Developments in Y-factor Noise Figure Measurements

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Agilent Technologies, Inc.

Anticipate __Accelerate __Achieve

Agenda

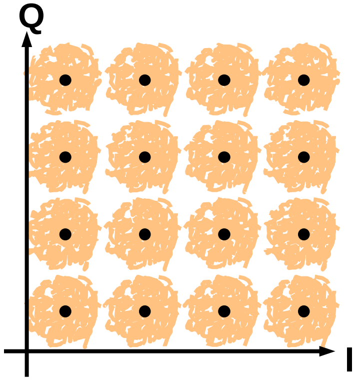
- Why measure noise figure?
- The Y-factor method of noise figure measurement
- When to use the Y-factor method
- Feature enhancements
- Measurement uncertainty
- Configuring a basic measurement
- Other methods (cold source)
- Further reading

Why Do We Care About Noise?

Noise causes system impairments

- Degrades image quality of TV, voice quality of cell phone
- Limits range of radar systems
- Causes increased bit-error rate in digital systems

How can we improve system signal-to-noise ratio (SNR)?



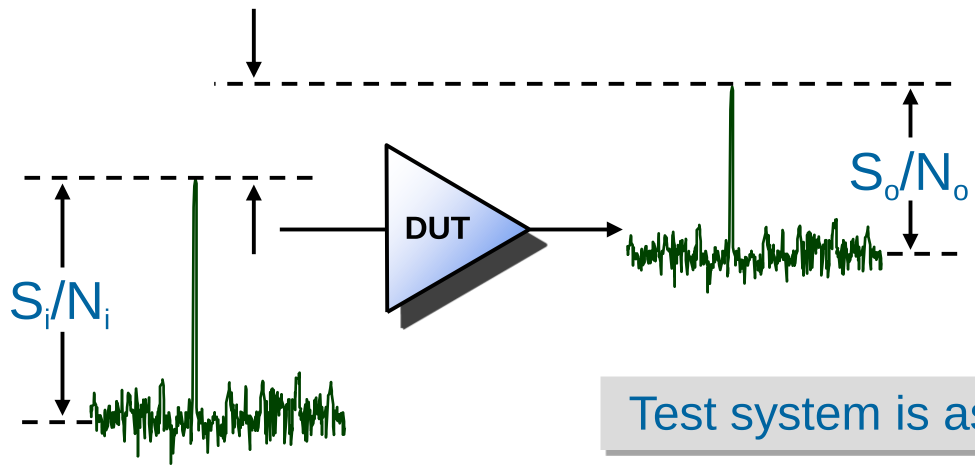
- Increase transmitter power (need larger antennas and/or bigger, more powerful amplifiers)
- Decrease path loss (this may not be under our control)
- Lower receiver-contributed noise (LNA at front end is critical)
- Generally easier and less expensive to decrease receiver noise than to increase transmitter power

Noise Figure Definition

Noise figure is defined in terms of SNR degradation:

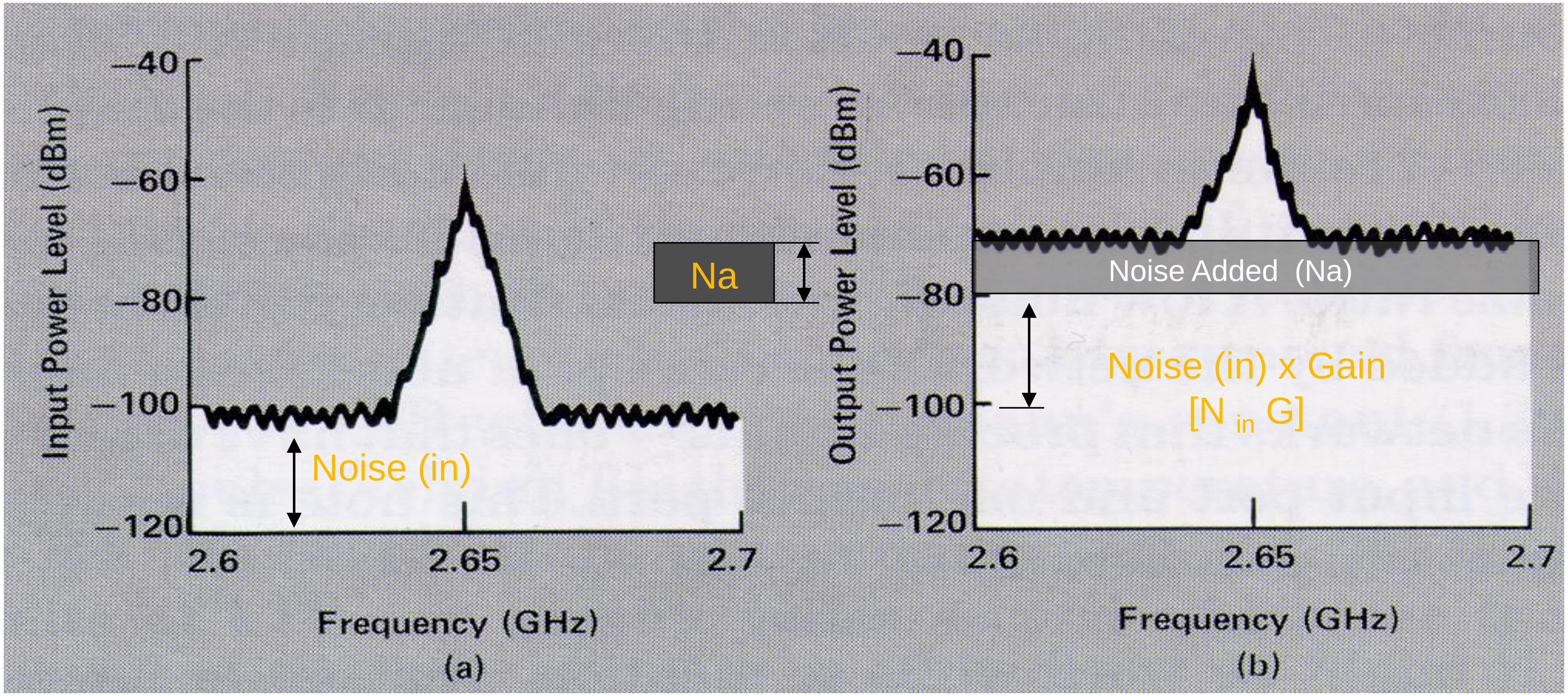
$$F = \frac{(S_i/N_i)}{(S_o/N_o)} = \frac{(N_o)}{(G \times N_i)} \qquad \text{(noise factor)}$$

$$NF = 10 \times \log(F) \qquad \text{(noise figure)}$$



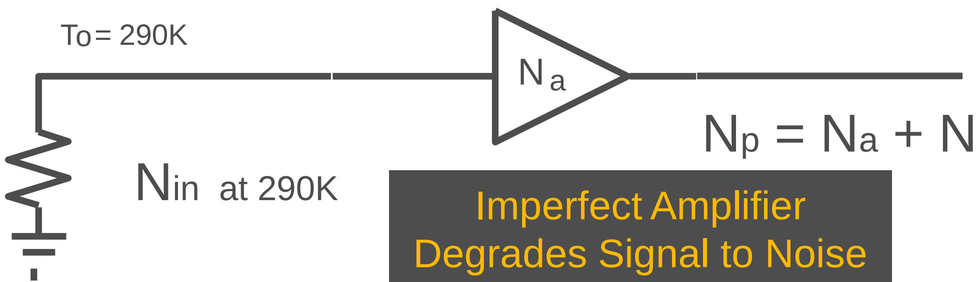
Test system is assumed to be 50 Ω

Noise Figure Graphically Defined



Gain 20dB

NF 10dB



$N_p = N_a + N_{in} G$

Imperfect Amplifier Degrades Signal to Noise Ratio

Effective Noise Temperature

Available noise power of a passive termination = kTB

- k is Boltzmann's constant (1.38 x 10^{-23} J/K)
- kTB = -174 dBm in a 1 Hz bandwidth
- For a given system bandwidth, noise is proportional to temperature

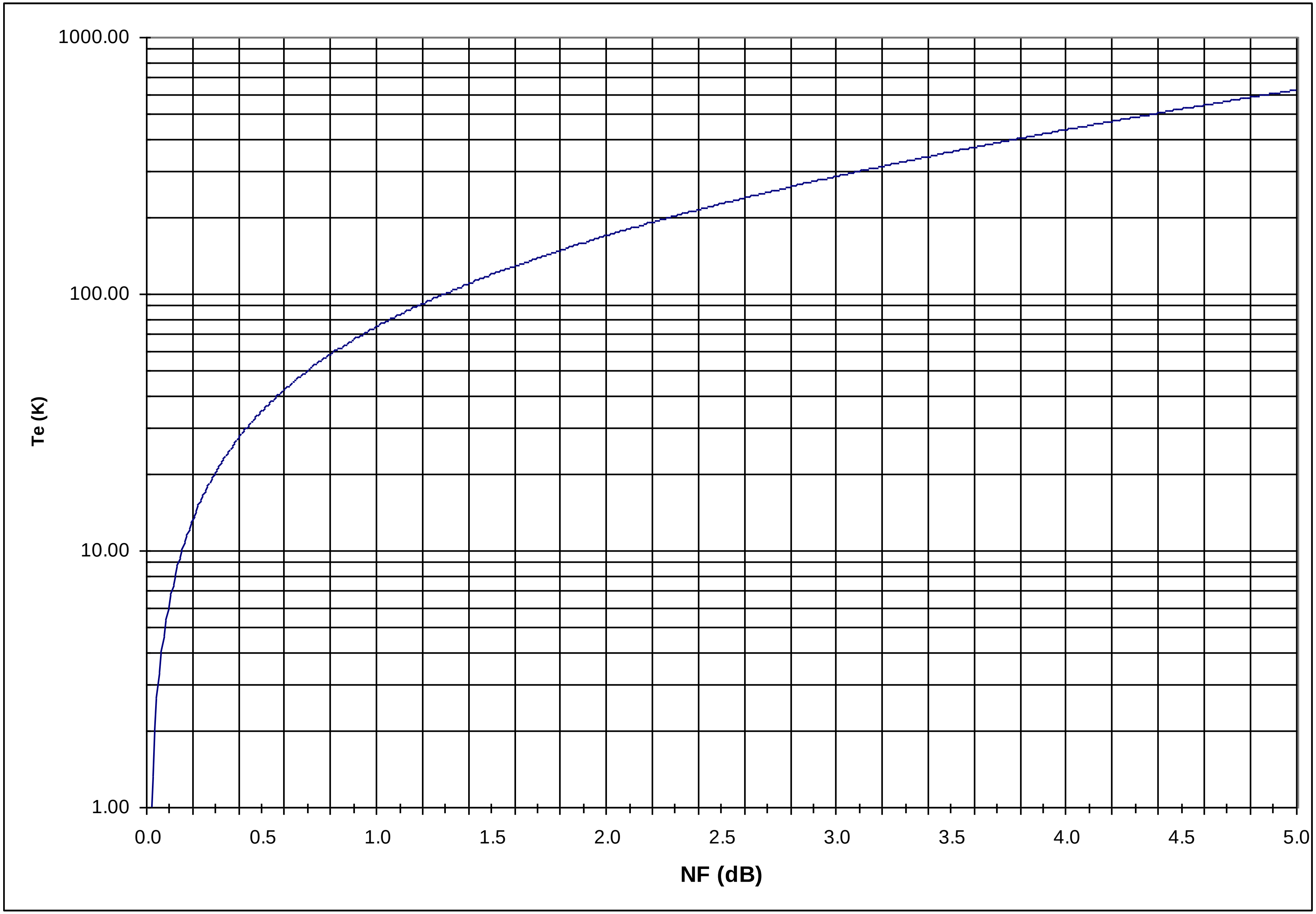
Amount of noise produced by a device can be expressed as an equivalent noise temperature (e.g. 15 dB ENR → 8880K)

Noise factor can be expressed as effective input noise temperature

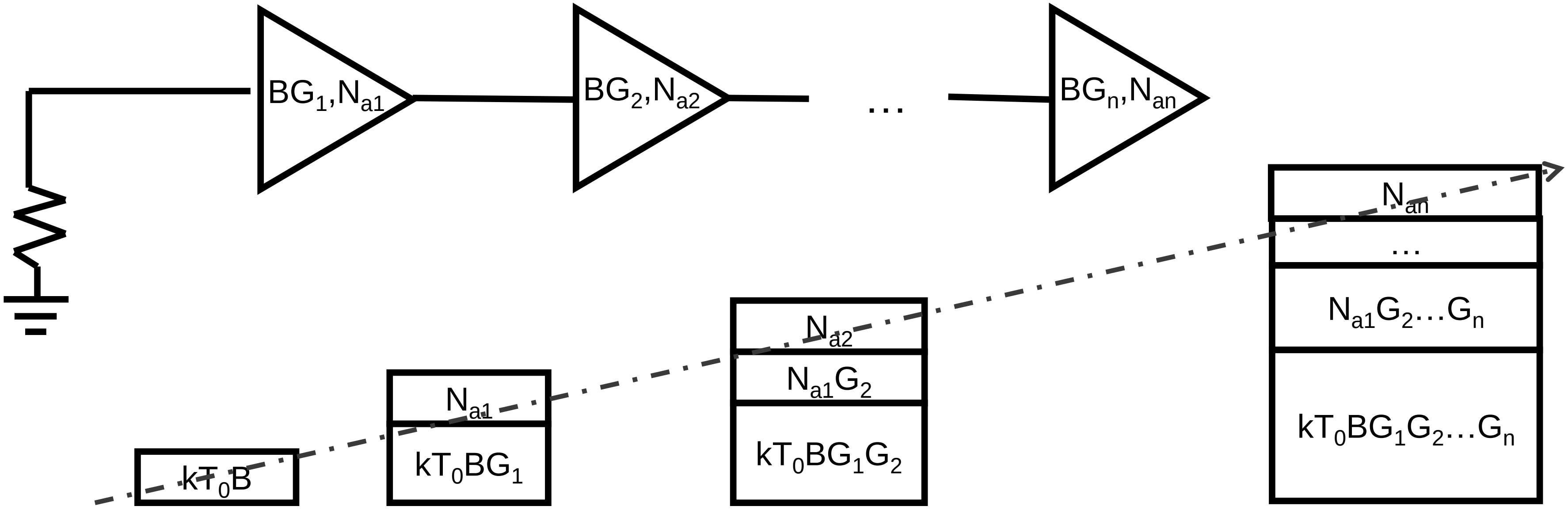
- Not the physical temperature of the input termination
- Theoretical temperature of input termination connected to a noiseless device resulting in the same output noise power

$$T_e = 290 \times (F-1)$$

Effective Temperature Versus Noise Figure



The Friis Equation (cascade noise equation)



