Modern Methods of Absolute & Residual Phase Noise Tests on CW and Pulsed Signals

Dr. Wolfgang Wendler, Rohde & Schwarz

ROHDE&SCHWARZ

Modern Methodsof Absolute & ResidualPhase Noise Tests on CW and Pulsed Signals

Content

- **Motivation**
  - Phase noise test with spectrum analyzer/phase noise tester
- Architecture of R&S FSWP
  - Analog Signal Path
  - Digital Signal Path
  - FFT and Cross-Correlation
- Instrument Features and Instrument Performance
  - Sensitivity
  - Pulsed phase noise
  - Additive/residual phase noise
  - Jitter analysis
  - VCO measurements
  - Verification
- Conclusion

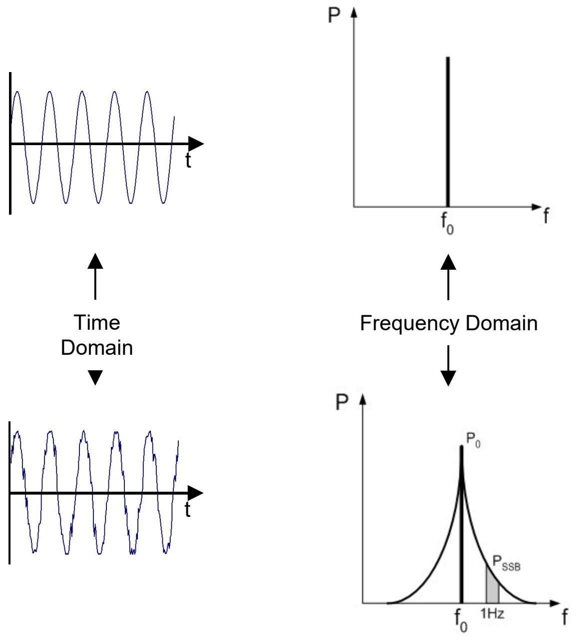
What is Phase Noise?

- **Ideal Signal (noiseless)**
  $V(t) = A \sin(2\pi\nu t)$

  where
  A = nominal amplitude
  ν = nominal frequency

- **Real Signal**
  $V(t) = [A + E(t)] \sin(2\pi\nu t + \phi(t))$

  where
  $E(t)$ = amplitude fluctuations
  $\phi(t)$ = phase fluctuations

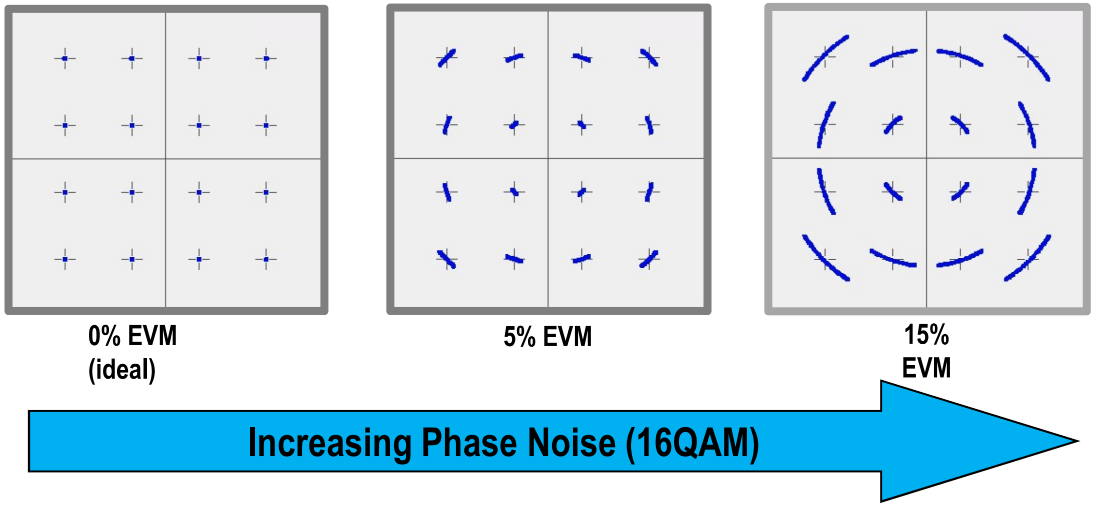


$$L(f_m) = 10\log\left(\frac{Single\_Sideband\_Power\_related\_to\_1Hz\_P_{SSB}}{Carrier\_Frequency\_Power\_P_0}\right) \quad [dBc(1Hz)]$$

Phase Noise

Important in Digital Modulation

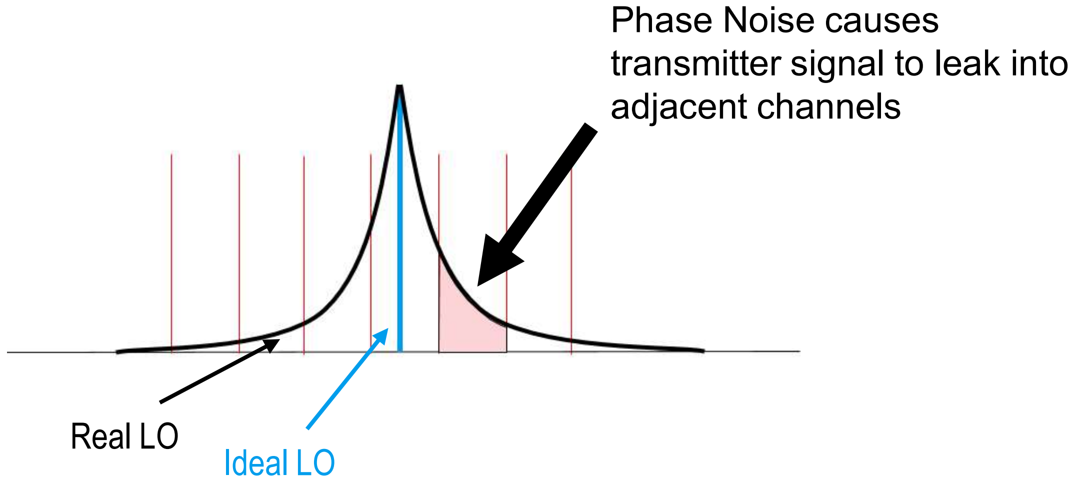
Modulation quality (phase error, EVM)
is degraded by phase noise



Phase Noise

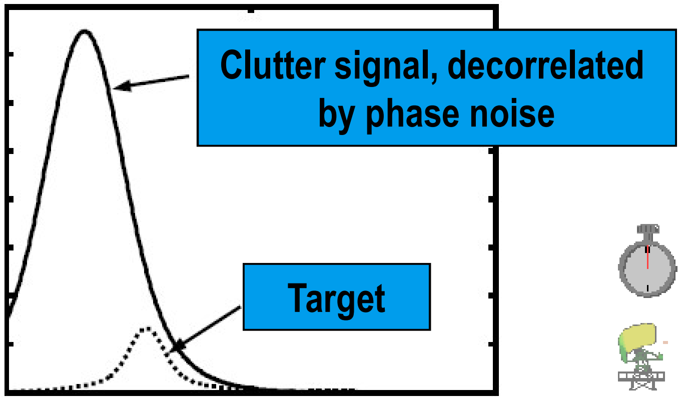
Important in Communication Systems Transmitters

Adjacent Channel Power



Phase Noise
Important for Radar

Radar Applications – Moving Target Indication



High phase noise in radar LO spreads clutter signal and masks desired low-level target response

Measurement with Spectrum Analyzer FSW-K40 / FPS-K40

- 2 modes:
  1.) „**Swept**“: „classical“, display spectrum trace right of carrier logarithmic
  2.) „**IQ FFT**“: run signal processing on captured IQ data

- „IQ FFT“ is more powerful, offering:
  - Higher measurement **speed**
  - Much better **frequency tracking** and correction function
  - **AM rejection** (measure ONLY phase noise, REMOVE AM noise)
  - More measurement **results** (e.g. level variation, frequency vs time)

  („IQ FFT“ uses the same signal processing DLL as used in the FSUP)

Instruments supported:

FSW (high end)

FPS (production)

Dedicated Phase Noise Tester R&S FSWP

- New Concept, **it's time for a digital phase detector**
  - A/D converters with 100 MS/s achieve -173 dBc/Hz wideband noise for full scale input
  - Middle-class FPGAs offer more than 2000 multipliers
    - Filters with more than 200 dB stopband attenuation
    - Data paths with 48 bit dynamic

Differences: R&S FSW-K40 – R&S

Faster!

