Measurement Uncertainty Analysis and Traceability for Phase Noise

Application Note

Products:

- R&S®FSWP

This application note reviews the measurement uncertainty analysis and traceability for phase noise with the new R&S®FSWP Phase Noise Analyzer.

It describes the new approach for measuring phase noise with the R&S®FSWP using direct down-conversion with cross correlation and focuses on traceability using a derived primary measurement standard.

Please find the most up-to-date document on our homepage http://www.rohde-schwarz.com/appnote/1EF95.

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1 Introduction

The R&S FSWP phase noise analyzer and VCO tester is the optimal test solution for radar applications and when developing and manufacturing synthesizers, OCXOs, DROs and VCOs. It can be easily configured to meet the required application. The instrument's low-noise internal local oscillator makes it possible to measure most commercially available synthesizers and oscillators without any additional options. For high-end applications, the R&S FSWP can be equipped with a second receive path, which enables cross-correlation and, depending on the number of correlations used, increases sensitivity – by up to 25 dB.

This application note describes shortly the fundamentals of phase noise and phase noise measurement, the architecture of the R&S FSWP and focuses on the measurement error and traceability to standards of national metrology institutes.

2 Fundamentals of Phase Noise and Phase Noise Measurement

Phase noise is measured using an R&S FSWP phase noise analyzer.

In order to display RF signals with as little phase noise as possible, a 100 MHz low phase noise (LPN) oscillator is used.

Describing a CW signal

The CW signal from an oscillator is described as follows:

$$V(t) = V_0[1 + \alpha(t)] \cos[2\pi f_0 t + \phi(t)] \tag{1}$$

where f_0 is the carrier frequency, V_0 is the amplitude, $\alpha(t)$ is the normalized amplitude fluctuation and $\phi(t)$ is the phase fluctuation.

The power spectral density of the phase fluctuation S_ϕ is:

$$S_\phi(f) = \frac{\langle \Delta\phi_{\mathrm{rms}}(f)\rangle^2}{\mathrm{NBW}} \tag{2}$$

where $\langle \Delta\phi_{rms}(f)\rangle^2$ is the average phase fluctuation at offset frequency $f \quad (0 < f < \infty)$ referenced to carrier frequency f_0. NBW (noise bandwidth) represents the equivalent noise bandwidth used to measure the phase fluctuation. The unit is rad2 / Hz. $S_\phi(f)$ is the sum of the fluctuations from the lower and upper sidebands.

(The measurement system's true bandwidth is bell-shaped. Because this is a digital bandwidth, a mathematical transducer factor is used to calculate the equivalent noise bandwidth; see also Influence of Filter Bandwidth $\delta\mathcal{L}_{BW}$)

Measurand: phase noise

The measurand is the phase noise $\mathcal{L}$ of an oscillator or RF signal generator This results from the power spectral density (PSD) of the phase fluctuation S_ϕ [6]:

$$\mathcal{L}(f) = \frac{1}{2} S_\phi(f) \tag{3}$$

The phase noise $\mathcal{L}(f)$ only refers to the noise power density of a sideband. It is accepted that the phase noise symmetrically surrounds the carrier frequency.

Phase noise is typically expressed in dBc/Hz.

The following applies:

$$\mathcal{L}(f) = 10 \cdot \log\left(\frac{1}{2} S_\phi(f)\right) \ [\mathrm{dBc/Hz}] \tag{4}$$

$\mathcal{L}(f)$ is measured as the ratio of carrier power P_c to the phase noise power density from the two sidebands:

$$\mathcal{L}(f) = 10 \cdot \log\left(\frac{\text{phase noise power density from both sidebands per Hz at offset } f}{2 \cdot \text{carrier power}}\right) \tag{5}$$

Test setup

The oscillator or RF signal generator is connected directly to the DUT via an RF cable (Figure 1).

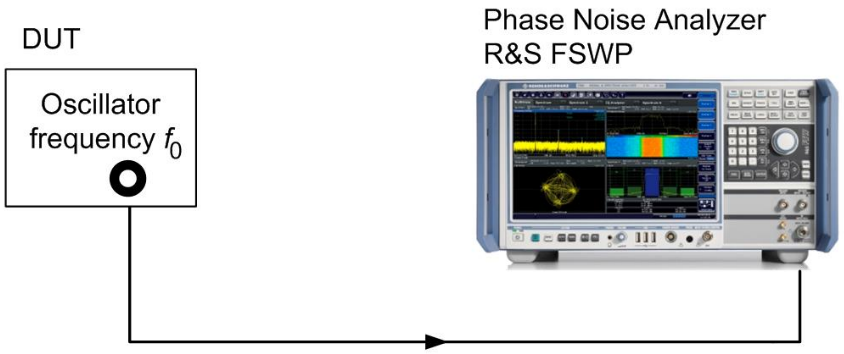


Figure 1: Test setup for phase measurements using an R&S FSWP phase noise analyzer.

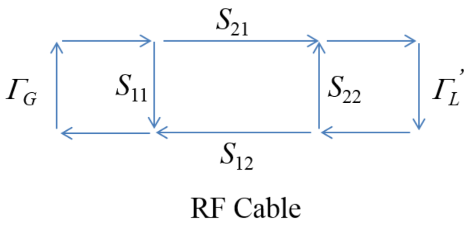


Figure 2: Equivalent circuit model of the test setup.

The equivalent circuit model for the test setup (see Figure 2) shows the S-parameters for the RF measurement cable (S_{11}, S_{21}, S_{12}, S_{22}) and the input reflection from the DUT Γ_G and from the phase noise analyzer Γ_L'.

Influences from impedance mismatch can be expected if the impedance matching changes as a function of the offset frequency. It can help to use a short RF cable between the DUT and the FSWP phase noise analyzer.

3 Phase Noise Analysis Using Direct Down-Conversion with Cross Correlation

A brief description of the measurement procedure in the R&S FSWP is provided here (see Figure 3):

Traditional phase noise analyzers use an analog PLL to recover the phase difference between a local oscillator and the device under test (DUT). Phase locking and compensating the frequency characteristics of the PLL can be cumbersome. Digital phase noise measurements overcome these issues by sampling the RF waveforms directly and calculating the phase difference in the digital domain.

The new alternative approach used within the R&S FSWP requires only down-conversion of the DUT signal. An analog I/Q mixer with an extremely low-noise internal reference source shifts the signal to a low or zero IF, depending on the offset frequencies to be measured. A second receive path enables cross correlation with two narrow-band coupled reference oscillators. This increases the sensitivity by up to 25 dB depending on the number of correlations used.

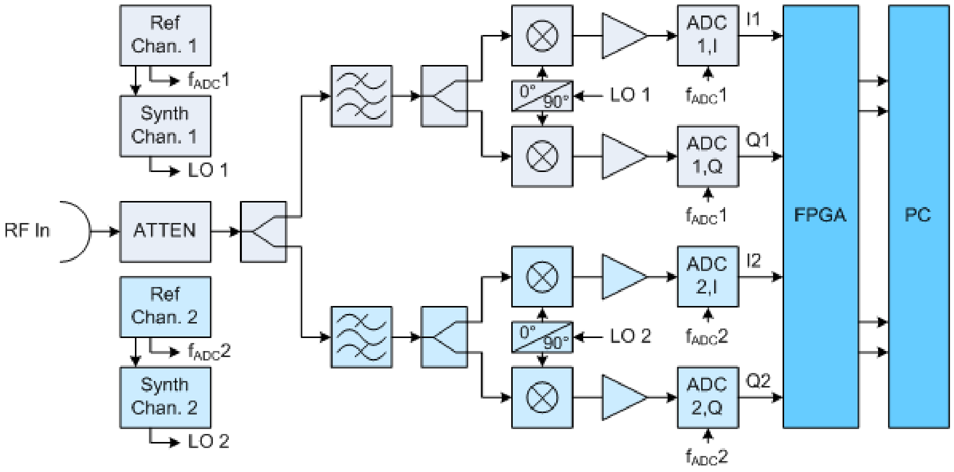


Figure 3: Simplified diagram for phase noise measurement using cross-correlation on the R&S FSWP phase noise analyzer.

The complex baseband signals of each path are sampled and the subsequent digital signal processing is done in real time on an FPGA. A digital FM demodulator replaces the PLL as a phase detector and for frequency tracking. The combination of an analog I/Q mixer and a digital equalizer keeps the AM rejection above 40 dB compared to 15-30 dB of a traditional analog PLL. An AM demodulator operates in parallel to the FM demodulator which allows for concurrent measurement of amplitude and phase noise. The demodulated signals are filtered, decimated and transferred to the instrument's processor for the FFT and cross correlation processing. The resulting frequency noise spectrum is converted back to an actual phase noise spectrum. Phase noise as low as 183 dBc/Hz at 100 MHz carrier frequency and 10 kHz offset can be measured within two minutes.

Mathematical breakdown of the measurement signal

Equation (1) can be rewritten [3] (page 4; equation 3) as:

$$V(t) = V_0 \cos(\omega_0 t) + x(t)\cos(\omega_0 t) - y(t)\sin(\omega_0 t) \quad (6)$$

where $x(t)$ and $y(t)$ are influences resulting from noise.

The result is:

$$\alpha(t) = V_0\sqrt{\left(1+\frac{x(t)}{V_0}\right)^2 - \left(\frac{y(t)}{V_0}\right)^2} - 1 \quad (7)$$

$$\phi(t) = \arg(x(t), V_0 + y(t))\ (3) \quad (8)$$

For low noise $|x/V_0| \ll 1$, $|y/V_0| \ll 1$ (small-signal approximation), the result is:

$$\alpha(t) = \frac{x(t)}{V_0} \quad (9)$$

$$\phi(t) = \frac{y(t)}{V_0} \quad (10)$$

Cross-correlation

This section provides a rough sketch of the cross-correlation method (see Figure 3). The calculations are derived from [4].

The objective is to introduce the variables m (number of averaged cross-correlations) and L_{Ref} (single-channel noise levels) and to display the dependency of the uncorrelated noise level $L_{Ref,m}$ on the number m of averaged cross-correlations.

Assumptions: the noise from reference channel 1 is in time domain a, the noise from reference channel 2 is in b and the noise from the DUT is in c.

The following applies in the time domain:

Channel 1: $x = a + c$

Channel 2: $y = b + c$

The following applies for Fourier transform during measurement time T in the frequency domain:

Channel 1: $X = A + C$

Channel 2: $Y = B + C$

The phase noise of the DUT S_{cc} is obtained by cross-correlation between channels 1 and 2:

$$S_{cc} = \langle S_{xy}\rangle_m = \frac{1}{T}\langle XY^*\rangle_m = \frac{1}{T}\langle CC^*\rangle_m + \frac{1}{T}\langle CB^*\rangle_m + \frac{1}{T}\langle AC^*\rangle_m + \frac{1}{T}\langle AB^*\rangle_m \quad (11)$$

The expression $\frac{1}{T}\langle XY^*\rangle_m$ defines the mathematical operation of m averagings of the measurement results obtained in the individual channels during measurement time T.

