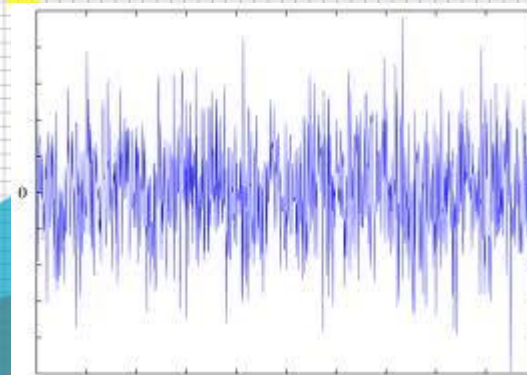
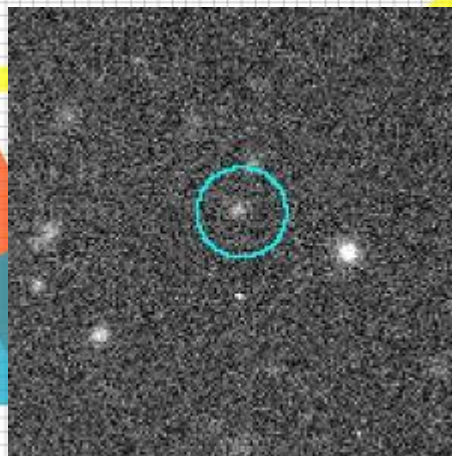
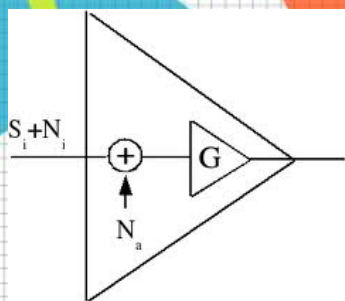


# Noise Figure

## Definitions and Measurements

What is this all about?...

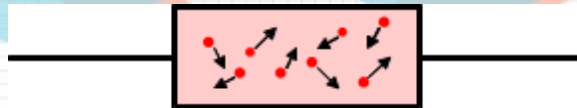


# Today's Program on Noise Figure

- What is RF noise, how to quantify it,
- What is Noise Factor and Noise Figure,
- Evolution of NF over the years,
- NF in multiple stages,
- How to measure NF,
- Measurement Uncertainties,
- The challenges in designing for best NF.
- Hands on...

# What is RF Noise?

- Various sources make RF Noise
  - **Thermal Noise** arises from vibrations of conduction electrons and holes due to their finite temperature.
  - **Shot Noise** arises from the quantized (not continuous) nature of current flow... electrons jump.
  - Other random Noises in electronic devices.
  - **Excludes man-made noise**
- Every real life device or component (active or passive) generates RF noise, especially if its temperature is above absolute zero K.
- Noise is what ultimately limits the performance of any system...



# How to quantify RF noise?

- Thermal Noise Power

$$P_N = kTB$$

where  $P_N$  is the noise power (watts)

$k$  is Boltzmann's constant,  $1.38 \times 10^{-23}$  J/K  
(joules per kelvin)

$B$  is the bandwidth (hertz)

