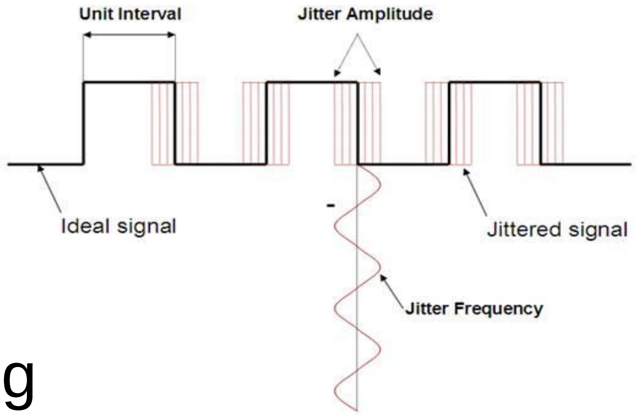
Phase Noise and Jitter Measurements

ROHDE&SCHWARZ

Agenda

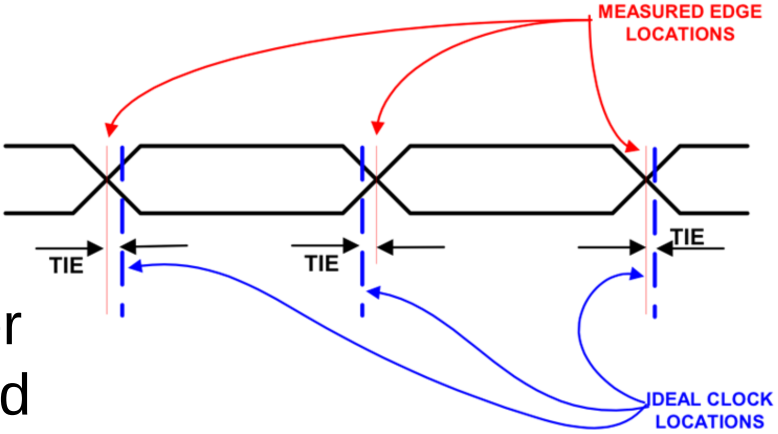
- **Jitter Review**
- **Time-Domain and Frequency-Domain Jitter Measurements**
- **Phase Noise Concept and Measurement Techniques**
- **Deriving Random and Deterministic Jitter from Phase Noise**
- **PLL/Filter Weighting of Jitter Spectrum**
- **Calculating Peak-to-Peak Jitter from RMS Jitter**

What is Jitter?



- Jitter is the short-term time-domain variations in clock or data signal timing
- Jitter includes instability in signal period, frequency, phase, duty cycle or some other timing characteristic
- Jitter is of interest from cycle to cycle, over many consecutive cycle, or as a longer term variation
- Jitter is equivalent to Phase Noise in the frequency domain
- Variations with frequency components >10Hz are *Jitter*
- Variations with frequency components <10Hz are *Wander*

Types of Jitter



- **Time Interval Error (TIE)**
  - Fundamental measurement of jitter
  - Time difference between measured signal edge and ideal edge
  - Instantaneous phase of signal
- **Period Jitter**
  - Short-term stability, basic parameter for clocks
- **Cycle to Cycle**
  - Important for parallel data transfer
- **N-Cycle**
  - Important when clock and data routing differ

Jitter Measurement Techniques

- **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) ✓

What is Phase Noise?

- **Ideal Signal (noiseless)**

  $V(t) = A \sin(2\pi\nu t)$

  where

  A = nominal amplitude

  ν = nominal frequency

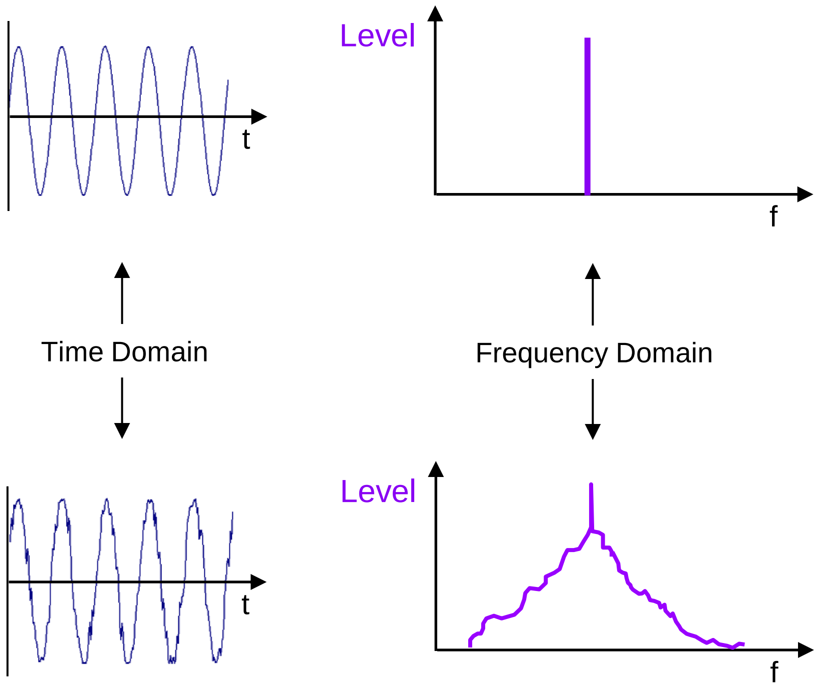
- **Real Signal**

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

  where

  $E(t)$ = amplitude fluctuations

  $\phi(t)$ = phase fluctuations

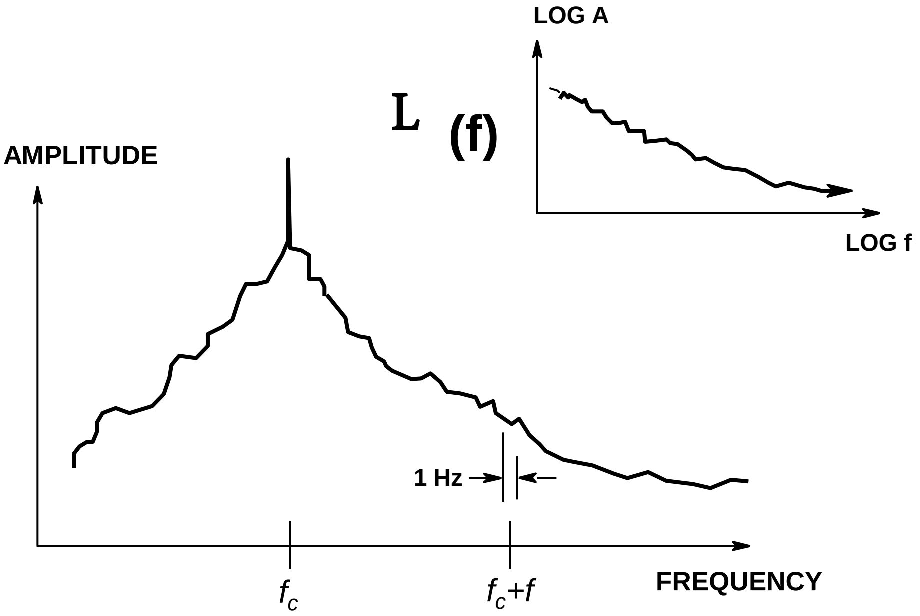


Phase Noise is unintentional phase modulation that spreads the signal spectrum in the frequency domain.

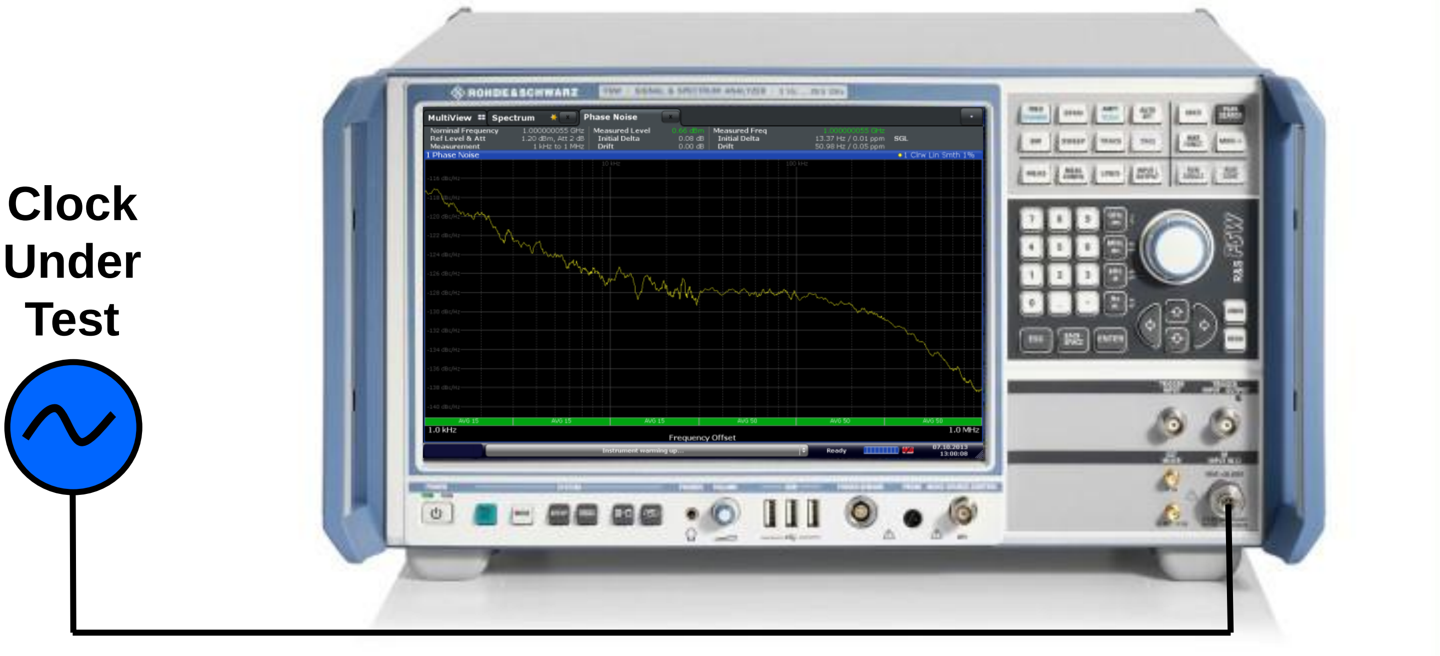
Phase Noise is equivalent to jitter in the time domain.