If the noise level is dominant (when the phase noise from the DUT is limited $\mathcal{L}_{Dut} \approx 0$), the following applies with normalization of the signal S_{xx} or S_{yy} [4] (page 35, equation 59):

$$S_{cc}(m) = \sqrt{\frac{\pi}{4}\frac{1}{\sqrt{m}}} \quad (12)$$

This means that already during the first measurement ($m = 1$), the noise level of the reference oscillators is attenuated by a factor of $\sqrt{\frac{\pi}{4}}$ (corresponds to 0.52 dB).

With a very low phase noise DUT $\mathcal{L}_{DUT} \ll \mathcal{L}_{Ref1}$, the displayed $m = 1$ can be used to estimate the noise levels $\mathcal{L}_{Ref1}$ of the reference oscillators:

$$\mathcal{L}_{\mathrm{Ref1}} \approx \mathcal{L}_{\mathrm{Anz,1}} \qquad (13)$$

In the case of $\mathcal{L}_{DUT} = 0$, only the noise from the reference oscillators is measured. This noise is reduced by means of averaging m [4].

$$\mathcal{L}_{\mathrm{Refm}} \approx \mathcal{L}_{\mathrm{Ref1}} - 5 \cdot \log \mathrm{m} \qquad (14)$$

where m is the number of averaged correlations in the measuring instrument.

$\mathcal{L}_{Refm}$ is equal to the displayed noise $\mathcal{L}_{Anzm}$ output by the instrument for $\mathcal{L}_{DUT} = 0$ during averaging m.

If $\mathcal{L}_{DUT} \gg \mathcal{L}_{Refm}$, then the measured noise $\mathcal{L}_{Anzm}$ is the noise from the DUT.

The noise level $\mathcal{L}_{Refm}$ has two consequences.

On the one hand, the noise from the reference oscillators will cause dispersion of the measurement results. On the other hand, the superposition of the phase noise from a reference oscillator and from the DUT results in a positive systematic measurement error, called a bias. This bias is strongly dependent on the difference between the phase noise from the DUT and that from the reference oscillator ($\Delta\mathcal{L}_{SNR} = \mathcal{L}_{DUT} - \mathcal{L}_{Refm}$).

The dispersion of the measured values can be reduced and determined by averaging the measurement results.

The bias calculation is not a trivial undertaking. There is no simple relationship such as that below:

$$\mathcal{L}_{\mathrm{Anzm}} = \mathcal{L}_{\mathrm{Refm}} + \mathcal{L}_{\mathrm{DUT}} \qquad (15)$$

If $\mathcal{L}_{Refm} \approx \mathcal{L}_{DUT}$, then the displayed value would be expected to be 3 dB greater than $\mathcal{L}_{DUT}$.

A mathematical simulation shows that cross-correlation provides a greater reduction of the influence of the noise from the reference oscillator. Refer to "Noise Cancellation Using Cross-Correlation" for more on this topic.

4 Traceability

The phase noise standard is calibrated using a derived primary measurement standard. This means that the measurand is determined without a direct comparison to a standard for that measurand. This in turn means that traceability is provided primarily via the measurand RF attenuation / RF linearity.

Traceability of the phase noise measurand is provided in three ways:

1. Qualifying examination: Comparison of the phase noise of a low phase noise (LPN) standard at 100 MHz as measured by a national metrology institute or an accredited laboratory. Comparison of an R&S signal generator (R&S SMA100A in this case) that has been measured at various frequencies by a national metrology institute or an accredited laboratory (see "Verification Measurements by National Institutes").
2. Optional calibration of the R&S FSWP phase noise analyzer for the relevant parameters: Linearity with reference to the offset frequency and hardware limit. The phase noise measurand is derived in an uninterrupted chain of calibrations for the basic RF parameters, including linearity and RF power.
3. Verification measurement using a digitally modulated oscillator.

Statements regarding the traceability process

Re 1) A very low phase noise, 100 MHz oscillator and an R&S SMA100A generator were sent for calibration and measured using the phase noise analyzer.

Re 2) Optional calibration:

- Linearity:

  In a first step, the linearity of the R&S FSWP phase noise analyzer is confirmed in spectrum analyzer mode; see Figure 4. This is done by confirming the linearity in 10 dB increments using an NRPC power standard.

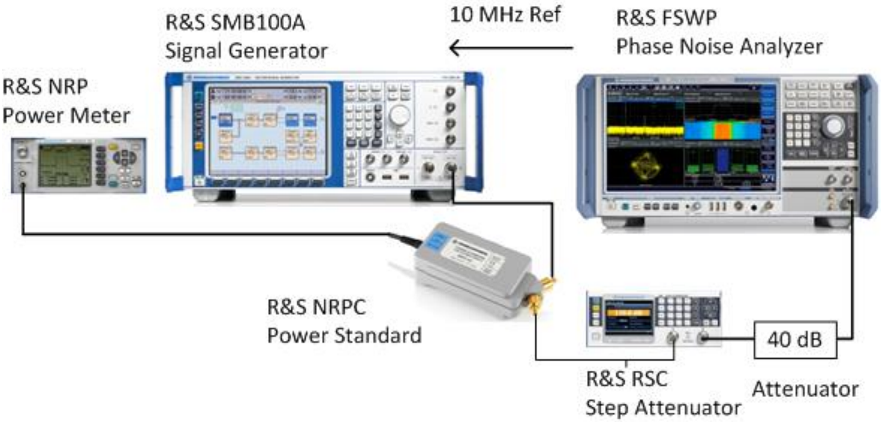


Figure 4: Calibration of the R&S FSWP phase noise analyzer linearity in spectrum analyzer mode.

In a second step, the carrier signal is supplemented with a second signal at a frequency offset f by means of a power combiner; see Figure 5. The level offset is determined in spectrum analyzer mode. The result is compared against the displayed phase noise measurement. The offset during the phase noise measurement is 6 dB higher than that in spectrum analyzer mode [2].

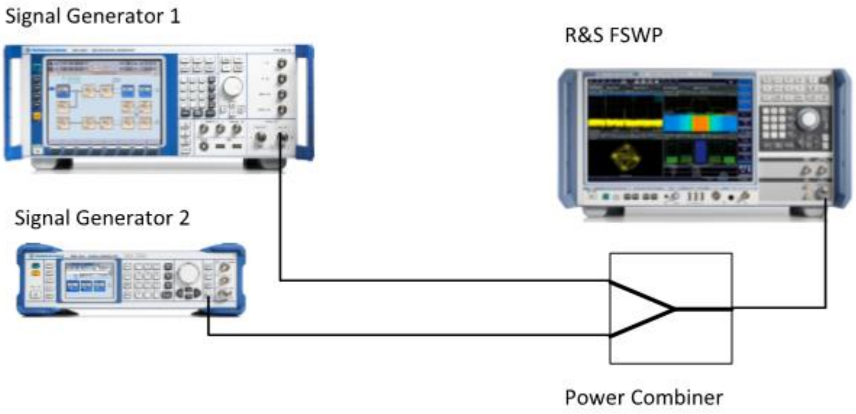


Figure 5: Calibration of the R&S FSWP with two generators in phase noise mode.

- Frequency characteristics:

  The frequency characteristics are tested by applying a second signal together with the carrier signal. The second signal is recognized as spurious oscillation. The frequency characteristics is determined by applying the spurious oscillation, tuned to the carrier frequency as a function of the offset frequency, at constant power; see Figure 5.

- Noise levels:

  The noise levels for the two oscillators cannot simply be suppressed when using the cross-correlation method. It is therefore important that the noise levels from the internal reference oscillators be detected. In service mode, this can happen within the measuring instrument. To do this, one of the reference oscillators is connected to the input (analog like the DUT); the other oscillator is now the reference oscillator for both channels. The cross-correlation then suppresses only the uncorrelated noise caused in the various paths. Because the same noise is present on both channels, it is possible to estimate the noise from the reference oscillators based on an assumed symmetry.

Re 3) Digitally modulated noise signal

The carrier frequency of an I/Q-modulated generator is digitally modulated with white noise. The measurement result is expected to be noise that decreases at a rate of 20 dB per frequency decade. The phase noise of the digitally modulated signal is calculated mathematically and compared against the measured noise.

4.1 Example Equation for Phase Noise

The model function for phase noise L is defined as:

$$\mathcal{L}_{Readm} = \mathcal{L}_{Readm} + \Delta\mathcal{L}_{SNR} + \Delta\mathcal{L}_{Sp} + \delta\mathcal{L}_{FR} + \delta F + \delta\mathcal{L}_{Lin} + \delta\mathcal{L}_{Rep} + \delta\mathcal{L}_{Cor} + \delta\mathcal{L}_{BW} + \delta\mathcal{L}_{Cab} + \delta\mathcal{L}_{Att} + \delta\mathcal{L}_{deg} \tag{16}$$

where $\mathcal{L}_{Readm}$ is the average value of the measured values from various measurement series.

The following influences are taken into consideration:

$\mathcal{L}_{Readm}$	Measurement result from the phase noise analyzer
$\Delta\mathcal{L}_{SNR}$	Correction of the noise from the reference oscillators using the cross-correlation method
$\Delta\mathcal{L}_{Sp}$	Unwanted disturbance signals
$\delta\mathcal{L}_{FR}$	Frequency characteristics
δF	Mutual influence resulting from impedance mismatch
$\delta\mathcal{L}_{Lin}$	Linearity
$\delta\mathcal{L}_{Rep}$	Short-term repeatability
$\delta\mathcal{L}_{Cor}$	Hardware limit (correlated noise levels)
$\delta\mathcal{L}_{BW}$	Filter bandwidth
$\delta\mathcal{L}_{Cab}$	RF cable
$\delta\mathcal{L}_{Att}$	Internal attenuator on the FSWP
$\delta\mathcal{L}_{deg}$	Small-angle approximation

Measurement result $\mathcal{L}_{Readm}$

The measured value from the phase noise analyzer is output digitally with a large number of frequency points. The display resolution can therefore be skipped when considering the measurement uncertainty.

Correction of noise from the reference oscillators using cross-correlation method $\Delta\mathcal{L}_{SNR}$

There are two limiting cases:

- Insufficient averaging ($\mathcal{L}_{Refm} \geq \mathcal{L}_{DUT}$):

  The noise from the reference oscillators dominates the noise from the DUT. The measurement result is usable only for specifying a limit for the noise from the DUT.

  The measurement result $\mathcal{L}_{Readm}$ approximately corresponds to the noise from the reference oscillator $\mathcal{L}_{Refm}$.

$$\mathcal{L}_{\mathrm{Readm}} \approx \mathcal{L}_{\mathrm{Refm}} \tag{17}$$

In principle, it is possible to reduce $\mathcal{L}_{Refm}$ as necessary by selecting many averagings. In practice, there is a limit as defined by the hardware limit $\delta\mathcal{L}_{Cor}$.