At 290K,  $P_N = 4 \times 10^{-21}$  W/Hz = -174dBm / Hz

- Equiv. Noise Temperature

$$T_e = \frac{N_a}{kGB}$$

$T_e$  = Equiv. Noise Temp. of DUT

$G$  = Gain of DUT

$N_a$  = Additional DUT noise

- All types of RF noise are captured in the above definitions

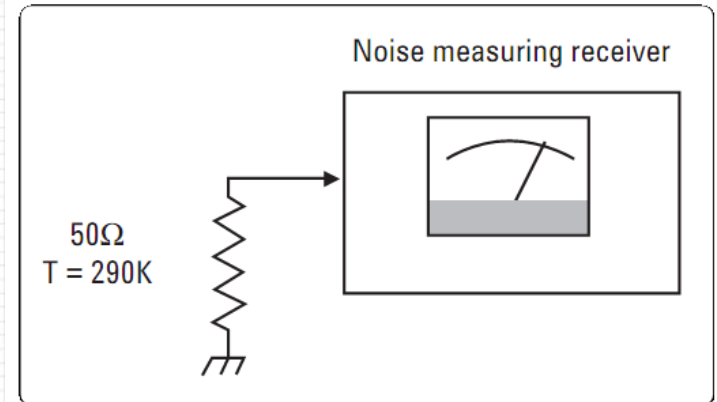


Figure 2-1 A resistor at any temperature above absolute zero will generate thermal noise.

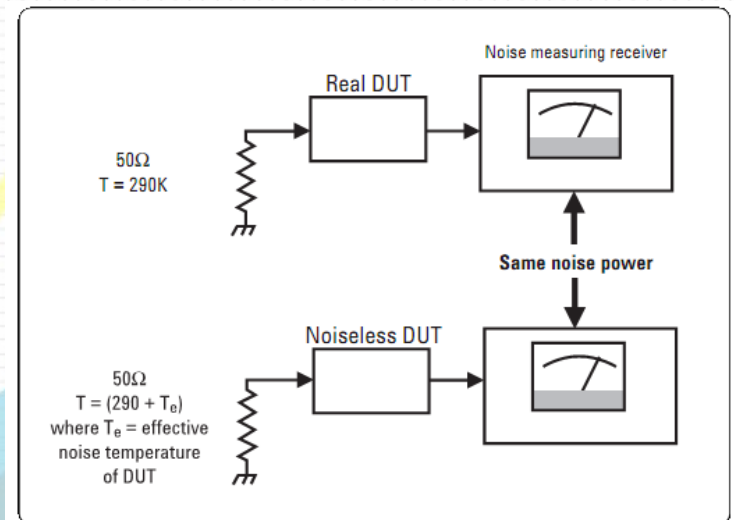
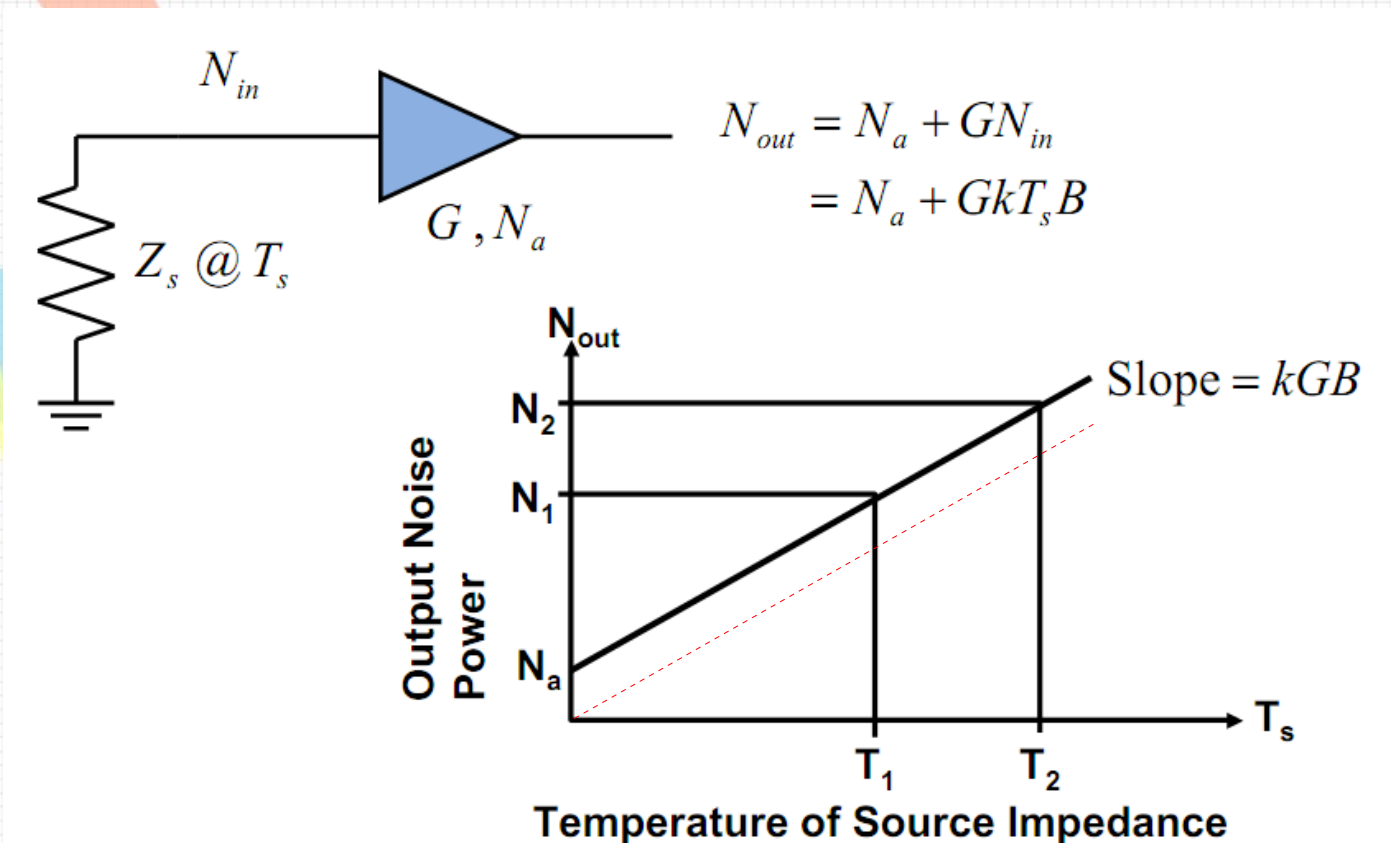