	Spectrum Analyzer **FPS & K40**	Spectrum Analyzer **FSW & K40**	Phase Noise Analyzer **FSWP**
Measure Phase Noise	✓	✓	✓
Pulsed Phase Noise	✗	✗	✓
Measure VCO's (phase noise)	✓	✓	✓
Dedicated VCO Measurements	✗	✗	✓
Cross Correlation (improve phase noise performance)	✗	✗	✓
Sensitivity (1 GHz, 10 kHz Offset)	**-110 dBc/Hz**	**- 135 dBc/Hz**	**- 172 dBc/Hz**
AM Noise Suppression	✓	✓	✓
AM Noise Measurement	✗	✗	✓
Additive Phase Noise	✗	✗	✓

R&S Signal and Spectrum Analyzers

A&D symposium

Top Class

- **85 GHz**
- **Real time**
- **Wideband**
- **Puls analysis**
- **…**

FSW

Premium Performance Class Spectrum / Signal Analyzer
Industry leading Phase Noise Performance and Optimized Sweep Speed
1.2 GHz / 2GHz Analysis Bandwidth, Multi-Measurement / Touchscreen Control
512 MHz Real-time Signal Analysis , POI=0.91µs

Top Class

Special applications

FSWP

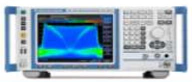
Phase Noise and VCO Tester
Phase Noise Tester and High- End Spectrum Analyzer in a single box
Pulsed and additive phase noise

FSMR

Measuring Receiver
One Box Solution for calibrating Signal Generators / Attenuators

Real-Time

FSVR



Real-Time Spectrum Analyzer
First combination of spectrum, signal, and real-time analysis
In the mid range up to 40 GHz

General Purpose

FSV/A

Signal Analysis at its best
Fast mid range signal & spectrum analyzer

FPS

Signal Analysis for Production
Exceptional fast signal & spectrum analyzer

FSL

Portable Spectrum Analyzer
Up to 18 GHz with high end functions

Handheld & Portable

FSH FPH

Handheld Spectrum / Network / Modulation Analyzer for Field Applications up to 20 GHz

ZVH

Handheld Cable & Antenna Analyzer
for Installation & Maintenance

FSC

General Purpose Spectrum Analysis
Compact, Low Power Consumption

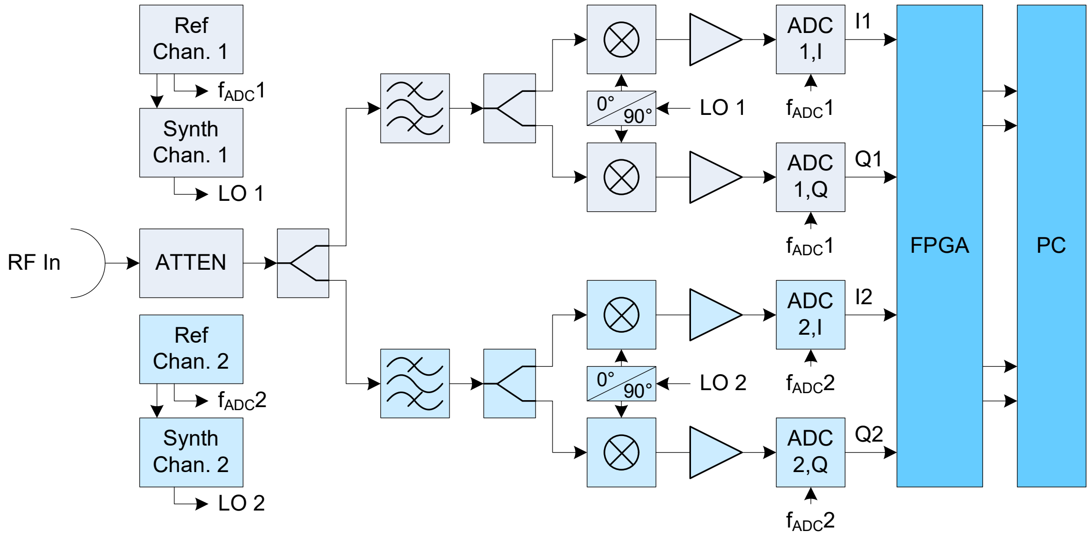
R&S FSWP - Phase Noise and VCO Tester

- **Signal- and spectrum analyzer** and phase noise tester in one box
- **Unrivalled phase noise performance** of local oscillators for phase noise measurements
  - **Cross correlation**
  - Ultra low phase noise reference for high end applications
  - AM noise measurment with cross correlation (PM/AM simultanously)
- Measurement of **pulsed phase noise** by push of a button
- Internal source (up to 18 GHz) for **residual/additive phase noise** measurements
  - Without ext. phase shifter , just connect the DUT

- Based on high end signal and spectrum analyzer R&S FSW
  - Same user interface with touch screen
  - Channel concept
  - 80 MHz analysis bandwidth

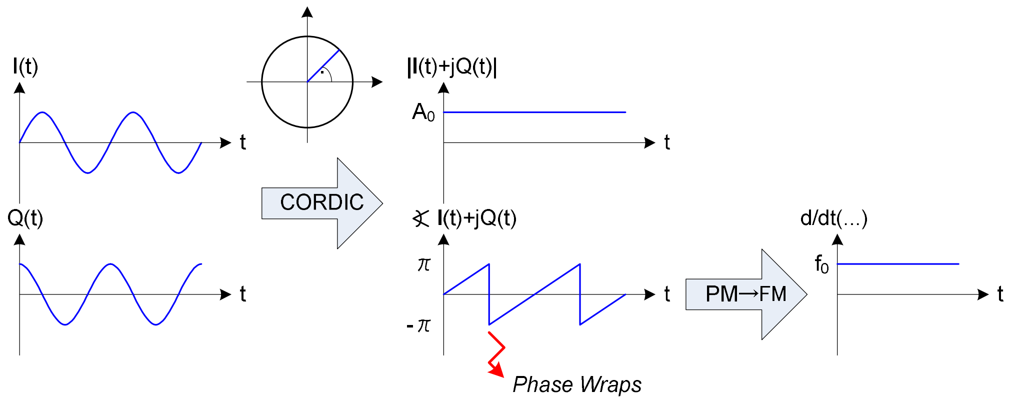
Analog Signal Path

100 Msamples/s,
16bit
$20 \log 2^{16} + 10 * \log 100\text{MHz} = 176\ \text{dBc/Hz}$



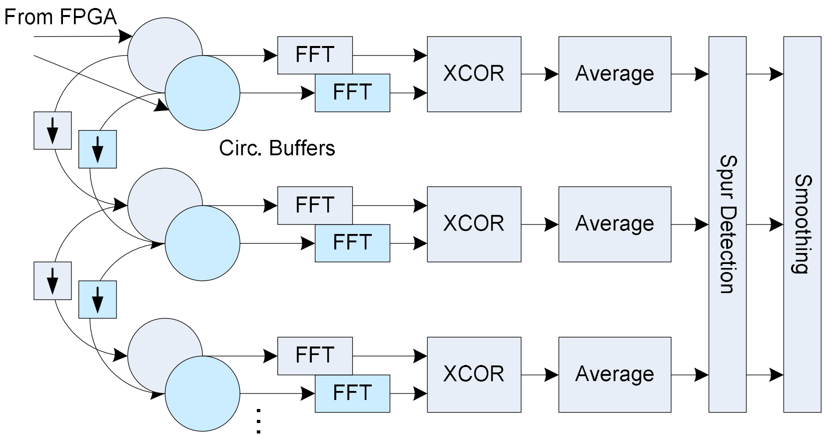
- Two loosely coupled reference sources (PLL bandwidth < 0.1 Hz)
- Analog I/Q mixer with low- or zero-IF
  - IF depends on frequency offset to be measured
  - Optimized to avoid spurious emissions

Digital Signal Path – FM Demodulator



- PM signal has phase wraps at ±π. No filtering or FFT possible.
- FM demodulator preferred to digital PLL due to its simplicity
- FM demodulator frequency response decreases with 20 dB per decade toward DC
  - Analog FM demodulators are insensitive close to the carrier
  - White noise, e.g. quantization noise, must be hold below the FM slope
  - 48 bit signal dynamic do the job!