Phase Noise – Unit of Measure

- **Phase Noise is expressed as $\mathcal{L}$(f)**
- **$\mathcal{L}$(f) is defined as single sideband power due to phase fluctuations in a rectangular 1Hz bandwidth at a specified offset, f, from the carrier**
- **$\mathcal{L}$(f) has units of dBc/Hz**

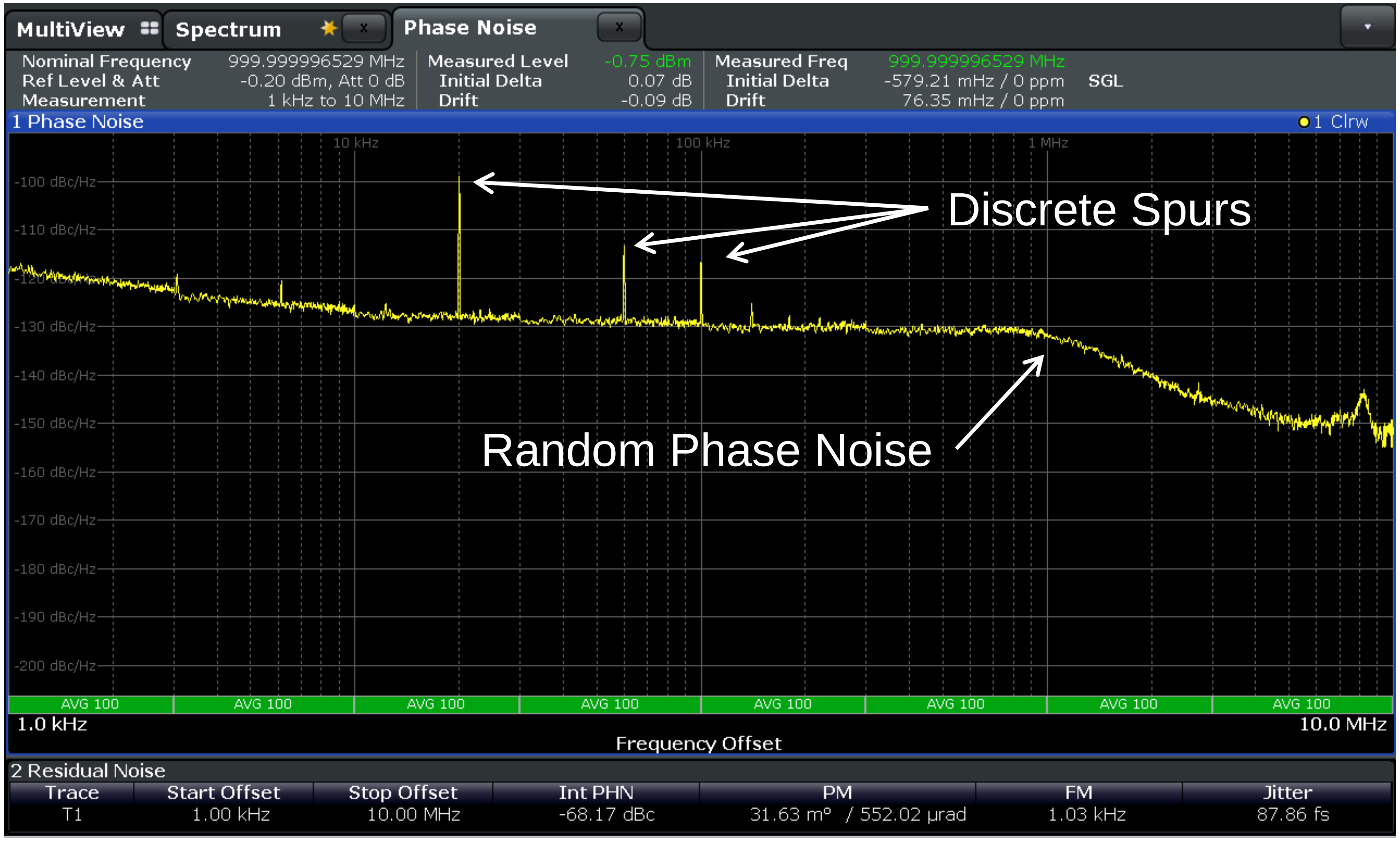


Phase Noise Measurement Setup



Clock Under Test

Example Phase Noise Measurement Plot



Nominal Frequency 999.999996529 MHz
Ref Level & Att -0.20 dBm, Att 0 dB
Measurement 1 kHz to 10 MHz
Measured Level -0.75 dBm
Initial Delta 0.07 dB
Drift -0.09 dB
Measured Freq 999.999996529 MHz
Initial Delta -579.21 mHz / 0 ppm
Drift 76.35 mHz / 0 ppm
SGL

2 Residual Noise

Trace	Start Offset	Stop Offset	Int PHN	PM	FM	Jitter
T1	1.00 kHz	10.00 MHz	-68.17 dBc	31.63 m° / 552.02 µrad	1.03 kHz	87.86 fs

Discrete Spurs

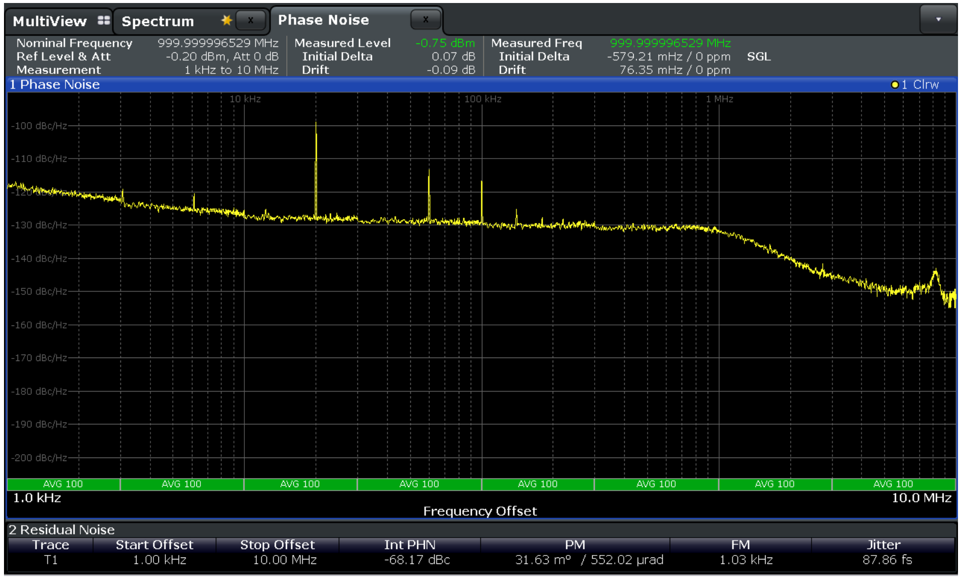
Random Phase Noise

Phase Noise (dBc/Hz) →

Offset from Fundamental Frequency →

Phase Noise Measurement

- Shows phase noise over a range of offset frequencies: $\mathcal{L}(f)$
- RMS Jitter = $\dfrac{1}{2\pi f_c}\sqrt{2\int \mathcal{L}(f)\,df}$
- Phase noise including spurs yields TJ, or Total Jitter (random plus deterministic)
- Phase noise without spurs yields RJ, or Random Jitter



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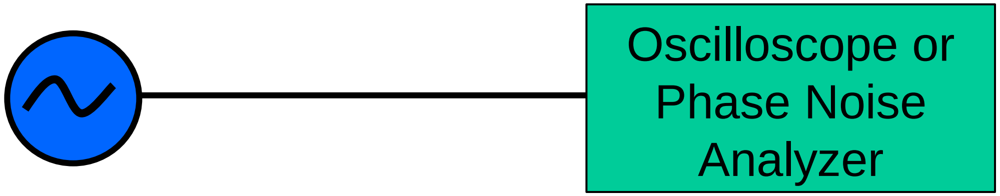
Jitter/Phase Noise Measurements: Golden Rule

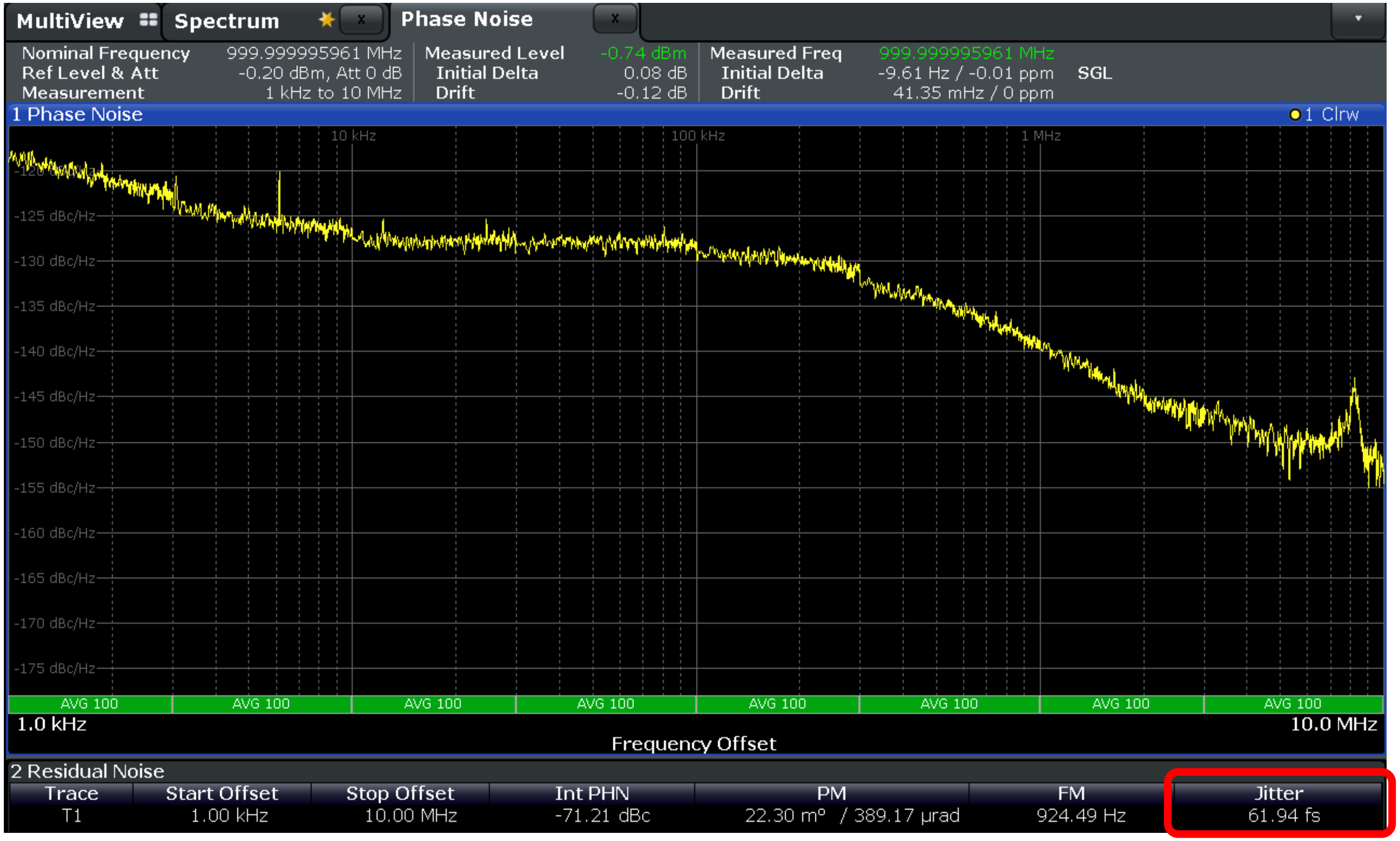


Oscilloscope or Phase Noise Analyzer

- **Jitter measured by an oscilloscope or phase noise analyzer is <u>always</u> the RMS sum of the clock jitter and the internal jitter of the measuring instrument**
- **Internal jitter/phase noise limits measurement sensitivity**
- **Examples:**
  - **Clock Jitter: 1ps Instrument Jitter: 1ps → Measured Jitter: 1.4ps**
  - **Clock Jitter: 500fs Instrument Jitter: 1ps → Measured Jitter: 1.118ps**
  - **Clock Jitter: 500fs Instrument Jitter: 300fs → Measured Jitter: 583fs**
  - **Clock Jitter: 200fs Instrument Jitter: 5fs → Measured Jitter: 200.06fs**

Measurement on FSW Spectrum Analyzer

- Total RMS Jitter (RJ): 61.94 fs



Nominal Frequency	999.999995961 MHz	Measured Level	-0.74 dBm
Ref Level & Att	-0.20 dBm, Att 0 dB	Initial Delta	0.08 dB
Measurement	1 kHz to 10 MHz	Drift	-0.12 dB