Figure 2-2 Effective noise temperature is the additional temperature of the resistor that would give the same output noise power density as a noiseless DUT.

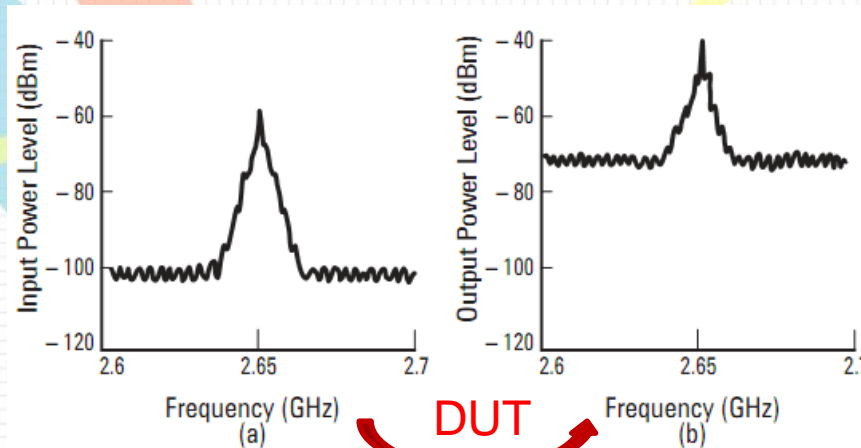
# How to quantify RF noise?

- Noise Power is linear with temperature.
- DUT-added noise shifts the curve upward.



# What is Noise Figure?

- Noise figure (NF) is a measure of degradation of the signal-to-noise ratio (SNR) caused by the noise generated within a system.
  - A perfect amplifier would amplify the noise at its input along with the signal, maintaining the same SNR at its input and output.
  - A realistic amplifier also adds some extra noise from its own components and degrades the SNR.



# What is Noise Figure?

- Mathematical representation

$$F = \frac{S_i/N_i}{S_o/N_o}$$

F = Noise FACTOR:

Signal-to-noise power ratio at the input divided by the signal-to-noise power ratio at the output. Always a positive value, >1.

$$F = \left( \frac{N_a + G \cdot N_i}{G \cdot N_i} \right)$$

$$NF = 10 \log F$$

NF = Noise FIGURE:

Logarithmic representation of Noise Factor, expressed in dB. Always a positive value, >0.

