Low Noise Amplifiers for Phased Array Feeds

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1. Tutorial about Noise Parameters
   a. Physical basis and choice of 4 noise parameters
   b. Noise and gain match
   c. LNA special requirements for PAF
2. Technologies for LNA's
   a. Design options
   b. Field Effect (HEMT, CMOS) and Bipolar (HBT) transistors
   c. Materials: InP, GaAs, and SiGe
3. Current State of the Art LNA's
   a. InP HEMT
   b. SiGe HBT
4. System Considerations
   a. System noise budget
   b. Cooling

Noise Temperature, Tn, for any Source Impedance, Zs

- Tn as a function of 4 noise parameters (Tmin, Zopt, and N) and either the source impedance, Zs, source admittance, Ys, or reflection coefficient, Γs is given below.

- The “criticalness” parameter is given by, N = Rn*Gopt, where Rn is more commonly specified, and Gopt is the optimum source conductance, *Re* (Yopt).

$$T_n = T_{min} + N T_0 \frac{|Z_s - Z_{op}|^2}{R_s R_{op}}$$

$$T_n = T_{min} + N T_0 \frac{|Y_s - Y_{op}|^2}{G_s G_{op}}, \quad Y_s = Z_s^{-1} \quad Y_{op} = Z_{op}^{-1}$$

$$T_n = T_{min} + \frac{4 N T_0 |\Gamma_s - \Gamma_{op}|^2}{(1 - |\Gamma_s|^2)(1 - |\Gamma_{op}|^2)}, \quad \Gamma_{op} = \frac{Z_{op} - Z_0}{Z_{op} + Z_0}$$

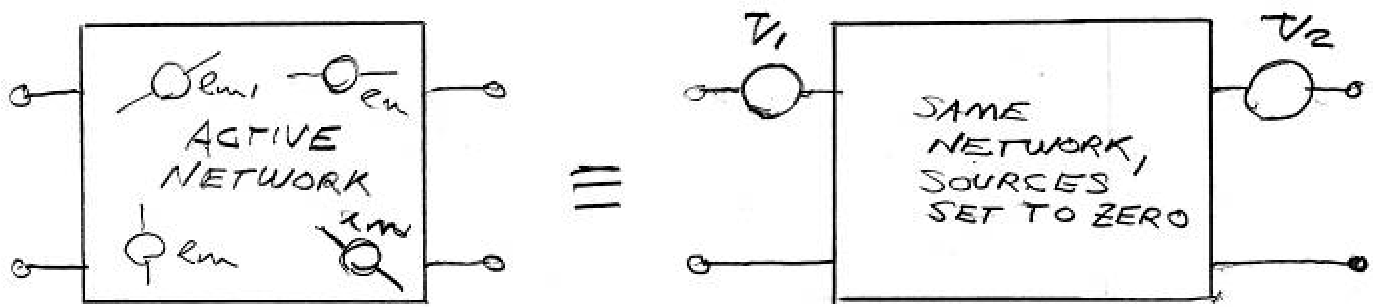
Basis of Noisy Network Theory

• The basis is the Thevenin theorem (Helmholtz, 1853, Thevenin, 1883, see Wikipedia, 2009) which states that any two-port network containing sources can be represented by the network with sources (series voltage or shunt current) added at the terminals.

• This theorem is independent of the waveforms or number of the internal sources; they can always be represented by two external sources.

• Thus all noise of any source (thermal, shot, avalanche, etc) in a network can be represented by two terminal noise sources. For noise sources the complex correlation coefficient, ρ, between the two sources must be specified, leading to 4 real numbers to describe all noise in the network.

