2-Port Residual Noise Measurements
Application Note

Products:

- R&S®FSWP

As phase noise becomes an increasingly important system-level specification for electronic test equipment, communications systems, and radar systems. It is not only important to quantify the noise produced by oscillators, but also the noise added by each component in the signal processing chain. This application note reviews the fundamentals of residual or additive noise and addresses measurement techniques for determining the amplitude (AM) and phase noise added by two-port devices such as: amplifiers, mixers, block frequency converters, multipliers, dividers, and frequency synthesizers.

Additionally, the Rohde & Schwarz FSWP phase noise analyzer will be introduced and a discussion of residual noise measurement techniques for the above-mentioned devices will be provided.

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http://www.rohde-schwarz.com/appnote/1EF100.

Application Note
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ROHDE&SCHWARZ

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1 Introduction

In the not too distant past radar systems engineers were happy simply to detect targets; however, today it is not enough to simply detect a target, but the target's extremely small return signal must be extracted from high amplitude ground or sea clutter. This is typically accomplished by only processing target signals that are Doppler shifted away from the radar's carrier frequency and rejecting those signals with zero Doppler. This is the concept of the so-called moving target indicator (MTI) radar. Also, most modern fire control radars are required to measure the target's velocity, again by processing the target's Doppler return. Accurate velocity information is critical when trying to predict target track and a firing solution for weapons systems.

In both of the examples mentioned above radar system phase noise is the key parameter defining the radar's ability to extract small signals from a noisy background.

Similarly, in digital communications systems, both terrestrial and satellite, the current trend is to try to squeeze more information into a smaller bandwidth. Generally, this is accomplished by increasing the complexity of the modulation constellation with the risk of increased sensitivity to symbol errors caused by factors such as phase noise. As constellations become more complex, they become more sensitive to both AM and phase noise. As can be seen in the following figure, phase noise causes a constellation to rotate around its origin, increasing error vector magnitude (EVM) and bit-error rate (BER). This effect is most noticeable at the extreme corners of the constellation.

Fig. 1-1: Effect of Phase Noise on a 16-QAM Constellation

For both radar and communications systems, system-level phase noise must be maintained at sufficiently low levels over the offset frequency range from the carrier where signal information is processed. Thus, critical offset frequencies can range from 0.1 Hz to greater than 100 MHz, depending on system requirements.

1.1 Phase Noise

Before discussing residual phase noise, a basic review of phase noise would be helpful. Essentially, phase noise is a figure of merit describing the frequency stability of a signal. Frequency stability can be viewed in several different ways. In most cases frequency stability is specified over some time interval. For example, for a crystal oscillator that may be used as the time base for a clock it may be important that clock accuracy is maintained over a very long time period such as days, weeks, or even years. However, when we think of phase noise we are concerned with an oscillator's frequency stability over a very short observation time, possibly only for a fraction of a second to possibly a few seconds.

As we think about phase noise, we could start by thinking of an ideal sine wave with some amplitude A_0 and compare it to a real-world signal that has been corrupted by noise.

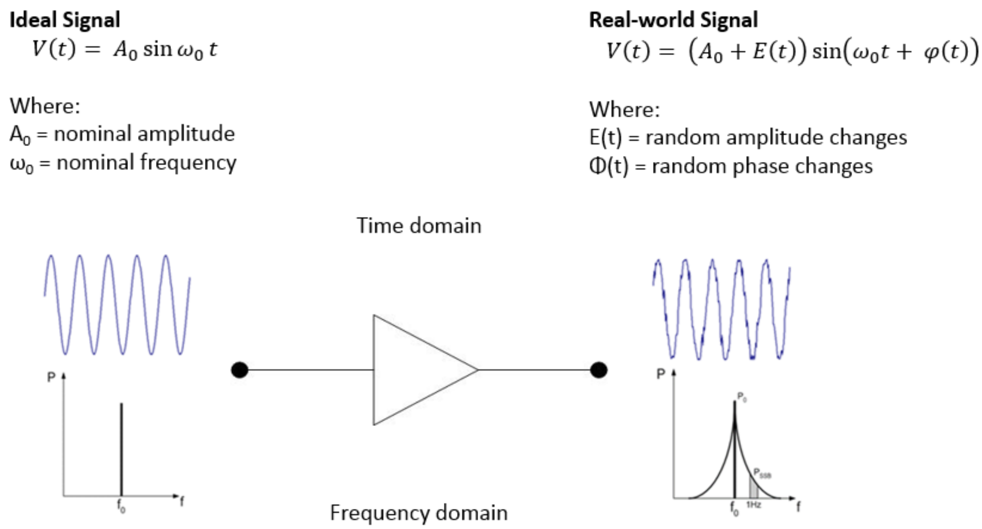


Fig. 1-2: Phase Noise of an Ideal vs. Real-world Signal

In the above example the real-world signal has both unintentional amplitude noise modulation and phase noise modulation described by the terms E(t) and Φ(t) in the equation shown above. This added unintentional modulation can be visualized in the time-domain waveform and frequency domain spectrum. Generally, phase noise is associated with oscillators; however, the primary focus of this paper is the phase noise added by other components, such as amplifiers.

1.2 Residual Noise

Residual or additive noise is noise added to a signal by two-port devices used to process the signal. In the remainder of this paper we will use the term residual noise, referring to both AM noise and phase noise.

The terms residual and additive noise are used interchangeably in the literature; however, the term additive noise is more descriptive since the noise adds in a linear fashion to the input signal of the two-port device.

Two-port devices of interest could include:

- Amplifiers
- Frequency multipliers
- Frequency dividers
- Frequency synthesizers
- Up or down converters
- Mixers
- Filters, and
- Any other two-port device.

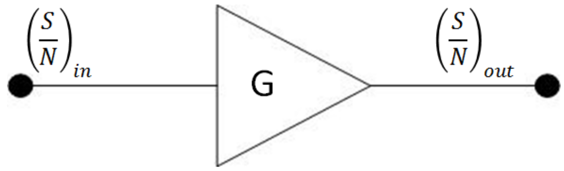
In an effort to accurately predict and manage total system noise, the RF systems engineer not only needs to quantify the noise generated by the oscillators used in his system, but he must account for the noise added to a clean oscillator signal by every stage that processes the signal. This is equally important for receivers as well as transmitters.

1.2.1 Noise Mechanisms

The first noise mechanism to be considered is thermal or Johnson noise. It is common understanding that every amplifier adds some noise to signals, as described by the concept of noise figure (FN). Noise figure (dB form) or noise factor (linear form) is described as a degradation of signal to noise ratio (SNR) as a signal passes through an amplifier. This is a good example of additive noise and is broadband or white noise.

Another example noise mechanism is shot or flicker noise. Flicker noise is a near DC noise with a power spectral density of 1/f. All active electronic devices exhibit flicker noise. In the case of amplifiers and multipliers, the near DC flicker noise is multiplied with the carrier and the resulting mixing action convolves the flicker noise spectrum with that of the carrier. Additional forms of multiplicative noise include baseband power supply noise and noise generated by digital clocks. These noise sources are mixed with the carrier signal due to non-linearities in the two-port device.

Returning to noise factor (F), noise factor is the ratio of input signal to noise ratio to output signal to noise ratio.



$$F = \frac{\left(\frac{S}{N}\right)_{in}}{\left(\frac{S}{N}\right)_{out}}$$

Fig. 1-3: Noise factor of an amplifier

Rearranging the above equation and inserting values for S_{in} and N_{in}, we can solve for the output signal and noise power of the amplifier. Where $S_{in} = P_{in}$ and $N_{in} = kTB_n$ where k is Boltzman's constant, T = the absolute Kelvin temperature generally; 290°K at room temperature; and B_n is the noise bandwidth in Hertz, resulting in a noise power density of -174 dBm/Hz.

Assuming that the amplifier's gain $G = S_{out}/P_{in}$

The output signal will be equal to $S_{out} = P_{in}G$ and the output noise power will be:

$$N_{out} = GFkTB_n$$

From this point on, bandwidth references will be assumed noise bandwidth and B will simply replace B_n. Next, the output noise power and signal powers (N_{out} and S_{out}) are converted to voltages, assuming a resistance R.

$$V_{out} = \sqrt{RGP_{in}} + \sqrt{RGFkTB}$$

The question that should now be addressed is: What does noise factor have to do with phase noise? To answer this question, we need to look at the above equation on a phasor diagram.

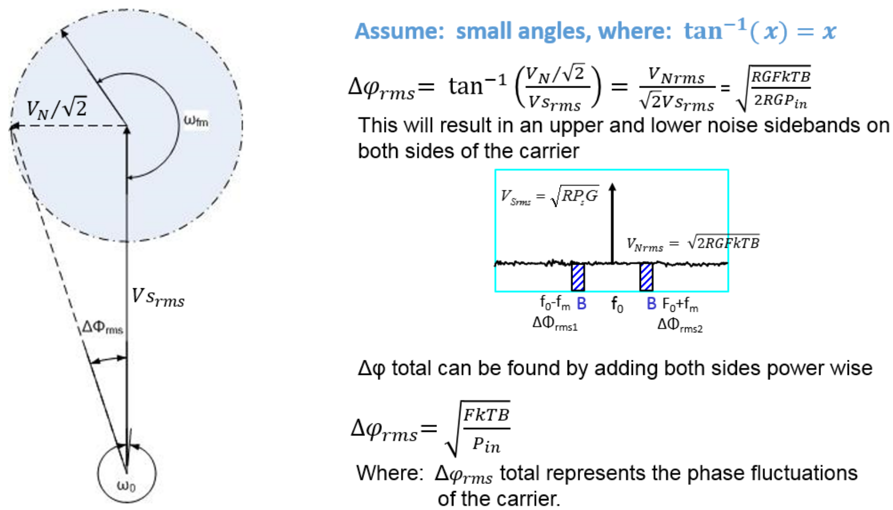


Fig. 1-4: Phasor diagram, showing effect of noise factor

$\Delta\Phi_{rms}$ describes the phase fluctuations about the carrier, in radians, or the broadband phase noise because of the amplifier's input noise and its noise factor. Phase noise is usually displayed as a spectral density plot in a log format. The spectral density of phase fluctuations $s_\Phi(f)$ can be found by squaring $\Delta\Phi_{rms}$ and dividing by the bandwidth.

$$S_\varphi(f) = \frac{\Delta\varphi_{rms}^2(f)}{B} = \frac{FkT}{P_{in}}\left[\frac{rad^2}{Hz}\right]$$

$S_\varphi(f)$ is the double side-band phase noise, as would be measured using a phase detector, whose voltage output is digitized by an FFT analyzer. However, the more common term for phase noise is single side-band phase noise denoted as script $\mathcal{L}(f)$, where $\mathcal{L}(f) \equiv S\varphi(f)/2$ (1) (2).

Therefore:

$$\mathcal{L}(f) \equiv \frac{S_\varphi(f)}{2} = \frac{FkT}{2P_{in}}\left[\frac{rad^2}{Hz}\right]$$

Finally, it can be useful to convert the above equation into dB form, as follows:

$$\mathcal{L}(f) = 10\log(kT) + 10\log(F) - 10\log(P_{in}) - 10\log(2)$$

Note that the 10•Log (2) term is 3 dB which can be subtracted from the 10•Log (kT) term resulting in a thermal noise floor of -177 dBm/Hz at room temperature. A fundamental assumption in phase noise measurement is that thermal noise (kT) is composed of a phase noise component and an equal amplitude noise component with their sum being equal to -174 dBm/Hz. We can then simplify the above equation to:

$$\mathcal{L}(f) = N_{TH} + FN - P_{in}$$

Where N_{TH} = -177 dBm/Hz.

The above equation only applies to the broadband or white noise portion of the amplifier's phase noise. In addition, it shows that the broadband portion of an amplifier's phase noise is dependent on the input power level of the amplifier and noise figure. Therefore, it is important to make residual phase noise measurements at a specified input drive level.

In summary, there are two primary components of residual or additive phase noise of an amplifier:

- Shot or flicker noise and
- Noise factor.

The following graph illustrates this concept.

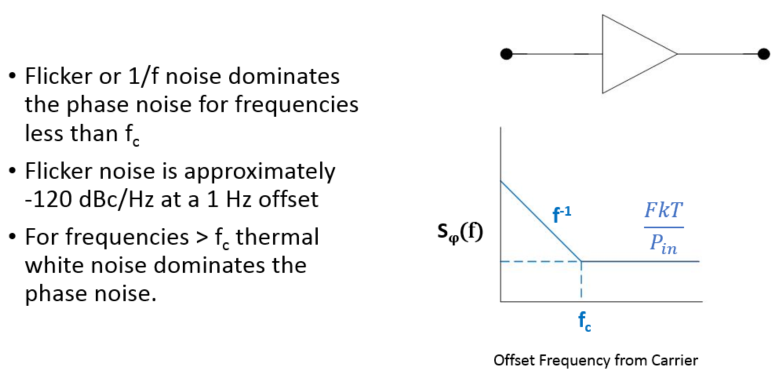


Fig. 1-5: Two Phase Noise Components of an Amplifier

1.3 Residual Phase Noise Measurement

Traditionally, residual phase noise is measured by splitting the output of a signal generator with a two-way power divider. One of the outputs of the power splitter is used to drive the input to the device under test (DUT) and the DUT's output is fed to an input of a phase detector. The remaining power divider output is fed to a phase shifter whose output is fed to the remaining phase detector input; however, the phase shifter could be placed in either path. The phase shifter is used to adjust the phase between the two phase detector inputs into quadrature. In most cases, a double-balanced mixer is used as the phase detector.

The mixer's output will contain both sum and difference signals of the two input signals. The low-pass filter removes the sum and leaves the difference signal to be processed by the FFT analyzer. With the two inputs of the phase detector in phase quadrature, the nominal DC output voltage of the phase detector goes to zero and all that remains is a voltage that is proportional to the phase fluctuations (phase noise) around the quadrature point.

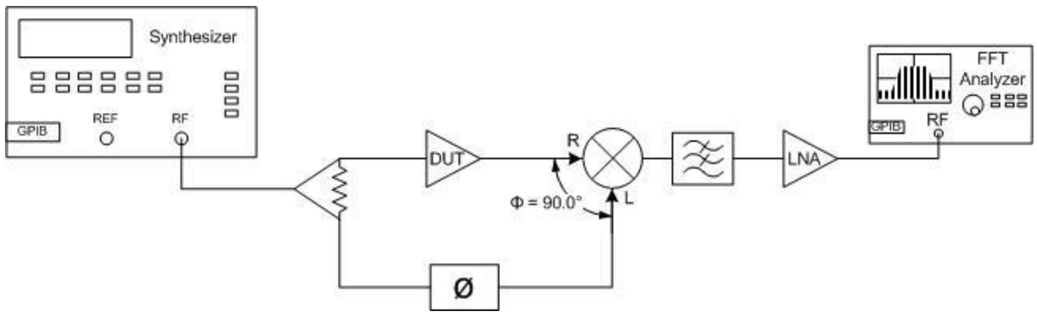


Fig. 1-6: Residual Phase Noise Measurement, Using a Double-Balanced Mixer as a Phase Detector

Since the residual noise signal may be very small compared to the absolute phase noise of the signal generator used to drive the DUT it is imperative that the signal generator noise be cancelled. Examining the above diagram, it is apparent that the signal generator noise is common mode or correlated at both inputs of the phase detector. With this configuration, the signal generator noise is cancelled or subtracted from the measurement by the mixing action of the phase detector, leaving only the residual noise of the DUT.

NOTE: In residual noise measurements the signal generator noise must be cancelled to ensure that the DUT's noise is measured and not the signal generator's noise.