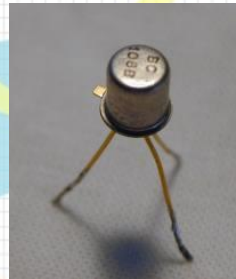
$$F = 1 + T_e / T_o$$

where  $T_o = 290 \text{ K}$

Noise figure NF	Noise factor F	Noise temperature $T_e$
0dB	1	0K (absolute zero)
1dB	1.26	75.1K
3dB	2.00	290K
10dB	10	2,610K
20dB	100	28,710K

# An Idea of NF Over The Years

1940-1960:	Tubes, Nuvistor, BJT:	$> 3\text{dB}$
1960-1980:	BJT, FET, MOSFET:	$1\text{dB}-3\text{dB}$
1980-2000:	GaAs FET:	$0.5\text{dB}-1\text{dB}$
2000-...:	HEMPT, pHEMPT:	$< 0.2\text{ dB}$



# NF in Multi-Stage Systems?

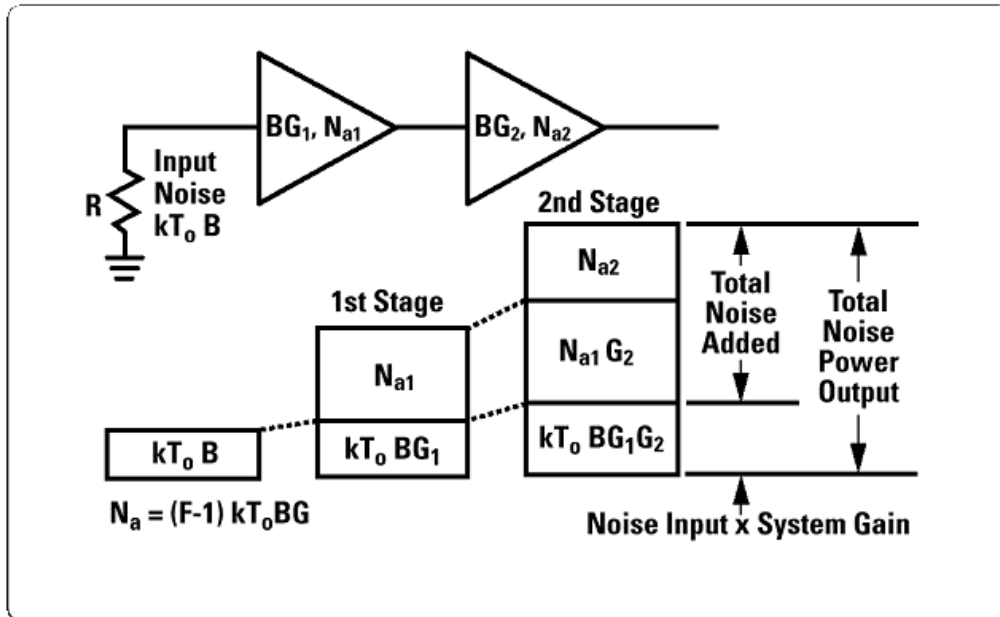


Figure 2-3. How noise builds up in a two-stage system.

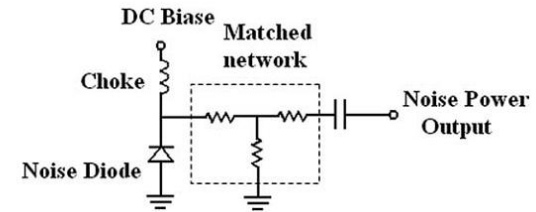
If  $G_1$  (gain of first stage) is sufficiently large, System NF is mostly dominated by first stage NF.