Noise adds through each stage but SNR doesn't necessarily degrade. With a page of algebra, you can show that the cumulative noise degrades SNR according to Friis' equation:

$$F_{sys} = \frac{(S_i/N_i)}{(S_o/N_o)} = \frac{(N_o)}{(G \times N_i)} = F_1 + \frac{F_2-1}{G_1} + \frac{F_3-1}{G_1G_2} + \ldots \frac{F_n-1}{G_1G_2\ldots G_n}$$

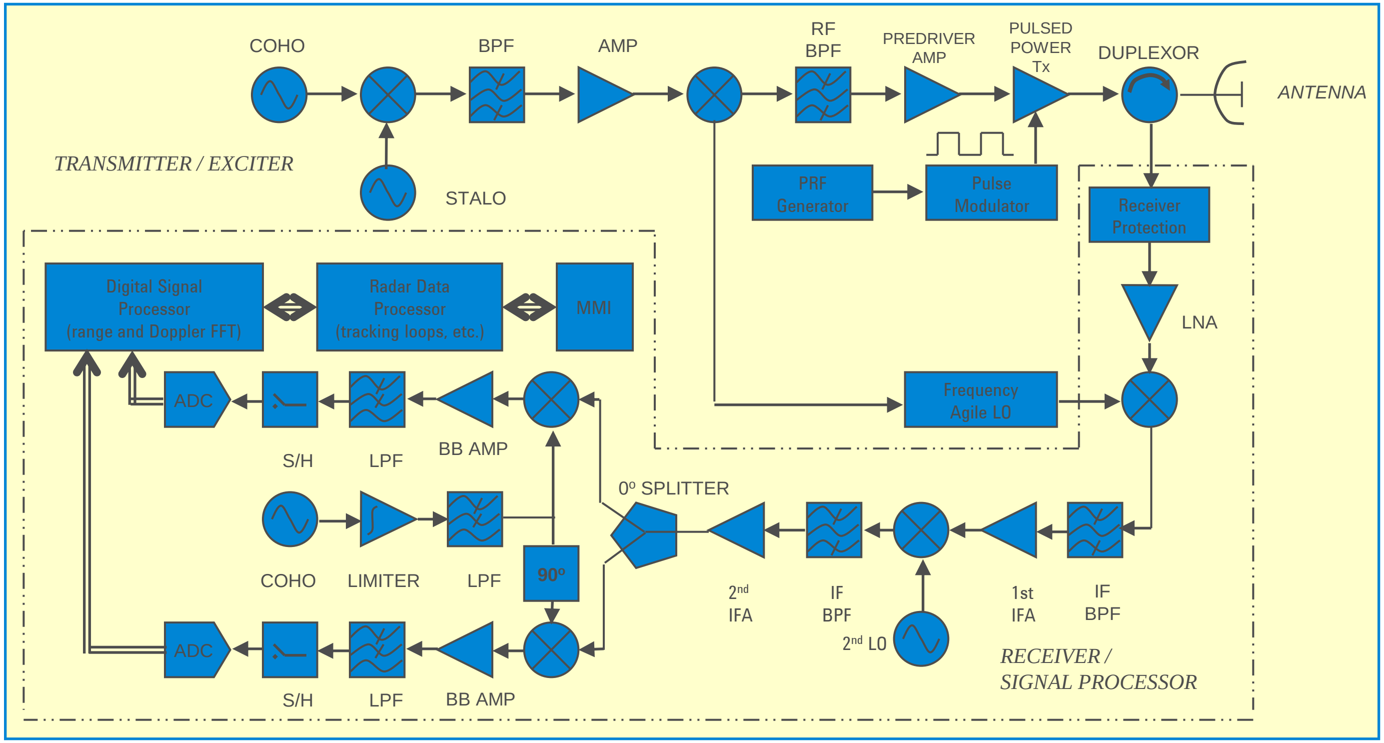
Importance of Noise Figure Accuracy – R&D

Better correlation between simulation and measurement

Better optimization of transmit/receive systems

- Improved measurement accuracy results in smaller guard bands
- Tighter specifications on LNA means lower-power transmit amplifiers

Radar example



Importance of Noise Figure Accuracy – Mfg

Improved measurement accuracy results in smaller guard bands

Smaller guard bands yields better component specifications

Better specifications means more competitive products which command higher prices or attain higher market share

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- Other methods (cold source!)
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Agilent's Noise Figure Legacy

340A
1958

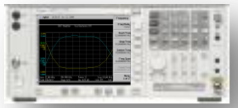
8970
1980

8560/90 with NF
1995

85120
1999

NFA
2000

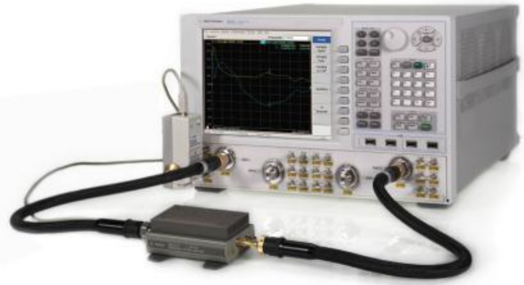
Over 50 years of Leadership!



PSA with NF
2002

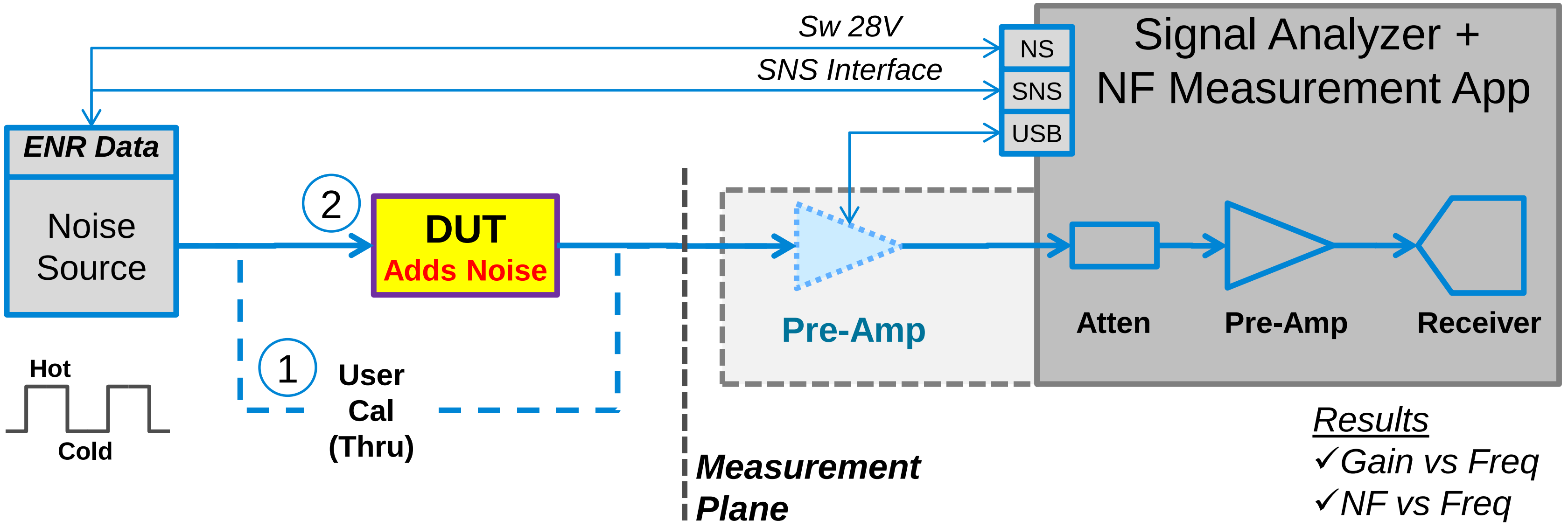
ESA with NF
2003

X-series to 50 GHz
2007-present



PNA-X with 50 GHz NF
2007-present

Y-Factor Method – What is It?

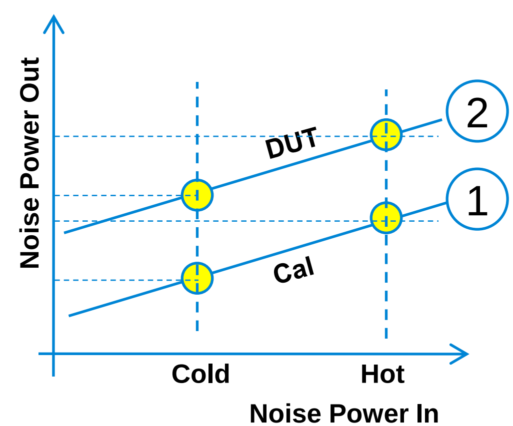


Stimulus is *broad-band noise*, at 2 levels of noise density.

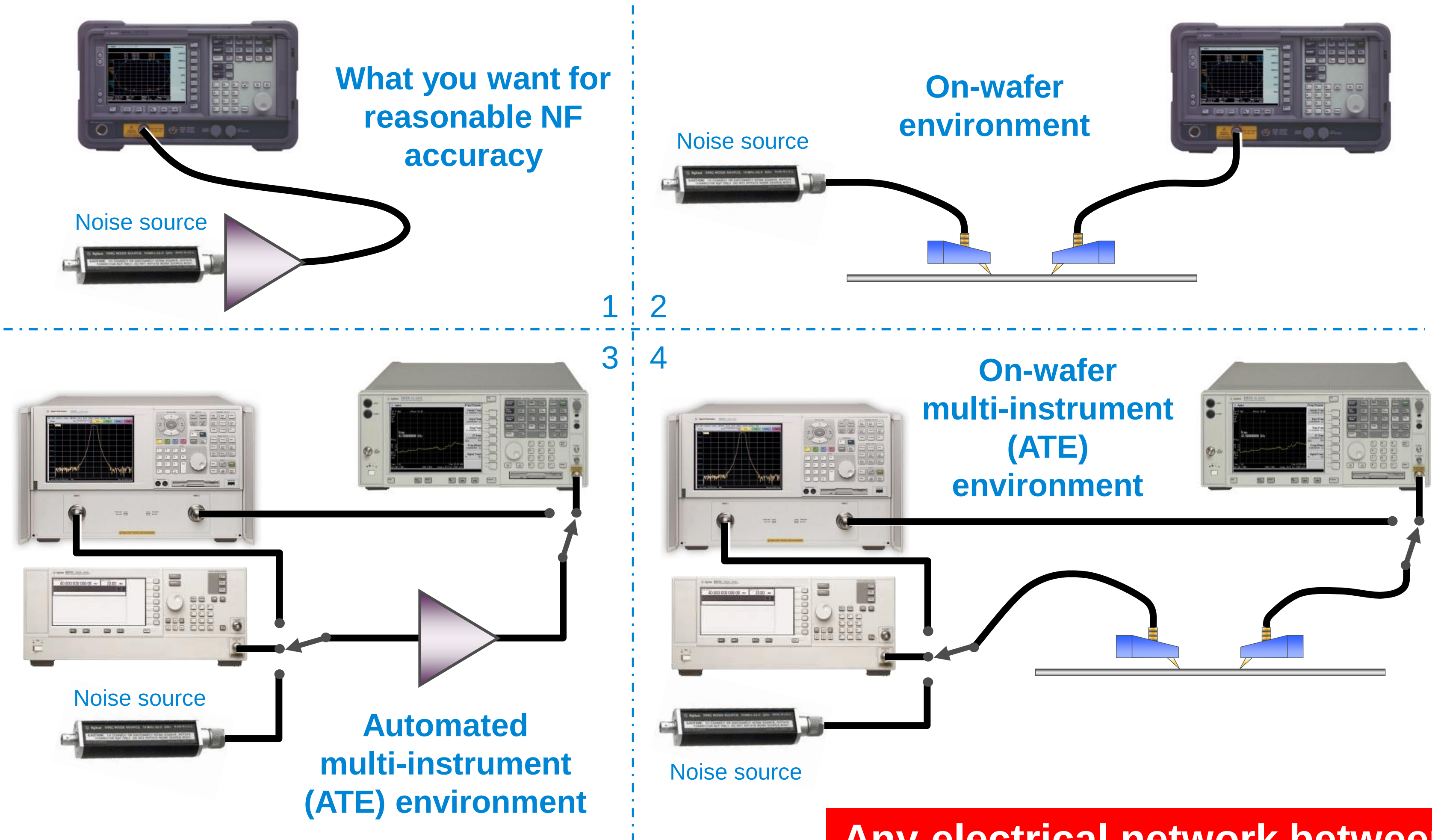
Amplifiers
LNAs

Freq-Conv. Dev.
Low-Noise Receivers
Tuners
Up-Converters
Down-Converters

Analyzer controls noise source, tunes to each frequency, and sets the BW of noise power measurements.