Referring to Figure 1-6, the signal at the input (R port) of the mixer is represented as $V_R(t)$ and the signal at the reference port (port L) is represented as $V_L(t)$. Where:

$$V_R(t) = \cos\left(\omega_C t + \Delta_{\varphi Gen} + \Delta_{\varphi Amp}\right)$$

$$V_L(t) = \sin\left(\omega_C t + \Delta_{\varphi Gen}\right)$$

Where: $\Delta_{\varphi Gen}$ is the signal generator's phase noise and $\Delta_{\varphi Amp}$ is the phase noise produced by the DUT.

When used as a phase detector, the mixer acts as a multiplier and its output voltage would be:

$$V(t) = V_R(t) \cdot V_L(t)$$

$$V(t) = \cos\left(\omega_C t + \Delta_{\varphi Gen} + \Delta_{\varphi Amp}\right) \cdot \sin\left(\omega_C t + \Delta_{\varphi Gen}\right)$$

$$= \frac{1}{2}\left[\sin\left(\omega_C t + \Delta_{\varphi Gen} + \Delta_{\varphi Amp} + \omega_C t + \Delta_{\varphi Gen}\right) - \sin\left(\omega_C t + \Delta_{\varphi Gen} + \Delta_{\varphi Amp} - \omega_C t - \Delta_{\varphi Gen}\right)\right]$$

$$= \frac{1}{2}\left[\sin\left(2\omega_C T + 2\Delta_{\varphi Gen} + \Delta_{\varphi Amp}\right) + \sin\left(\Delta_{\varphi Amp}\right)\right]$$

The low-pass filter will now remove the doubled components leaving only:

$$V(t) = \sin\left(\Delta_{\varphi Amp}\right)$$

Now referring back to the assumption made in Figure 1-4 that the small-angle criterion will be used, where sin(x) = x:

$$V(t) = \Delta_{\varphi Amp}$$

For the sake of simplicity, any discussion of proportionality constants used to calibrate a measurement have been left out. Normally these constants are lumped together to form a phase detector constant denoted as K_φ with units of V/radian. Therefore:

$$V(t) = K_\varphi \Delta_{\varphi Amp}$$

As can be seen from the above discussion, if the phase noise produced by the signal generator is correlated on both ports of the phase detector it will be cancelled, leaving only the phase noise of the device under test. This assumes an ideal double-balanced mixer and that the source phase noise would be completely cancelled, when using real-world mixer this is not the case and one could expect to only achieve 40 to 60 dB of cancellation.

2 Rohde & Schwarz FSWP

The Rohde & Schwarz (R&S) FSWP Phase Noise Analyzer (3) is a modern alternative to the classical phase detector method of phase noise measurement described in Section 1.3, above. FSWP is available in three frequency range dependent models:

- 1 MHz to 8 GHz
- 1 MHz to 26.5 GHz, and
- 1 MHz to 50 GHz.

FSWP can also be augmented with the following options to increase capability and performance:

Option	Description
B1	Signal and Spectrum Analyzer
B4	High stability OCXO
B60	Cross correlation
B61	Low Phase Noise Cross-Correlation
B64	Residual (two-port) phase noise measurements
B80	80 MHz analysis bandwidth
K4	Pulsed Carrier Noise Measurements **Note:** This option is required for pulsed carrier noise (AM and PM) measurements
K6	Pulse measurements--detailed pulse analysis and trends--not necessary for phase noise measurement
K7	Analog modulation analysis for AM, FM, and PM
K30	Noise figure measurements
K33	Security Write Protect--Prevents storage of classified information on instrument's mass storage
K70	Vector Signal Analysis

Table 2-1: FSWP Options

Traditional phase noise test sets utilize an analog double-balanced, mixer with the two inputs in phase quadrature, as a phase detector. With the inputs in phase quadrature, the DC component of the mixer's output goes to zero and only the small phase variations about the quadrature point (phase noise) are present at the output. The primary disadvantage of this method is that quadrature must be closely maintained between the input ports and the set up must be calibrated to determine the phase detector constant K_φ for each measurement.

In comparison, the R&S FSWP (4) directly down converts the signal under test to a low or zero IF frequency using a pair of In-phase and Quadrature (I/Q) mixers. The IF signals are then digitized and demodulated for phase and amplitude variations, using digital signal processing (DSP). Moving the phase detector into the digital domain provides much easier measurement set up and calibration for the user and greatly improves measurement accuracy. Since the characteristics of the digital components are predefined, any measurement inaccuracies can be compensated in DSP yielding absolute precision.

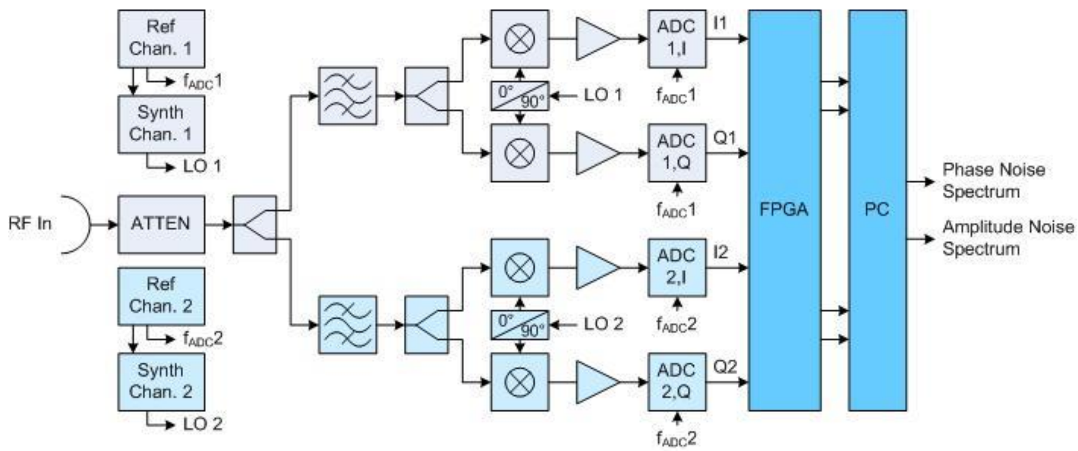


Fig. 2-1: FSWP Analog Block Diagram

Referring to Figure 2-1 above, the RF input signal is filtered and split between two independent channels. Each channel in filtered and then introduced to an I/Q mixer, where the input signal is mixed with an ultra-low phase noise local oscillator. The local oscillators (LOs) for channel 1 and 2 are derived from two independent reference clocks to ensure they are uncorrelated over the offset frequency range of interest. The reference of Channel 2 is loosely coupled to the reference of Channel 1 by a phase lock loop (PLL) with a loop bandwidth of less than 0.1 Hz. This loose coupling allows cross correlation down to offset frequencies of 0.1 Hz.

Since the mixers and amplifiers are analog components, their performance is non-ideal introducing quadrature errors, gain imbalance, and LO feed through. During manufacturing, gain and phase deviations are factory calibrated over the instrument's frequency range, while the DC offset caused by LO feedthrough is calibrated prior to each measurement. One of the primary advantages of this architecture is that it typically achieves an AM rejection of 40 dB, compared to the 15 to 30 dB achieved by typical phase detector designs. This excellent AM rejection reduces the likelihood of cross-spectrum collapse that has been attributed to anti-correlated AM/PM conversion in most cross-correlated phase noise measurement systems (5).

Once the signal has been down converted and amplified each I and Q signal for both Channels 1 and 2 are digitized by an independent 100 Msa/s ADCs. Since the carrier is not suppressed, as in the case of a classical phase detector, the ADC's dynamic range must be sufficient to capture the carrier and all noise sidebands of interest. Each of the four ADCs, shown in Figure 2-1, contains four parallel channels with 16 bits of resolution. The four parallel ADCs outputs are then averaged for improved SNR. Since the only signal that is correlated for both Channels 1 and 2 is the signal under test, system noise from the LOs, amplifiers, and ADCs can be reduced using cross-correlation.

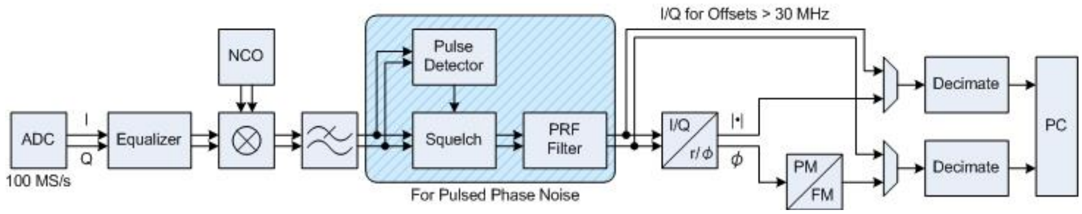


Fig. 2-2: FSWP DSP for One Channel

Figure 2-2 shows the digital signal processing following the I/Q sampling. This process is implemented two times in FPGA for cross-correlation measurements. The equalizer at the beginning of the DSP chain serves two primary purposes: First, it compensates for the channel frequency response of the analog hardware for both I and Q paths and second, it compensates the I/Q imbalance and DC offset errors introduced by the analog I/Q mixers. The equalized signal is shifted in frequency by a numerically controlled oscillator (NCO) and mixer. Frequency shifting is used to center the spectrum on the carrier frequency. A low-pass filter next removes any frequency components that fall outside the frequency range of interest. A pulse detector, squelch, and PRF filter block is invoked for processing pulsed carrier noise measurements and is bypassed for CW noise measurements. More information on pulsed residual noise measurements is provided in Section 2.1.2.

Following the pulse signal processing block, the carrier is demodulated to obtain the AM and PM noise spectrums. The demodulation process begins with a CORDIC (Coordinate Rotation Digital Computer) algorithm to separate the complex I/Q baseband signals into their phase and magnitude components. The magnitude signal is used directly to calculate the AM noise spectrum and the phase signal is converted into a frequency signal prior to further processing. One key point is that FSWP simultaneously measures both phase noise and AM noise, saving the user the time and effort of making a separate AM noise measurement with a different configuration.

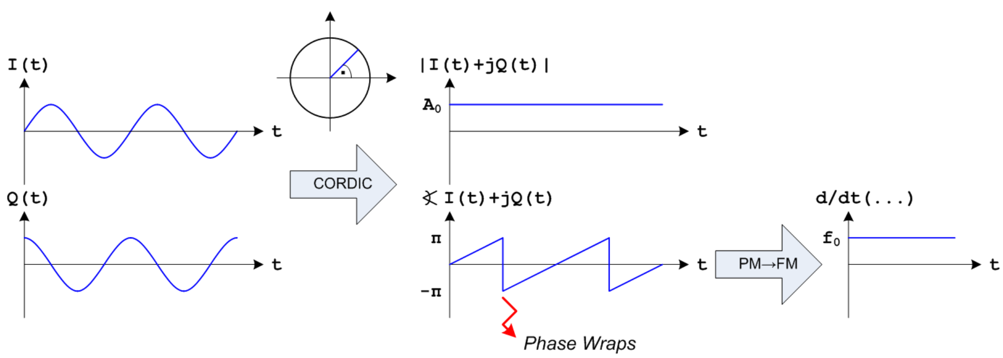


Fig. 2-3: AM and FM Demodulation of a Carrier

Considering that the DUT's carrier frequency may not be exactly the same as FSWP's LOs, the demodulated phase would have a linearly increasing phase which would wrap at ±π radians, making it difficult to determine the signal's phase noise. Therefore, FSWP converts the phase demodulated signal into a non-wrapping FM signal. Slow DUT frequency drift is converted into a low or zero frequency component of the FM signal. Following decimation and Fast Fourier Transform of the FM signal, the spectral density of frequency fluctuations $S_\nu(f)$ is obtained. $S_\nu(f)$ can easily be converted into the spectral density of phase fluctuations $S_\varphi(f)$ by dividing by f^2. Single sideband phase noise $\mathcal{L}(f)$ can now be calculated by simply dividing by 2.

$$\mathcal{L}(f) = \frac{S_\varphi(f)}{2} = \frac{S_\nu(f)}{2f^2}$$

The digital FM demodulator, as realized in FSWP, can be viewed as an ideal FM demodulator and does not suffer from low sensitivity close to the carrier as is typical of analog delay-line FM demodulators, where frequency sensitivity of the demodulator decreases at a rate of 20 dB per decade approaching DC.

2.1 Residual Phase Noise Measurements with FSWP

With the addition of Option B64, FSWP is capable of residual or additive noise measurements. Option B64 provides the following:

- Instrument firmware for processing residual noise measurements
- An internal RF source covering the frequency range of 10 MHz to 18 GHz with up to +10 dBm of signal power that can be used as a stimulus for residual noise measurements
- Two front-panel SMA connectors that can be used to connect external LOs to FSWP's channel 1 and 2 I/Q mixers for residual noise measurements.

The first step in making a residual noise measurement is to invoke the additive noise measurement by pressing the **[MEAS]** hard key on the instrument's front panel, followed by selecting the **{Additive Noise}** measurement from the menu, as shown below:

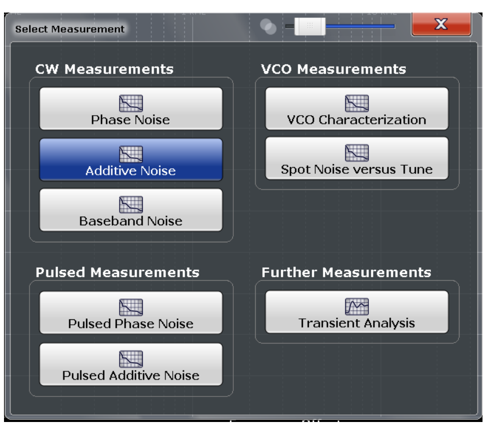


Fig. 2-4: FSWP Measurement Menu, Showing Additive Noise Measurement

With the Additive Noise measurement selected, the instrument is automatically configured to make the residual noise measurement. By default, FSWP is set up to use its internal source as the stimulus for additive noise measurements.

The internal source's output is available from the Type-N connector, labeled "Signal Source Output," located on the instrument's front panel. The internal source has the following characteristics:

FSWP B64 RF Signal Source Characteristics	
Frequency Range	10 MHz to 18 GHz
Signal Level	-50 to +10 dBm in 10 dB steps
Level Accuracy	±2 dB
Modulation	Pulse Modulation for Pulsed Additive Noise Measurement

Table 2-2: FSWP Option B64, Signal Source Characteristics

The B64 Internal Signal Source provides a general-purpose stimulus signal for basic residual noise measurements. As can be seen from Table 2-2 the source's frequency range is limited to 10 MHz through 18 GHz. This is sufficient for the majority of amplifier and frequency converter measurements. In the event that residual noise measurements are being made outside this frequency range, external multipliers or external mixers may be used to increase the instrument's frequency range. In addition, the source is limited to 10 dB amplitude steps, again this is intended to fill a general purpose requirement. If finer amplitude resolution is needed an external step-attenuator may be used. This can be important when trying to measure the residual noise of an amplifier near its compression point. The signal source is derived from one of FSWP's internal reference oscillators (LO), as shown in Figure 2-5.

