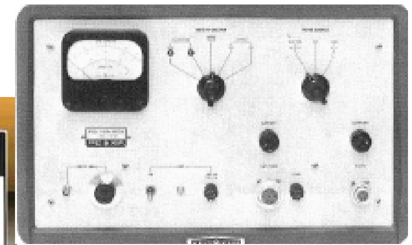
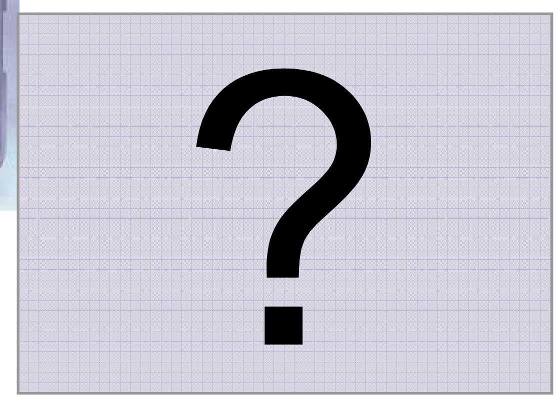
Advancements in Noise Measurement





by
Ken Wong, Senior Member IEEE
R&D Principal Engineer
Component Test Division
Agilent Technologies, Inc.

Objectives

Noise Figure Measurements

- *Y-Factor*
- *Cold source*
- *Noise Parameters*
- *Noise Wave*
- *Correcting for Source Impedance Mismatch*
- *Correcting for Receiver Mismatch and Noise*

VNA Noise Figure Measurements

- *Setup (S)*
- **Setting Input (Fwd) and Output (Rev) Powers**
- **Choosing Noise Bandwidth**
- **Setting Noise Averaging Factor**
- **Choosing the Receiver Gain Setting**

Objectives (cont)

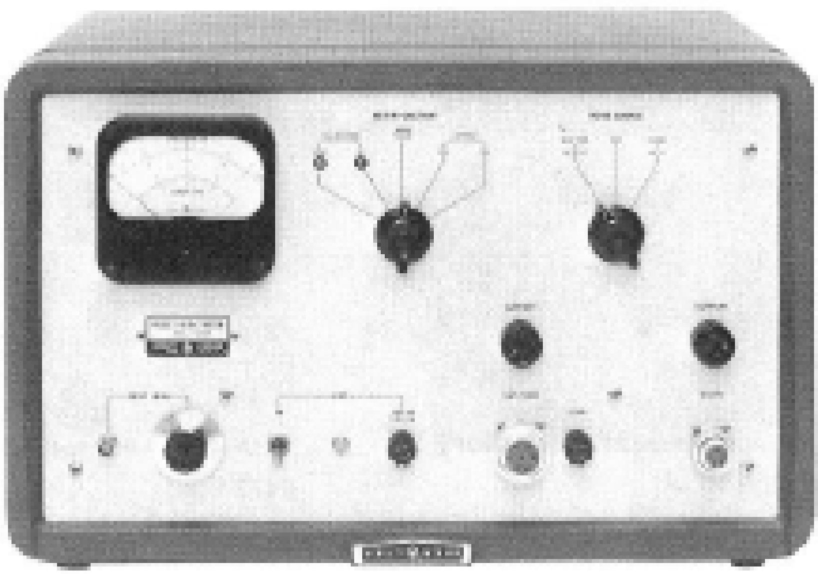
Calibration

- **Noise Source Calibration (S)**
- **S-parameter Calibration (S)**
- **Noise Tuner Calibration (S)**

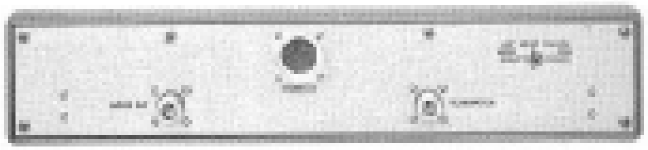
Verification

- **Mismatch Line**
- **Amp Characteristics**
- ***Combined S11***
- **Combined Gain**
- **Combined Noise Figure**

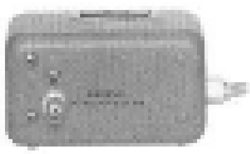
The Early Days



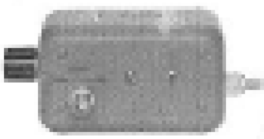
340B



349A



343A



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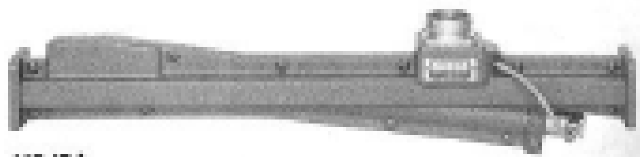
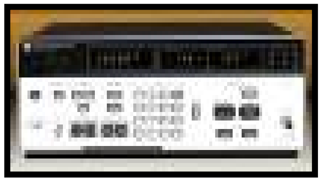


X347A

Agilent's Noise Figure Legacy

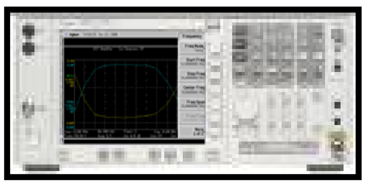
340A 1958



8970
1980

8560/90 with NF
1995

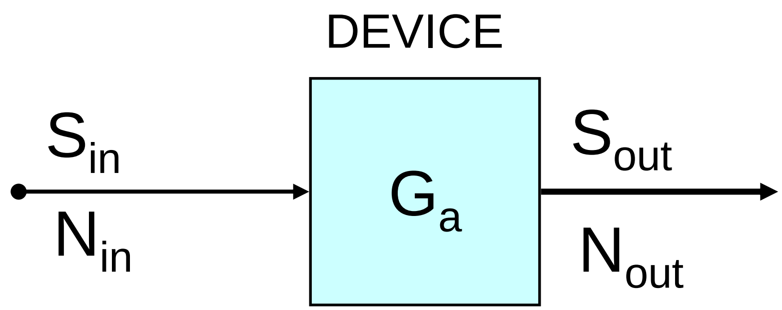
85120 1999



SA with NF
2002

NFA
2000

Definition



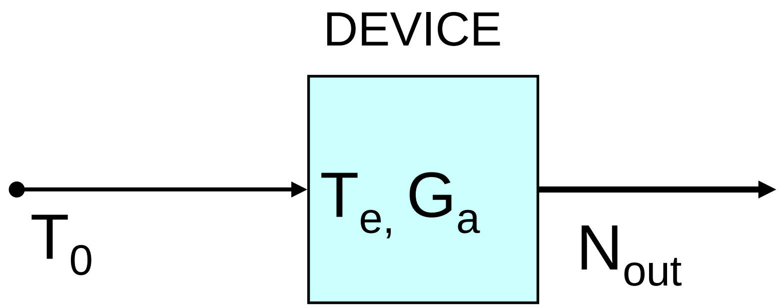
$$S_{out} = G_a * S_{in} \; ; \quad N_{out} = G_a * N_{in}\Big|_{T=T_0} + N_{add}\Big|_{T=T_0}$$

$$F(\text{noise factor}) = \frac{(S/N)_{in}}{(S/N)_{out}} = \frac{N_{out}}{G_a * N_{in}} = 1 + \frac{N_{add}}{G_a * N_{in}}$$

$G_a \equiv$ Available Gain, NF (Noise Figure) $\equiv 10*\log_{10}(F)$ dB

D. Vondran, “Noise Figure Measurement: Corrections Related to Match and Gain,” Microwave J., pp 22-38, Mar. 1999
Collantes, J. M., R. D. Pollard, et al. (2002). "Effects of DUT mismatch on the noise figure characterization: a comparative analysis of two Y-factor techniques." Instrumentation and Measurement, IEEE Transactions on **51**(6): 1150-1156.

Definition in Terms of Noise Temperature



$$N_{in} = k * T_0 * B\,; \quad N_{add} = G_a * k * T_e * B$$

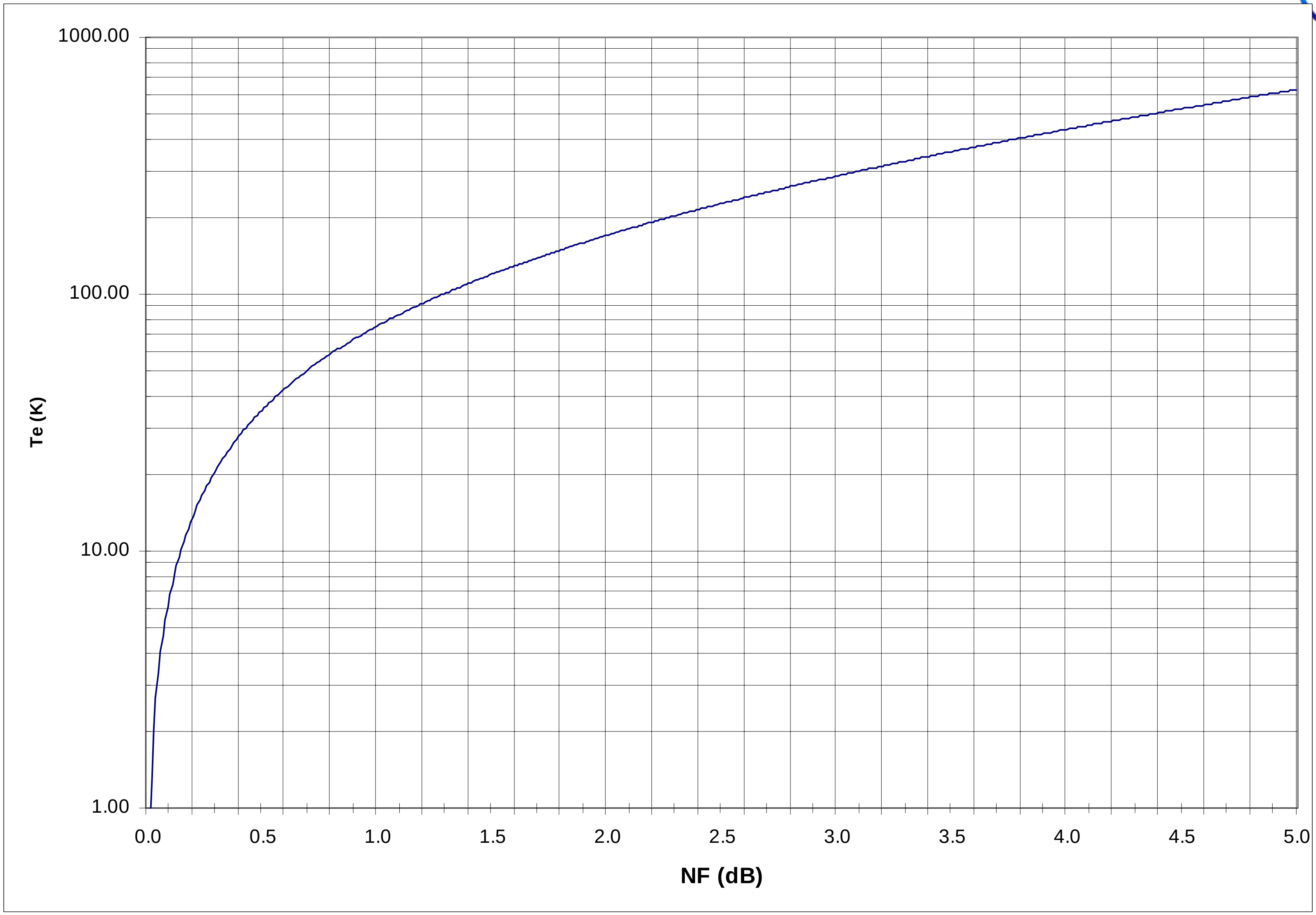
$T_0 \equiv 290K\,; \quad B \equiv$ bandwidth

$k \equiv$ Boltzmann's constant = $1.380\,6505 \times 10^{-23}$ joule/kelvin

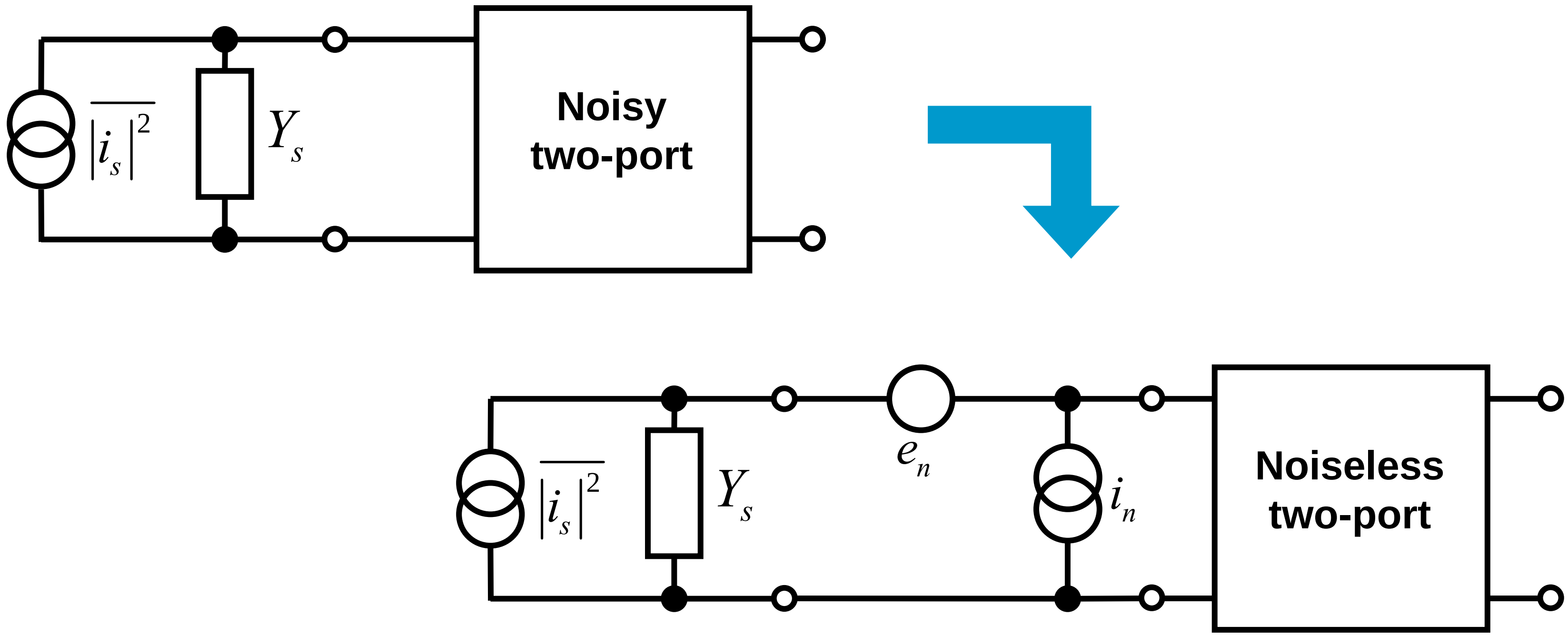
$T_e \equiv$ effective input noise temperature of device

$$F = \frac{N_{out}}{G_a * N_{in}} = 1 + \frac{T_e}{T_0}$$

Effective Temperature Versus Noise Figure



Definition In Terms Of Noise Parameters



$$F = F_{\min} + \left(\frac{R_n}{G_s}\right)\left|Y_s - Y_{opt}\right|^2 = F_{\min} + \frac{4R_n}{Z_0}\frac{\left|\Gamma_{opt} - \Gamma_s\right|^2}{\left|1+\Gamma_{opt}\right|^2\left(1-\left|\Gamma_s\right|^2\right)}$$

IRE Subcommittee 7.9 On Noise: "Representation Of Noise In Linear Two-ports," Proc. IRE, Vol. 48, Pp. 69-74, Jan. 1960

Noise parameters Definition (cont)

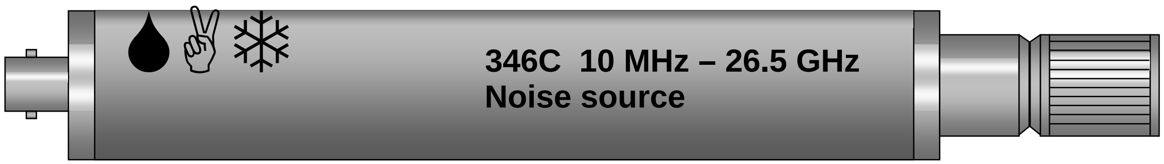
$$F = F_{\min} + \left(\frac{R_n}{G_s}\right)\left|Y_s - Y_{opt}\right|^2 = F_{\min} + \frac{4R_n}{Z_0}\frac{\left|\Gamma_{opt} - \Gamma_s\right|^2}{\left|1+\Gamma_{opt}\right|^2\left(1-\left|\Gamma_s\right|^2\right)}$$

$F_{\min} \equiv$ minimum noise factor
$R_n \equiv$ noise resistance

$Y_{opt} \equiv$ optimum input admittance
Y_s = source admittance
G_s = real part of Y_s

$\Gamma_{opt} \equiv$ optimum input noise match
Z_0 = reference impedance
Γ_s = source match

Noise Source ENR – Excess Noise Ratio

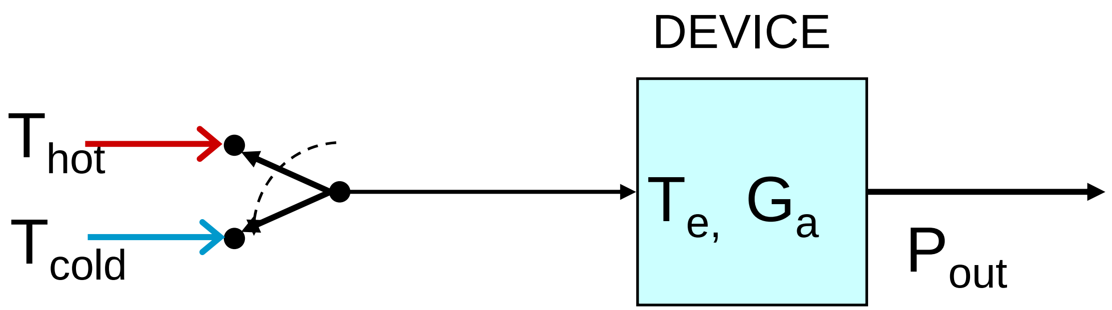


$$\mathrm{ENR} \equiv 10\log_{10}\left(\frac{T_h - T_c}{T_0}\right)$$

T_h = Hot Noise Temperature
T_c = Cold Noise Temperature
T_0 = 290 K

$T_c = T_0$ when noise sources are calibrated by reference labs.