- Sufficient averaging ($\mathcal{L}_{DUT} > \mathcal{L}_{Refm}$, $\mathcal{L}_{SNR} > 5$ dB):

  The noise from the DUT dominates the noise level component. The measurement result permits an assessment of the phase noise from the DUT. The influence of the bias, caused by the noise from the reference oscillators, is minimal.

  The measurement result $\mathcal{L}_{Readm}$ represents the noise from the DUT $\mathcal{L}_{DUT}$.

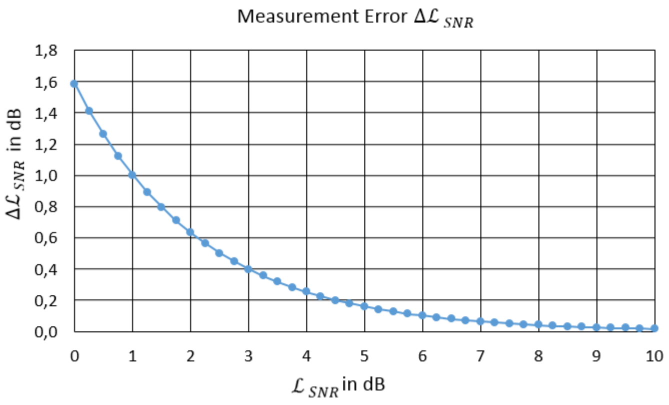
  $$\mathcal{L}_{\mathrm{Readm}} \approx \mathcal{L}_{\mathrm{DUT}} \tag{18}$$

If the noise from the reference oscillators $\mathcal{L}_{Refm}$ approximately matches the noise from the DUT ($\mathcal{L}_{DUT} \geq \mathcal{L}_{Refm}$,$\mathcal{L}_{SNR} \geq 0$ dB), then the bias $\Delta\mathcal{L}_{SNR}$ is a complex function of the offset $\mathcal{L}_{SNR} = \mathcal{L}_{DUT} - \mathcal{L}_{Refm}$. The bias additionally depends somewhat on the offset from $\mathcal{L}_{DUT}$ to $\mathcal{L}_{Ref}$. If $\mathcal{L}_{SNR} > 0$ dB, the influence of the bias can be estimated with:

$$\Delta\mathcal{L}_{\mathrm{SNR}} = 10^{(-0.2\cdot\mathcal{L}_{\mathrm{SNR}}+0.2)} \tag{19}$$

The formula was determined based on simulations and verified by means of measurements.

Example: For $\mathcal{L}_{Ref1} - \mathcal{L}_{DUT} = 5$ dB, and for a number of correlations m of 10, $\mathcal{L}_{Refm} - \mathcal{L}_{DUT} = 0$ dB, the resulting bias is $10^{(0.2)} = 1.6$ dB; see Figure 6.



$\mathcal{L}_{SNR}$ in dB	$\Delta\mathcal{L}_{SNR}$ in dB
0	1.6
0.5	1.3
1	1.0
2	0.65
3	0.40
5	0.16
8	0.04

Figure 6: Simulation for estimating the influence of the phase noise from the reference oscillators on the noise from the DUT.

The noise value $\mathcal{L}_{Refm}$ from the internal reference oscillators is dependent on the quality of the reference oscillators used in the phase noise analyzer and also on the selected number of cross-correlations. To determine $\mathcal{L}_{Refm}$, the conservative approach was followed in that instead of selecting the maximum number of possible correlations, the following decrements are used:

Table 4-1 Selected number of cross-correlations for estimating the possible reduction of $\mathcal{L}_{Refm}$

Offset Frequency	Number of correlations m	Suppression in dB	Example at $f_0 = 100$ MHz	
			$\mathcal{L}_{Ref1}$	$\mathcal{L}_{Refm}$
1 Hz	10	5 dB	–85 dBc/Hz	–90 dBc/Hz
3 Hz	100	10 dB	–94 dBc/Hz	–104 dBc/Hz
10 Hz	100	10 dB	–108 dBc/Hz	–118 dBc/Hz
100 Hz	1000	15 dB	–131 dBc/Hz	–146 dBc/Hz
1 kHz	10000	20 dB	–152 dBc/Hz	–172 dBc/Hz
10 kHz	10000	20 dB	–158 dBc/Hz	–178 dBc/Hz
100 kHz to 1 MHz	10000	20 dB	–164 dBc/Hz	–184 dBc/Hz
1 MHz to 10 MHz	100000	25 dB	–164 dBc/Hz	–189 dBc/Hz

In practice, the number of correlations m is a factor of 10 to 50 greater.

Unwanted disturbance signals $\Delta\mathcal{L}_{Sp}$

A mode without a smoothing function is used for the measurement. If disturbance signals are detected, e.g. due to poor reproducibility or an atypical curve characteristic, or because the measured values are dependent on the selected bandwidth, it is not possible to come to a definite conclusion for this frequency sample. When measuring very low phase noise, any very small spurious signals can remain undetected. This is considered to be an influence in the measurement uncertainty.

Frequency characteristics $\delta\mathcal{L}_{FR}$

The frequency characteristics are determined by means of a power standard.

Mutual influence resulting from impedance mismatch δF

The mutual influence δF is a result of the impedance mismatch between the DUT and the calibration item.

When the influence from impedance mismatch is taken into consideration, equation $\mathcal{L}(f) = 10 \cdot \log\left(\frac{PSD[\text{Noise}(f_0-f)]+PSD[\text{Noise}(f_0+f)]}{2P_C(f_0)}\right)$ becomes

$$\mathcal{L}(f) = 10 \cdot \log\left(\frac{PSD[\text{Noise}(f_0-f)]\Big/|1-\Gamma_{G+}\Gamma_{L+}|^2 + PSD[\text{Noise}(f_0+f)]\Big/|1-\Gamma_{G-}\Gamma_{L-}|^2}{2P_C(f_0)\Big/|1-\Gamma_G\Gamma_L|^2}\right) \quad (20)$$

The incident power is assessed by the phase noise analyzer based on three frequency samples, i.e. at the carrier frequency f_0 as well as above and below $f_0 + f, f_0 - f$ the carrier frequency.

The term $|1-\Gamma_G\Gamma_L|^2$ represents the mutual influence resulting from impedance mismatch between the oscillator and measuring instrument with an RF cable at the carrier frequency f_0. Γ_L is the impedance matching of the measuring instrument including the test cable. Accordingly, the terms $|1-\Gamma_{G+}\Gamma_{L+}|^2$ and $|1-\Gamma_{G-}\Gamma_{L-}|^2$ represent the mutual influence resulting from impedance mismatch at the offset frequency above and below the carrier frequency.

It therefore follows that the impedance matching at the following frequencies is key: f_0, $\delta f_- = f_0 - f$ and $\delta f_+ = f_0 + f$. The following applies as a result of the symmetry of the phase noise around the carrier frequency ($PSD[Noise(f_0 - f)] = PSD[Noise(f_0 + f)]$):

$$\mathcal{L}(\mathrm{f}) = 10 \cdot \log\left(\frac{\mathrm{PSD[Noise(f)]}}{\mathrm{P_c(f_0)}} \cdot \frac{1}{2}\left(\frac{|1-\Gamma_G\Gamma_L|^2}{|1-\Gamma_{G+}\Gamma_{L+}|^2} + \frac{|1-\Gamma_G\Gamma_L|^2}{|1-\Gamma_{G-}\Gamma_{L-}|^2}\right)\right) \tag{21}$$

If the impedance matching between the oscillator and measuring instrument does not change in magnitude and phase as a function of the frequency, the impedance matching terms are cancelled out by the correlation.

If a change occurs in the mutual influence, the effect of the mutual influence δF on the measurement result is as follows:

$$\delta \mathrm{F} = 10 \log\left(\frac{1}{2}\left(\frac{|1-\Gamma_G\Gamma_L|^2}{|1-\Gamma_{G+}\Gamma_{L+}|^2} + \frac{|1-\Gamma_G\Gamma_L|^2}{|1-\Gamma_{G-}\Gamma_{L-}|^2}\right)\right) \tag{22}$$

Approximated to: $\delta F \approx 5 \log(1 - 4 r_G r_L \cos(\alpha) + 2 r_{G+} r_{L+} \cos(\alpha_+) + 2 r_{G-} r_{L-} \cos(\alpha_-))$.

The factor $(r_G r_L \cos(\alpha))$ is distributed in a U-shape.

In the worst-case scenario, the angle is $\alpha = 90°$ or $270°$. An angle change $\delta\alpha$ of α_+ or α_- as compared to α causes the greatest change of the two positive terms as compared to the first term, resulting therefore in a large deviation δF.

As a function of phase change $\delta\alpha_+$ and $\delta\alpha_-$, the influence δF can be estimated.

Under the worst-case assumption $\cos(\alpha) = 0$ where $\alpha = 90°$ or $270°$, the following applies:

$$\mathrm{U}(\delta \mathrm{F}) = 10 \log\big(1 + 2 \mathrm{r_G r_L} \cdot (\sin(\delta\alpha_+) + \sin(\delta\alpha_-))\big) \tag{23}$$

$\delta\alpha_+$ and $\delta\alpha_-$ represent the relative phase change of the angle between the impedance matching vector for the oscillator and the measuring instrument as a function of the offset frequency. As a rule, the following applies: $\delta\alpha_+ \approx -\delta\alpha_-$. In this case, the impedance mismatch is averaged out. Because from $\delta\alpha_+ = -\delta\alpha_-$, it follows that $\sin(\delta\alpha_+) + \sin(\delta\alpha_-) = 0$.

A conservative calculation is ($\delta\alpha < 50°$):

$$\mathrm{U}(\delta \mathrm{F}) \approx 10 \log(1 + 2 \mathrm{r_G r_L} \cdot \delta\alpha) \tag{24}$$

where $u(\delta F) = \frac{1}{\sqrt{2}} U(\delta F)$. $\delta\alpha$ is the estimated change in angle between the vectors of the DUT and the R&S FSWP measuring instrument as a function of the offset frequency. (In the calculation of the measurement uncertainty, the unit of the angle is expressed in rad.)

Linearity $\delta\mathcal{L}_{Lin}$

The linearity is checked by means of a second CW signal. This is applied to the path via a directional coupler. The directional coupler ensures a separation between the two CW signals and thus prevents mutual influences. The same instrument set to spectrum mode determines the offset between the wanted CW signal and the second CW signal. The linearity of the instrument in spectrum mode was previously incrementally proven using a power meter.

In spectrum mode, the second CW signal is 6 dB higher than in phase noise mode. A 3 dB suppression results because the CW signal contributes one half to the phase noise and the other half to the amplitude noise. An additional 3 dB results from the definition of the phase noise measurand. The phase noise is referenced to a single sideband. In phase noise mode, the measured CW disturbance signal is assessed by a factor of 4 lower than in spectrum mode.