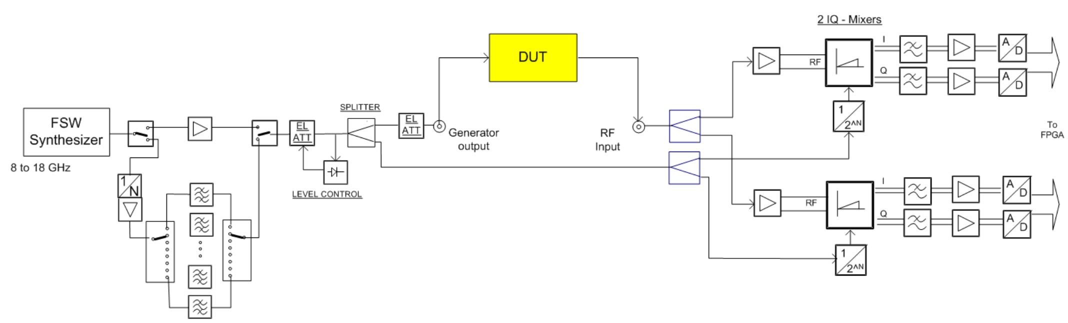


Fig. 2-5: FSWP B64 Signal Source Block Diagram

A frequency divider chain is used to obtain frequencies below the synthesizer's basic tuning range of 8 to 18 GHz. An electronic attenuator is provided to establish the correct output power. Prior to the electronic attenuator, the signal is split. Half of the signal goes through the electronic attenuator and is output on the front-panel Type-N connector. The output from the remaining power splitter port is fed to a second power splitter that provides the LO signal to the Channel 1 and 2 I/Q mixers. In this configuration it is obvious that the noise generated by the internal source is common mode (correlated) for the Channel 1 and

2 mixer inputs and their LO inputs. Using the same rationale that was developed in Section 1.3, we can conclude that the source noise cancels through the multiplication process of the mixers for both of the I and Q mixers.

A simple menu, shown in Figure 2-6, is provided to allow the user to configure the internal signal source. The menu is accessed by pressing the **[MEAS CONFIG]** hard key followed by pressing the **{Source Config}** soft key. This menu can also be accessed by pressing the **[INPUT/OUTPUT]** hard key followed by pressing the **{Output Config}** soft key for both the Phase Noise and Spectrum Analyzer modes.

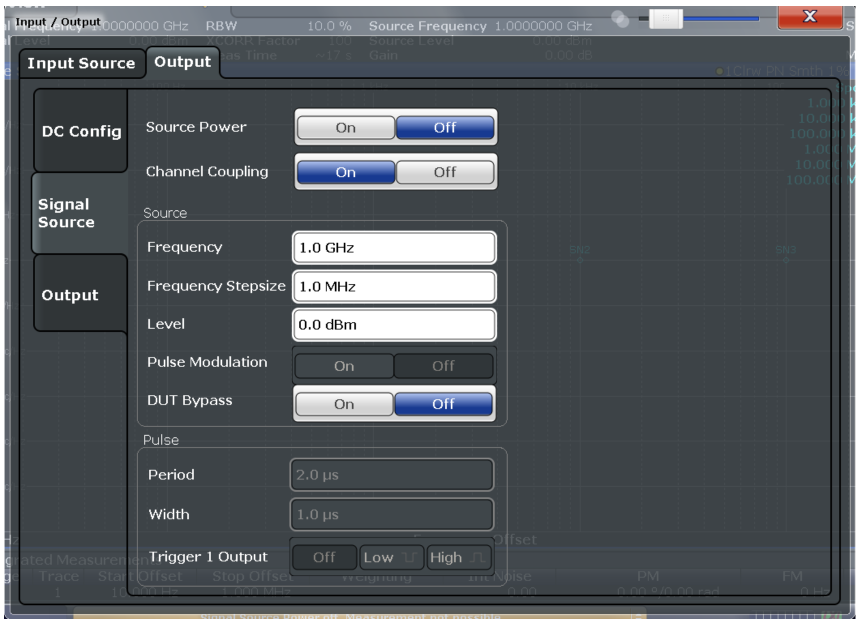


Fig. 2-6: FSWP Source Control Menu

The source control menu provides the following functions:

Control	Description
Source Power radio button	Turns the source RF output on and off
Channel coupling	This function allows signal source settings made in the phase noise mode to be coupled with signal source settings in other modes, such as the spectrum analyzer mode
Frequency	Sets the source output frequency between 10 MHz and 18 GHz
Frequency step size	Sets the frequency step size when using the Up and Down arrow keys
Level	Sets the source output amplitude from -50 to +10 dBm in 10 dB steps
Pulse Modulation	Turns ON and OFF the internal pulse modulator, when in the Pulsed Additive Noise measurement mode
DUT Bypass	Provides a convenient way to bypass a connected DUT and measure the sources noise characteristics directly. For measuring the instrument noise floor for specific measurements setups without removing the DUT.
Pulse Controls	Set the pulse modulation characteristics, PW and PRI

Table 2-3: FSWP Source Controls

In summary, FSWP offers a self-contained residual noise measurement system that can make residual noise measurements on two-port devices without the need of external delay lines to tune the measurement into phase quadrature and external signal generators. As a bonus, AM noise measurements are made without the need of external AM detectors, resulting in improved dynamic range for AM noise measurements.

2.1.1 Using an External Source for Residual Noise Measurements

As mentioned in Section 2.1, above, FSWP Option B64 provides two LO input connectors on the front panel to allow use of an external signal source for residual noise measurements. Figure 2-7 shows the connection of the external LO inputs to the Channel 1 and 2 I/Q mixers

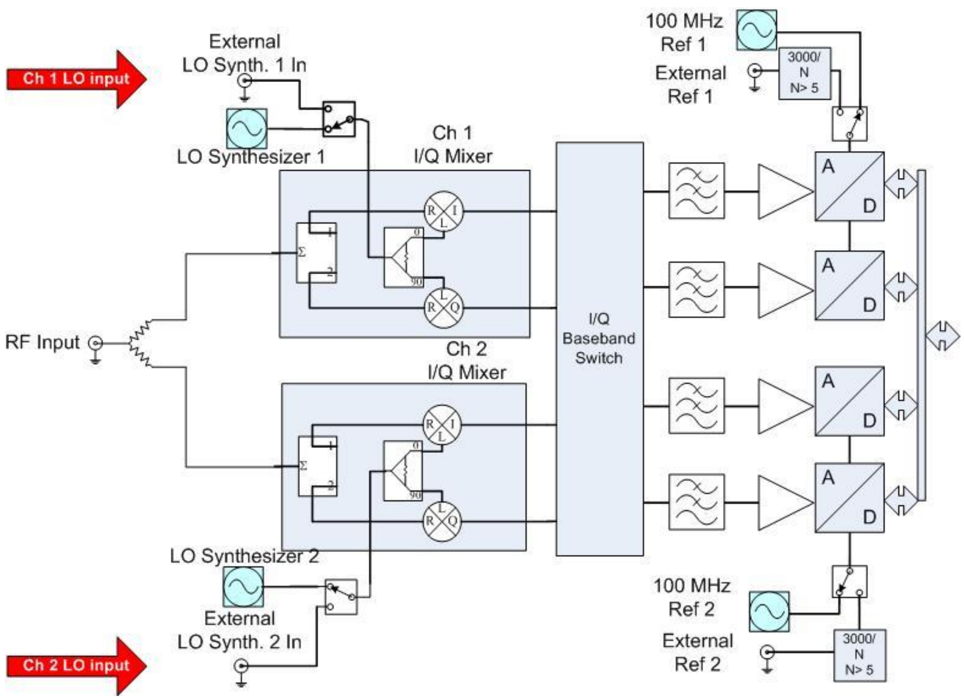


Fig. 2-7: FSWP Block Diagram, Showing External LO Inputs

Use of external LO inputs may be desirable for some residual noise measurements:

- Where precise amplitude control is necessary to ensure that a residual noise measurement is made at a specific drive level relative to an amplifier's 1-dB compression point
- When DUT pulse modulation must be closely synchronized with DUT bias voltages. This is common for high-power pulsed devices like traveling wave tubes (TWTs)

- When making measurements of high-power devices where a booster amplifier is necessary to provide a high-power drive signal for the DUT and it is desired to remove the noise contributed by the booster amp.

The external LO inputs have the same 10 MHz to 18 GHz frequency range as the FSWP internal source. The external LO inputs require between +5 to +10 dBm of drive, depending on frequency. (6)

More information on the use of FSWP external LO inputs can be found in Section 3.2 of this application note.

2.1.2 Pulsed Residual Noise Measurements

Pulsed residual noise measurements using the R&S FSWP are very similar to making CW residual noise measurements. FSWP has a special measurement personality for pulsed residual noise measurements, which is accessed through the **[MEAS]** hard key menu as shown in Figure 2.4. In this case, the bottom radio button would be selected. FSWP has special features for measuring pulsed carrier noise. More information on pulsed carrier noise measurements is available in Application Note "Pulsed Phase Noise Measurements". (7)

3 Residual Noise Measurement Techniques

This section will discuss residual noise measurement techniques for several common classes of two-port devices.

3.1 Simple Amplifier Residual Noise Measurements

As an introduction to residual noise measurements, a good starting point is to measure the residual noise produced by a simple amplifier. Before making the measurement we need to know a few things about the amplifier we plan to test, such as:

- The frequency range of interest
- The small-signal gain
- The 1-dB compression point, and
- The noise figure.

Consider making a residual phase noise measurement on an amplifier with the following characteristics:

Test Amplifier Characteristics	
Frequency Range	50 to 4000 MHz
Gain	20 dB
Input 1-dB Compression Point	0 dBm
Saturated Output Power	+20 dBm
Noise Figure	1.5 to 2 dB

Table 3-1: Amplifier Characteristics

The first things to consider are the frequency and drive levels that will be used for the measurement. For the above amplifier a good starting point might be to choose a stimulus frequency of 1 GHz at an amplifier drive level of -20 dBm. This drive level was chosen to ensure small signal operation. Next, the amplifier is connected to FSWP as shown below:

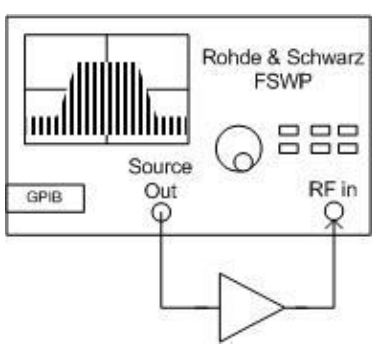


Fig. 3-1: FSWP DUT Connections for a Simple Residual Noise Measurement

As shown above, the DUT connections can really be quite simple. In addition to an internal RF source, FSWP provides three low-noise internal power supplies that can be used to bias many typical DUTs. The supply outputs are available on three front-panel BNC connectors. The supply labeled V Supply is capable of supplying up to 16 Volts DC with a maximum current of 2 Amperes. These power supplies are primarily intended for testing voltage-controlled oscillators (VCOs), but can be used in many applications. Like the RF source, the power supplies can be used in more than just the phase noise mode.

With the amplifier connected and FSWP's internal source set up and turned on the measurement will proceed automatically. The following figure shows the measurement results for this amplifier:

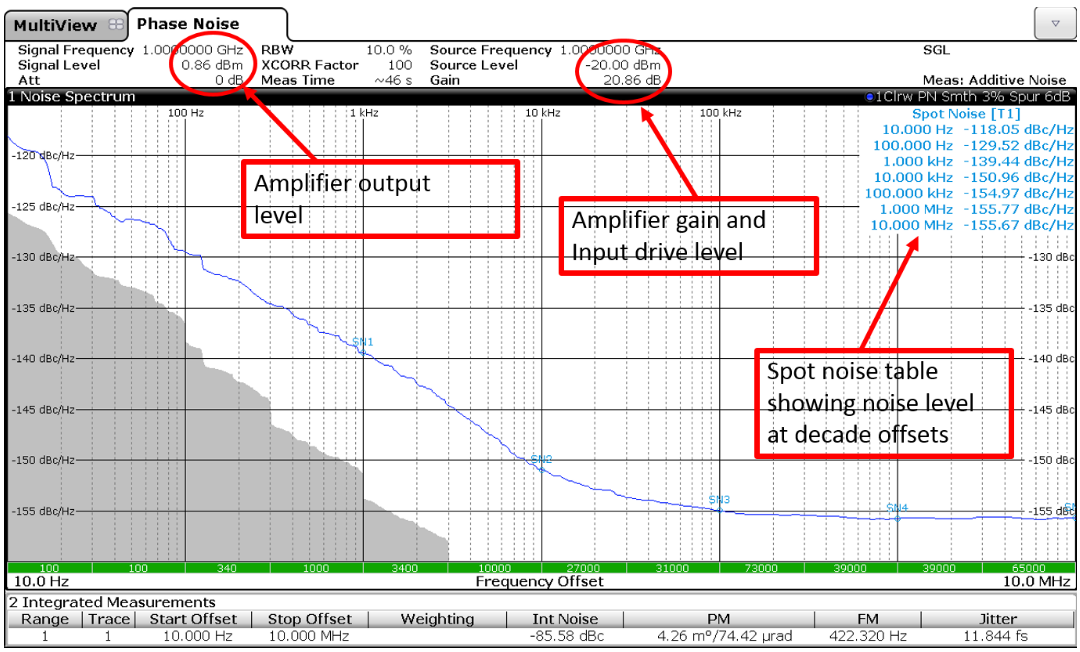


Fig. 3-2: Amplifier Residual Phase Noise Measurement

Figure 3-2 shows the graphical results of our phase noise measurement. In addition to the phase noise plot, notice the annotated locations on the instrument screen showing amplifier output power, amplifier input power, and amplifier gain. These indicators provide a quick view of the amplifier's performance, giving the operator confidence that the amplifier is working as expected. A spot-noise table shows the phase noise at each decade offset frequency.

Referring back to Section 1.2.1 the 1/f noise and the broadband noise of the amplifier can clearly be seen with the 1/f corner frequency at approximately 12 kHz. At an offset frequency of 1 MHz the broadband noise is well established at -155.77 dBc/Hz. Recalling our equation for single sideband phase noise, relative to noise figure from Section 1.2.1:

$$\mathcal{L}(f) = N_{TH} + FN - P_{in}$$

Using the information from Figure 3-2 and rearranging the above equation for phase noise we can solve for the noise figure of the amplifier, where:

$$FN = \mathcal{L}(f) - N_{TH} + P_{in}$$

For our test amplifier:

$$FN = -155.77 + 177 - 20 = 1.23\ dB$$

This is well within the expected noise figure for this amplifier. The noise figure can be verified by making a traditional Y-factor measurement using FSWP's noise figure application (Option K30), with the following results:

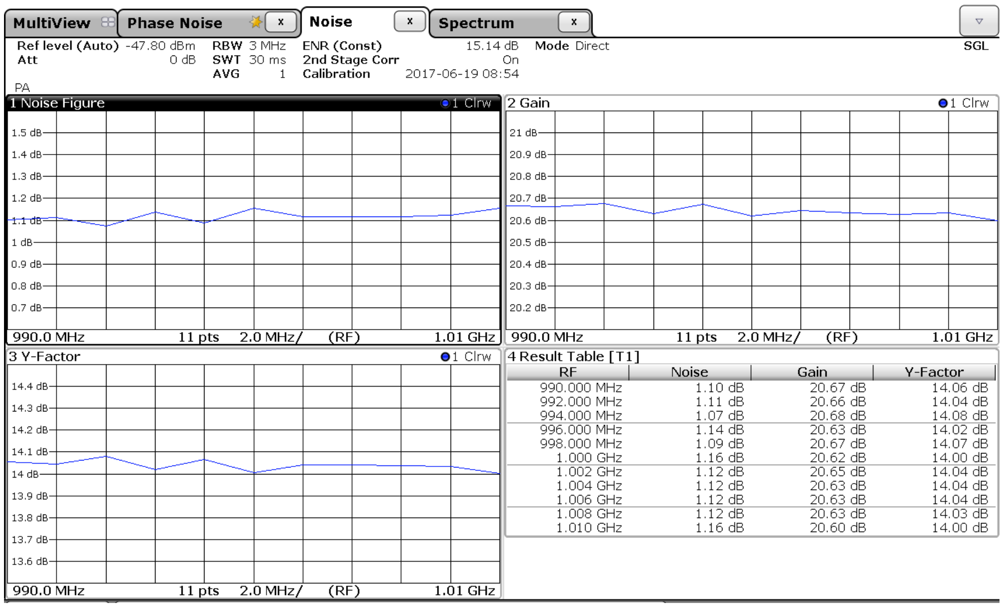


Fig. 3-3: FSWP-K30 Noise Figure Measurement of Test Amplifier

Figure 3-3 shows a noise figure for our test amplifier of 1.16 dB at our test frequency of 1 GHz, as measured with a classical Y-factor method using FSWP-K30. Comparing the Y-factor measurement with that derived from the residual phase noise measurement shows a difference of 0.07 dB. Although excellent, this difference could be explained by several factors, such as:

- Measurement uncertainty for both methods
- The Y-factor measurement was made using a 15 dB excess noise ratio (ENR) noise source, which is not the best choice for a moderate gain low noise figure device
- The input power to the DUT, that was used to calculate noise figure, was simply the selected output power of FSWP's internal source, making no corrections for cable losses. Better accuracy could be obtained by using a power meter at the input of the DUT.