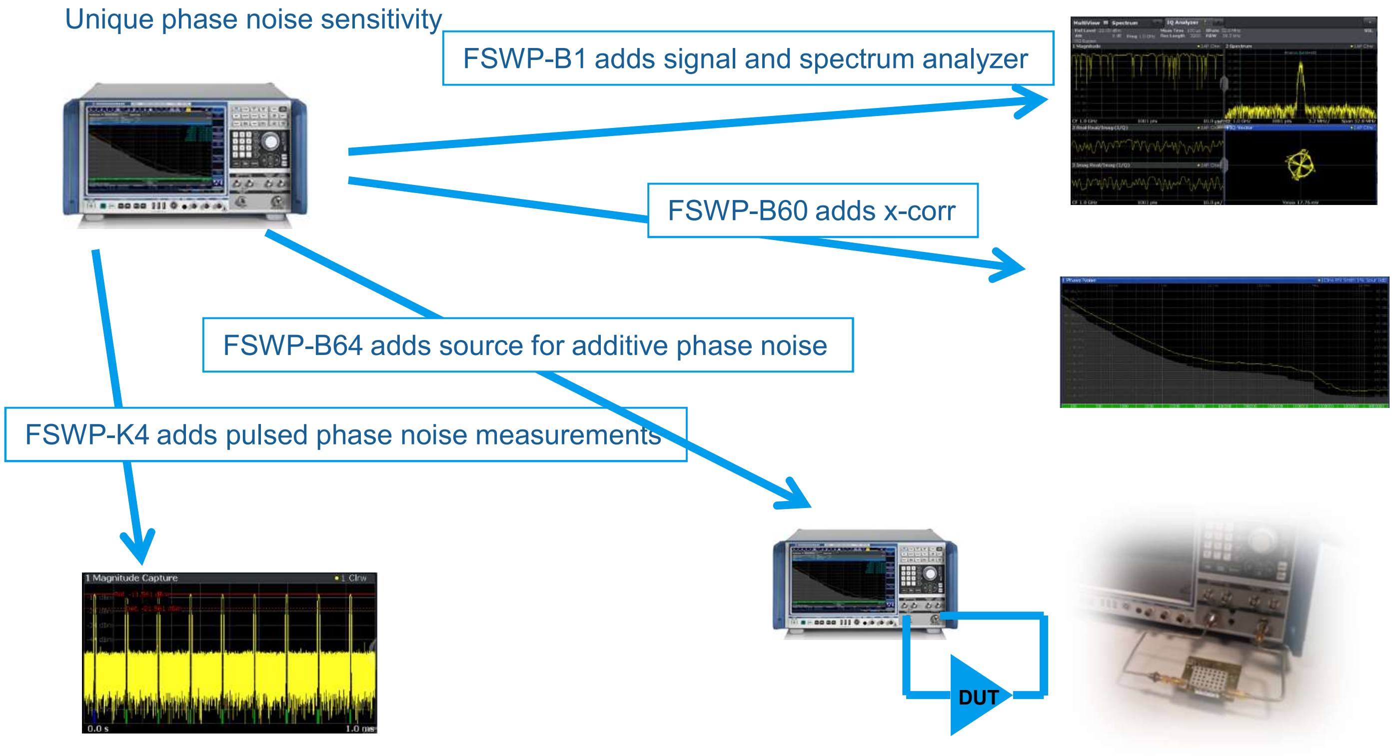
FFT and Cross-Correlation



- Spectrum is divided into half decades (1 Hz to 3 Hz, 3 Hz to 10 Hz, …)
- Result is the magnitude of cross-correlation averages

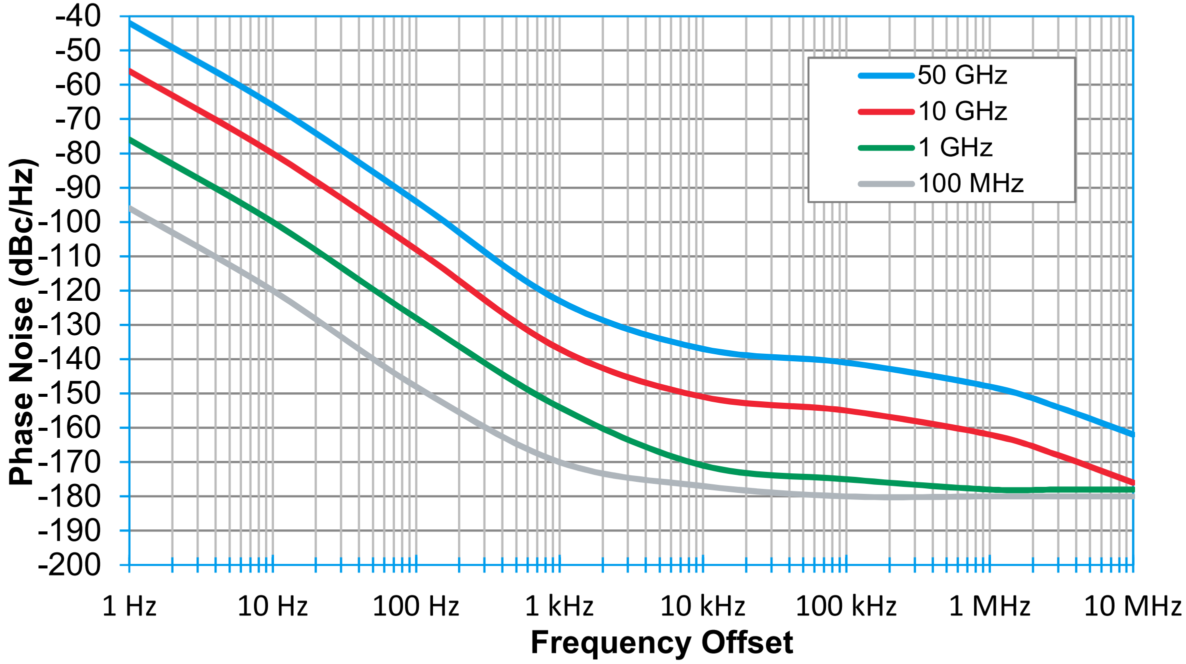
$$\hat{S}_{YX} = \frac{1}{N} \cdot \left| \sum_{i=0}^{N-1} Y_i \cdot \mathrm{conj}\left(X_i\right) \right|$$

R&S FSWP- Phase Noise and VCO Tester



R&S FSWP Performance

- Typical noise floor (10 seconds measurement time, 10 % RBW)



Phase Noise of High End OCXO

R&S FSWP-B61, Cross-Correlation (low phase noise),

- Specification:

Phase noise sensitivity with R&S®FSWP-B60 cross correlation option

Start offset 1 Hz, correlation factor = 1, frequency reference internal, signal level ≥ 10 dBm, without R&S®FSWP-B4 option.
Specified values in dBc (1 Hz). For typical values subtract 6 dB.

RF input frequency	**Offset frequency from the carrier**								
	1 Hz	10 Hz	100 Hz	1 kHz	10 kHz	100 kHz	1 MHz	10 MHz	≥ 30 MHz
10 MHz	–96	–128	–140	–158	–170	–170	–170		
100 MHz	–76	–108	–136	–163	–170	–173	–175	–175	–175
1 GHz	–56	–88	–116	–143	–166	–173	–173	–173	–173
3 GHz	–46	–78	–106	–133	–156	–158	–163	–170	–170
7 GHz	–39	–71	–99	–130	–152	–153	–157	–166	–166
10 GHz									
16 GHz									
26 GHz									
50 GHz									

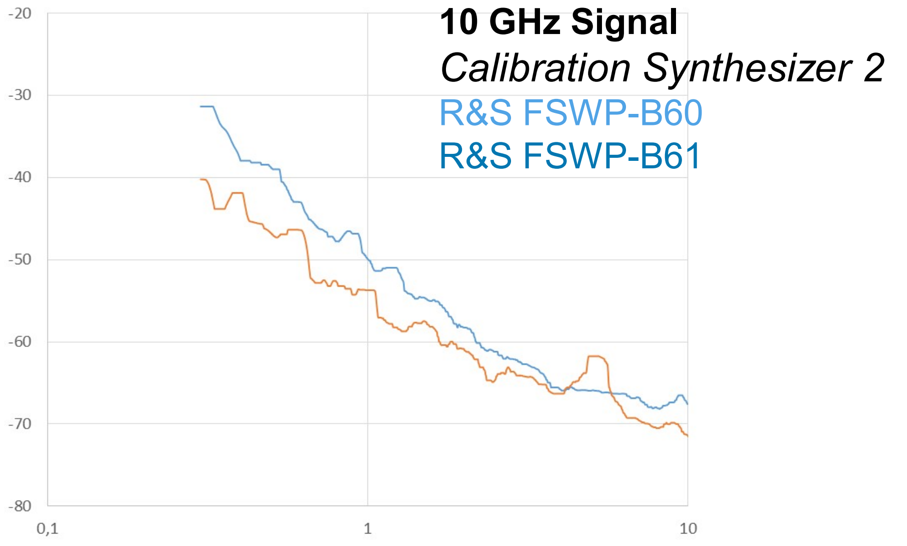
Phase noise sensitivity with R&S®FSWP-B61 cross correlation (low phase noise) option

Start offset 1 Hz, correlation factor = 1, frequency reference internal, internal reference loop bandwidth 30 Hz, signal level ≥ 10 dBm.
Specified values in dBc (1 Hz). For typical values subtract 6 dB.

RF input frequency	**Offset frequency from the carrier**								
	1 Hz	10 Hz	100 Hz	1 kHz	10 kHz	100 kHz	1 MHz	10 MHz	≥ 30 MHz
10 MHz	-108	-130	-142	-160	–170	–170	–170		
100 MHz	-92	-115	-140	-166	–170	–173	–175	–175	–175
1 GHz	-72	-95	-120	-150	–166	–173	–173	–173	–173
3 GHz	-62	-85	-110	-140	–156	–158	–163	–170	–170
7 GHz	-55	-78	-103	-133	–152	–153	–157	–166	–166
10 GHz	-52	-75	-100	-133	-152	-153	-157	-173	-175
16 GHz	-48	-71	-96	-129	-148	-149	-153	-170	-171
26 GHz	-44	-67	-92	-125	-144	-145	-149	-166	-167
50 GHz	-38	-61	-86	-119	-138	-139	-143	-160	-161