Short-term repeatability $\delta\mathcal{L}_{Rep}$

The short-term repeatability takes the following influences into account:

- Repeatability of the carrier power
- Repeatability resulting from the phase noise from the DUT
- Repeatability of the noise cancellation on the measuring instrument
- Repeatability of the test setup

The repeatability is assessed using multiple measurements and the readings are averaged. The number of measurements can be reduced if the short-term repeatability is known.

Hardware limit $\delta\mathcal{L}_{Cor}$ (correlated noise levels)

The noise level $\Delta\mathcal{L}_{Cor}$ caused by the hardware limit is the most difficult influence quantity to assess. Hardware noise is noise in the instrument that, like the DUT noise, is present correlated in both channels, for example due to crosstalk or feedback. The hardware noise $\Delta\mathcal{L}_{Cor}$ causes a measurement error $\delta\mathcal{L}_{Cor}$. This noise can be overlaid with noise from the DUT using either an additive or subtractive method [5].

$$\mathrm{U}(\delta\mathcal{L}_{\mathrm{Cor}}) = 10 \cdot \log\left(1 + 10^{-(\mathcal{L}_{\mathrm{DUT}} - \Delta\mathcal{L}_{\mathrm{Cor}})/10}\right) \text{ dB} \tag{25}$$

e.g.: $\mathcal{L}_{DUT} = -180$ dBc, $\Delta\mathcal{L}_{Cor} = -185$ dBc, $U(\delta\mathcal{L}_{Cor}) = 1.2$ dB.

The influence is assumed to be distributed in the shape of a rectangle.

There is a link between the hardware limit and the noise after m averaged cross-correlations. Under the assumption that the cross-correlation method functions ideally, the hardware limit is specified by the maximum number of times the cross-correlation can be averaged. The hardware limit is conservatively calculated in line with Table 1. This means that the hardware limit is set to be equal to the noise $\mathcal{L}_{Refm}$ for a fixed number of cross-correlations. In practice, the number of averagings for cross-correlations is a factor of 10 to 50 greater.

The hardware limit is checked using an excellent 100 MHz low phase noise (LPN) reference oscillator. The LPN oscillator was previously measured by the NIST national metrology institute. The hardware limit and the short-term repeatability $\delta\mathcal{L}_{Rep}$ are the most important influence quantities when measuring the lowest levels of phase noise.

Filter bandwidth $\delta\mathcal{L}_{BW}$

The filter bandwidth can be set between 0.1 % and 30 %. In principle, a small bandwidth is preferable because any measurement errors resulting from unwanted disturbance signals are more easily detected. A smaller bandwidth however leads to greater deviations when measurement values are acquired. A reasonable compromise is therefore to set the greatest possible bandwidth when the disturbance signals are known.

As a rule, a bandwidth of 1 % to 10 % is used. The filter bandwidth shows no errors as a result of the digitization. Measurement errors result for large filter bandwidths (> 100 kHz) if analog detectors do not maintain a constant frequency characteristics over the bandwidth.

RF cable $\delta\mathcal{L}_{Cab}$

The RF cable changes the impedance matching for the measuring instrument. The cable increases the wave amplitude as a function of the frequency when matching the measuring instrument impedance to that of the DUT. An RF cable must be connected to measure the impedance matching on the measuring instrument, so it is important to use a well matched and stable RF cable.

The RF cable should experience little attenuation in the frequency range over 20 MHz. This change in attenuation is conservatively estimated from measurements at less than 0.05 dB.

Internal attenuator $\delta\mathcal{L}_{Att}$

The selection of a 5 dB or 10 dB attenuator pad additionally improves the impedance matching for the measuring instrument. To fully utilize the dynamic range of the measuring instrument, for example to provide evidence of very low phase noise, the signal level at the input of the measuring instrument should be greater than 10 dBm. Obviously, the hardware limit is reached more quickly as the signal level decreases. This greatly restricts the use of an attenuator, so the measurements are performed without an internal attenuator. However, it is possible to use an attenuator for verification of the measurement results.

Small-angle approximation $\delta\mathcal{L}_{deg}$

The small-angle approximation (see equations (9) and (10) is applicable only for low noise. In practice, the noise is measured as incidental FM modulation. Only the zeroth order of the Bessel functions applies. This leads to errors when the noise angle is greater than 1 rad. Errors resulting from the small-angle approximation are negligible because the phase noise is typically small [1] (page 256).

4.2 Intrinsic Characteristics of the R&S FSWP

The quality of the R&S FSWP and thus its ability to measure low phase noise depend primarily on the following intrinsic characteristics:

- Linearity
- Frequency characteristics up to 10 MHz
- Noise level with cross-correlation $m = 1$
- Impedance matching
- Hardware limit

Linearity

Linearity is ensured by the high-resolution A/D converter in the FSWP. Evidence of the measuring instrument linearity can be provided by means of attenuators and by the traceable calibration of the measuring instrument linearity in spectrum mode.

Frequency characteristics in the range to 10 MHz

The frequency characteristics in the range to 10 MHz can be measured very accurately by means of a power standard (R&S NRPC).

Noise levels with cross-correlation $\boldsymbol{m = 1}$

The noise levels (uncorrelated) can theoretically be reduced almost at will by using cross-correlation. However, this is limited by the measurement time and the correlated noise levels (hardware limit). It is clear that lower noise levels from the reference oscillators in the measuring instrument equate to a lower residual measurement uncertainty once the cross-correlation method has been used to correct the noise level from the reference oscillators.

For $m = 1$, the noise level is estimated using very good LPN reference oscillators.

Impedance matching

The impedance matching of the R&S FSWP can be improved by using an external attenuator. To utilize the full dynamic range of the measuring instrument, the signal level should be greater than 10 dBm. This is why impedance matching of the measuring instrument is so important. A network analyzer can be used to determine the impedance matching of the R&S FSWP very precisely. A network analyzer is also used to measure the impedance matching of the DUT. (The VNA is operated with low port power (-30 dBm), high selectivity and narrow bandwidth (1 Hz).

Hardware limit

The hardware limit is determined by the correlated noise level and the limited dynamic range of the instrument. The hardware limit is verified by means of measurements with low phase noise oscillators. A very low phase noise reference oscillator is used at 100 MHz.

Theoretical limit of phase noise in a DUT

At offset frequencies > 1 kHz, the theoretical phase noise limit is defined by the thermal noise. At room temperature (300 K), the thermal noise is -174 dBm/Hz. Because this noise is equally divided between amplitude and phase noise, the phase noise limit is referenced to the output power P_c (expressed as dBm) of the DUT:

$\mathcal{L} = -177$ dBc/Hz - P_c.

Table 4-2 List of Influence Quantities

Sym-bol	Parameter 1	Parameter 2	Parameter 3	Values (nom.)	Expanded Uncertainty	Comments
$\Delta\mathcal{L}_{SNR}$	f_0: 100 MHz to 8 GHz	SNR: 0 to 8 dB		0 dB	$10^{(-0.2 \cdot L_{SNR}+0.2)}$ db	typ.: $\Delta L_{SNR} >$ 5 dB, $\sqrt{3}\sigma$
		SNR: 5 dB		0 dB	0.16 dB	$\Delta L_{SNR} \approx$ 5 dB
		SNR > 8 dB		0 dB	0.04 dB	
$\delta\mathcal{L}_{FR}$	f_0: 100 MHz to 8 GHz	f: < 10 kHz		0 dB	0.2 dB	$\sqrt{3}\sigma$
		f: < 10 MHz		0 dB	0.5 dB	
δF	f_0: 100 MHz	f: < 1 MHz		0 dB	0.028 dB	$\delta\alpha$ < 5°/MHz, $\sqrt{2}\sigma$ $\delta\alpha$ < 50°/MHz,
		f: > 1 MHz		0 dB	0.28 dB	
	f_0: >100 MHz to 8 GHz	f: < 1 MHz		0 dB	0.055 dB	$\delta\alpha$ < 50°/MHz, $\sqrt{2}\sigma$ $\delta\alpha$ < 50°/MHz
		f: > 1 MHz		0 dB	0.55 dB	
$\delta\mathcal{L}_{Lin}$	f_0: 100 MHz to 8 GHz	f: 1 Hz to 10 MHz		0 dB	0.1 dB	measured, 2σ
$\delta\mathcal{L}_{Rep}$	f_0: 100 MHz to 8 GHz	f: 1 Hz to 10 MHz		0 dB	1 dB	typ., measured, 2σ
$\delta\mathcal{L}_{BW}$	f_0: 100 MHz to 8 GHz	f: 1 Hz to 10 MHz		0 dB	0.1 dB	conservatively estimated, $\sqrt{3}\sigma$
$\delta\mathcal{L}_{Cab}$	f_0: 100 MHz to 8 GHz	f: 1 Hz to 10 MHz		0 dB	0.05 dB	conservatively estimated, $\sqrt{3}\sigma$
$\Delta\mathcal{L}_{Sp}$	f_0: 100 MHz to 8 GHz	$\Delta\mathcal{L}_{DUT} - \Delta\mathcal{L}_{Cor}$		0 dB	2 dB	estimated, $\sqrt{3}\sigma$
				5 dB	1 dB	
				> 8 dB	0.1 dB	
$\delta\mathcal{L}_{Cor}$	f_0: 100 MHz	f: 1 Hz	$\mathcal{L}_{DUT}$: –85 dBc/Hz	0 dB	1.2 dB	m > 10, $\sqrt{3}\sigma$
		f: 3 Hz	$\mathcal{L}_{DUT}$: –105 dBc/Hz	0 dB	1.2 dB	m > 100
		f: 10 Hz	$\mathcal{L}_{DUT}$: –115 dBc/Hz	0 dB	1.2 dB	m > 100
		f: 100 Hz	$\mathcal{L}_{DUT}$: –140 dBc/Hz	0 dB	1.2 dB	m > 1000
		f: 1 kHz	$\mathcal{L}_{DUT}$: –170 dBc/Hz	0 dB	1.2 dB	m > 10000
		f: 10 kHz	$\mathcal{L}_{DUT}$: –180 dBc/Hz	0 dB	1.2 dB	m > 100000
		f: > 100 kHz	$\mathcal{L}_{DUT}$: –185 dBc/Hz	0 dB	1.2 dB	m > 100000