Y factor Method



$$P_{out,hot} = kBG_a(T_{hot} + T_e) \qquad P_{out,cold} = kBG_a(T_{cold} + T_e)$$

$$Y = \frac{P_{out,hot}}{P_{out,cold}} \qquad T_e = \frac{T_{hot} - YT_{cold}}{Y - 1}$$

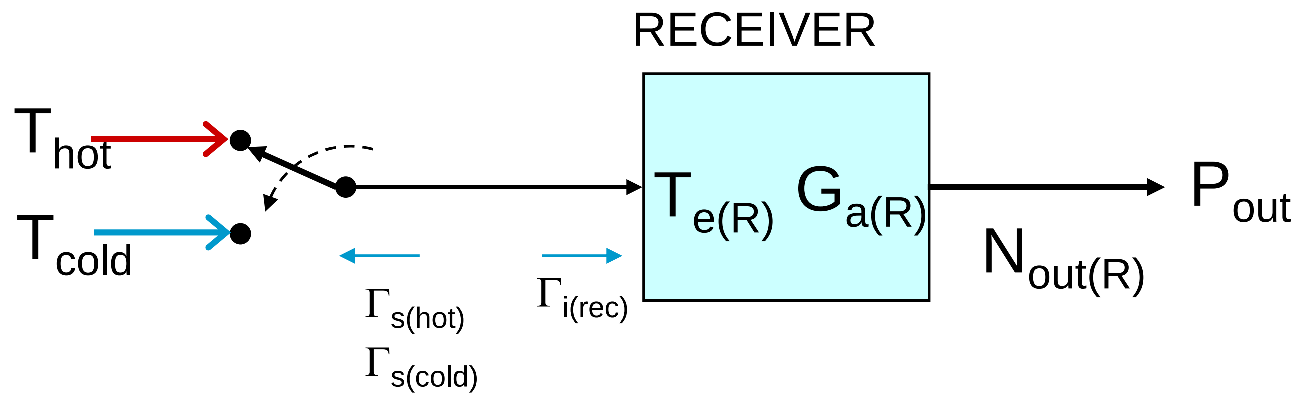
$$F = \frac{N_{out}}{G_a * N_{in}} = 1 + \frac{T_e}{T_0} = 1 + \frac{T_{hot} - Y * T_{cold}}{(Y - 1) * T_0}$$

Assumes ALL Reflections are the same.

"Fundamentals of RF and Microwave Noise Figure Measurements," Hewlett-Packard Application Note 57-1, Palo Alto, CA July 1983

Actual Y factor Measurement Calibration

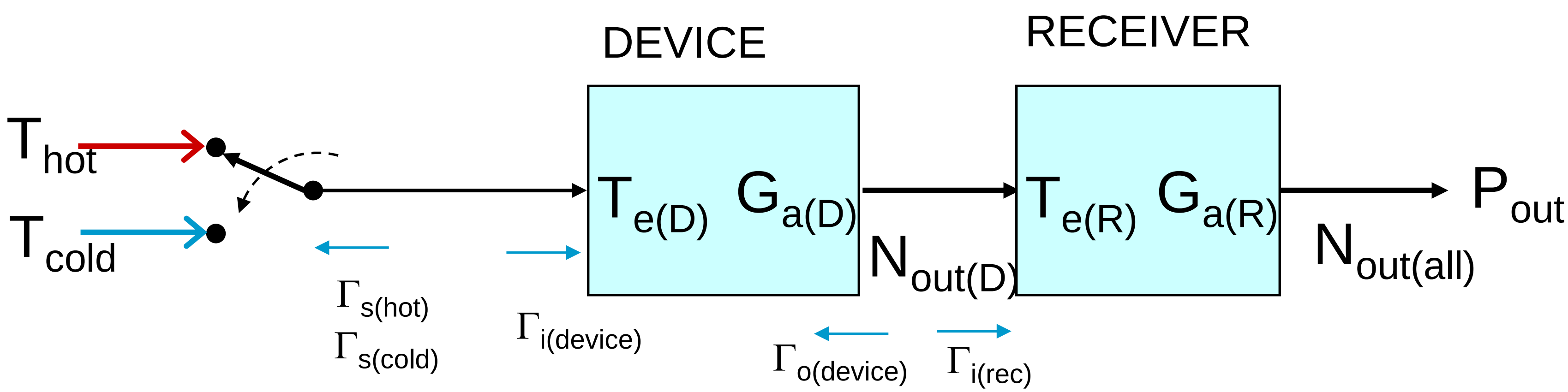
Receiver Calibration



$$F_{(R)}\Big|_{\Gamma_s} = \frac{N_{out(R)}}{G_{a(R)} * N_{in}} = 1 + \frac{T_{e(R)}}{T_0} = 1 + \frac{T_{hot} - Y * T_{cold}}{(Y-1) * T_0}$$

Assumes $\Gamma_{s(hot)} = \Gamma_{s(cold)}$

Actual Y factor Measurement



$$F_{(all)}\Big|_{\Gamma_s} = 1 + \frac{T_{hot} - Y * T_{cold}}{(Y-1) * T_0}$$

$$F_{(device)}\Big|_{\Gamma_s} = F_{(all)} - \frac{F_{(R)}\Big|_{\Gamma_{o(device)}} - 1}{G_{a(D)}}$$

Note that $F_{(R)}\Big|_{\Gamma_{o(device)}} \neq F_{(R)}\Big|_{\Gamma_s}$

Some Y factor Measurement Assumptions

$$\Gamma_{s(hot)} = \Gamma_{s(cold)}$$

$$F_{(R)}\Big|_{\Gamma_{o(device)}} = F_{(R)}\Big|_{\Gamma_s}$$

$$G_{a(device)} = \frac{N_{hot(all)} - N_{cold(all)}}{N_{hot(R)} - N_{cold(R)}}$$

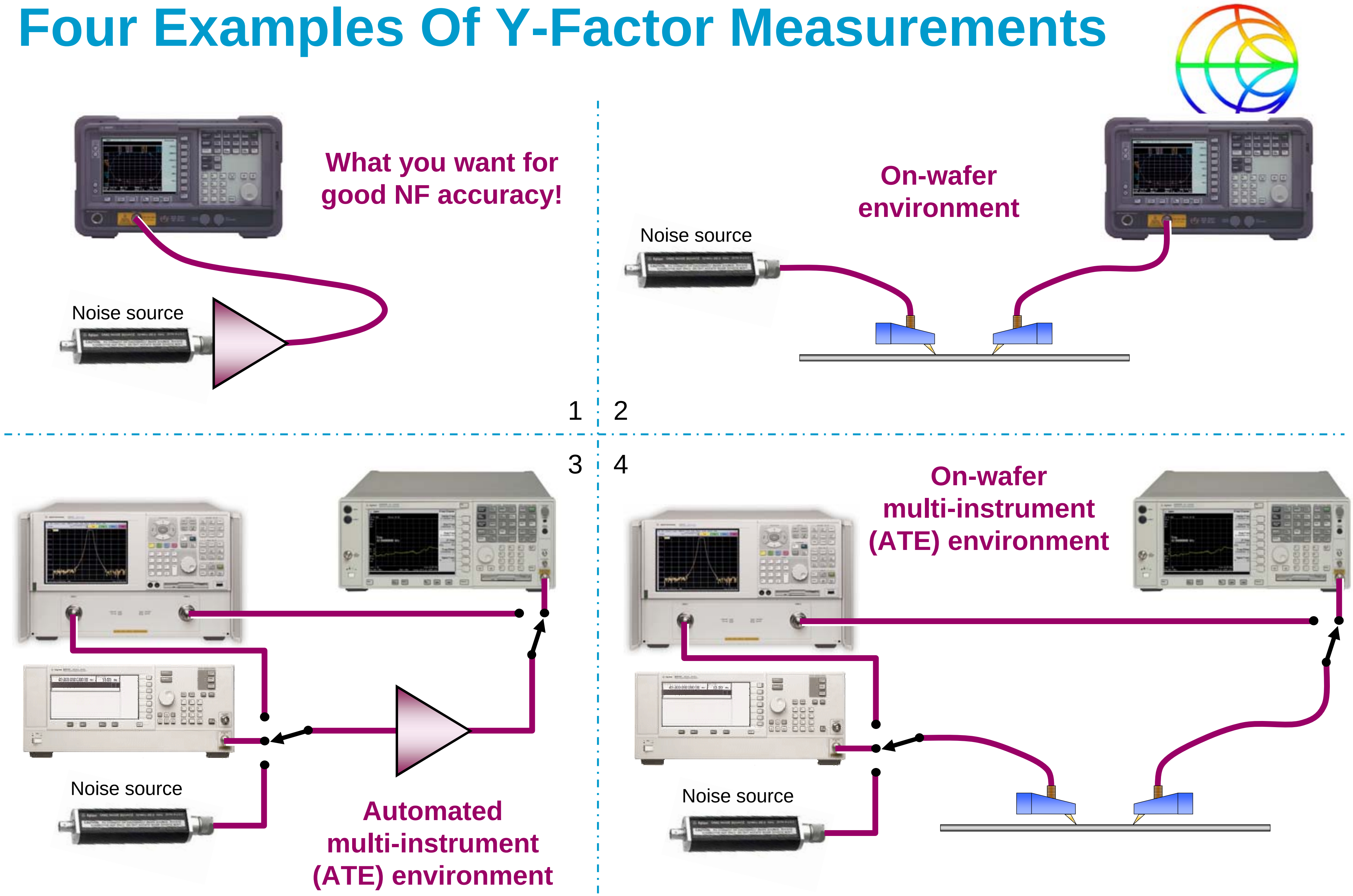
True only if S_{11} and S_{22} are <<1

Notes:

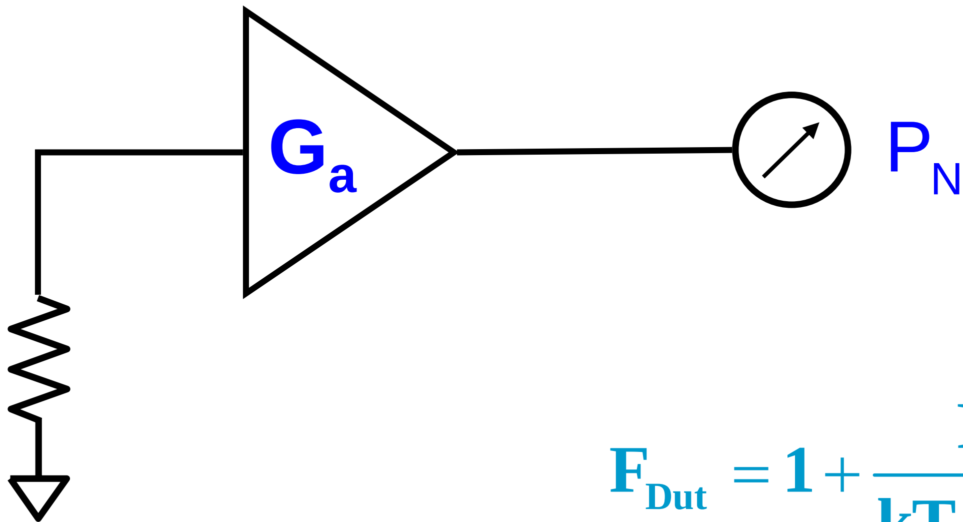
G_a (available gain) is a function of S_{11}, S_{22} and Γ_s

$\Gamma_s \equiv$ source reflection of the incident signal

Four Examples Of Y-Factor Measurements



Cold Noise Source Technique



$$F_{Dut} = 1 + \frac{P_n}{kT_0BG_a}$$

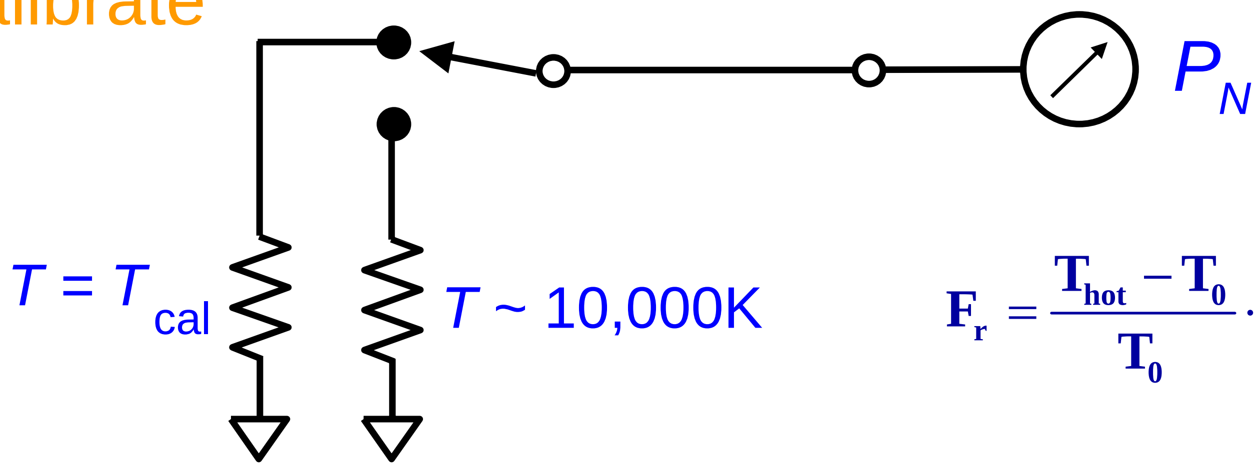
Need to know gain very accurately

Ga is a function of of S_{11}, S_{22} and Γ_s

Cold Noise Figure Cal and Measurement

$$\mathbf{kGB = k \cdot Gain \cdot Bandwidth}$$

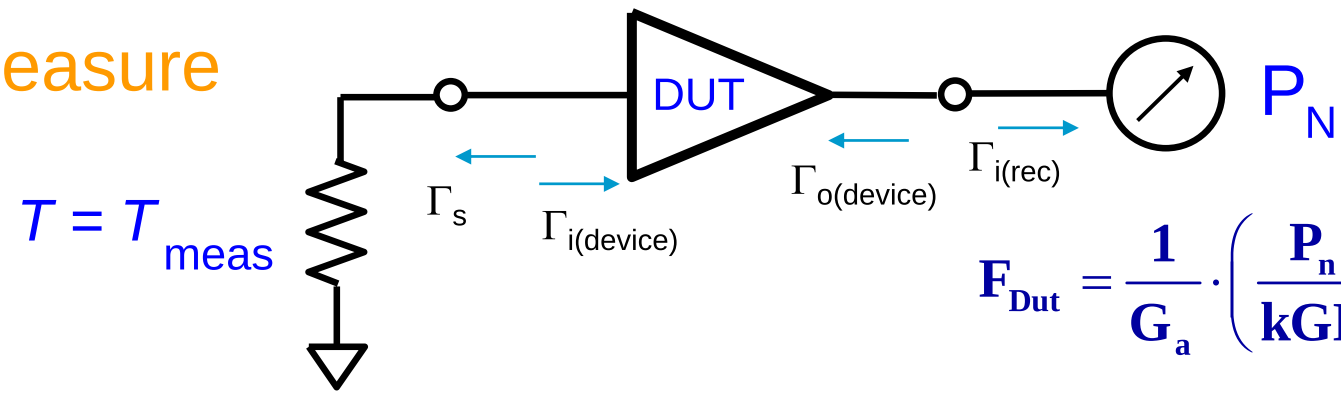
Calibrate



$$\mathbf{kGB} = \frac{\mathbf{P_{hot} - P_{cold}}}{\mathbf{T_{hot} - T_{cold}}}$$

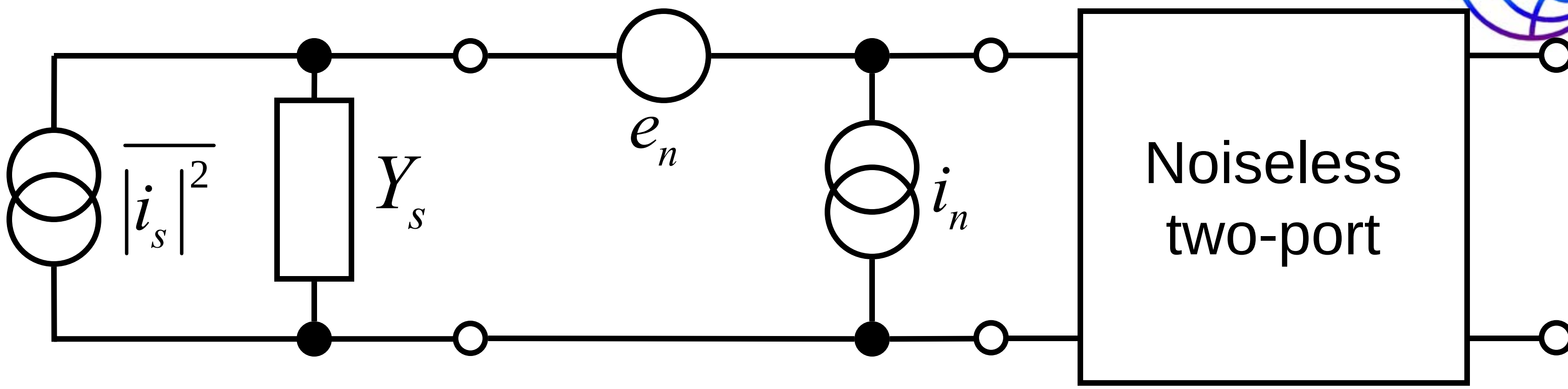
$$\mathbf{F_r} = \frac{\mathbf{T_{hot} - T_0}}{\mathbf{T_0}} \cdot \frac{\mathbf{1}}{\left(\mathbf{P_{nhot}} / \mathbf{P_{ncold}} - \mathbf{1} \right)}$$