Considering all of these factors there is excellent agreement between the two noise figure measurements.

As compared to noise figure, the real value of a residual noise measurement is that it provides a more complete understanding of the noise contributed by the amplifier (8). The above example demonstrates that noise figure alone does not accurately represent the noise added by the amplifier and only provides limited information about the small-signal noise an amplifier adds to a signal at offsets greater than about 1 MHz from the carrier; whereas, a residual noise measurement provides:

- The flicker or 1/f noise characteristics close to the carrier
- The broad band noise
- The AM noise modulated onto the carrier
- Any spurious signals that result from power supply or digital clock noise.

In addition, the residual noise measurement can provide great insight into the noise characteristics of an amplifier under large-signal conditions.

3.1.1 Additional FSWP Measurements

FSWP provides up to six measurement traces to view measured data. Each trace can display:

- Phase noise
- AM noise, or
- The sum of AM and phase noise.

Any of the above data can be viewed showing measured spurious signals or spurs can be suppressed to provide a cleaner view of the noise trace.

In addition, traces can be stored and displayed as references to compare measured data. A menu of trace math functions are also available for the user to manipulate trace data. Traces can also be exported to CSV files allowing analysis of trace data with common analysis software such as Microsoft Excel®.

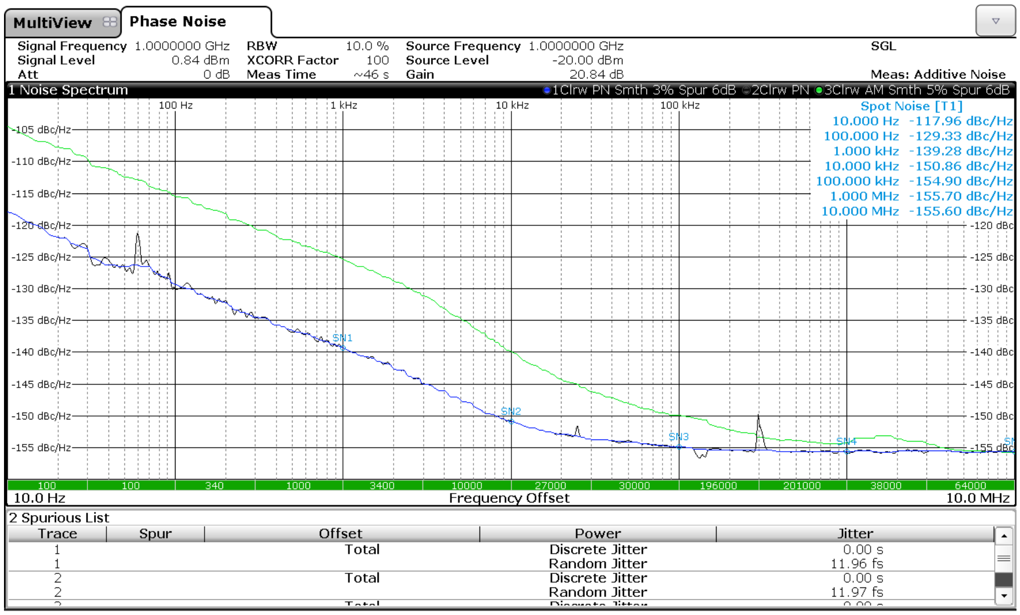


Fig. 3-4: **Residual Noise Measurement Showing AM Noise and Spurs**

The measured data shown in Figure 3-2 was displayed showing phase noise only, with spurs suppressed. This was done to simplify discussion of the measurement.

Figure 3-4 shows a measurement of the same amplifier tested under the same drive conditions. In this figure, the blue trace (trace 1) is the phase noise and matches that shown in Figure 3-2. The black trace (trace 2) is also a phase noise trace, except in this case spur suppression was turned off. Examining this trace, a power-line spur is shown at 60 Hz. Measured spurs are also listed in the spur table in the bottom portion of the screen. Finally, the green trace (trace 3) shows the amplifier's AM noise.

3.1.2 Measuring the Instrument's Noise floor

In addition to measuring the DUT's residual phase noise, it is often a good idea to measure the test instrument's residual noise floor. By making a noise floor measurement with the DUT residual noise measurement the operator can ensure that the measured phase noise is sufficiently greater than the instrument noise to verify the validity of the measurement. For the amplifier measurement described above it is a simple matter to measure FSWP's noise floor.

With the DUT and FSWP configured as shown in Figure 3-1 the user would turn on the DUT bypass function in the FSWP signal source control menu, as illustrated in Figure 2-6 and make a phase noise measurement.

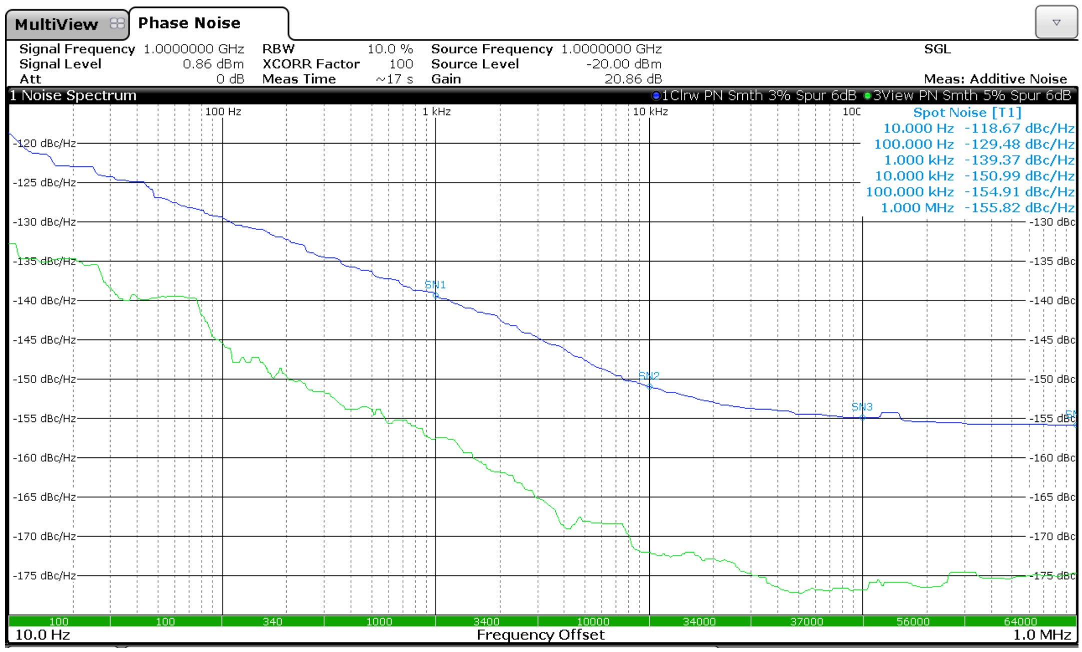


Fig. 3-5: Amplifier Phase Noise and FSWP Noise Floor

Figure 3-5 shows the residual phase noise of our test amplifier under the same test conditions shown previously (see Figure 3-2). However, the green trace in Figure 3-5 shows the FSWP's residual phase noise floor for the conditions established in Section 3.1.

The following procedure was used to make the noise floor measurement:

1. Set up the DUT and FSWP as described in Section 3.1
2. Press the **[RUN SINGLE]** hard key to put the FSWP in single-sweep mode. This will force FSWP to stop making measurements when it finishes the current measurement.
3. Open the source control menu and turn on the DUT bypass, as follows: Press the **[MEAS CONFIG]** hard key followed by pressing the **{Source Config}** soft key. From the source config menu press the **{DUT Bypass}** radio button.
4. With the DUT bypassed the output of the internal signal generator is directly connected to FSWP's receiver input. Next increase the signal generator's output power to match the output power expected from the DUT. In this case 0 dBm. See the annotations at the top of Figure 2.6. This is very important! To get an accurate measurement of the noise floor the instrument must measure the same dynamic range signal as it does in the actual residual noise measurement.
5. Press the **[RUN SINGLE]** hard key to start the noise floor measurement
6. When the measurement is complete (see ready flag at the bottom of the screen) copy the current measurement trace to trace 3 (the green trace), by pressing the **[TRACE]** hard key followed by pressing the **{Copy Trace}** soft key. From the copy trace menu, select Trace 1 as the source trace. Then press the **{Copy to Trace 3}** radio button to copy the trace. Now close the copy trace menu.

7. Open the source control menu, see step 3 above, and reduce the source power to the desired level for the amplifier residual noise test, in this example -20 dBm. Next turn off the DUT bypass and close the source control menu.
8. Press the **[RUN SINGLE]** hard key to start the amplifier residual noise measurement.
9. When the measurement is complete, the yellow trace (trace 1) will display the residual phase noise of the amplifier and the green trace (the trace saved to trace 3 in step 6) will display the instrument's noise floor for this specific measurement configuration. See example in Figure 3-5.

In general, it is desirable to have at least 10 dB of margin between the measured phase noise trace and the instrument noise floor, depending on acceptable measurement uncertainty.

3.1.3 Dynamic Noise Figure

As mentioned in Section 1.2.1 there are two primary components of amplifier noise: flicker or 1/f noise and broadband noise associated with noise figure. From these the amplifier's dynamic range under operating conditions can be determined. In addition, the amplifier's small-signal noise figure can be determined, as discussed in Section 3.1. In this manner the noise figure will correlate quite closely with that of a standard Y-factor measurement, if the amplifier is operated well below the 1-dB compression point (as great as 20 dB). As amplifier drive is increased, the calculated noise figure may vary greatly from the small-signal value, due to non-linear behavior of the amplifier. These effects may be manifest even at 10 dB below the 1-dB compression point in some amplifiers. Nearing the compression point and in deep compression, noise present on the amplifier's bias circuitry may undergo AM to PM conversion and further add to the amplifier's phase noise.

The unique advantage of a residual phase noise measurement is that the measurement can be made at various amplifier drive levels allowing system engineers to evaluate overall system noise using real-world amplifier operating conditions. This concept is illustrated in Figure 3-6 below:

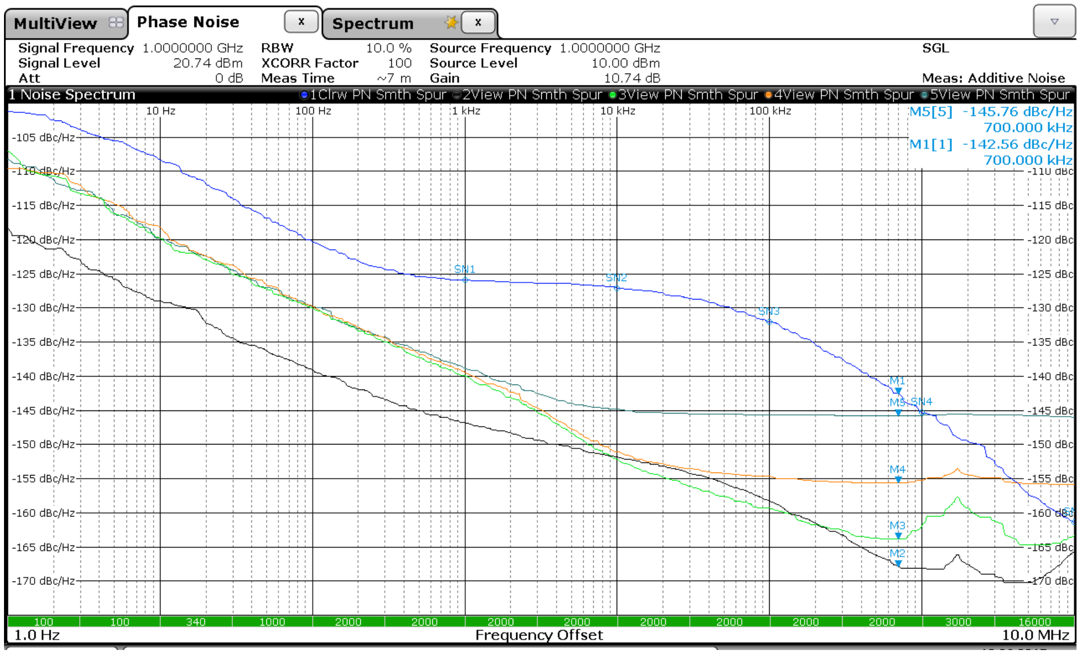


Fig. 3-6: Residual Phase Noise of Amplifier at Various Drive Levels

Figure 3-6 shows several residual phase noise measurements of the amplifier used previously described in Section 3.1 of this paper, but at various drive levels. Test results are summarized in Table 3-2

Trace	DUT Drive	BB Noise	Calc. NF	Notes
5 - Teal	-30 dBm	-145.7	1.3	Amplifier small-signal performance and noise floor
4 - Orange	-20 dBm	-155.77	1.2	Same as previous measurements
3 - Green	-10 dBm	-163.8	3.2	Notice as drive is increased the 1/f corner is moved out in frequency. Still 10 dB below compression.
2 - Black	0 dBm	-168	9	With additional drive, the 1/f corner moves further to the right and the 1/f noise is compressed. This is the 1-dB compression point for this amplifier
1 - Blue	+10 dBm	-142.6	44.4	This trace is 10 dB into compression. Notice the 1/f noise is greatly increased and the broadband noise increased, as compared to trace 4.

Table 3-2: Explanation of Test Results from Figure 3-6

As can be seen from Figure 3-6 and Table 3-2, our amplifier produces more noise as it starts to go into compression. Noise figure was calculated at each drive level to demonstrate the amplifier's characteristics in compression; however, the choice of offset frequency from the carrier (1 MHz) was only used as an example and may not be appropriate at the higher drive levels. These data demonstrate that noise figure does not tell the full story of amplifier behavior from an added noise standpoint as drive level is changed.