Symbol	Parameter 1	Parameter 2	Parameter 3	Values (nom.)	Expanded Uncertainty	Comments
$\delta\mathcal{L}_{Cor}$	f_0: 500 MHz	f: 1 Hz	$\mathcal{L}_{DUT}$: –72 dBc/Hz	0 dB	1.2 dB	m > 10, $\sqrt{3}\sigma$
		f: 3 Hz	$\mathcal{L}_{DUT}$: –93 dBc/Hz	0 dB	1.2 dB	m > 100
		f: 10 Hz	$\mathcal{L}_{DUT}$: –105 dBc/Hz	0 dB	1.2 dB	m > 100
		f: 100 Hz	$\mathcal{L}_{DUT}$: –130 dBc/Hz	0 dB	1.2 dB	m > 1000
		f: 1 kHz	$\mathcal{L}_{DUT}$: –160 dBc/Hz	0 dB	1.2 dB	m > 10000
		f: 10 kHz	$\mathcal{L}_{DUT}$: –165 dBc/Hz	0 dB	1.2 dB	m > 100000
		f: > 100 kHz	$\mathcal{L}_{DUT}$: –177 dBc/Hz	0 dB	1.2 dB	m > 100000
$\delta\mathcal{L}_{Cor}$	f_0: 1 GHz	f: 1 Hz	$\mathcal{L}_{DUT}$: –65 dBc/Hz	0 dB	1.2 dB	m > 10, $\sqrt{3}\sigma$
		f: 3 Hz	$\mathcal{L}_{DUT}$: –86 dBc/Hz	0 dB	1.2 dB	m > 100
		f: 10 Hz	$\mathcal{L}_{DUT}$: –98 dBc/Hz	0 dB	1.2 dB	m > 100
		f: 100 Hz	$\mathcal{L}_{DUT}$: –123 dBc/Hz	0 dB	1.2 dB	m > 1000
		f: 1 kHz	$\mathcal{L}_{DUT}$: –153 dBc/Hz	0 dB	1.2 dB	m > 10000
		f: 10 kHz	$\mathcal{L}_{DUT}$: –165 dBc/Hz	0 dB	1.2 dB	m > 100000
		f: > 100 kHz	$\mathcal{L}_{DUT}$: –171 dBc/Hz	0 dB	1.2 dB	m > 100000
$\delta\mathcal{L}_{Cor}$	f_0: 3 GHz	f: 1 Hz	$\mathcal{L}_{DUT}$: –56 dBc/Hz	0 dB	1.2 dB	m > 10, $\sqrt{3}\sigma$
		f: 3 Hz	$\mathcal{L}_{DUT}$: –77 dBc/Hz	0 dB	1.2 dB	m > 100
		f: 10 Hz	$\mathcal{L}_{DUT}$: –90 dBc/Hz	0 dB	1.2 dB	m > 100
		f: 100 Hz	$\mathcal{L}_{DUT}$: –115 dBc/Hz	0 dB	1.2 dB	m > 1000
		f: 1 kHz	$\mathcal{L}_{DUT}$: –145 dBc/Hz	0 dB	1.2 dB	m > 10000
		f: 10 kHz	$\mathcal{L}_{DUT}$: –163 dBc/Hz	0 dB	1.2 dB	m > 100000
		f: > 100 kHz	$\mathcal{L}_{DUT}$: –163 dBc/Hz	0 dB	1.2 dB	m > 100000
$\boldsymbol{\delta\mathcal{L}_{Cor}}$	f_0: 8 GHz	f: 1 Hz	$\mathcal{L}_{DUT}$: -47 dBc/Hz	0 dB	1.2 dB	m > 10, $\sqrt{3}\sigma$
		f: 3 Hz	$\mathcal{L}_{DUT}$: -69 dBc/Hz	0 dB	1.2 dB	m > 100
		f: 10 Hz	$\mathcal{L}_{DUT}$: -80 dBc/Hz	0 dB	1.2 dB	m > 100
		f: 100 Hz	$\mathcal{L}_{DUT}$: -105 dBc/Hz	0 dB	1.2 dB	m > 1000
		f: 1 kHz	$\mathcal{L}_{DUT}$: -135 dBc/Hz	0 dB	1.2 dB	m > 10000
		f: 10 kHz	$\mathcal{L}_{DUT}$: -145 dBc/Hz	0 dB	1.2 dB	m > 100000
		f: > 100 kHz	$\mathcal{L}_{DUT}$: -151 dBc/Hz	0 dB	1.02 dB	m > 100000

Table 4-3 Additional influence quantities

Symbol	Parameter 1	Parameter 2	Values (nom.)	Expanded Uncertainty	Comments
Γ_G	f_0: 100 MHz to 8 GHz	f: 1 Hz to 100 Hz	0.2	0.01	
		f: 1 kHz	0.2	0.01	
		f: 10 kHz to 10 MHz	0.2	0.01	
Γ_L	f_0: 100 MHz	f: 1 Hz to 100 Hz	0.1	0.01	Phase change < 5°/MHz with RF cable
		f: 1 kHz	0.1	0.01	
		f: 10 kHz to 10 MHz	0.1	0.01	
	f_0: 200 MHz to 2 GHz	f: 1 Hz to 100 Hz	0.2	0.01	
		f: 1 kHz	0.2	0.01	
		f: 10 kHz to 10 MHz	0.2	0.01	
	f_0: 2 GHz to 8 GHz	f: 1 Hz to 100 Hz	0.3	0.01	
		f: 1 kHz	0.3	0.01	
		f: 10 kHz to 10 MHz	0.3	0.01	
$\mathcal{L}_{Ref1}$	f_0: 100 MHz	f: 1 Hz	< –85 dBc/Hz		m = 1
		f: 3 Hz	< –94 dBc/Hz		
		f: 10 Hz	< –108 dBc/Hz		
		f: 100 Hz	< –131 dBc/Hz		
		f: 1 kHz	< –152 dBc/Hz		
		f: 10 kHz	< –158 dBc/Hz		
		f: 100 kHz to 1 MHz	< –166 dBc/Hz		
		f: 1 MHz to 10 MHz	< –166 dBc/Hz		
$\Delta\mathcal{L}_{Cor}$	f_0: 100 MHz	f: 1 Hz	< –90 dBc/Hz		m > 10
		f: 3 Hz	< –104 dBc/Hz		m > 100
		f: 10 Hz	< –118 dBc/Hz		m > 100
		f: 100 Hz	< –146 dBc/Hz		m > 1000
		f: 1 kHz	< –172 dBc/Hz		m > 10000
		f: 10 kHz	< –178 dBc/Hz		m > 10000
		f: 100 kHz to 1 MHz	< –186 dBc/Hz		m > 10000
		f: 1 MHz to 1 MHz	< –192 dBc/Hz		m > 1000000
$\mathcal{L}_{Ref1}$	f_0: 500 MHz	f: 1 Hz	< –72 dBc/Hz		m = 1
		f: 3 Hz	< –84 dBc/Hz		
		f: 10 Hz	< –97 dBc/Hz		
		f: 100 Hz	< –120 dBc/Hz		
		f: 1 kHz	< –140 dBc/Hz		
		f: 10 kHz	< –157 dBc/Hz		
		f: 100 kHz to 10 MHz	< –159 dBc/Hz		

Sym-bol	Parameter 1	Parameter 2	Values (nom.)	Expanded Uncertainty	Comments
$\Delta\mathcal{L}_{Cor}$	f_0: 500 MHz	f: 1 Hz	< –77 dBc/Hz		m > 10
		f: 3 Hz	< –94 dBc/Hz		m > 100
		f: 10 Hz	< –107 dBc/Hz		m > 100
		f: 100 Hz	< –135 dBc/Hz		m > 1000
		f: 1 kHz	< –165 dBc/Hz		m > 10000
		f: 10 kHz	< –182 dBc/Hz		m > 10000
		f: 100 kHz to 10 MHz	< –184 dBc/Hz		m > 10000
$\mathcal{L}_{Ref1}$	f_0: 1 GHz	1 Hz	< –62 dBc/Hz		m = 1
		3 Hz	< –73 dBc/Hz		
		10 Hz	< –87 dBc/Hz		
		100 Hz	< –111 dBc/Hz		
		1 kHz	< –133 dBc/Hz		
		10 kHz	< –153 dBc/Hz		
		100 kHz to 10 MHz	< –155 dBc/Hz		
$\Delta\mathcal{L}_{Cor}$	f_0: 1 GHz	1 Hz	< –67 dBc/Hz		m > 10
		3 Hz	< –83 dBc/Hz		m > 100
		10 Hz	< –97 dBc/Hz		m > 100
		100 Hz	< –126 dBc/Hz		m > 1000
		1 kHz	< –158 dBc/Hz		m > 10000
		10 kHz	< –178 dBc/Hz		m > 10000
		100 kHz to 10 MHz	< –180 dBc/Hz		m > 10000
$\mathcal{L}_{Ref1}$	f_0: 3 GHz	1 Hz	< –56 dBc/Hz		m = 1
		3 Hz	< –64 dBc/Hz		
		10 Hz	< –78 dBc/Hz		
		100 Hz	< –102 dBc/Hz		
		1 kHz	< –125 dBc/Hz		
		10 kHz	< –143 dBc/Hz		
		100 kHz to 10 MHz	< –145 dBc/Hz		
$\Delta\mathcal{L}_{Cor}$	f_0: 3 GHz	1 Hz	< –61 dBc/Hz		m > 10
		3 Hz	< –74 dBc/Hz		m > 100
		10 Hz	< –88 dBc/Hz		m > 100
		100 Hz	< –117 dBc/Hz		m > 1000
		1 kHz	< –150 dBc/Hz		m > 10000
		10 kHz	< –168 dBc/Hz		m > 10000
		100 kHz to 10 MHz	< –170 dBc/Hz		m > 10000

Sym-bol	Parameter 1	Parameter 2	Values (nom.)	Expanded Uncertainty	Comments
$\mathcal{L}_{Ref1}$	f_0: 8 GHz	1 Hz	< –45 dBc/Hz		m = 1
		3 Hz	< –56 dBc/Hz		
		10 Hz	< –70 dBc/Hz		
		100 Hz	< –92 dBc/Hz		
		1 kHz	< –114 dBc/Hz		
		10 kHz	< –130 dBc/Hz		
		100 kHz to 10 MHz	< –134 dBc/Hz		
$\Delta\mathcal{L}_{Cor}$	f_0: 8 GHz	1 Hz	< –50 dBc/Hz		m > 10
		3 Hz	< –66 dBc/Hz		m > 100
		10 Hz	< –80 dBc/Hz		m > 100
		100 Hz	< –107 dBc/Hz		m > 1000
		1 kHz	< –134 dBc/Hz		m > 10000
		10 kHz	< –150 dBc/Hz		m > 10000
		100 kHz to 10 MHz	< –154 dBc/Hz		m > 10000

Measurement uncertainty budget

Table 4-4 $f_0 = 100$ MHz, $f = 1$ Hz, $\mathcal{L} = -82$ dBc/Hz

Value Xi	Est. Value xi	Probability Distribution wi	Standard Uncertainty u(xi)	Sensitivity Coefficient |ci|	Effective Range γi	Rel. Uncertainty u(yi)
			[dB]			[dB]
$\mathcal{L}_{Anz}$	–82 dBc/Hz	normal				
$\Delta\mathcal{L}_{SNR}$	0 dB	rectangular	0.023	1	∞	0.023
$\Delta\mathcal{L}_{Sp}$	0 dB	rectangular	0.058	1	∞	0.058
$\delta\mathcal{L}_{FR}$	0 dB	rectangular	0.115	1	∞	0.115
δF	0 dB	U-shaped	0.021	1	∞	0.021
$\delta\mathcal{L}_{Lin}$	0 dB	normal	0.050	1	∞	0.050
$\delta\mathcal{L}_{Rep}$	0 dB	normal	0.500	1	∞	0.500
$\delta\mathcal{L}_{Cor}$	0 dB	rectangular	0.369	1	∞	0.369
$\delta\mathcal{L}_{BW}$	0 dB	rectangular	0.058	1	∞	0.058
$\delta\mathcal{L}_{Cab}$	0 dB	rectangular	0.029	1	∞	0.029
$\mathcal{L}_{DUT}$	–82 dBc/Hz				∞	0.640

Expanded measurement uncertainty: $U(\mathcal{L}_{DUT}) = 1.3$ dBc/Hz (95 % coverage interval)

Because the measured value lies in the interval from –86 dBc/Hz to –78 dBc/Hz, a measurement uncertainty of 2.5 dB is conservatively defined.

