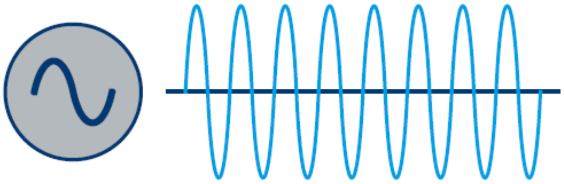


Figure1: Oscillator with sinusoidal output

2.1 Voltage controlled oscillators

A voltage controlled oscillator (VCO) is an oscillator whose output frequency is controlled by an external voltage. This control voltage is often referred to as the “tune” or “tuning” voltage, abbreviated V_{tune}. There is no requirement regarding the relationship between tuning voltage and output frequency, but in most VCO designs, output frequency increases linearly and monotonically with tuning voltage; that is, increasing or decreasing V_{tune} increases or decreases the oscillator output frequency in a continuous and linear fashion. Note that the tune voltage may be changed in discrete steps (as shown in Figure 2) or continuously.

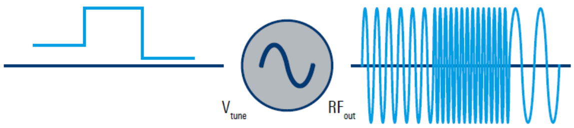


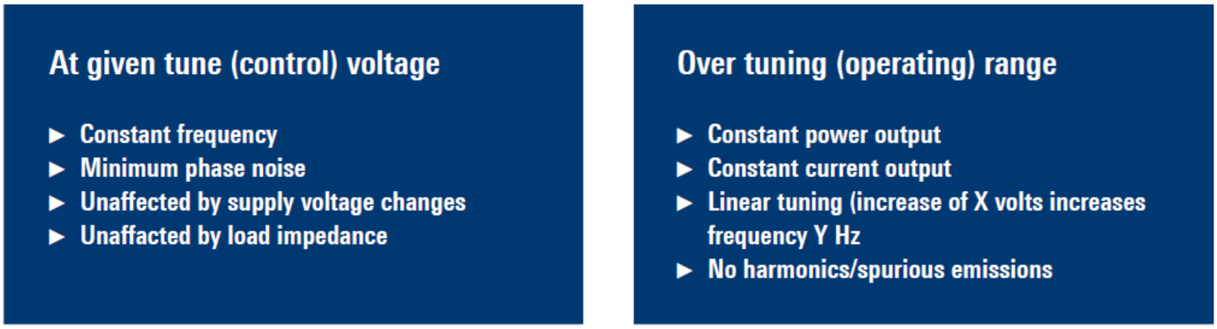
Figure 2: Tuning voltage (in discrete steps) and output frequency

Commercially produced VCO are available in a wide variety of form factors such as surface mount, plug-in, and connectorized. VCOs are also available with a wide range of different specifications and operating parameters. The flexibility provided by different VCO form factors and performance characteristics makes it possible for VCOs to be used in many different applications. One of the most common applications of VCOs is in phase locked loops or as part of a synthesizer. VCOs are also common in communications systems, particularly those involving some type of frequency modulation. For example, a VCO can be used as an analog FM modulator if V_{tune} is a continuously-varying modulating signal. Similarly, a VCO can be used to create an FSK (frequency shift keying) signal by changing V_{tune} between discrete states. VCOs are also commonly used in some radar applications, such as in linear FM or “chirped” radar.

3 Characterizing Voltage Controlled Oscillators

3.1 Ideal VCO behavior

Aside from basic parameters such as frequency range and output power, VCO characterization is often concerned with how much a given VCO design deviates from “ideal” behavior. The output of an ideal VCO at a given tune or control voltage would have a constant frequency and minimum phase noise. An ideal VCO would be unaffected by minor deviations in its supply voltage or by changes in its load impedance. Across its entire operating or tuning range, an ideal VCO would also have a constant output power and current consumption, independent of tune voltage or frequency. The ideal VCO would have linear tuning sensitivity, meaning that every increase of X volts would always increase output frequency by Y Hz. And lastly, an ideal VCO would not produce any harmonics or other types of spurious emissions. These parameters, or the deviations from ideal behavior, are another important goal of VCO characterization.



At given tune (control) voltage

- Constant frequency
- Minimum phase noise
- Unaffected by supply voltage changes
- Unaffected by load impedance

Over tuning (operating) range

- Constant power output
- Constant current output
- Linear tuning (increase of X volts increases frequency Y Hz
- No harmonics/spurious emissions

3.2 How VCOs are characterized

There are various methods and instruments that can be used when characterizing VCOs. There are however two fundamental requirements for any VCO characterization measurement system. The first requirement is the ability to supply fixed and variable DC voltages that are both very stable and highly precise. The second requirement is the ability to very precisely measure changes in the VCO's output frequency, power, phase noise, etc. as one of these voltages is changed.

Because VCOs are a special type of oscillator, phase noise testers with integrated voltage sources are often used to characterize VCOs. In most cases, these instruments also provide automatic measurement of common VCO characteristics – for example, output frequency as a function of tune voltage. The ability to automate VCO characterization measurements increases accuracy and decreases both test time and the probability of user error.

3.3 Common VCO measurements

The most basic VCO measurements are tuning range, tuning sensitivity, output power, current consumption, harmonic power and frequency pushing. All these will all be covered in detail in this application note. How these measurements are performed is described in chapter 4. The use of a combined phase noise and VCO tester also enables many other types of measurements, such as phase noise and spot noise vs tune (see chapter 5)

3.3.1 Frequency tuning range

The frequency tuning range is the most fundamental characteristic of a VCO and is the difference between the specified minimum and maximum VCO output frequencies. Tuning range is determined by sweeping the tuning voltage (V_{tune}) and measuring the output frequency (f_{out}) at different tuning voltage levels. Figure 3 shows the tuning range of a real VCO, the tuning voltage is swept between -0,5 V and 23 V and the output frequency is plotted as a function of the tuning voltage. The tuning range in this example is 10.65 GHz. Ideally, the plot of f_{out} as a function of V_{tune} would produce a straight line or a line with a constant slope.

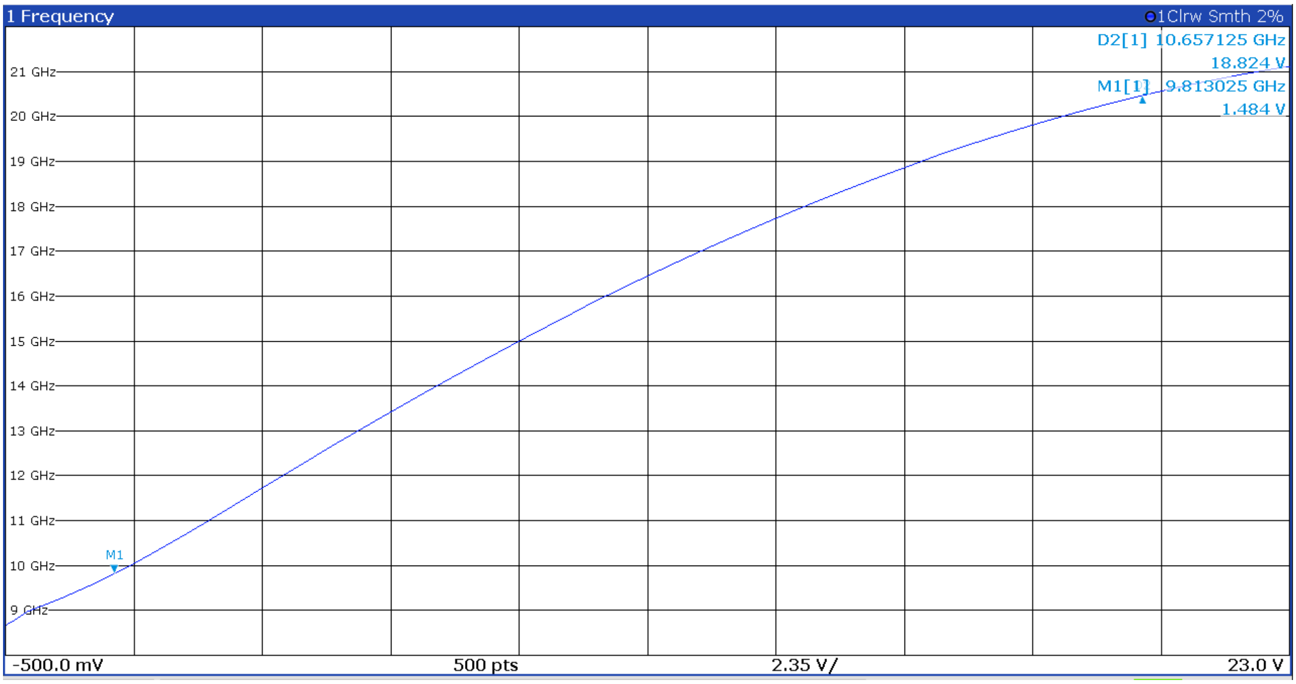


Figure 3: Frequency tuning range

3.3.2 Output power

VCOs are often connected to other devices, such as mixers, which require an input power within a certain range. Therefore, another aspect of VCO characterization is RF output power. However, the output power of real VCOs is often different at different tune voltages, respectively different output frequencies. VCO output power is normally characterized by plotting output power a as a function of the tuning voltage, as shown in Figure 4. Like all other power measurements, when characterizing VCO output power, the load impedance should be specified. Load impedance affects the amount of forward or delivered RF power versus the amount of reflected or RF power. For most VCOs, the “standard” RF impedance of 50 Ω is used.

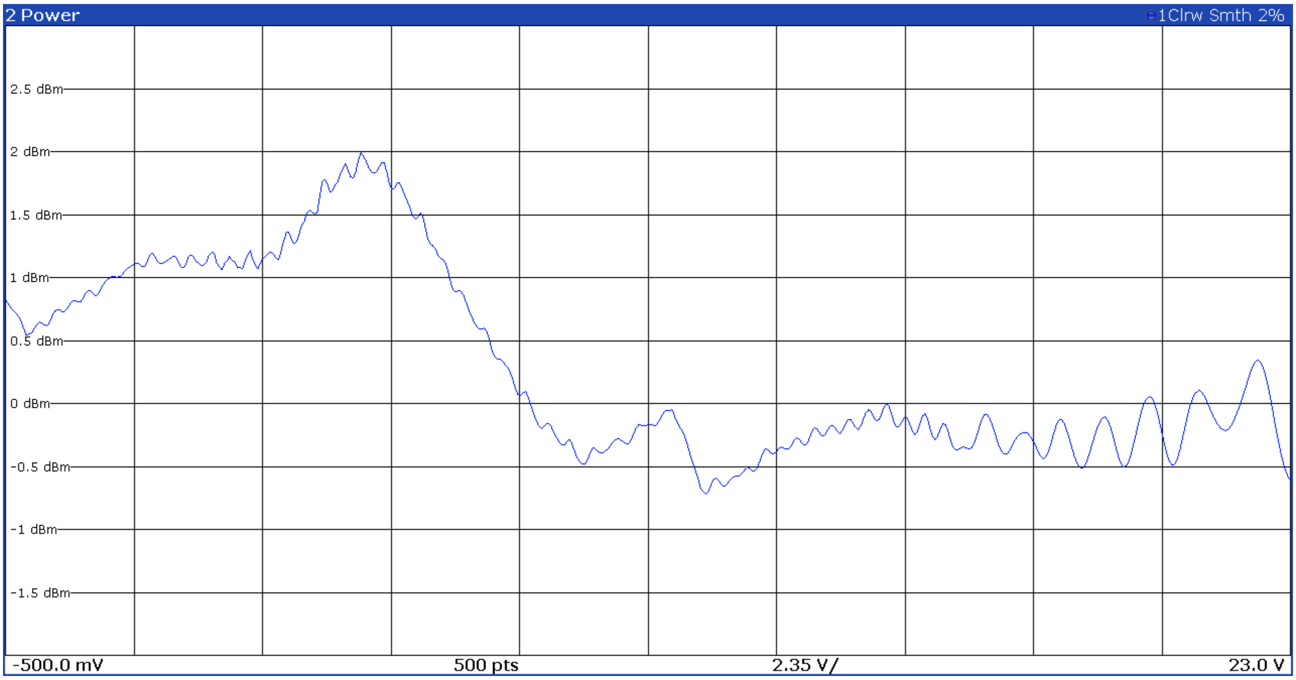


Figure 4: Output power vs. V_{tune}

3.3.3 Tuning sensitivity

Another VCO measurement related to output frequency is tuning sensitivity. Tuning sensitivity is the change in output frequency per unit change in tuning voltage: in other words, does each additional tune volt change the output frequency by the same amount? Sensitivity is measured in MHz per Volt. In Figure 3, the specified tuning range and the tune voltage range can be used to calculate tuning sensitivity: here 10.65 GHz / 23.5 V = 453.2 MHz per volt. Recall that with an ideal VCO, the tuning sensitivity would be constant as possible over the tune voltage range. Having a consistent or flat tuning sensitivity simplifies VCO tuning since a simple linear equation can be used to calculate the tune voltage needed to produce a given output frequency. Figure 5 shows the tuning sensitivity of a real VCO.