3.1.4 Residual Noise Measurement Considerations

- The source noise must be correlated at FSWP's mixer RF and LO inputs. This condition is automatically satisfied if using the internal signal source and must be satisfied when using an external signal generator with the external LO inputs
- Correlated phase noise at both the mixer input and LO input will cancel, improving measurement performance.
- When making low-noise measurements with an external source it is important to ensure that the source and any necessary amplifiers are placed before the power splitter to ensure that the noise added by the source and amplifier are correlated out of the measurement.
- When using an external signal generator (LO), the user must ensure that sufficient LO drive is provided to FSWP's front-panel LO input connectors (5 to 10 dBm, see *FSWP Phase Noise Analyzer Specifications*, reference 8 in the bibliography.) If an amplifier is necessary it should have sufficient gain to drive the DUT and the LO inputs. The amplifier should not be driven into compression to avoid non-linear behavior and generation of multiplicative noise. The amplifier should be selected based on required gain and low AM and broadband noise. Attenuators may also be required before or after the DUT to achieve proper power levels.
- When selecting a signal generator for use with FSWP's external LO inputs, the source should have good broadband noise characteristics because at large offset frequencies the source's broadband noise can decorrelate, when measuring components with large delays, resulting in poor source noise cancellation.
- Likewise, the external source's AM noise should be kept to a minimum to minimize AM to PM conversion in the DUT.
- When making residual noise measurements, cable lengths between the source and DUT and between the DUT and the analyzer's input must be kept as short as practicable. Also, use of semi-rigid cables is preferred to minimize phase changes caused by cable movement, vibrations, and temperature changes.
- When making low-level phase noise measurements it is often helpful to place the DUT on a sheet of soft foam rubber to isolate the DUT and cables from bench vibrations
- Avoid Radio Frequency Interference (RFI) by ensuring that all components of the measurement are well shielded, that all connectors are properly torqued, and that semi-rigid cable is used, where possible. Residual noise measurements are especially susceptible to RFI.
- When making analyzer noise floor measurements ensure that the input power to the analyzer is within 1 or 2 dB of the expected output power of the DUT.

3.2 High-Power Amplifier Residual Noise Measurements

The first consideration when making residual noise measurements of high-power devices with FSWP is to ensure that sufficient attenuation is provided between the output of the device and FSWP's input. In most cases, high-power attenuators or directional couplers will be used. The next point to consider is how much RF power will be required to drive the DUT into the proper operating region. If a booster amplifier will be required for the measurement, the use of an external signal generator and the FSWP external LO inputs may also be necessary.

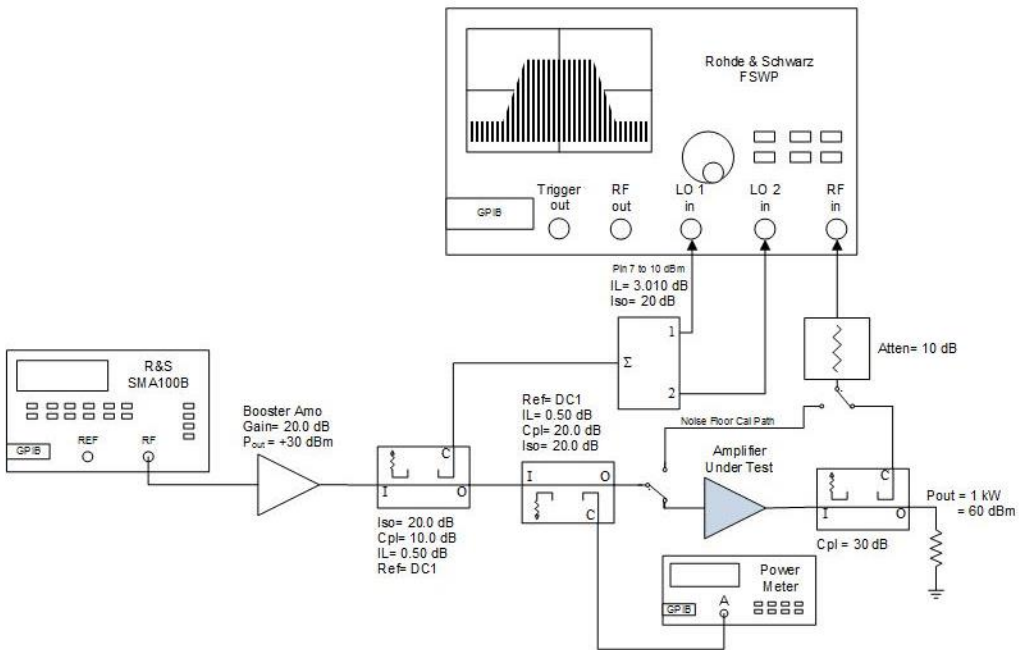


Fig. 3-7: Residual Noise Measurement Setup, Using an External Booster Amplifier

Figure 3-7 illustrates one possible way to measure the residual noise of a high-power amplifier using FSWP. For this example, the device to be tested is a high-power amplifier with a saturated output power of 1 kW and a gain of 30 dB. The amplifier requires 1 Watt of RF drive to achieve full rated power. For this measurement it was determined that an amplifier would be required to boost the signal generator's output power up to the +30 dBm level required to drive the DUT (however, signal generators such as the Rohde & Schwarz SMA100B are available with sufficient output power for this application.) Therefore, it is necessary to use the FSWP external LO inputs to facilitate cancellation of the signal generator and amplifier noise.

To invoke the additive noise measurement using the external LO inputs of FSWP the operator must select the external LO inputs by pressing the **[INPUT OUTPUT]** hard key and then pressing the **{Input Source Config}** soft key. From this menu, under the Local Oscillator heading press the **External** radio button, as shown in the Figure 3-8.

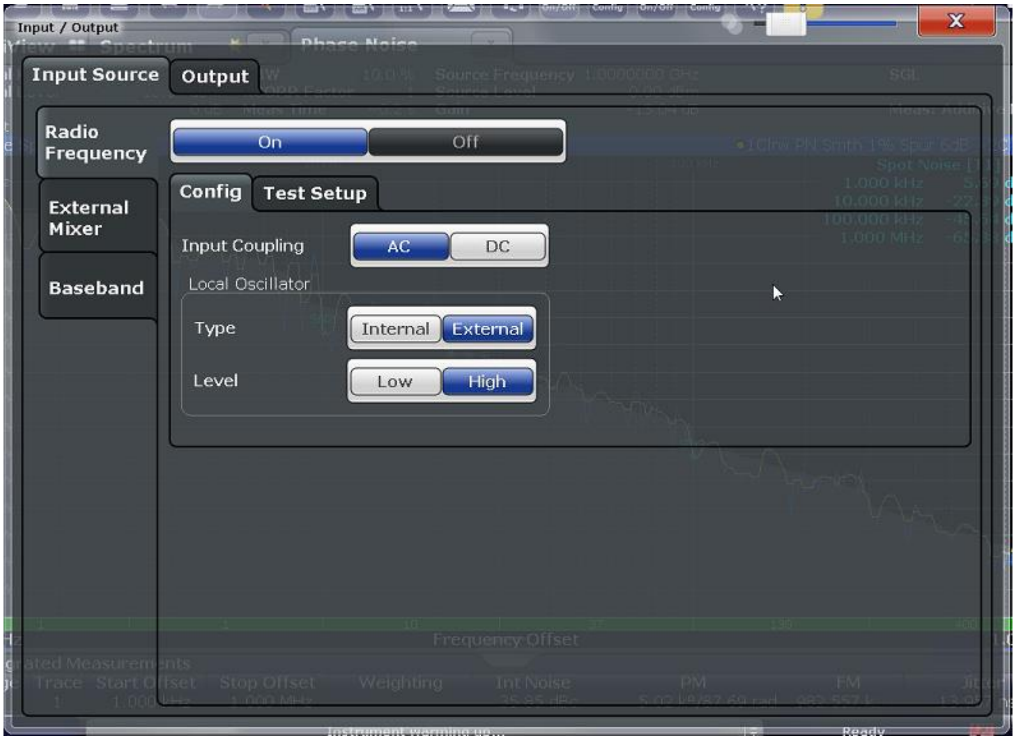


Fig. 3-8: FSWP External LO Control Setup

With this accomplished (refer to Figure 3-7), a 20 dB directional coupler was selected to reduce the DUT's input power down to +10 dBm. The coupled arm of the directional coupler is then connected to a power divider that provides +7 dBm of LO drive to the two FSWP LO input connectors. A 6-dB resistive power splitter could have been used; however, the 3-dB splitter offers superior port isolation and lower loss. The through arm of the directional coupler is then connected to a second directional coupler that is used to sample the input power to the DUT. This is critical to allow monitoring of the DUT input power to ensure the residual noise measurements are made at the correct operation point on the amplifier's compression curve. One additional component that could prove valuable on the input side of the DUT is a variable attenuator to allow adjustment the DUT drive level, while leaving the FSWP LO drive power constant.

The output of the DUT is connected to a 30 dB directional coupler and a dummy load. The coupler is necessary to reduce the DUT's output power down to a level that will not damage the FSWP (less than 1 Watt). The coupled arm of the coupler is routed to a 10 dB fixed attenuator, which reduces the input power to FSWP to +20 dBm.

Prior to making the phase noise measurement of the DUT the analyzer's noise floor using the external signal generator and booster amplifier should be determined. This can be accomplished by disconnecting the coupled arm of the DUT's output coupler and connecting the input of the 10 dB attenuator to the output of the DUT's input coupler, essentially bypassing the DUT. The test setup in Figure 3-7 provides a set of coaxial switches to facilitate the setup of the noise floor measurement. Notice that by using a DUT output coupler with a coupling factor that is equal to the DUT's gain the drive level to FSWP for the noise floor test will be the same as for the actual noise measurement (+20 dBm). With this setup the DUT's output is always terminated in its correct load impedance to prevent any damage to an expensive device.

Before leaving this subject it would be good to briefly discuss source noise cancellation using the external LO inputs of FSWP.

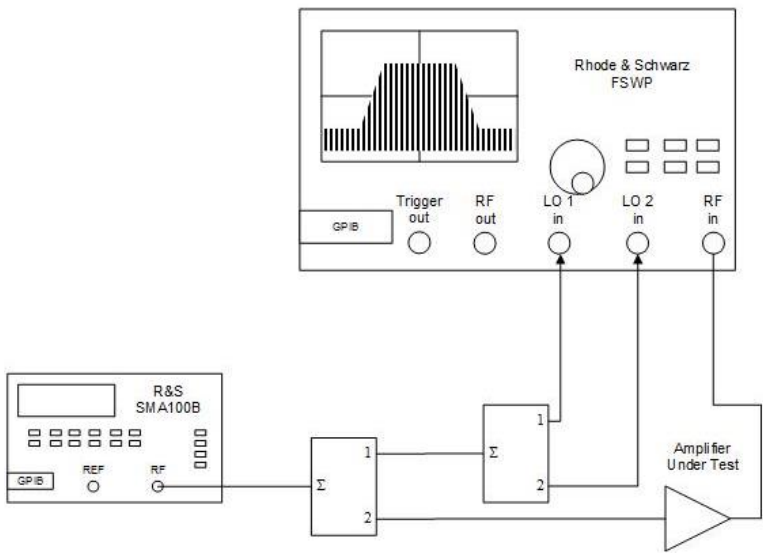


Fig. 3-9: Simple Two-Port Residual Noise Measurement, Using an External Source

Figure 3-9 shows a test configuration for a simple two-port residual noise measurement of a DUT, using an external signal generator as the test stimulus. Looking closely, one can see that this is a simplification of Figure 3-7 and could be used for DUTs with lower output power. To measure the residual noise floor for this configuration the DUT is simply replaced with a bypass cable and the noise floor is directly measured.

Fig. 3-10: FSWP Noise Floor Measurement, Using an External LO

Figure 3-10 shows an example of such a measurement. In this case, the test setup was as described above and in Figure 3-9 (the DUT in Figure 3-9 was replaced with a bypass cable). Prior to making the noise floor measurement an absolute phase noise measurement was made of the signal generator to be used as the signal source at a frequency of 10 GHz. Next the residual phase noise floor was measured to establish the quality of source noise cancellation. As shown in Figure 3-10, 30 to 50 dB of source noise cancellation was achieved, depending on offset frequency. This illustrates the importance of using a quality signal generator as the external LO. The better the phase noise and AM noise of the LO signal generator the better your measurement will be.

3.2.1 Residual Noise Measurements for Pulsed High-Power Devices

Two-port residual noise measurements for high-power pulsed devices are very similar to those described for CW devices in Section 3.2, above. The primary difference is setting up the pulse modulation. FSWP provides a dedicated measurement personality for pulsed additive noise measurements. The pulsed additive noise measurement is invoked by pressing the **Additive Noise** radio button from the **MEAS** menu, shown in Figure 2-4.

NOTE: For more information about pulsed carrier noise measurements please refer to Bibliography item Number 8.

Generally, for pulsed residual noise measurements, particularly for high power devices, an external signal generator will be required. An external signal generator will usually provide improved control of the pulse signal to include pulse shape, rise time, fall time, and pulse delay relative to an external trigger. Trigger delay control is important to allow the RF drive pulse for the DUT to be properly positioned within the DUT's bias pulse. A typical example might be a traveling wave tube amplifier (TWTA). In many cases, pulsed TWTAs will require a pulse modulated power supply to properly bias the tube. The bias pulse can be 50 to 100 per-cent wider than the RF pulse applied to the tube's helix.

For many pulsed residual noise measurements use of an oscilloscope will be necessary to simultaneously view the bias pulse and the RF drive pulse. While viewing the oscilloscope, the RF signal generator's pulse delay function is adjusted to center the RF drive pulse within the bias pulse.

3.3 Measurement of Frequency Converters

Measurement of residual or additive noise of a frequency converter is similar to that of an amplifier, as discussed previously. The primary difference is that the input frequency and output frequency of the converter are different. For FSWP to make a proper phase noise measurement the FSWP mixer’s LO and RF input frequencies must be the same, requiring the use of multiple converters. The subject of frequency converters can be rather broad and the differences between various converter types can mandate different measurement techniques. The following list of converter types is a starting point for discussion of converter residual noise measurement techniques.

- Multipliers
- Dividers
- Mixers
- Block converters, and
- Direct Digital Synthesizers (DDS).

As in the case of residual noise measurements for amplifiers, FSWP's internal signal source can be used in a stand-alone mode for residual noise measurements of some classes of frequency converters while other frequency measurements will benefit by using FSWP's external LO inputs with either the internal source or the external signal generator.

3.3.1 Residual Noise Measurements for Block Frequency Converters

Generally, block frequency converters utilize an embedded LO for use with a mixer and filters to perform the frequency conversion. In some cases, the LO may be free running, but in most cases an external input is provided to allow the LO to be frequency locked with an external reference, generally 10 MHz. In most cases the phase noise of a block frequency converter will be dominated by the phase noise of the internal local oscillator, which may moderately high.

When the phase noise of the block converter is dominated by its internal LO, the simplest approach to making a residual noise measurement is to actually make an absolute phase noise measurement of the converter's output, using a stimulus signal whose phase noise is much lower that of the converter's own LO. This can easily be accomplished by connecting the DUT to FSWP as shown in Figure 3-11. FSWP's phase noise measurement personality allows the operator to use the internal source tuned to the converter's input frequency. In this configuration the receiver will automatically acquire the converter's output signal and measure the phase noise. This approach works quite well for up converters with an input frequency less than 18 GHz and for many down converters, within the frequency range of FSWP.