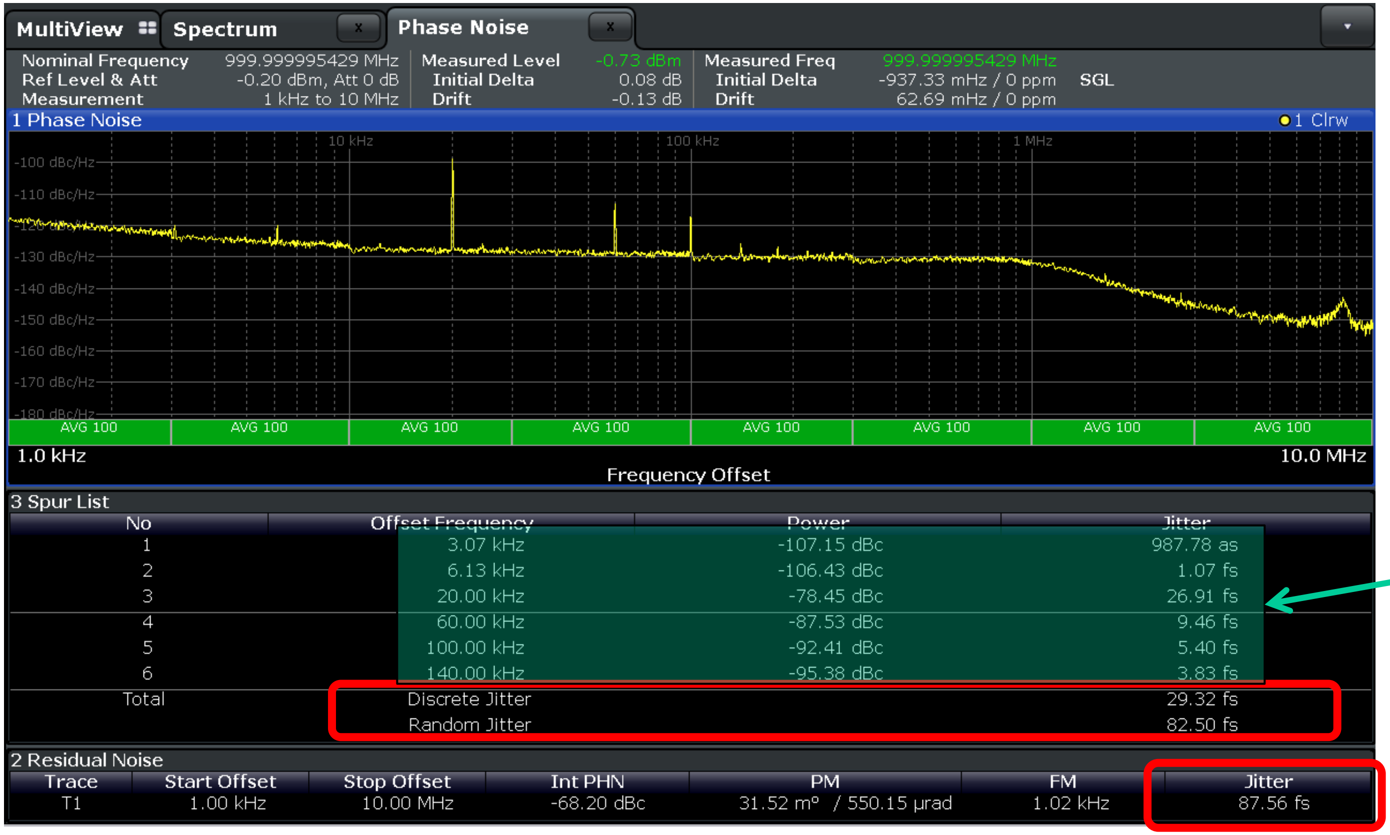
Measured Freq	999.999995961 MHz
Initial Delta	-9.61 Hz / -0.01 ppm
Drift	41.35 mHz / 0 ppm

2 Residual Noise

Trace	Start Offset	Stop Offset	Int PHN	PM	FM	Jitter
T1	1.00 kHz	10.00 MHz	-71.21 dBc	22.30 m° / 389.17 µrad	924.49 Hz	61.94 fs

Measurement on FSW Spectrum Analyzer (w/spurs)

- DJ: 29.32 fs RJ: 82.50 fs TJ: 87.56 fs



Nominal Frequency 999.999995429 MHz
Ref Level & Att -0.20 dBm, Att 0 dB
Measurement 1 kHz to 10 MHz
Measured Level -0.73 dBm
Initial Delta 0.08 dB
Drift -0.13 dB
Measured Freq 999.999995429 MHz
Initial Delta -937.33 mHz / 0 ppm
Drift 62.69 mHz / 0 ppm
SGL

3 Spur List

No	Offset Frequency	Power	Jitter
1	3.07 kHz	-107.15 dBc	987.78 as
2	6.13 kHz	-106.43 dBc	1.07 fs
3	20.00 kHz	-78.45 dBc	26.91 fs
4	60.00 kHz	-87.53 dBc	9.46 fs
5	100.00 kHz	-92.41 dBc	5.40 fs
6	140.00 kHz	-95.38 dBc	3.83 fs
Total	Discrete Jitter		29.32 fs
	Random Jitter		82.50 fs

2 Residual Noise

Trace	Start Offset	Stop Offset	Int PHN	PM	FM	Jitter
T1	1.00 kHz	10.00 MHz	-68.20 dBc	31.52 m° / 550.15 µrad	1.02 kHz	87.56 fs

Individual discrete jitter contributions

Phase Noise Measurement Instruments

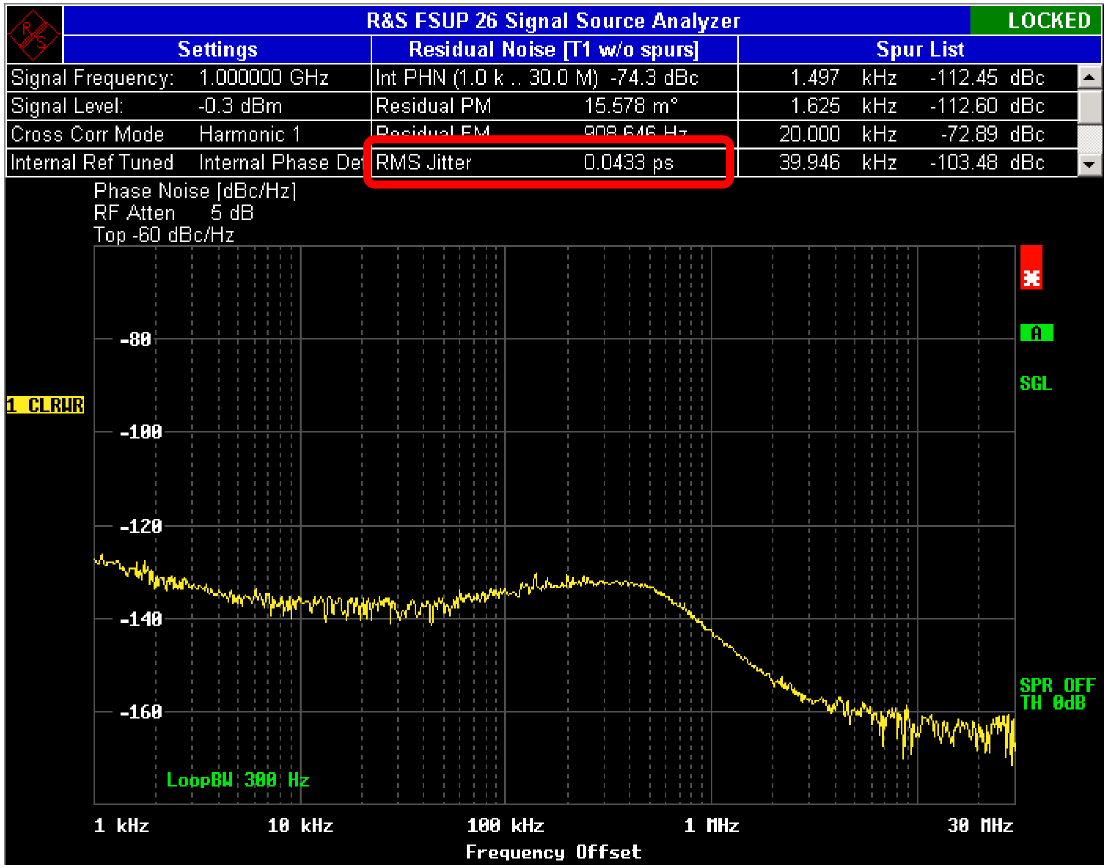
- Spectrum analyzer (with a phase noise personality option) is a good way to measure phase noise/jitter
- Sensitivity is limited by spectrum analyzer architecture and internal local oscillator phase noise
- Phase noise analyzer (or Signal Source Analyzer) uses a different measurement technique to get the best possible sensitivity

FSW Spectrum Analyzer

FSUP Signal Source Analyzer

Phase Noise Measurement on FSUP

- Total RMS Jitter (RJ)
  - 43.3 fs

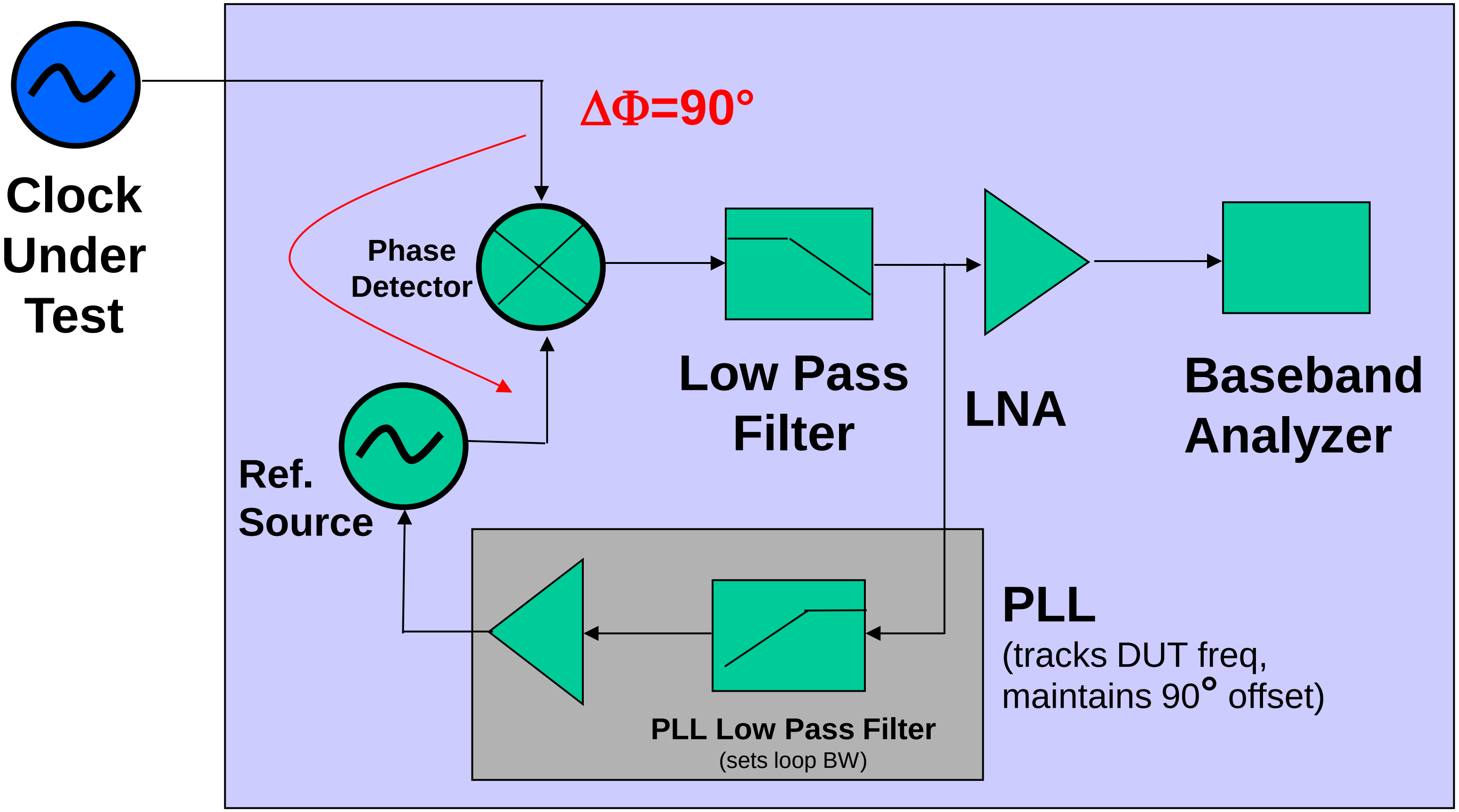


R&S FSUP 26 Signal Source Analyzer — LOCKED

Settings		Residual Noise [T1 w/o spurs]		Spur List			
Signal Frequency:	1.000000 GHz	Int PHN (1.0 k .. 30.0 M)	-74.3 dBc	1.497	kHz	-112.45	dBc
Signal Level:	-0.3 dBm	Residual PM	15.578 m°	1.625	kHz	-112.60	dBc
Cross Corr Mode	Harmonic 1	Residual FM	908.646 Hz	20.000	kHz	-72.89	dBc
Internal Ref Tuned	Internal Phase Det	RMS Jitter	0.0433 ps	39.946	kHz	-103.48	dBc