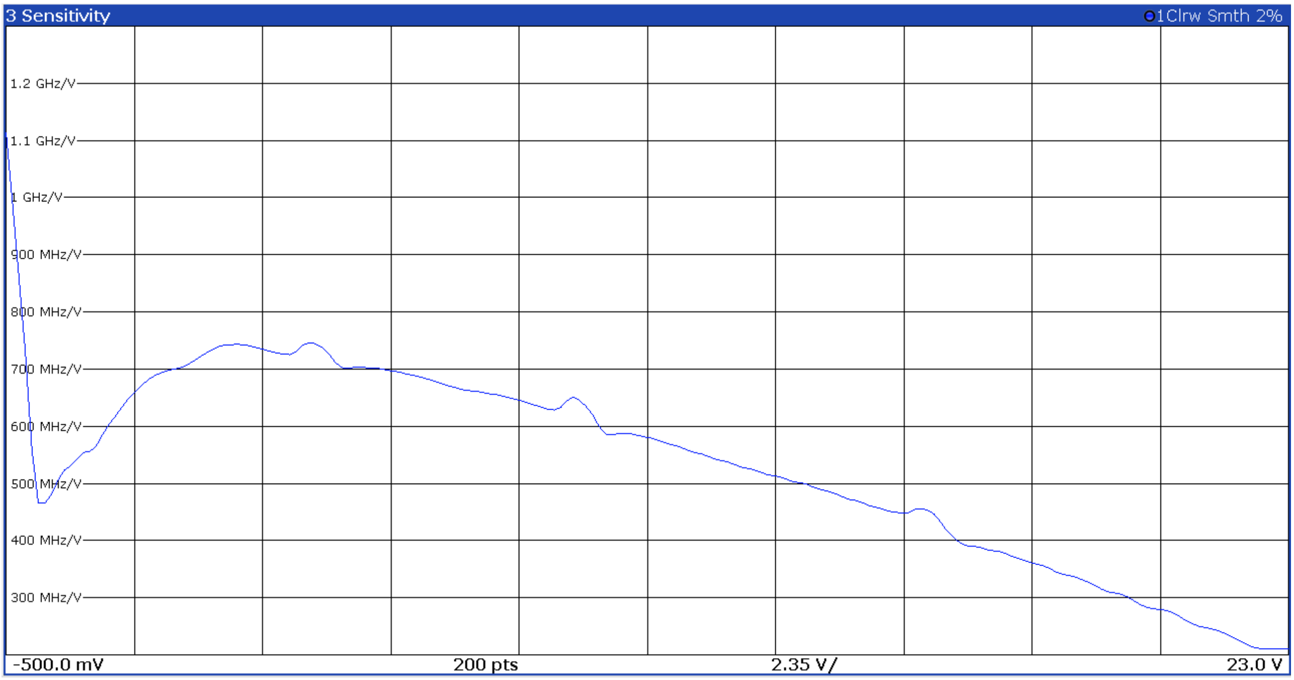


Figure 5: VCO sensitivity

3.3.4 Current consumption

In many applications, particularly in battery-powered applications, current or power consumption is a significant concern, and therefore current consumption is part of most VCO characterization. This measurement indicates how much supply current the VCO draws at different tuning voltages (Figure 6). Ideally, the current consumption of a VCO should be as low as possible and flat across the tune voltage range; that is, the VCO would draw the same amount of current regardless of output frequency. Figure 6 shows the current consumption of a real VCO.

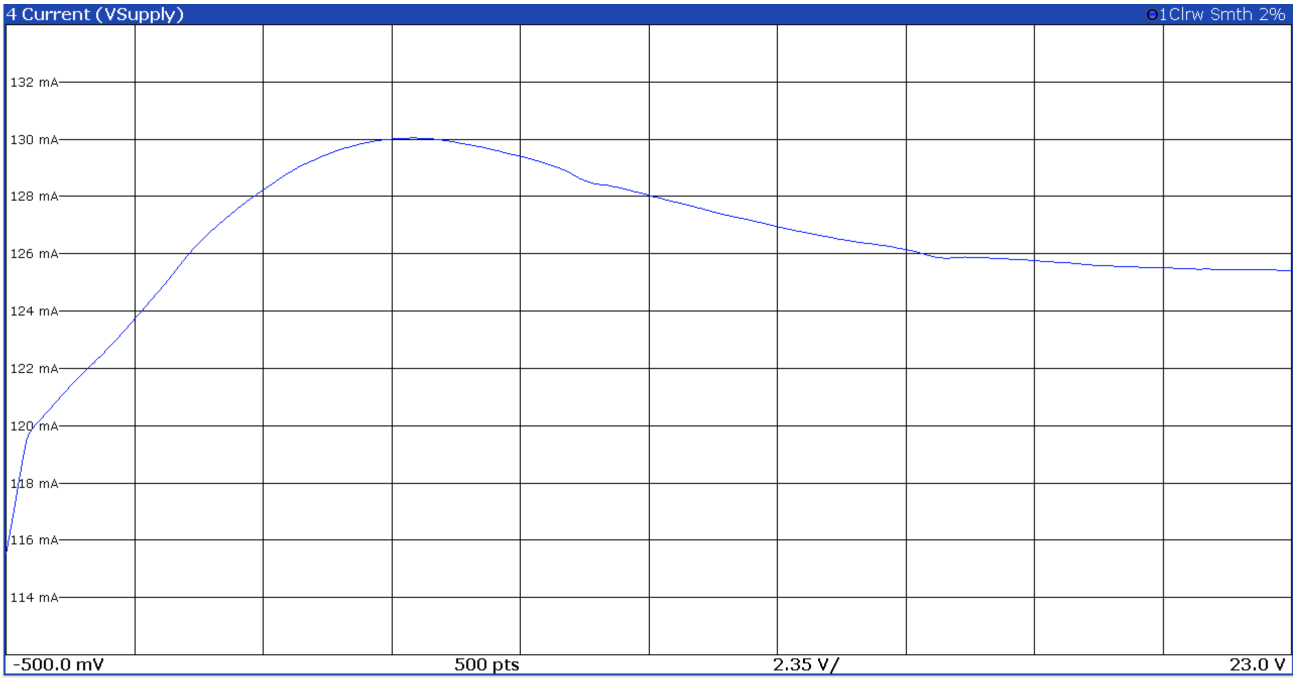


Figure 6: Current consumption vs. V_{tune}

3.3.5 Harmonic power

Like all other types of oscillators, VCOs generate harmonics, which are signals that appear at integer multiples of the fundamental frequency. For example, if the VCO output frequency is 500 MHz, harmonics will also be present at 1000 MHz, 1500 MHz, etc. Harmonics are almost always undesirable and therefore the level of these harmonics should be kept as low as possible: 10s of dB is a common design goal. Harmonic suppression is so important that some VCO designs incorporate filters or other methods for suppressing harmonics. The power of harmonics is measured and plotted as function of the tune voltage, V_{tune}. Figure 7 shows a combined plot of the powers of the fundamental (blue trace), second harmonic (black trace), third harmonic (green trace) and forth harmonic (orange trace). Although these powers are measured in absolute units, such as dBm, in many cases harmonic power is reported in dBc, that is, relative to the carrier or fundamental.

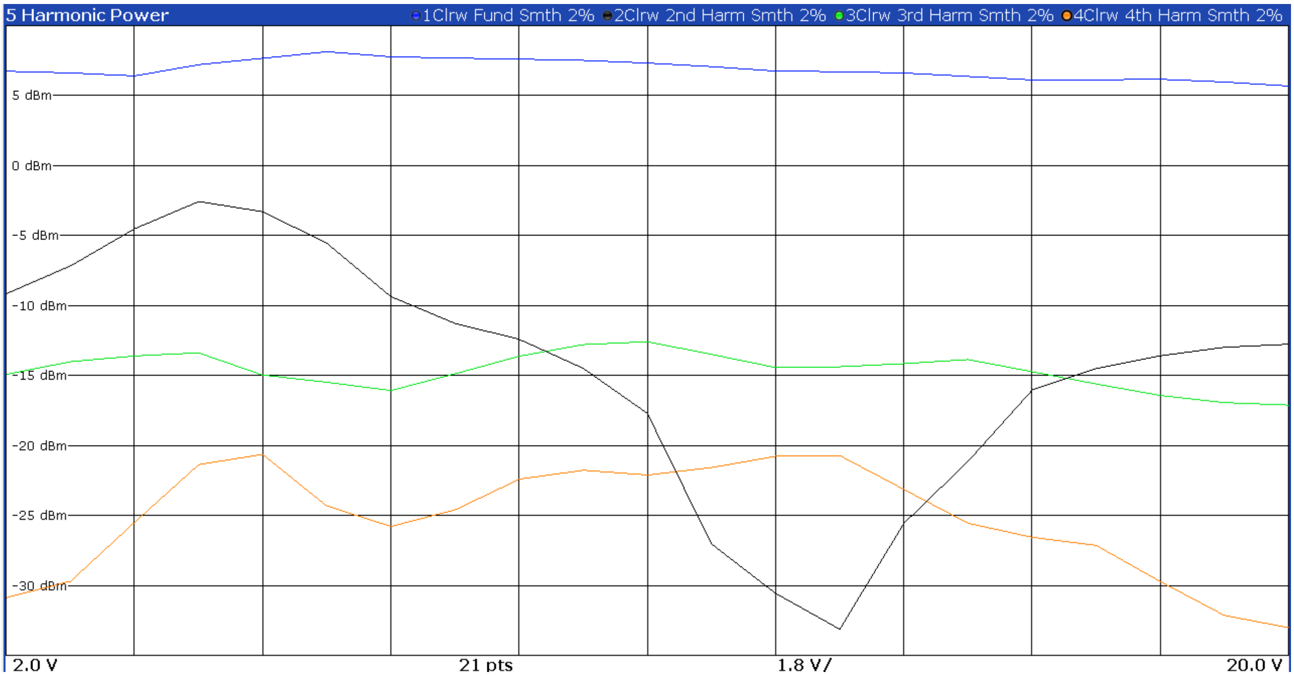
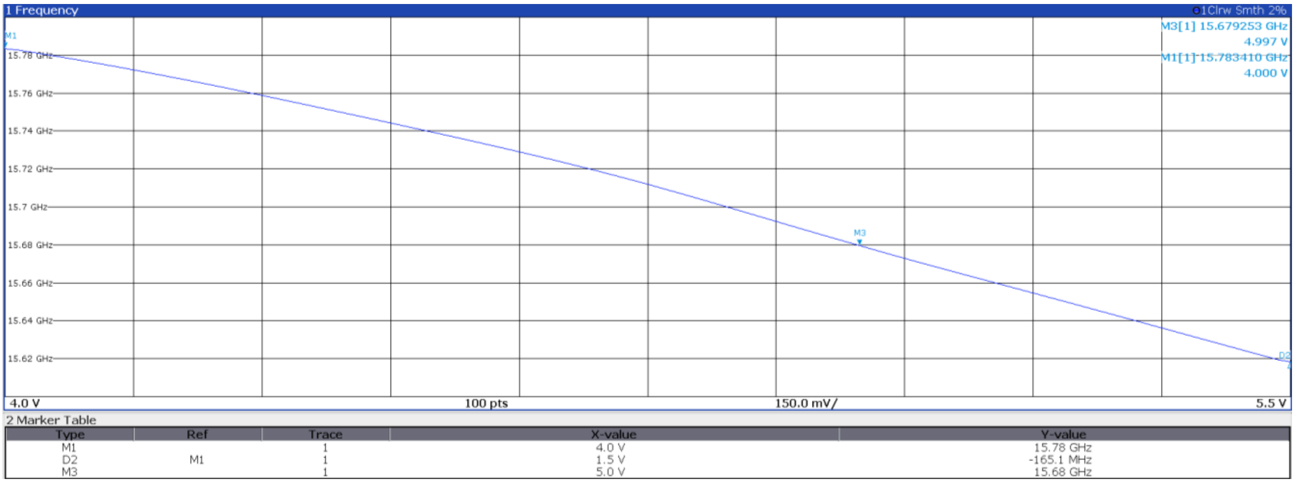


Figure 7: Harmonic power vs. V_{tune}

3.3.6 Frequency pushing

VCO frequency pushing is the change in the output frequency caused by a change in supply voltage while the control voltage remains constant. Ideally, small variations in the supply voltage should not have an effect on the generated RF frequency. In real VCO however, some variations will occur, depending on the deviation from the nominal supply voltage. Even very small variations in the supply voltage may cause undesired frequency changes or phase noise in the VCO output signal. Frequency pushing is the reason why VCOs require very stable, low-noise supply voltages. Frequency pushing can also occur when the VCO is supplied by a battery whose voltage begins to drop over time.

In Figure 8, V_{tune} has been fixed at 10 V, which corresponds to a VCO output frequency of 15.68 GHz for this particular VCO. This VCO has a standard supply voltage of 5 V, the frequency pushing is tested by sweeping the supply voltage between 4 V and 5.5 V, recording the output frequency over this voltage range. In this example, the VCO output frequency varies in a range of 165.1 MHz from 15.783 GHz to 15.618 MHz, and frequency pushing is (165.1 MHz / (4 V – 5.5 V)) = 110,07 MHz / V.