This is why Preamp NF is so important in low noise Rx applications (VHF/UHF/uWave)

$$F_{\text{sys}} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \dots + \frac{F_n - 1}{G_1 G_2 \dots G_{n-1}}$$

# How to Measure NF ?

- Easiest way to measure NF involves the use of a calibrated Noise Source
  - Usually made of a stable noise diode and attenuator.
  - Calibration data provides Excess Noise Ratio (ENR) expressed in dB.
    - ENR is the difference in Noise Power (N) between “ON” and “OFF” source conditions.
    - Sources typically come with ENR of 5dB or 15dB.
    - Expressed vs. Frequency (tabular).



$$\text{ENR}_{\text{dB}} = 10 \log \left( \frac{T_h - T_c}{T_o} \right)$$

$T_h$ : T of active source  
 $T_c$ : T of inactive source  
 $T_o$ : 290° Kelvin



# How to Measure NF ?

- What techniques used?
  - **Y Factor Method: The most used, accurate, repetitive.**
    - Noise Figure Meter: The simplest and fastest.
    - Spectrum Analyzer: More tedious and labor-intensive. Requires modern S.A. Not quite as accurate.
  - Signal Generator Twice-Power Method: OK for high NF
  - Direct Noise Measurement Method: OK for high NF
- What instruments required?
  - Noise Figure Meter: Best but more expensive -> dedicated.
  - Spectrum analyzer: More common but less accurate
  - Known bandwidth receiver: Much cheaper...
  - Build your own? See reference at end of presentation.

# Y-Factor NF Measurement Method

- Used by most NF meters and Spectrum Analyzers
- Can be automated or performed manually,
- Calibrated Noise Source required,
- DUT gain not required,
- Accurate, repetitive.



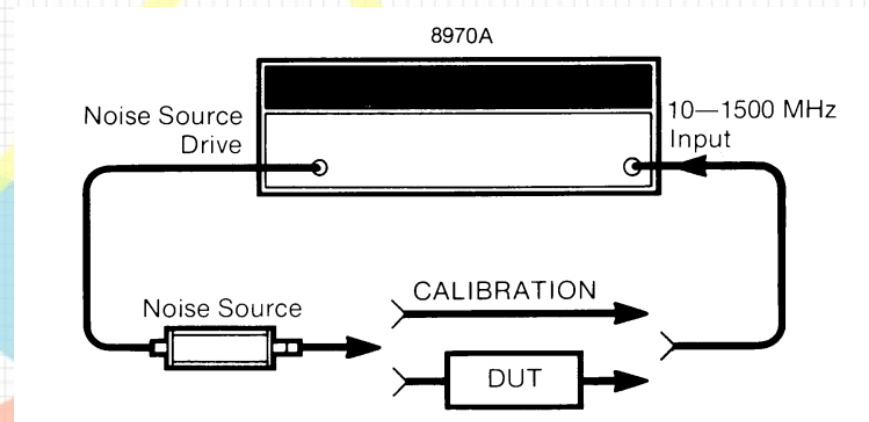
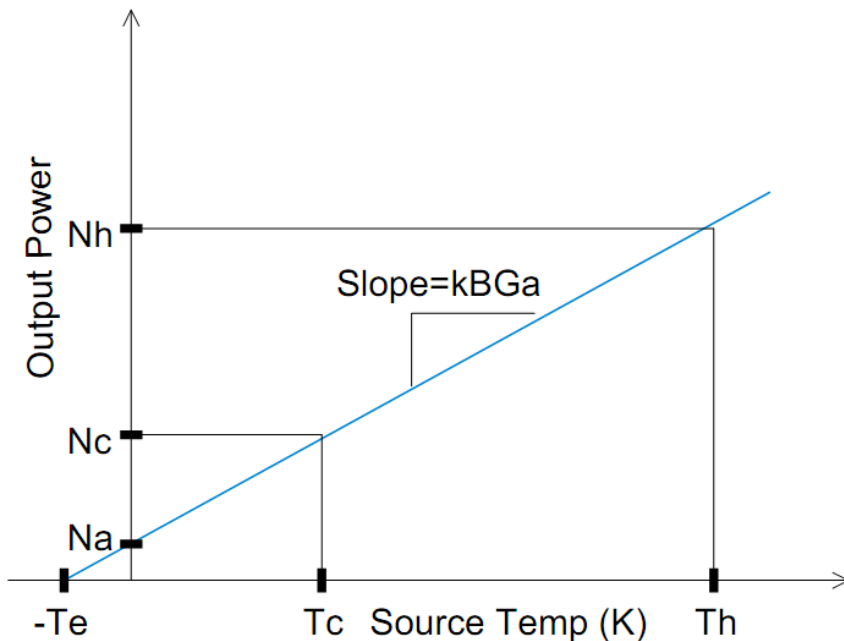
# Y-Factor NF Measurement Method