Measure



$$\mathbf{F_{Dut}} = \frac{\mathbf{1}}{\mathbf{G_a}} \cdot \left(\frac{\mathbf{P_n}}{\mathbf{kGB}} - \mathbf{F_r} + \mathbf{1} \right)$$

Noise Parameters



$$F = F_{min} + \frac{4R_n}{Z_o} \frac{\left|\Gamma_{opt} - \Gamma_s\right|^2}{\left|1+\Gamma_{opt}\right|^2 \left(1-\left|\Gamma_s\right|^2\right)}$$

Noise figure varies as a function of source impedance

Four noise parameters: F_{min}, R_n, $\Gamma_{opt\ (mag)}$, $\Gamma_{opt\ (phase)}$

Noise parameters Definition

$$F = F_{\min} + \left(\frac{R_n}{G_s}\right)\left|Y_s - Y_{opt}\right|^2 = F_{\min} + \frac{4R_n}{Z_0}\frac{\left|\Gamma_{opt} - \Gamma_s\right|^2}{\left|1+\Gamma_{opt}\right|^2\left(1-\left|\Gamma_s\right|^2\right)}$$

F_{min} ≡ minimum noise factor
R_n ≡ noise resistance

Y_{opt} ≡ optimum input admittance
Y_s = source admittance
G_s = real part of Y_s

Γ_{opt} ≡ optimum input noise match
Z_0 = reference impedance
Γ_s = source match

Noise parameters Definition –
Noise Temperature

$$T_n = T_{\min} + \frac{(R_n T_0)\left|Y_s - Y_{opt}\right|^2}{G_s} = T_{\min} + \frac{4T_0 R_n}{Z_0} \frac{\left|\Gamma_{opt} - \Gamma_s\right|^2}{\left|1+\Gamma_{opt}\right|^2 \left(1-\left|\Gamma_s\right|^2\right)}$$

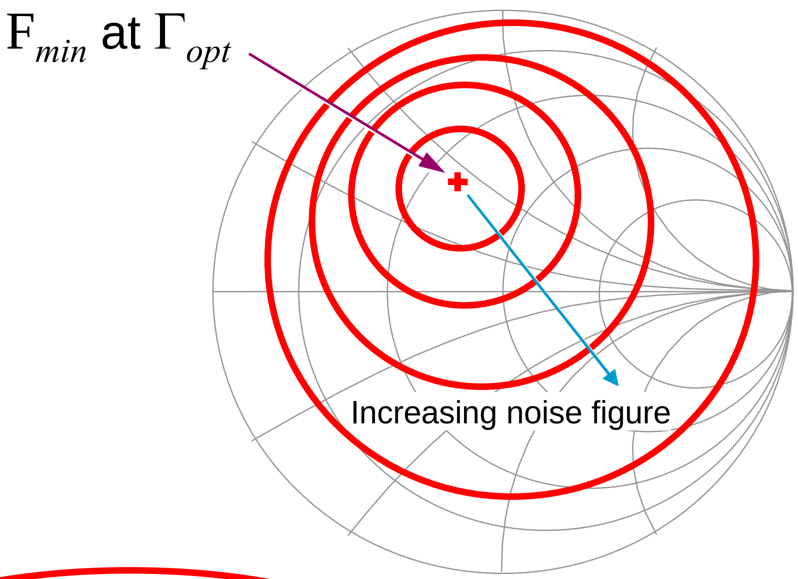
$T_{\min} \equiv$ minimum noise Temperature
$R_n \equiv$ noise resistance
$T_0 \equiv$ 290°K

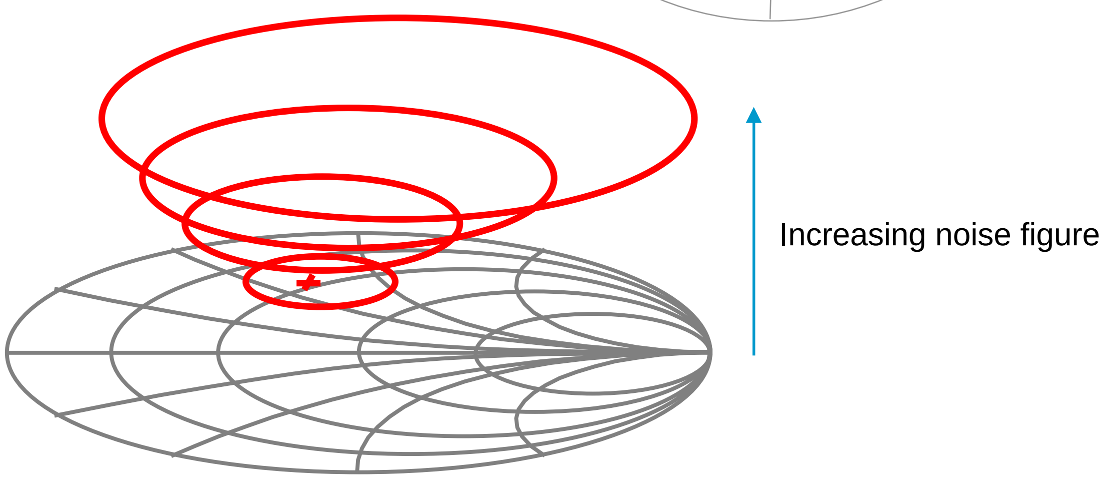
$Y_{opt} \equiv$ optimum input admittance
Y_s = source admittance
G_s = real part of Y_s

$\Gamma_{opt} \equiv$ optimum input noise match
Z_0 = reference impedance
Γ_s = source match

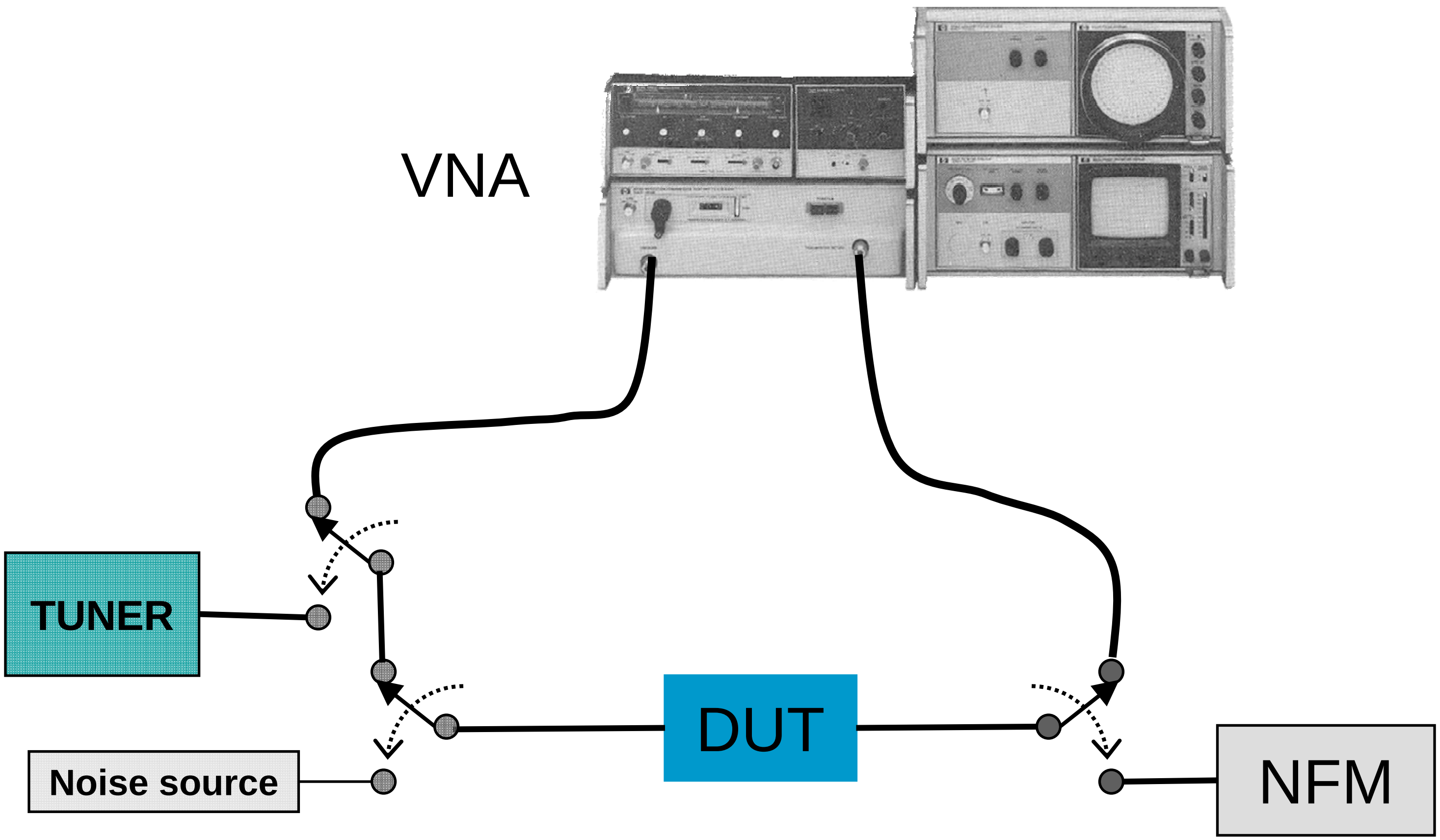
Noise Parameters

- Plots of noise figure circles versus impedance (at one frequency)
- F_{min} is lowest noise figure and occurs at Γ_{opt}
- F changes with Γ
- F changes with device bias



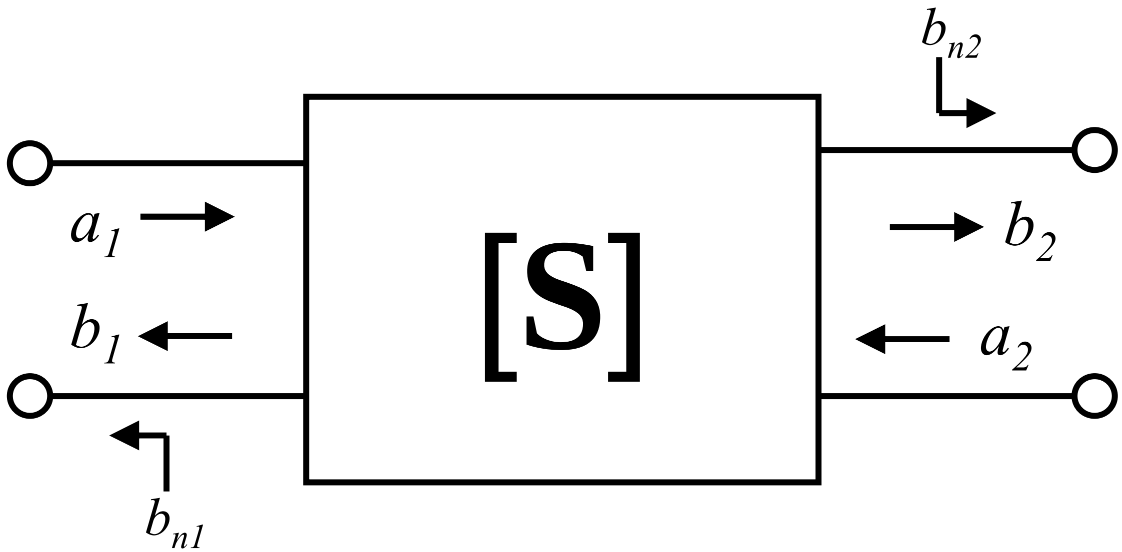


Measuring Noise parameters



A. C. Davidson, B. W. Leake, et al. (1989). "Accuracy improvements in microwave noise parameter measurements." Microwave Theory and Techniques, IEEE Transactions on **37**(12): 1973-1978.

Noise wave representation – S-parameters



$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} + \begin{pmatrix} b_{n1} \\ b_{n2} \end{pmatrix}$$

$$\mathbf{C}_s = \begin{pmatrix} \overline{|b_{n1}|^2} & \overline{b_{n1} b_{n2}^*} \\ \overline{b_{n2} b_{n1}^*} & \overline{|b_{n2}|^2} \end{pmatrix} = \begin{pmatrix} cs_{11} & cs_{12} \\ cs_{21} & cs_{22} \end{pmatrix}$$

P. Penfield, Jr "Wave Representation of Amplifier Noise." IRE Transactions On Circuit Theory: Mach (1962) pp. 84-86
K. Hartmann, "Noise Characterization of Linear Circuits," IEEE Transactions on Circuits and Systems, Vol. cAS-23, No. 10, Oct. 1976, pp. 581-590
R.P. Meys, "A Wave Approach to the Noise Properties of Linar Microwave Devices," IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-26, No. 1, Jan. 1978, pp 34-37
S. W. Wedg ,and D. B. Rutledge (1992). "Wave techniques for noise modeling and measurement." Microwave Theory and Techniques, IEEE Transactions on **40**(11): 2004-2012.

Measurement using (S) noise correlation matrix

Noise output power from two-port is

$$P_{out} = kBG_{av}\left(T_e + T_0\right)$$

$$P_{out} = \left(\frac{kB\left|s_{21}\right|^2}{\left|1-\Gamma_s S_{11}\right|^2}\right)\left\{\begin{matrix}\left(1-\left|\Gamma_s\right|^2\right)T_s + \left|\Gamma_s\right|^2 X_1 + \\ \left|1-\Gamma_s S_{11}\right|^2 X_2 + 2\operatorname{Re}\left[\left(1-\Gamma_s S_{11}\right)^* \Gamma_s X_{21}\right]\end{matrix}\right\}$$

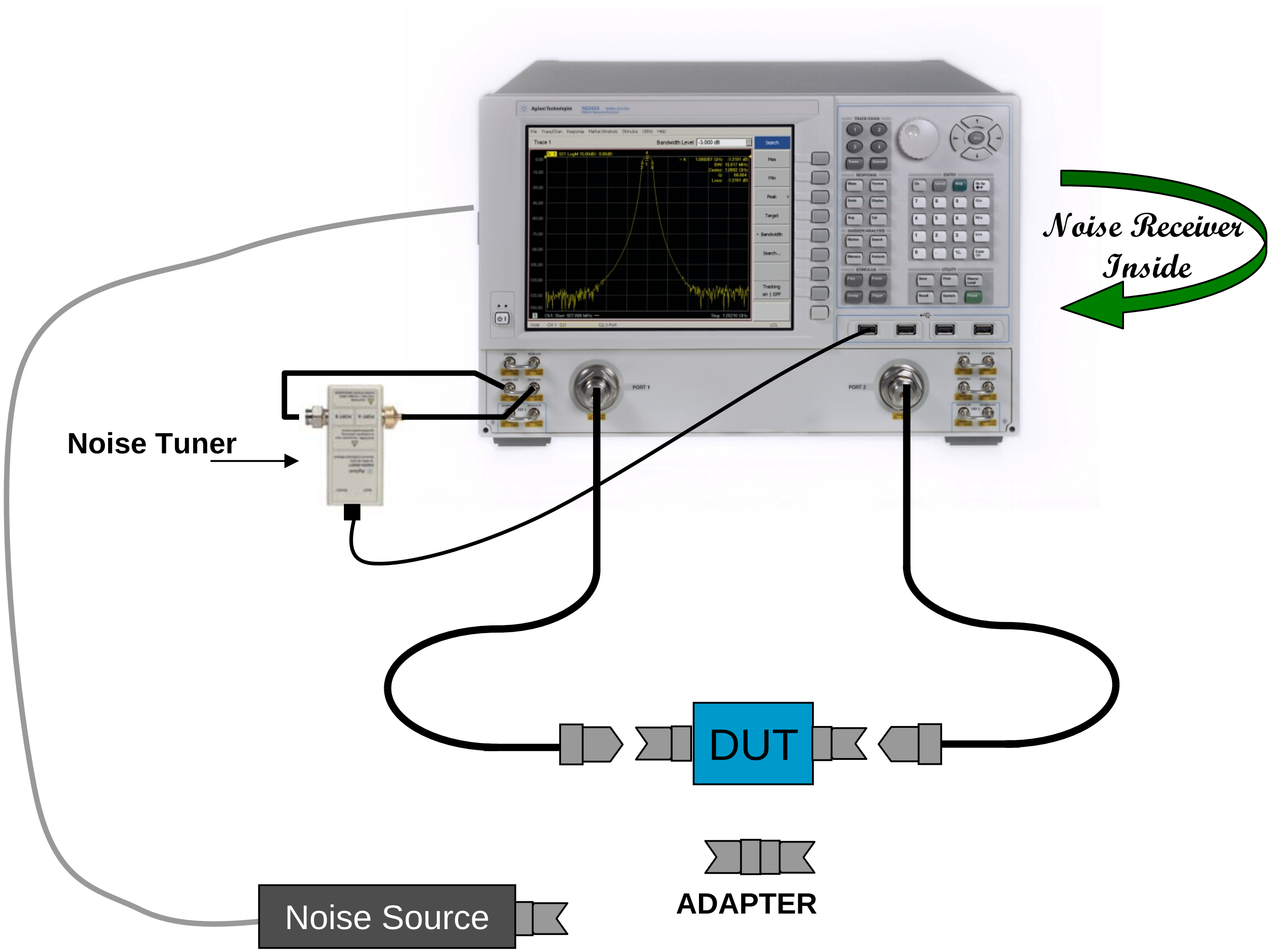
$$X_1 = \overline{\left|b_{n1}\right|^2} = cs_{11}\,, \quad X_2 = \frac{\overline{\left|b_{n2}\right|^2}}{\left|S_{21}\right|^2} = \frac{cs_{22}}{\left|S_{21}\right|^2}\,, \quad X_{12} = \frac{\overline{b_{n1}b_{n2}^*}}{S_{21}^*} = \frac{cs_{12}}{S_{21}^*}$$