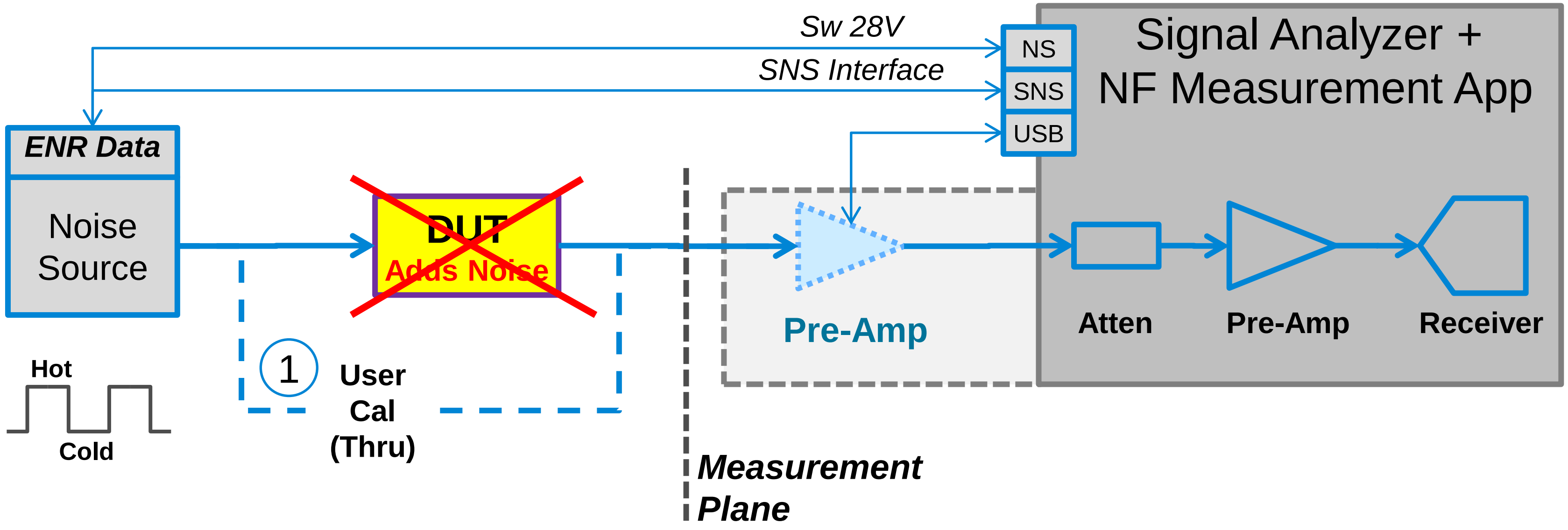


Noise Figure Measurements with Y-Factor Method



Any electrical network between noise source and DUT degrades accuracy

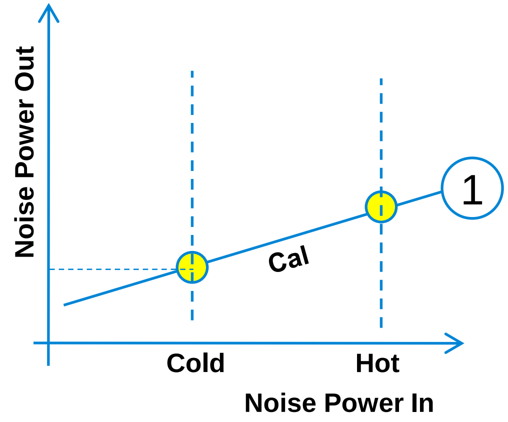
Y-Factor Method: Calibration Loop



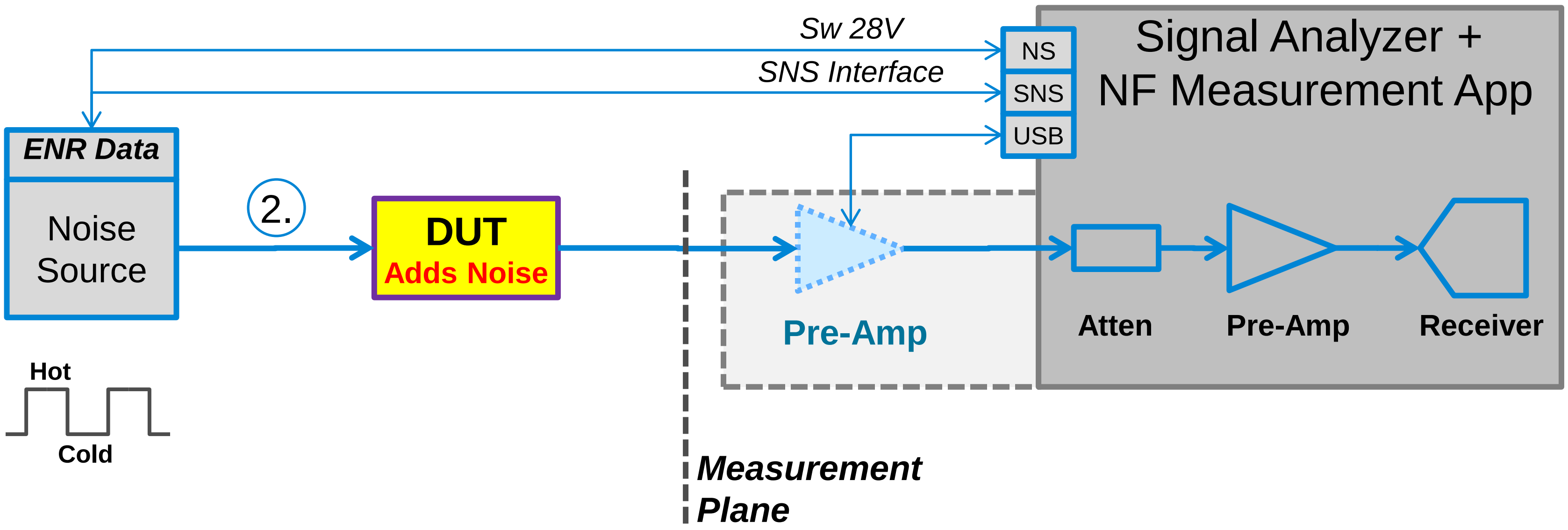
$$NF_{meas} = NF_{DUT}$$

$$NF_{meas} = \frac{ENR}{\frac{N_{hot}}{N_{cold}} - 1}$$

ENR is known; hot and cold noise power are measured



Y-Factor Method: DUT inserted

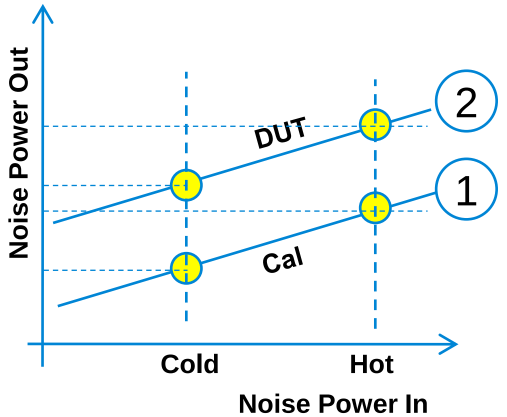


$$NF_{meas} = NF_{DUT} + \frac{NF_{instr}}{G_{DUT}}$$

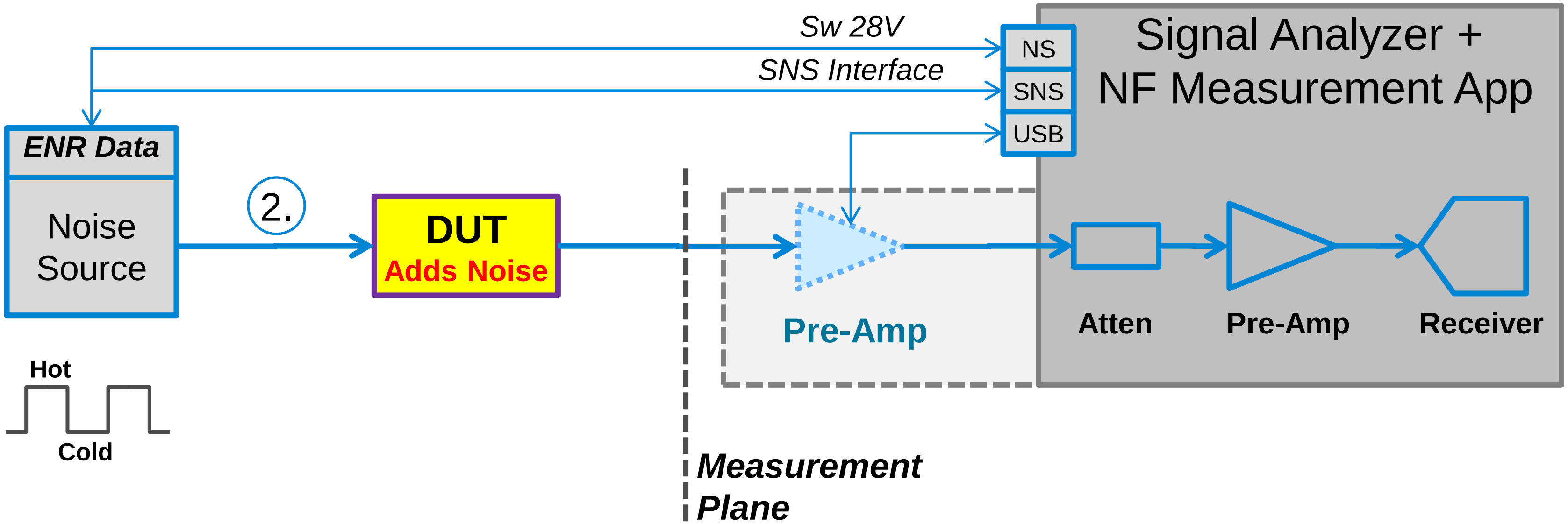
Our cascaded noise figure with DUT inserted

$$NF_{meas} = \frac{ENR}{\frac{N_{hot}}{N_{cold}} - 1}$$

ENR is known; hot and cold noise power are measured



Y-Factor Method: Calculating DUT noise figure and gain

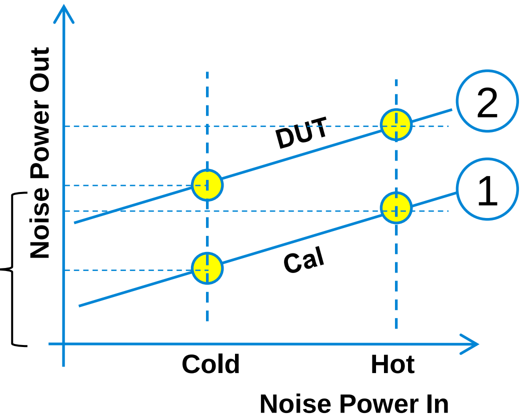


$$NF_{DUT} = NF_{meas} - \frac{NF_{inst} - 1}{G_{DUT}}$$

Equation used to calculate noise figure of the DUT. We measured the noise figure of the instrument, we need to compute DUT gain

$$G_{DUT} = \frac{N_{inst+DUT_{hot}} - N_{inst+DUT_{cold}}}{N_{inst_{hot}} - N_{inst_{cold}}}$$

Gain is noise power out/noise power in



$$NF_{DUT} = NF_{meas} - \frac{NF_{inst} - 1}{G_{DUT}}$$

Compute DUT NF

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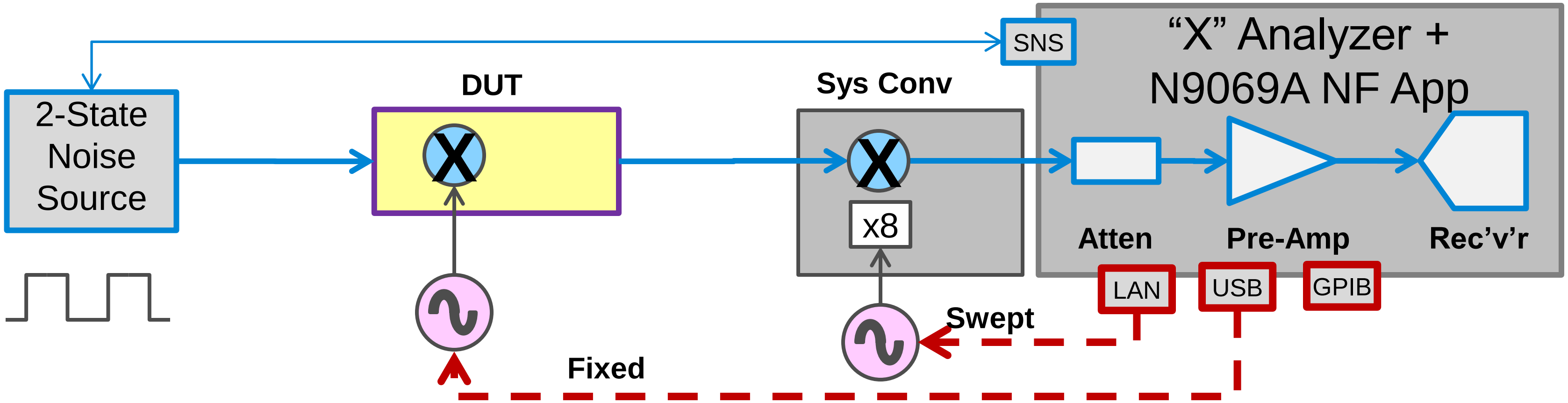
Enhanced LO Control in N Fig (Aug-2013)

✓Formally supports **<u>all</u> I/O types** (GPIB, LAN, USB, USB-GPIB).

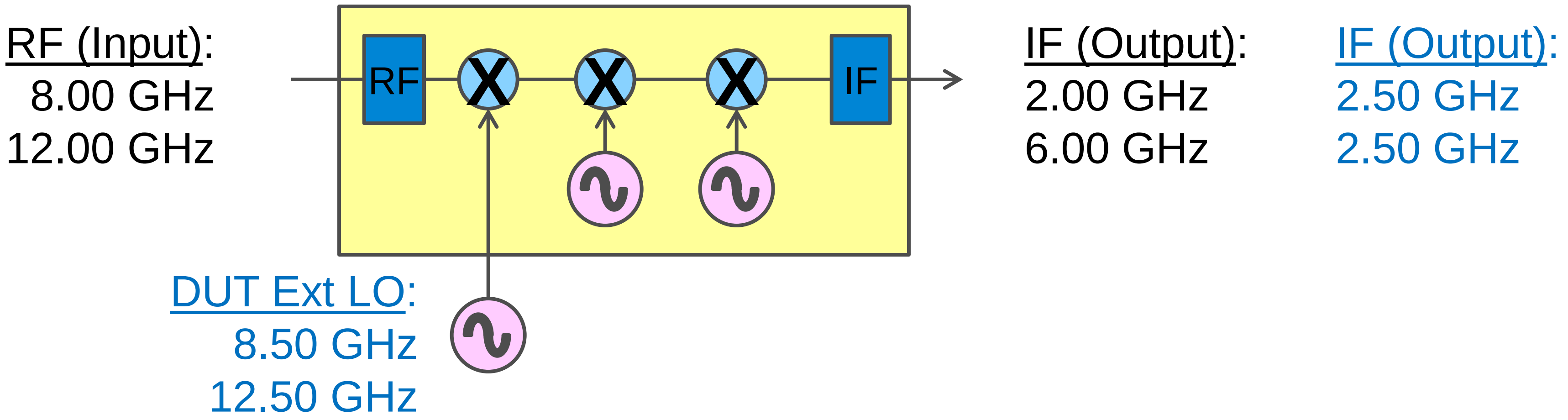
✓Supports "smart" source discovery (e.g. can "scan" GPIB for a source).