2 Marker Table

Type	Ref	Trace	X-value	Y-value
M1		1	4.0 V	15.78 GHz
D2	M1	1	1.5 V	-165.1 MHz
M3		1	5.0 V	15.68 GHz

Figure 8: Frequency pushing

4 VCO Characterization with R&S®FSPN

4.1 Brief introduction of the used instrument

Figure 9: R&S® FSPN Phase Noise Analyzer

The R&S®FSPN phase noise analyzer and VCO tester is very sensitive, with high measurement speeds for characterizing sources such as synthesizers, VCOs, OCXOs, and DROs. It is ideal for development and production phase noise and VCO analysis. Equipped with two low phase noise synthesizers and a real-time cross-correlation engine for increased measurement sensitivity, just a few correlations are needed to measure very high-quality oscillators, synthesizers or VCOs in production. Increase the number of correlations to characterize the most sensitive commercially available synthesizers and oscillators in R&D. The built-in SCPI recorder helps generate test automation scripts easily, directly from the user interface.

Key facts:

- Pure phase noise analyzer and VCO tester with high measurement speed
- Simultaneous measurement of phase noise and amplitude noise
- Frequency range from 1 MHz to 8GHz/26.5 GHz
- Very high sensitivity for phase noise measurements thanks to dual synthesizers and cross-correlation included in the base unit, typ. –163 dBc (1 Hz) at 1 GHz carrier frequency and 10 kHz offset
- Extremely low-noise internal DC sources for automatic VCO characterization
- High measurement speed with real-time cross-correlation
- Automatic SCPI recording and 100% SCPI compatible with R&S®FSWP

4.2 Measurement setup for the VCO measurements

Figure 10 below shows the VCO test configuration. For the VCO measurements tree connections are necessary between the VCO and the phase noise analyzer R&S® FSPN.

- The first of these is the supply voltage V_{supply}, which the VCO requires to operate. This is normally a fixed voltage.
- The second is the control or tuning voltage V_{tune} which controls the VCO output frequency.
- The third connection is between the VCO RF_{output} and the RF_{input} of the R&S®FSPN.

The most common types of VCO tests involve holding V_{supply} constant, varying V_{tune}, and measuring some characteristic of the VCO RF output signal.

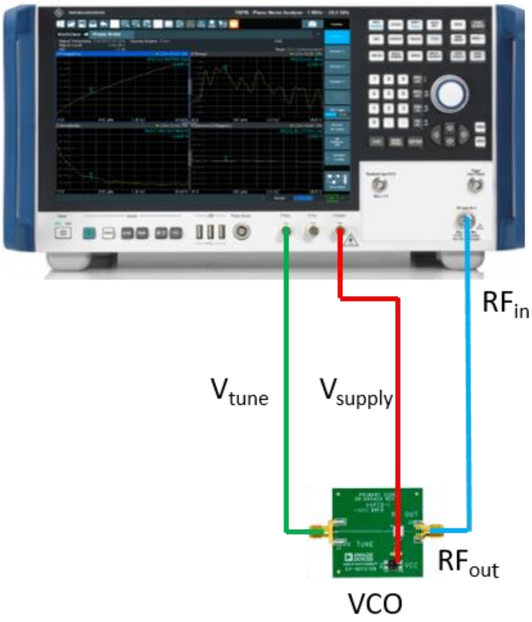
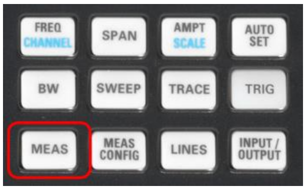


Figure 10: VCO measurement setup with R&S® FSPN

For the VCO characterization the R&S®FSPN provides three integrated highly precise and stable voltage sources. The internal voltage sources can be adjusted for the different requirements of the used VCO to be tested.

For starting the VCO measurements, perform an instrument *PRESET* then press the *MEAS* hardkey on the R&S®FSPN front panel (see the Figure below):



As shown Figure 11 in, the VCO measurements are spitted in two groups, *VCO Characterization* and *Spot Noise versus Tune.*

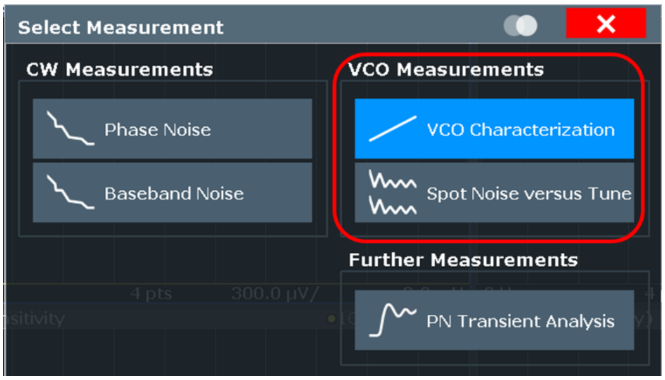


Figure 11 : VCO measurements

The VCO characterization allows to perform the following measurements:

- Frequency versus V_{tune} (tuning range)
- Power versus V_{tune}
- Tuning Sensitivity
- Current versus V_{tune}
- Harmonic power

4.2.1 Configuration of the voltage sources

For the measurement usually one fixed voltage source and one swept voltage source is used. Before starting the measurements for the *VCO Characterization* the voltage sources must be configured with the right settings for the VCO under test. Therefore, the R&S®FSPN provides two different menus as shown in (Figure 12). (Note: you can always reach this side menu by pressing the MEAS CONFIG hardkey)

Figure 12: Configuration of the voltage sources

Please note the proper configuration of the DC port:
Setting DC voltages and currents properly is an important step during the configuration in order not to damage the device under test (DUT) by applying too much voltage or current! Therefore, it is recommended to connect the device under test (DUT) to the instrument after the DC settings have been made and verified, or check that all power states are off during the DC voltage configuration. It is also recommended to apply the DUT specific voltage and current limits to prevent damage.

Device under test (DUT):

For the following example the EV-ADF5709 evaluation board from ANALOG DEVICES which includes the ADF5709 VCO. This VCO provides a wide frequency range from 9.85 GHz to 20.5 GHz and a V_{tune} range from -0.5 V to 23 V. The supply voltage VCC = 5 V. The source should be able to deliver at least 90 mA current.

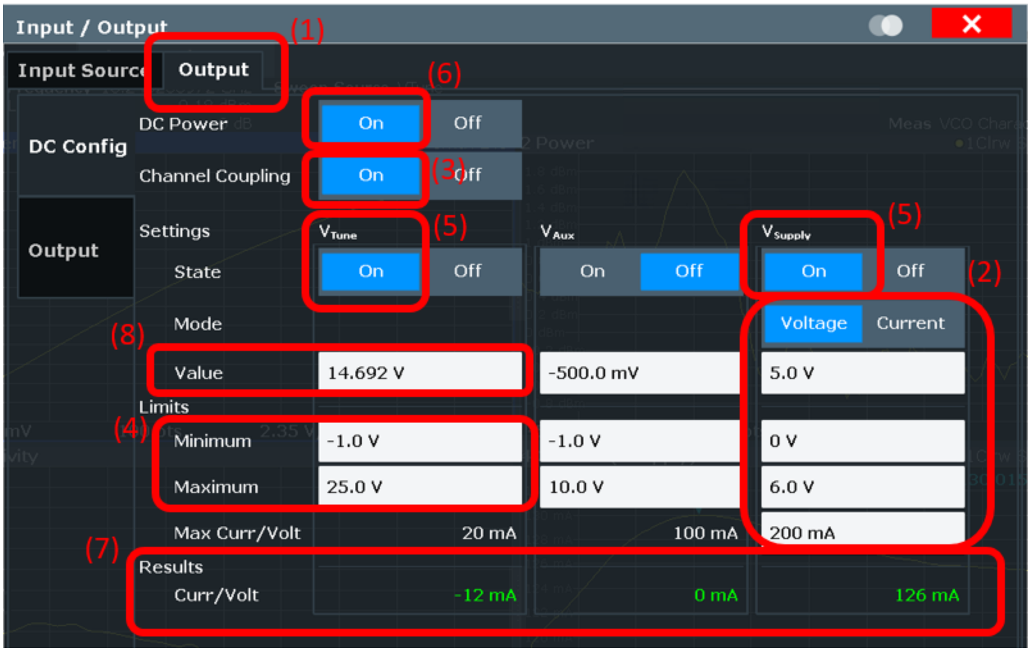
DC Source Configuration:

The DC source configuration dialog allows enabling and disabling all three available DC sources. Individual values and limits can be set for each source.

The value of the fixed supply voltage can be defined in the *DC config* menu.

► Press the *DC config* softkey

Figure 13 shows the possible settings for the DC source configuration:



DC Power: On
Channel Coupling: On

Settings	V_{Tune}	V_{Aux}	V_{Supply}
State	On	Off	On
Mode			Voltage
Value	14.692 V	-500.0 mV	5.0 V
Limits			
Minimum	-1.0 V	-1.0 V	0 V
Maximum	25.0 V	10.0 V	6.0 V
Max Curr/Volt	20 mA	100 mA	200 mA
Results			
Curr/Volt	-12 mA	0 mA	126 mA

Figure 13: Sweep configuration menu for the VCO characterization measurements

(1) Select the *Output* tab

(2) Enter the supply voltage for the used DUT and define the allowed voltage range by entering the upper and lower limit and select the *Voltage* mode. For oscillators that are controlled by a current like YIG oscillators you can also enter the supply current by selecting the *Current* mode.

(3) When you turn on coupling, all active measurement channels apply the same configuration. When you turn off coupling, you can define a different configuration for each measurement channel. In this case the coupling is on.

(4) In order to protect the DUT, enter the min and max values for the V_{tune} range that must not be exceeded.

(5) Switch the voltage output V_{tune} and V_{supply} *On*.

(6) If you are sure that all output voltages are entered correctly, switch on the global DC power for the connected VCO.

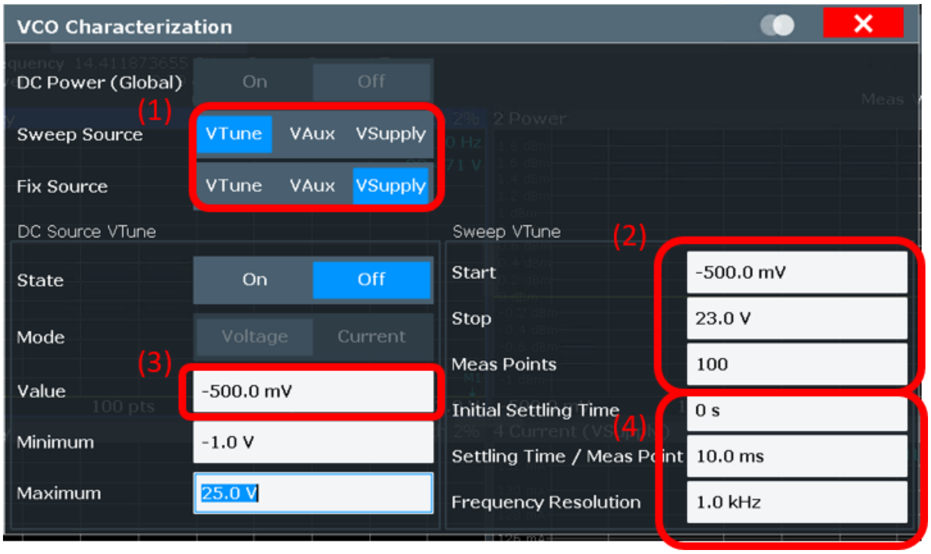
(7) This value shows the updated current values while the measurement is running.

(8) This value shows the updated sweep voltage while the measurement is running.

Sweep Configuration:

► Press the *Sweep Config* softkey

Figure 14 shows the possible settings for the sweep configuration:



DC Power (Global): On | Off

Sweep Source: **VTune** | VAux | VSupply

Fix Source: VTune | VAux | **VSupply**

DC Source VTune

State: On | **Off**

Mode: Voltage | Current

Value: -500.0 mV

Minimum: -1.0 V

Maximum: 25.0 V

Sweep VTune

Start: -500.0 mV

Stop: 23.0 V

Meas Points: 100

Initial Settling Time: 0 s

Settling Time / Meas Point: 10.0 ms

Frequency Resolution: 1.0 kHz

Figure 14: Sweep configuration menu for the VCO characterization measurements

(1) This dialog allows to configure which voltage source is swept and which one is fixed. For the following measurements V_{tune} is sweeping and V_{supply} is configured as a fixed voltage source.

(2) Enter the start and stop value for the V_{tune} range of the DUT. In this case the full V_{tune} range of the VCO, mentioned above is used for the measurement. For good measurement results it is important to use enough measurement points. In this example 100 measurement points are used between the start and stop voltage of V_{tune}.

(3) This value shows the current sweep voltage as soon the measurement is running.

(4) Allows to enter additional timing parameters and frequency resolution depending on the measured VCO.