ρ ≡ correlation coefficient

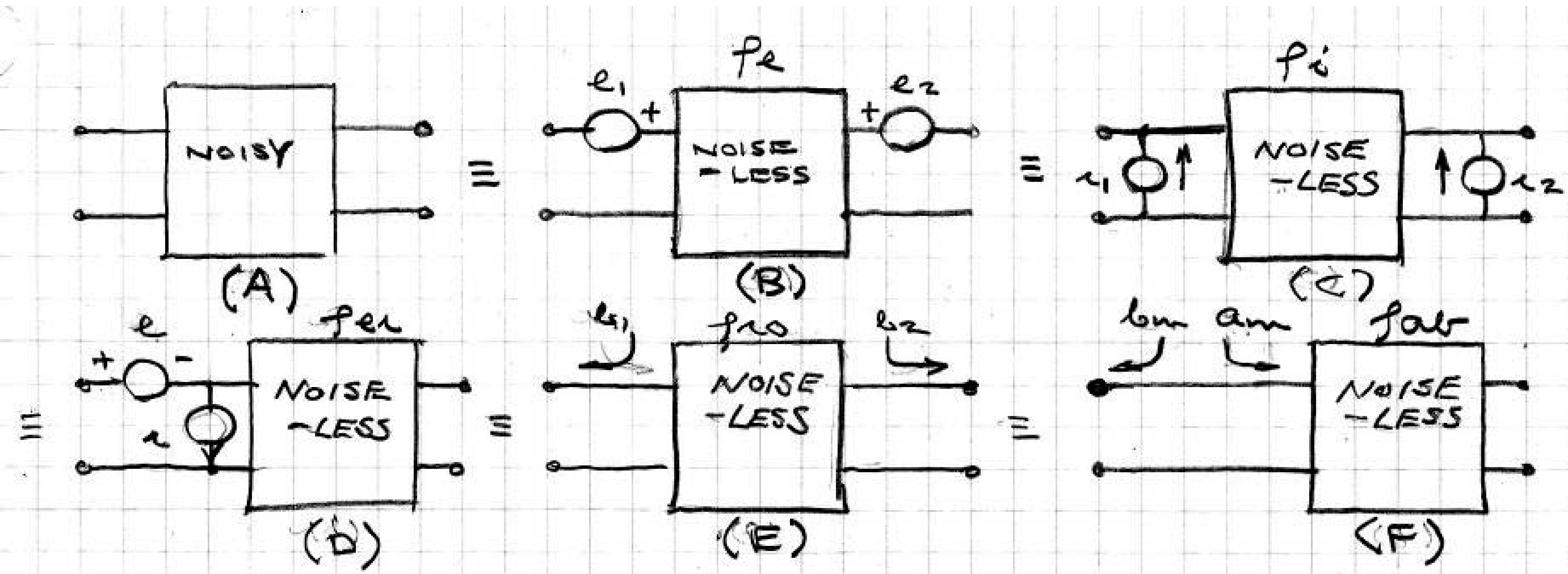


Choice of Noise Parameters

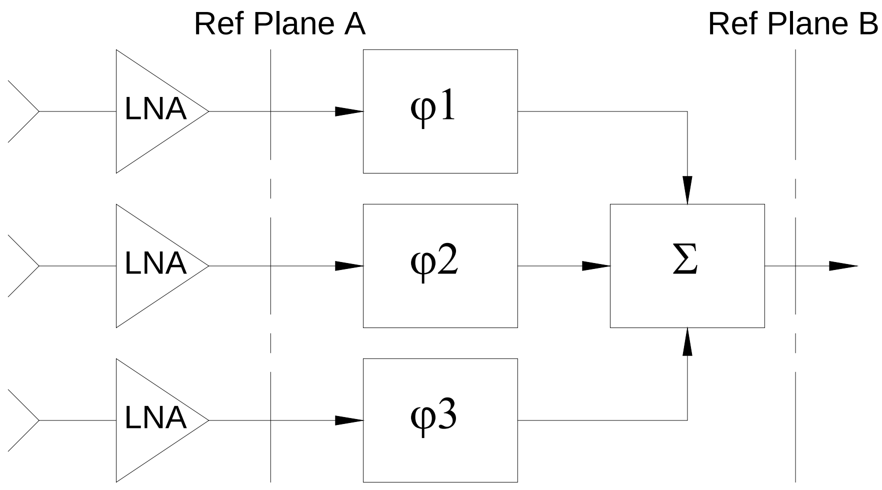
• There are many sets of 4 parameters to specify a noisy network and the choice depends upon what is known about the internal sources and upon the application

• For FET or HEMT noise analysis, (C) is most often applied,. for op amps (D) is given in data sheets, for arrays systems studies, (E) is most meaningful

• Once one set is known, transformation to another set is straight-forward



Noise Figure of a Combined Array



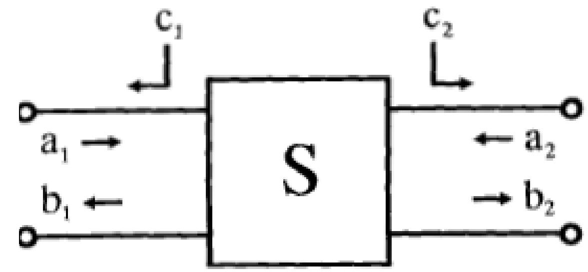
1. The NF measured at Ref Plane A is independent of the phase shifter values even if there is coupling between the antennas.
2. The NF measured at Ref Plane B is dependent upon the phase shifter values when there is coupling between the antennas
3. The NF measured at Ref Plane B is only weakly dependent upon phase shifter values if the noise wave coming out of the input of each LNA is uncorrelated with the noise wave coming out of the output of each LNA>

LNA Input and Output Noise Waves are Uncorrelated if Γopt = S11=0

IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 40, NO. 11, NOVEMBER 1992

Wave Techniques for Noise Modeling and Measurement

Scott W. Wedge, *Member, IEEE*, and David B. Rutledge, *Senior Member, IEEE*



Appendix

Noise wave parameters for active devices may be derived from the standard noise parameters or calculated from equivalent circuit values. In terms of $T_{\min}$, Γ_{opt}, and R_n the noise wave parameters are

$$\overline{|c_1|^2} = kT_{\min}(|s_{11}|^2 - 1) + \frac{kt\,|1 - s_{11}\Gamma_{\text{opt}}|^2}{|1 + \Gamma_{\text{opt}}|^2} \tag{32}$$

$$\overline{|c_2|^2} = |s_{21}|^2\left(kT_{\min} + \frac{kt\,|\Gamma_{\text{opt}}|^2}{|1 + \Gamma_{\text{opt}}|^2}\right) \tag{33}$$

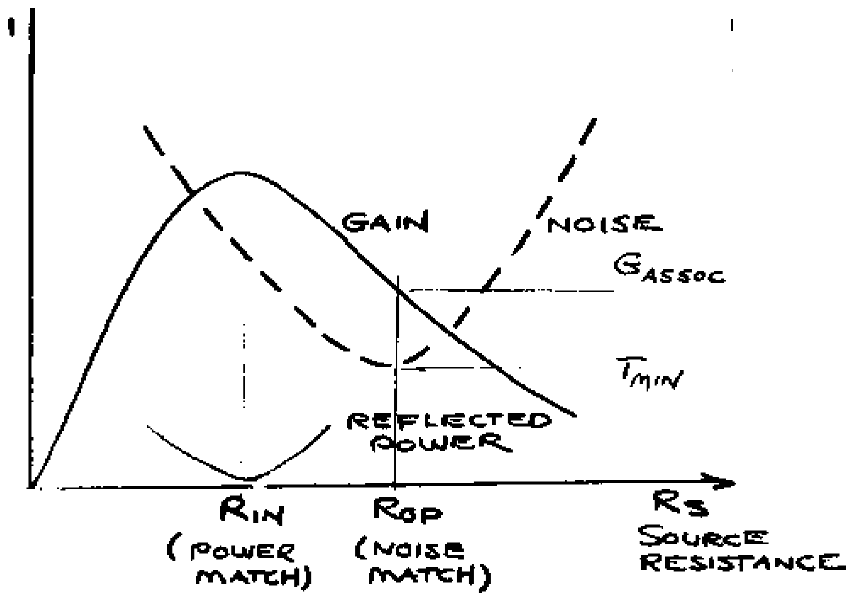
$$\overline{c_1 c_2^*} = \frac{-s_{21}^*\Gamma_{\text{opt}}^* kt}{|1 + \Gamma_{\text{opt}}|^2} + \frac{s_{11}}{s_{21}}\overline{|c_2|^2} \tag{34}$$