✓Supports both **<u>DUT</u>** Ext LO ***and*** a **<u>Sys Conv</u>** Ext LO. Each can be Upper- or Lower-Sideband. Each can be Fixed or Swept (but not both Swept).



Generic "Converter" DUT in N Fig (Aug-2013)

✓New generic **"Converter"** DUT type (in addition to Amplifier, Up-Conv, & Down-Conv). Handles *multi-stage* converters with *any "frequency plan"*, suppresses error checking.

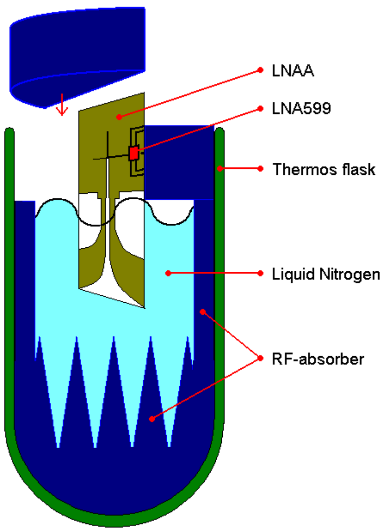


- *User describes start-stop frequency pair for input and output only; user does not describe each stage's LO, up- or down-conv, USB vs LSB, etc.*
- *One DUT stage may have Ext LO controlled by app, and swept .*
- *Pre-existing Up-Conv and Down-Conv can still be used for 1-stage DUTs.*

"Manual" Measurement in N Fig (Aug-2013)

✓"**Manual**" measurement algorithm, to handle cases where the noise source state (hot/cold) is not under control of app:

a) Temperature control of noise source is ***s-l-o-w*** (mechanical, thermal).
b) Hot and cold noise sources are ***physically separate*** and connected sequentially.
c) Radio-telescope receivers are tested with antenna and LNA combined (G/T). Hot & cold standards are in *free space* (e.g. sun & empty sky), change by ***antenna pointing*** (slow).
d) Custom noise sources that won't accept normal control signals.



Hot = Room

Cold = Liq N2

Normal Algorithm 1: Cal 2: Meas	Manual Algorithm 1: Cal 2: Meas
For Each **Freq** Switch NS to **Hot** Measure **Power A** Switch NS to **Cold** Measure **Power B** Next **Freq** Display Results, Repeat if Cont	Prompt User to Set NS to **Hot**, ***Pause*** For Each **Freq** Measure **Power A** Next **Freq** Prompt User to Set NS to **Cold**, ***Pause*** For Each **Freq** Measure **Power B** Next **Freq** Display Results, ***Pause*** (Single)

- *"Manual" algorithm Pause for user to change temperature; and nests the **Freq** loops inside.*

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Noise Figure Uncertainty Calculator (NFUC)

Uncertainty for a noise figure measurement depends on several factors and elements of the system, *including the DUT itself*, that interact in complex ways. See App Note 57-2. Therefore, Agilent provides calculators to automate these calculations.

Input Parameters from:
- DUT (incl. NF and Gain)
- Noise source
- Analyzer instrument
- External preamp (if used)

→ **NFU Calculator** →

Noise Fig Uncertainty * for various calibration types:
- Full "User Cal" (thru path)
- "Internal Cal" (noise subtraction)
- Uncalibrated

** Does not provide uncertainty for Gain.*

Type	Platform	Extra Features
Spreadsheet	Excel download to PC	▪ Exposed equations ▪ Many comments, background info, examples ▪ Editable
On-Line	Java 7 in browser	▪ "Sweep" any single parameter over range
In-Box	N9069A NF app, on X-series SA	▪ Sets parameters based on actual instrument setup, including N400x SNS and U7227 USB preamp ▪ "Sweep" a DUT parameter over range

All 3 were significantly updated since Oct-2012, especially w.r.t. statistics per GUM; handling of mismatch errors (VSWR); and to provide NFU for all 3 cal types.

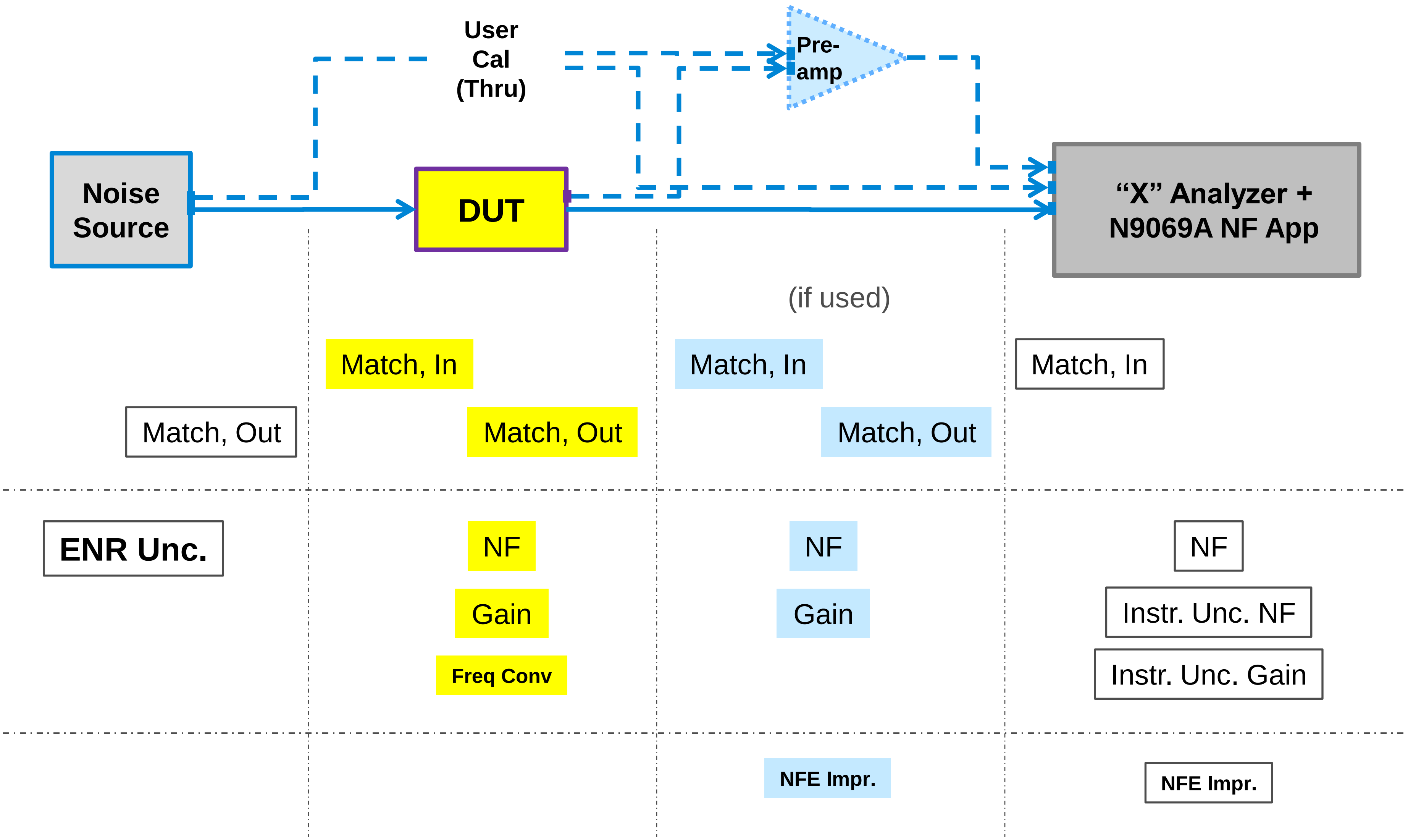
Noise Figure Uncertainty Calculators—Major Rework in late 2012

Why rewrite the NFUCs?

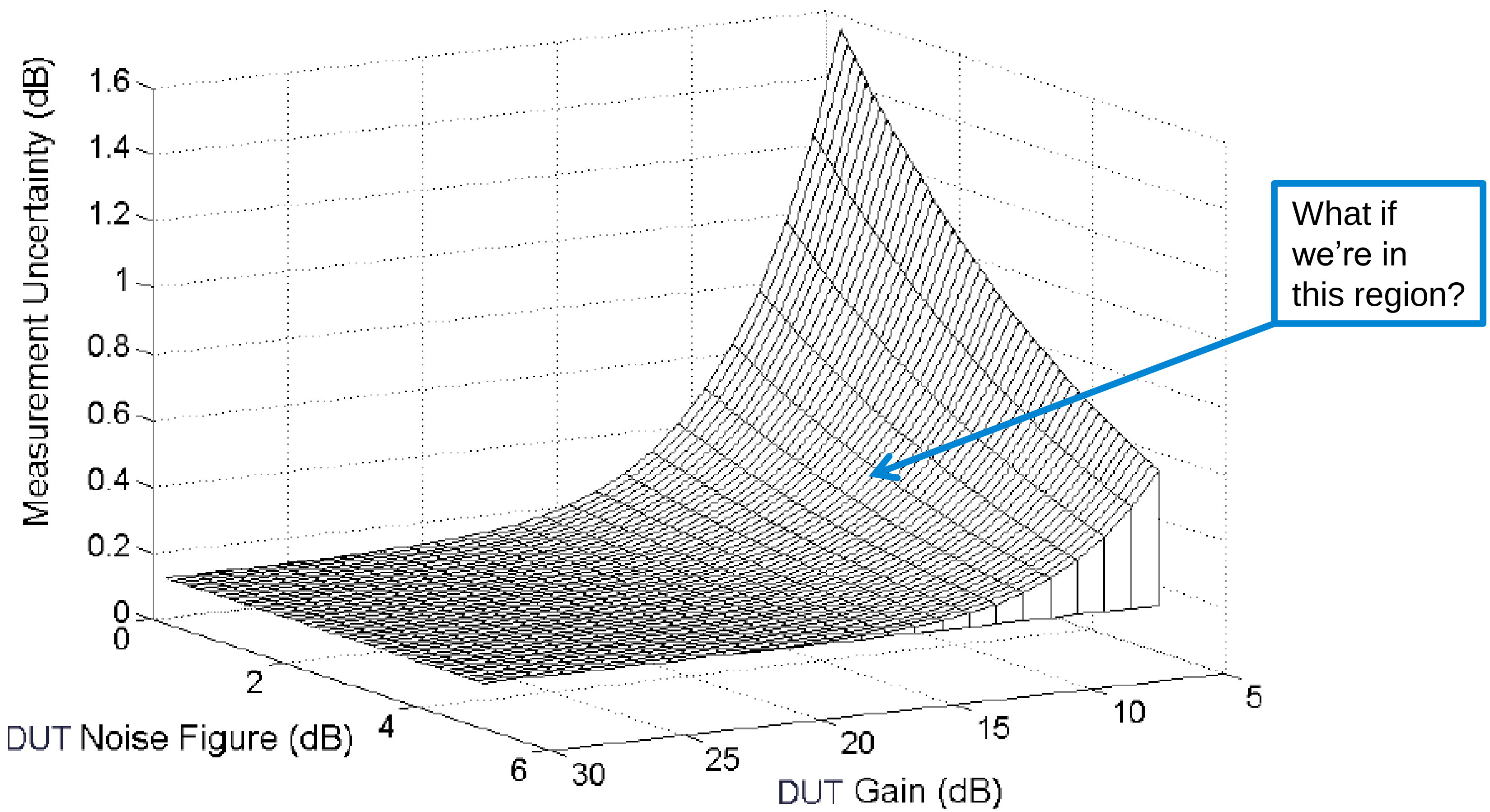
- **GUM (Guide to the Expression of Uncertainty in Measurement, the fundamental "how to" for ISO-9000 standard organizations) tells us how the old calculator was wrong (it combined 2σ, 3σ and worst-case indiscriminately)**
- **Dobbert & Gorin 2011 paper, "Revisiting Mismatch Uncertainty with the Rayleigh Distribution," showed how we overestimated a significant error contributor for 50 years**
- **Add uncertainty analysis for "internal cal" and "uncal" cases**
- **Add ease of using a preamp to the calculator**

UNCERTAINTY IS LOWER with the better estimations too!