- Two-Step Method

- **Calibration:** Necessary to correct for the noise contribution of the test system and take temperature into account. Includes the input of the ENR data into the meter. Doing a “zero” by measuring  $N_h$  and  $N_c$ .
- **Measurement:** Introduces the DUT. Again, measuring  $N_h$  and  $N_c$ . Yields NF and Gain.

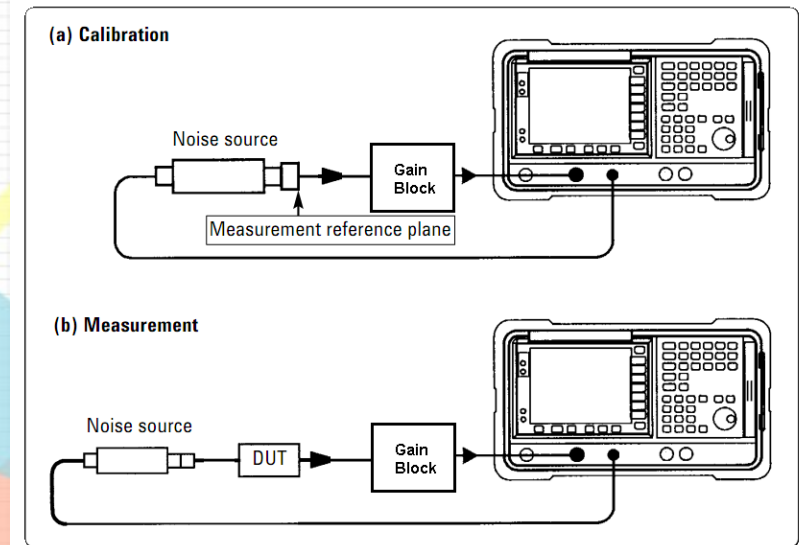
$$Y = N_h / N_c = T_h / T_c$$

$$F = \frac{ENR}{Y-1}$$



# Y-Factor NF Measurement Method

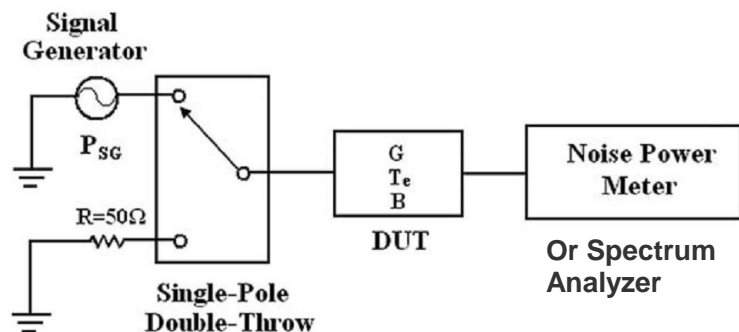
- ...Using a Spectrum Analyzer
  - Requires modern S.A that computes Noise Spectral Density dB/Hz of plotted spectrum (computerized S.A.).
  - Four measurements must be made.
  - Requires a calibrated noise head...
  - Requires the 1-3MHz Resolution Bandwidth option to pick up enough noise for a meaningful measurement.
  - Needs at least 30-40dB of low noise gain block ahead of the S.A. to compensate for its poor input noise figure.
  - Will work for NF values as low as a 1-2 dB. But likely not accurate/stable/linear enough for sub-dB NF measurements.