J. Randa, W. Wiatr, "Conte Carlo Estimation of Noise Parameter Uncertainties," IEE Proc. Sci. Meas. Technology, Vol. 149, No. 6, Nov. 2002, pp. 333-337

Noise correlation matrix (C_S) in terms of noise parameters

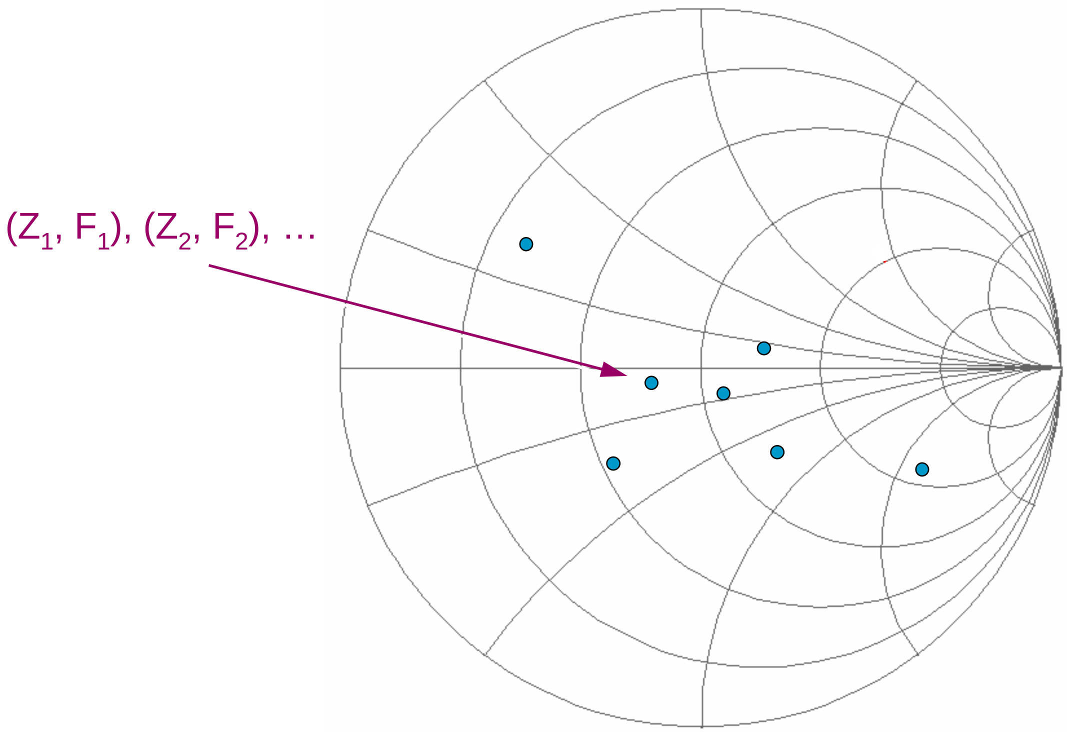
$$
\mathbf{C_s} = \begin{pmatrix}
\left(F_{\min} - 1\right)\left(\left|s_{11}\right|^2 - 1\right) + \dfrac{4R_n}{Z_0}\dfrac{\left|1 - s_{11}\Gamma_{opt}\right|^2}{\left|1 + \Gamma_{opt}\right|^2} & \overline{s_{21}}\left(\left(F_{\min} - 1\right)s_{11} - \dfrac{4R_n\overline{\Gamma_{opt}}\left(1 - s_{11}\Gamma_{opt}\right)}{Z_0\left|1 + \Gamma_{opt}\right|^2}\right) \\
\overline{\overline{s_{21}}\left(\left(F_{\min} - 1\right)s_{11} - \dfrac{4R_n\overline{\Gamma_{opt}}\left(1 - s_{11}\Gamma_{opt}\right)}{Z_0\left|1 + \Gamma_{opt}\right|^2}\right)} & \left|s_{21}\right|^2\left(F_{\min} - 1\dfrac{4R_n\left|\Gamma_{opt}\right|^2}{Z_0\left|1 + \Gamma_{opt}\right|^2}\right)
\end{pmatrix}
$$

New Noise Measurement System



ECal as Noise Tuner

PNA-X varies source match around 50 ohms using an ECal module
- ECal can provide 7 impedance states



Noise Figure in PNA – contributions

Speed and accuracy –

- Single Connection S-parameters and Noise Figure
- Fast Step Frequency Sweep
- Complete Mismatch Correction

Use of ECal or Compatible Impedance Tuner

Embedding and De-embedding of Probes in On-Wafer Noise Measurements

Can Accommodate Coax Noise Source for On-Wafer Noise Measurements

Calibration of the receiver

$$P_{out} = \left(\frac{kB\left|S_{21}\right|^2}{\left|1-\Gamma_s S_{11}\right|^2} \right) \left\{ \begin{array}{l} \left(1-\left|\Gamma_s\right|^2\right) T_s + \left|\Gamma_s\right|^2 X_1 + \\ \quad \left|1-\Gamma_s S_{11}\right|^2 X_2 + 2\,\mathrm{Re}\left[\left(1-\Gamma_s S_{11}\right)^* \Gamma_s X_{21} \right] \end{array} \right\}$$

5 unknowns, linear equation

Note: The PNA-X uses a different form of the above equation.

Calibration of receiver
- solution of equations

Require Minimum Of 5 Equations To Solve

Can Be Over-determined

At Least One Measurement Must Be Made With Different Source Temperature

Use Noise Source (Known ENR, Measure Γ_{Cold}, Γ_{Hot})

ECal Module Provides 7 Terminations

Noise Figure Mode Instrument Default Settings

S-parameter Mode Source Power → -30 dBm

Noise RF BW → 4 MHz

Noise IF BW → 2 MHz

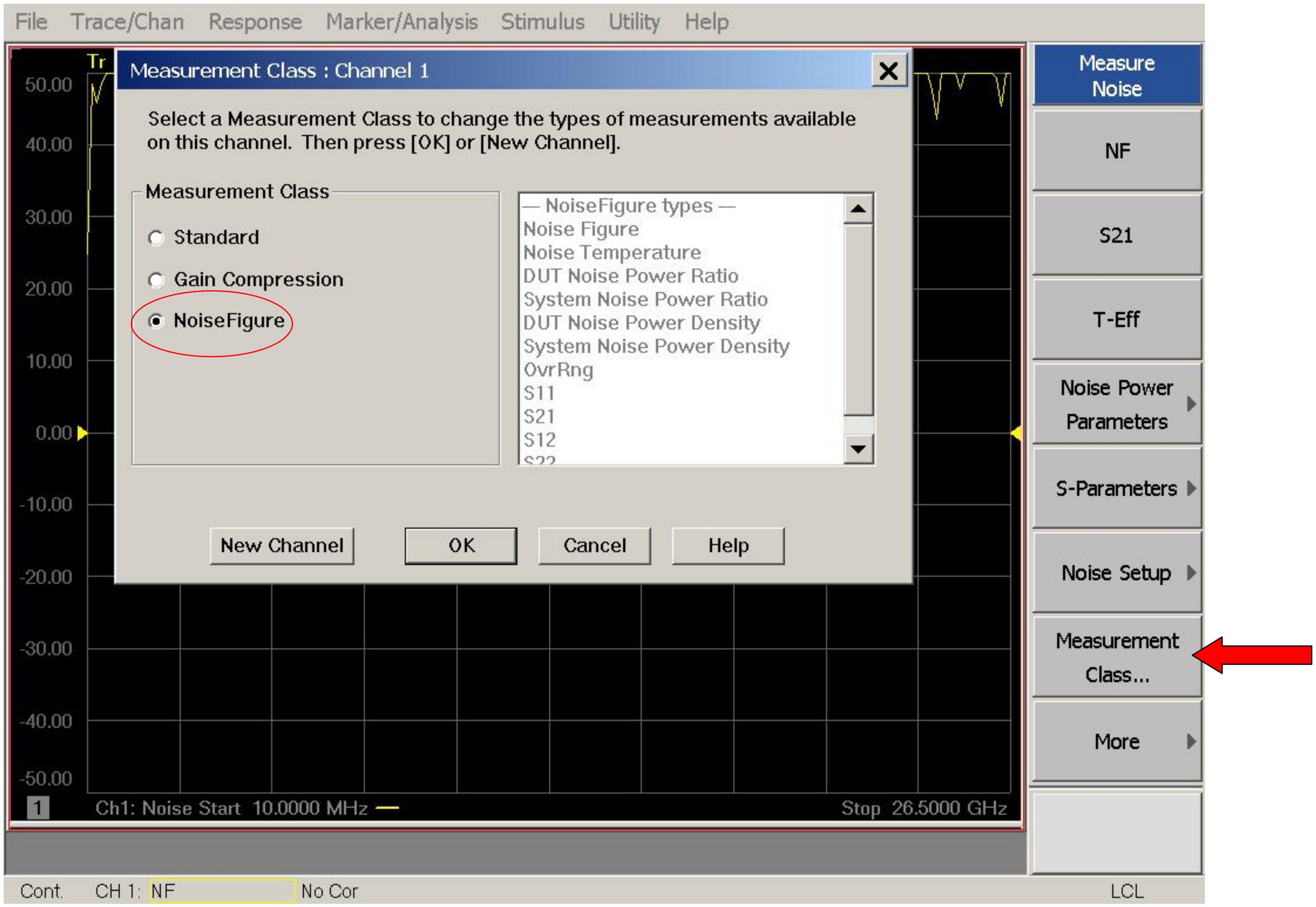
Noise Averaging → Point to Point (1 = 10K)

Noise Receiver Gain → 30 dB

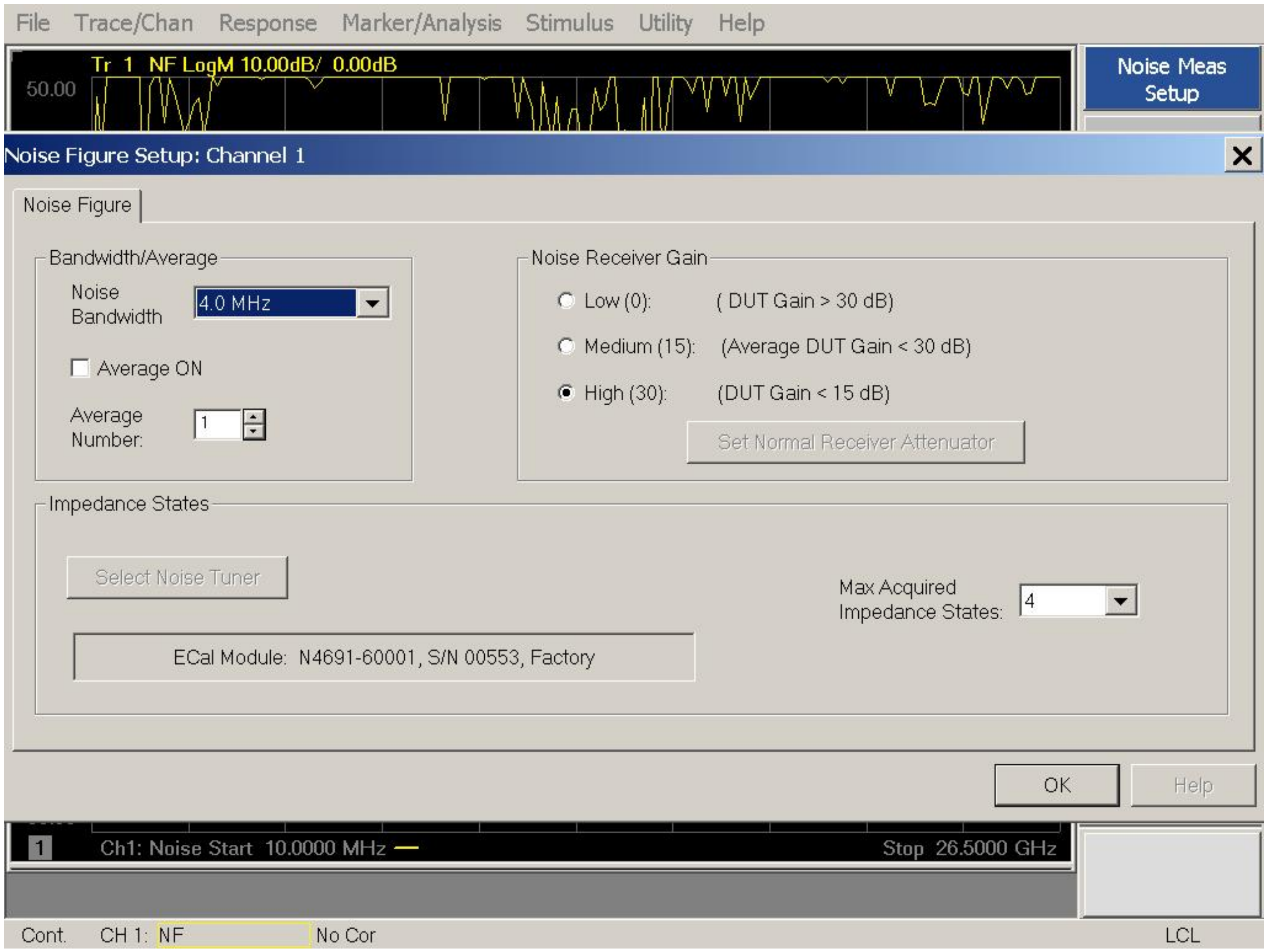
Factory Receiver Cal → ON

Noise Figure Measurement Instrument Setup

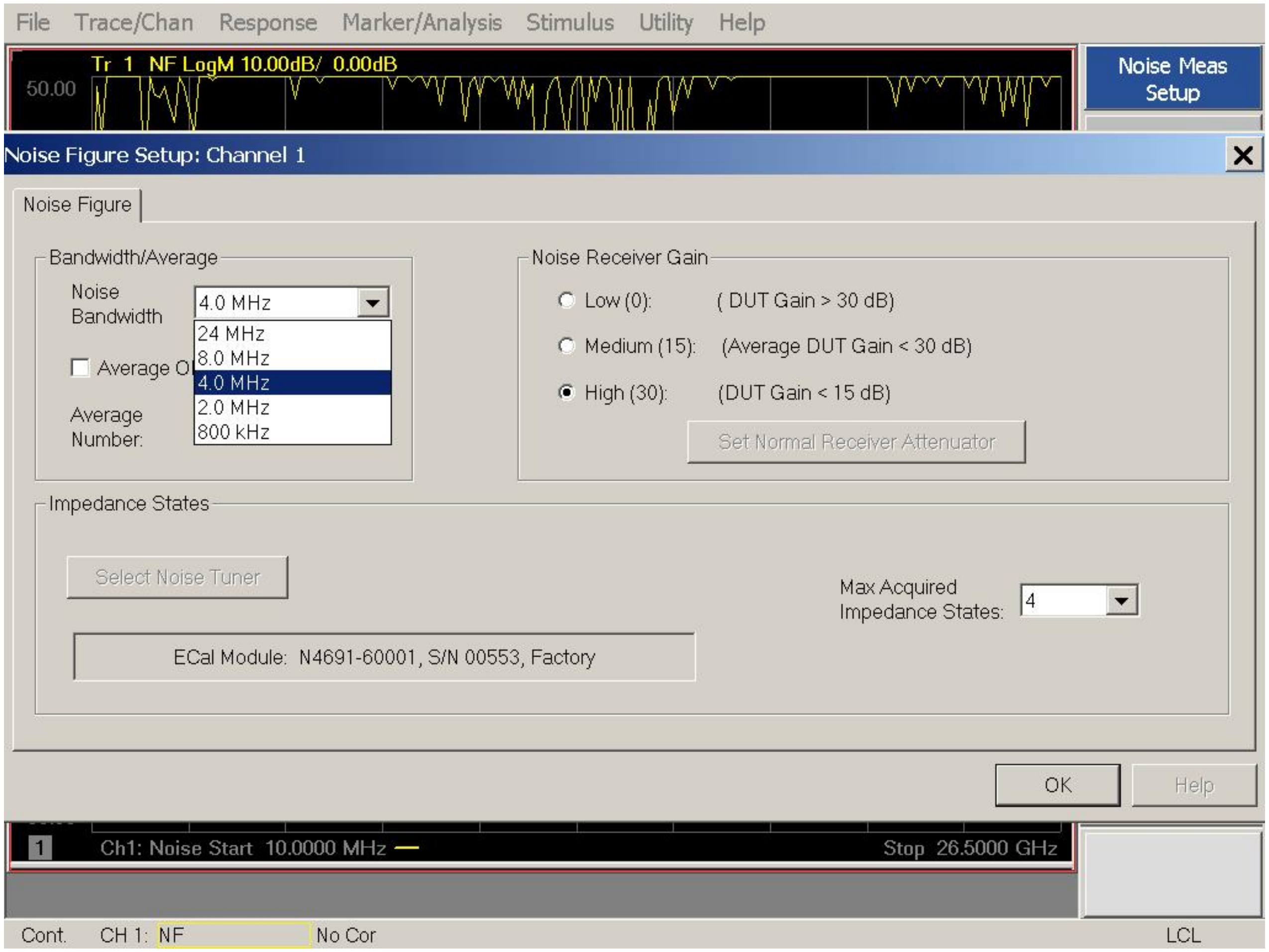
Noise Measurement Softkeys



Noise Set Up


File Trace/Chan Response Marker/Analysis Stimulus Utility Help
Tr 1 NF LogM 10.00dB/ 0.00dB
50.00
Noise Meas Setup
Noise Figure Setup: Channel 1
Noise Figure
Bandwidth/Average
Noise Bandwidth
4.0 MHz
Average ON
Average Number:
1
Noise Receiver Gain
Low (0): (DUT Gain > 30 dB)
Medium (15): (Average DUT Gain < 30 dB)
High (30): (DUT Gain < 15 dB)
Set Normal Receiver Attenuator
Impedance States
Select Noise Tuner
Max Acquired Impedance States:
4
ECal Module: N4691-60001, S/N 00553, Factory
OK
Help
1
Ch1: Noise Start 10.0000 MHz
Stop 26.5000 GHz
Cont. CH 1: NF No Cor
LCL