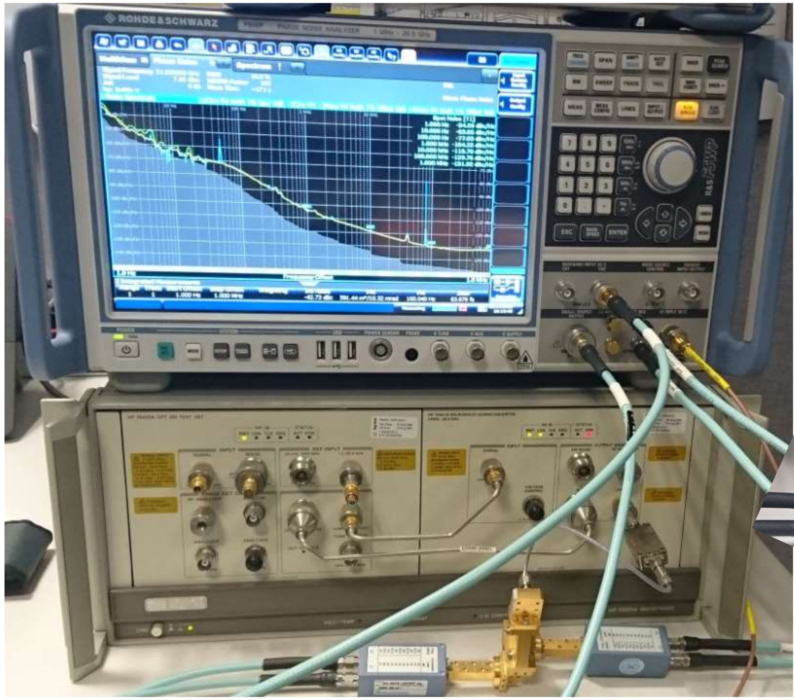
R&S FSWP-B61, Cross-Correlation (low phase noise),

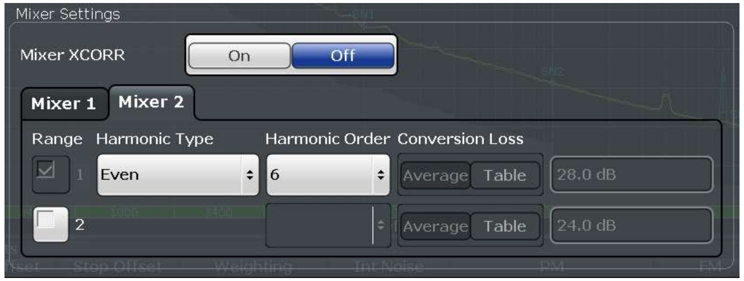
- The difference in performance can be seen with calibration of synthesizer 2



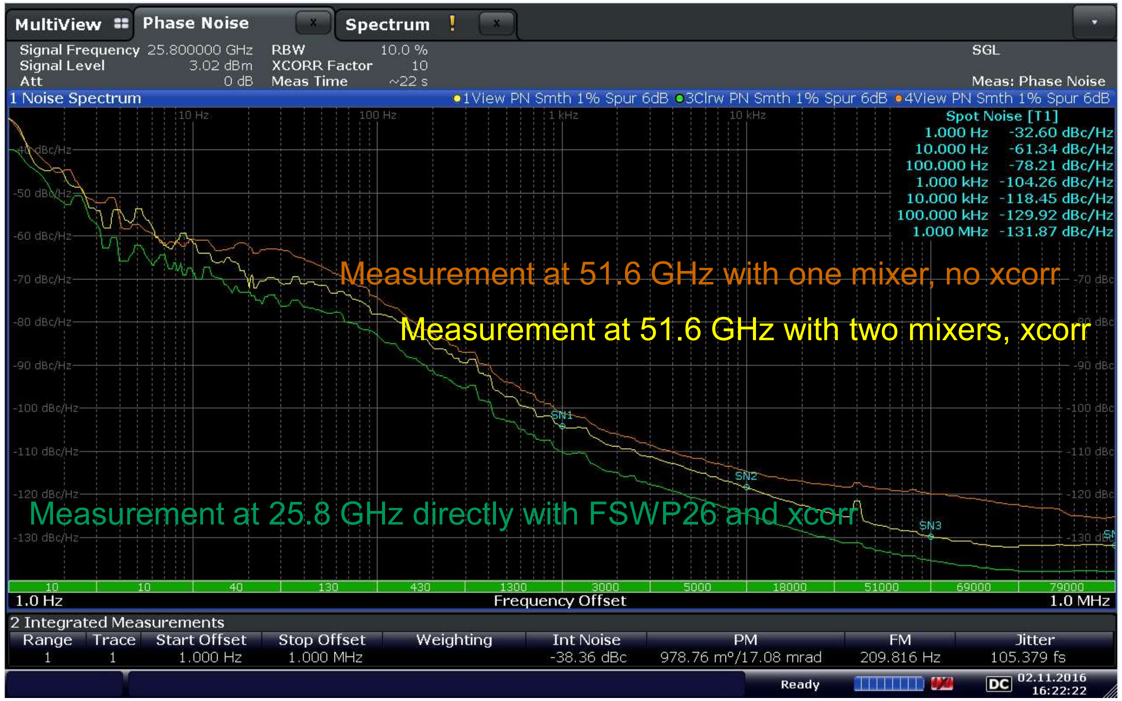
AM/PM Noise of DRO and X SAW Phase Noise

Phase Noise Measurement with external Harmonic Mixers





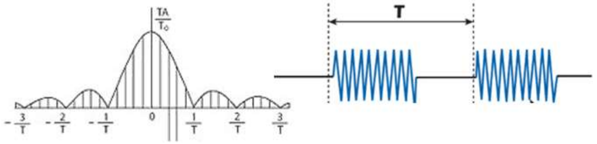
Phase Noise Measurement with external Harmonic Mixers



Phase Noise Measurement with external Harmonic Mixers

R&S FSWP – Pulsed Phase Noise

Complete Characterization of Pulsed Signals – in One Box

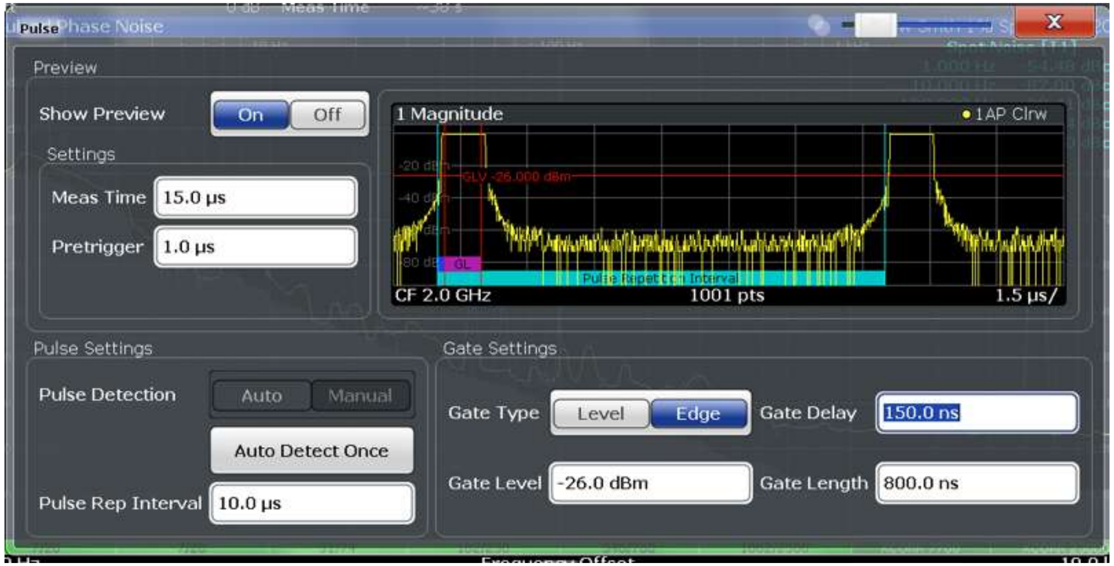


- **FSWP-K4**
  - Measurement of phase noise of pulsed signals

- **FSWP-K6**
  - Automatic detection of RF pulses
  - Measures pulse envelope parameters
    - Timing (e.g. Width, Rise/Fall Time, PRI, etc.)
    - Amplitude (e.g. Peak Power, Average On, etc.)
    - Phase / Frequency
  - Different Measurement Displays
    - Pulse statistics
    - Parameters over time (i.e. phase vs. time)
    - Parameter over all pulses (trending)
  - 80 MHz analysis bandwidth

R&S FSWP – FSWP-K4

Defininition Measurement Gate



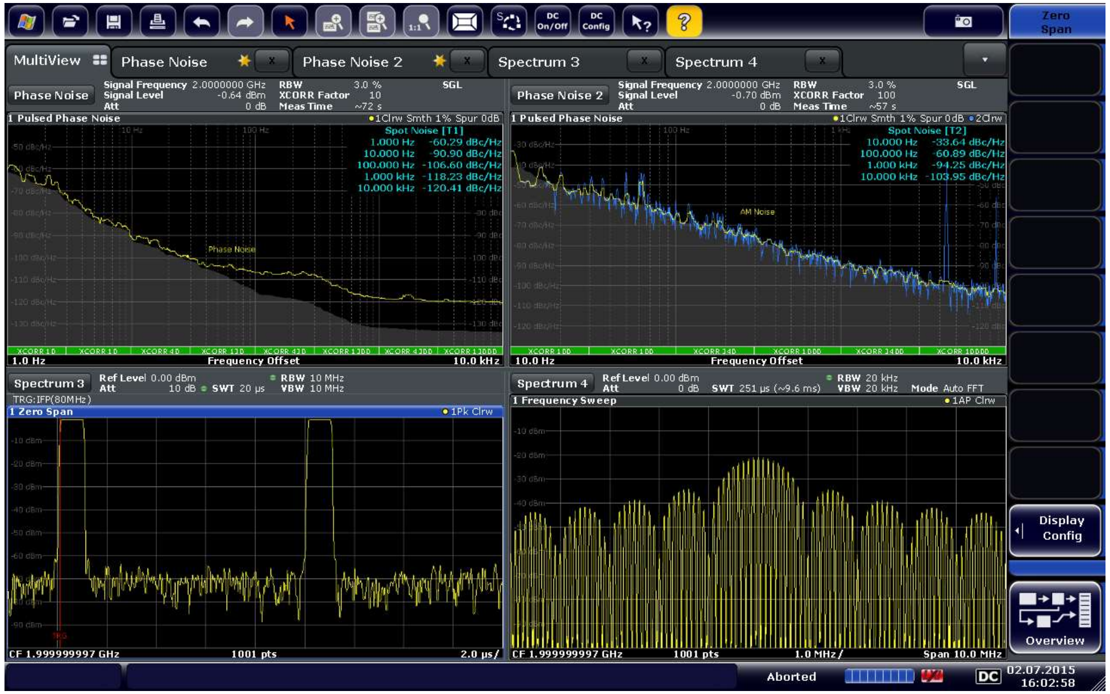
Pulse desensitization (dB) = 20 Log10(τ/T)
Gating: reduction of noise floor (dB) = 10 Log10(τ/T)
Overall reduction of sensitivity only:
10 Log10(τ/T)