Enter the frequency range for the auto signal search function:

► Press the *AutoSet* hardkey (Figure 15)

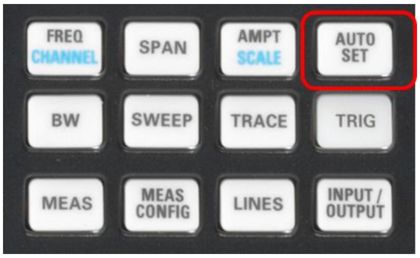
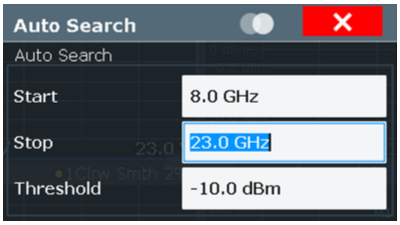


Figure 15: Select the auto set function

► Enter the frequency range for the auto signal search function as shown in the figure below.


Auto Search

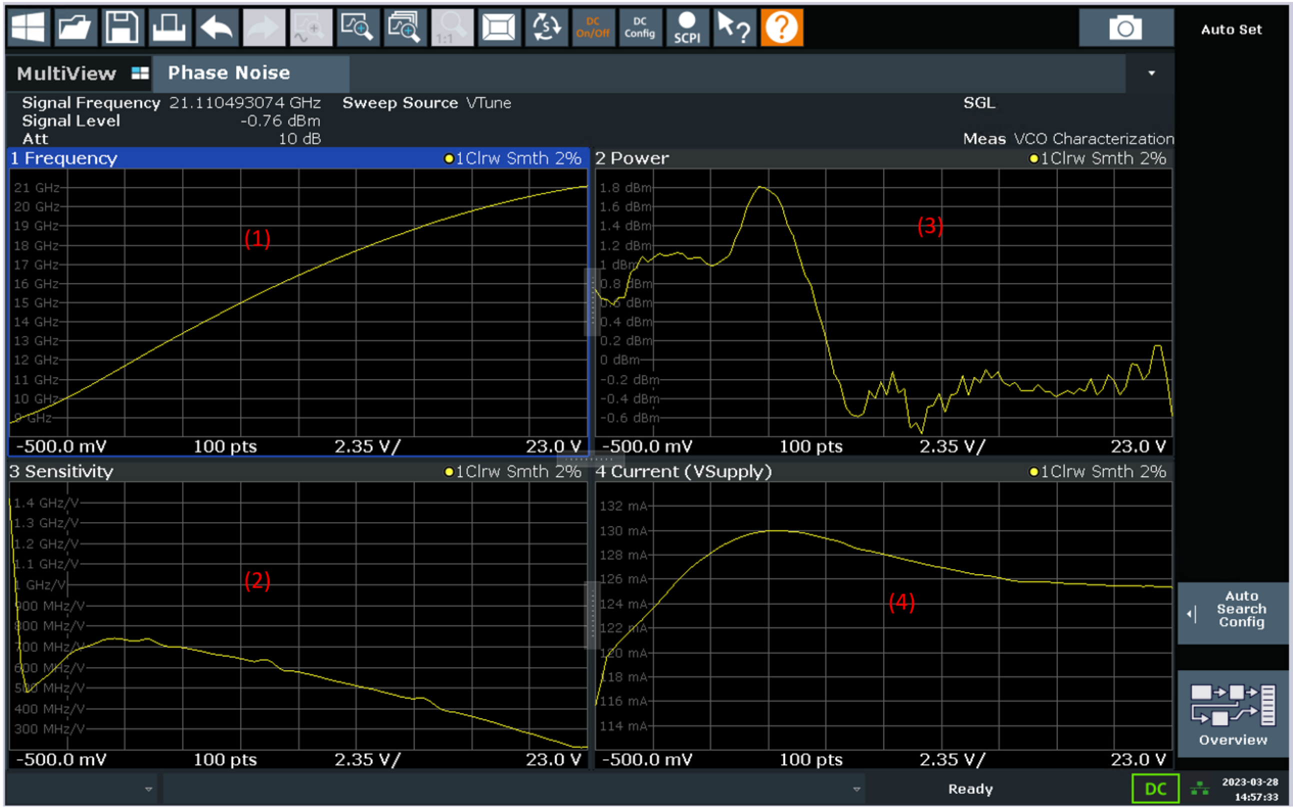
Start 8.0 GHz

Stop 23.0 GHz

Threshold -10.0 dBm

4.2.2 Measurement results

Start the measurement by pressing the *Run Single* hardkey. The R&S® FSPN now displays the four different measurement results for the VCO characterization as shown in Figure 16


Signal Frequency 21.110493074 GHz

Signal Level -0.76 dBm

Att 10 dB

Sweep Source VTune

SGL

Meas VCO Characterization

Figure 16: Measurement results of the VCO characterization

These four measurements include:

(1) Frequency versus V_{tune} (see 13.3.1 Frequency tuning range)

(2) Tuning Sensitivity (see 3.3.3 Tuning sensitivity)

(3) Power versus V_{tune} (see 3.3.2 Output power)

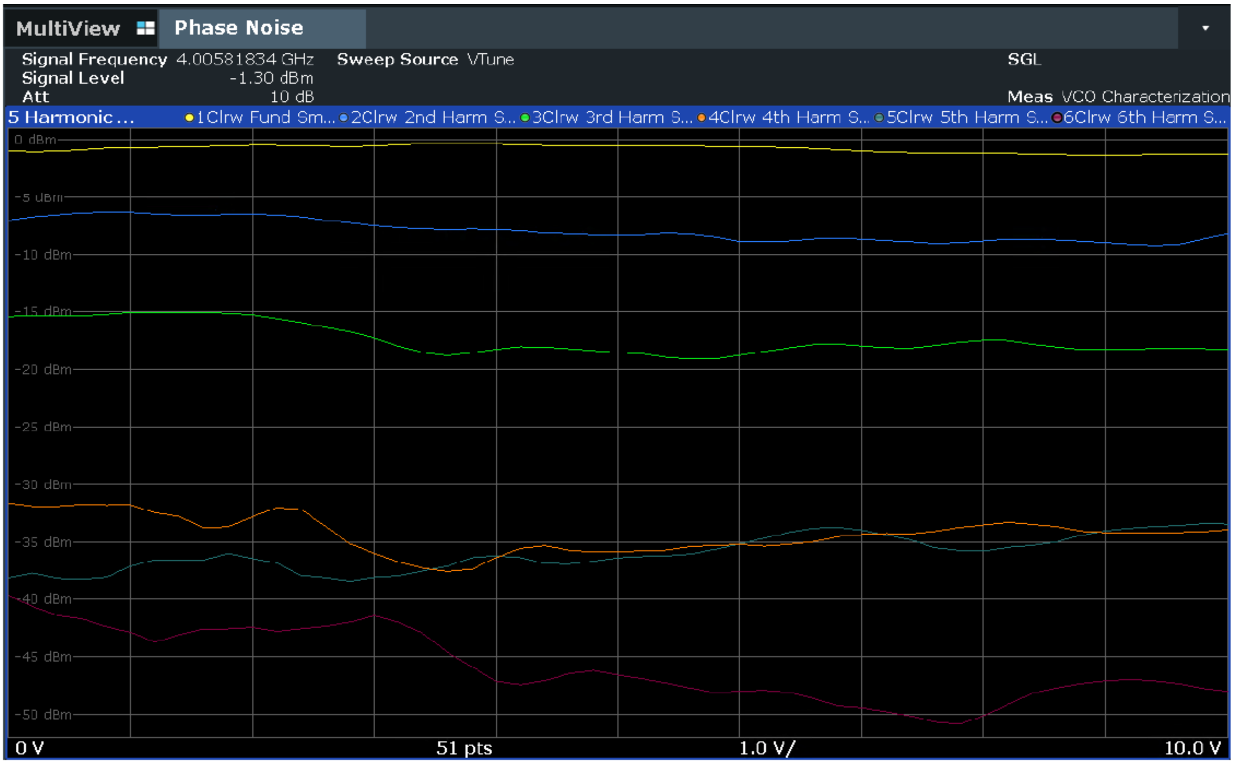
(4) Current versus V_{tune} (see 3.3.4 Current consumption)

Figure 16 shows the above described measurements in a preconfigured measurement screen. In order to reconfigure the screen in a different way (f.e. changing the order of the measurements or add or remove a measurement) press the *MEAS CONFIG* hardkey and choose the *Display Config* softkey on the right side of the R&S® FSPN screen. The display config mode is shown in Figure 17 and allows to change the display configuration. Windows can be moved by drag & drop on the hand icon, removed using the trash icon, and new measurement windows can be added by dragging one of the available items from the list on the right into the main screen area.

Signal Frequency 21.121827705 GHz
Signal Level -0.52 dBm
Att 10 dB
Sweep Source VTune
SGL
Meas VCO Characterization

Figure 17: Measurement screen configuration

In this example the additional harmonic power measurement is shown in one screen (Figure 18) by Drag&Drop of the harmonic power measurement softkey and removing all other measurements via the trash symbol. Every result window can also be displayed in full screen without having to remove the other result windows by double clicking the window. Another double click closes the full screen again. Instead of a double click, the hardkey shown below can be used as well:



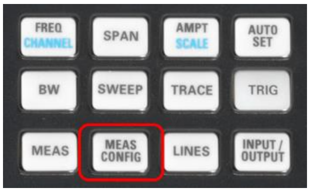
Signal Frequency 4.00581834 GHz
Signal Level -1.30 dBm
Att 10 dB
Sweep Source VTune
SGL
Meas VCO Characterization

Figure 18: Harmonic Power (VCO with f_{out} = 1.8 GHz to 4.4 GHz and V_{tune} = 0 V to 10 V)

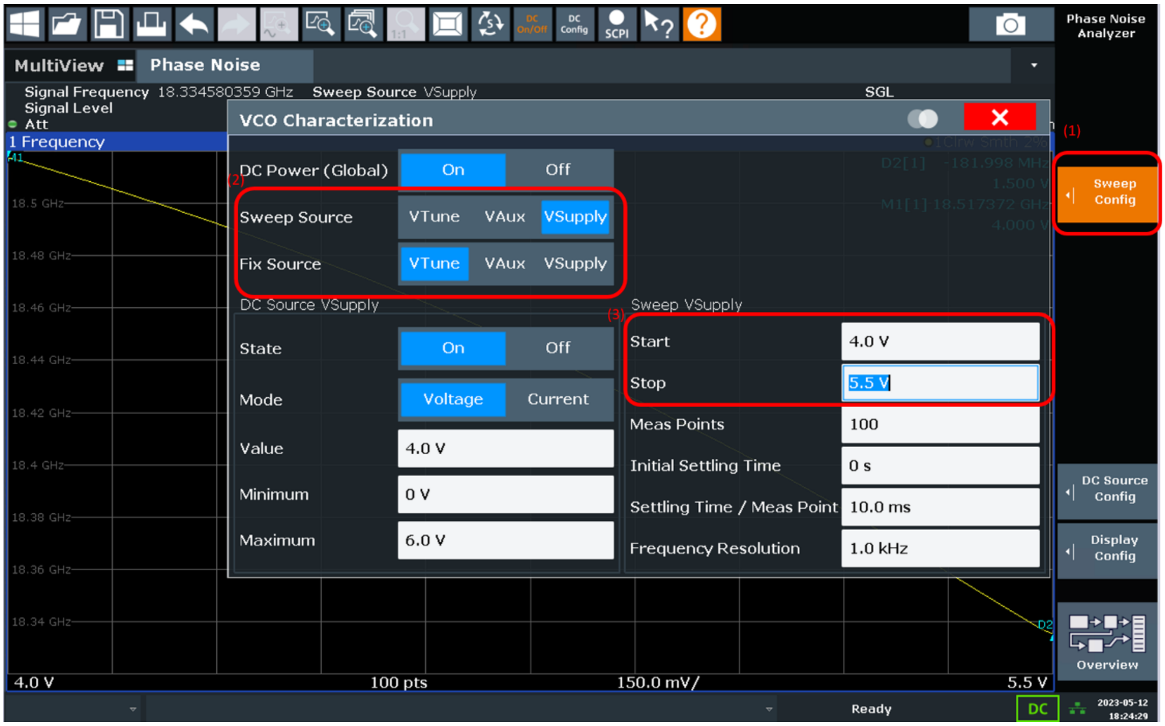
4.2.3 Frequency pushing

As the DC sources of the R&S®FSPN can be configured freely, a frequency pushing measurement is set up easily and quickly. Instead of sweeping the tuning voltage, the supply voltage is varied to identify the effect on output frequency.