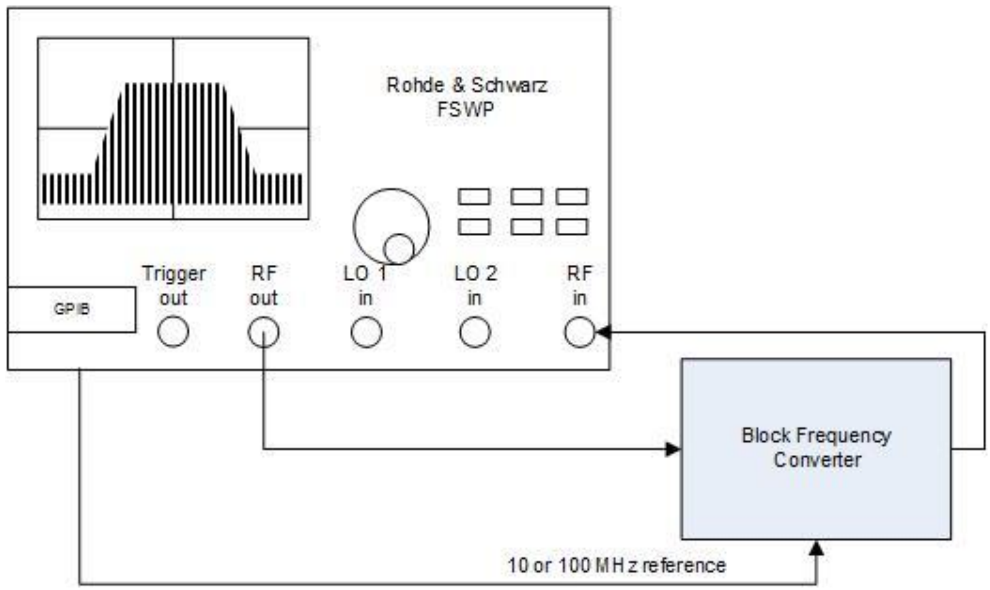


Fig. 3-11: Phase Noise Measurement Setup for a Block Frequency Converter

Figure 3-11 shows a simple method for measuring the total phase noise of frequency converters whose phase noise is dominated by an internal LO and the converter's phase noise is not particularly challenging to measure. In this case, the FSWP source is tuned to the converter’s input frequency and the receiver is tuned to the converter’s output frequency. This is not a true residual phase noise measurement, but an absolute phase noise measurement of the converter’s total noise including:

- The noise generated by the FSWP internal source
- The phase noise of the converter’s internal LO, and
- The residual phase noise of the converters mixers and amplifiers.

Since FSWP’s internal signal source is derived from one of the channel LOs the source noise and its contribution to the DUT’s total noise is no longer uncorrelated between channels 1 and 2 and cross correlation no longer provides any advantage.   Therefore, crosscorrelation is turned off and an orange warning banner is displayed at the bottom of the phase noise measurement.

As an example of this type of simple total noise measurement, consider the Ku-Band satellite up converter described below. The converter's manufacturer provides the following specifications:

Parameter	Specification
Input Frequency	950 to 1450 MHz
Output Frequency	14 to 14.5 GHz
Embedded LO Frequency	13.05 GHz
Noise Figure	15 dB
Gain	26 dB
Power Output at 1 dB compression	+13 dBm
LO Phase Noise @ 10 Hz	-45 dBc/Hz
LO Phase Noise @ 100 Hz	-67 dBc/Hz
LO Phase Noise @ 1 kHz	-77 dBc/Hz
LO Phase Noise @ 10 kHz	-87 dBc/Hz
LO Phase Noise @ 100 kHz	-97 dBc/Hz
LO Phase Noise @ 1 MHz	-97 dBc/Hz

Table 3-3: Ku-Band Satellite Up Converter Specifications

For the above up converter an absolute phase noise measurement was set up as follows:

1. FSWP's internal power supplies were set up to power the converter and provide necessary control voltages
2. The FSWP internal source was set to 1.2 GHz with an output power of -10 dBm
3. The output of the DUT was measured with FSWP's spectrum analyzer (Option B1) and output frequency was verified to be 14.25 GHz at a level of +10 dBm
4. With the DUT operation successfully verified the FSWP internal source was set to DUT bypass with a signal level of +10 dBm to match the DUT output level as measured in Step 3, above.
5. Next the phase noise of the internal source was measured to establish FSWP's source contribution to the total noise at the output of the DUT and the results were saved to trace 3
6. In preparation for the DUT phase noise measurement, the FSWP internal source output level was reduced to -10 dBm (see Step 2) and the DUT bypass was turned off.
7. Finally, the **[RUN SINGLE]** hard was pressed to start the measurement

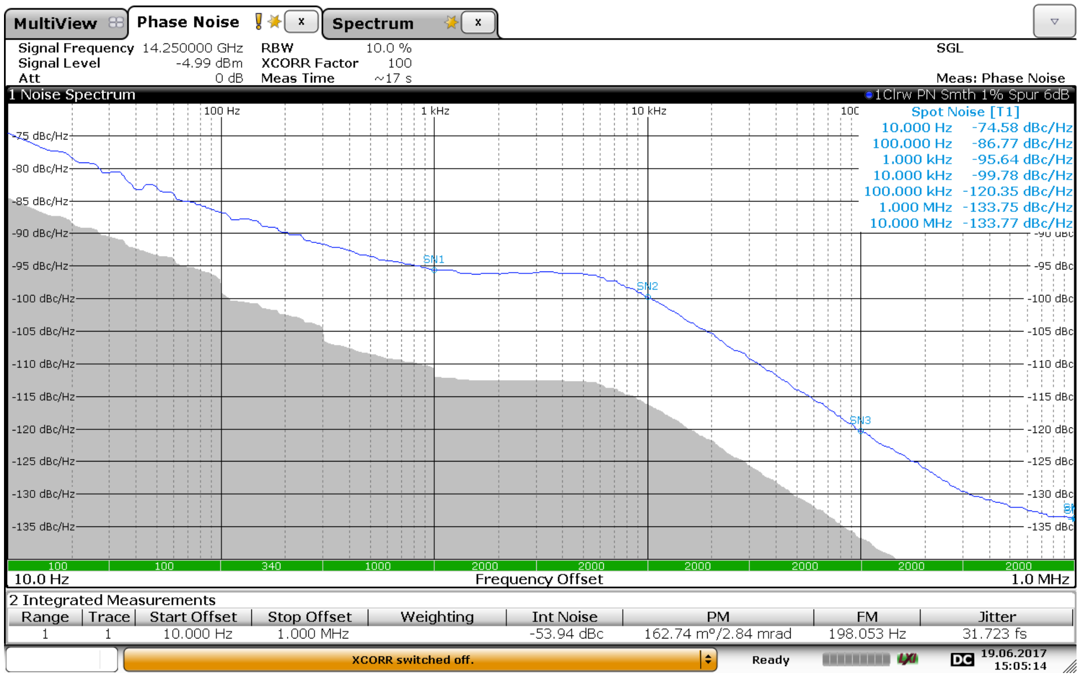


Fig. 3-12: Phase Noise of a Ku-Band Satellite up Converter

The total phase noise for our satellite up converter, as shown in Figure 3-12 is the sum of the stimulus signal (from FSWP's internal source) plus the converter's own LO noise and any other residual noise generated in the converter. Referring to table 3-3 and Figure 3-12 it is apparent that the total phase noise of the converter is much lower than the worst case LO noise specification in the manufacturer's data sheet for the converter.

Again, this is a simplified measurement that may only be useful on some frequency converters with an embedded LO that is much noisier than FSWP's internal signal source and higher than FSWP's noise floor for this configuration (See FSWP data sheet for specifications). This same technique is also useful for measuring frequency dividers and some frequency multipliers. A more rigorous method of frequency converter residual noise measurements will be presented in upcoming sections of this paper.

3.3.2 The Two Converter Method

As mentioned in Section 3.3 one of the problems with making a residual noise measurement of frequency converters is that the input and output frequencies are different. One method of getting around this problem is to measure two converters together. The concept is that two converters are driven by the same source. If the converters are assumed to be identical they would have the same output frequency and the same additive phase noise; therefore, one converter could supply the input signal to the analyzer and the other could supply the LO. In this case, the noise of the two converters would add and the analyzer would measure a noise spectrum 3 dB higher than that of each individual converter. An approximation of the actual phase noise can be obtained by simply subtracting 3 dB from the phase noise trace, using the trace-offset control in the analyzer **[TRACE]** menu.

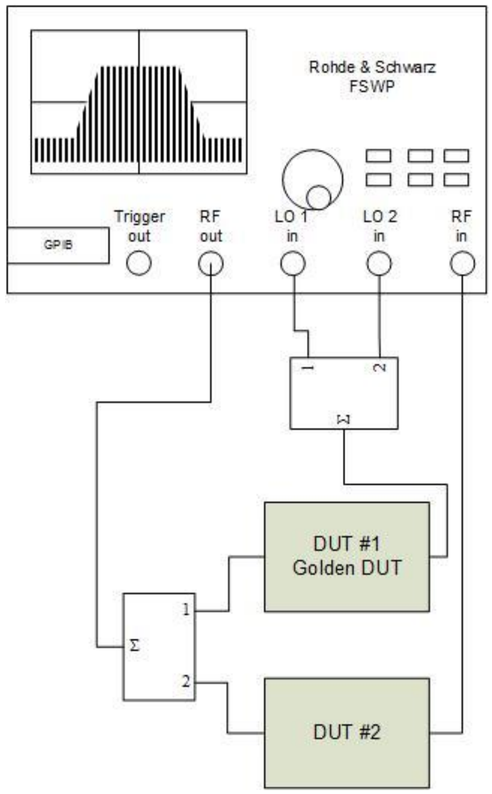


Fig. 3-13: Setup for Two-Converter Method

Figure 3-13 shows the basic test setup for making a two-converter residual noise measurement using the FSWP internal source as the stimulus for both converters. If desired, an external signal generator could also be used. The important thing to remember for this measurement is to provide the proper LO drive levels to FSWP's external LO ports, as described in Section 3.2 when measuring amplifiers using an external LO

Since the signal generator noise (internal or external) is correlated for both the RF and LO ports of FSWP's mixers the source noise will cancel.

The problem with the two-converter method, as mentioned above, is that we are measuring the combined noise of the two converters and we can only assume that one of the converters is 3 dB better than the total measured noise, but we do not know which one. The traditional technique for getting around this problem is to measure three converters against each other in three separate measurements and then solve for the noise of each converter using a set of three simultaneous equations in three unknowns. FSWP provides a greatly simplified method for determining the actual noise of the converter under test, as shown in the next section.

3.3.3 The Three-Converter Method

As mentioned in the previous section, the two-converter method has the disadvantage that the two converters used for the measurement must be identical and that once the measurement is completed the user only knows that the measured noise of one of the two converters is 3 dB lower than the total measured noise. This problem is solved by using the three-converter method.

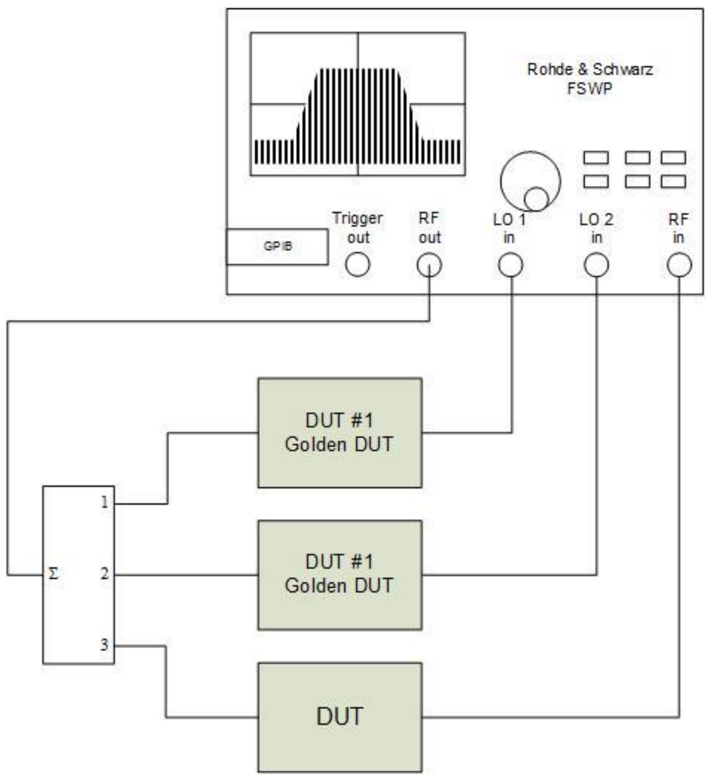


Fig. 3-14: Setup for the Three-Converter Method

The three-converter method uses three frequency converters to provide the RF input for FSWP and its two LO inputs. All three converters are driven by the same source (internal or external) and therefore the source noise is correlated on both the LO and RF input ports of each mixer and is therefore cancelled. With the two LO inputs being supplied by two independent frequency converters the phase noise of these two converters in uncorrelated with each other and that of the DUT. Therefore, the only signal that is correlated in the two measurement channels of FSWP is that of the DUT. With this configuration the noise of the two converters supplying the LO signal is uncorrelated and is cancelled through cross correlation leaving only the noise of the DUT. The three-converter method greatly improves the uncertainty of frequency converter measurements at the expense of requiring a third converter.

Another important class of frequency converter residual noise measurement is that of a block frequency converter that uses and external LO or the case of the residual noise of a mixer. Again, the three-converter method is the best method for measuring the residual noise of these devices.

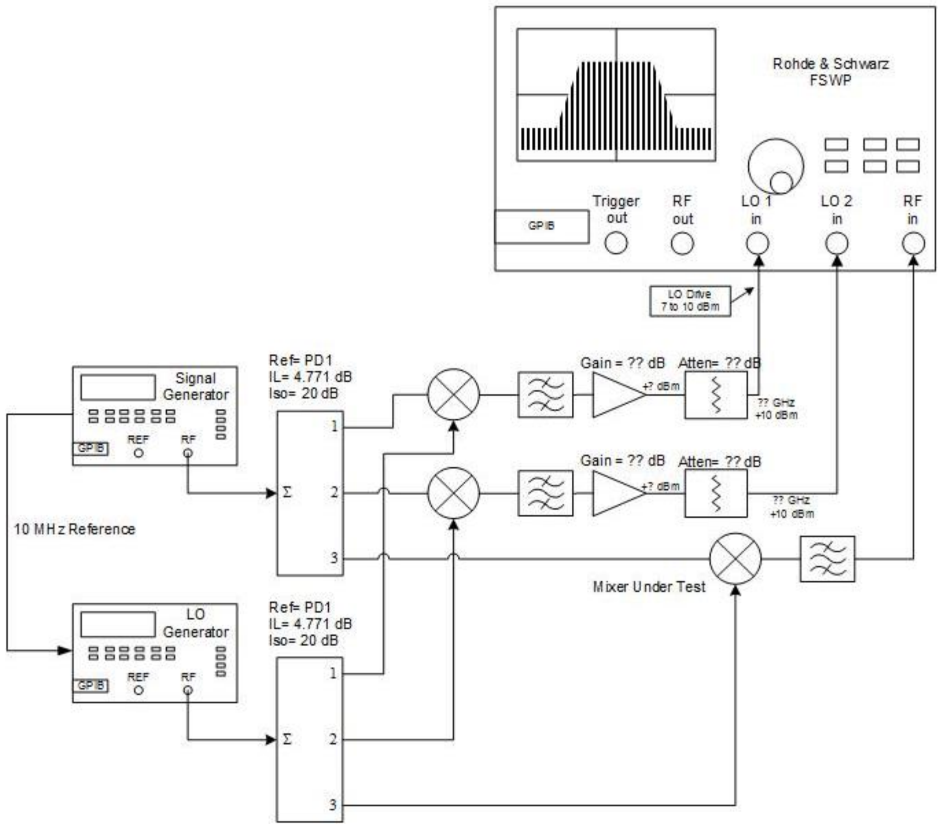


Fig. 3-15: Three-Converter Residual Noise Setup Using a Shared LO

Quite often, it is necessary to measure the residual noise of a frequency converter that uses an external LO. This can be accomplished by using two signal generators, where one provides the RF input and the second generator supplies the LO signal for the mixer (or converter) under test. Figure 3-15 shows a three-converter setup where external signal generators are used for both the RF and LO inputs to the converters. If desired, FSWP's internal signal source could be used to replace one of these signal generators. As with other examples using FSWP's external LO inputs, it is important to provide the required LO drive levels to the FSWP LO inputs. It should be noted that the signal generator's noise is common mode on both the LO and RF ports of FSWP's internal mixers and therefore cancels. Also, the noise generated in the two mixers and amplifiers that are used to drive the LO inputs is uncorrelated between FSWP Channel 1 and Channel 2 and therefore will be cancelled by cross correlation.