A&D symposium

R&S FSWP – FSWP-K4

… and Show Everything on one Sight

- **Phase Noise**
- **AM Noise**
- **Pulse in Time Domain**
- **Pulse in Frequency Domain**

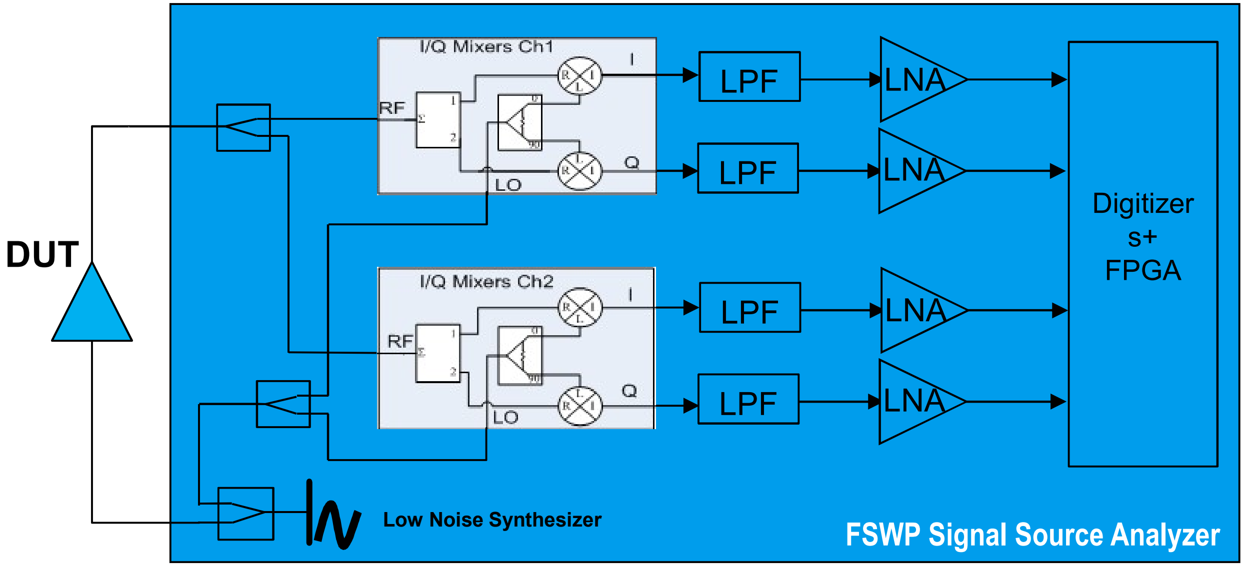


R&S FSWP – FSWP-B64

Residual/Additive Phase Noise Measurement

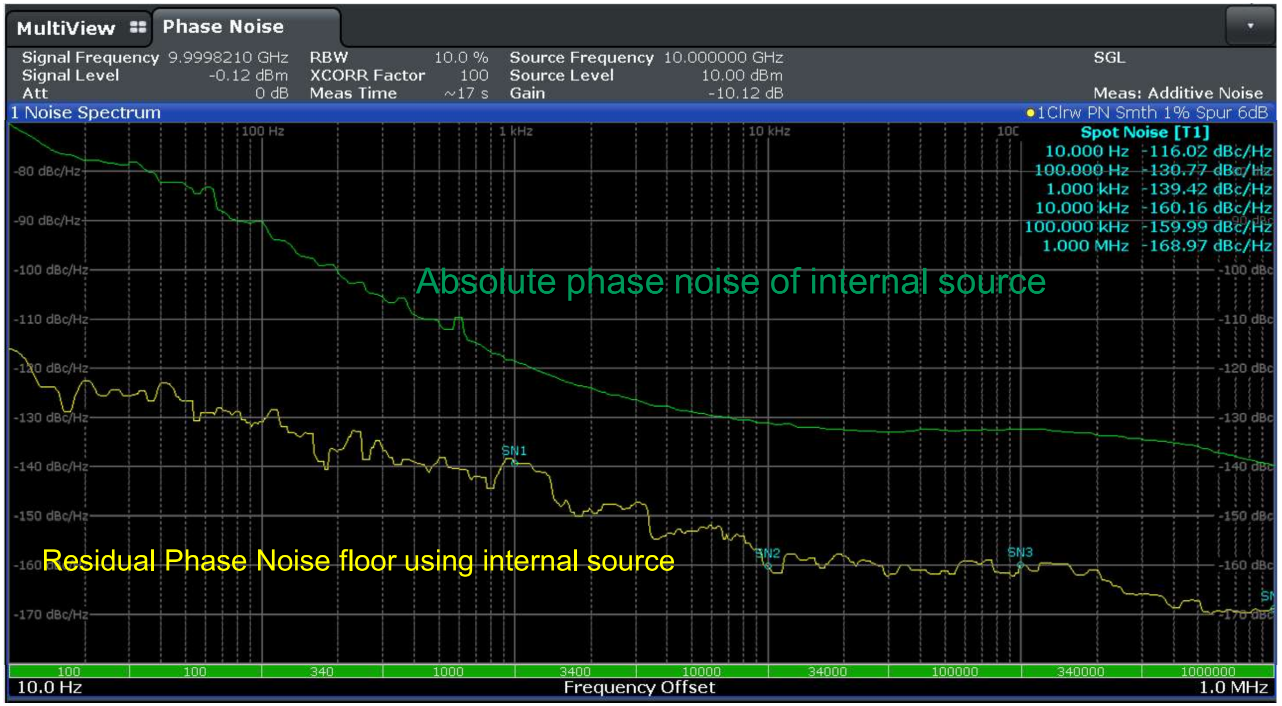
Additive Phase Noise – Digital Phase Demodulator

- Internal hardware automatically reconfigures when “Additive” is selected
- No phase detector or need for quadrature – no phase shifter
- Greatly simplifies measurement setup and calibration
- Internal Low Noise Synthesizer as DUT stimulus