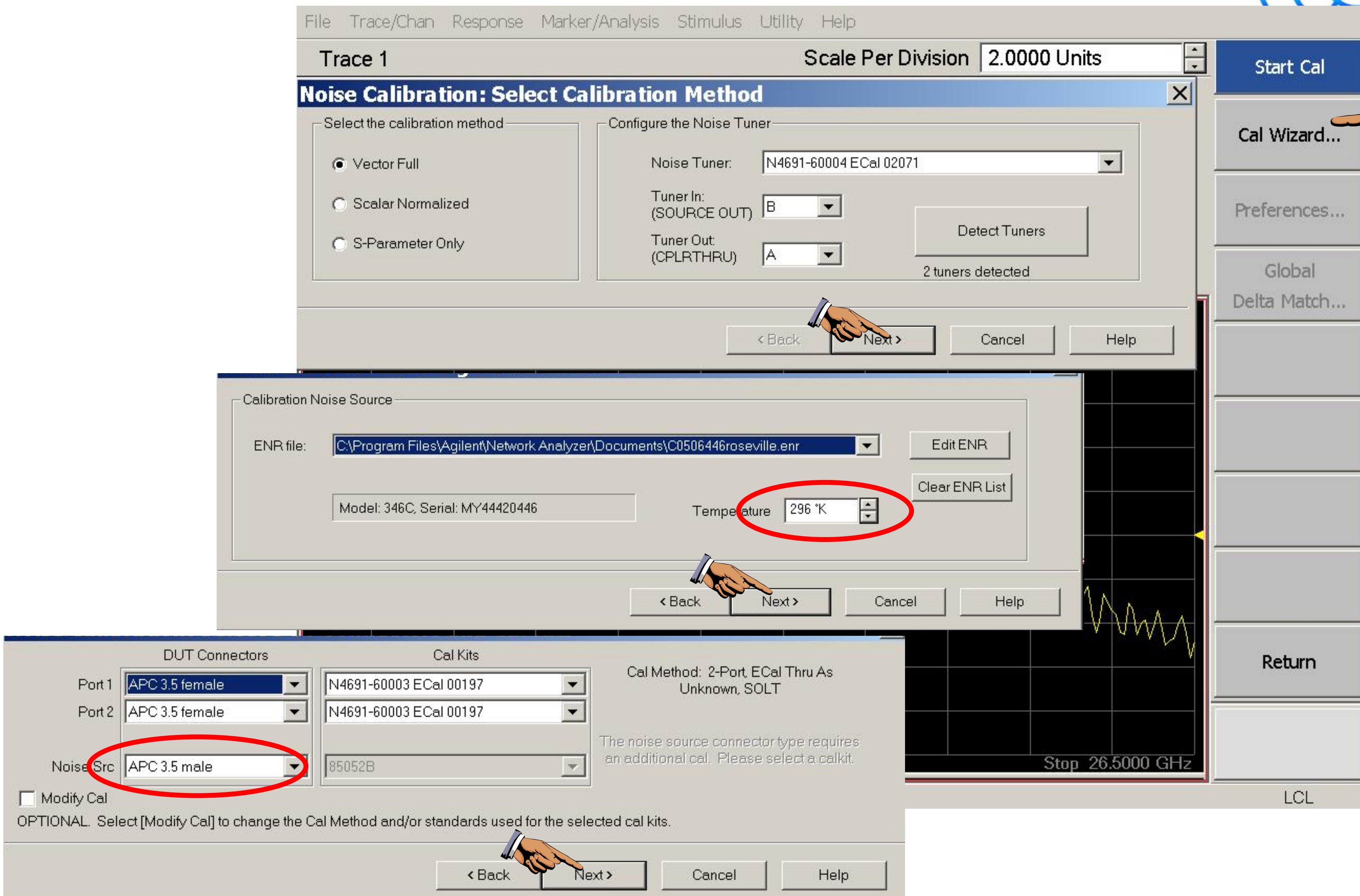
Noise Set Up



File Trace/Chan Response Marker/Analysis Stimulus Utility Help
Tr 1 NF LogM 10.00dB/ 0.00dB
50.00
Noise Meas Setup
Noise Figure Setup: Channel 1
Noise Figure
Bandwidth/Average
Noise Bandwidth
4.0 MHz
24 MHz
8.0 MHz
4.0 MHz
2.0 MHz
800 kHz
Average O
Average Number:
Noise Receiver Gain
Low (0): (DUT Gain > 30 dB)
Medium (15): (Average DUT Gain < 30 dB)
High (30): (DUT Gain < 15 dB)
Set Normal Receiver Attenuator
Impedance States
Select Noise Tuner
Max Acquired Impedance States: 4
ECal Module: N4691-60001, S/N 00553, Factory
OK
Help
Ch1: Noise Start 10.0000 MHz
Stop 26.5000 GHz
Cont. CH 1: NF No Cor
LCL

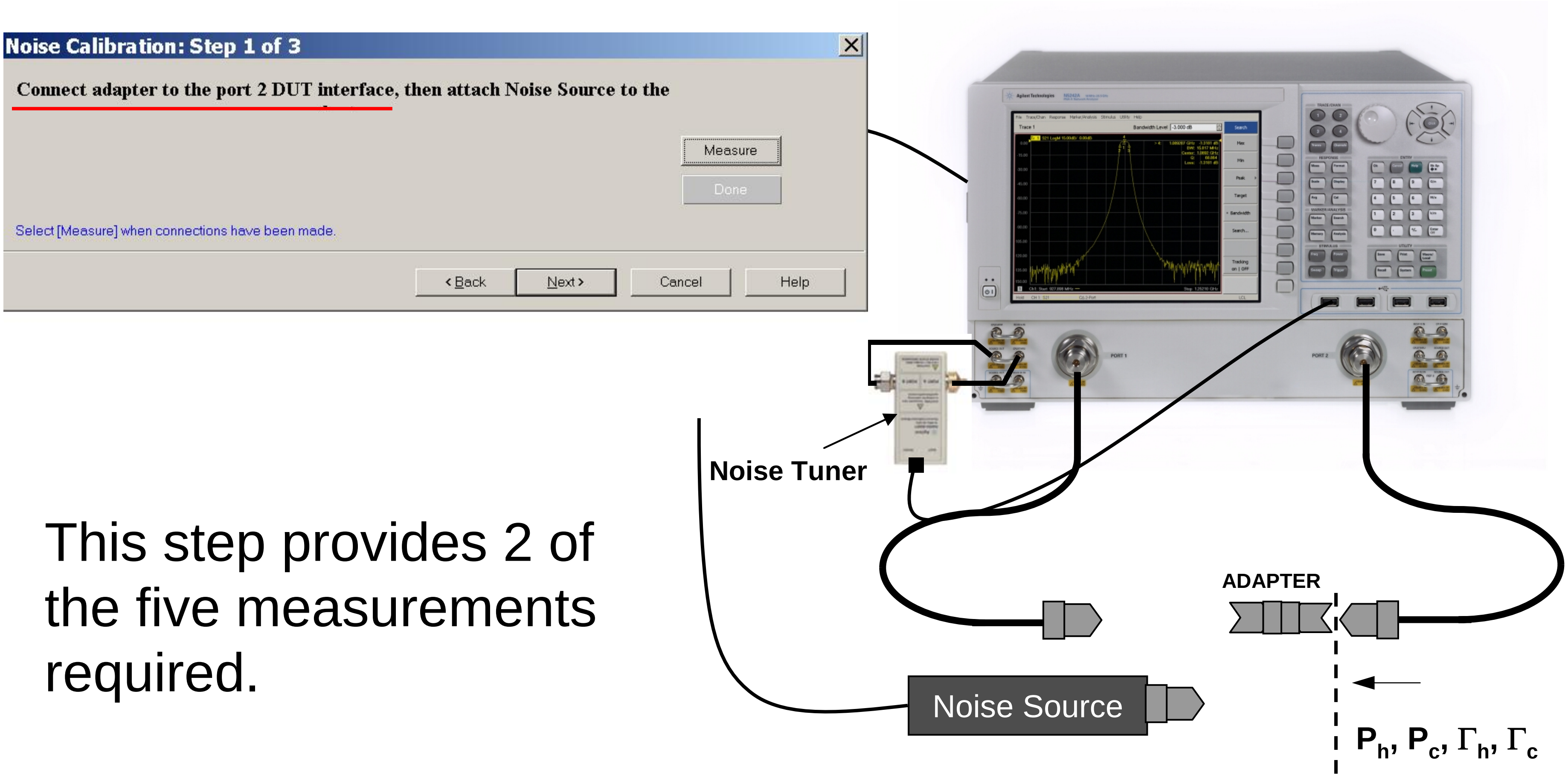
Noise Figure Measurement Calibration

Noise Cal



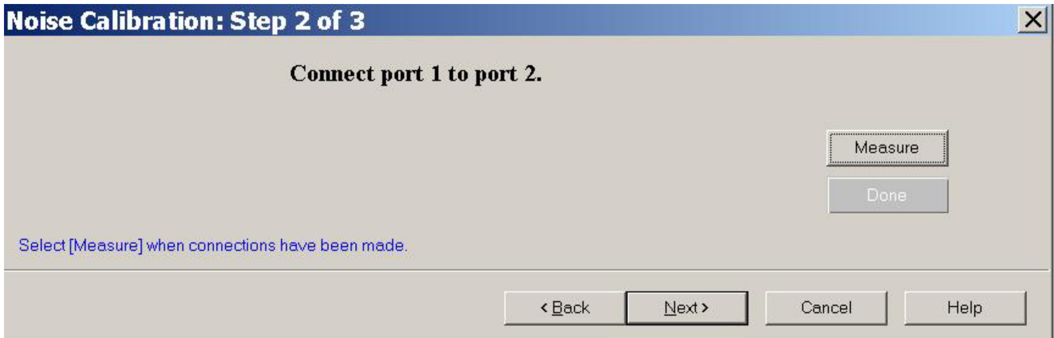
File Trace/Chan Response Marker/Analysis Stimulus Utility Help
Trace 1
Scale Per Division 2.0000 Units
Start Cal
Cal Wizard...
Preferences...
Global Delta Match...
Return
LCL
Noise Calibration: Select Calibration Method
Select the calibration method
Vector Full
Scalar Normalized
S-Parameter Only
Configure the Noise Tuner
Noise Tuner: N4691-60004 ECal 02071
Tuner In: (SOURCE OUT) B
Tuner Out: (CPLRTHRU) A
Detect Tuners
2 tuners detected
< Back Next > Cancel Help
Calibration Noise Source
ENR file: C:\Program Files\Agilent\Network Analyzer\Documents\C0506446roseville.enr
Edit ENR
Clear ENR List
Model: 346C, Serial: MY44420446
Temperature 296 °K
< Back Next > Cancel Help
DUT Connectors
Cal Kits
Port 1 APC 3.5 female N4691-60003 ECal 00197
Port 2 APC 3.5 female N4691-60003 ECal 00197
Noise Src APC 3.5 male 85052B
Cal Method: 2-Port, ECal Thru As Unknown, SOLT
The noise source connector type requires an additional cal. Please select a calkit.
Stop 26.5000 GHz
Modify Cal
OPTIONAL. Select [Modify Cal] to change the Cal Method and/or standards used for the selected cal kits.
< Back Next > Cancel Help

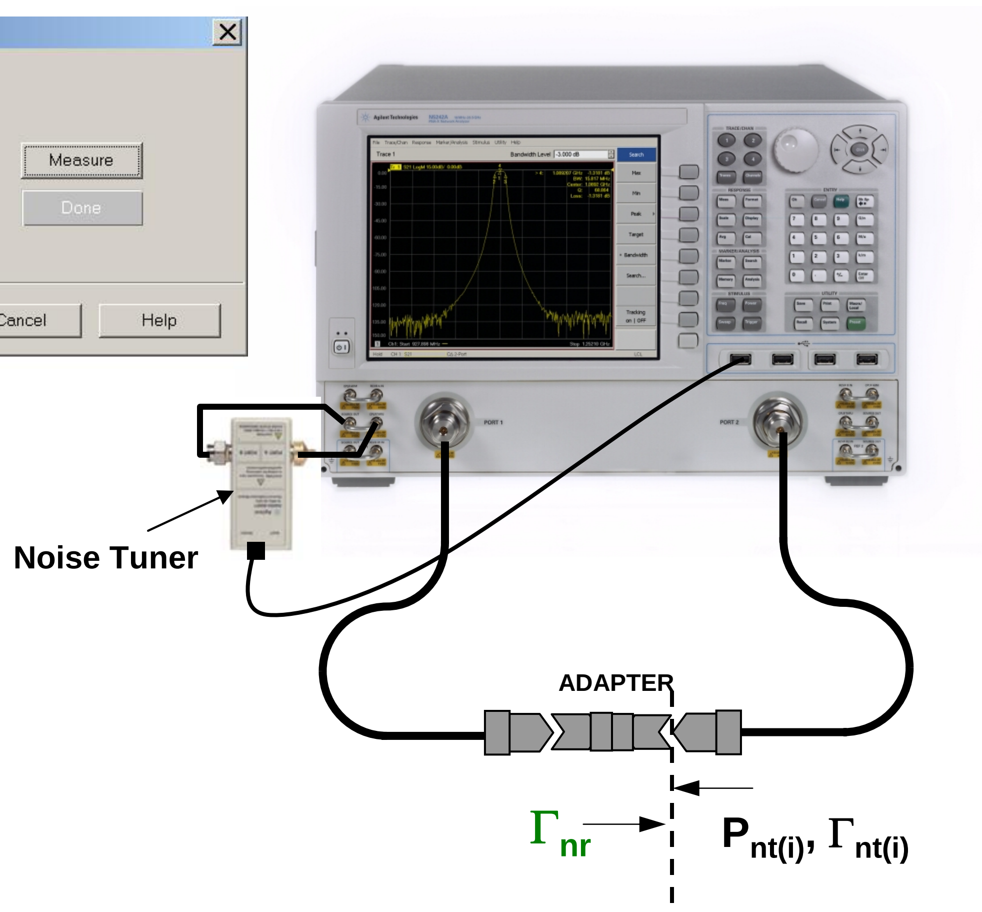
S-parameters and Noise Calibrations



This step provides 2 of the five measurements required.