For the configuration of the DC source and sweep settings press the *MEAS CONFIG* hardkey:



Configure the sweep settings as shown in Figure 19:



Signal Frequency 18.334580359 GHz Sweep Source VSupply

Signal Level

VCO Characterization

DC Power (Global) On Off

Sweep Source VTune VAux VSupply

Fix Source VTune VAux VSupply

DC Source VSupply

State On Off

Mode Voltage Current

Value 4.0 V

Minimum 0 V

Maximum 6.0 V

Sweep VSupply

Start 4.0 V

Stop 5.5 V

Meas Points 100

Initial Settling Time 0 s

Settling Time / Meas Point 10.0 ms

Frequency Resolution 1.0 kHz

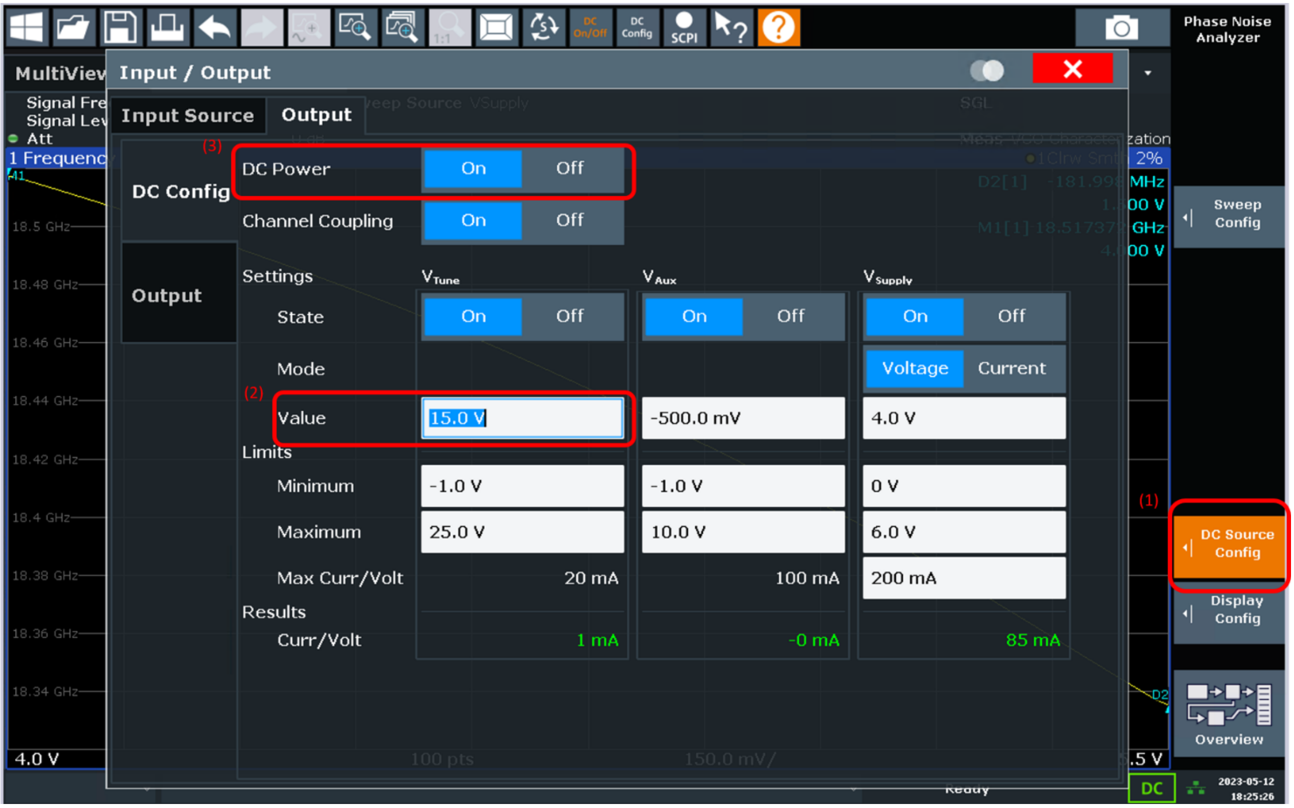
Figure 19: Sweep configuration for the frequency pushing measurement

(1) Press the *Sweep Config* softkey

(2) This dialog allows to configure which voltage source is swept and which one is fixed. For the frequency pushing measurement V_{supply} is sweeping and V_{tune} is configured as a fixed voltage source.

(3) The tested VCO has a standard supply voltage of 5 V. For this case a meaningful sweep range for the frequency pushing measurement is between 4 V and 5.5 V. Enter the start and stop value for the mentioned sweep range.

Next step is to configure the fixed tune voltage as shown in Figure 20:



Input / Output

Input Source | Output

DC Config (3)

DC Power: On | Off

Channel Coupling: On | Off

Output

Settings	V_{Tune}	V_{Aux}	V_{Supply}
State	On	On	On
Mode			Voltage
Value (2)	15.0 V	-500.0 mV	4.0 V
Limits			
Minimum	-1.0 V	-1.0 V	0 V
Maximum	25.0 V	10.0 V	6.0 V
Max Curr/Volt	20 mA	100 mA	200 mA
Results			
Curr/Volt	1 mA	-0 mA	85 mA

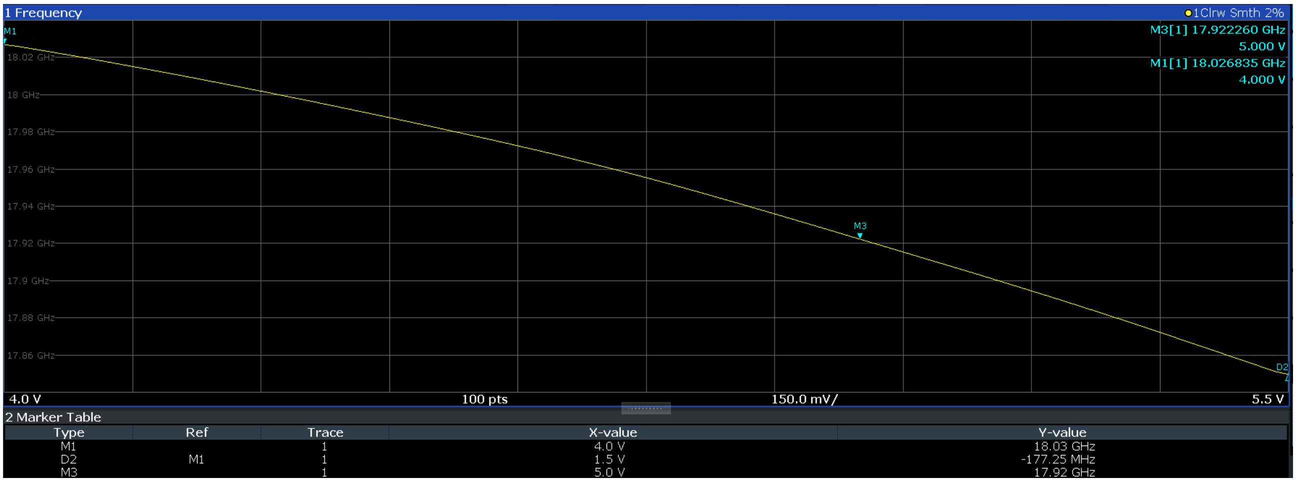
Figure 20: DC source configuration for the frequency pushing measurement

(1) Press the *Sweep Config* softkey

(2) Set V_{tune} to a fixed value, in this example 15.0 V which corresponds to a VCO output frequency of 17.92 GHz for this particular VCO.

(3) Turn the DC power on

Figure 21 shows the result, of the frequency pushing measurement (frequency versus V_{supply}). In this example, the VCO output frequency varies in a range of 177.25 MHz and frequency pushing is (177.25 MHz / (4 V – 5.5 V)) = 118,2 MHz / V (see also chapter 3.3.6).



2 Marker Table

Type	Ref	Trace	X-value	Y-value
M1		1	4.0 V	18.03 GHz
D2	M1	1	1.5 V	-177.25 MHz
M3		1	5.0 V	17.92 GHz

Figure 21: Frequency pushing (V_{tune} = 15 V => f_{VCOout} = 17.92 GHz, V_{supply} = 4 V to 5.5V)

5 Phase Noise

Phase noise is the term used to describe short term variations in phase or frequency stability, with "short term" referring to time intervals on the order of seconds or less. Another way of defining or describing phase noise is as random or unintentional phase modulation. Short term stability or "good phase noise performance" is very important in a wide variety of RF applications, but this short term stability can be difficult to obtain, with a substantial cost and complexity often associated with even modest increases in phase noise performance.

5.1 Single sideband phase noise

In Figure 22, phase noise was measured at a positive frequency offset from the carrier. Since the “sidebands” created by phase noise are usually symmetrical around the carrier, measured phase noise is normally the same for a given positive or negative offset from the carrier. In Figure 23, phase noise is –70 dBc/Hz at both +10 kHz and –10 kHz offsets from the carrier. Therefore, phase noise is only measured on one side of the carrier (Figure 24) and this measurement is called “single sideband phase noise”. By convention, positive offsets (the upper sideband) are used when measuring and reporting phase noise

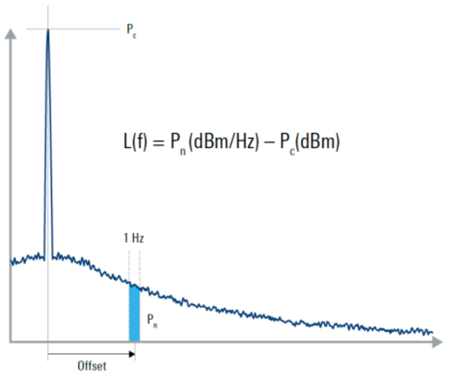


Figure 22: Single sideband phase noise

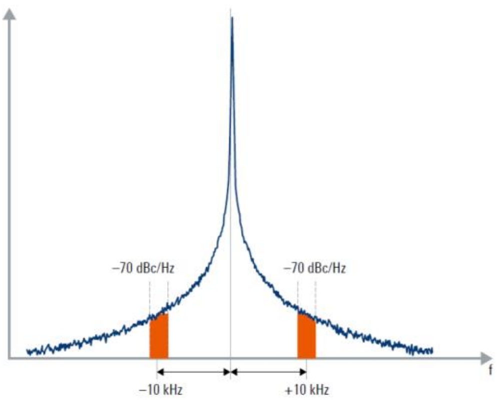


Figure 23: Symmetrical phase noise

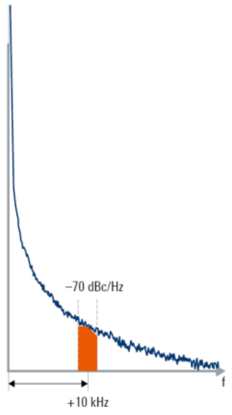


Figure 24: Upper Sideband

5.2 Phase noise test solution

There are two types of RF test and measurement instruments that can be used to measure or analyze phase noise: spectrum analyzers and phase noise analyzers. Outwardly, these instruments are often very similar in appearance and display results in similar ways, but there are important differences between them.

Spectrum analyzers are general-purpose instruments and are the traditional tool used for measuring phase noise. In almost all cases phase noise measurements using spectrum analyzers are performed by means of an automated phase noise measurement application. The greatest advantage of using a spectrum analyzer for phase noise measurements is that a spectrum analyzer is a flexible, general-purpose instrument that can be used for a wide range of other measurements as well. Typically, phase noise measurements using a spectrum analyzer are performed by measuring the spectral power at different offsets of the carrier. However, thereby not distinguishing between noise created by phase or amplitude variations.

A **phase noise analyzer**, as the name implies, is an instrument containing specialized hardware specifically designed for making phase noise measurements. Phase noise analyzers usually have higher measurement speed and higher sensitivity than traditional spectrum analyzers, the increased sensitivity primarily being a result of the cross-correlation method implemented in many phase noise analyzers – this will be covered in chapter 5.3. In addition, many modern phase noise analyzers also have other functionality used in testing oscillators, such as the ability to measure amplitude noise and spurious emissions or the ability to characterize voltage controlled oscillators.

5.3 Phase noise analyzer cross-correlation method

5.3.1 Phase noise measurement challenges

There are many different methods for measuring phase noise. Some of the more common methods are the spectrum analyzer method discussed above, the PLL method, and both phase detector and digital phase demodulator methods. Each of these methods has different strengths and weaknesses but they all share the common limitation that phase noise from the instrument is added to the phase noise from the device under test. Most of this added noise comes from the instrument’s local or reference oscillator(s) and this noise is problematic because it makes it difficult to determine how much phase noise is present in the DUT signal and how much is added by the measuring instrument. The traditional way of dealing with this issue is to use an instrument that has “better” phase noise performance than the DUT, with “better” usually being defined as at least 10 dB or more. However, this approach still may not be sufficient or possible when measuring modern DUTs with very low levels of phase noise.

5.3.2 DUT phase noise versus instrument phase noise

Figure 25 illustrates the issue of instrument phase noise. The device under test has a certain amount of phase noise to be measured. Within the measuring instrument, this signal is processed using one of the different phase noise measurement methods. Regardless of the method used, processing or measuring the signal requires at least one local or reference oscillator, and the phase noise of this oscillator is combined with the DUT phase noise. Depending on the relative levels of the phase noise in the DUT and reference oscillator, the resulting phase noise measurement results may not be an accurate measurement of the DUT phase noise.