Table 4-5 $f_0 = 100$ MHz, $f = 1$ kHz, $\mathcal{L} = -162$ dBc

Value Xi	Est. Value xi	Probability Distribution wi	Standard Uncertainty u(xi)	Sensitivity Coefficient |ci|	Effective Range γi	Rel. Uncertainty u(yi)
			[dB]			[dB]
$\mathcal{L}_{Anz}$	–162 dBc/Hz	normal				
$\Delta\mathcal{L}_{SNR}$	0 dB	rectangular	0.023	1	∞	0.023
$\Delta\mathcal{L}_{Sp}$	0 dB	rectangular	0.058	1	∞	0.058
$\delta\mathcal{L}_{FR}$	0 dB	rectangular	0.115	1	∞	0.115
δF	0 dB	U-shaped	0.021	1	∞	0.021
$\delta\mathcal{L}_{Lin}$	0 dB	normal	0.050	1	∞	0.050
$\delta\mathcal{L}_{Rep}$	0 dB	normal	0.500	1	∞	0.500
$\delta\mathcal{L}_{Cor}$	0 dB	rectangular	0.098	1	∞	0.098
$\delta\mathcal{L}_{BW}$	0 dB	rectangular	0.058	1	∞	0.058
$\delta\mathcal{L}_{Cab}$	0 dB	rectangular	0.029	1	∞	0.029
$\mathcal{L}_{DUT}$	–162 dBc/Hz				∞	0.53

Because the measured value is greater than –166 dBc/Hz, a measurement uncertainty of 2.5 dB is conservatively defined.

Table 4-6 $f_0 = 100$ MHz, $f = 1$ MHz, $\mathcal{L} = -170$ dBc

Value Xi	Est. Value xi	Probability Distribution wi	Standard Uncertainty u(xi)	Sensitivity Coefficient |ci|	Effective Range γi	Rel. Uncertainty u(yi)
			[dB]			[dB]
$\mathcal{L}_{Anz}$	–170 dBc/Hz	normal				
$\Delta\mathcal{L}_{SNR}$	0 dB	rectangular	0.023	1	∞	0.023
$\Delta\mathcal{L}_{Sp}$	0 dB	rectangular	0.058	1	∞	0.058
$\delta\mathcal{L}_{FR}$	0 dB	rectangular	0.289	1	∞	0.289
δF	0 dB	U-shaped	0.206	1	∞	0.206
$\delta\mathcal{L}_{Lin}$	0 dB	normal	0.050	1	∞	0.050
$\delta\mathcal{L}_{Rep}$	0 dB	normal	0.500	1	∞	0.500
$\delta\mathcal{L}_{Cor}$	0 dB	rectangular	0.062	1	∞	0.062
$\delta\mathcal{L}_{BW}$	0 dB	rectangular	0.058	1	∞	0.058
$\delta\mathcal{L}_{Cab}$	0 dB	rectangular	0.029	1	∞	0.029
$\mathcal{L}_{DUT}$	–170 dBc/Hz				∞	0.624

Expanded measurement uncertainty: $U(\mathcal{L}_{DUT}) = 1.2$ dBc/Hz (95% coverage interval).

Because the measured value is greater than –180 dBc/Hz, a measurement uncertainty of 1.5 dB is conservatively defined.

The measurement uncertainty is scaled over the carrier frequency and the offset frequency and can be displayed as a function of the phase noise. For very low phase noise that lies close to the hardware limit of the measuring instrument, only an upper limit can be specified for the phase noise. As a result of the logarithmic display, the measurement uncertainty is strongly asymmetrical.

Two ranges are defined for the measurement uncertainty of the phase noise measurements:

- Phase noise 12 dB above the hardware limit. A measurement uncertainty of at least 1.5 dB is assumed.

  $\mathcal{L}_{DUT} = -140\ (\pm 1.5)$ dBc/Hz , $\Delta\mathcal{L}_{Cor} = -160$ dBc/Hz

- Phase noise in the range of 4 dB to 12 dB above the hardware limit. A measurement uncertainty of at least 2.5 dB is assumed.

  $\mathcal{L}_{DUT} = -152\ (\pm 2.5)$ dBc/Hz , $\Delta\mathcal{L}_{Cor} = -160$ dBc/Hz

4.3 Verification Measurements by National Institutes

Comparison of a 100 MHz oscillator against the metrology institute NIST (USA)

A very low-noise 100 MHz oscillator was measured at the national metrology institute NIST.

A comparison of the calibration data showed a maximum EN value of 0.55; see

Table 4-7.

The calibration certificate issued by the NIST is number: 286895-15.

The oscillator with model number 501-25900 and serial number 100003 was used for the comparison.

(Abbr.: Ref NIST or Ref LNE: Reference value from the NIST or LNE national metrology institute; MU Ref: Measurement uncertainty of the reference value)

Table 4-7 Measurement results from the comparison with an LPN oscillator at a carrier frequency of 100 MHz

Frequency	Ref NIST.	MU Ref (k = 2)	Measured value	EN Value	MU (k = 2)
[Hz]	[dBc(Hz)]	[dB]	[dBc(Hz)]	1	[dB]
1 Hz	–81.5	+1.1/–1.4	–80.2	0.46	+2.6/–2.6
2 Hz	–90.5	+1.1/–1.4	–88.9	0.55	+2.6/–2.6
5 Hz	–102.7	+1.1/–1.4	–101.2	0.54	+2.6/–2.6
10 Hz	–112.6	+1.0/–1.4	–111.2	0.50	+2.6/–2.6
20 Hz	–122.5	+1.0/–1.4	–121.3	0.43	+2.6/–2.6
40 Hz	–132.0	+1.0/–1.4	–130.9	0.36	+2.6/–2.6
95 Hz	–142.6	+1.0/–1.4	–141.8	0.31	+2.6/–2.6
160 Hz	–148.5	+1.0/–1.4	–147.8	0.27	+2.6/–2.6
205 Hz	–150.7	+1.0/–1.4	–149.2	0.50	+2.6/–2.6
500 Hz	–159.5	+1.0/–1.4	–159.1	0.07	+2.6/–2.6
1000 Hz	–165.1	+1.0/–1.4	–164.9	0.11	+2.7/–2.7

NIST measured the oscillator in its primary measurement system. The comparison showed a very good correlation.

Comparison of an R&S SMA100A generator against the metrology institute LNE-LTFB (France)

The R&S SMA100A generator with model number 1400.0000K02 and serial number 101741 was calibrated at the French national metrology institute LNE-LTFB. Certificate number: 150007.

Table 4-8 Measurement results from the comparison of an R&S SMA100A generator with a carrier frequency of 100 MHz. At 100 Hz, the interpolated value is calculated to lie between 95 Hz and 105 Hz.

Frequency	Ref LNE	MU Ref (k = 2)	Measured value	Deviation	MU (k = 2)
[Hz]	[dBc(Hz)]	[dB]	[dBc(Hz)]	[dB]	[dB]
100 Hz	–130	4	–130.2	0.2	1.5
1 kHz	–146	4	–146.0	0.0	1.5
10 kHz	–156	4	–155.6	–0.4	1.5
100 kHz	–155	4	–155.1	0.1	1.5
1 MHz	–164	4	–163.7	–0.3	1.5
10 MHz	–166	4	–166.1	0.2	1.5

Table 4-9 Measurement results from the comparison of an R&S SMA100A generator with a carrier frequency of 500 MHz. At 100 Hz, the interpolated value is calculated to lie between 95 Hz and 105 Hz.

Frequency	Ref LNE	MU Ref (k = 2)	Measured value	Deviation	MU (k = 2)
[Hz]	[dBc(Hz)]	[dB]	[dBc(Hz)]	[dB]	[dB]
100 Hz	–116	4	–115.8	–0.2	1.5
1 kHz	–132	4	–132.2	0.2	1.5
10 kHz	–143	4	–143.0	0.0	1.5
100 kHz	–143	4	–142.7	–0.3	1.5
1 MHz	–155	4	–155.3	0.3	1.5
10 MHz	–161	4	–161.5	–0.2	1.5

Table 4-10 Measurement results from the comparison of an R&S SMA100A generator with a carrier frequency of 640 MHz. At 100 Hz, the interpolated value is calculated to lie between 95 Hz and 105 Hz.

Frequency	Ref LNE	MU Ref (k = 2)	Measured value	Deviation	MU (k = 2)
[Hz]	[dBc(Hz)]	[dB]	[dBc(Hz)]	[dB]	[dB]
100 Hz	–114	4	–113.9	–0.1	1.5
1 kHz	–131	4	–131.0	0.0	1.5
10 kHz	–143	4	–143.2	0.2	1.5
100 kHz	–143	4	–143.0	0.0	1.5
1 MHz	–154	4	–153.7	–0.3	1.5
10 MHz	–161	4	–161.5	–0.1	1.5

Table 4-11 Measurement results from the comparison of an R&S SMA100A generator with a carrier frequency of 1 GHz. At 100 Hz, the interpolated value is calculated to lie between 95 Hz and 105 Hz.

Frequency	Ref LNE	MU Ref(k = 2)	Measured value	Deviation	MU (k = 2)
[Hz]	[dBc(Hz)]	[dB]	[dBc(Hz)]	[dB]	[dB]
100 Hz	–110	4	–110.0	0.0	1.5
1 kHz	–126	4	–126.4	0.4	1.5
10 kHz	–138	4	–137.7	–0.3	1.5
100 kHz	–137	4	–136.9	–0.1	1.5
1 MHz	–150	4	–150.6	0.6	1.5
10 MHz	–165	4	–165.6	0.0	1.5

The phase noise measurements were performed in the French national lab on a secondary phase noise measurement station. The secondary measurement system is the Agilent E5052B phase noise analyzer. The national institute's measurement uncertainty is set unusually high at 4 dB. In spite of this fact, the measurements still show an excellent correlation.

Digitally generated phase noise using a vector signal generator

The R&S FSWP phase noise analyzer is calibrated using a CW signal with a known phase noise component.

This is done by modifying the phase noise of a CW signal by means of frequency and amplitude modulation until the phase noise is dependent only on the defined modulation parameters. The requirement is that the intrinsic phase noise of the CW signal, i.e., the phase noise without modulation, be significantly lower (min. 10 dB offset). The phase noise artificially generated by the modulation is then known as a function of the mathematical relationships.