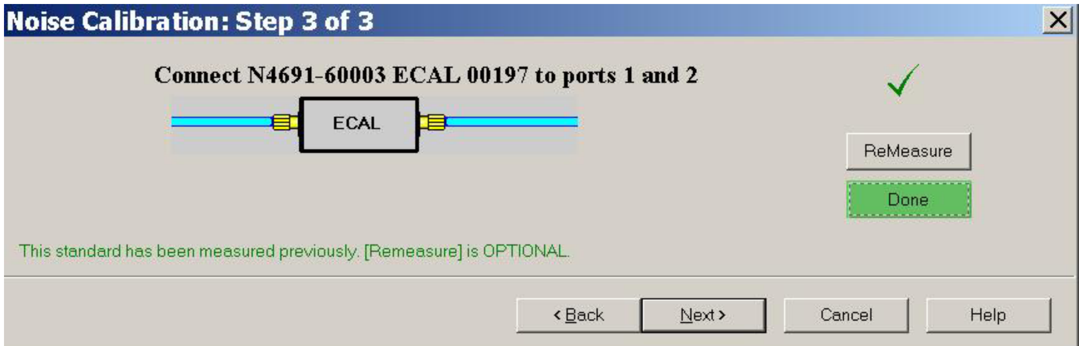
S-parameters and Noise Calibrations



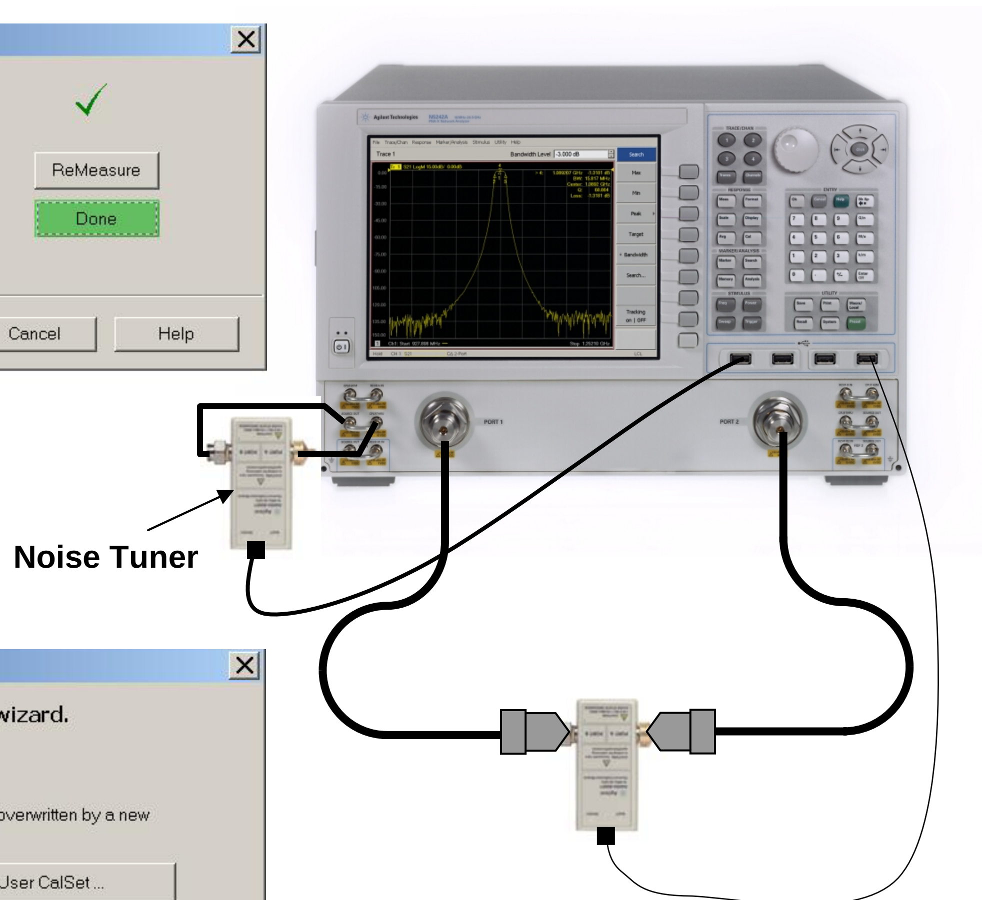


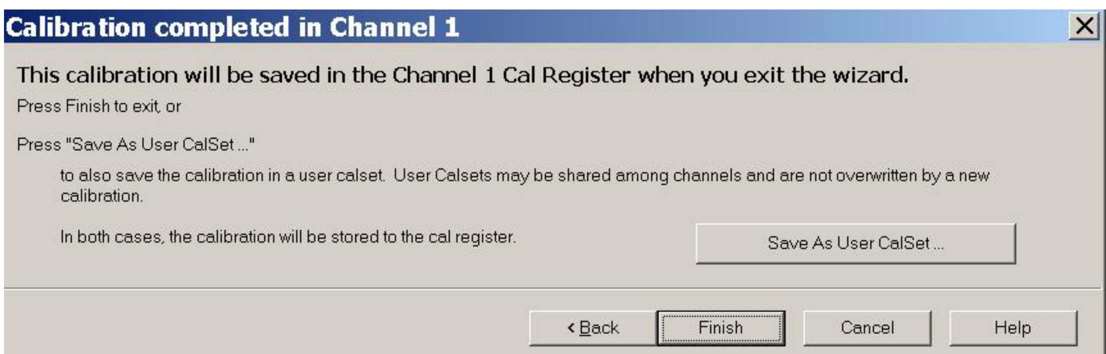
This step provides the rest of measurements required to calibrate the noise receiver.

S-parameters and Noise Calibrations



S-parameter calibration completes the calibration sequence.





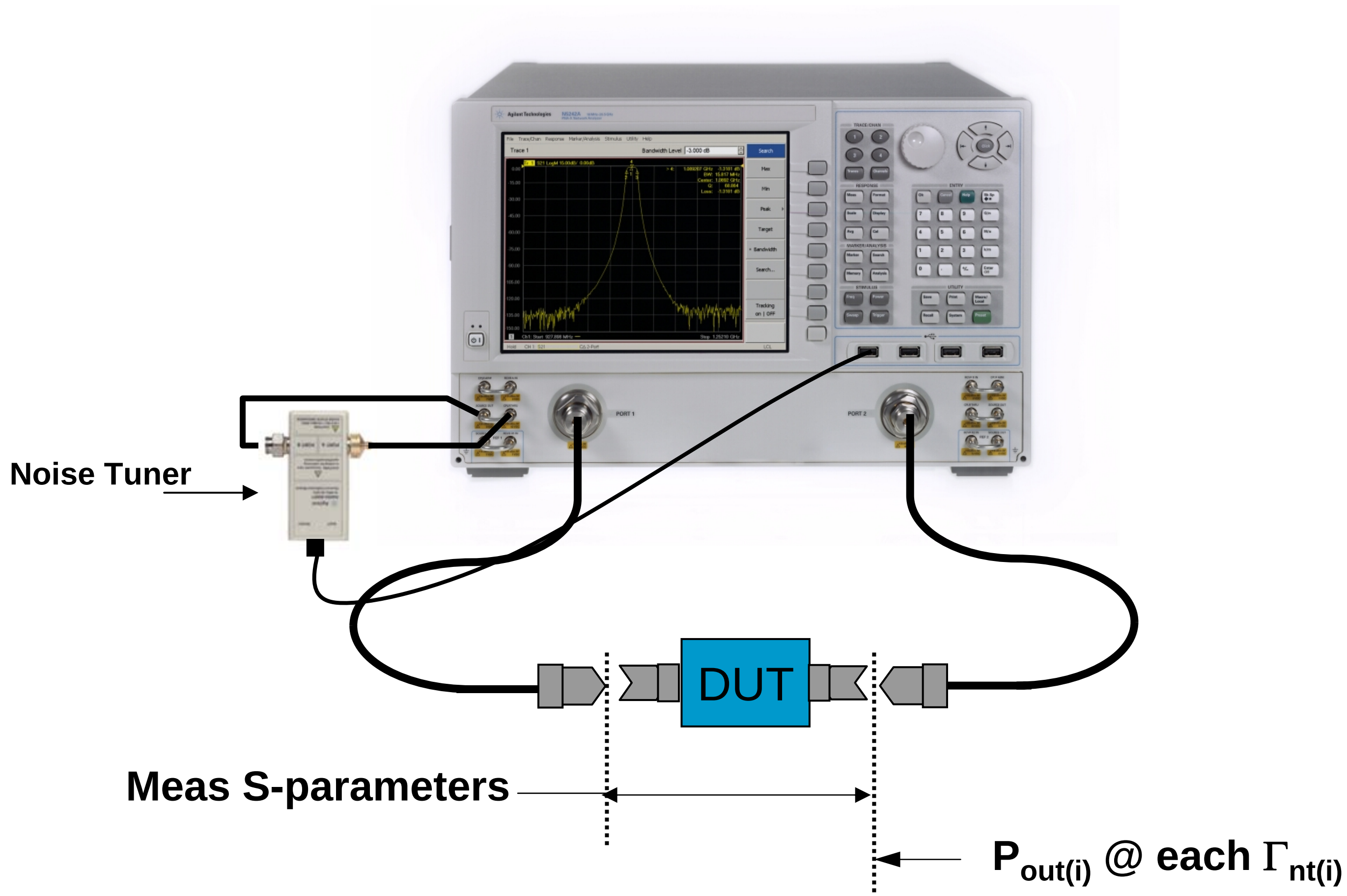
Measurement of DUT

Known from Measured S-parameters

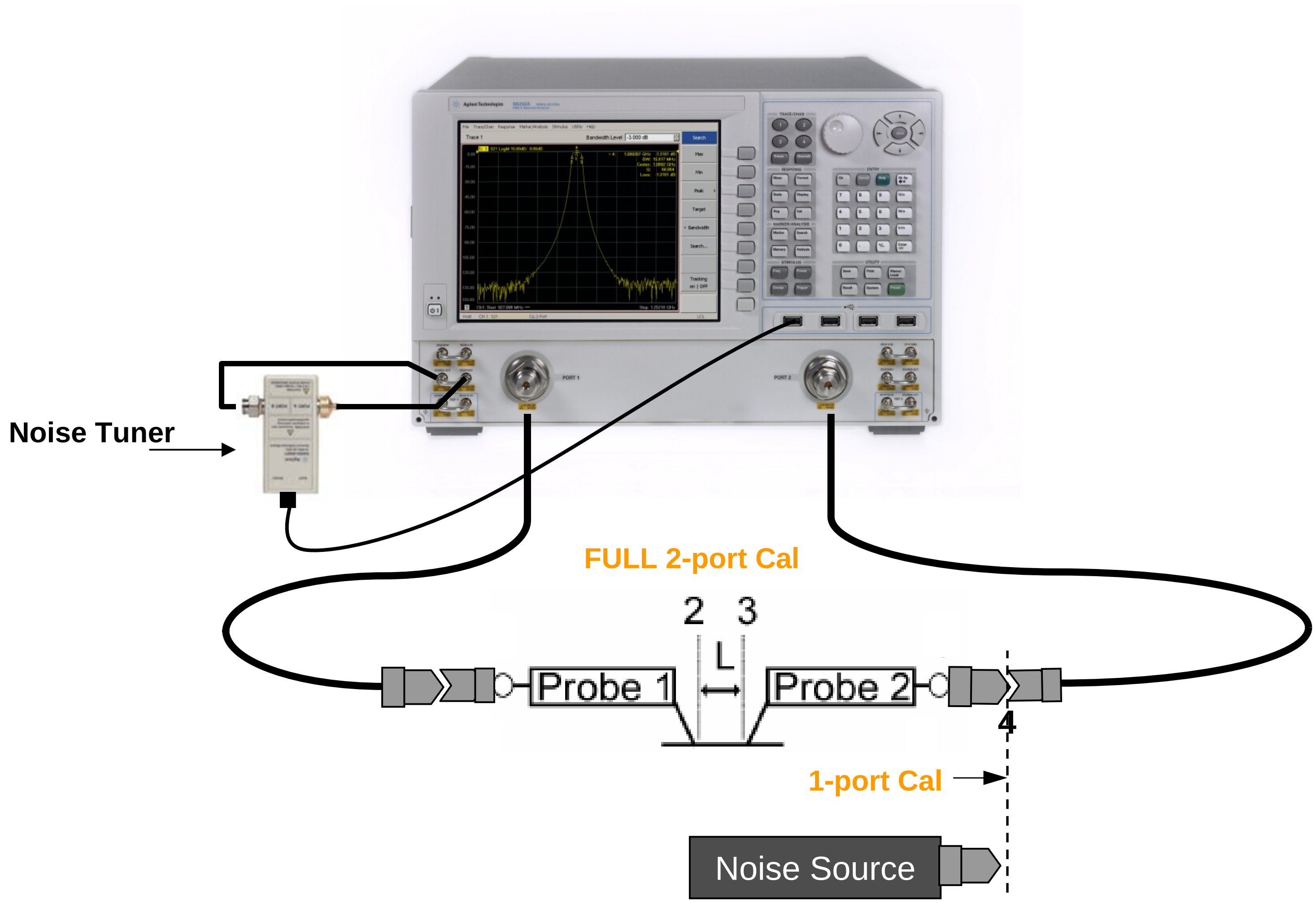
$$P_{out} = \left(\frac{k\boxed{B\left|S_{21}\right|^2}}{\left|1-\Gamma_s S_{11}\right|^2} \right) \left\{ \begin{array}{l} \left(1-\left|\Gamma_s\right|^2\right) T_s + \left|\Gamma_s\right|^2 X_1 + \\ \quad \left|1-\Gamma_s S_{11}\right|^2 X_2 + 2\,\mathrm{Re}\left[\left(1-\Gamma_s S_{11}\right)^* \Gamma_s X_{21}\right] \end{array} \right\}$$