where kt is the normalized temperature-energy given by

$$kt = \frac{4kT_0 R_n}{Z_0} \tag{35}$$

Noise Match and Gain Match Are Not for Same Zs

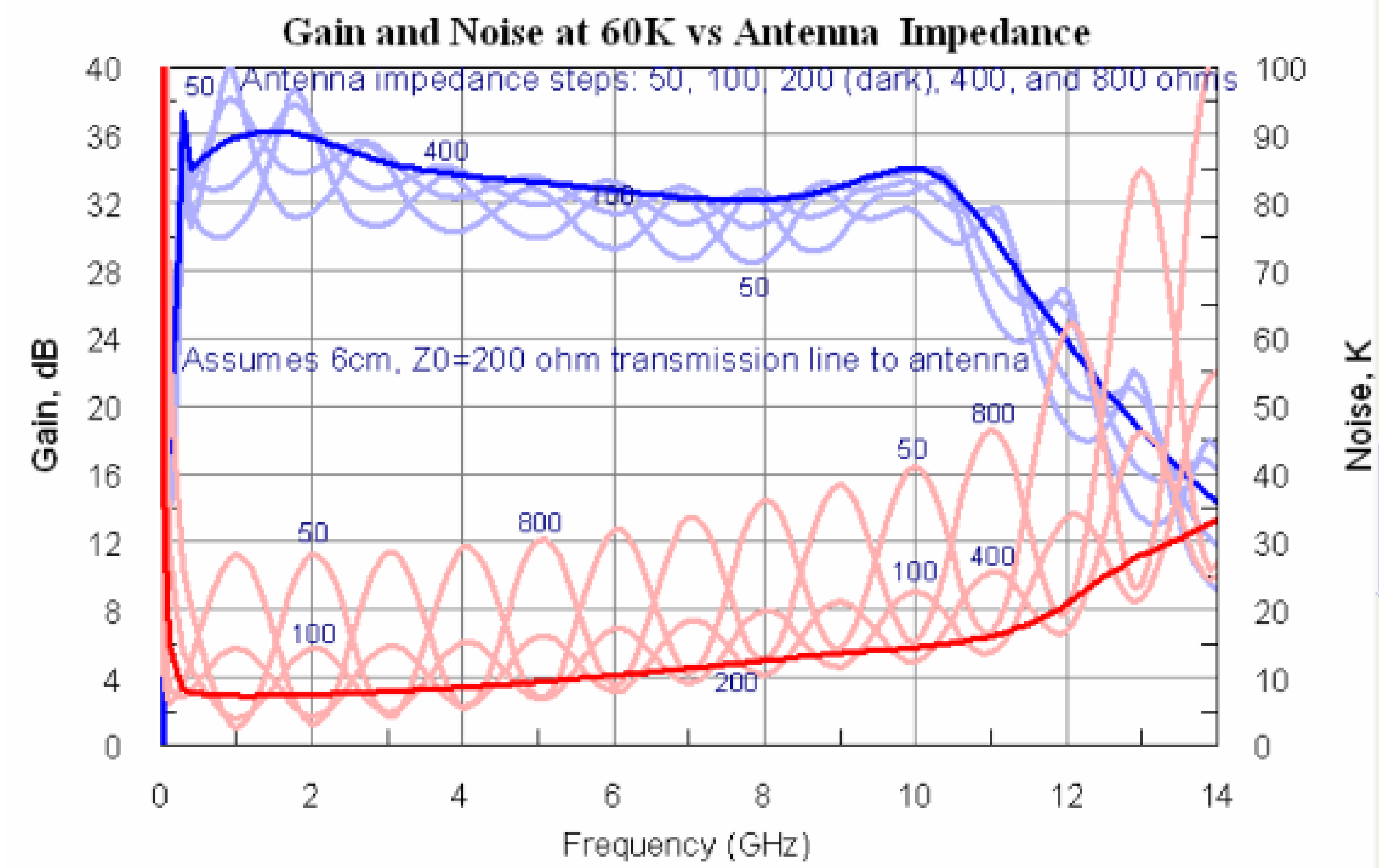
- Zopt ≠ Zin* which increases the sensitivity of either Tn or gain to antenna impedance.
- Remedies are: 1) isolator, 2) balanced amplifier, or 3) feedback



•An important case for phased-arrays is that the input-to-output noise wave correlation coefficient, ρio = 0 when an amplifier has been designed for both noise and gain matched to the wave normalization impedance, Zn.

Effect of Mismatched Antenna on Noise and Gain of an LNA

- Modeled gain and noise of a differential InP LNA at 60K as a function of antenna impedance driving a 6cm long transmission line with Zo = 200 ohms
- At 2 GHz VSWR of 2:1 causes noise to vary 4K to 14K and gain to vary +/- 2dB
- At some frequencies noise is improved because Zopt is not equal 200 ohms.



LNA Options

- **Transistor technology – SiGe, InP or GaAs HEMT, and CMOS**

  All are competitive the 1.2 to 1.5 GHz range.
- **Discrete transistor vs integrated circuit**

  In this frequency range discretes on printed circuits have low non-recurring costs and can incorporate more recent transistors
- **Single-ended vs differential input**

  Most wideband LNA’s have differential output though passive baluns can be incorporated in the feed in some cases. Single-ended LNA’s for 50 ohm generator are more mature in development.
- **Cooled vs uncooled**

  Typical noise: 18K at 300K, 9K at 77K, 3K at 18K
- **Gain and Noise Matched?**

  Provides uncorrelated input and output waves. Achievable by feedback, balanced amplifier, or isolator.