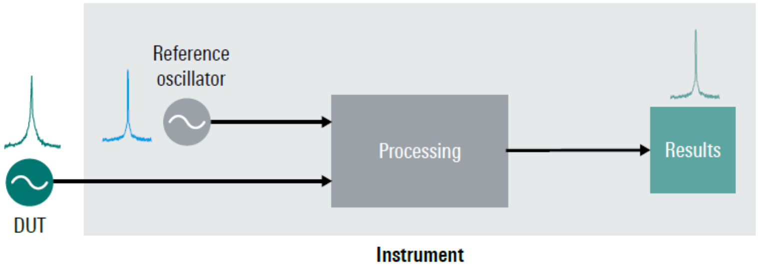


Figure 25: Phase noise added by the instrument

5.3.3 Improving phase noise measurements

Using an instrument whose local oscillators have low phase noise and using a modern phase noise measurement method, such as digital phase demodulation, can greatly improve phase noise results, but this still may not be sufficient for measuring very “quiet” oscillators. In these cases, being able to remove, or at least reduce, the influence of instrument phase noise would be particularly advantageous. This would increase sensitivity, that is, allow measurement of very low levels of phase noise. Since the 1990s, cross-correlation has been the primary method for reducing or removing the effect of instrument phase noise.

5.3.4 Cross-correlation

Cross-correlation is a measure of the similarity between two different series or signals, and it can also provide the time delay needed for maximum similarity. Cross-correlation is very widely used in many different signal processing applications, such as radar, direction finding, etc. Because cross-correlation identifies the similarities between two signals, it also can be used reduce or remove the “differences” between sets of data. In other words, cross-correlation can be used to separate data into “correlated” or similar parts and “uncorrelated” or dissimilar parts. In addition, cross-correlation can be performed as an iterative or repeated process: performing repeated cross-correlations more clearly separates the correlated and uncorrelated elements in two sets of data.

5.3.5 Cross-correlation in phase noise measurements

Because cross-correlation involves measuring the similarity of two different signals, it is implemented by adding a second measurement path to the measuring instrument. The signal from the device under test is split and processed by these two, nominally “identical,” paths. Because the DUT signal is simply being split, the DUT phase noise remains the same or “correlated” on each path. However, each path uses its own independent local oscillator for measuring phase noise, and the phase noise introduced by these local oscillators is therefore uncorrelated or "different" on each path. Therefore, the measurement results from each path are a combination of the correlated DUT phase noise and the uncorrelated local oscillator phase noise. When these two paths are fed into a cross-correlation function, the uncorrelated instrument noise is removed or reduced, leaving only the correlated phase noise of the DUT. This process is depicted graphically in Figure 26. Note that because of the need for two separate paths and the need to compare two sets of data, cross-correlation can only be implemented in dedicated phase noise analyzers, not in traditional single-path spectrum analyzers.

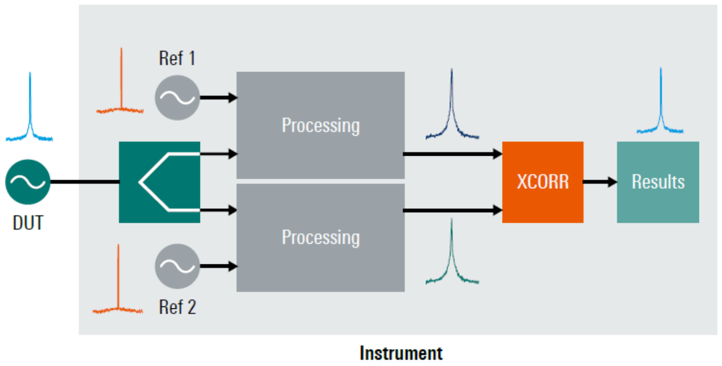
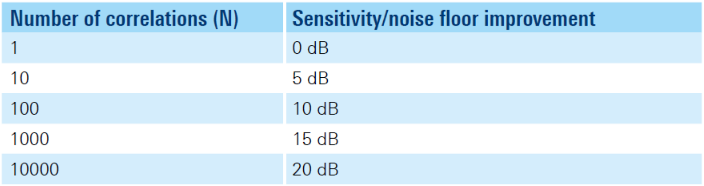


Figure 26: Cross-correlation in phase noise measurements

5.3.6 Correlation count

Recall that cross-correlation can be performed iteratively or repeatedly. If the number of correlations, N, is increased, this will reduce the level of uncorrelated instrument noise in the measurement results. This in turn provides increased sensitivity or a lower noise floor, allowing the accurate measurement of even very low levels of phase noise. The improvement obtained by increasing the number of correlations is logarithmic and follows the formula 5 · log10(N) dB. Every time the number of correlations is increased by an order of magnitude, sensitivity increases by 5 dB. For example, 10 000 correlations will lead to a 20 dB improvement. Increasing the number of correlations will also increase the total time required for the measurement, but the benefits of cross-correlation normally far outweigh the increase in measurement time. Depending on the frequency offset, the number of correlations used in phase noise measurements can be in the range of several thousand to one million.



Number of correlations (N)	Sensitivity/noise floor improvement
1	0 dB
10	5 dB
100	10 dB
1000	15 dB
10000	20 dB

Figure 27: Correlation count and sensitivity improvement

5.3.7 Visualizing cross-correlation gain

The next question is how many cross-correlations to perform. The correlation count should be high enough to lower the instrument noise floor below the level of DUT phase noise, ideally with some margin to spare. This helps ensure that only the DUT phase noise is being measured. In addition to the measured phase noise trace, some phase noise analyzers can also display the so-called cross-correlation gain, which can be used to visually verify that sufficient measurement margin exists. In Figure 28, the gray area beneath the phase noise trace shows the cross-correlation gain. The higher the trace lies above this region, the higher the realized cross-correlation gain. It is important to note, that the cross-correlation gain does not show the absolute instrument noise level, but only the mathematical, relative gain, as achieved by repeated correlation. If the trace is too close to or touches this region, while the measurement could be valid, there is no guarantee that it is. The instrument can be configured to perform a higher number of cross-correlations to further increase the cross-correlation gain and lower the measurement floor. In Figure 28, increasing number of correlations from 100 to 10 000 clearly improves the measurement margin, particularly for phase noise at close-in offsets.

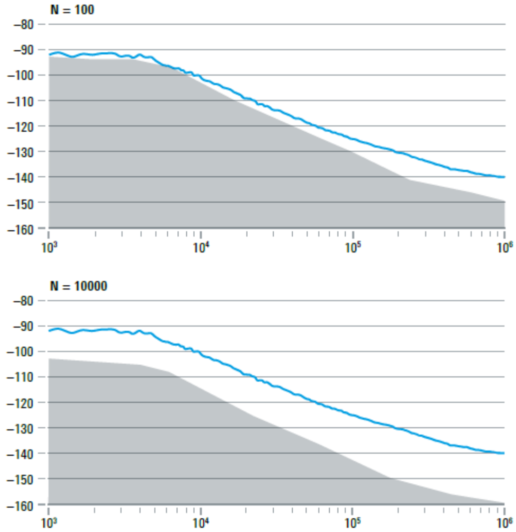


Figure 28: Visualizing cross correlation gain

5.4 Phase noise measurement with R&S®FSPN

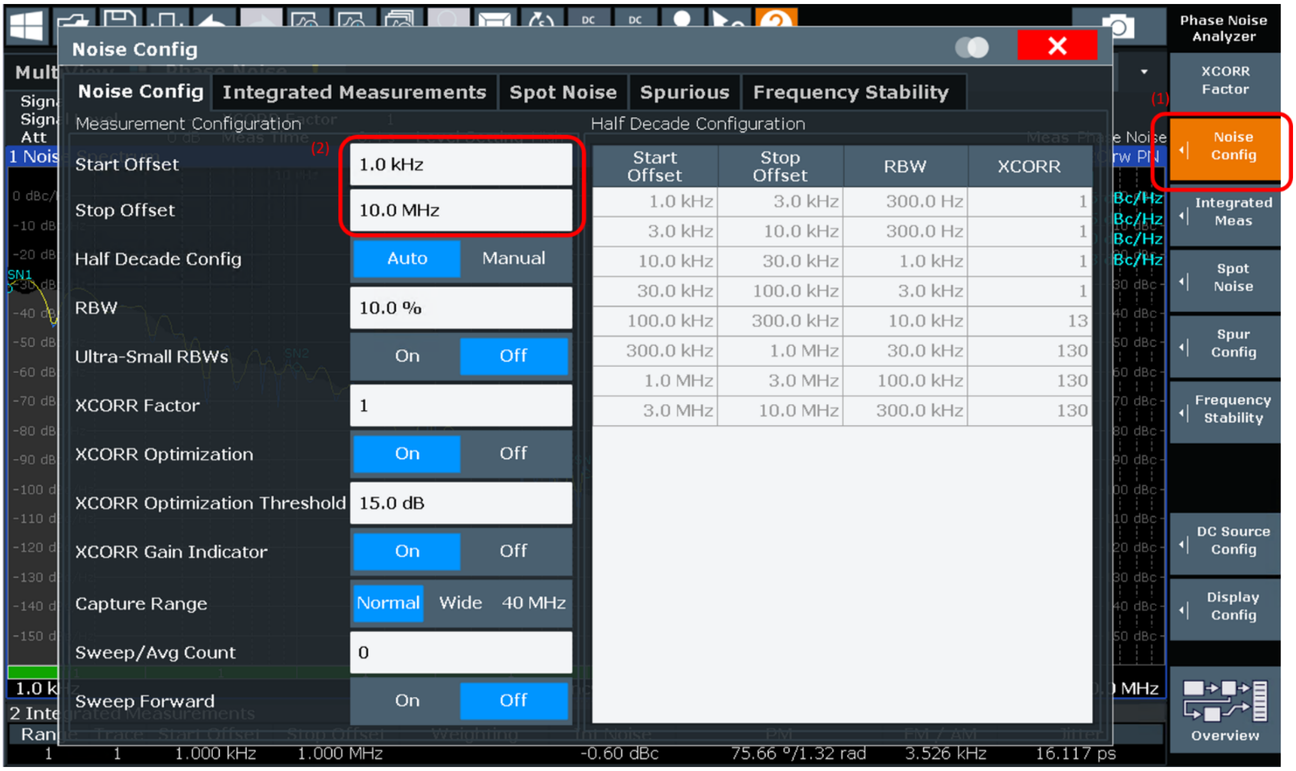
In comparison with the VCO characterization described in 3.3 the phase noise measurement evaluates the phase and amplitude noise at a fixed frequency and results in a trace of noise (y) over offset frequency (x). For the following measurements the VCO under test is the same as described in chapter 4.

Before starting the phase noise measurements, perform an instrument *PRESET.*

(1) When using a VCO as DUT, set up the DC voltages similar to the setup performed in 4.2.1.

(2) In order to configure the phase noise measurement, press the *Noise Config* softkey (Figure 29)

(3) Enter the start and stop frequency for the phase noise offset range (Figure 29)



Measurement Configuration

Start Offset: 1.0 kHz

Stop Offset: 10.0 MHz

Half Decade Config: **Auto** | Manual

RBW: 10.0 %

Ultra-Small RBWs: On | **Off**

XCORR Factor: 1

XCORR Optimization: **On** | Off

XCORR Optimization Threshold: 15.0 dB

XCORR Gain Indicator: **On** | Off

Capture Range: **Normal** | Wide | 40 MHz

Sweep/Avg Count: 0

Sweep Forward: On | **Off**

Half Decade Configuration

Start Offset	Stop Offset	RBW	XCORR
1.0 kHz	3.0 kHz	300.0 Hz	1
3.0 kHz	10.0 kHz	300.0 Hz	1
10.0 kHz	30.0 kHz	1.0 kHz	1
30.0 kHz	100.0 kHz	3.0 kHz	1
100.0 kHz	300.0 kHz	10.0 kHz	13
300.0 kHz	1.0 MHz	30.0 kHz	130
1.0 MHz	3.0 MHz	100.0 kHz	130
3.0 MHz	10.0 MHz	300.0 kHz	130

Figure 29: Phase noise measurement configuration

As mentioned above the phase noise measurement requires a fixed tuning voltage. The settings are shown in Figure 30.

(1) Press the DC Source Config softkey

(2) Enter the right value for the VCO supply voltage

(3) Enter the fixed VCO tune voltage. In this case 6 V which leads to a VCO output frequency of approximately 13 GHz (see Figure 32).

(4) Switch V_{supply}, V_{tune} and DC Power *On*

Input / Output

Input Source | **Output**

DC Config

	V_{Tune}	V_{Aux}	V_{Supply}
DC Power	On		
Channel Coupling	On		
Settings			
State	On	On	On
Mode			Voltage
Value	6.0 V	-500.0 mV	5.0 V
Limits			
Minimum	-1.0 V	-1.0 V	0 V
Maximum	25.0 V	10.0 V	6.0 V
Max Curr/Volt	20 mA	100 mA	200 mA
Results			
Curr/Volt	0 mA	-0 mA	130 mA

Figure 30: DC voltage configuration for the phase noise measurement

Enter the frequency range for the auto signal search function:

- ► Press the *AutoSet* hardkey

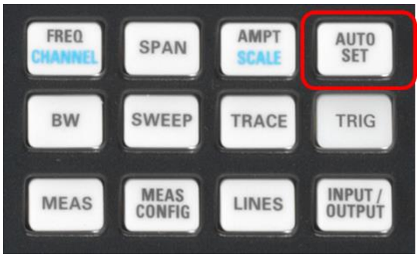
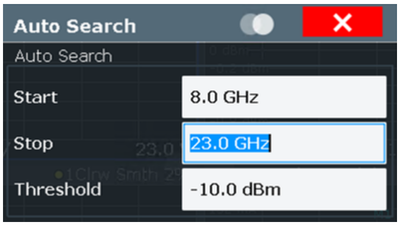


Figure 31: Select the auto set function

- ► Enter the frequency range for the auto signal search function as shown in the figure below.