4 unknowns, linear equation

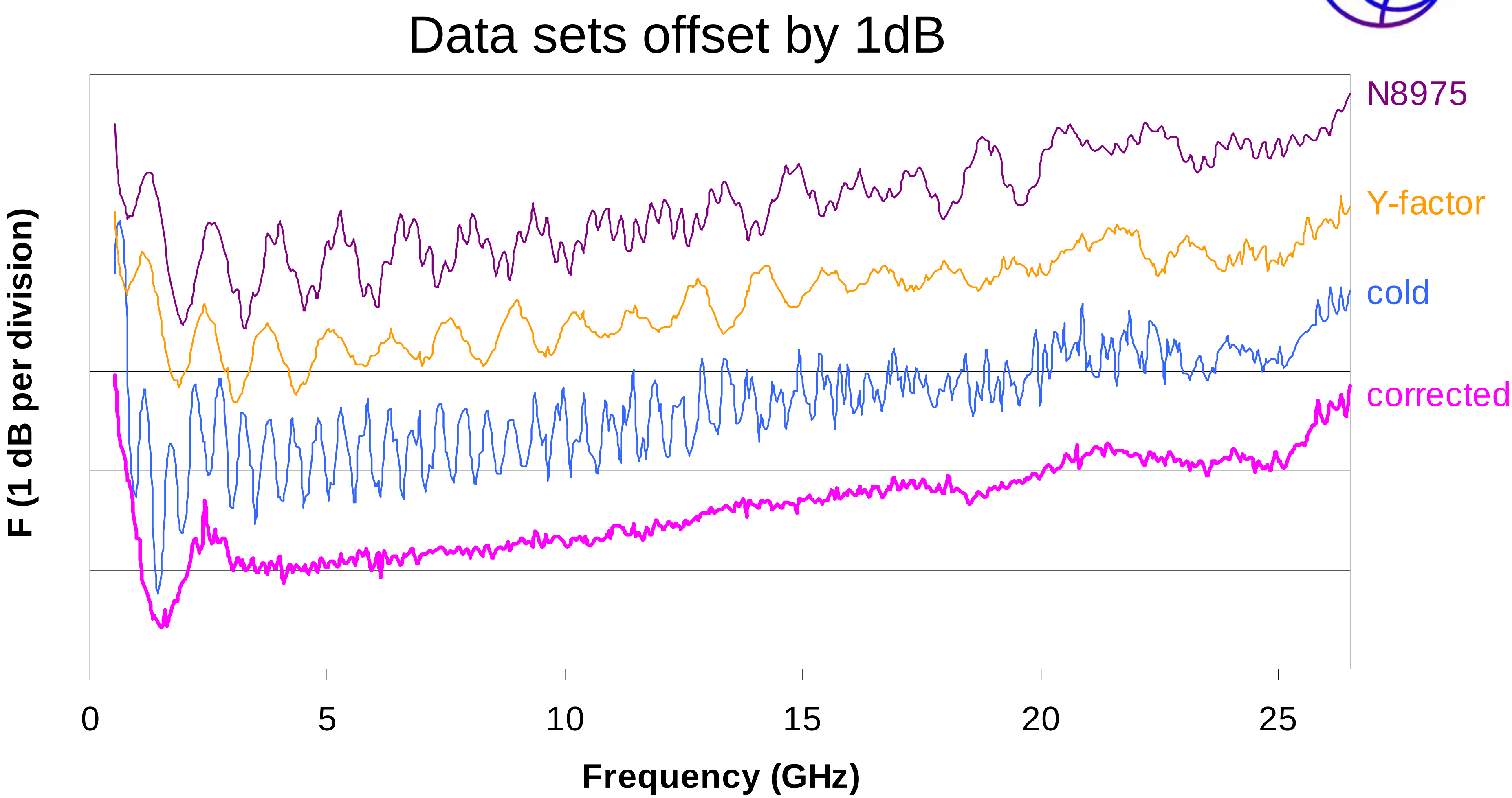
DUT S-parameters and Noise Measurement



Noise Measurement System With On-Wafer Probes

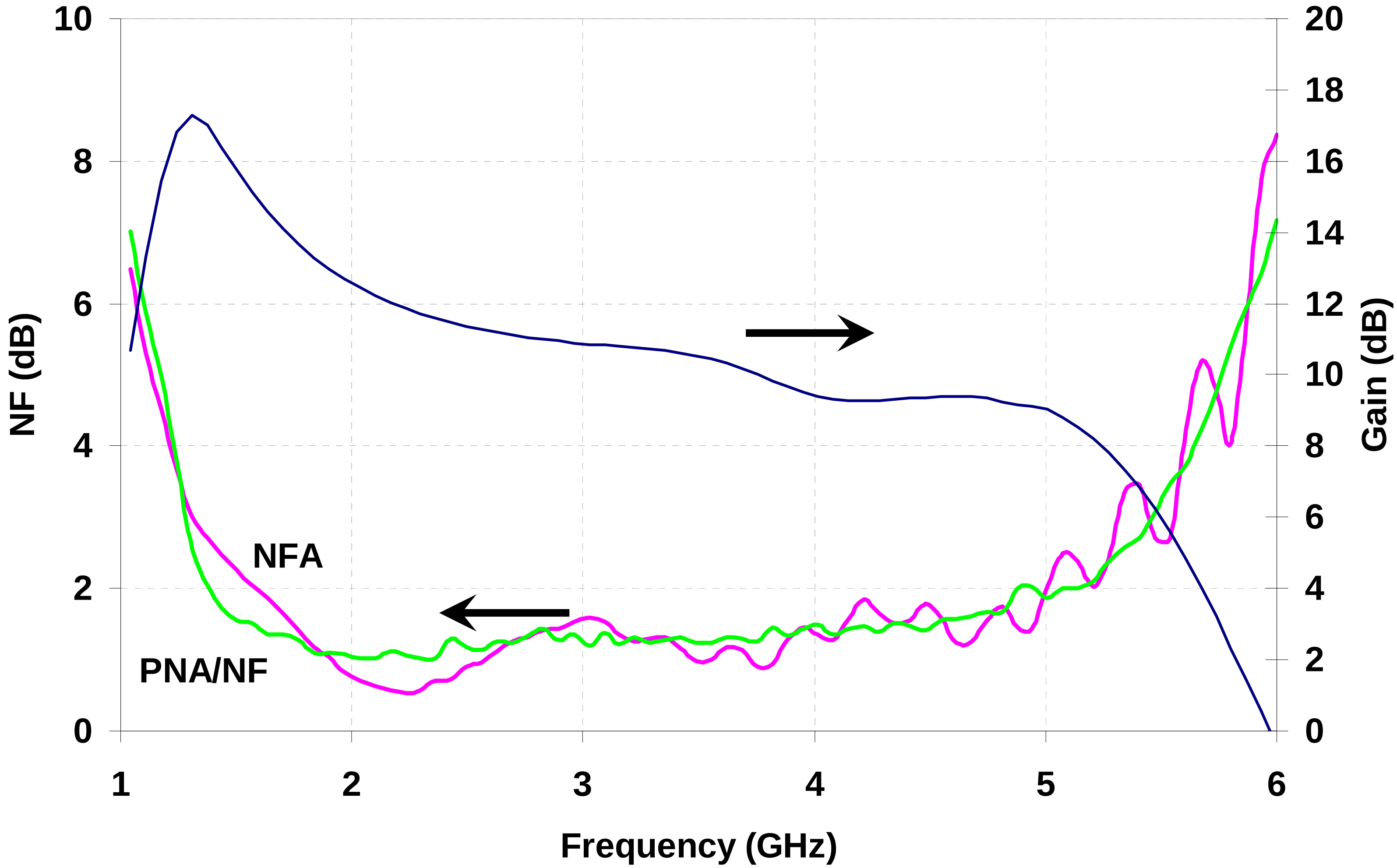


60 µm FET

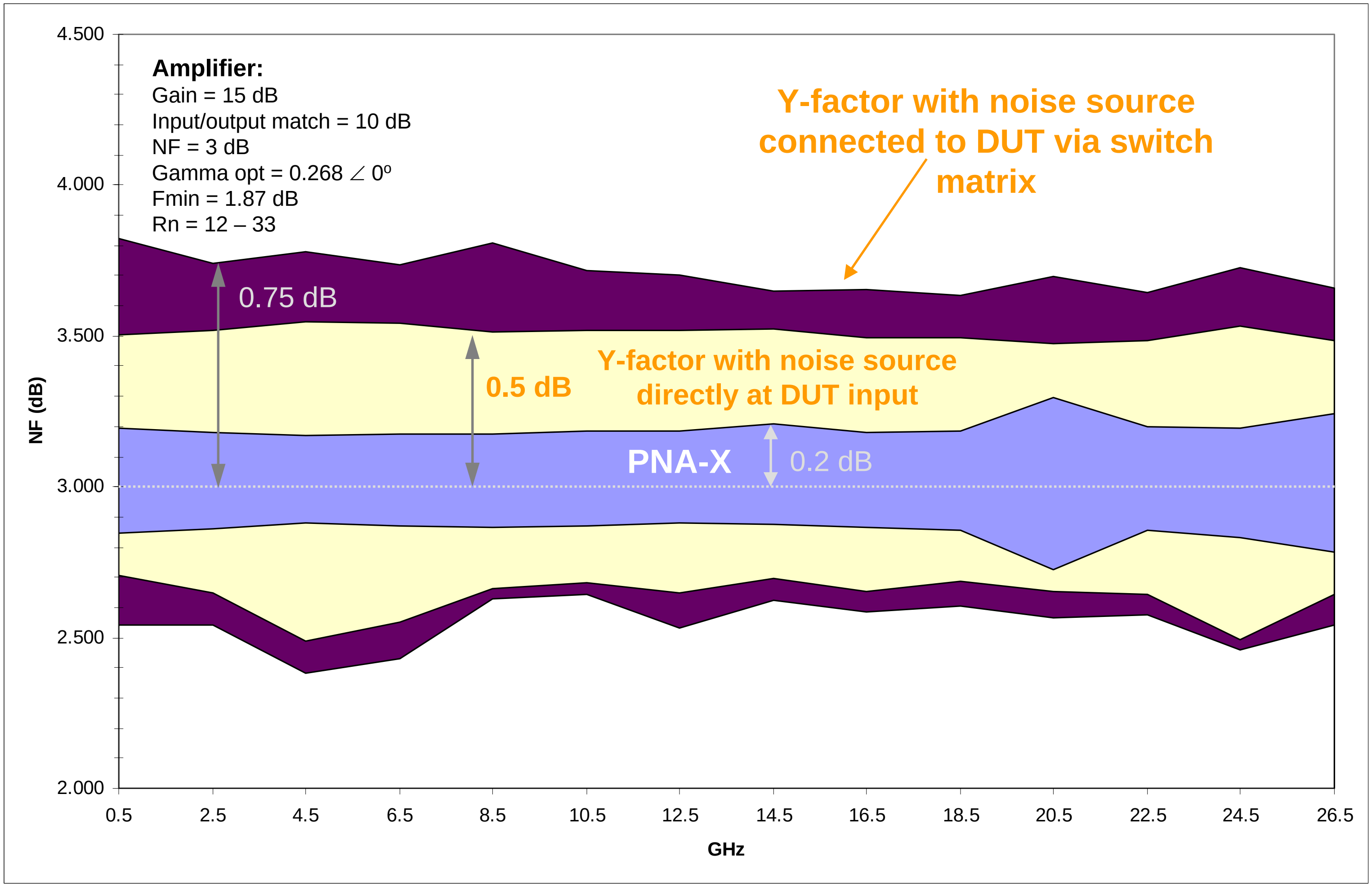


Data sets offset by 1dB
N8975
Y-factor
cold
corrected
F (1 dB per division)
0
5
10
15
20
25
Frequency (GHz)

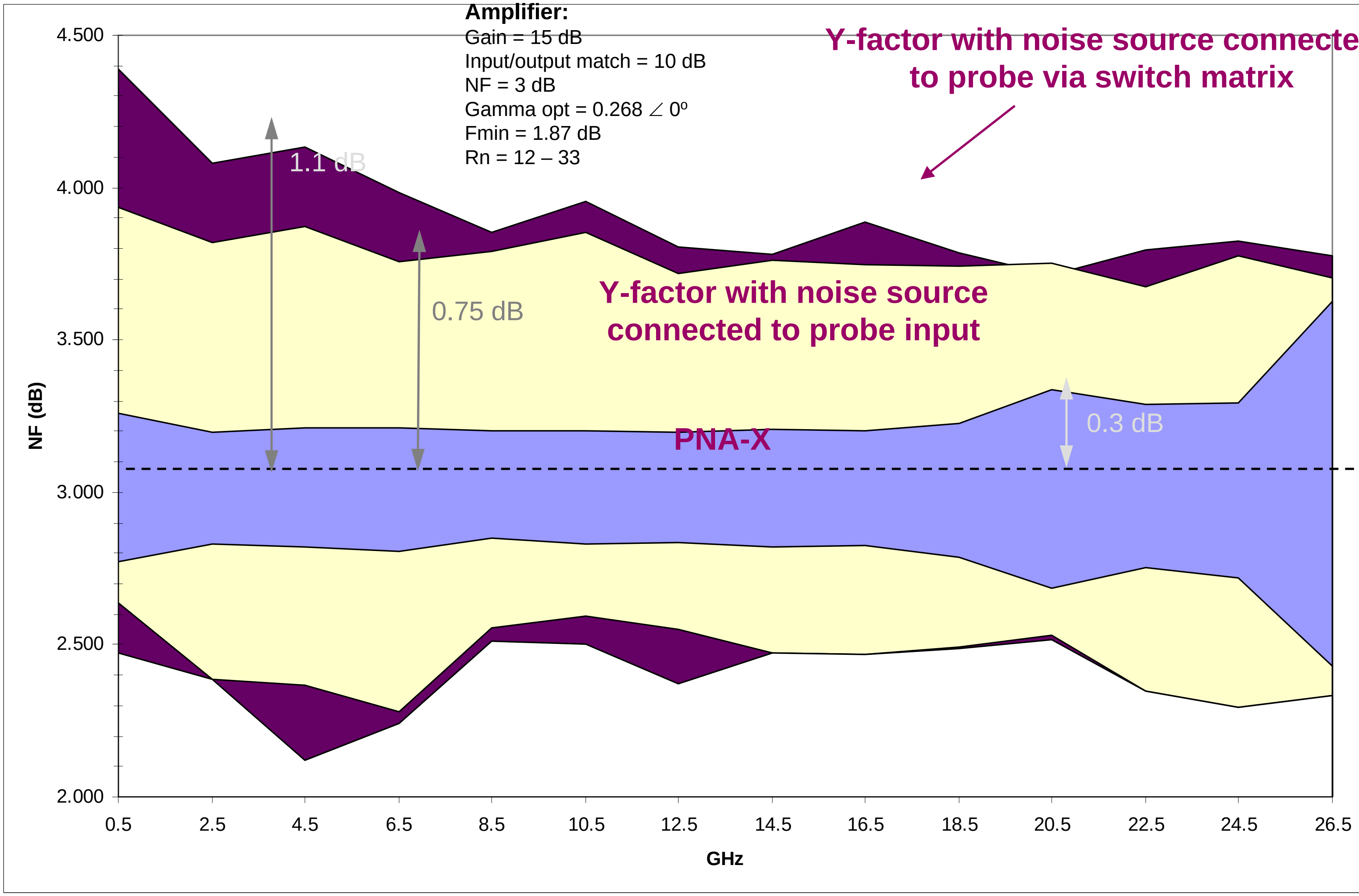
Measurements Compared



Noise Figure Uncertainty Example (ATE Setup)



Noise Figure Uncertainty Example (Wafer Setup)



Verification approach

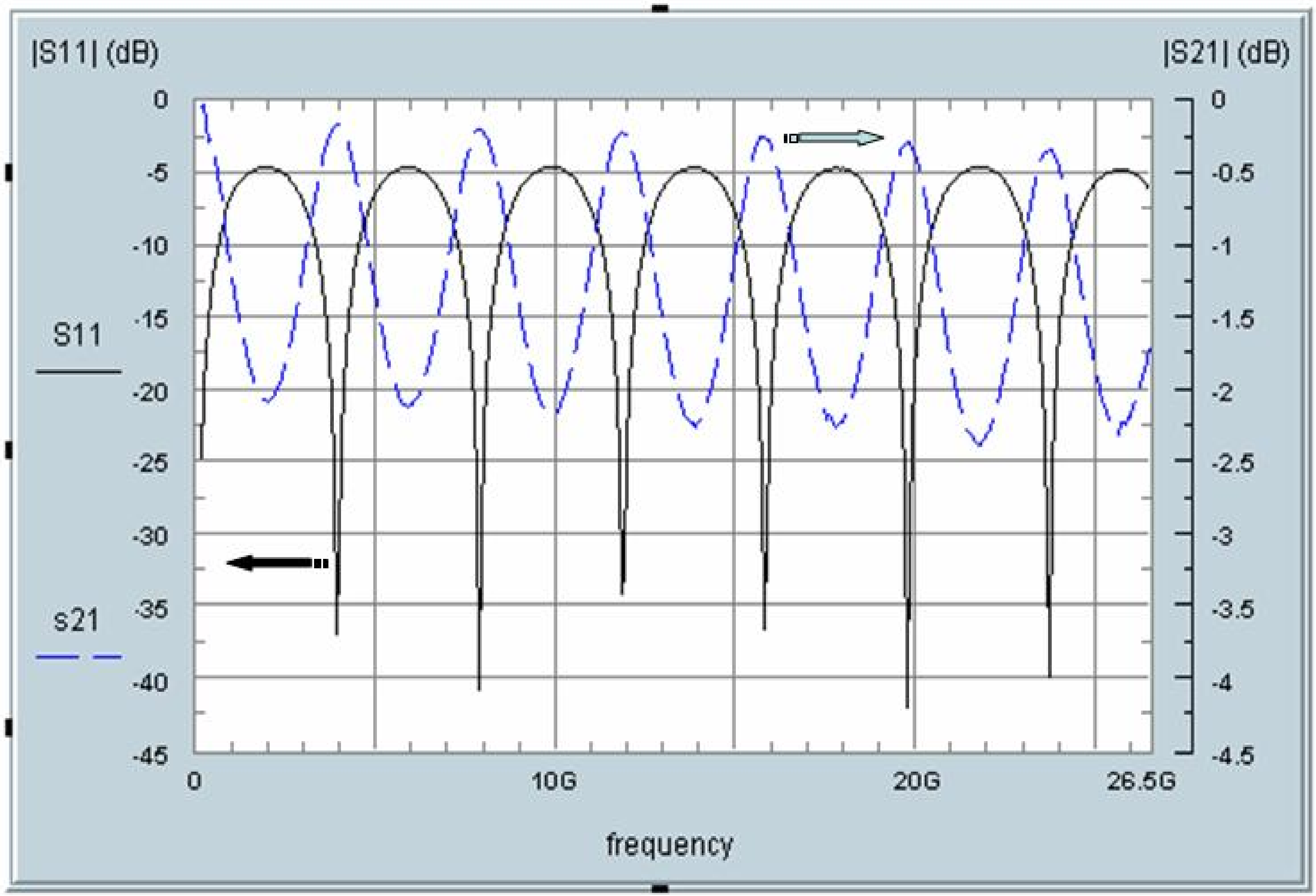
Need To Avoid Using An Active Device

- Cannot Guarantee Behavior Over Time
- Dependence On Temperature
- Noise May Be Injected Through Bias Supply

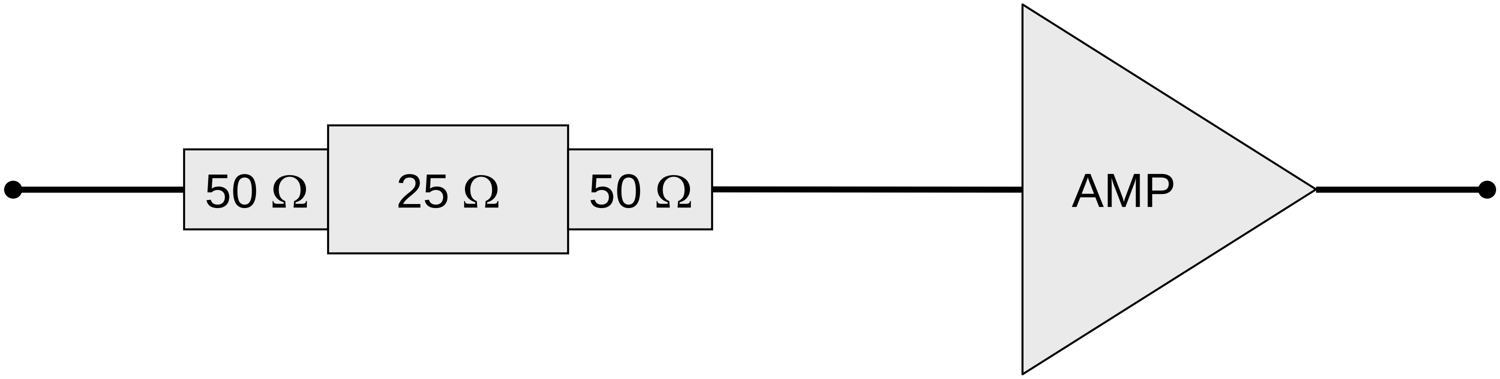
Use Mismatched Transmission Line, Passive Device

- Noise Parameters, Noise Figure Are Calculated From S-parameters
- Can Cascade With Any Amplifier And De-embed

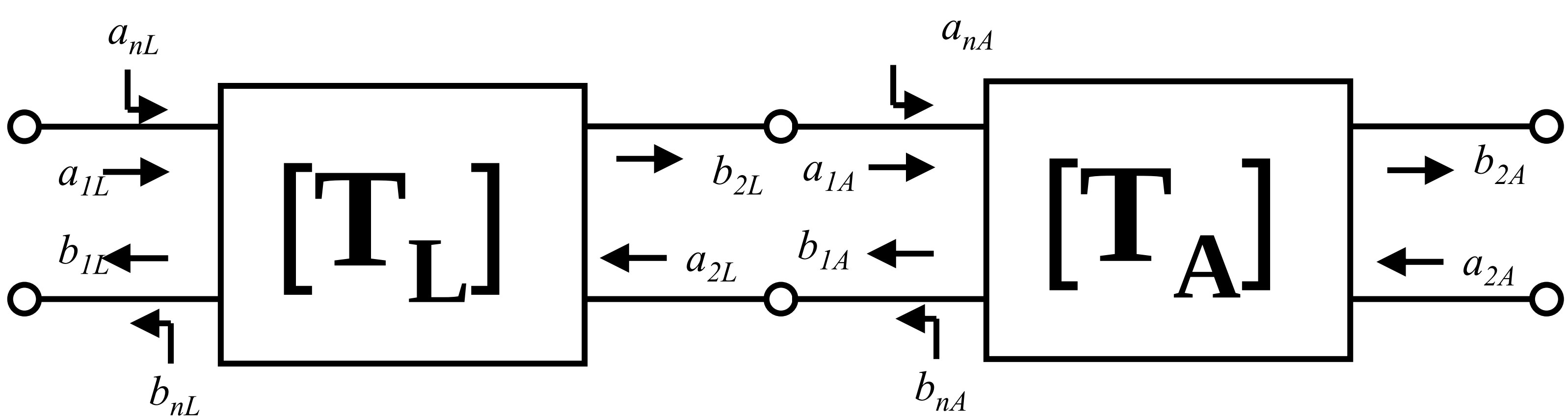
Mismatch Transmission Line Characteristics