Noise Measure and Tcasmin

- Tmin is not the best figure of merit of a low noise transistor since it does not take gain into account.

- Feedback can reduce Tmin to zero! Proof: Consider a feedback network that directly connects input to output and does not connect to the transistor. Tmin =0 but Gain =1

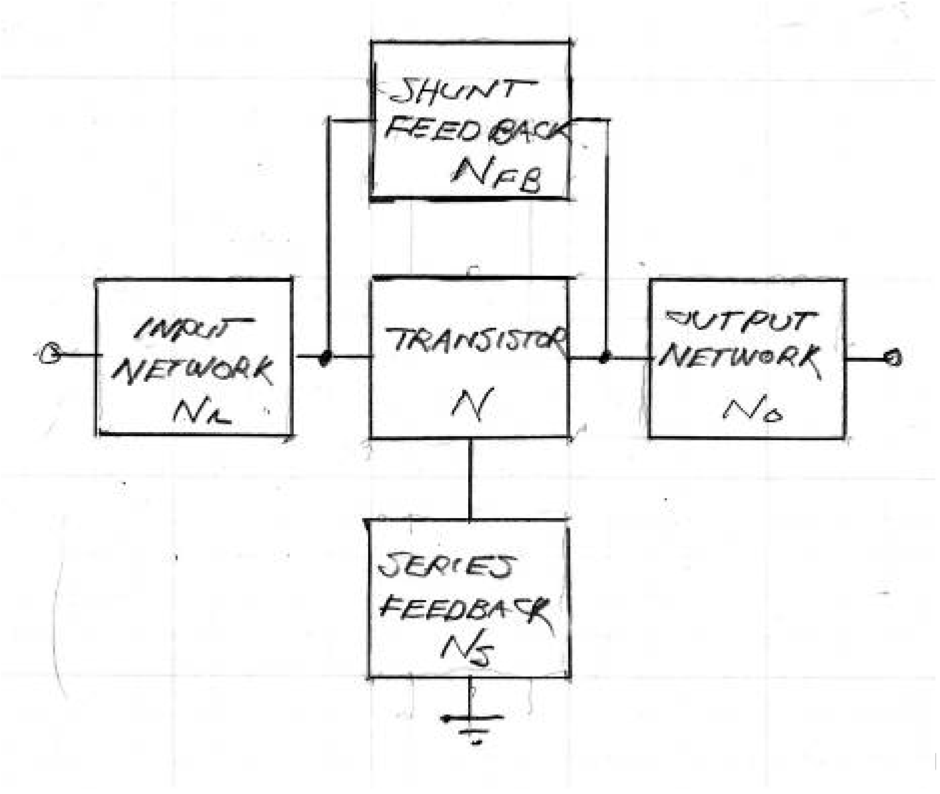
- The correct figure of merit is the noise measure, M, or expressed as a noise temperature, Tcas = M*290K = Tn / (1 – 1/G) where G is the available power gain. It is the noise temperature of an infinite cascade of identical amplifiers. For G >>1, Tcas ~ Tn.

- The golden rule: Tcasmin, the minimum value of Tcas with respect to source impedance, is independent of all lossless network embedding including feedback networks. [Haus, 1958]. As feedback reduces gain, Tmin, is reduced so Tcas is constant.

Obey the Laws!

What limits the overall network performance in terms of an embedded network (i.e. a transistor) performance?

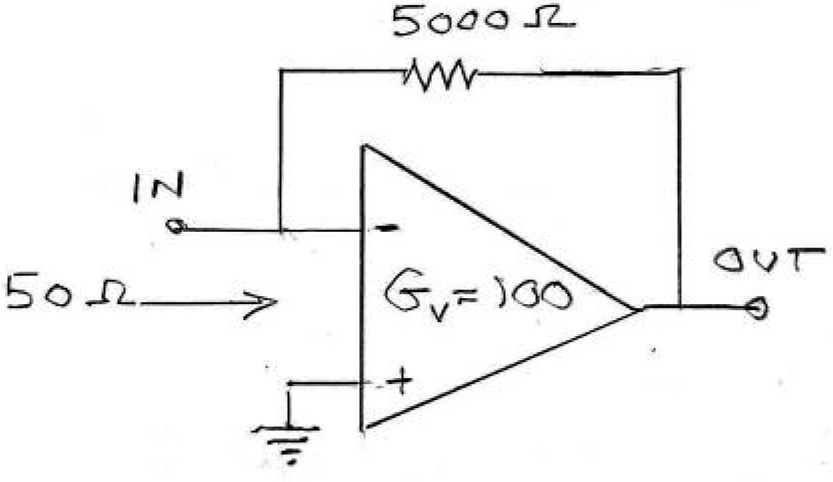
Very powerful theorems regarding the effect of feedback on the noise and gain of amplifiers were published by H. Haus in the 1958-1960 era. The papers are not easily understood and are often ignored in the current literature.



Resistive Feedback, Simple Example

- Reactive feedback can provide simultaneous noise and gain match in narrow band amplifiers. This is usually in the from of inductance in the source or emitter common terminal to ground.