To modulate the CW signal, a vector signal generator is used – in this case the R&S SMU – whose CW signal can be modulated using an internal I/Q modulator.

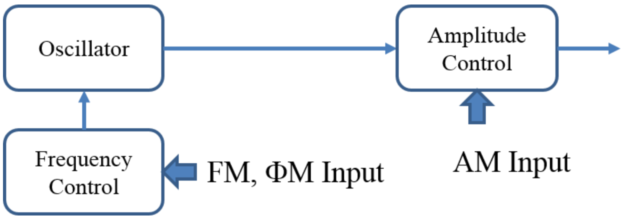


Figure 7: Diagram of an FM and AM modulation of a CW oscillator.

In equation (1): $V(t) = V_0[1 + \alpha(t)]\cos[2\pi f_0 t + \phi(t)]$, the term $\alpha(t)$ describes the additive amplitude fluctuation and $\phi(t)$ describes the multiplicative phase fluctuation.

As shown in equation (2), the following applies for the spectral density of the phase fluctuations $S_\phi(f) = \frac{\langle \Delta\phi_{rms}(f)\rangle^2}{NBW}$.

From this, the ratio $\Delta f = \frac{f(t)-f_0}{f_0} = \frac{1}{2\pi f_0}\frac{d}{dt}\phi$ can be used to specify the spectral density of the frequency fluctuations:

$$S_{\Delta f}(f) = \frac{\langle \Delta f(f)\rangle^2}{NBW} = \left(\frac{1}{2\pi f_0}\right)^2 \cdot (2\pi f)^2 \cdot S_\phi(f) = \left(\frac{f}{f_0}\right)^2 S_\phi(f) \qquad (26)$$

$$S_\phi(f) = \left(\frac{f_0}{f}\right)^2 \cdot \frac{\langle \Delta f(f)\rangle^2}{NBW}$$

If the oscillator is now modulated with white FM noise $S_{\Delta f}(f) = \text{const.}$, then equation (26) shows that the phase noise $\mathcal{L}(f)$ drops by 20 dB per frequency decade:

$$S_{\Delta f}(f) \propto \text{const.(white FM noise)} \Rightarrow S_\phi(f) \propto \frac{1}{f^2} \Rightarrow \mathcal{L}(f) \propto -20 \text{ dB per decade}$$

This white FM noise of the CW signal is digitally generated in the vector signal generator by means of a noise-shaped FM modulation. An additive white noise is also added to this signal. Figure 8 shows the measurement of the phase noise generated using modulation in this manner.

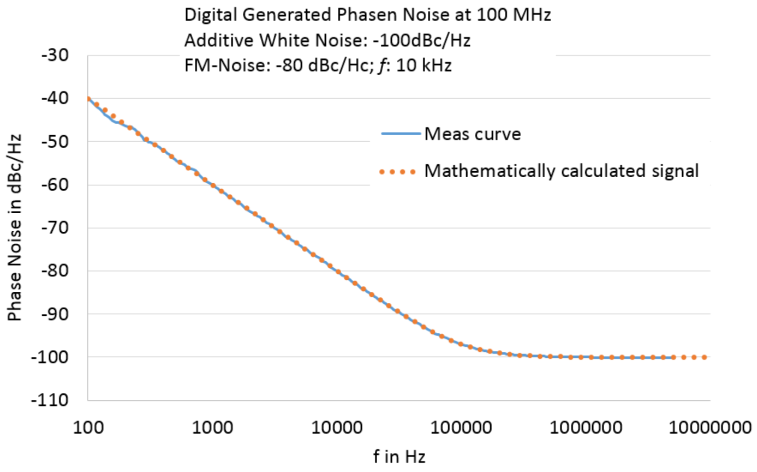


Figure 8: Phase noise measurement of a CW signal generated by means of amplitude and frequency modulation. In comparison, the mathematically expected phase noise.

The phase noise is mathematically calculated in the baseband using a MATLAB® script. The phase noise is then converted to a waveform file and loaded in the vector signal generator. There, the phase noise is upconverted to a CW signal by means of I/Q modulation. The verification shows very good correlation with the mathematically generated signal.

In Figure 9 a to c, the mathematically generated signal in the baseband is displayed as the I/Q image and as the spectrum for the various noise components.

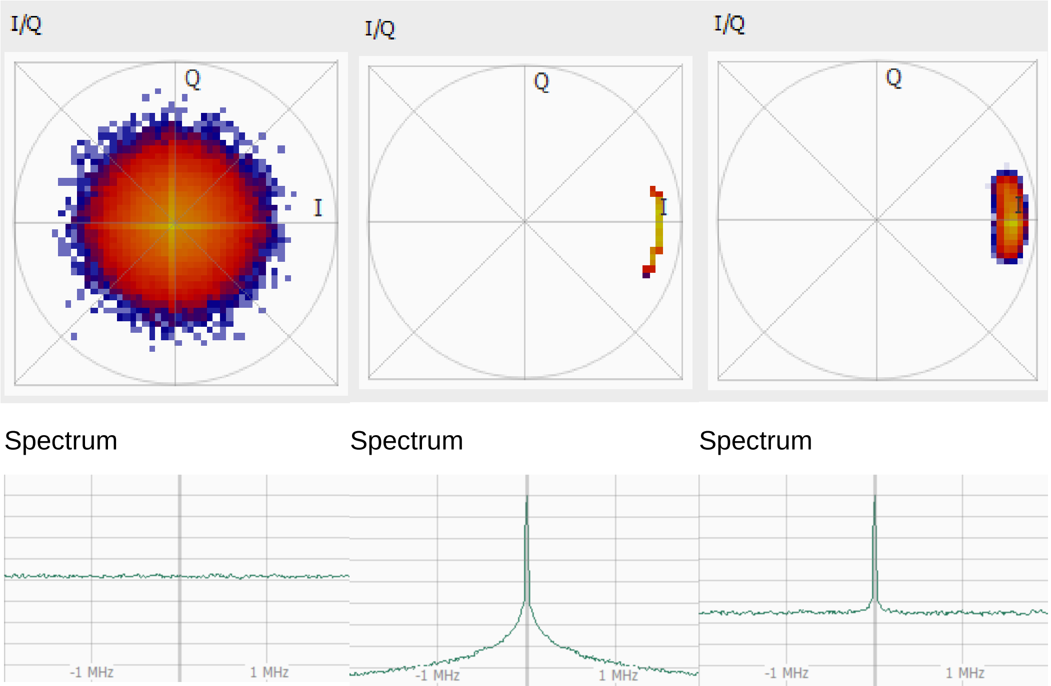


Figure 9: a) I/Q image of the baseband for broadband noise with spectrum.
b) I/Q image of the baseband for FM noise with spectrum.
c) I/Q image of the baseband for total noise consisting of FM noise and broadband noise with spectrum.

Symbols

$\boldsymbol{\alpha}$	Current amplitude deviation
$\boldsymbol{\alpha}$	Angle between vector Γ_G and Γ_L
$\boldsymbol{\delta\alpha}$	Angle change between Γ_G and Γ_L as a function of offset frequency
$\boldsymbol{\alpha_+, \alpha_-}$	Angle between vector Γ_G and Γ_L at offset frequencies f_+, f_-
$\boldsymbol{\phi}$	Current phase deviation
$\boldsymbol{\Delta\phi_{rms}}$	Average phase deviation
$\boldsymbol{\Gamma_G}$	Impedance matching on DUT
$\boldsymbol{\Gamma_L}$	Impedance matching on measuring instrument with RF cable
$\boldsymbol{\Gamma_L'}$	Impedance matching on measuring instrument without RF cable
$\boldsymbol{\Gamma_{G+}, \Gamma_{G-}}$	Impedance matching on DUT at offset frequencies f_+, f_-
$\boldsymbol{\Gamma_{L+}, \Gamma_{L-}}$	Impedance matching on measuring instrument at offset frequencies f_+, f_-
$\boldsymbol{\omega_0}$	Angular frequency of RF signal
$\boldsymbol{a}$	Instrument-dependent noise component for measured values in measurement channel 1
$\boldsymbol{b}$	Instrument-dependent noise component for measured values in measurement channel 2

c	DUT-dependent noise component for reading in measurement channels 1 and 2
x	Measured value in measurement channel 1
y	Measured value in measurement channel 2
AM	Amplitude modulation
A, B, C	Fourier transform of a, b, c
f_0	Carrier frequency
f	Offset frequency
δf	Normalized frequency fluctuation
δF	Influence of impedance mismatch between DUT and measuring instrument
FM	Frequency modulation
ΦM	Phase modulation
$\mathcal{L}$	Phase noise expressed in dBc/Hz
$\mathcal{L}_{Read}$	Displayed reading
$\mathcal{L}_{Readm}$	Displayed measured value with number of correlations m
$\mathcal{L}_{DUT}$	Phase noise of the DUT
$\mathcal{L}_{Ref1}$	Phase noise of the measuring instrument with number of correlations $m = 1$
$\mathcal{L}_{Refm}$	Phase noise from the measuring instrument with number of correlations m
$\Delta\mathcal{L}_{Cor}$	Measuring instrument-dependent correlated noise in both channels, hardware limit
$\Delta\mathcal{L}_{SNR}$	Noise level correction with cross-correlation
$\Delta\mathcal{L}_{Sp}$	Unwanted interference signals
$\delta\mathcal{L}_{FR}$	Influence of the frequency characteristics of the measuring instrument
$\delta\mathcal{L}_{Lin}$	Influence of linearity
$\delta\mathcal{L}_{Rep}$	Influence of short-term repeatability
$\delta\mathcal{L}_{Cor}$	Influence of the hardware limit (correlated noise level)
$\delta\mathcal{L}_{BW}$	Influence of selected filter bandwidth
$\delta\mathcal{L}_{Att}$	Influence of an attenuator pad
$\delta\mathcal{L}_{deg}$	Influence of small-angle approximation
m	Number of correlations
NBW	Square-wave bandwidth (noise bandwidth)
r_G, r_{G+}, r_{G-}	DUT reflection as a function of the frequency f
r_L, r_{L+}, r_{L-}	Measuring instrument reflection as a function of frequency f
S_{cc}	Measured phase noise with correlation method expressed in rad2/Hz
S_ϕ	Spectral density of phase noise expressed in rad2/Hz

S_f	Spectral density of frequency noise expressed in 1/Hz
S_{11}, S_{21}	S-parameters for the RF cable
t	Time
T	Measurement time
V_0	Amplitude of the RF signal
V	RF signal amplitude as a function of time
x, y	Measured value in measurement channel 1 or 2
X, Y	Fourier transform of X, Y