Inputs to NFUC



DUT NF and gain determine uncertainty



Total NF uncertainty:

$$\delta NF_1 = \sqrt{\left(\frac{F_{12}}{F_1}\delta NF_{12}\right)^2 + \left(\frac{F_2}{F_1 G_1}\delta NF_2\right)^2 + \left(\frac{F_2 - 1}{F_1 G_1}\delta G_{1,dB}\right)^2 + S\left(\left(\frac{F_{12}}{F_1} - \frac{F_2}{F_1 G_1}\right)\delta ENR_{dB}\right)^2}$$

U7227x USB Preamps *April 2014*

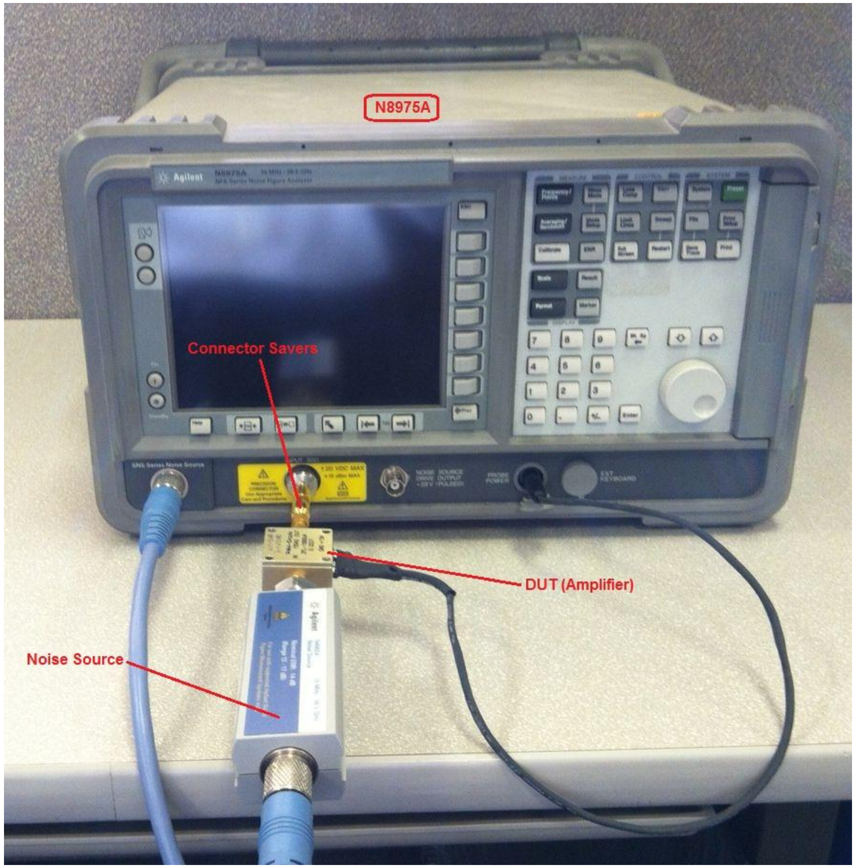
✓Noise Fig ~ 5dB.
✓Gain >17 dB (makes N Fig of SA negligible).
✓USB provides power to Preamp, and reads factory-cal data from flash. Data includes gain, noise fig, and S-parameter data.

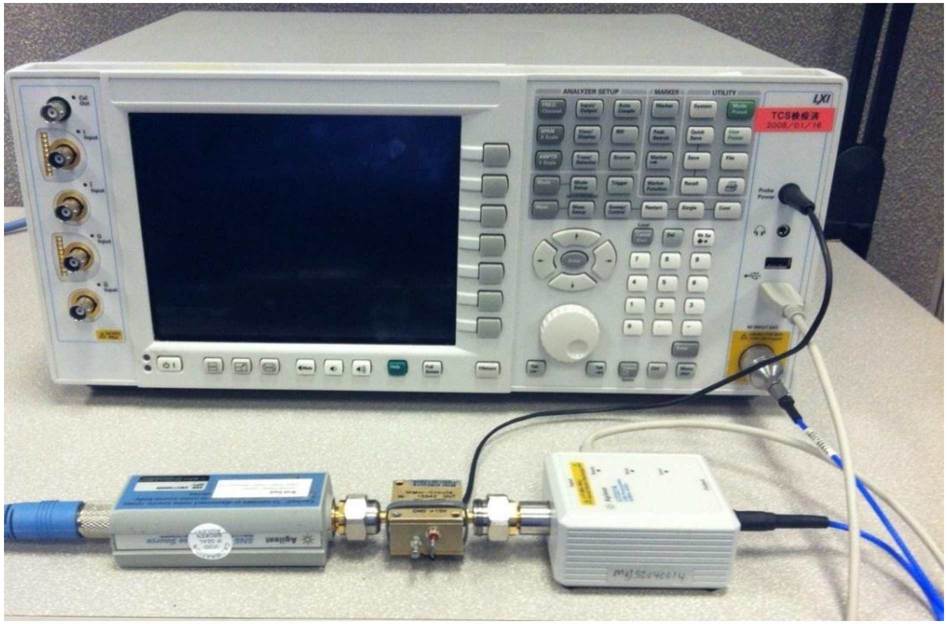
❑"X" <u>SA app</u> uses amp as "remote front end"; gain data read over USB to correct displayed abs-amp vs frequency.

❑"X" <u>N Fig app</u> uses amp to improve noise figure; noise data read over USB to support "***Internal Cal***".

Model	Fmax
U7227A	10 MHz to 4 GHz
U7227C	100 MHz to 26.5 GHz
U7227F	2 to 50 GHz

Comparing Y-factor noise figure measurement solutions

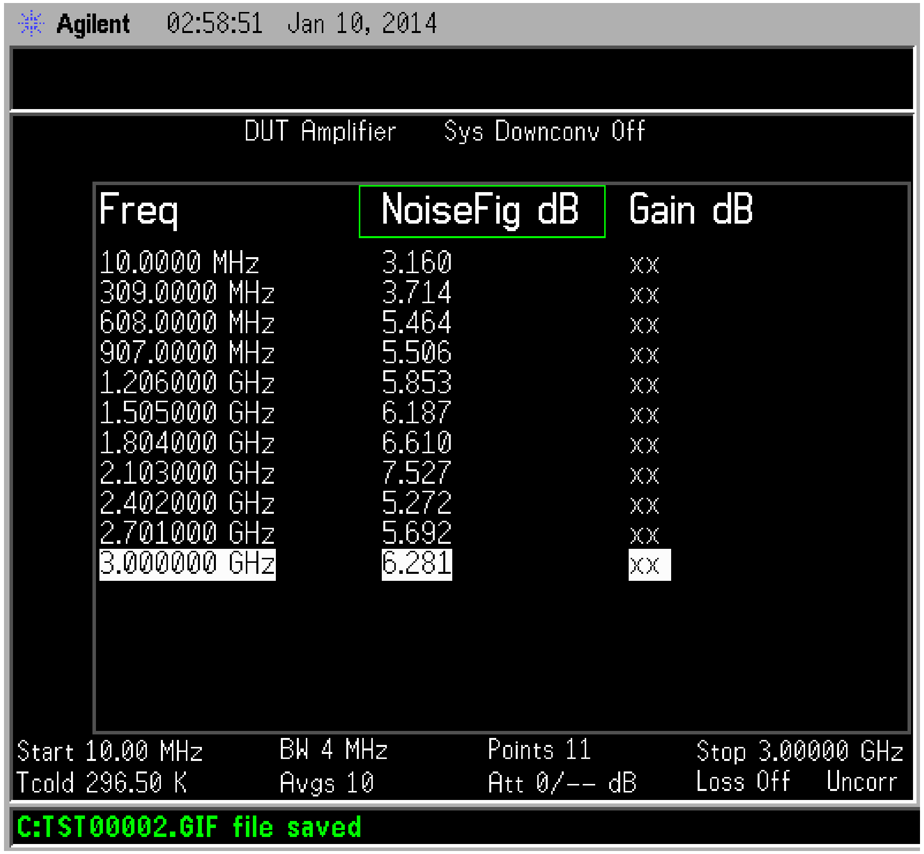


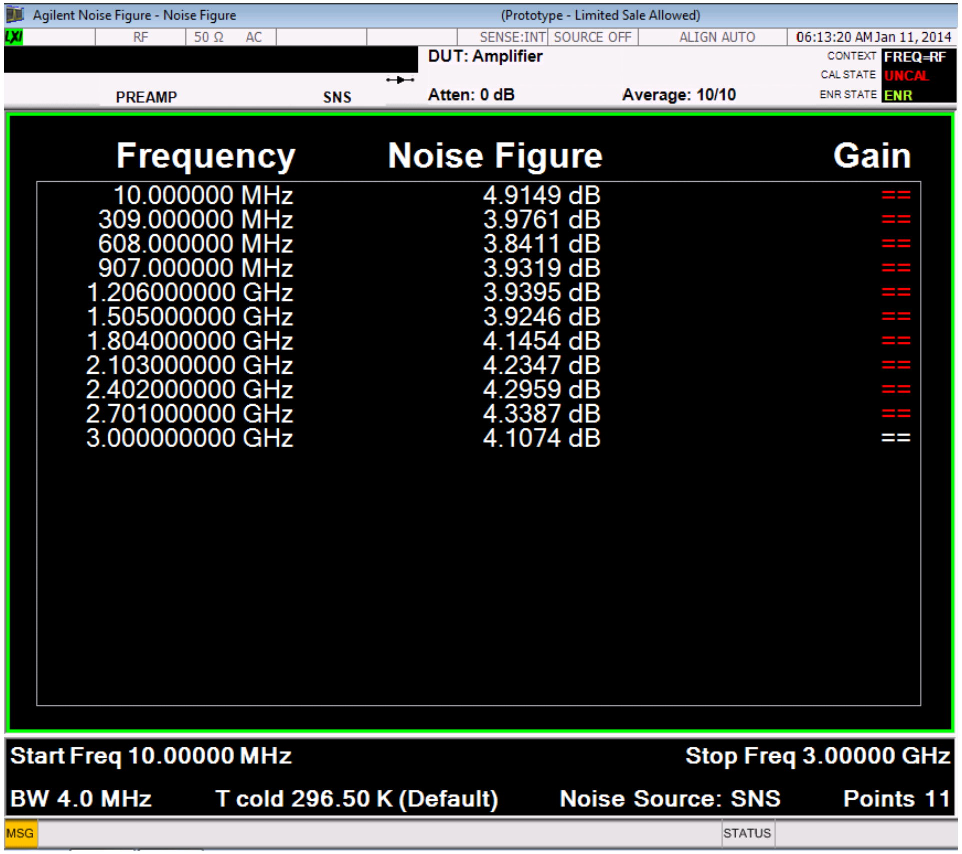


N8975A noise figure analyzer

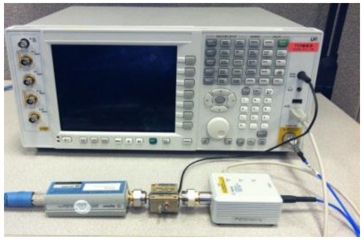
EXA + U7227A preamp

Instrument noise figure comparison





Noise Figure Analyzer



X-series analyzer with USB preamp

Measurement Comparison

Agilent 03:04:18 Jan 10, 2014

DUT Amplifier Sys Downconv Off

Freq	NoiseFig dB	Gain dB
10.0000 MHz	2.492	25.202
309.0000 MHz	2.591	25.353
608.0000 MHz	2.604	25.442
907.0000 MHz	4.295	25.511
1.206000 GHz	2.630	25.530
1.505000 GHz	2.703	25.268
1.804000 GHz	2.607	24.172
2.103000 GHz	2.677	23.059
2.402000 GHz	3.255	21.808
2.701000 GHz	3.388	20.297
3.000000 GHz	3.507	18.983

Start 10.00 MHz BW 4 MHz Points 11 Stop 3.00000 GHz
Tcold 296.50 K Avgs 10 Att 0/-- dB Loss Off Corr

A:TST00003.GIF file saved

Agilent Noise Figure - Noise Figure (Prototype - Limited Sale Allowed)

RF 50 Ω AC SENSE:INT SOURCE OFF ALIGN AUTO 05:32:47 AM Jan 11, 2014

Average Num 10 DUT: Amplifier CONTEXT FREQ=RF

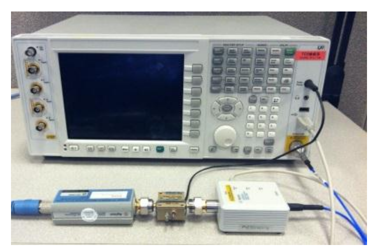
PREAMP SNS Atten: 0 dB Average: 10/10 CAL STATE CAL ENR STATE ENR

Frequency	Noise Figure	Gain
10.000000 MHz	2.6158 dB	25.281 dB
309.000000 MHz	2.7092 dB	25.434 dB
608.000000 MHz	2.6897 dB	25.549 dB
907.000000 MHz	3.2714 dB	25.673 dB
1.206000000 GHz	2.7137 dB	25.693 dB
1.505000000 GHz	2.7385 dB	24.960 dB
1.804000000 GHz	2.6950 dB	24.150 dB
2.103000000 GHz	2.7612 dB	23.327 dB
2.402000000 GHz	3.1764 dB	21.938 dB
2.701000000 GHz	3.4215 dB	20.226 dB
3.000000000 GHz	3.5414 dB	18.711 dB

Start Freq 10.00000 MHz Stop Freq 3.00000 GHz
BW 4.0 MHz T cold 296.50 K (Default) Noise Source: SNS Points 11