–See VE2AZX reference.

# Other NF measurement Methods

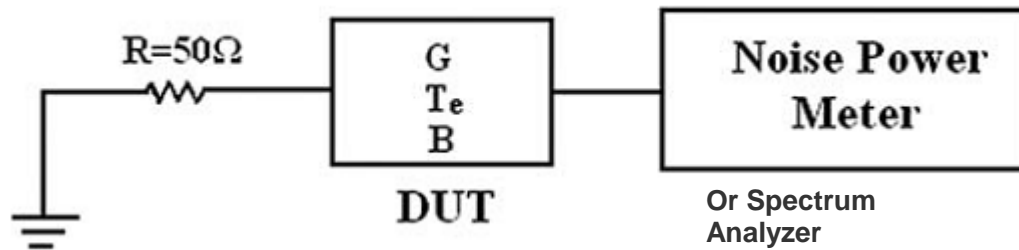
- Signal Generator Twice-Power Method
  - Does not require a Noise Source,
  - Useful for High NF devices,
  - Need to know Rx Bandwidth,
  - Two step Method
    - Measure output power of terminated input DUT @ ~290K.
    - Attach Signal Generator to input and adjust it to produce a 3dB increase in output power. The signal generator output power is equal to the total output noise power divided by the gain of DUT. Use formula below:



$$F_{\text{sys}} = \frac{P_{\text{gen}}}{kT_0B}$$

# Other NF measurement Methods

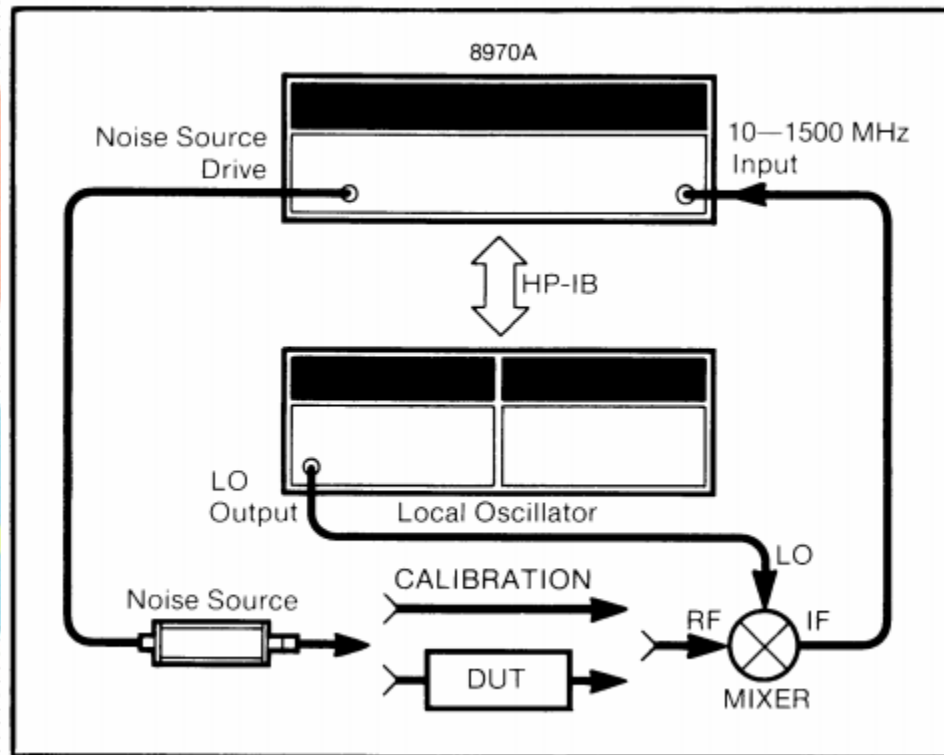
- Direct Measurement Method
  - Does not require a Noise Source.
  - Useful for High NF devices
  - Need to know DUT Gain, Rx Bandwidth
  - One step Method
    - Measure output power of terminated input DUT @ ~290K. Use formula below:



$$F_{\text{sys}} = \frac{N_o}{kT_0BG}$$

# Measuring NF in the Microwaves?

- Use an external Microwave Signal Generator
- Add a Double-Balanced Mixer



# Measurement Uncertainties?

- One must understand the potential measurement uncertainties.
  - Actual temperature at measurement time
  - Uncertainties increase as gain of DUT decreases
  - Uncertainties increase as NF of DUT increases
  - Externally induced noise (Lights, Power supplies, RF sources, noisy LO...)
  - Impedance mismatch between source and DUT.
  - Be careful with coaxial adapters and cables introduced or removed after calibration.

# NF Meas. Recommendations

- Minimize the noise figure of the test system (especially when measuring low gain DUTs).
- Reduce the magnitude of all mismatches by using isolators or pads. See Agilent Calculation spreadsheet.
- Minimize the number of adapters, and take good care of them.
- Avoid DUT non-linearities. Avoid S.A. non-linearities.
- Use Averaging to Avoid Display Jitter.
- Choose the Appropriate Bandwidth.
- Calibrate Noise Source ENR values regularly and use good pedigree calibration... (easier said than done!)

# The Challenges in Designing for Best NF

- **Stability: Be Careful!**
  - Watch for excessive out-of-band gain, usually at the low end.
  - Scale back on gain to improve stability.
- **Narrowband vs. Broadband**
  - Best NF is usually not at a device input impedance of 50 Ohms.
    - Narrowband: Input/Output matching optimization for best NF “relatively” straightforward.
    - Broadband: Compromise on NF, Gain, S-Parameters, Stability...
- **Keep Input Losses to Minimum**
  - Every bit of attenuation is a direct hit on overall NF.

# References

- Agilent, AN 57-1 Fundamentals of RF and Microwave Noise Figure Measurements
  - <http://cp.literature.agilent.com/litweb/pdf/5952-8255E.pdf>
- Agilent, AN 57-2 Noise Figure Measurement Accuracy – The Y-Factor Method
  - <http://cp.literature.agilent.com/litweb/pdf/5952-3706E.pdf>
- Agilent, Noise Figure Basics Presentation, Feb 24, 2009
  - [http://www.ieee.li/pdf/viewgraphs/noise\\_figure\\_measurements.pdf](http://www.ieee.li/pdf/viewgraphs/noise_figure_measurements.pdf)
- Agilent, Spectrum and Signal Analyzer Measurements and Noise
  - <http://cp.literature.agilent.com/litweb/pdf/5966-4008E.pdf>
- Agilent, Online Noise Figure Uncertainty Calculator.
  - <http://sa.tm.agilent.com/noisefigure/NFUcalc.html>
- VE2AZX, Noise Figure Testing using a Spectrum Analyzer (spreadsheet)
  - <http://ve2azx.net/technical/NoiseFigMeasure.xls>
- VE2ZAZ, Amateur Radio and Electronics Website
  - <http://ve2zaz.net>
- VE5FP, An automatic Noise Figure Meter, Jim Koehler, QEX May/June 2007

# Measurement Time!

- The HP 8970A
  - 10 MHz to 1500/1600 MHz, 1MHz increments,
  - Temperature compensated,
  - Calculates NF (0dB to +30dB)
  - Calculates Gain (-20dB to +40dB).
  - Accommodates typical Noise Sources on the market.
  - Rapidly turns on/off the noise source to perform calculations
- Hands on!



The background of the slide features three thick, overlapping wavy lines. The top-most line is orange, the middle line is blue, and the bottom-most line is yellow. They all follow a similar wavy pattern across the slide. A light gray grid is visible in the background.

Thanks!