Phase Noise Measurement

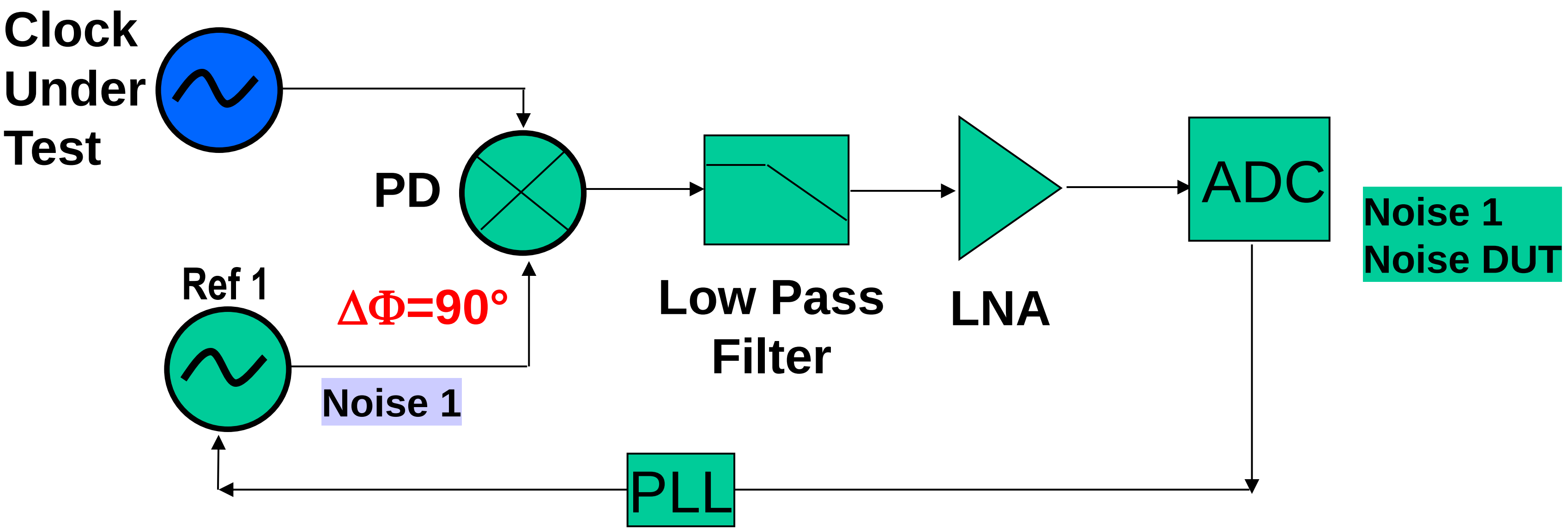
Phase Detector Technique



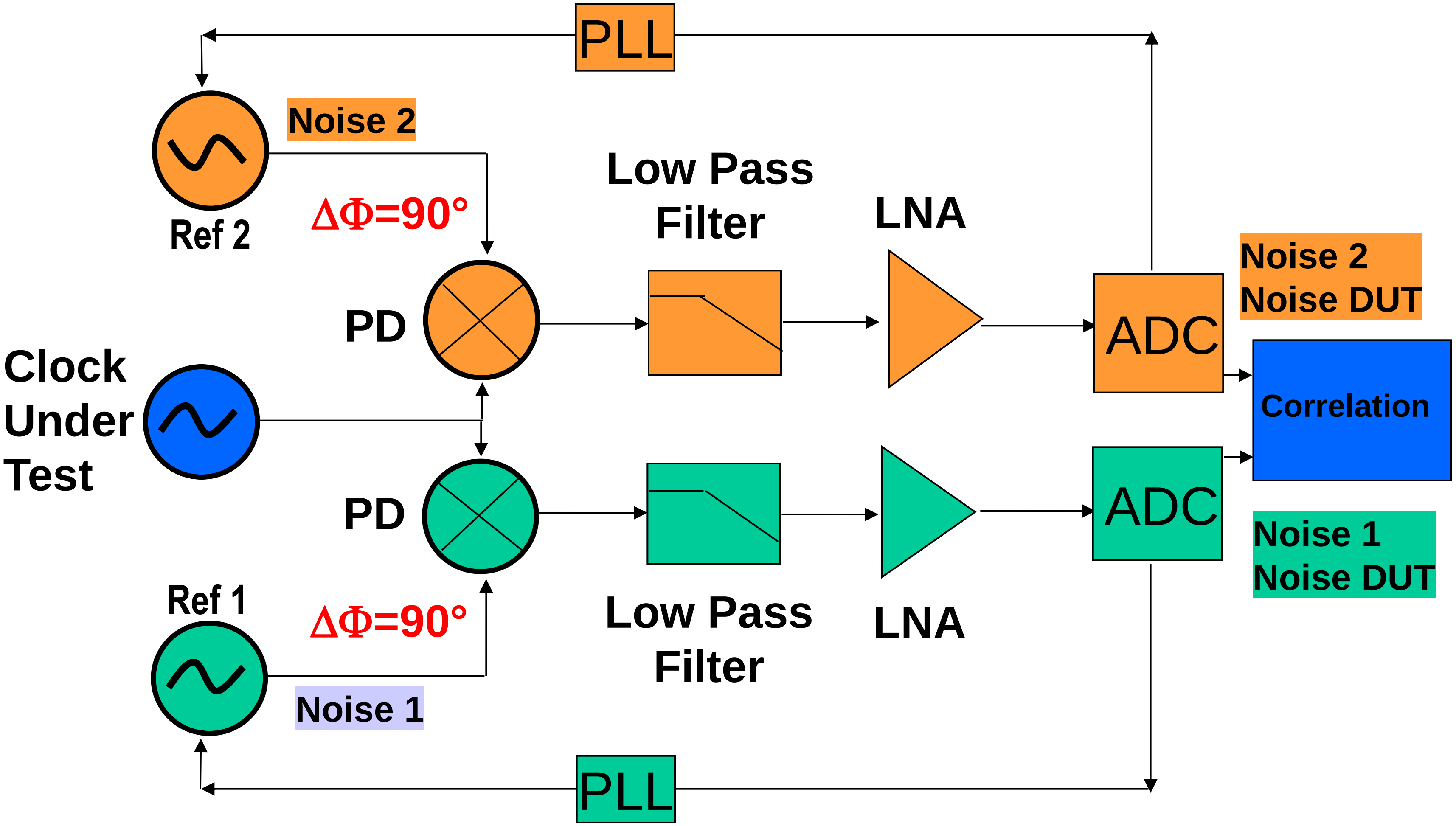
PLL
(tracks DUT freq,
maintains 90° offset)

Reference source is tuned to same frequency as clock with 90° phase offset (quadrature)

Phase Detector without Cross-Correlation



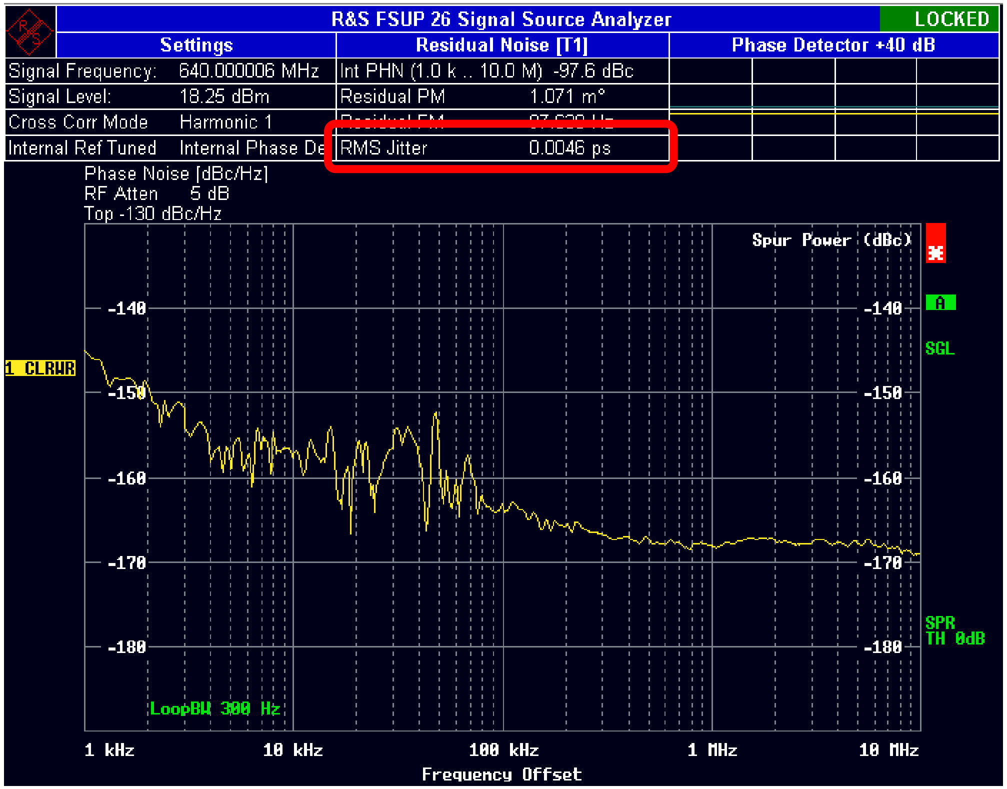
Phase Detector with Cross-Correlation



Cross-correlating both measurements reduces effective noise from reference sources up to 20dB – up to 10x improvement in jitter measurement sensitivity

Measurement of a Very Low Jitter Device with FSUP

- Crystal based 640MHz oscillator with very low phase noise/jitter
  - **4.6fs**
- Cross-correlation technique provides this measurement sensitivity