3.4 Measurement of Binary Frequency Dividers

Residual noise measurements for binary frequency dividers and some multipliers can be made using the same setup that was described in Section 3.3.1 for block frequency converters. Referring back to figure 2-5, note that there are a set of binary dividers and multipliers immediately preceding FSWP’s LO inputs for the I/Q mixers. These dividers and multipliers are provided to generate LO signals for the mixers when the source and receiver frequencies of FSWP are set to binary multiples of each other, allowing phase noise measurements for external multipliers and dividers. For these measurements, it is only necessary to refer to the FSWP data sheet and determine FSWP's noise floor at the output frequency of the divider. The user should ensure that the measured phase noise is well above the instrument's specified noise floor.

3.5 Measurement of Comb Frequency Multipliers

Since a comb generator can be a frequency-converting device, the two or three converter method is recommended for this measurement, with the three-converter method being preferred. The basic concept of the comb generator is that it produces a frequency line at each multiple of the input frequency, where:

$$F_{out} = \sum_{n=1}^{n=m} F_{in} \cdot n$$

When measuring the residual noise of a comb generator only one comb line can be measured at a time. Therefore, band-pass filters are required to isolate the one frequency line of interest. In addition to the requirement for filtering, the following points should be considered:

- Most comb generators, including devices like step recovery diodes (SRD) and non-linear transmission lines (NRTL), are vulnerable to AM to PM conversion; therefore, it is important to use a source with very low AM noise
- Comb generators are also sensitive to output match. Since a band-pass filter will be required following the comb generator, an isolator will also probably be necessary between the comb generator and the filter to minimize the filter's out of band reflections
- Most comb generators require high drive power. An amplifier may be required to achieve sufficiently drive level
- Comb generators also exhibit high loss, particularly when using the higher frequency comb lines. To that end, an amplifier following the comb generator may be required to drive the FSWP external LO inputs.

As an example, consider a three-converter measurement of a comb generator with a 600 MHz input frequency and a 9.6 GHz output frequency (16th harmonic).

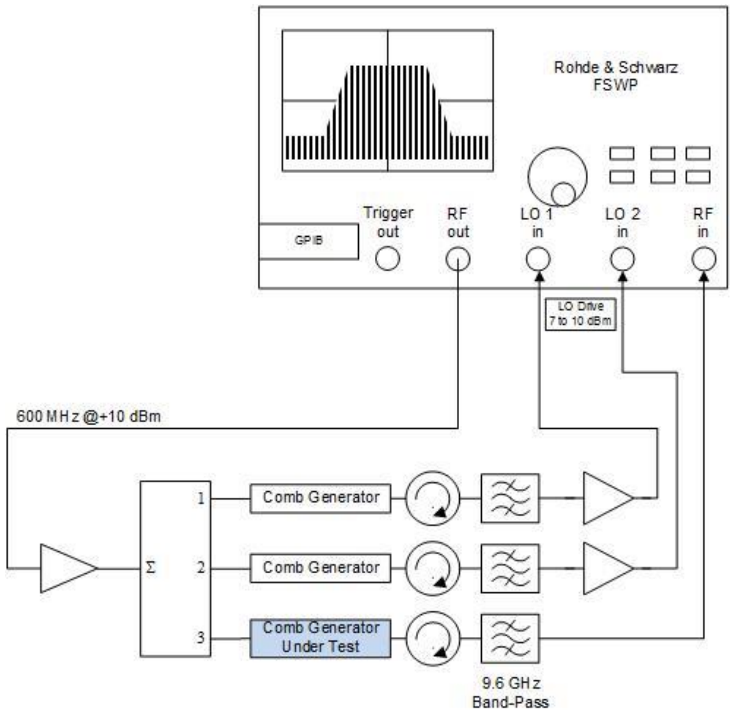


Fig. 3-16: Residual Noise Setup for a Comb Generator

Figure 3-16 shows a residual noise test setup for a comb generator, using the three-converter method. The following considerations apply to this measurement:

- The internal signal source of the FSWP provides the stimulus signal for this measurement. The source output is amplified to the +30 dBm level to provide approximately +25 dBm of drive for each of the three comb generators
- The two comb generators that are driving the FSWP LO inputs are amplified to achieve the desired FSWP LO drive level by two low-noise amplifiers. The additive noise produced by these amplifiers should be verified to ensure it does not influence the final phase noise measurement; however, most of this noise will be cancelled through cross correlation.
- An isolator follows each comb generator to improve the comb generator's load match preventing parametric oscillations, which would spoil the phase noise measurement.
- Finally, a 9.6 GHz band-pass filter removes all of the unwanted frequency lines in the output spectrum of the comb generator ensuring that FSWP only processes the frequency line of interest, in this case 9.6 GHz
- Since the three-converter method was used, the phase noise measured is that of the DUT connected to FSWP's RF input. If the two-converter method was used 3 dB will need to be subtracted from the measured phase noise, assuming both devices have identical phase noise.

- To get an idea of the noise contributed by the comb generator, in excess of that of a perfect multiplier, make an absolute phase noise measurement of the signal source and scale the phase noise in frequency by 20·Log(n), where n is the frequency multiplier (in this case 16). The measured phase noise of the comb generator can now be compared to the theoretical performance of a perfect multiplier.

3.6 Residual Phase Noise of a DDS

The direct digital synthesizer or DDS is a frequency synthesizer that is used for creating arbitrary waveforms from a single fixed clock signal. DDSs are key components in radar and communications system and their phase noise is therefore a critical system-level specification. The residual phase noise of the DDS is the DDS noise minus the effects of the clock oscillator.

For the DDS residual noise measurement the two or three-converter methods are both satisfactory based on expected phase noise. However, the three-converter method provides better performance due to the advantages of cross correlation.

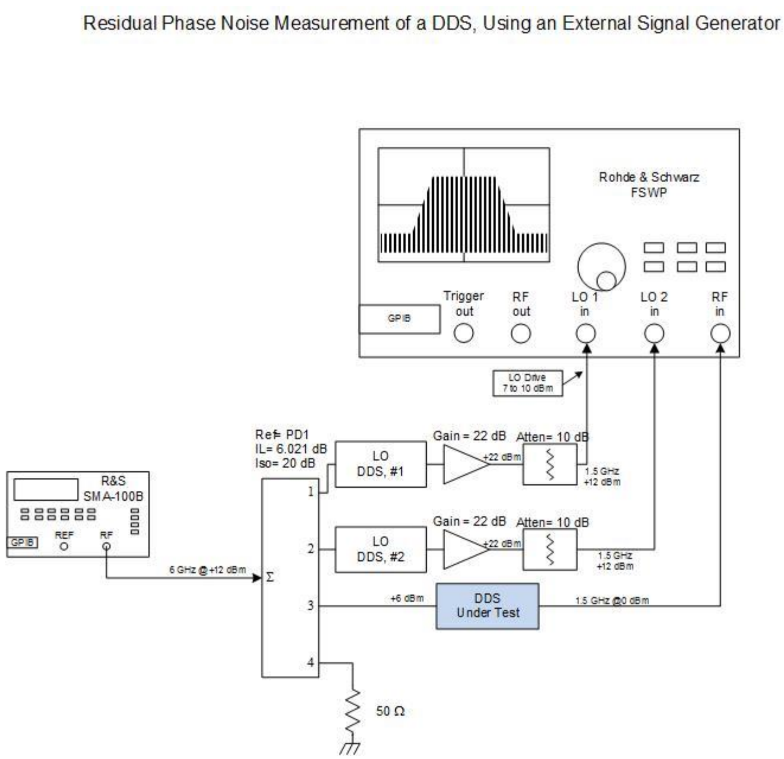


Fig. 3-17: Residual Noise Measurement Setup for a DDS

Figure 3-17 shows a three-converter measurement setup for measuring the residual noise of a DDS. The following considerations apply to this setup:

- Either the two-converter method or three-converter method are required for this as in other frequency converter residual noise measurements. The three-converter method was chosen for this measurement to allow cross correlation to minimize the noise generated by the DDSs that were used to provide FSWP's LO signals.
- The noise produced by the signal generator is common mode to the RF and LO inputs of FSWP's mixers and is therefore cancelled
- For this setup, a signal generator (R&S SMA100B) was used as a 6 GHz clock signal for the DDS. A four-way power divider (due to lack of a three-way) delivered approximately +6 dBm of drive level to each of three DDSs.
- Since the DDS had insufficient output power to drive FSWP's LO inputs, an amplifier was used to boost the power with an attenuator to reduce the amplified signal to the proper level
- All three of the DDSs were configured to produce a 1.5 GHz output signal. This signal was used for both FSWP LO inputs and the RF input.

Fig. 3-18: Phase Noise Measurement of a DDS

Figure 3-18 shows the measurement results for the DDS phase noise measurement. The spot-noise table lists the phase noise at the cardinal offset frequencies for the yellow trace. The green trace, showing the phase noise hump near the 10 MHz offset frequency, was made using a small packaged oscillator; whereas, the yellow trace was made using a Rohde & Schwarz SMA100B signal generator as the source. The hump in the green trace is the result of high AM noise from the test oscillator, showing the need for using test signals with low AM and broadband noise.

3.7 Residual Noise Measurement of Frequency Synthesizers

Frequency synthesizers are important building blocks for many radar and communications systems. The idea of residual phase noise of a synthesizer is to measure the phase noise of the synthesizer's PLL excluding the contribution of the reference section of the synthesizer. Knowing the residual noise of a synthesizer is important for synthesizer designers that are trying to optimize a design or for system engineers that want to know how a synthesizer in their design will affect overall system phase noise assuming that they employ a system clock that acts as a reference for several system blocks. Lastly, one important synthesizer residual noise measurement is for calibration laboratories where the residual phase noise of off-the-shelf signal generators must be verified, as part of the instrument's calibration process.

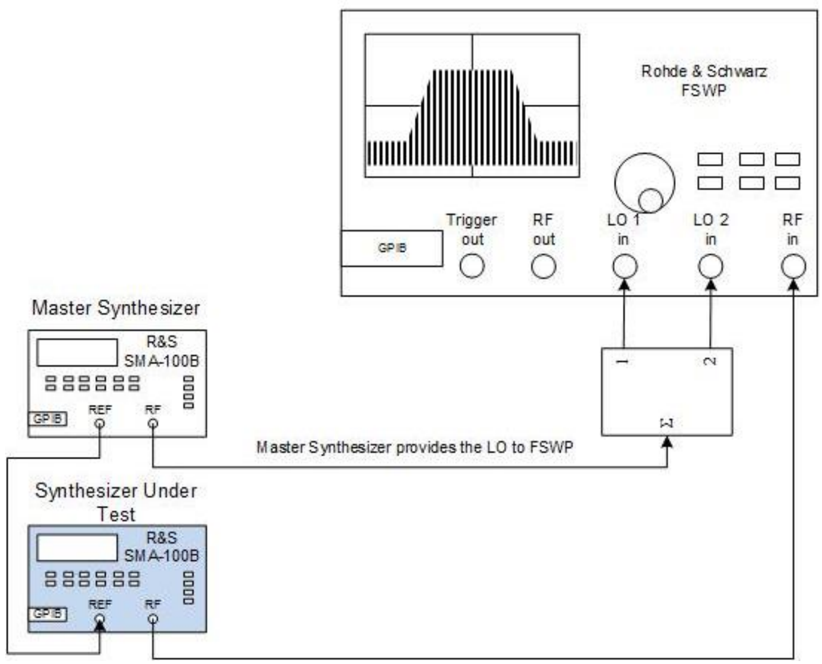


Fig. 3-19: Setup for measuring the Residual Noise of a Frequency Synthesizer

The following conditions apply for the synthesizer residual noise measurement shown in Figure 3-19:

- The two-converter method was used for this measurement.
- The two synthesizers are assumed to be identical. If this is not a valid assumption, the three-converter method must then be used.
- The measured noise is the sum of the two synthesizers shown in Figure 3-19; therefore, 3 dB must be subtracted from the measurement results.

- The master synthesizer provides the LO signals for FSWP. Additionally, the master synthesizer provides the reference clock to the synthesizer under test. Therefore, the reference clock's noise is common mode to both the RF and LO inputs of FSWP's mixers and is cancelled, leaving only the noise generated by the remaining sections of the synthesizer under test.
- Both synthesizers must be set to the same frequency.

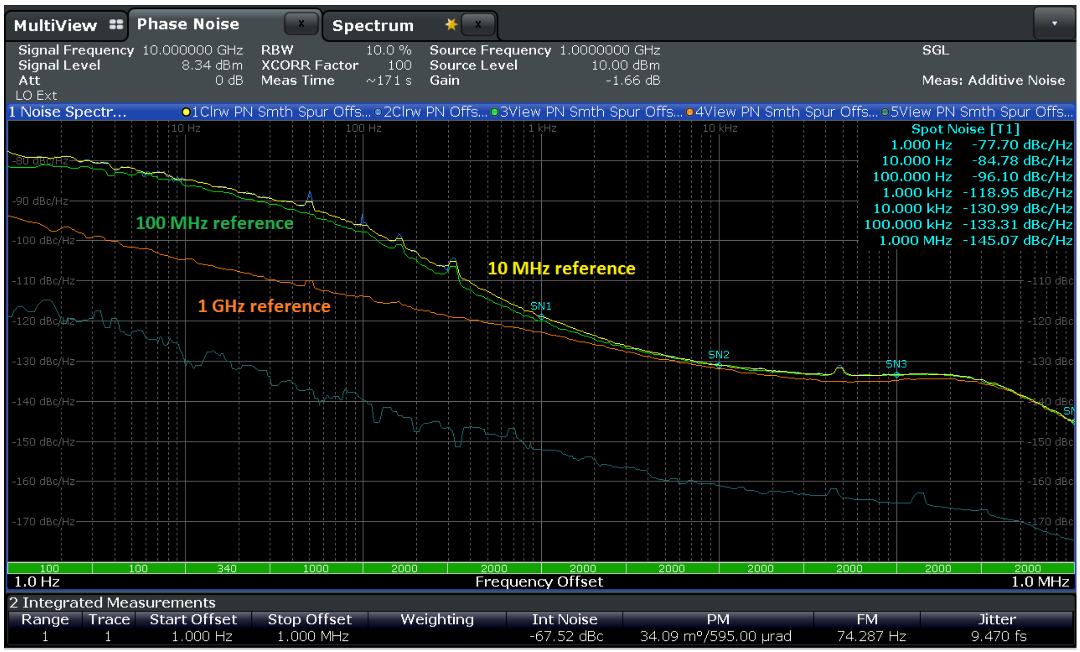


Fig. 3-20: Residual Phase Noise of R&S SMA100 Signal Generator

Figure 3-20 shows the measured phase noise of two R&S SMA100B signal generators. The SMA100B has three reference inputs: 10 MHz, 100MHz, and 1 GHz. Each of these references can be shared with other generators or can be connected to customer house references.