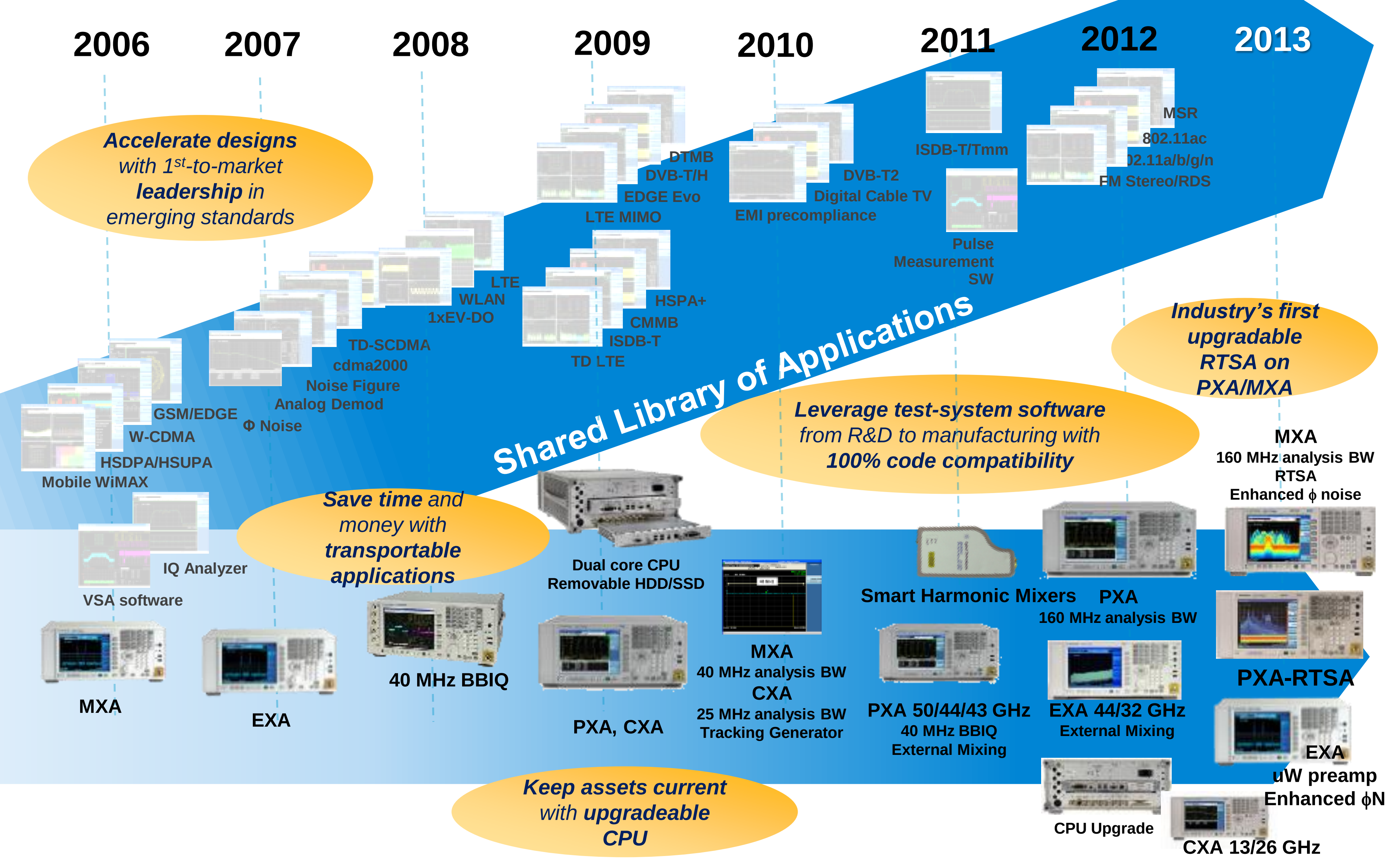
MSG STATUS

NFA

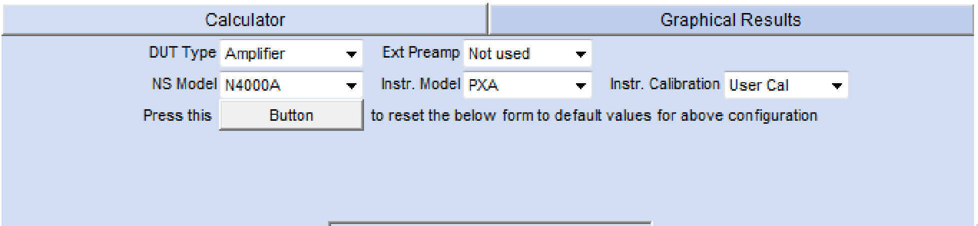


X-series analyzer with USB preamp

X-Series Analyzer Enhancements



Total NFU calculation: effect of DUT Gain

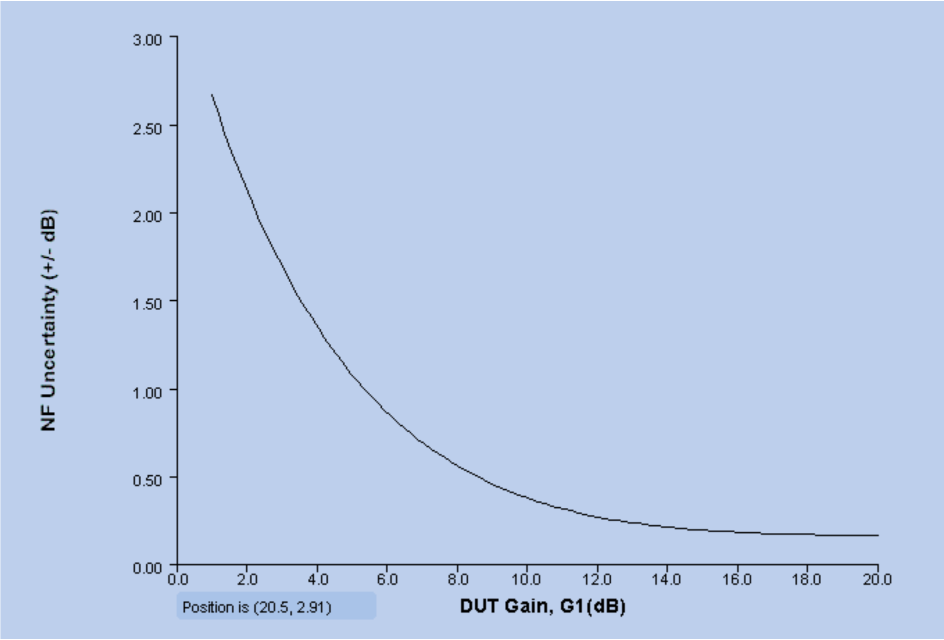


	Value	Specification Style	Distribution
DUT NF, NF1 (dB)	1	Fixed	
DUT Gain, G1 (dB)	Sweep Parameter	Fixed	
DUT Input Match *	1.500	Fixed	Fixed
DUT Output Match *	1.500	Fixed	Fixed
NS ENR Uncert (±dB)	0.150	95th %ile (2σ)	Gaussian
NS Match *	1.130	Maximum	Rayleigh
Instr. NF, NF2 (dB)	12.000	Fixed	
Instr. NF Uncert (±dB)	0.030	Maximum (3σ)	Gaussian
Instr. Gain Uncert (±dB)	0.070	Maximum (3σ)	Gaussian
Instr. Match *	1.450	95th %ile	Rayleigh
Instr. NFE Improvement	9.000	95th %ile (2σ)	Gaussian
Ext Preamp NF (dB)	3.500	Fixed	
Ext Preamp Gain (dB)	21.000	Fixed	
Ext Preamp Match *	1.300	Fixed	Fixed
Ext Preamp NFE Improvement	9.000	95th %ile (2σ)	Gaussian

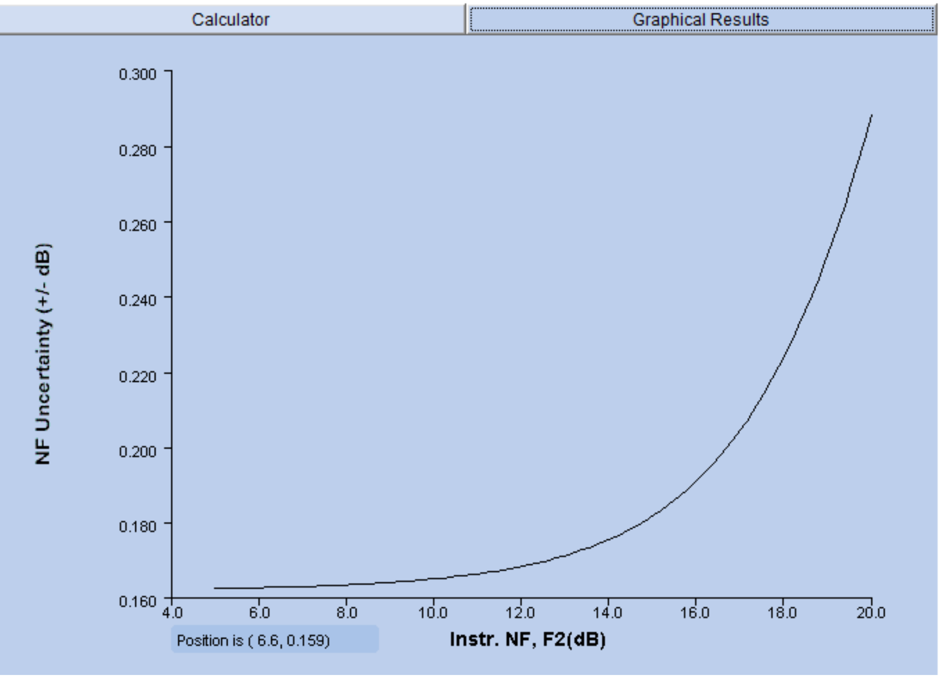
	Parameter	Lower Value	Upper Value	Number of Points
Sweep	DUT Gain, G1(dB)	1	20	100

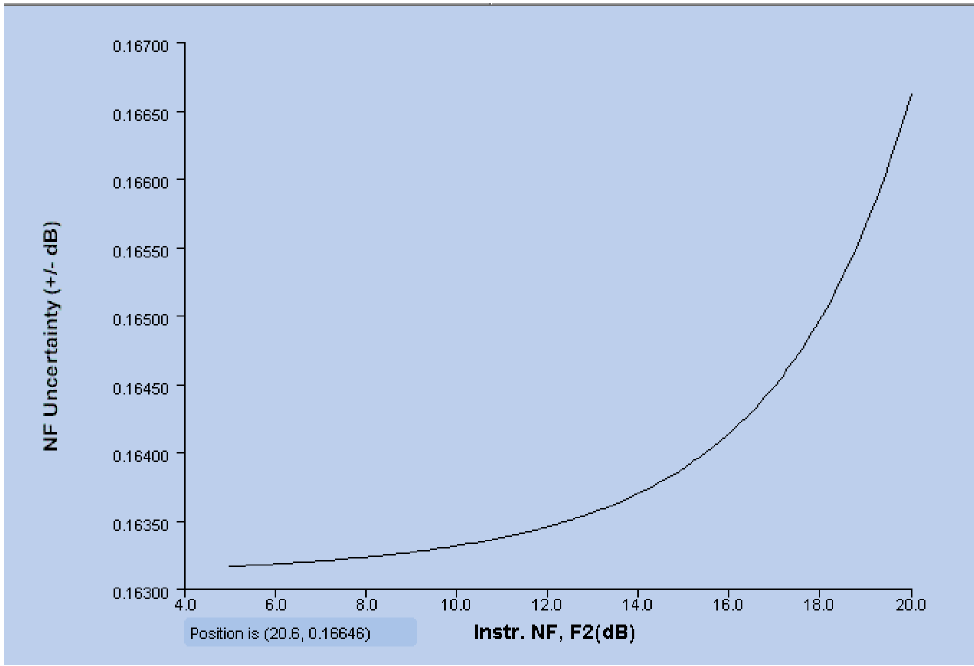
* This term can be entered in RL dB(Sxx), VSWR or reflection coefficient. e.g. -15 (dB) = 1.43 (VSWR) = 0.178 (Refl. Coef.)

For a perfect match, enter 1 for VSWR = 1; for a total reflection, enter 0 for RL(return loss) = 0 dB.



Total NFU calculation: effect of analyzer noise figure with 20 and 30 dB gain DUTs