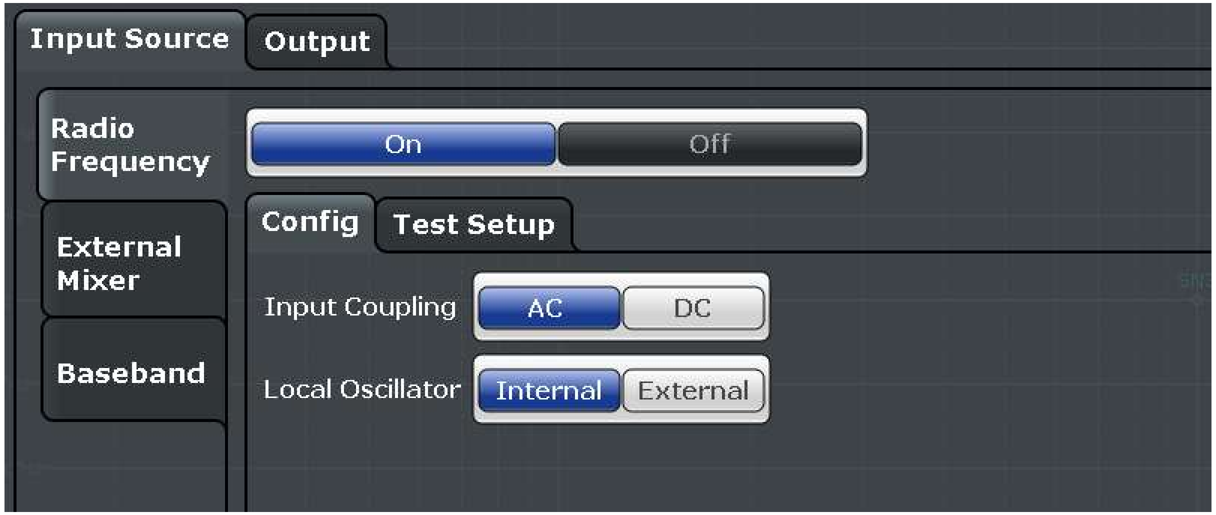
R&S FSWP – FSWP-B64

Residual/Additive Phase Noise Measurement



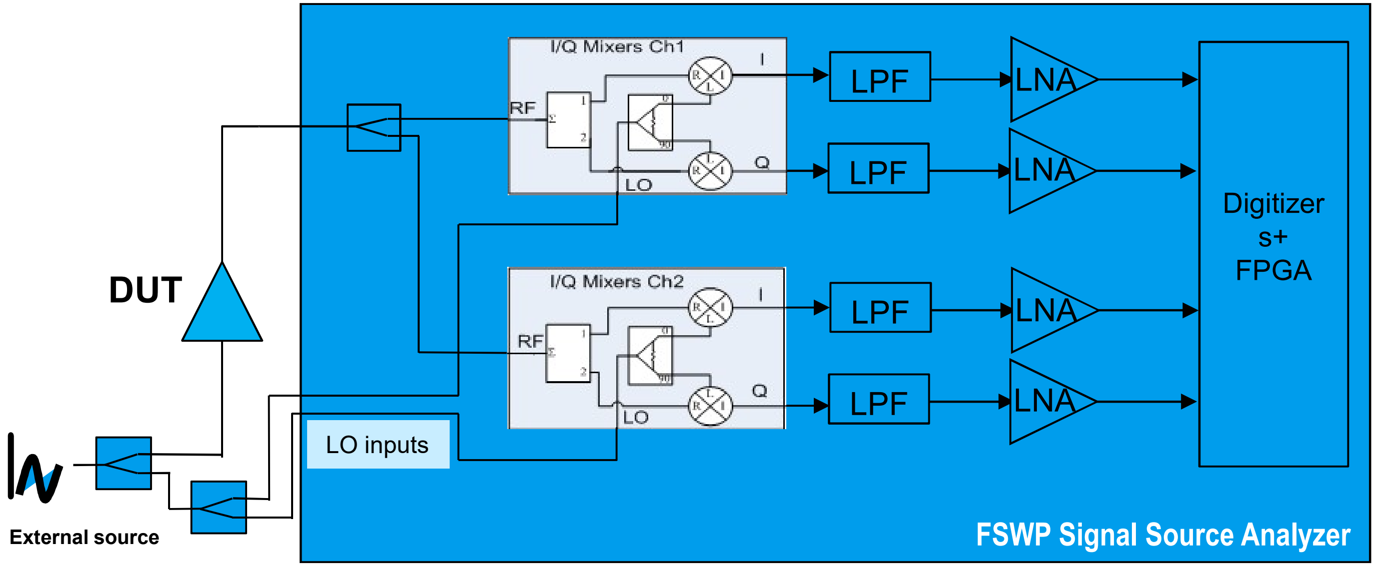
FSWP - External LO Inputs (Q4/2016)

FSWP - External LO Inputs

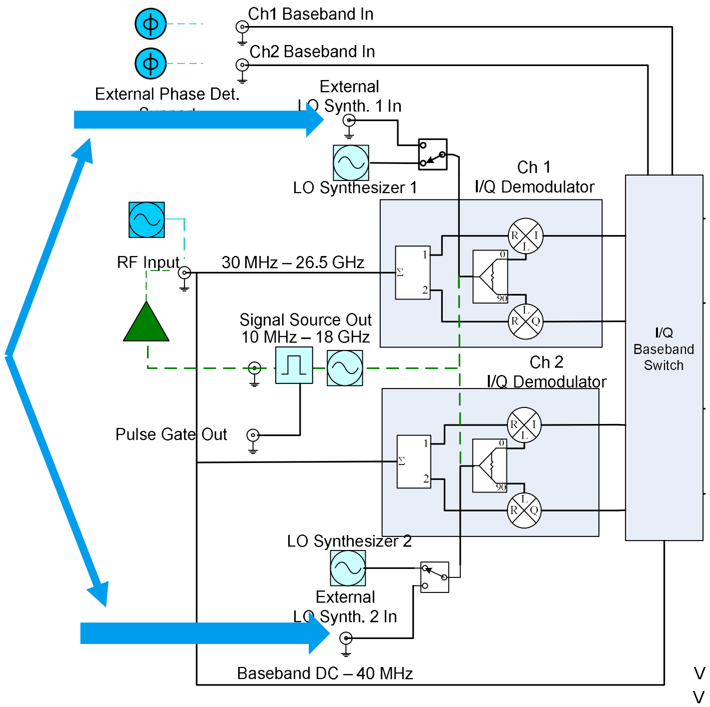


Additive Phase Noise – Digital Phase Demodulator

- No phase detector or need for quadrature – no phase shifter
- Greatly simplifies measurement setup and calibration
- External Low Noise Synthesizer as DUT stimulus can be selected
  - High end source can be used
  - Support of freq. converting DUTs is possible

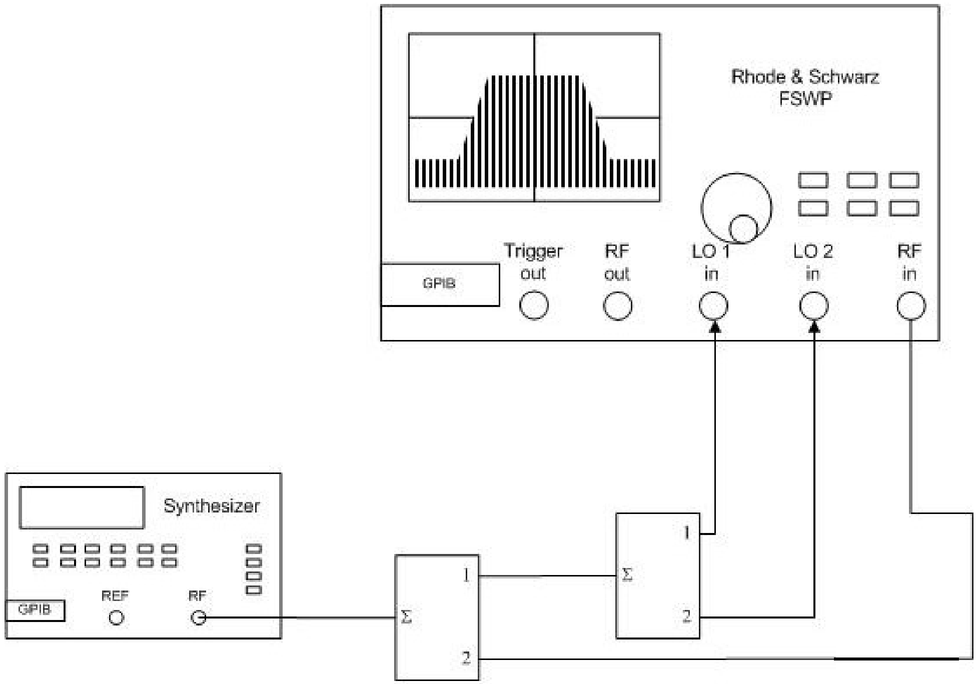


Using External LOs for Residual Phase Noise



- When the internal source doesn't have enough drive, correct pulse modulation, or frequency an external LO may be used
- External LO connectors are provided on FSWP front panel with Option B64
- FSWP firmware Beta 1.40 provides control for these inputs
  - FSWP 1.40 final firmware will be released by the end of Dec 2016

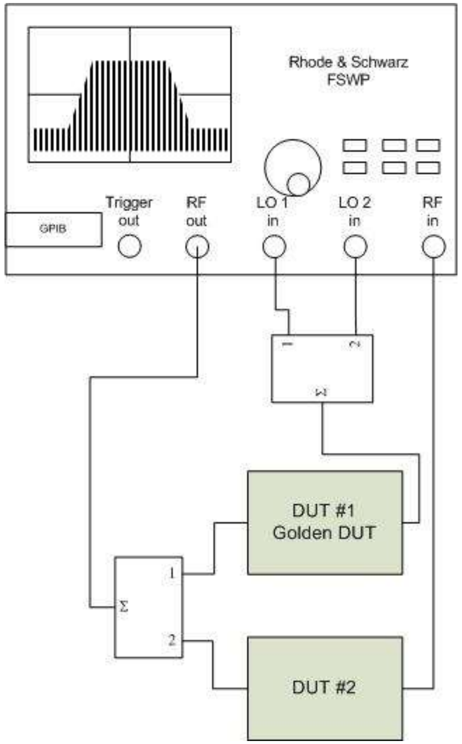
Simplified Residual Noise Setup Using an External Synthesizer