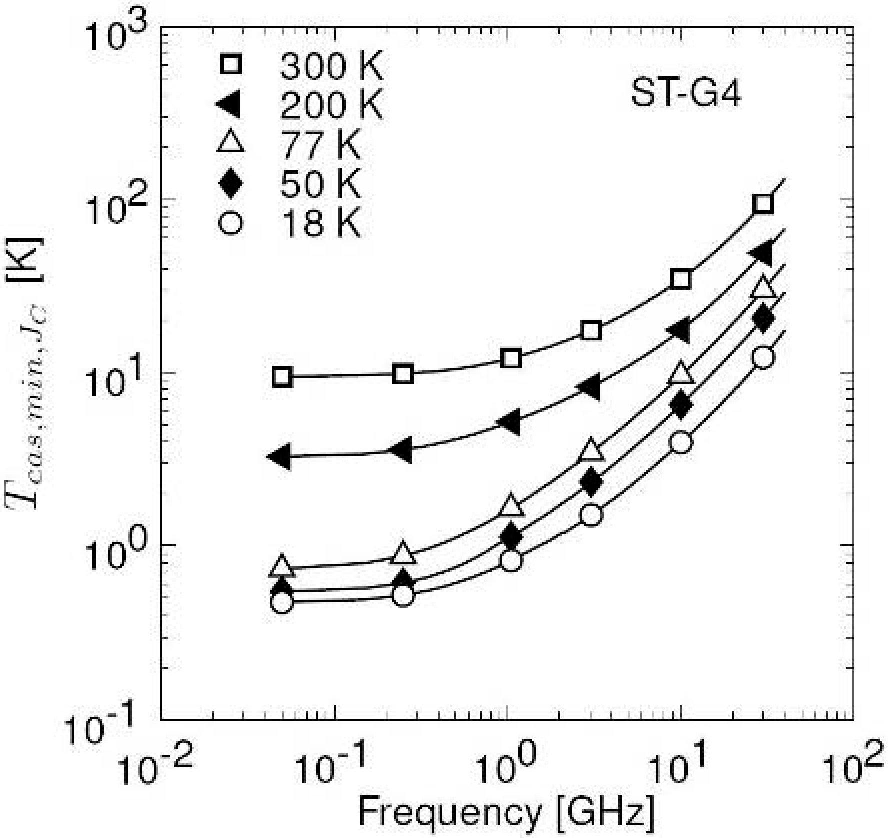
- Resistive feedback can provide gain match in a wideband amplifier with little effect on the noise. In the circuit below 5000 ohms to an output node with voltage gain of -100 provides 50 ohm input impedance at all frequencies. The effect on noise is the same as 5000 ohms from input to ground which contributes a noise of 50/5000 *300K = 3K for the feedback resistor at room temperature.



Tcasmin for a ST BiCMOS9MW SiGe Transistor

From *Silicon-Germanium Heterojunction Bipolar Transistors For Extremely Low-Noise Applications,* J. C. Bardin, Ph.D. thesis, Caltech, June, 2009

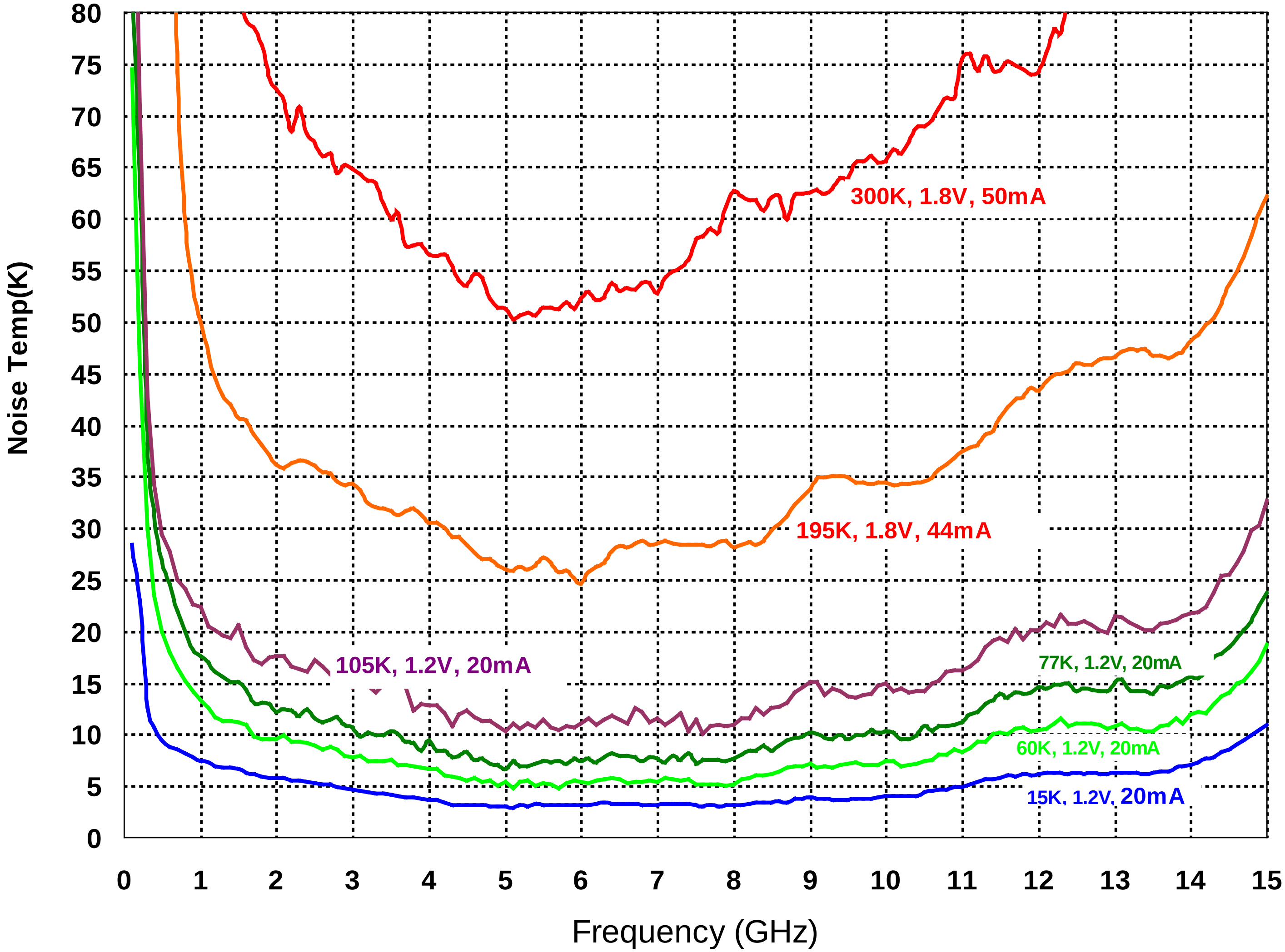
- Curves are at optimum current density for each frequency and temperature; see thesis for details and other noise parameters
- At 300K Tcasmin at 1 GHz is ~ 10K and at 77K is ~1K.