Measurement conditions:

- For the above measurement, both of the signal generators were tuned to 10 GHz
- The measurement noise floor was established by inserting a power splitter at the output of master synthesizer and connecting one of the outputs to the FSWP's input and the other to the LO splitter. Then a normal residual phase noise measurement was made and saved to the cyan trace.
- Three separate phase noise measurements were made with each of the three references (10 MHz, 100 MHz, and 1 GHz) inter-connected between the two signal generators. The results of these measurements were saved on one screen to allow comparison.

3.8 Extending Residual Noise Measurements above 18 GHz

As described in Section 2.1, FSWP's internal source and external LO connectors are limited to a frequency range of 10 MHz through 18 GHz. This frequency range can be extended above 18 GHz by using external mixers. One example is the Marki Microwave MLIQ-1845L. The Marki MLIQ-1845L is a connectorized 18 to 45 GHz double-balanced I/Q mixer. When used with FSWP, the mixer's I/Q outputs are connected to FSWP's baseband inputs.

The simplest measurement setup, when using the Marki mixer, is for a residual noise measurement of a small-signal amplifier. For this measurement the output of an external signal source is split with one splitter path providing the LO signal for the mixer and the remaining splitter path driving the DUT, whose output is connected to the mixer's RF port.

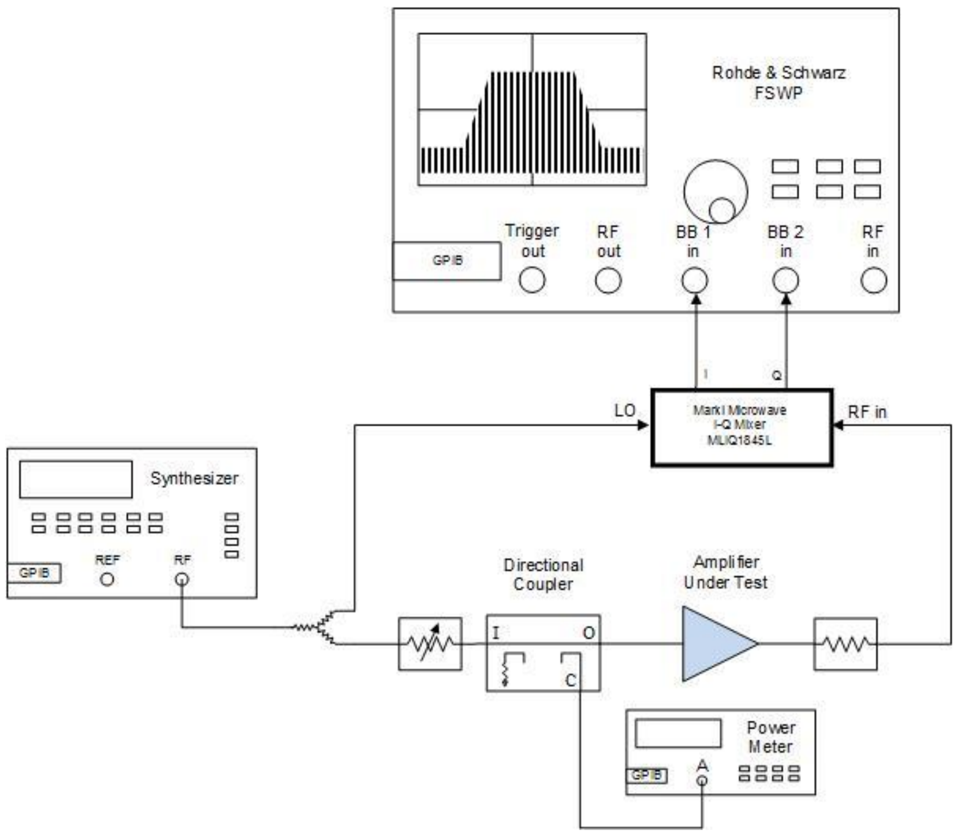


Fig. 3-21: Amplifier Residual Noise Setup Using a Marki MLIQ-1845L Mixer

Test Conditions, for Figure 3-21:

- For the measurement shown in Figure 3-12, a Marki Microwave MLIQ-1845L double-balanced I/Q mixer was used to convert the amplifier's output down to base band
- The signal generator's output is split to drive the DUT and the mixer's LO input, with the DUT's output driving the mixer's RF input port

- The signal generator was tuned to 25 GHz and the generator's output level was adjusted to achieve the correct LO drive for the mixer
- The attenuator at the DUT's input was adjusted to achieve the correct DUT drive level
- A power meter is included to allow monitoring of the DUT drive level
- The attenuator on the DUT's output was selected to prevent overdrive of the mixer.

FSWP's external mixer configuration menu is accessed by pressing the **[INPUT / OUTPUT]** hard key and selecting the **{Base Band}** tab, while in the Additive Phase Mode, as shown below:

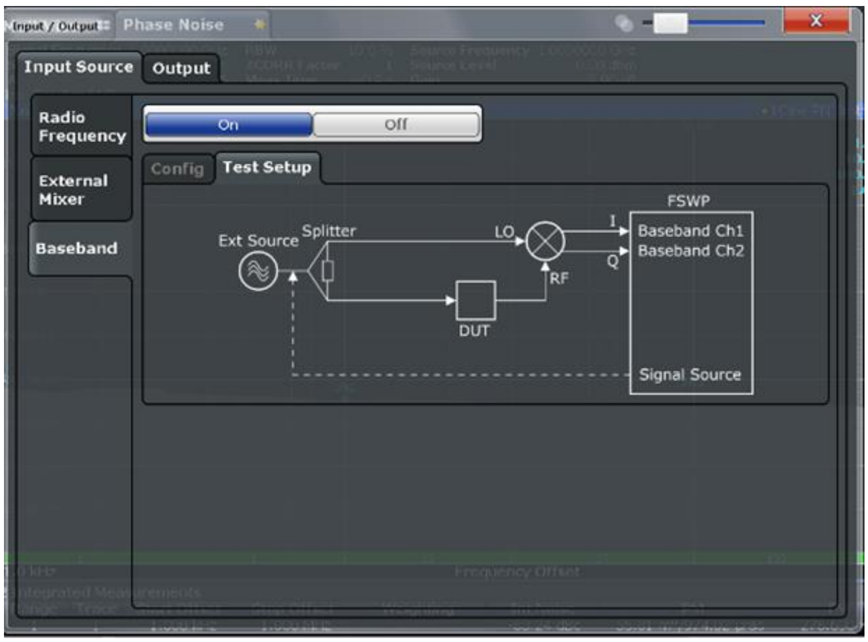


Fig. 3-22: FSWP External Mixer Menu

3.8.1 Using an External Mixer for Frequency Converter Measurements.

The Marki Mixer described in Section 3.8 may also be used for residual phase noise measurements of frequency converters, using the two-converter method.

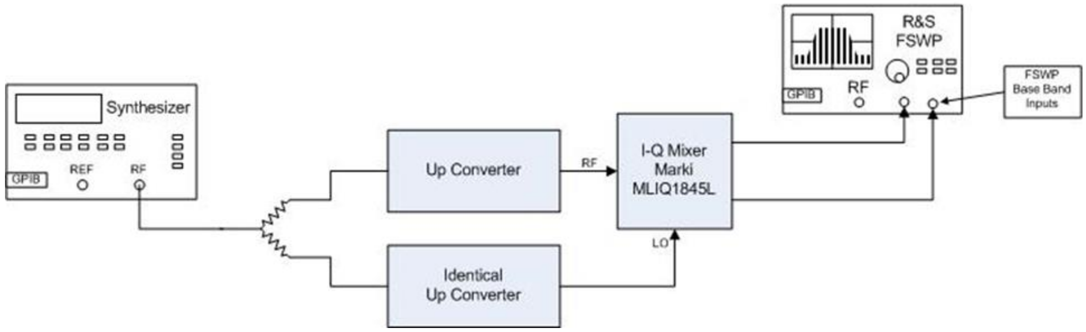


Fig. 3-23: Frequency Converter Residual Phase Noise, Using an External Mixer

Figure 3-23 shows the connection diagram when using the Marki MLIQ1845L mixer for residual phase noise measurements of frequency converters. The considerations for a two-converter measurement also apply when using an external mixer. The following items should also be considered:

- As with other two-converter measurements, the converters should be identical and the measurement result will be the sum of the noise produced by both converters; therefore, 3 dB should be subtracted from the measurement
- Attenuators and or amplifiers may be necessary to achieve proper mixer LO and RF port drive levels
- Measurement noise floor can be established by connecting the output of the source splitter directly to the mixer's LO and RF ports, with appropriate attenuation to provide the same signal levels that will be used for the final measurement
- Other mixers may be selected to cover different frequency ranges.

4 Conclusions

Although noise figure is one of the most common specifications for amplifiers and frequency converters, it does not represent the true added noise of the device under anything but small-signal conditions and is an average of the noise in carrier offsets within a 4 MHz bandwidth. If you want to measure the added noise of a device, using noisy power supplies or in compression, noise figure will reveal little regarding the device performance. In addition, noise figure does not provide any information about the noise close to the carrier, which may be of vital importance in many RF systems, such as, digital radios and radar systems.

A residual phase noise measurement:

- Provides detailed information pertaining to the additive noise of a two-port device over a wide range of offset frequencies from the carrier
- Provides an understanding of the device noise performance over a broad range of input power, from small signal to deep compression
- Can define large-signal noise figure.

In the past, residual phase noise measurements have been considered too difficult and time consuming and have generally been avoided for this reason. Today, FSWP simplifies residual noise measurements to the point that there is no longer an excuse for not measuring residual noise (both AM and PM) of two-port devices.

5 Bibliography

[1] **Frequency, IEEE Standards Coordinating Committee 27 on Time and.** *IEEE Standard 1139, Definitions of Physical Quantities for Fundamental Time and Frequency.* New York, New York : IEEE, 2009.

[2] *Phase Noise and AM Noise Measurements in the Frequency Domain.* **Algie L Lance, Wendell D Seal, and Frederik Labaar.** Redondo Beach, California, USA : Milimeter Waves, 1984. Vol 11, Page 239-289.

[3] **Rohde & Schwarz.** R&S FSWP Phase Noise Analyzer and VCO Tester, Product Brochure. Munich Germany : Rohde & Schwarz, 2017.

[4] *A 1 MHz to 50 GHz Direct Down-Conversion Phase Noise Analyzer with Cross-Correlation.* **Feldhaus, Gregor and Roth, Alexander.** York, UK : IEEE, April 2016. European Frequency and Time Forum (EFTE), 2016.

[5] *A Collapse of the Cross-Spectral Function in Phase Noise Metrology.* **Nelson, C.W., Hati, A. and Howe, D.A.** Boulder, Colorado 80305, USA : National Institute of Standards and Technology, 2014.

[6] *FSWP Phase Noise Analyzer Specifications.* **Rohde & Schwarz.** 4 Dec 2016, Munich : s.n., 2016. FSWP_dat-sw_en_3607-2090-22_v0500.

[7] *Pulse Phase Noise Application Note.* **Rohde & Schwarz.** Munich : Rohde & Schwarz, 2016. 5.2016-1EF94_01E.

[8] **Breitbarth, Jason and Koebel, Joe.** Additive (Residual) Phase Noise Measurement of Amplifiers, Frequency Dividers and ... *Microwave Journal.* 2008, 16 June 2008.

[9] *Noise Figure vs. PM Noise Measurements: A Study at Microwave Frequencies.* **A. Hati, D.A. Howe, F.L. Walls, and D. Walker.** 2003. Proceedings of the 2003 International Frequency and Control Symposium.

6 Ordering Information

Designation	Type	Order No.
Phase Noise Analyzer, 1 MHz to 8 GHz	R&S®FSWP8	1322.8003.08
Phase Noise Analyzer, 1 MHz to 26.5 GHz	R&S®FSWP26	1322.8003.26
Phase Noise Analyzer, 1 MHz to 50 GHz	R&S®FSWP50	1322.8003.50

Options

Designation	Type	Order No.	Retrofit-table	Remarks
Cross-Correlation, 8 GHz	R&S®FSWP-B60	1322.9800.08	yes	for R&S®FSWP8; contact service center
Cross-Correlation, 26 GHz	R&S®FSWP-B60	1322.9800.26	yes	for R&S®FSWP26; retrofittable in factory
Cross-Correlation, 50 GHz	R&S®FSWP-B60	1322.9800.50	yes	for R&S®FSWP50; retrofittable in factory
Cross-Correlation (low phase noise), 8 GHz	R&S®FSWP-B61	1325.3719.08	yes	for R&S®FSWP8; contact service center includes R&S®FSWP-B4
Cross-Correlation (low phase noise), 26 GHz	R&S®FSWP-B61	1325.3719.26	yes	for R&S®FSWP26; retrofittable in factory includes R&S®FSWP-B4
Cross-Correlation (low phase noise), 50 GHz	R&S®FSWP-B61	1325.3719.50	yes	for R&S®FSWP50; retrofittable in factory includes R&S®FSWP-B4
Additive Phase Noise Measurements	R&S®FSWP-B64	1322.9900.26	yes	frequency range 10 MHz to 8 GHz for R&S®FSWP8, 10 MHz to 18 GHz for R&S®FSWP26 and R&S®FSWP50; R&S®FSWP-B60 or B61 op-tion required; contact service center
High Stability OCXO	R&S®FSWP-B4	1325.3890.02	yes	user-retrofittable
Spectrum Analyzer, 10 Hz to 8 GHz	R&S®FSWP-B1	1322.9997.08	yes	for R&S®FSWP8; retrofittable in factory
Spectrum Analyzer, 10 Hz to 26 GHz	R&S®FSWP-B1	1322.9997.26	yes	for R&S®FSWP26; retrofittable in factory

Designation	Type	Order No.	Retrofit-table	Remarks
Spectrum Analyzer, 10 Hz to 50 GHz	R&S®FSWP-B1	1322.9997.50	yes	for R&S®FSWP50; retrofittable in factory
External Generator Control	R&S®FSWP-B10	1325.5463.02	yes	contact service center
Resolution Bandwidth > 10 MHz	R&S®FSWP-B8	1325.5028.26	no	for R&S®FSWP8/26 with R&S®FSWP-B1 option; the signal analysis bandwidth is defined by the R&S®FSWP-B80 option, not by the R&S®FSWP-B8 option.
Resolution Bandwidth > 10 MHz	R&S®FSWP-B8	1325.5028.02	no	for R&S®FSWP50 with R&S®FSWP-B1 option; the signal analysis bandwidth is defined by the R&S®FSWP-B80 option, not by the R&S®FSWP-B8 option; export license required
High-pass Filter for Harmonic Measurements	R&S®FSWP-B13	1325.4350.02	yes	for R&S®FSWP8/26/50 with R&S®FSWP-B1 option; user-retrofittable
LO/IF Connections for external mixers	R&S®FSWP-B21	1325.3848.02	yes	for R&S®FSWP26/50; contact service center
RF Preamplifier, 100 kHz to 8 GHz	R&S®FSWP-B24	1325.3725.08	yes	for R&S®FSWP8 with R&S®FSWP-B1 option; contact service center
RF Preamplifier, 100 kHz to 26.5 GHz	R&S®FSWP-B24	1325.3725.26	yes	for R&S®FSWP26 with R&S®FSWP-B1 option; contact service center
RF Preamplifier, 100 kHz to 50 GHz	R&S®FSWP-B24	1325.3725.50	yes	for R&S®FSWP50 with R&S®FSWP-B1 option; contact service center
80 MHz Analysis Bandwidth	R&S®FSWP-B80	1325.4338.02	yes	for R&S®FSWP8/26/50 with R&S®FSWP-B1 option; user-retrofittable
Spare Solid State Drive (removable hard drive)	R&S®FSWP-B18	1331.4313.02	yes	user-retrofittable

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