Noise wave representations

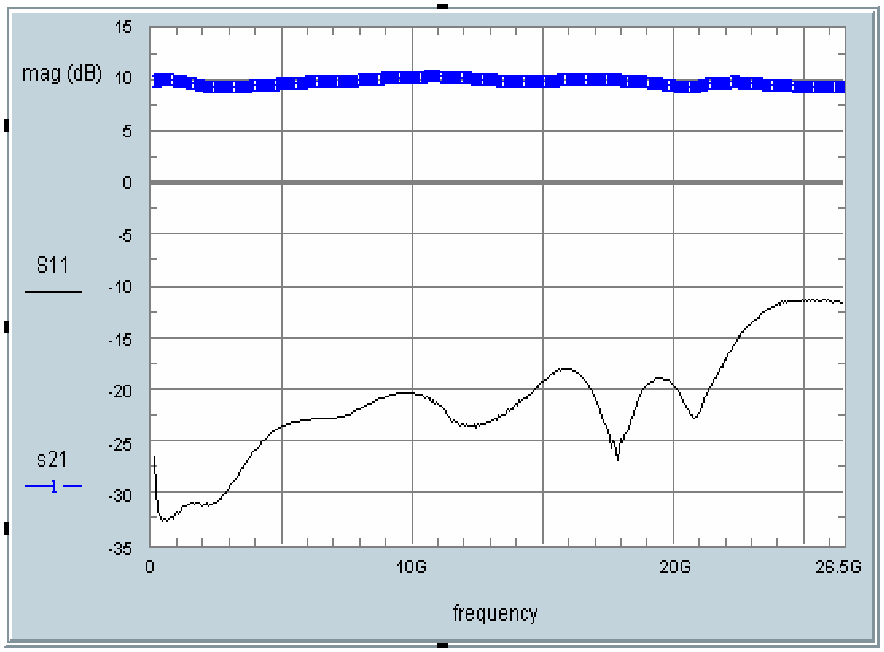


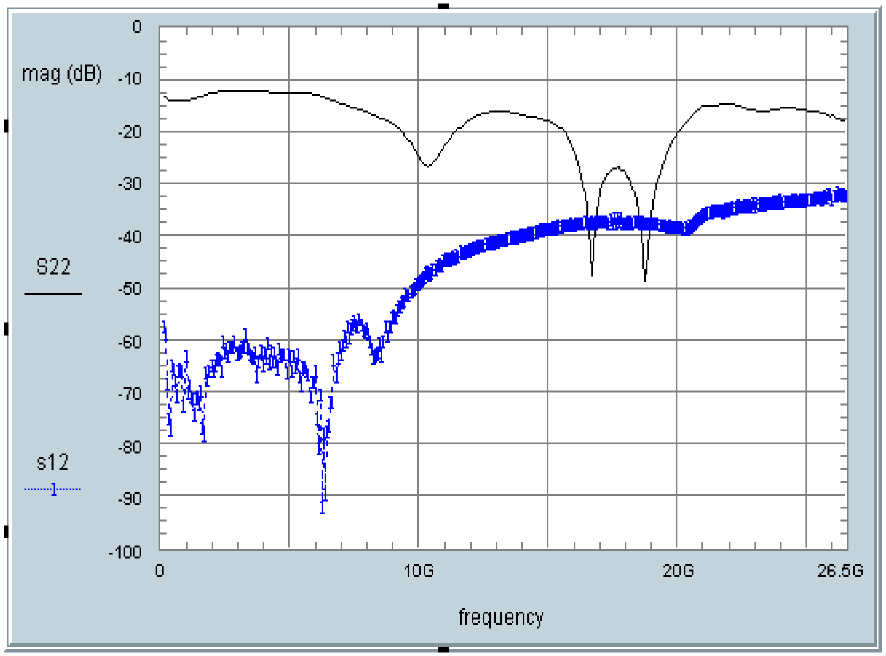
$[T_L]$, $[C_L]$ $[T_A]$, $[C_A]$



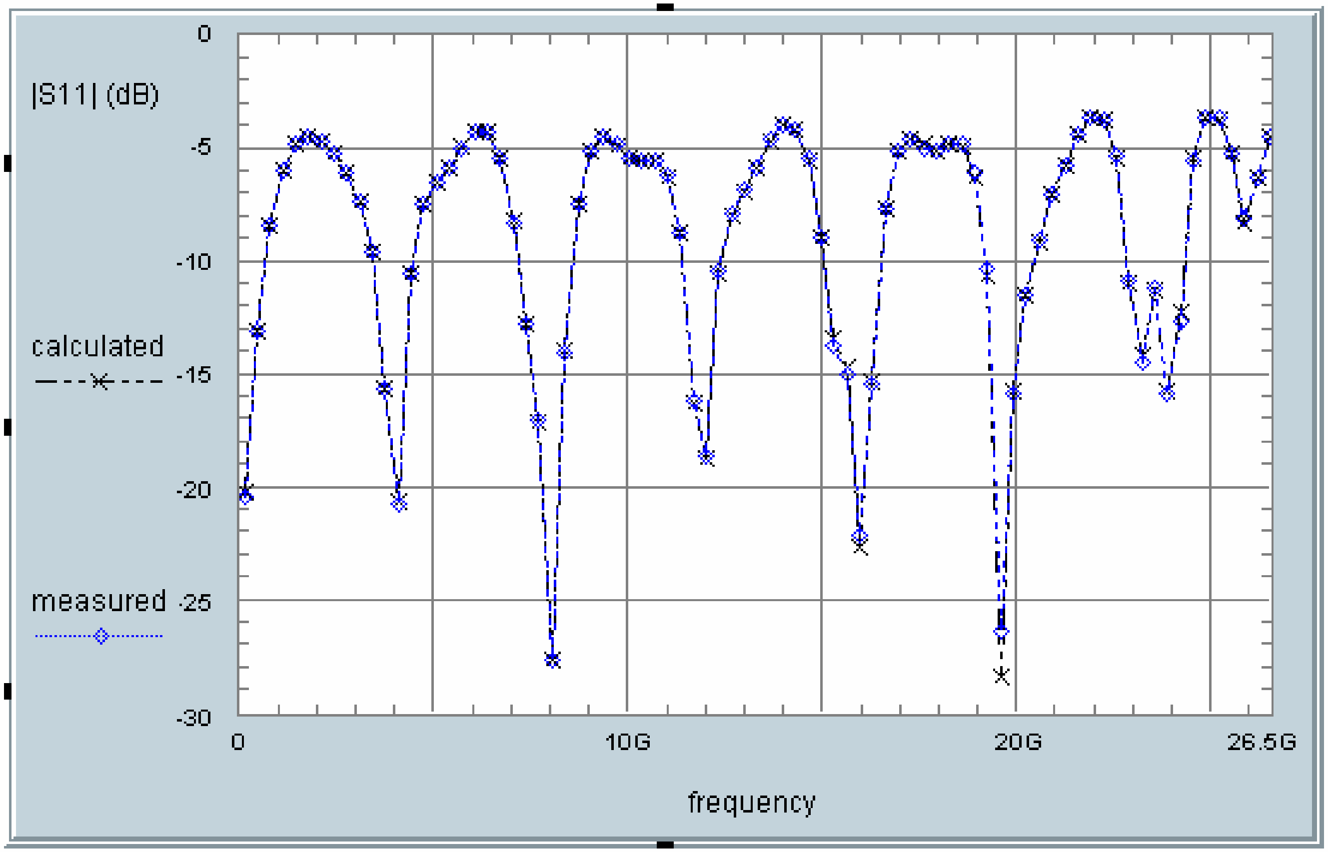
$$\mathbf{C}_{tL} = \begin{pmatrix} \overline{|a_{nL}|^2} & \overline{a_{nL} b_{nL}^*} \\ \overline{b_{nL} a_{nL}^*} & \overline{|b_{nL}|^2} \end{pmatrix}; \quad \mathbf{C}_{tA} = \begin{pmatrix} \overline{|a_{nA}|^2} & \overline{a_{nA} b_{nA}^*} \\ \overline{b_{nA} a_{nA}^*} & \overline{|b_{nA}|^2} \end{pmatrix}$$

Measured S-parameters of Amplifier

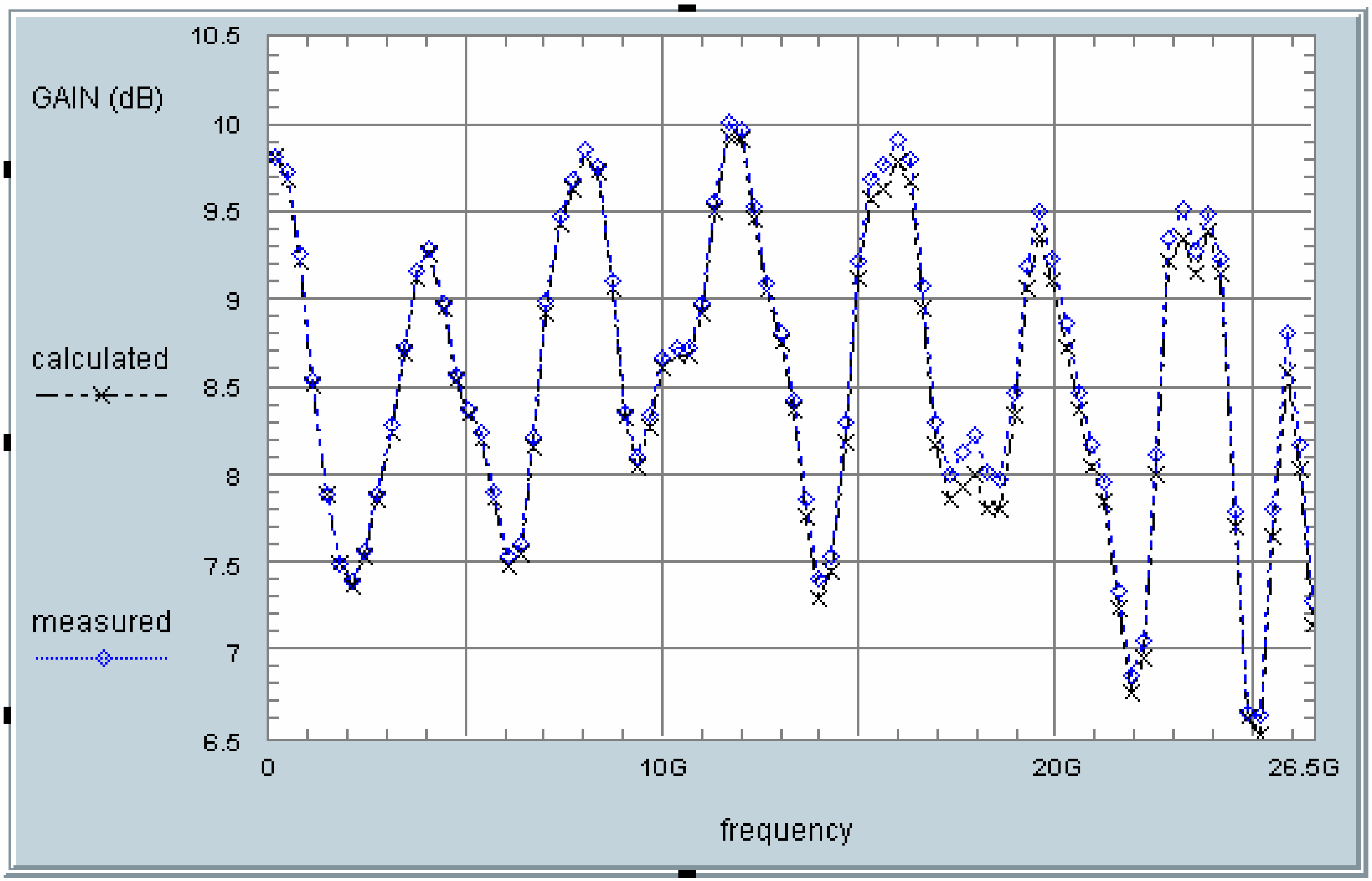




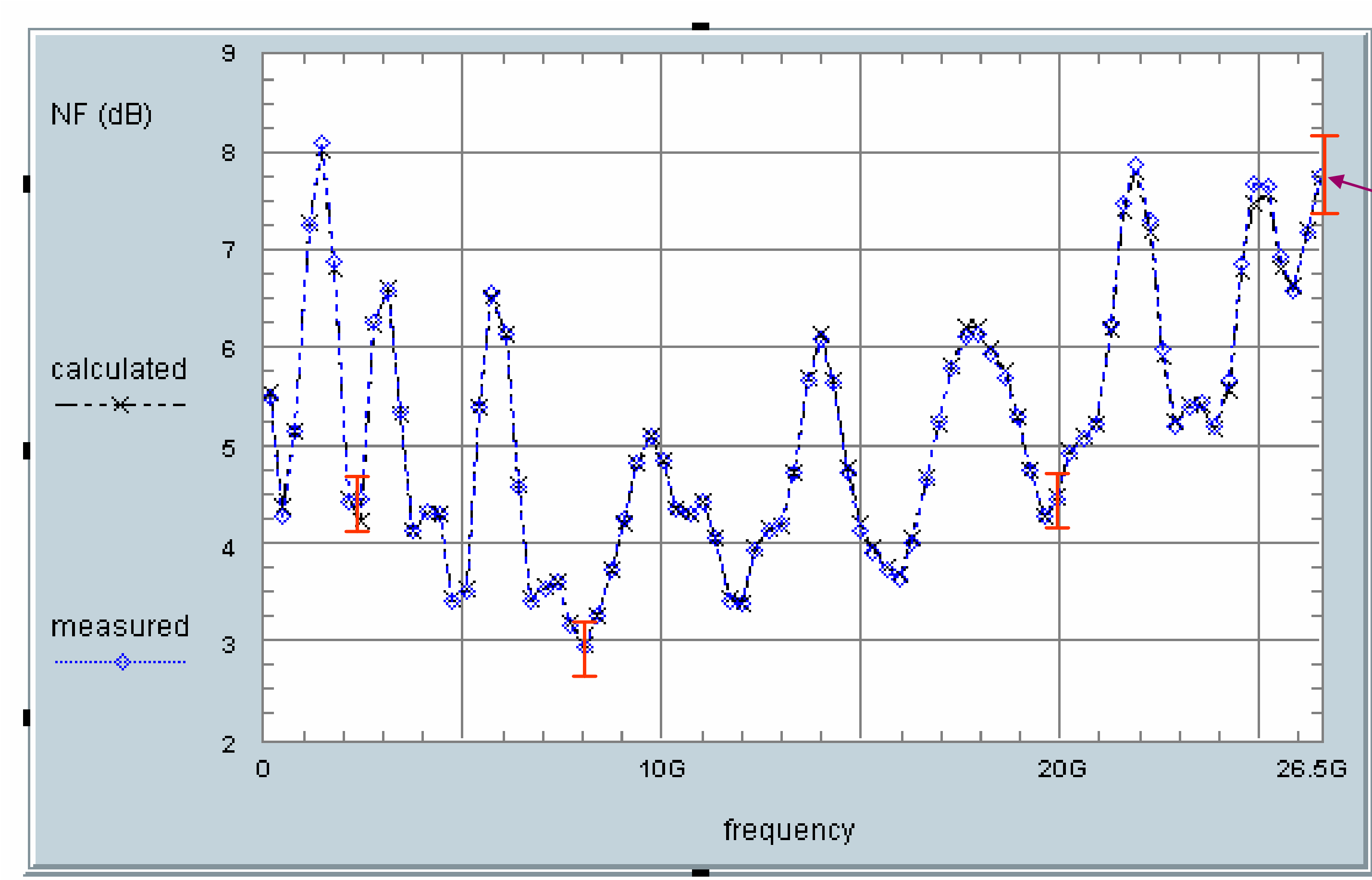
Calculated vs. Measured Combined $|S_{11}|$



Calculated vs. Measured Combined Gain



Calculated vs. Measured Combined Noise Figure



Uncertainty Bar
k=2

Additional References:

[1] D. Vondran, "Noise Figure Measurement: Corrections Related to Match and Gain," Microwave J., pp 22-38, Mar. 1999

[2] Collantes, J. M., R. D. Pollard, et al. (2002). "Effects of DUT mismatch on the noise figure characterization: a comparative analysis of two Y-factor techniques." Instrumentation and Measurement, IEEE Transactions on **51**(6): 1150-1156.

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[4] A. C. Davidson, B. W. Leake, et al. (1989). "Accuracy improvements in microwave noise parameter measurements." Microwave Theory and Techniques, IEEE Transactions on **37**(12): 1973-1978.

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[6] P. Penfield, Jr "Wave Representation of Amplifier Noise." IRE Transactions On Circuit Theory: Mach (1962) pp. 84-86

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[8] R.P. Meys, "A Wave Approach to the Noise Properties of Linar Microwave Devices," IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-26, No. 1, Jan. 1978, pp 34-37

[9] S. W. Wedg ,and D. B. Rutledge (1992). "Wave techniques for noise modeling and measurement." Microwave Theory and Techniques, IEEE Transactions on **40**(11): 2004-2012.

[10] J. Randa, W. Wiatr, "Conte Carlo Estimation of Noise Parameter Uncertainties," IEE Proc. Sci. Meas. Technology, Vol. 149, No. 6, Nov. 2002, pp. 333-337

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Noise Option Block Diagram