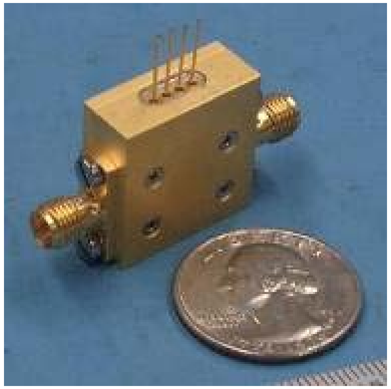


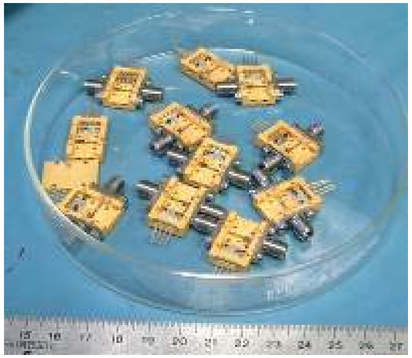
Noise Temperature vs Frequency at 300K, 195K, 105K, 77K, 60K, and 15K

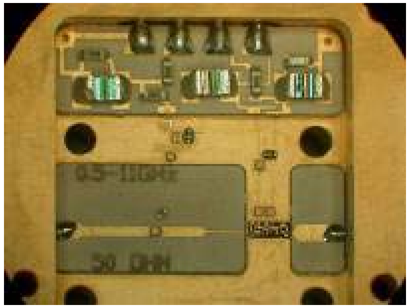
InP HEMT MMIC, WBA13, Tested at Caltech May, 2007

Over 300 of these modules in use in radio astronomy and physics research.