Auto Search

Auto Search

Start: 8.0 GHz

Stop: 23.0 GHz

Threshold: -10.0 dBm

The R&S® FSPN now measures the VCO phase noise at 13 GHz and within an offset range from 1 kHz to 1 MHz (Figure 32).

Signal Frequency 13.039769922 GHz
Signal Level 0.34 dBm
Att 5 dB
RBW 10 %
XCORR Factor 1
Meas Time ~0.4 s
Level Setting High
Meas Phase Noise

Spot Noise [T1]	
1.000 kHz	-32.35 dBc/Hz
10.000 kHz	-58.54 dBc/Hz
100.000 kHz	-96.59 dBc/Hz
1.000 MHz	-119.05 dBc/Hz
10.000 MHz	-138.16 dBc/Hz

2 Integrated Measurements

Range	Trace	Start Offset	Stop Offset	Weighting	Int Noise	PM	FM / AM	Jitter
1	1	1.000 kHz	10.000 MHz		-59.98 dBc	81.25 m°/1.42 mrad	4.320 kHz	17.308 fs

Figure 32: VCO phase noise measurement

As you can see in the measurement result (Figure 32) there is no gap between the phase noise measurement curve (yello trace) and the grey cross correlation gain area. This is because only a single correlation has been performed (visible by the 1 in the green bar on the bottom), and there is no significant cross-correlation gain. To be sure, that the actual DUT noise is measured instead of the instrument noise, the cross-correlation factor can be increased, as shown in Figure 33 (see also chapter 5.3 Phase noise analyzer cross-correlation method).

XCORR Factor: 20

Signal Frequency 13.039553605 GHz
Signal Level 0.32 dBm
Att 5 dB
RBW 10 %
XCORR Factor 20
Meas Time ~0.4 s
Level Setting High
Meas Phase Noise

Spot Noise [T1]	
1.000 kHz	-26.55 dBc/Hz
10.000 kHz	-62.12 dBc/Hz
100.000 kHz	-95.18 dBc/Hz
1.000 MHz	-119.69 dBc/Hz
10.000 MHz	-139.39 dBc/Hz

2 Integrated Measurements

Range	Trace	Start Offset	Stop Offset	Weighting	Int Noise	PM	FM / AM	Jitter
1	1	1.000 kHz	10.000 MHz		-1.49 dBc	68.22 °/1.19 rad	5.220 kHz	14.533 ps

Figure 33: Setting the cross-correlation factor

(1) Press the *XCORR Factor* Softkey and increase the value until there is a certain gap between the phase noise measurement curve and the grey cross correlation gain over the complete frequency offset range.

(2) The displayed result trace shows the real phase noise, without AM noise. The TRACE hardkey and softkeys can be used to display also the AM noise, or the combined PN + AM noise. The R&S®FSPN is distinguishing between PN and AM noise by demodulating the carrier signal for phase and amplitude.

(3) In addition to the single sideband phase noise plot, another common way of representing phase noise measurement results, is spot noise. Spot noise is the numerical phase noise result (in dBc/Hz) at one or more specific frequency offsets. Spot noise is often measured at decade offsets, that is, offsets which are powers of ten, e.g. 1 kHz, 10 kHz, 100 kHz, etc., although it is also possible to measure spot noise at arbitrary, user-defined offsets. Here, the spot noise is reported in a table format.

5.5 Spot noise versus tune measurements

Spot noise vs Tune is a measure of noise values at different offset frequencies, over discrete carrier frequencies by tuning V_{tune}. This means that this measurement is a combination of phase noise and VCO characterization. The spot noise vs tune can be divided in spot noise vs. tune PN (phase noise) and spot noise vs. AM (AM noise).

Please note: before staring a spot noise versus tune measurement make sure, that the cross-correlation factor for the phase noise measurement has the right setting as described in chapter 5.4. Due the fact, that the correlation gain indicator (gray area) is only visible and usable in the phase noise measurement mode, it is meaningful to perform a phase measurement before like it is described under 5.4 .

For the measurement perform the following steps:

- Press the *MEAS* Hardkey and select *Spot Noise Versus Tune* (Figure 34)

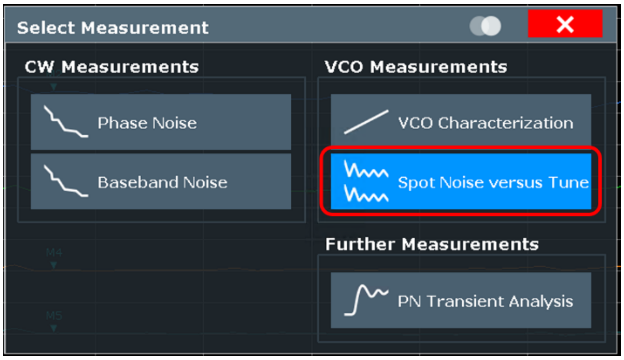
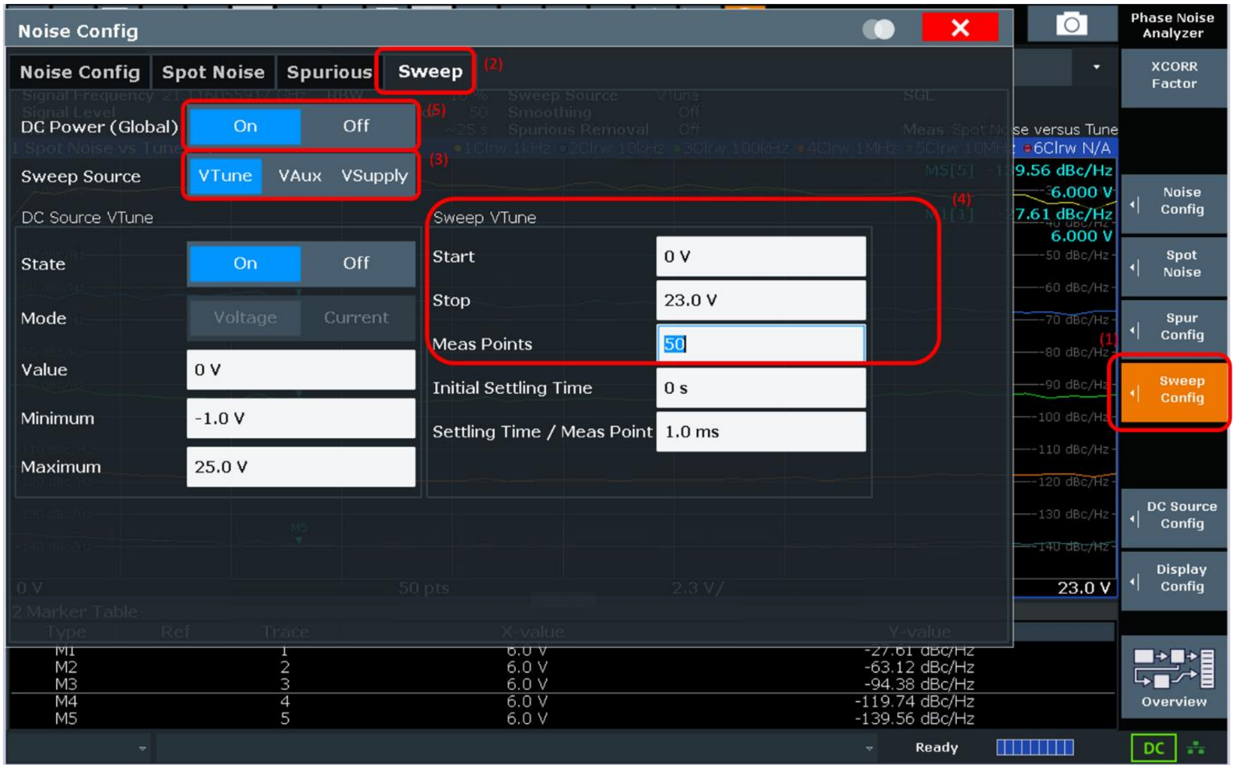


Figure 34: Start spot noise vs tune measurement



DC Power (Global): On | Off

Sweep Source: VTune | VAux | VSupply

DC Source VTune

State	On | Off
Mode	Voltage | Current
Value	0 V
Minimum	-1.0 V
Maximum	25.0 V

Sweep VTune

Start	0 V
Stop	23.0 V
Meas Points	50
Initial Settling Time	0 s
Settling Time / Meas Point	1.0 ms

Type	Ref	Trace	X-value	Y-value
M1		1	6.0 V	-27.61 dBc/Hz
M2		2	6.0 V	-63.12 dBc/Hz
M3		3	6.0 V	-94.38 dBc/Hz
M4		4	6.0 V	-119.74 dBc/Hz
M5		5	6.0 V	-139.56 dBc/Hz

Figure 35: Spot noise vs tune sweep configuration

For the spot noise vs tune configuration, perform the following steps (see also Figure 35)

(1) Press the *Sweep Config* Softkey softkey

(2) Select the *Sweep* tab

(3) Choose V_{tune} as sweep source

(4) Enter the tuning range for V_{tune} and the number of measurement points

(5) Switch the DC power on

Take over the settings for the phase noise measurement configuration including frequency offset range (see Noise Fig tab) and auto Search range (AUTO SET hardkey) from the phase noise measurement described in chapter 5.4.

Figure 36 shows the measurement result for spot noise versus tune PN measurement.

Signal Frequency 21.116055917 GHz RBW 10 % Sweep Source VTune SGL
Signal Level -1.38 dBm XCORR Factor 50 Smoothing Off
Att 10 dB Meas Time ~25 s Spurious Removal Off Meas Spot Noise versus Tune

1 Spot Noise vs Tune PN ●1Clrw 1kHz ●2Clrw 10kHz ●3Clrw 100kHz ●4Clrw 1MHz ●5Clrw 10MHz ●6Clrw N/A

M5[5] -139.56 dBc/Hz 6.000 V
M1[1] -27.61 dBc/Hz 6.000 V

0 V 50 pts 2.3 V/ 23.0 V

2 Marker Table

Type	Ref	Trace	X-value	Y-value
M1		1	6.0 V	-27.61 dBc/Hz
M2		2	6.0 V	-63.12 dBc/Hz
M3		3	6.0 V	-94.38 dBc/Hz
M4		4	6.0 V	-119.74 dBc/Hz
M5		5	6.0 V	-139.56 dBc/Hz

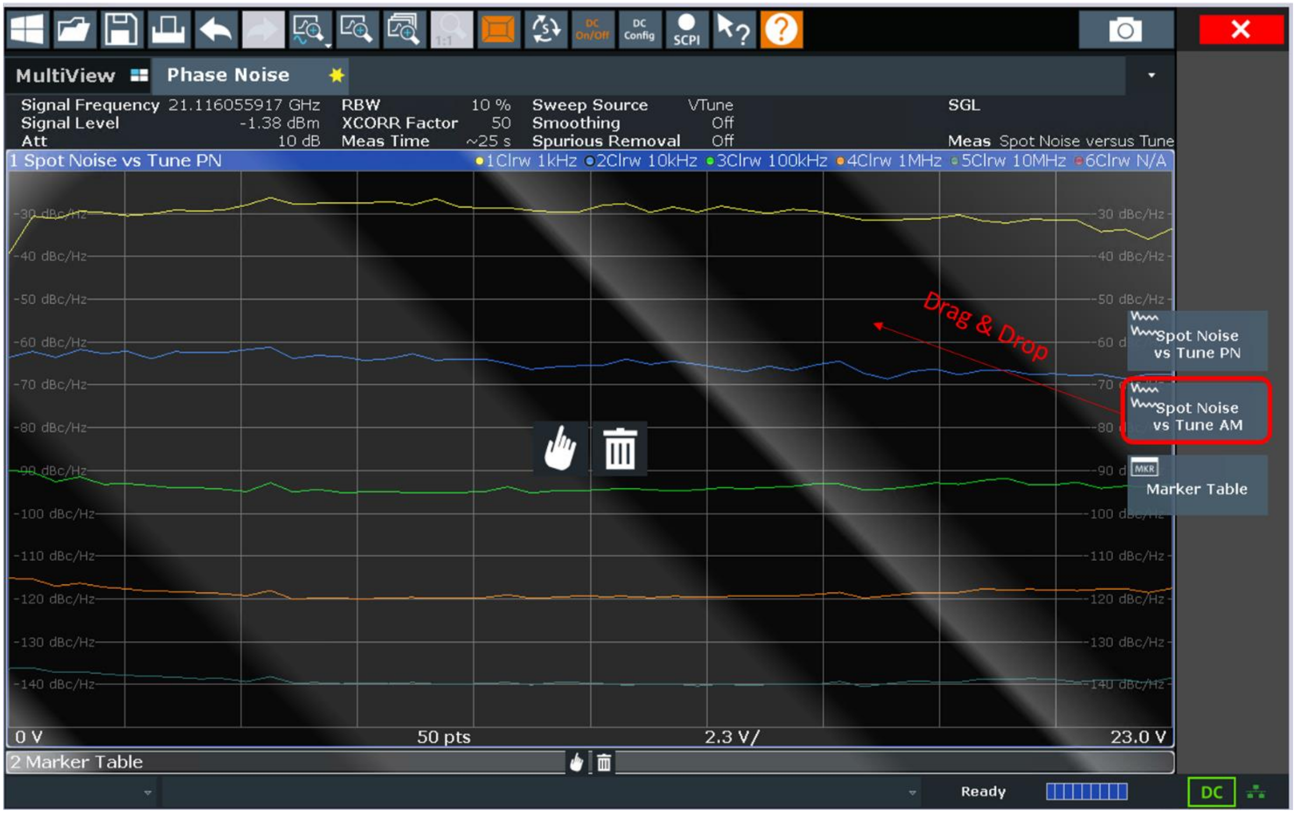
Figure 36: Spot noise vs tune PM measurement result

The sweeping tuning voltage resulting in different carrier frequencies. The R&S®FSPN performs a phase noise measurement at those frequencies and plots the spot noise values from the phase noise measurement over the tuning voltage. In this case the spot noise versus tune PN is measured at five different offset frequencies (1 kHz, 10 kHz, 100 kHz and 1 MHz). The marker table shows the current spot noise values at V_{tune}= 6V for each frequency offset trace. Because the V_{tune} marker values and the V_{tune} voltage of the phase noise measurement, described in chapter 5.4, results in the same VCO carrier frequency, the spot noise values of the phase noise measurement in Figure 33 are approximately the same.