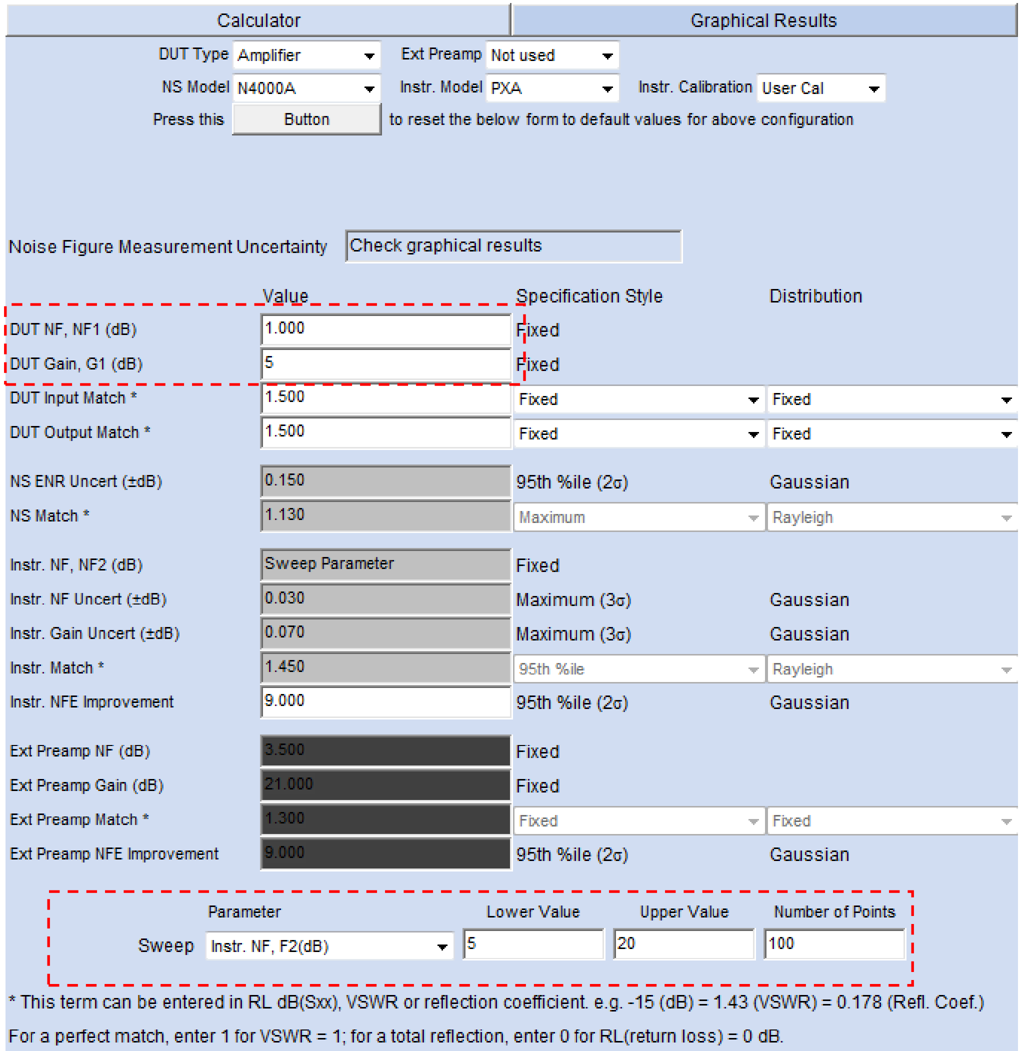


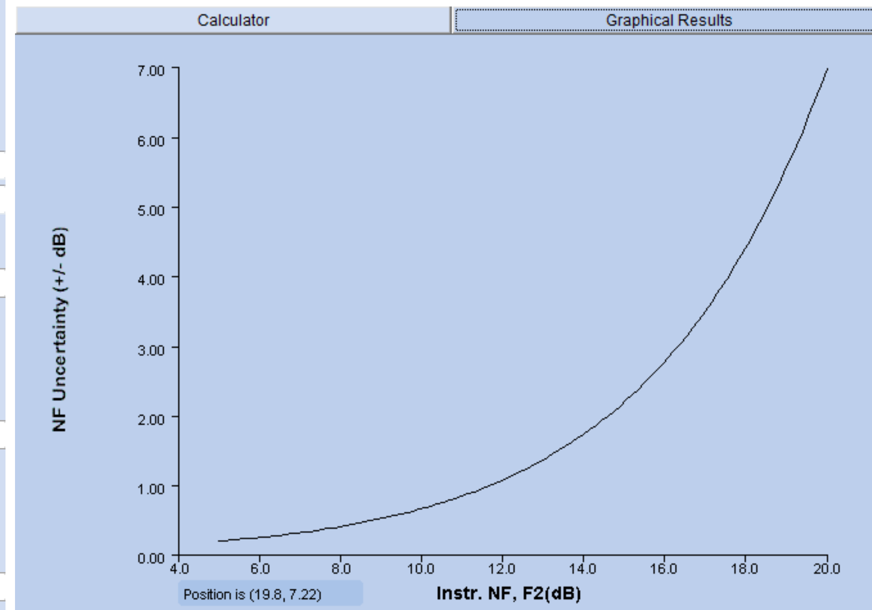
20 dB DUT gain: uncertainty improved .1 dB using preamp

30 dB DUT gain: uncertainty improved .002 dB using preamp

NFsys = NF1 + (NF2 – 1)/G1

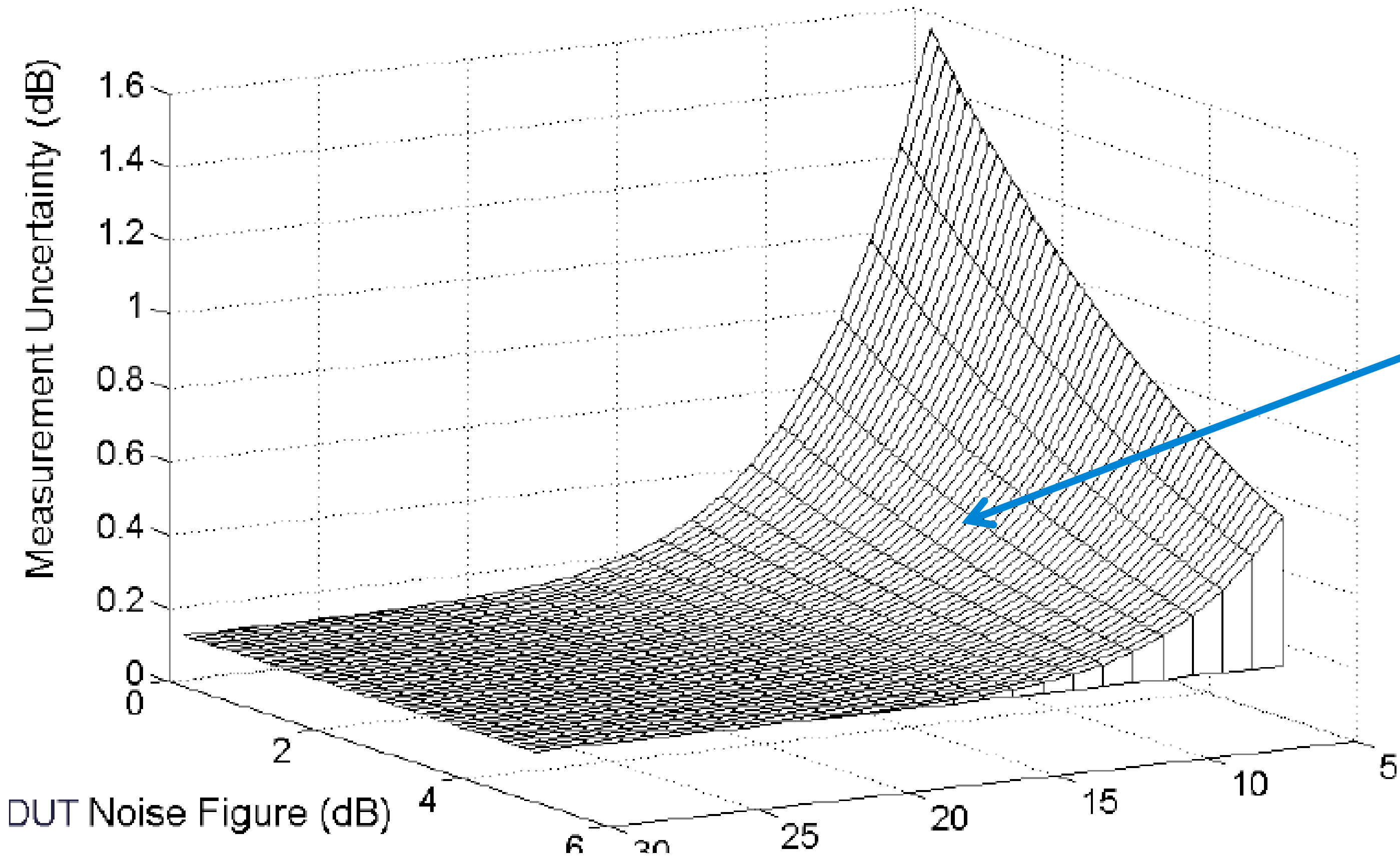
Total NFU calculation: effect of analyzer noise figure with low gain DUTs





NFsys = NF1 + (NF2 – 1)/G1

Summary: Use the preamp with low gain DUTs, especially at higher frequencies



Use the preamp on the slope

Total NF uncertainty:

$$\delta NF_1 = \sqrt{\left(\frac{F_{12}}{F_1}\delta NF_{12}\right)^2 + \left(\frac{F_2}{F_1 G_1}\delta NF_2\right)^2 + \left(\frac{F_2 - 1}{F_1 G_1}\delta G_{1,dB}\right)^2 + S\left(\left(\frac{F_{12}}{F_1} - \frac{F_2}{F_1 G_1}\right)\delta ENR_{dB}\right)^2}$$

Biggest Contributor to Uncertainty*:
ENR (Excess Noise Ratio) Uncertainty of Noise Source

	J	K	L	M	N	O	P
21		Sens * Uncertainties, User Cal			Relative Contribution (User Cal)		
22		δNF12 * F12/F1	0.0376 dB		20%		
23		δNF2 * F2/F1G1	0.0010 dB		0%		
24		δG1 * (F2-1)/F1G1	0.0063 dB		1%	Summa	
25		δENR * ((F12/F1)...	0.0746 dB		79%		
26						Calibra	
27		RSS Combined	0.0837 dB			Normal	

Uncertainty of ENR

Percentage of Uncertainty from ENR Uncertainty

*assuming a properly configured measurement

2013 Improvements in Uncertainty of ENR (Noise Sources)

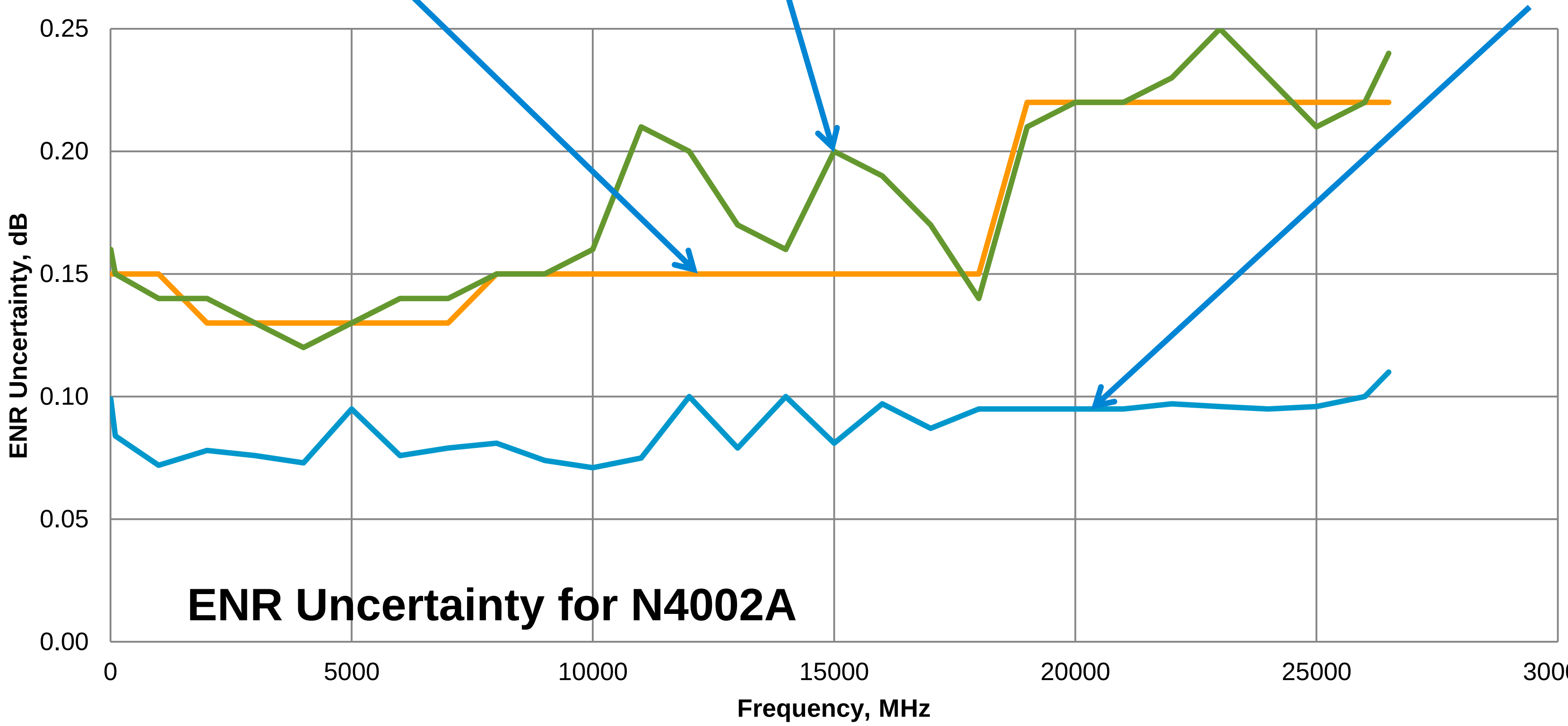
- Improvement in accuracy of estimation of calibration linearity
- Improvement in metrology at NMI (NPL) 18 to 26.5 GHz
- Improved field calibrations
  - Vector compensation new to "Agilent Cal" for 346 and SNS (compensation is even better than Rayleigh estimation).
  - "Standards Lab Cal" in Roseville for SNS even better—allows calibration "A1R" (against a reference one-level removed from the primary measurement at NPL) versus A2R for an "Agilent Cal" and A1R for production SNS.

N4002A Example of Improved Calibration Reports

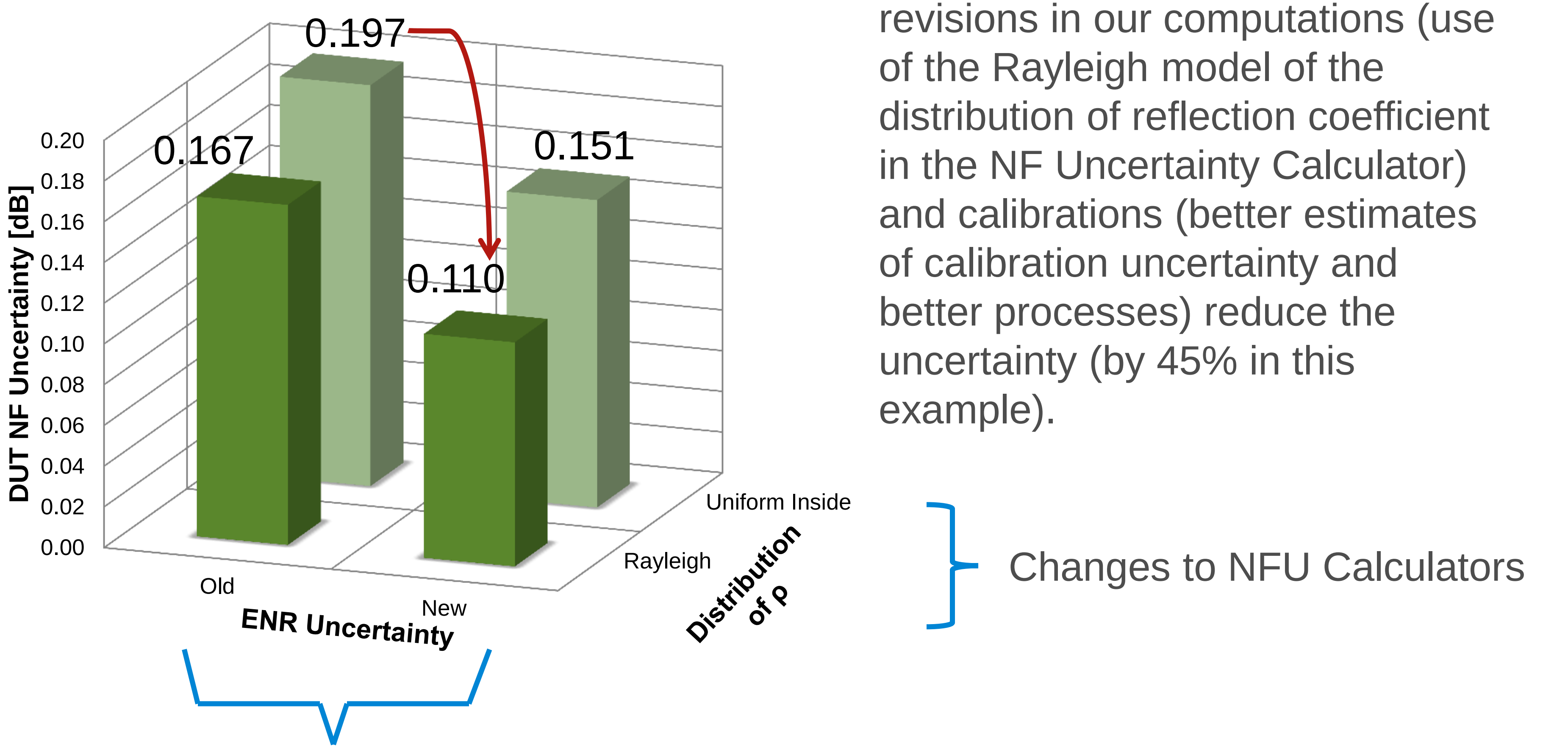
90%ile Spec = SNS Operating and Service Guide Table (textual)