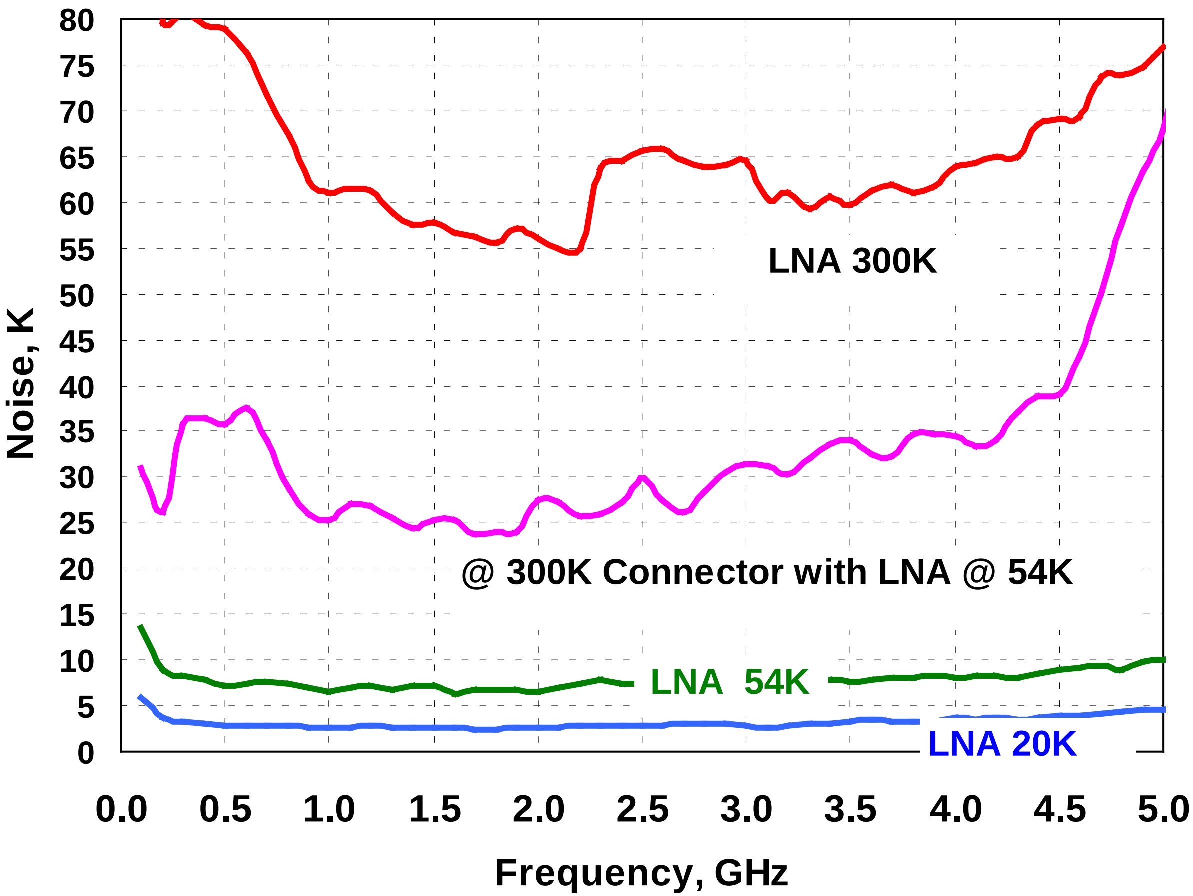


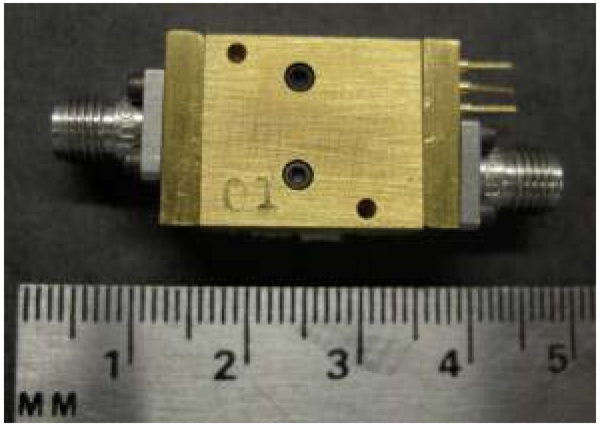


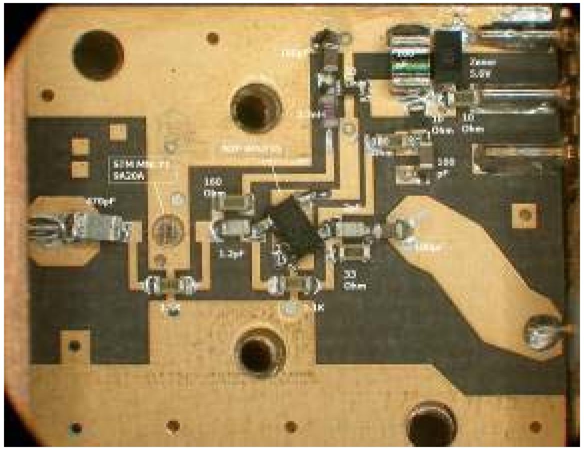
Noise vs Frequency of SiGe Transistor LNA at 3 Temperatures

ST first stage, NXP 2nd stage, tested May, 2008

Typical gain 35 dB, typical bias 2V, 12mA







S. Weinreb, Jun 2009

Complete Packaged SiGe LNA's

REVIEW OF SCIENTIFIC INSTRUMENTS **80**, 044702 (2009)

Matched wideband low-noise amplifiers for radio astronomy

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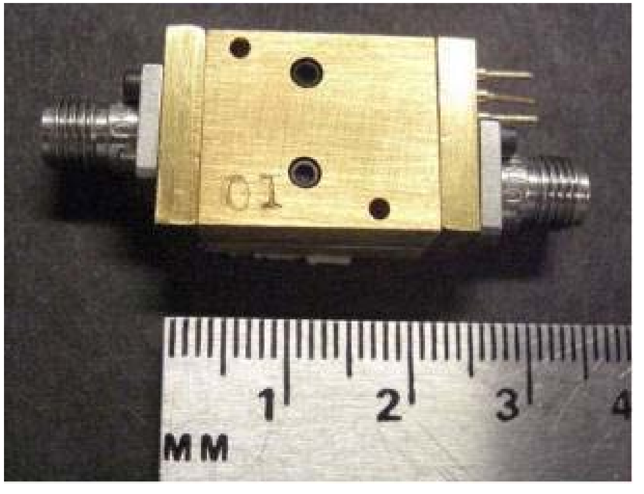
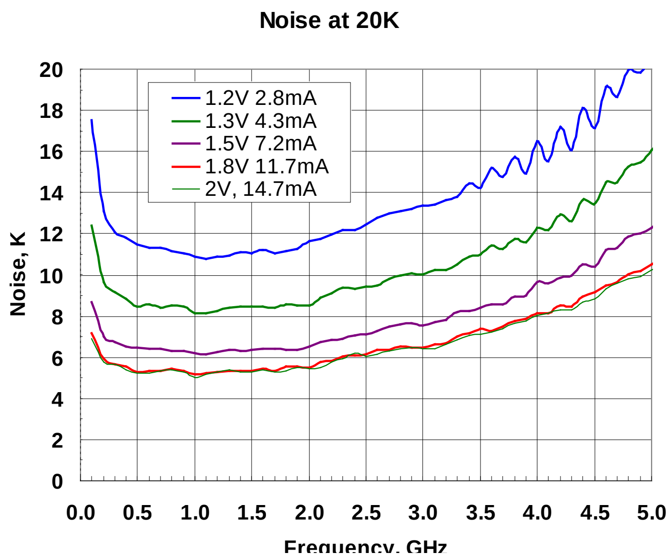
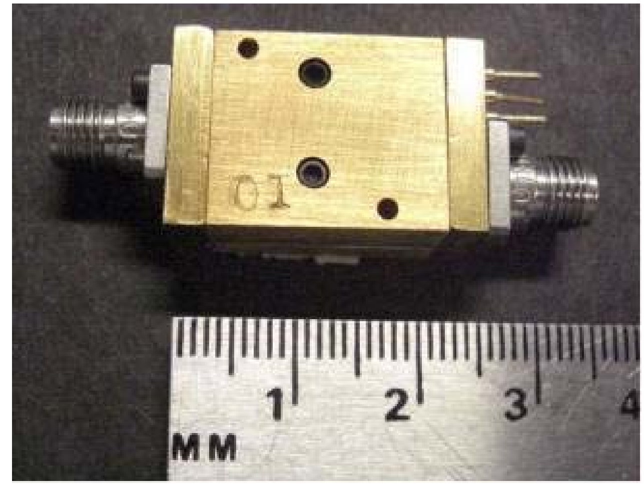
Two packaged low noise amplifiers for the 0.3–4 GHz frequency range are described. The amplifiers can be operated at temperatures of 300–4 K and achieve noise temperatures in the 5 K range (<0.1 dB noise figure) at 15 K physical temperature. One amplifier utilizes commercially available, plastic-packaged SiGe transistors for first and second stages; the second amplifier is identical except it utilizes an experimental chip transistor as the first stage. Both amplifiers use resistive feedback to provide input reflection coefficient $S11 < -10$ dB over a decade bandwidth with gain over 30 dB. The amplifiers can be used as rf amplifiers in very low noise radio astronomy systems or as i.f. amplifiers following superconducting mixers operating in the millimeter and submillimeter frequency range. © *2009 American Institute of Physics.* [DOI: 10.1063/1.3103939]