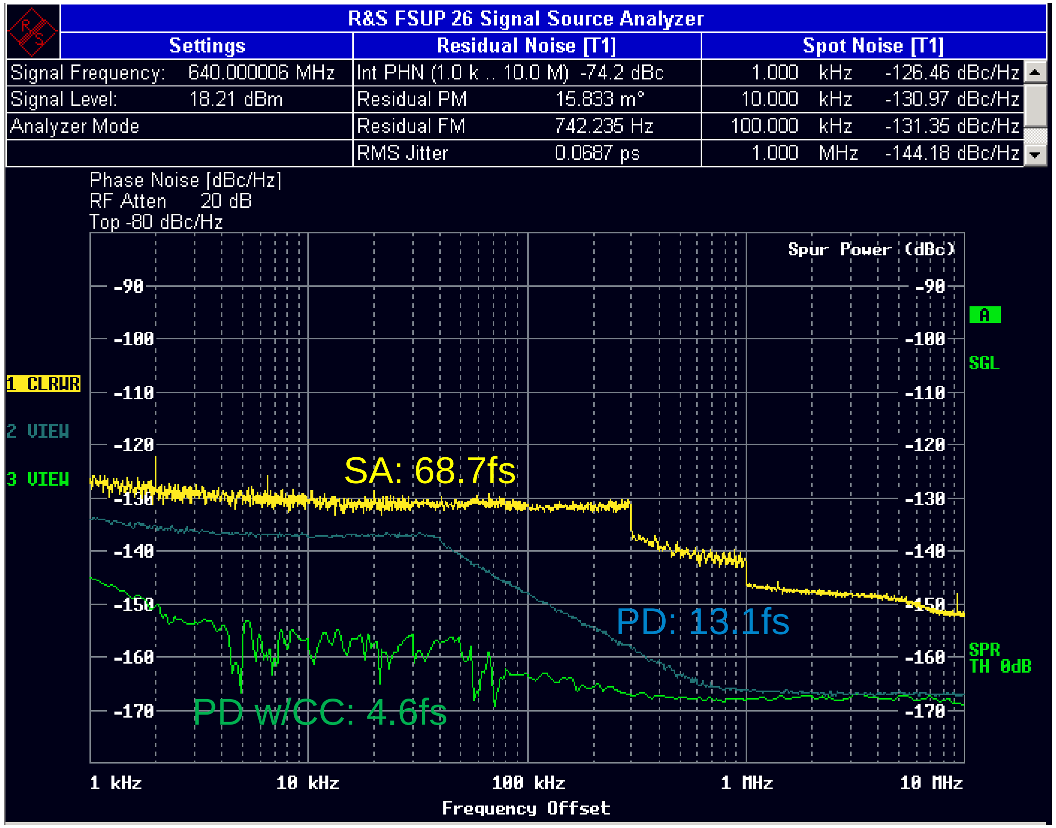
R&S FSUP 26 Signal Source Analyzer — LOCKED

Settings		Residual Noise [T1]	
Signal Frequency:	640.000006 MHz	Int PHN (1.0 k .. 10.0 M)	-97.6 dBc
Signal Level:	18.25 dBm	Residual PM	1.071 m°
Cross Corr Mode	Harmonic 1	Residual FM	[illegible]
Internal Ref Tuned	Internal Phase De	RMS Jitter	0.0046 ps

Phase Noise [dBc/Hz]
RF Atten 5 dB
Top -130 dBc/Hz

Phase Noise/Jitter Measurement

Spectrum Analyzer vs Phase Detector vs PD with Cross-Correlation



R&S FSUP 26 Signal Source Analyzer

Settings		Residual Noise [T1]		Spot Noise [T1]	
Signal Frequency:	640.000006 MHz	Int PHN (1.0 k .. 10.0 M)	-74.2 dBc	1.000 kHz	-126.46 dBc/Hz
Signal Level:	18.21 dBm	Residual PM	15.833 m°	10.000 kHz	-130.97 dBc/Hz
Analyzer Mode		Residual FM	742.235 Hz	100.000 kHz	-131.35 dBc/Hz
		RMS Jitter	0.0687 ps	1.000 MHz	-144.18 dBc/Hz

SA: 68.7fs

PD: 13.1fs

PD w/CC: 4.6fs

Same signal measured with three different techniques

Phase Detector with Cross-Correlation is the most sensitive way to measure phase noise and jitter

Jitter Measurement Instruments

High
Flexibility

Real time (Oscilloscope)

- Single-shot or repetitive events (clock or data)
- Bandwidths typically 60 MHz to >30 GHz
- Lowest sensitivity (highest jitter noise floor)
- Measures adjacent cycles

Repetitive (Sampling Oscilloscope)

- Repetitive events only (clock or data)
- Bandwidths typically 20 GHz to 100 GHz
- Generally can not discriminate based on jitter frequency
- Cannot measure adjacent cycles

Phase noise (SA / Phase Noise Analyzer)

- Clock signals only (50% duty cycle)
- Integrate phase noise over frequency to measure jitter
- Highest sensitivity (lowest jitter noise floor)
- Cannot measure adjacent cycles

High
Sensitivity

Phase Noise Measurement (including spurs)

- FSUP Phase Noise Analyzer requires manual calculation of discrete jitter

- Total RMS Jitter (RJ & DJ)
  - 67.5 fs

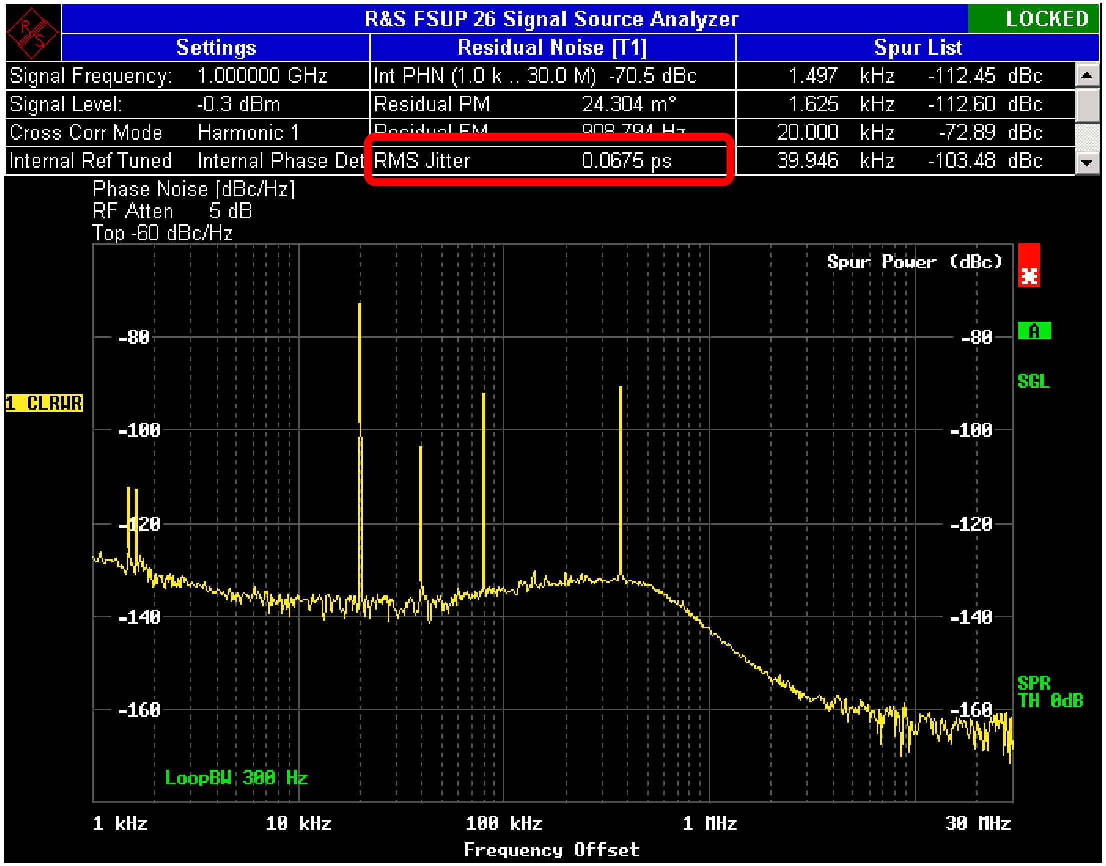
- Total Jitter (TJ) is RMS sum of RJ and DJ:

$$TJ = \sqrt{RJ^2 + DJ^2}$$

- DJ can be calculated as:

$$DJ = \sqrt{TJ^2 - RJ^2}$$

- TJ = 67.5 fs, RJ = 43.3 fs
  - Calculated DJ = 51.8 fs



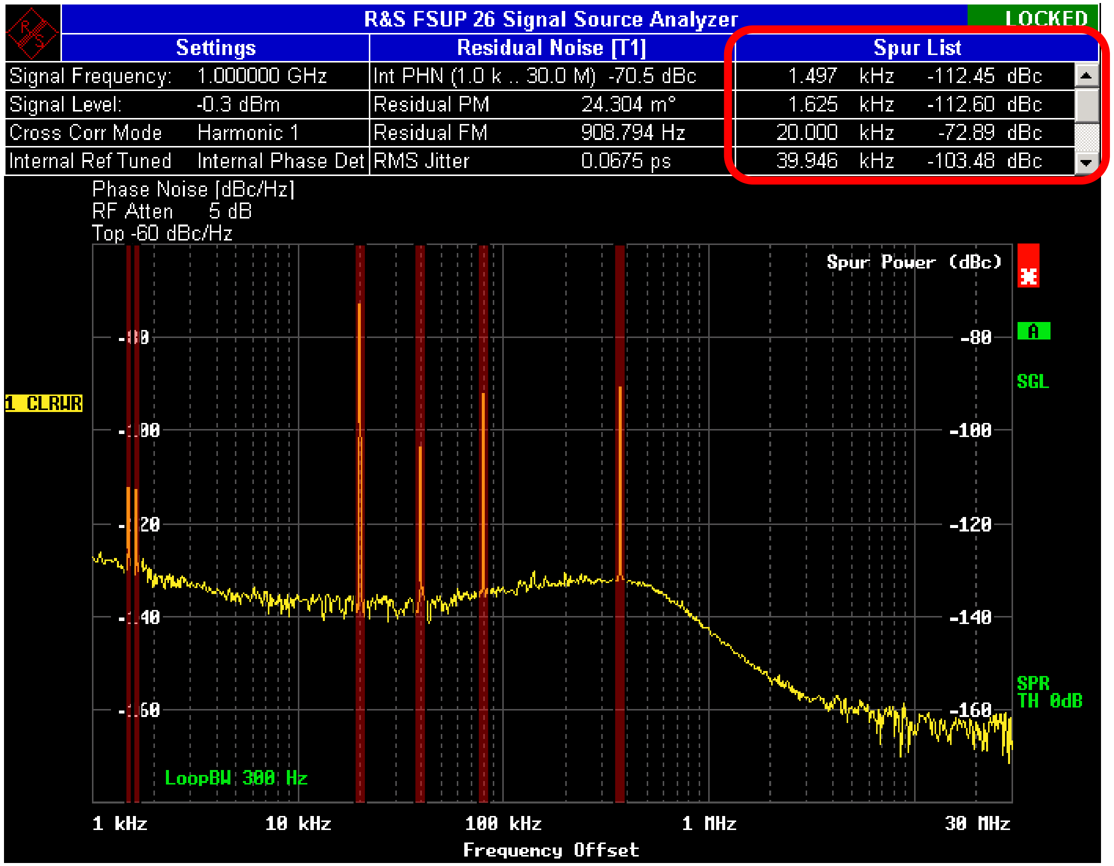
R&S FSUP 26 Signal Source Analyzer — LOCKED

Settings		Residual Noise [T1]		Spur List		
Signal Frequency:	1.000000 GHz	Int PHN (1.0 k .. 30.0 M)	-70.5 dBc	1.497	kHz	-112.45 dBc
Signal Level:	-0.3 dBm	Residual PM	24.304 m°	1.625	kHz	-112.60 dBc
Cross Corr Mode	Harmonic 1	Residual FM	908.794 Hz	20.000	kHz	-72.89 dBc
Internal Ref Tuned	Internal Phase Det	RMS Jitter	0.0675 ps	39.946	kHz	-103.48 dBc