Cancellation of Source Noise, Using FSWP External LO Inputs

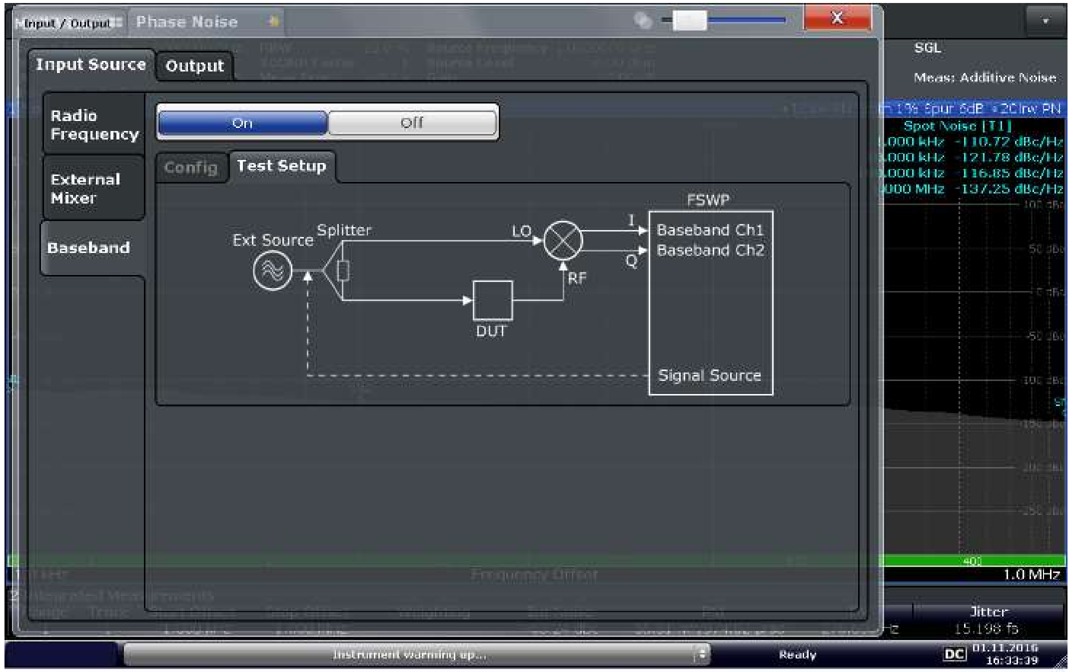
- This slide shows the phase noise of an R&S SMF signal generator at 10 GHz (green trace). Set up as in the previous slide.
- The yellow trace shows the residual noise floor and demonstrates the excellent source noise cancellation of FSWP

Phase Noise Measurement of Frequency Converter (two converter method)



- Two identical up or down converters may be used
  - Converter under test directly supplies FSWP RF input
  - Second converter supplies the local oscillator signal for FSWP
  - Since both converters are identical FSWP measures the combined phase noise, 3-dB higher than DUT alone.
- An external synthesizer could also be used in place of the FSWP internal source, if required
- A three converter setup allows measurement of the DUT only and noise of the two LO converters is reduced by cross correlation.

Residual Phase Noise Measurement for Frequencies > 18 GHz

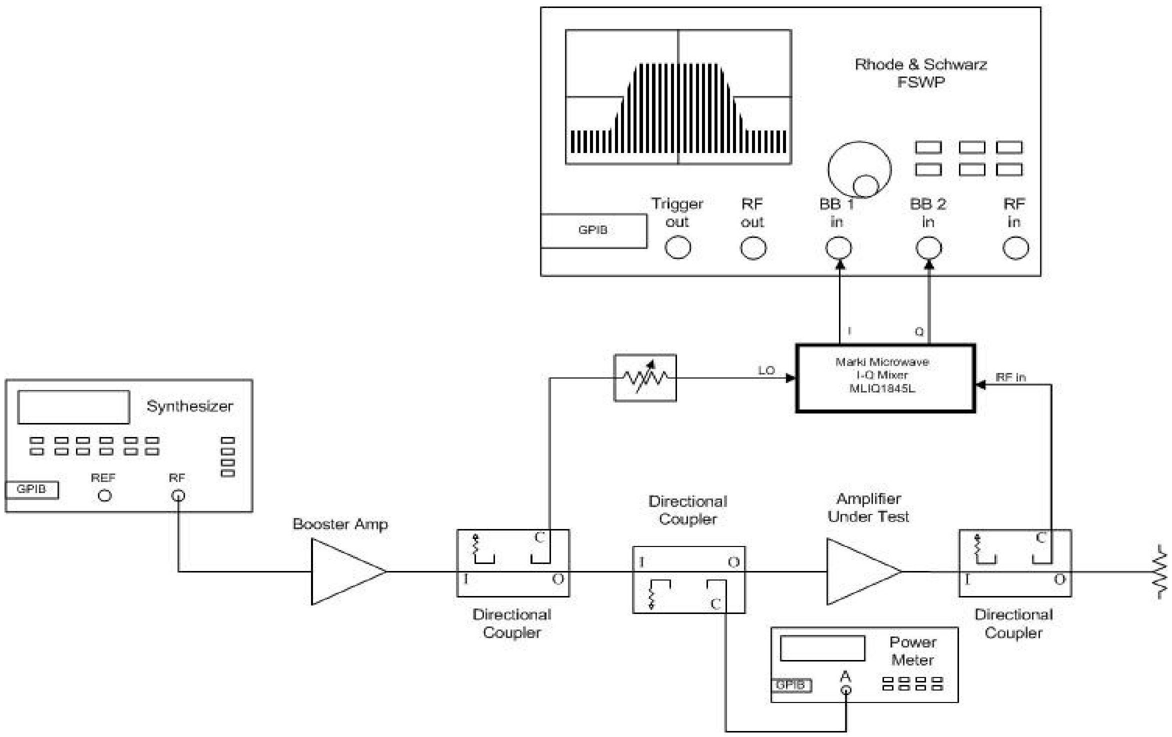


Date: 1.NOV 2016 16:33:39

- For frequencies > 18 GHz an external I-Q mixer may be used
- An external signal generator drives both the DUT and mixer LO
- Mixer I-Q outputs are connected to FSWP's baseband inputs
- From the input menu select the **Baseband** tab and select the **ON** radio button

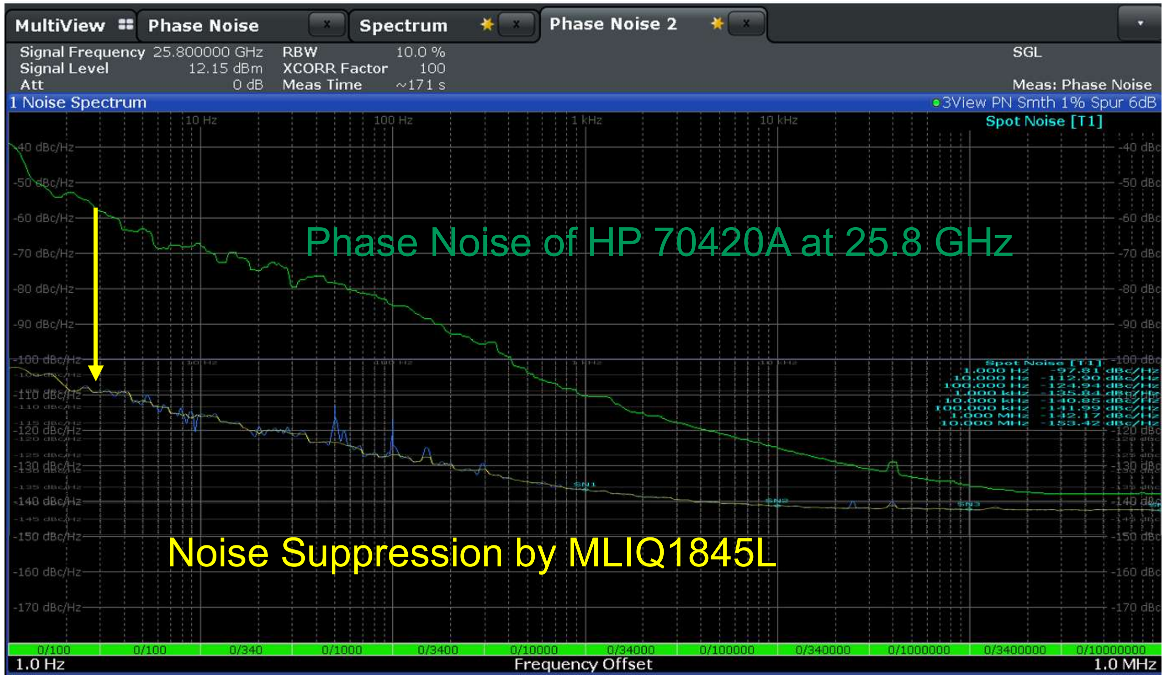
Ka-Band High-Power Residual Noise Set Up,

(Using an External I-Q Mixer)



- For frequencies > 18 GHz an external I-Q mixer may be used to extend FSWP’s frequency range
- Booster Amp provides high drive power for DUT
  - Phase noise of booster amp is subtracted out of measurement
- Directional coupler limits input power to mixer.