2012 = Example of current Agilent Calibration (field) result

StdLab = Standards Lab Cal, starting 11/2013



Summary: Reduced NF Uncertainty



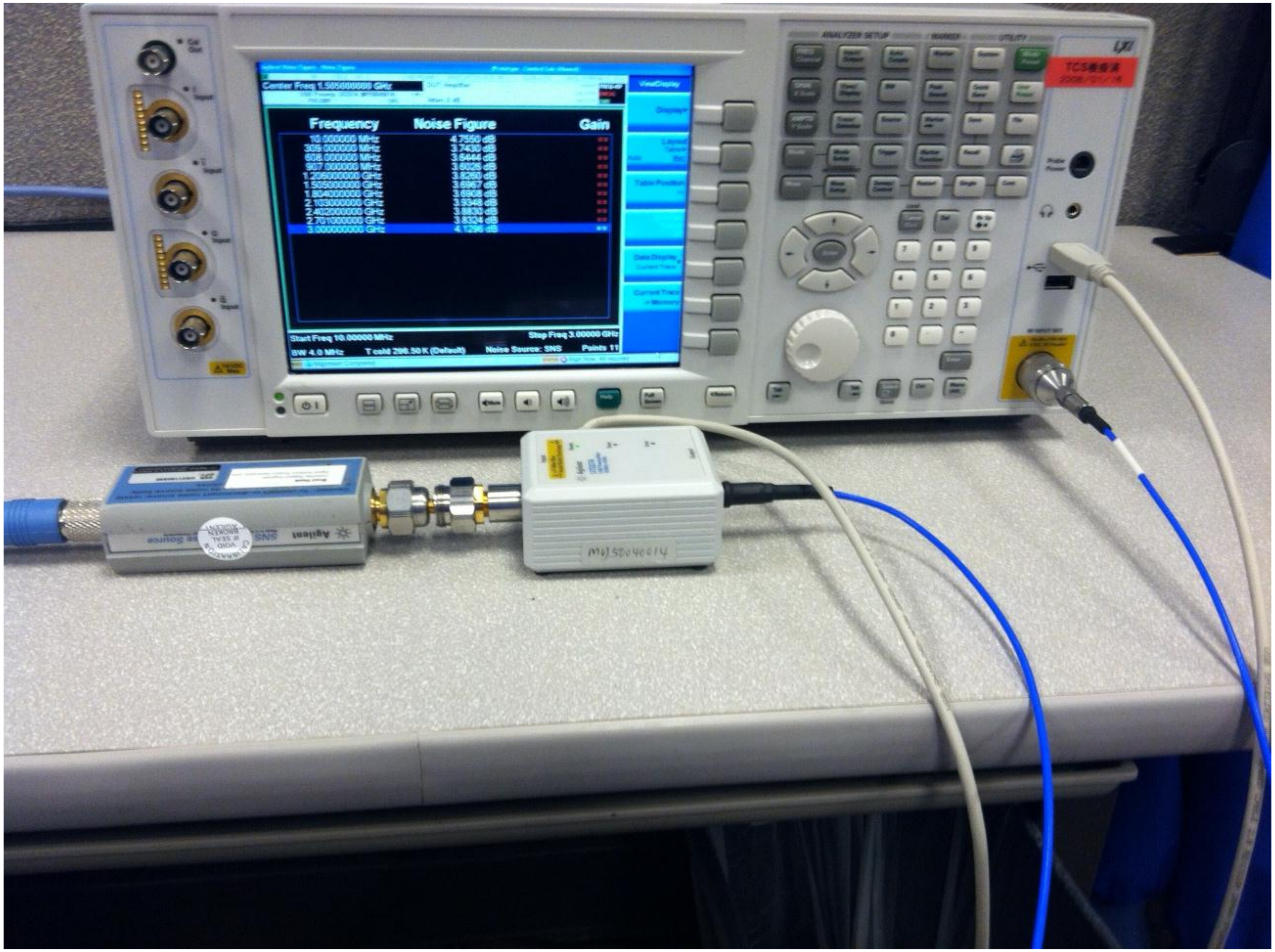
This presentation showed you how revisions in our computations (use of the Rayleigh model of the distribution of reflection coefficient in the NF Uncertainty Calculator) and calibrations (better estimates of calibration uncertainty and better processes) reduce the uncertainty (by 45% in this example).

(Uncertainty estimations and Cal practices)

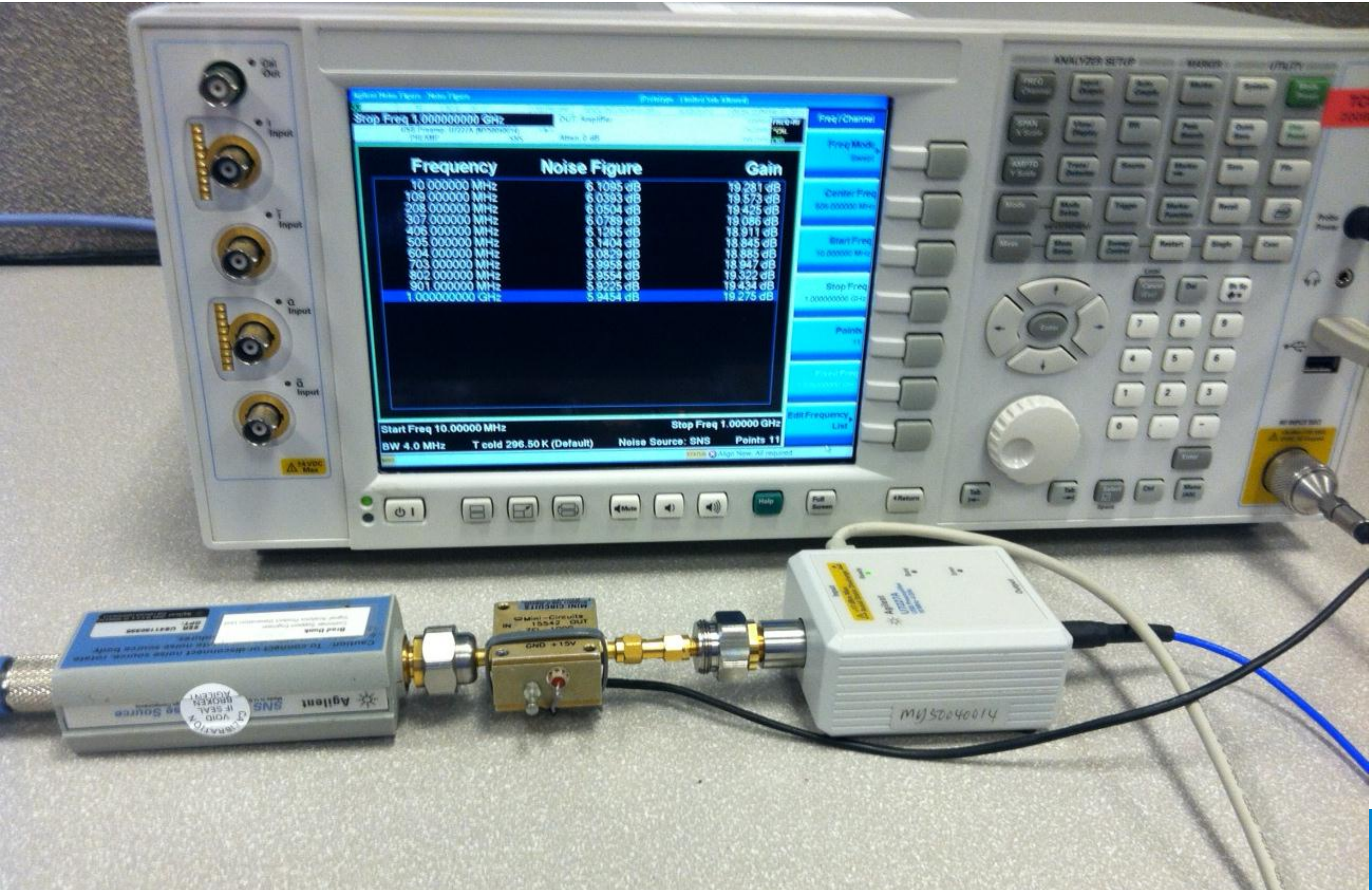
Agenda

- Why measure noise figure?
- The Y-factor method of noise figure measurement
- When to use the Y-factor method
- Feature enhancements
- Measurement uncertainty
- Configuring a basic measurement
- Other methods (cold source!)
- Further reading

Calibration



Measurement



Agenda

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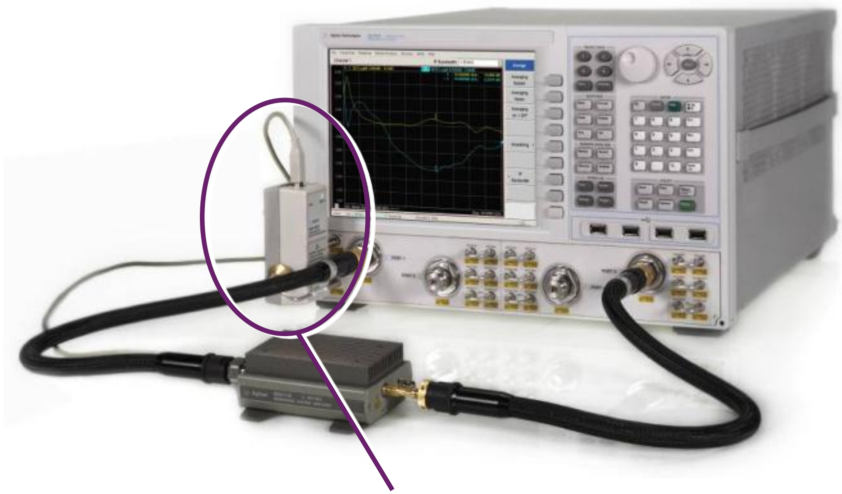
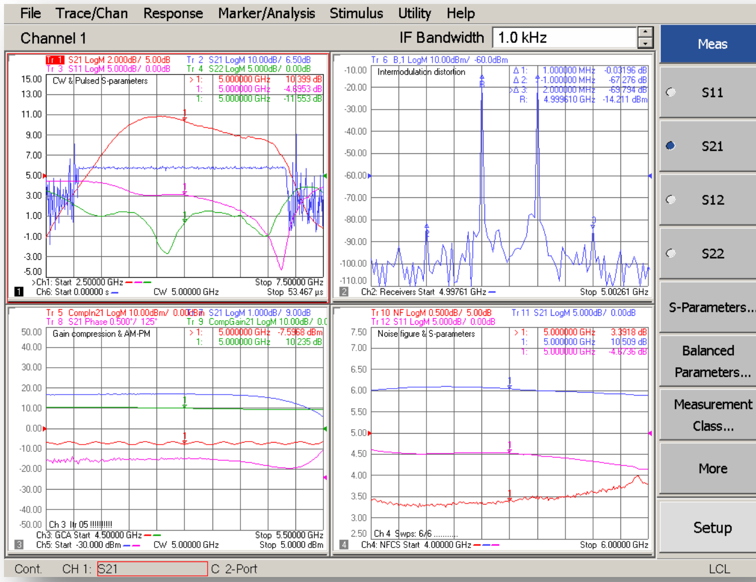
PNA-X Noise Figure Measurement Option 029



ECal module used as an impedance tuner to remove the effects of imperfect system source match



Application: **Measure key amplifier or converter parameters including noise figure up to 67 GHz with a single set of connections**

Performance: Achieve the **highest measurement accuracy** of any solution on the market

Speed: Typically 4 to 10 times **faster** than the NFA

Agilent Technologies

Agenda

- Why measure noise figure?
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Further Reading

- Fundamentals of RF and Microwave Noise Figure Measurements (AN 57-1) http://cp.literature.agilent.com/litweb/pdf/5952-8255E.pdf
- Noise Figure Measurement Accuracy – the Y-factor method (AN 57-2) http://cp.literature.agilent.com/litweb/pdf/5952-3706E.pdf
- 10 Hints for Making Successful Noise Figure Measurements (AN 57-3) http://literature.agilent.com/litweb/pdf/5980-0288E.pdf
- Guide to the Expression of Uncertainty in Measurement http://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf
- High Accuracy Noise Figure Measurements Using the PNA-X (AN 1408-2) http://cp.literature.agilent.com/litweb/pdf/5990-5800EN.pdf
- Handbook of Microwave Component Measurements http://www.amazon.com/Handbook-Microwave-Component-Measurements-Techniques/dp/1119979552/ref=sr_1_1?ie=UTF8&qid=1391460073&sr=8-1&keywords=handbook+of+microwave+component+measurements+with+advanced+vna+techniques