Phase Noise [dBc/Hz]
RF Atten 5 dB
Top -60 dBc/Hz

Measurement of DJ from Individual Contributors

- What is the contribution of individual discrete components (spurs) to total RMS jitter?
- Use the spur level values from the Spur List

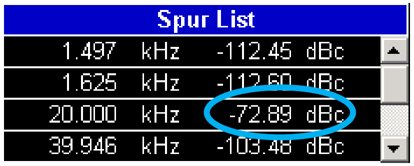


R&S FSUP 26 Signal Source Analyzer — LOCKED

Settings		Residual Noise [T1]		Spur List			
Signal Frequency:	1.000000 GHz	Int PHN (1.0 k .. 30.0 M)	-70.5 dBc	1.497	kHz	-112.45	dBc
Signal Level:	-0.3 dBm	Residual PM	24.304 m°	1.625	kHz	-112.60	dBc
Cross Corr Mode	Harmonic 1	Residual FM	908.794 Hz	20.000	kHz	-72.89	dBc
Internal Ref Tuned	Internal Phase Det	RMS Jitter	0.0675 ps	39.946	kHz	-103.48	dBc

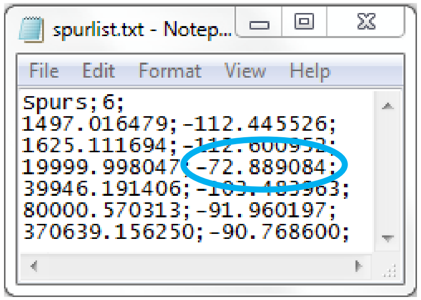
Measurement of DJ from Individual Contributors

- General formula to convert phase noise to jitter is: $\frac{1}{2\pi \cdot f_c}\sqrt{2\int \mathcal{L}(f)df}$
- Integral under the square root, $\int \mathcal{L}(f)df$, is “integrated phase noise”
- For discrete spurs the integrated phase noise is simply the ‘dBc’ level
- Jitter for a spur can be calculated from its dBc level using: $\frac{10^{dBc/20}}{\sqrt{2}\cdot\pi\cdot f_c}$
- Example: 20kHz spur at -72.889dBc on a 1GHz clock:



Spur List	
1.497 kHz	-112.45 dBc
1.625 kHz	-112.60 dBc
20.000 kHz	-72.89 dBc
39.946 kHz	-103.48 dBc

→



```
Spurs;6;
1497.016479;-112.445526;
1625.111694;-112.600953;
19999.998047;-72.889084;
39946.191406;-103.483963;
80000.570313;-91.960197;
370639.156250;-90.768600;
```

(exported spur list)

→

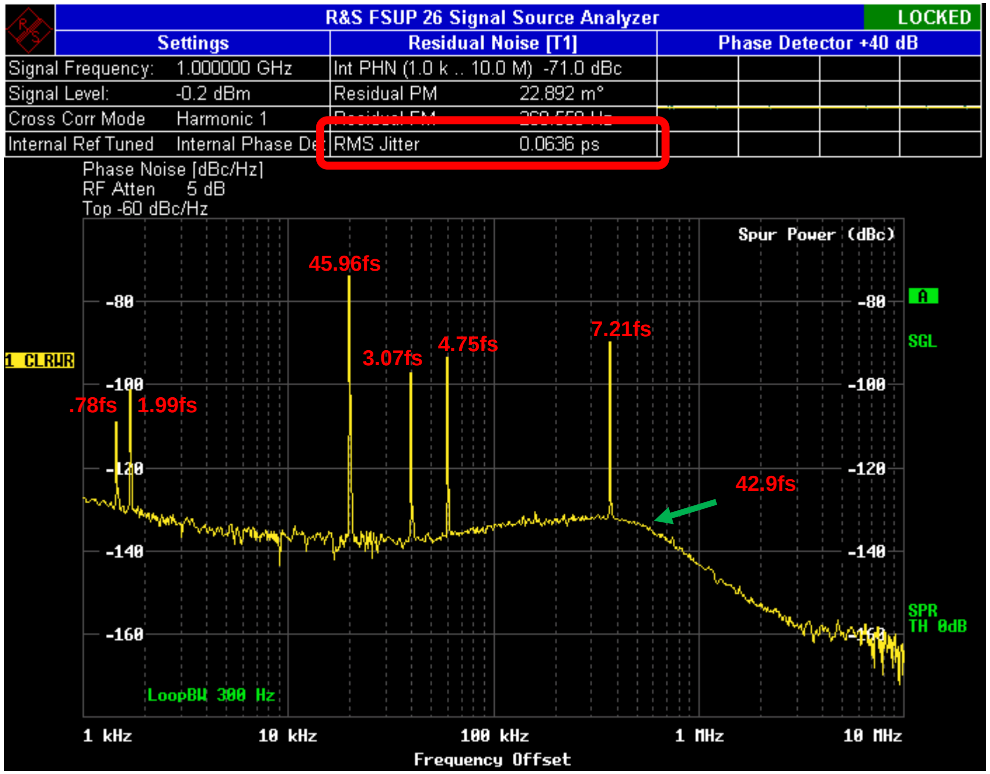
$$\frac{10^{dBc/20}}{\sqrt{2}\cdot\pi\cdot f_c} = \frac{10^{(-72.889/20)}}{\sqrt{2}\cdot\pi\cdot 10^9} = 51.04\,fs$$

Summary of Total Jitter

- TJ is RSS of all contributors

$$TJ = \sqrt{DJ_1^{\,2} + DJ_2^{\,2} + DJ_3^{\,2} + DJ_4^{\,2} + DJ_5^{\,2} + DJ_6^{\,2} + RJ^{\,2}}$$

$$= \sqrt{.78^2 + 1.99^2 + 45.96^2 + 3.07^2 + 4.75^2 + 7.21^2 + 42.9^2} = 63.6\,fs$$



R&S FSUP 26 Signal Source Analyzer LOCKED

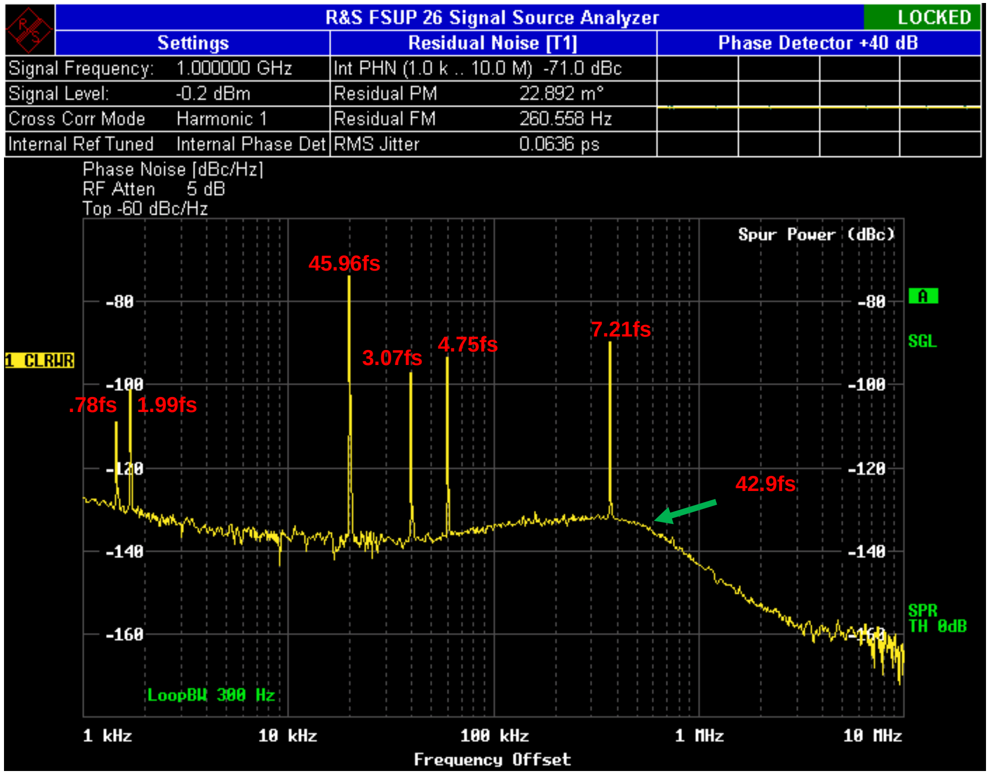
Settings		Residual Noise [T1]	
Signal Frequency:	1.000000 GHz	Int PHN (1.0 k .. 10.0 M)	-71.0 dBc
Signal Level:	-0.2 dBm	Residual PM	22.892 m°
Cross Corr Mode	Harmonic 1	Residual FM	[illegible]
Internal Ref Tuned	Internal Phase De	RMS Jitter	0.0636 ps

Phase Detector +40 dB

Phase Noise [dBc/Hz]
RF Atten 5 dB
Top -60 dBc/Hz

Summary of Total Jitter

- A simple utility can automate these calculations

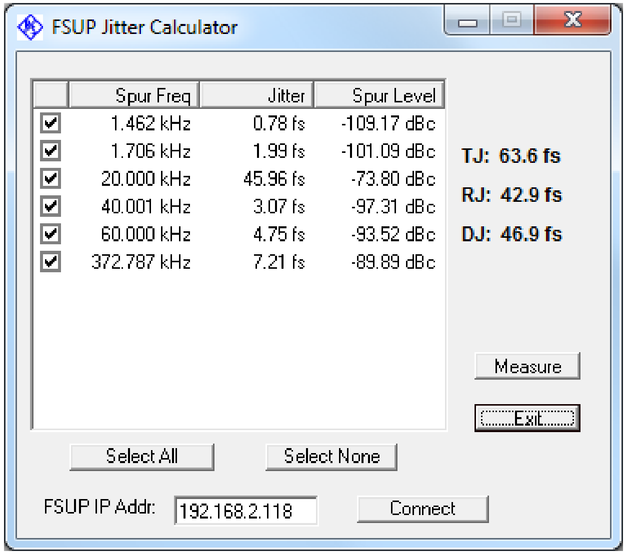


R&S FSUP 26 Signal Source Analyzer — LOCKED

Settings		Residual Noise [T1]	
Signal Frequency:	1.000000 GHz	Int PHN (1.0 k .. 10.0 M)	-71.0 dBc
Signal Level:	-0.2 dBm	Residual PM	22.892 m°
Cross Corr Mode	Harmonic 1	Residual FM	260.558 Hz
Internal Ref Tuned	Internal Phase Det	RMS Jitter	0.0636 ps

Phase Detector +40 dB

Phase Noise [dBc/Hz]
RF Atten 5 dB
Top -60 dBc/Hz



FSUP Jitter Calculator

	Spur Freq	Jitter	Spur Level
☑	1.462 kHz	0.78 fs	-109.17 dBc
☑	1.706 kHz	1.99 fs	-101.09 dBc
☑	20.000 kHz	45.96 fs	-73.80 dBc
☑	40.001 kHz	3.07 fs	-97.31 dBc
☑	60.000 kHz	4.75 fs	-93.52 dBc
☑	372.787 kHz	7.21 fs	-89.89 dBc