5.5.1 Spot noise vs tune AM measurement

The spot noise vs tune AM function measures the amplitude noise as a function of V_{tune} at different frequency offsets.

For this measurement press the *Display Config* softkey and activate the Spot Noise vs Tune AM measurement function via Drag&Drop (Figure 37).



Signal Frequency 21.116055917 GHz
Signal Level -1.38 dBm
Att 10 dB
RBW 10 %
XCORR Factor 50
Meas Time ~25 s
Sweep Source VTune
Smoothing Off
Spurious Removal Off
SGL
Meas Spot Noise versus Tune

Figure 37: Spot noise vs tune AM

Figure 37 shows the result of the spot noise vs tune AM measurement at five different offset frequencies. AM noise is usually much smaller than phase noise.

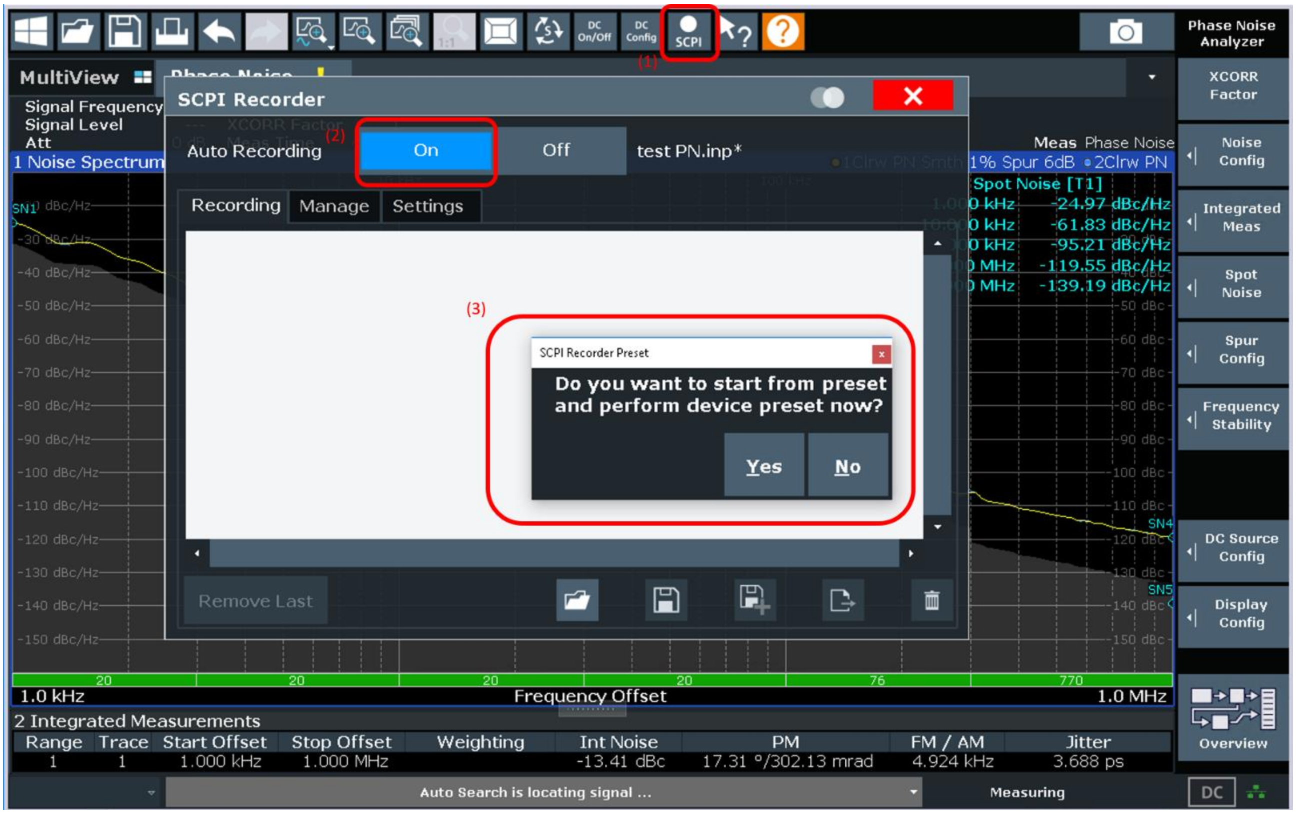
Signal Frequency 19.066872554 GHz
Signal Level 0.00 dBm
Att 10 dB
RBW 10 %
XCORR Factor 50
Meas Time ~25 s
Sweep Source VTune
Smoothing Off
Spurious Removal Off
Meas Spot Noise versus Tune

Figure 38: Spot noise vs tune AM measurement result

6 SCPI Command Recorder

For remote control applications the R&S®FSPN allows to create test automation scripts directly in the user interface. That means that users can completely configure a device with SCPI commands. To simplify the move from operator-controlled measurements to automated testing, the R&S®FSPN supports the automatic generation of SCPI scripts. The SCPI commands for changing settings, pressing buttons or querying data can be viewed and manually added to the current SCPI command list. The SCPI recorder can also be enabled and all user interactions with the instrument are automatically translated into SCPI commands.

In order to record SCPI commands during the manual operation of the instrument follow the following steps shown in Figure 39:



SCPI Recorder Preset

Do you want to start from preset and perform device preset now?

Yes No

2 Integrated Measurements

Range	Trace	Start Offset	Stop Offset	Weighting	Int Noise	PM	FM / AM	Jitter
1	1	1.000 kHz	1.000 MHz		-13.41 dBc	17.31 °/302.13 mrad	4.924 kHz	3.688 ps

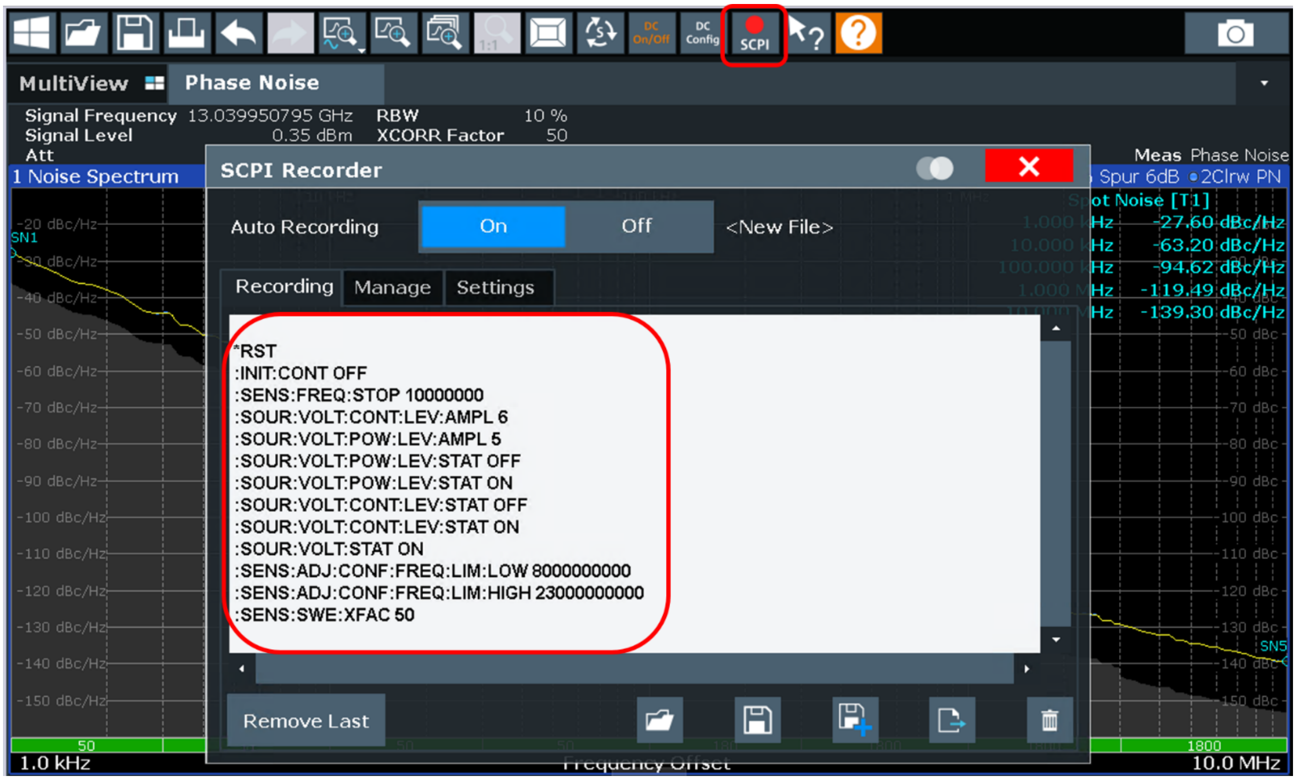
Figure 39: Starting the SCPI recording

(1) Select the *SCPI* softkey

(2) Switch the auto recording On

(3) Choose whether the SCPI recording should start with an instrument preset

- Make the required settings for the measurement manually on the instrument
- After the settings are finished press the *SCPI* softkey again
- The instrument displays the list of all corresponding SCPI commands of the manual operation (Figure 40). In this case the SCPI commands of the phase noise measurement described in chapter 5 is shown. Now it is possible to export the plain command list or ready-to-use scripts in different languages such as Matlab®, Python and C#.



Signal Frequency 13.039950795 GHz
Signal Level 0.35 dBm
Att
RBW 10 %
XCORR Factor 50

Auto Recording On Off <New File>

```
*RST
:INIT:CONT OFF
:SENS:FREQ:STOP 10000000
:SOUR:VOLT:CONT:LEV:AMPL 6
:SOUR:VOLT:POW:LEV:AMPL 5
:SOUR:VOLT:POW:LEV:STAT OFF
:SOUR:VOLT:POW:LEV:STAT ON
:SOUR:VOLT:CONT:LEV:STAT OFF
:SOUR:VOLT:CONT:LEV:STAT ON
:SOUR:VOLT:STAT ON
:SENS:ADJ:CONF:FREQ:LIM:LOW 8000000000
:SENS:ADJ:CONF:FREQ:LIM:HIGH 23000000000
:SENS:SWE:XFAC 50
```

Figure 40: Recorded SCPI commands after manual operation

7 Summary

A voltage controller oscillator produces an output signal whose frequency can be changed or controlled by means of an external tuning voltage. VCOs are used in many different applications and are one of the fundamental building blocks of RF systems. Different VCO designs are used for different applications, and measuring or characterizing VCOs is an important part of RF design, debug, and integration. VCO characterization requires the use of precise and adjustable voltage sources, which are integrated into the R&S®FSPN phase noise analyzer and VCO tester. Thanks to the optimized hardware, the R&S®FSPN provides higher speed and higher sensitivity than a traditional spectrum analyzer. The increased sensitivity is primarily a result of the implemented cross correlation method. The integrated SCPI recorder brings the R&S®FSPN very easily from the lab into a remote-controlled production line.

8 Literature

[1] P. Denisowski, *White paper: Understanding Voltage Controlled Oscillators,* Rohde&Schwarz, 2022.

[2] P. Denisowski, *White paper: Understanding Phase Noise Measurement Techniques,* Rohde&Schwarz, 2022.

[3] P. Denisowski, *White paper: Understanding Phase Noise Fundamentals,* Rohde&Schwarz.

9 Ordering Information

Designation	Type	Order No.
Phase noise analyzer and VCO tester, 1 MHz to 8 GHz	R&S® FSPN8	1322.8003.07
Phase noise analyzer and VCO tester, 1 MHz to 26.5 GHz	R&S® FSPN26	1322.8003.25

Rohde & Schwarz

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1SL386 | Version 0e | 05.2023
Application Note | VCO MEASUREMENTS with R&S FSPN Phase Noise Analyzer
Data without tolerance limits is not binding | Subject to change

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