Noise Suppression by IQ mixer at 25.8 GHz



Example of an Amplifier Residual Phase Noise Measurement at 25 GHz

Correlation between Phase Noise and Jitter

Measurement Instruments

- **Time Domain (Oscilloscope)**
  - Direct method for measuring jitter
  - Measures TIE, Period Jitter, Cycle-to-Cycle Jitter
  - Measures RMS or Peak-to-Peak Jitter
  - Measures data or clock signals
  - Limited sensitivity (100 – 1000 fs)

- **Frequency Domain (Phase Noise Analyzer)**
  - Calculates jitter from phase noise
  - Measures RMS Jitter
  - Measures clocks, not random data streams
  - Easy to separate random and discrete jitter components
  - Highest sensitivity (<5 fs)

Jitter Measurements with R&S FSWP

- The spur list– random jitter and periodic jitter

periodic jitter
for every spur

Listing of
- discrete/periodic jitter
- random jitter

Jitter Measurements with R&S FSWP

- Random jitter- define ranges + listing of discrete and random jitter

VCO measurements R&S FSWP

- All parameters at one view

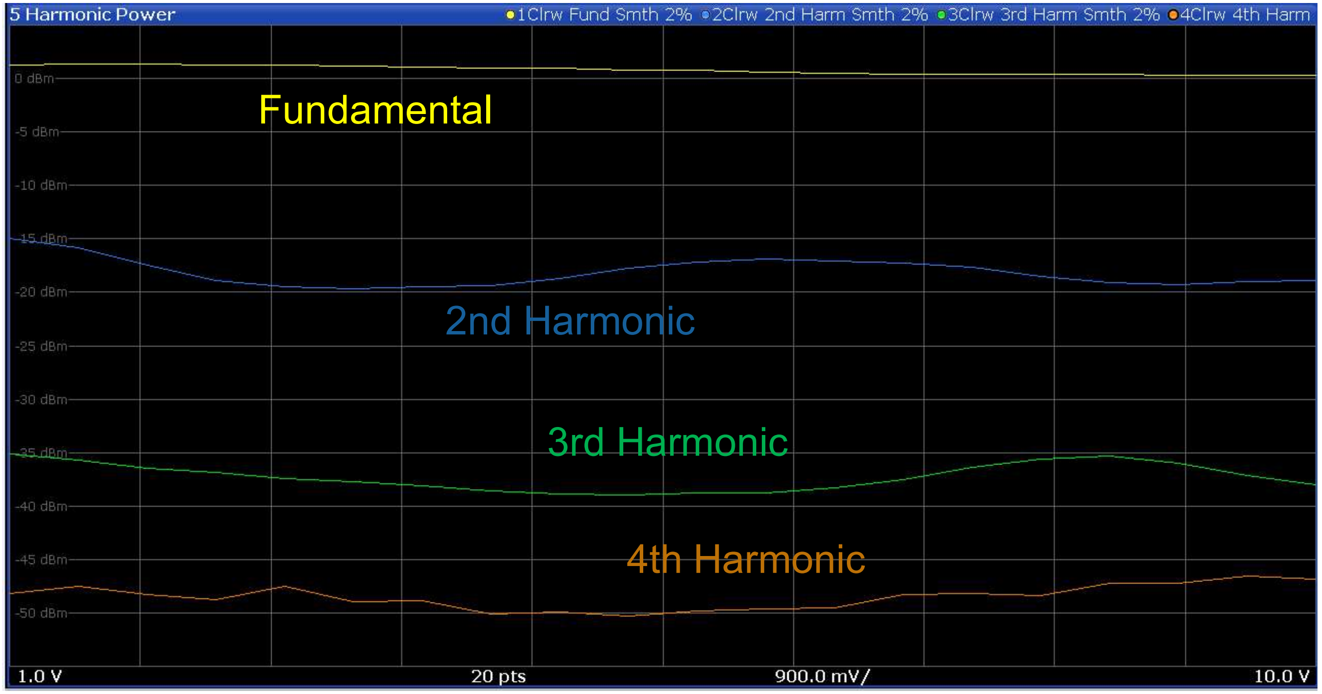
VCO measurements R&S FSWP

symposium

- VCO parameter and phase noise

VCO measurements R&S FSWP

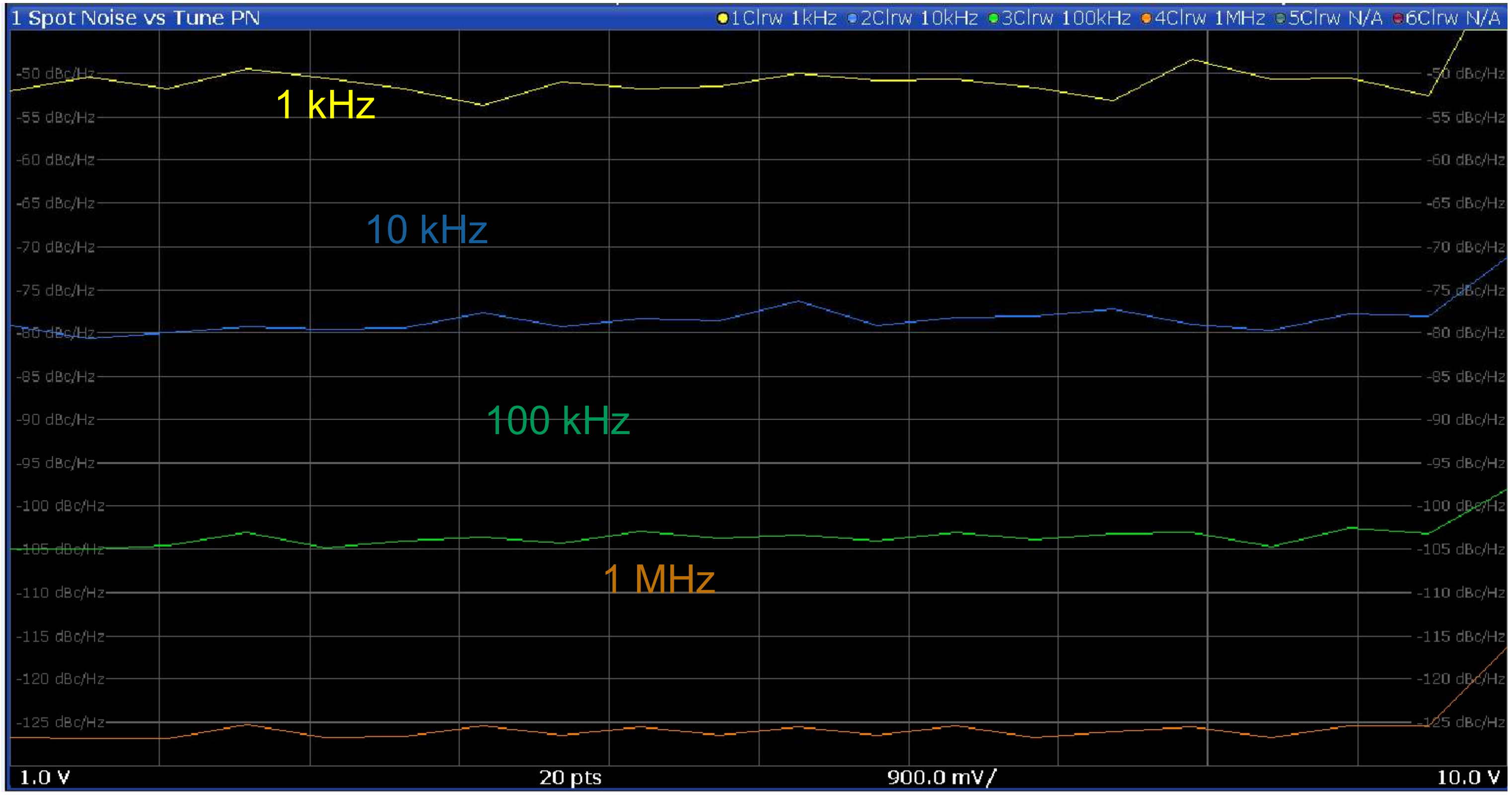
- Harmonic Power



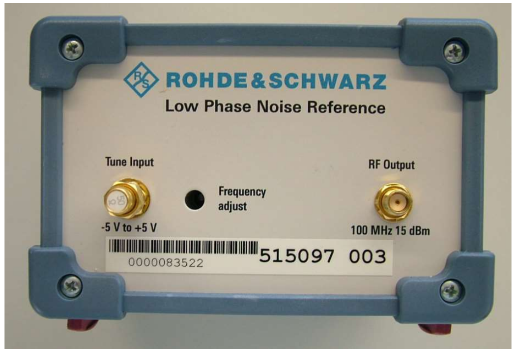
VCO measurements R&S FSWP

- Spot Noise versus Tune

Phase Noise at Different Offsets



Accredited Calibration of LPN by DAkkS-Laboratory Messgerätebau Memmingen



Material-Number: 5026.6520.02

Certificate by D-K-15195-01-00

4. Phase Noise at 100MHz

Frequency /MHz	Offset	Theoretical 1) dBc/Hz	DUL dBc/Hz	Actual dBc/Hz	Expanded uncertainty of measurement /dB
100	1 Hz		<- 73	-82.5	+2.6/-2.6
	2 Hz		<- 84	-91.2	+2.6/-2.6
	5 Hz		<- 95	-104.5	+2.6/-2.6
	10 Hz		<-105	-114.6	+2.6/-2.6
	20 Hz		<-115	-123.7	+2.6/-2.6
	40 Hz		<-124	-132.6	+2.6/-2.6
	95 Hz		<-135	-142.3	+2.6/-2.6
	100 Hz 2)	-141.9			*1)
	105 Hz		<-135	-141.6	+2.6/-2.6
	220 Hz		<-145	-150.6	+2.6/-2.6
	550 Hz		<-145	-148.7	+2.6/-2.6
	1kHz		<-160	-164.6	+2.7/-2.7
	2kHz		<-161	-170.8	+2.7/-2.7
	10kHz 3)	-182.8			*1)
	100kHz 3)	-189.8			*1)
	1MHz		<-170	-194.2	+9.0/-2.0

1. Comparison - NIST Data (ISO/IEC 17043)

A&D symposium

Table 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
2000 Hz	–171.1	+1.0/–1.4	–170.5	0.23	+2.7/–2.7

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

$$|E_n| = \frac{|x - X|}{\sqrt{U_{\text{lab}}^2 + U_{\text{ref}}^2}}$$

$x - X$: Deviation between measured value and reference value

U_{lab}: Expanded uncertainty of measured value

U_{ref}: Expanded uncertainty of reference value