TJ: 63.6 fs

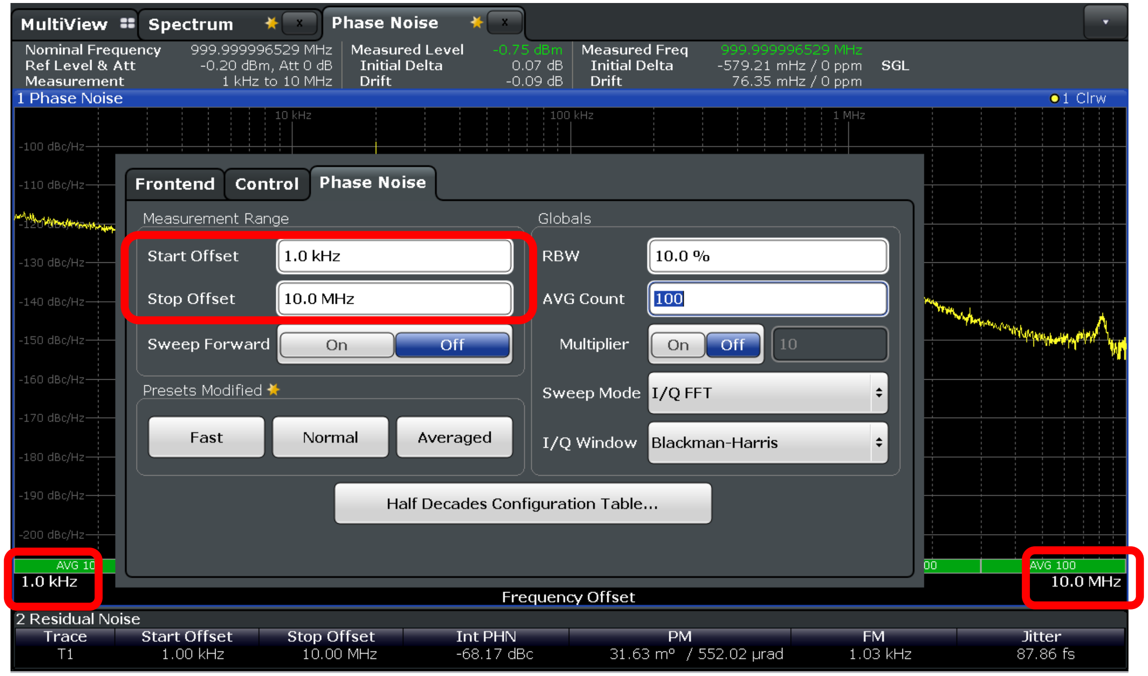
RJ: 42.9 fs

DJ: 46.9 fs

FSUP IP Addr: 192.168.2.118

Frequency Offset Range is Settable

- Measurements in this presentation have used offset range of 1kHz to 10MHz or 30MHz
- Upper offset range can be as high as 30GHz
- Lower offset can be as low as 1Hz on a SA or 10mHz on a Phase Noise Analyzer



Nominal Frequency 999.999996529 MHz
Ref Level & Att -0.20 dBm, Att 0 dB
Measurement 1 kHz to 10 MHz
Measured Level -0.75 dBm
Initial Delta 0.07 dB
Drift -0.09 dB
Measured Freq 999.999996529 MHz
Initial Delta -579.21 mHz / 0 ppm
Drift 76.35 mHz / 0 ppm
SGL

Start Offset: 1.0 kHz
Stop Offset: 10.0 MHz
Sweep Forward: On [✓ Off]
RBW: 10.0 %
AVG Count: 100
Multiplier: On [✓ Off] 10
Sweep Mode: I/Q FFT
I/Q Window: Blackman-Harris

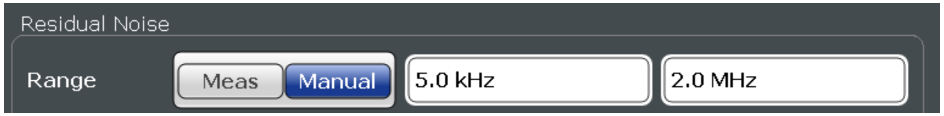
1.0 kHz
10.0 MHz

2 Residual Noise

Trace	Start Offset	Stop Offset	Int PHN	PM	FM	Jitter
T1	1.00 kHz	10.00 MHz	-68.17 dBc	31.63 m° / 552.02 µrad	1.03 kHz	87.86 fs

Jitter Calculation over Subset of Measured Range

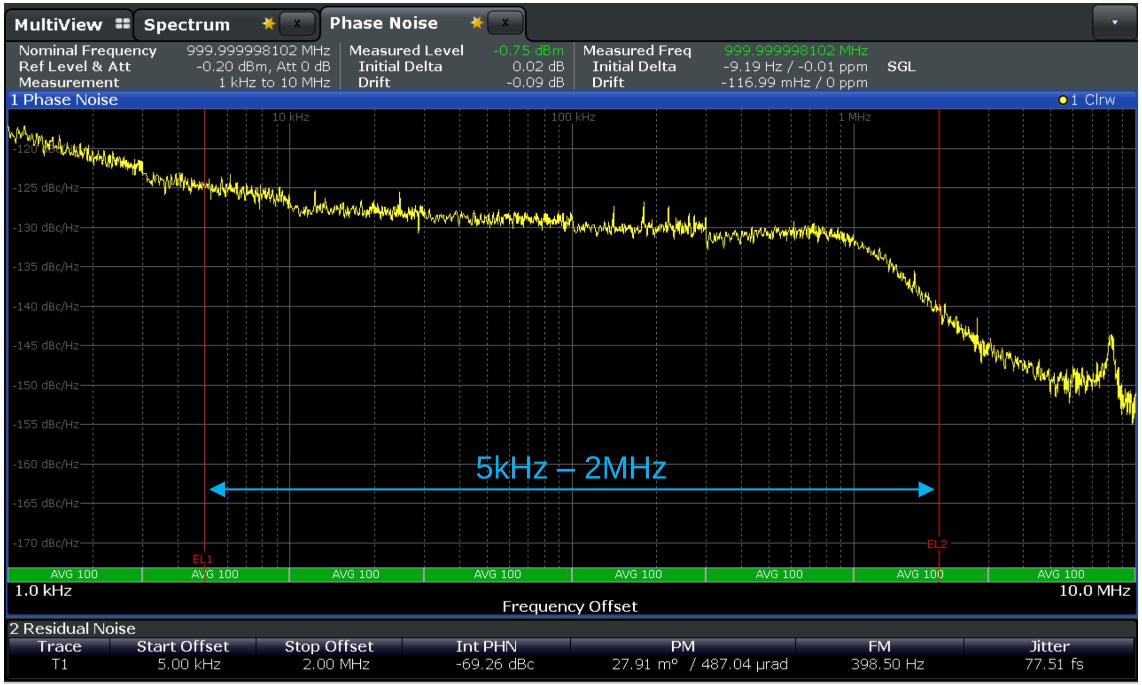
- By default, jitter is calculated over entire measured offset range
- A subset of the offset range may be specified for the jitter calculation



Residual Noise

Range: Meas [✓ Manual] 5.0 kHz 2.0 MHz

- Jitter calculated over full measured range of 1kHz – 10MHz is **83.09fs**
- For reduced range of 5kHz – 2MHz it is **77.51fs**



Nominal Frequency 999.999998102 MHz
Ref Level & Att -0.20 dBm, Att 0 dB
Measurement 1 kHz to 10 MHz
Measured Level -0.75 dBm
Initial Delta 0.02 dB
Drift -0.09 dB
Measured Freq 999.999998102 MHz
Initial Delta -9.19 Hz / -0.01 ppm SGL
Drift -116.99 mHz / 0 ppm

5kHz – 2MHz

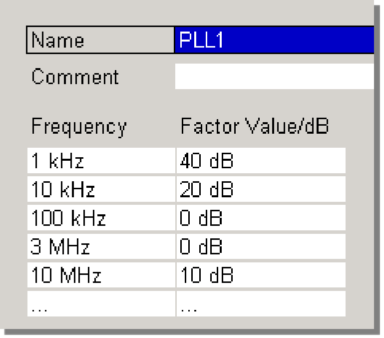
2 Residual Noise

Trace	Start Offset	Stop Offset	Int PHN	PM	FM	Jitter
T1	5.00 kHz	2.00 MHz	-69.26 dBc	27.91 m° / 487.04 µrad	398.50 Hz	77.51 fs

Jitter Calculation with PLL Weighting

- Basic measurement shows raw performance of clock
- Real systems use PLLs
- FSUP can apply a weighting function to simulate the frequency response of a PLL

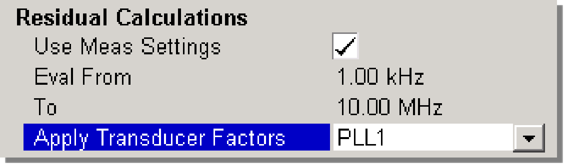
Define PLL Freq Response



Name: PLL1

Comment:

Frequency	Factor Value/dB
1 kHz	40 dB
10 kHz	20 dB
100 kHz	0 dB
3 MHz	0 dB
10 MHz	10 dB
…	…



Residual Calculations

Use Meas Settings ☑

Eval From 1.00 kHz

To 10.00 MHz

Apply Transducer Factors PLL1

Select PLL to apply to measurement

R&S FSUP 26 Signal Source Analyzer LOCKED

Settings		wg. Residual Noise [T1]	
Signal Frequency:	640.000006 MHz	Int PHN (1.0 k .. 10.0 M)	-100.4 dBc
Signal Level:	18.25 dBm	Residual PM	771.181 µ°
Cross Corr Mode	Harmonic 1	Residual FM	48.398 Hz
Internal Ref Tuned	Internal Phase Det	RMS Jitter	0.0033 ps