Accredited lowest measurement uncertainty for phase noise

Measurand / Calibration Item	Measurement Range / Span	Measurement Conditions / Method	Smallest Possible Measurement Uncertainty1)	Comments
Phase noise	1 Hz	> –77 dBc/Hz	1.5 dB	f: 100 MHz
Oscillators	1 Hz	–85 dBc/Hz to -77 dBc/Hz	2.5 dB	
	3 Hz to < 10 Hz	> –92 dBc/Hz	1.5 dB	
	3 Hz to < 10 Hz	–100 dBc/Hz to -92 dBc/Hz	2.5 dB	
	10 Hz to < 100 Hz	> – 106 dBc/Hz	1.5 dB	
	10 Hz to < 100 Hz	–114 dBc/Hz to -106 dBc/Hz	2.5 dB	
	100 Hz to < 1 kHz	> –136 dBc/Hz	1.5 dB	
	100 Hz to < 1 kHz	–146 dBc/Hz to -136 dBc/Hz	2.5 dB	
	1 kHz to < 10 kHz	> –160 dBc/Hz	1.5 dB	
	1 kHz to < 10 kHz	–168 dBc/Hz to -160 dBc/Hz	2.5 dB	
	10 kHz to < 100 kHz	> –167 dBc/Hz	1.5 dB	
	10 kHz to < 100 kHz	–175 dBc/Hz to -167 dBc/Hz	2.5 dB	
	100 kHz to < 1 MHz	> –174 dBc/Hz	1.5 dB	
	100 kHz to < 1 MHz	–182 dBc/Hz to -174 dBc/Hz	2.5 dB	
	1 MHz to < 10 MHz	> –186 dBc/Hz	1.5 dB	
	1 MHz to < 10 MHz	–192 dBc/Hz to -186 dBc/Hz	2.5 dB	
	1 Hz	> –64 dBc/Hz	1.5 dB	f: 500 MHz
	1 Hz	–73dBc/Hz to -64 dBc/Hz	2.5 dB	
	3 Hz to < 10 Hz	> –82 dBc/Hz	1.5 dB	
	3 Hz to < 10 Hz	–90 dBc/Hz to -82 dBc/Hz	2.5 dB	

Measurand / Calibration Item	Measurement Range / Span	Measurement Conditions / Method	Smallest Possible Measurement Uncertainty1)	Comments
	10 Hz to < 100 Hz	> –95 dBc/Hz	1.5 dB	
	10 Hz to < 100 Hz	–103 dBc/Hz to -95 dBc/Hz	2.5 dB	
	100 Hz to < 1 kHz	> –123 dBc/Hz	1.5 dB	
	100 Hz to < 1 kHz	–131 dBc/Hz to -123 dBc/Hz	2.5 dB	
	1 kHz to < 10 kHz	> –153 dBc/Hz	1.5 dB	
	1 kHz to < 10 kHz	–161 dBc/Hz to -153 dBc/Hz	2.5 dB	
	10 kHz to < 100 kHz	> –170 dBc/Hz	1.5 dB	
	10 kHz to < 100 kHz	–178 dBc/Hz to -170 dBc/Hz	2.5 dB	
	100 kHz to < 1 MHz	> –172 dBc/Hz	1.5 dB	
	100 kHz to < 1 MHz	–180 dBc/Hz to -172 dBc/Hz	2.5 dB	
	1 MHz to < 10 MHz	> –172 dBc/Hz	1.5 dB	
	1 MHz to < 10 MHz	–180 dBc/Hz to -172 dBc/Hz	2.5 dB	
	1 Hz	> –55 dBc/Hz	1.5 dB	f: 1 GHz
	1 Hz	–63 dBc/Hz to -55 dBc/Hz	2.5 dB	
	3 Hz to < 10 Hz	> –67 dBc/Hz	1.5 dB	
	3 Hz to < 10 Hz	–79 dBc/Hz to -67 dBc/Hz	2.5 dB	
	10 Hz to < 100 Hz	> – 85 dBc/Hz	1.5 dB	
	10 Hz to < 100 Hz	–93 dBc/Hz to -85 dBc/Hz	2.5 dB	
	100 Hz to < 1 kHz	> –114 dBc/Hz	1.5 dB	
	100 Hz to < 1 kHz	–122 dBc/Hz to -114 dBc/Hz	2.5 dB	
	1 kHz to < 10 kHz	> –146 dBc/Hz	1.5 dB	
	1 kHz to < 10 kHz	–154 dBc/Hz to -146 dBc/Hz	2.5 dB	
	10 kHz to < 10 kHz	> –166 dBc/Hz	1.5 dB	
	10 kHz to < 100 kHz	–174 dBc/Hz to -166 dBc/Hz	2.5 dB	
	100 kHz to < 1 MHz	> –168 dBc/Hz	1.5 dB	
	100 kHz to < 1 MHz	–176 dBc/Hz to -168 dBc/Hz	2.5 dB	
	1 MHz to < 10 MHz	> –168 dBc/Hz	1.5 dB	
	1 MHz to < 10 MHz	–176 dBc/Hz to -168 dBc/Hz	2.5 dB	
	1 Hz	–49 dBc/Hz	1.5 dB	f: 3 GHz
	1 Hz	–57 dBc/Hz	2.5 dB	
	3 Hz to 10 Hz	–62 dBc/Hz	1.5 dB	

Measurand / Calibration Item	Measurement Range / Span	Measurement Conditions / Method	Smallest Possible Measurement Uncertainty1)	Comments
	3 Hz to 10 Hz	–70 dBc/Hz	2.5 dB	
	10 Hz to 100 Hz	–76 dBc/Hz	1.5 dB	
	10 Hz to 100 Hz	–84 dBc/Hz	2.5 dB	
	100 Hz to 1 kHz	–105 dBc/Hz	1.5 dB	
	100 Hz to 1 kHz	–113 dBc/Hz	2.5 dB	
	1 kHz to 10 kHz	–138 dBc/Hz	1.5 dB	
	1 kHz to 10 kHz	–146 dBc/Hz	2.5 dB	
	10 kHz to 100 kHz	–156 dBc/Hz	1.5 dB	
	10 kHz to 100 kHz	–164 dBc/Hz	2.5 dB	
	100 kHz to 1 MHz	–158 dBc/Hz	1.5 dB	
	100 kHz to 1 MHz	–166 dBc/Hz	2.5 dB	
	1 MHz to 10 MHz	–158 dBc/Hz	1.5 dB	
	1 MHz to 10 MHz	–166 dBc/Hz	2.5 dB	
	1 Hz	–38 dBc/Hz	1.5 dB	f: 8 GHz
	1 Hz	–46 dBc/Hz	2.5 dB	
	3 Hz to 10 Hz	–54 dBc/Hz	1.5 dB	
	3 Hz to 10 Hz	–62 dBc/Hz	2.5 dB	
	10 Hz to 100 Hz	–68 dBc/Hz	1.5 dB	
	10 Hz to 100 Hz	–76 dBc/Hz	2.5 dB	
	100 Hz to 1 kHz	–95 dBc/Hz	1.5 dB	
	100 Hz to 1 kHz	–103 dBc/Hz	2.5 dB	
	1 kHz to 10 kHz	–122 dBc/Hz	1.5 dB	
	1 kHz to 10 kHz	–130 dBc/Hz	2.5 dB	
	10 kHz to 100 kHz	–138 dBc/Hz	1.5 dB	
	10 kHz to 100 kHz	–146 dBc/Hz	2.5 dB	
	100 kHz to 1 MHz	–142 dBc/Hz	1.5 dB	
	100 kHz to 1 MHz	–150 dBc/Hz	2.5 dB	
	1 MHz to 10 MHz	–142 dBc/Hz	1.5 dB	
	1 MHz to 10 MHz	–150 dBc/Hz	2.5 dB	

5 References

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6 Ordering Information

Designation	Type	Order No.
Phase Noise Analyzer and VCO Tester, 1 MHz to 8 GHz	R&S®FSWP8	1322.8003.08
Phase Noise Analyzer and VCO Tester, 1 MHz to 26.5 GHz	R&S®FSWP26	1322.8003.26
Phase Noise Analyzer and VCO Tester, 1 MHz to 50 GHz	R&S®FSWP50	1322.8003.50
Hardware options		
Spectrum Analyzer, 10 Hz to 8 GHz	R&S®FSWP-B1	1322.9997.08
Spectrum Analyzer, 10 Hz to 26.5 GHz	R&S®FSWP-B1	1322.9997.26
Spectrum Analyzer, 10 Hz to 50 GHz	R&S®FSWP-B1	1322.9997.50
High Stability OCXO	R&S®FSWP-B4	1325.3890.02
Resolution Bandwidth > 10 MHz 1)	R&S®FSWP-B8	1325.5028.26
Resolution Bandwidth > 10 MHz , for R&S®FSWP50 1)	R&S®FSWP-B8	1325.5028.02
External Generator Control 1)	R&S®FSWP-B10	1325.5463.02
Highpass Filter for Harmonic Measurements 1)	R&S®FSWP-B13	1325.4350.02
Spare Solid State Drive (removable hard drive)	R&S®FSWP-B18	1331.4313.02
RF Preamplifier, 100 kHz to 8 GHz 1)	R&S®FSWP-B24	1325.3725.08
RF Preamplifier, 100 kHz to 26.5 GHz 1)	R&S®FSWP-B24	1325.3848.26
RF Preamplifier, 100 kHz to 50 GHz 1)	R&S®FSWP-B24	1325.3848.50
Cross-Correlation, 8 GHz	R&S®FSWP-B60	1322.9800.08
Cross-Correlation, 26.5 GHz	R&S®FSWP-B60	1322.9800.26
Cross-Correlation, 50 GHz	R&S®FSWP-B60	1322.9800.50
Cross-Correlation (low phase noise), 8 GHz	R&S®FSWP-B61	1325.3719.08
Cross-Correlation (low phase noise), 26 GHz	R&S®FSWP-B61	1325.3719.26
Cross-Correlation (low phase noise), 50 GHz	R&S®FSWP-B61	1325.3719.50
Residual Phase Noise Measurements	R&S®FSWP-B64	1322.9900.26
80 MHz Analysis Bandwidth 1)	R&S®FSWP-B80	1325.4338.02
Firmware		
Pulsed Phase Noise Measurements	R&S®FSWP-K4	1325.5034.02
Pulse Measurements	R&S®FSWP-K6	1325.4221.02
Time Sidelobe Measurements	R&S®FSWP-K6S	1325.5363.02
Analog Modulation Analysis for AM/FM/φM 1)	R&S®FSWP-K7	1325.4238.02
Noise Figure Measurements 1)	R&S®FSWP-K30	1325.4244.02
Vector Signal Analysis 1)	R&S®FSWP-K70	1325.4280.02
Security Write Protection for Solid State Drive	R&S®FSWP-K33	1325.5040.02
Warranty		
Base unit	3 years	
All other items	1 year	
Options		
Extended Warranty, one year	R&S®WE1	Please contact your local Rohde & Schwarz sales office.
Extended Warranty, two years	R&S®WE2	
Extended Warranty with Calibration Coverage, one year	R&S®CW1	
Extended Warranty with Calibration Coverage, two years	R&S®CW2	
1) R&S®FSWP-B1 option required.		

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