Phase Detector +40 dB

Phase Noise [dBc/Hz]
RF Atten 5 dB
Top -130 dBc/Hz

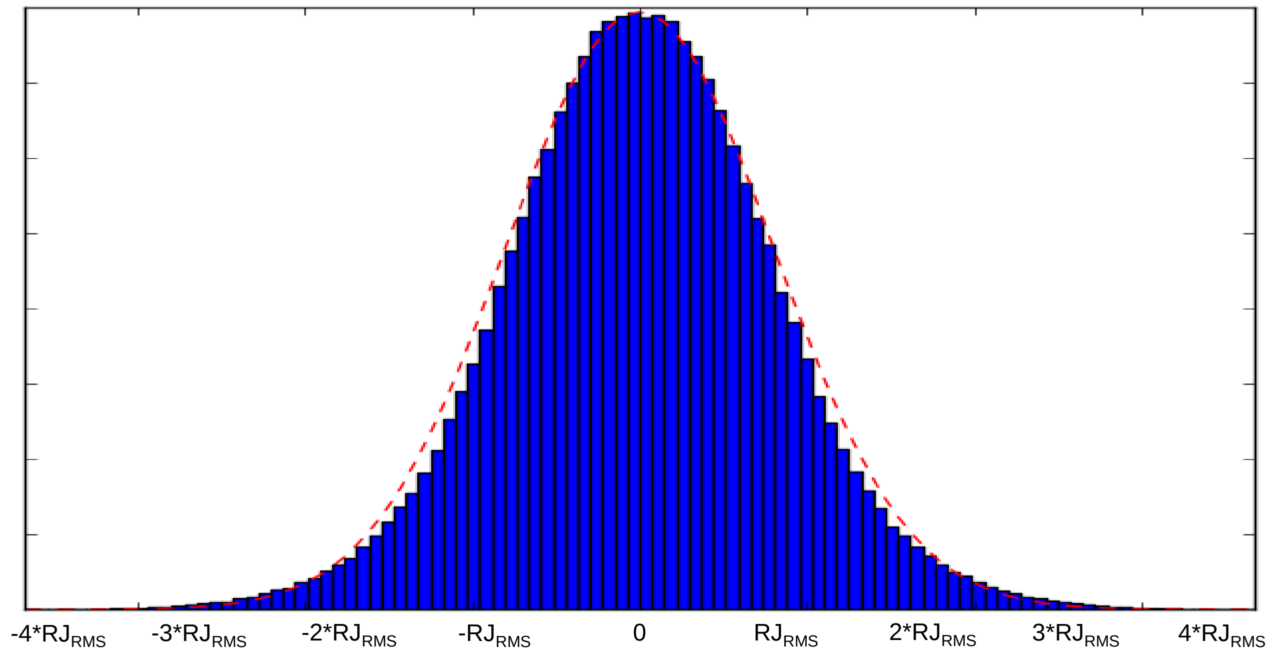
'PLL1' weighting curve

Unweighted Jitter: 4.6fs Weighted Jitter: 3.3fs

Calculating Peak-to-Peak Jitter from RMS Jitter

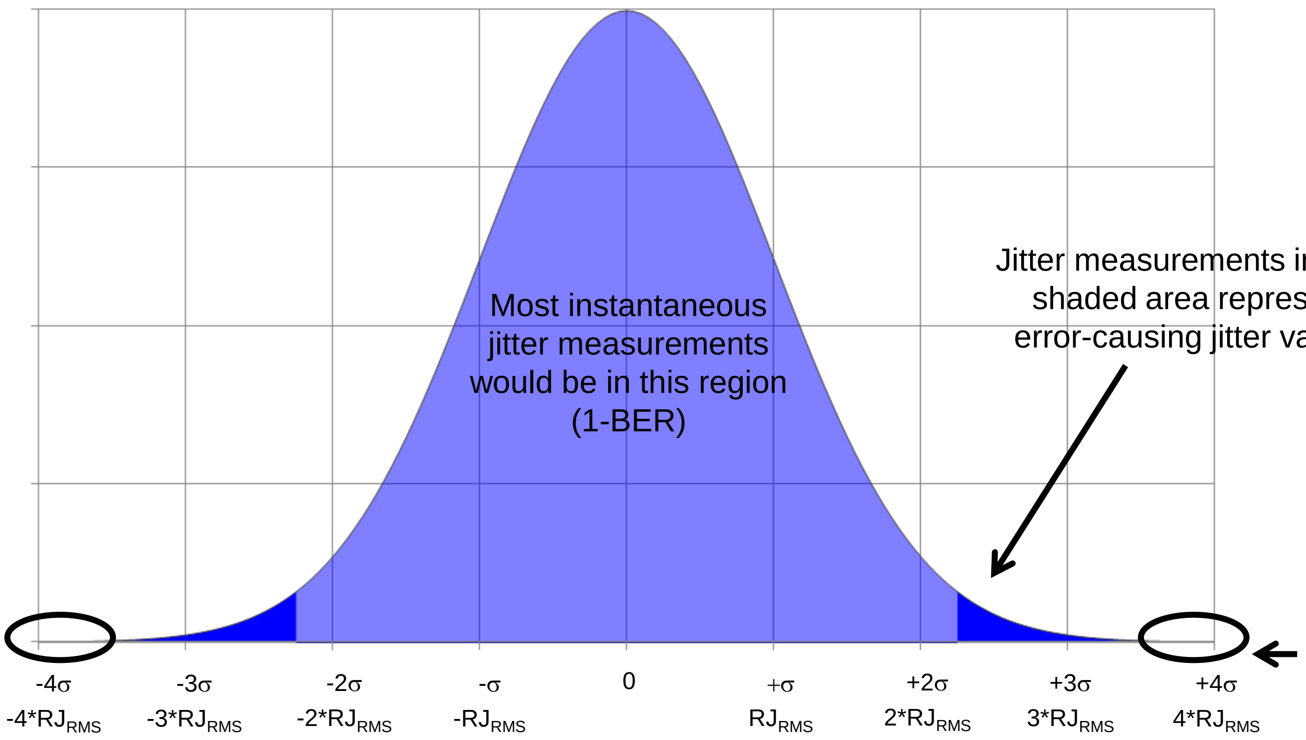
- Time-domain histogram of many oscilloscope-based jitter measurements shows a Gaussian distribution when jitter is purely random (RJ)

- The standard deviation (σ) is the RMS jitter (RJ)



Calculating Peak-to-Peak Jitter from RMS Jitter

- Phase noise measurement doesn’t provide a histogram, but does provide RMS jitter value (and therefore standard deviation)
- RJ has a Gaussian distribution so we can calculate pk-pk jitter for a given BER
  - Example: if BER=10^{-6} then we want 999,999 of 1,000,000 jitter measurements to fall in light shaded region, only 1 in dark shaded region



Most instantaneous jitter measurements would be in this region (1-BER)

Jitter measurements in dark shaded area represent error-causing jitter values

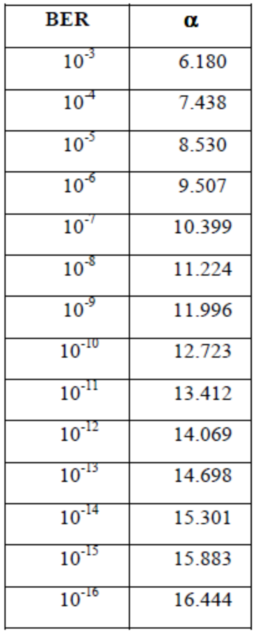
Never reaches 0% probability

Calculating Peak-to-Peak Jitter from RMS Jitter

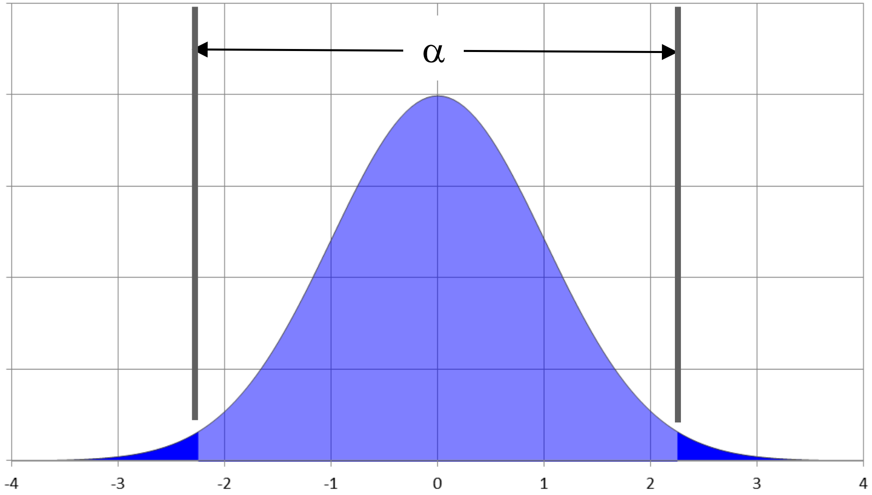
- We can use the complimentary Gaussian Error Function, erfc(x), to calculate peak-to-peak random jitter from RMS jitter

$$RJ_{pp} = \alpha * RJ_{RMS}$$ where is α is derived from: $$\frac{1}{2} erfc\left(\frac{\alpha}{2\sqrt{2}}\right) = BER$$

- Not closed form so use lookup table



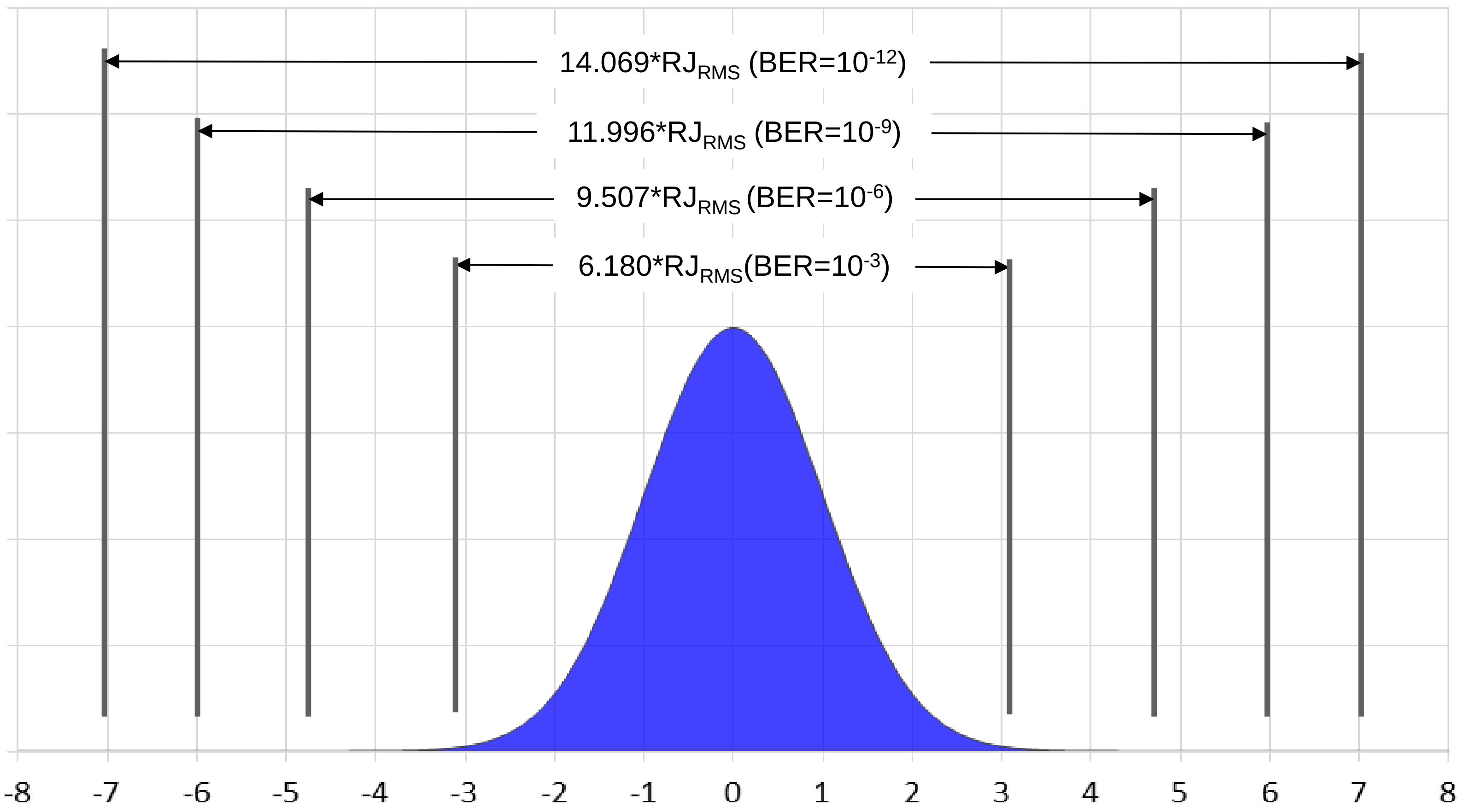
BER	α
10^{-3}	6.180
10^{-4}	7.438
10^{-5}	8.530
10^{-6}	9.507
10^{-7}	10.399
10^{-8}	11.224
10^{-9}	11.996
10^{-10}	12.723
10^{-11}	13.412
10^{-12}	14.069
10^{-13}	14.698
10^{-14}	15.301
10^{-15}	15.883
10^{-16}	16.444



Source: Maxim Application Note AN462

α vs. BER

- Factors to calculate RJ_{pp} from RJ_{RMS} based on BER
  - Example: $RJ_{pp} = 9.507 * RJ_{RMS}$ for $BER = 10^{-6}$



Useful References

- “Analysis of Jitter with the R&S FSUP Signal Source Analyzer”
  Rohde & Schwarz Application Note 1EF71
- “Converting Between RMS and Peak-to-Peak Jitter at a Specified BER”
  Maxim Integrated Application Note HFAN-4.0.2
- “Clock Jitter and Measurement”
  SiTime Application Note SiT-AN10007
- “A Primer on Jitter, Jitter Measurement and Phase-Locked Loops”
  Silicon Labs Application Note AN687
- “Determining Peak to Peak Frequency Jitter”
  Pletronics White Paper

Thanks for your attention!