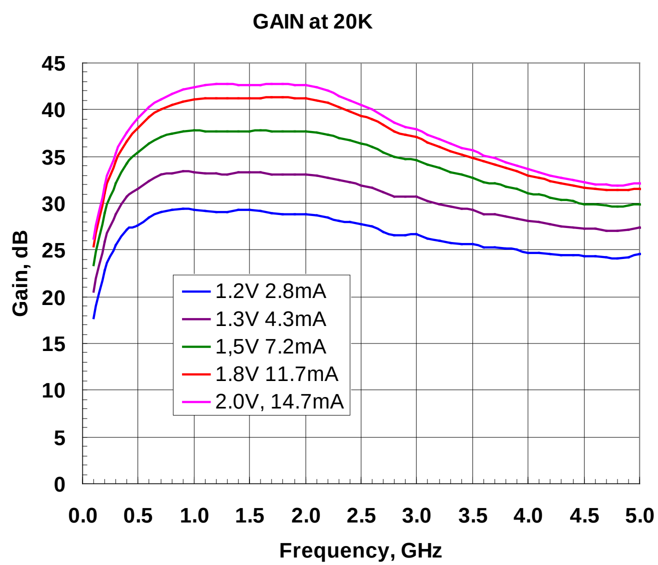


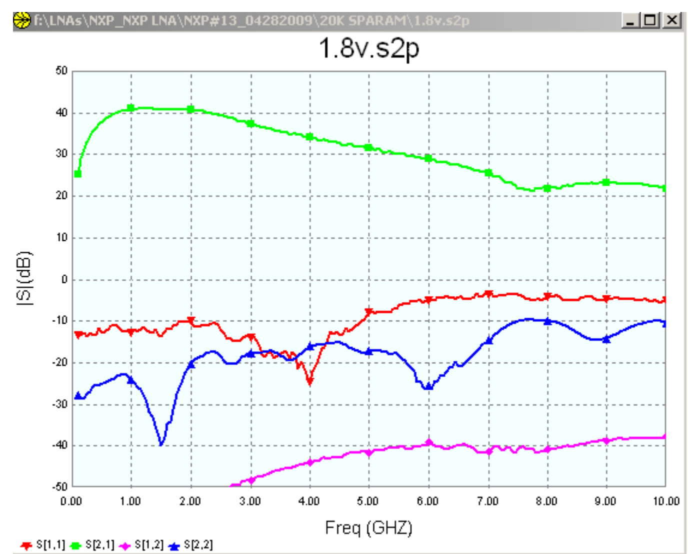
Noise, Gain, and S Parameters for SiGe LNA Using Commercially Available NXP BFU725F Packaged Transistors

6K noise, 20mW power, and -10 dB input return loss are feasible specs









Measured Results Reported in RSI Paper

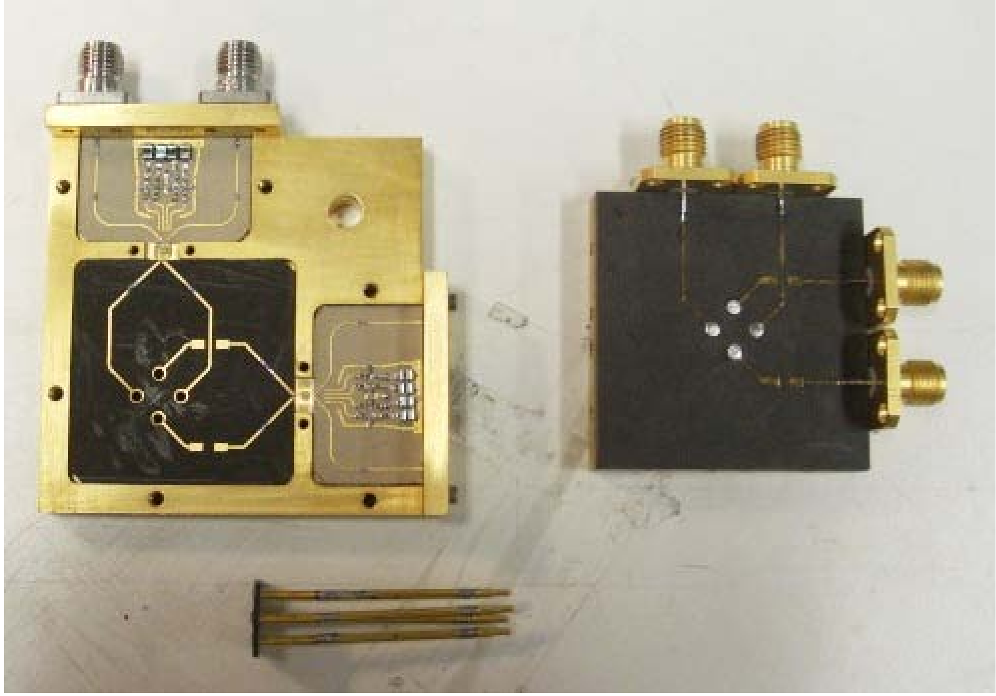
Two amplifiers are reported in the paper. One with ST chip transistors has 3K noist at 1.4 GHz while the other with an NXP transistor has 6K noise. However the ST transistor is not commercially available but the NXP is available at a low price.

TABLE II. Noise and gain at 1.4 GHz of both LNAs as a function of temperature and bias.

LNA	Temperature (K)	dc (V)	dc (mA)	(P) (mW)	Tn (K)	G (dB)	$S11$ (dB)
ST	17	1.3	3.8	5	3.5	32.2	NM
ST	17	2	12.5	25	2.6	39.9	NM
NXP	17	1.7	10	17	6.4	32.8	NM
NXP	17	1.4	5.6	8	6.9	29.8	
ST	50	2	12.2	24	7.0	30.0	NM
ST	300	2	15.2	30	66	32.6	−18
ST	300	3	27.6	83	55	36.5	−12
NXP	300	2.3	23.6	54	90	30.5	−11

Noise Temperature Measurement of Differential LNA's

- Noise temperature of a differential amplifier can be measured with the Y factor method by dipping a termination resistor in LN2 at 77K
- The resistance change vs temperature can be measured very accurately at DC with on ohmmeter. The change in typical thin-film resistance is negligible.
- Shown below is a small board with two 270 ohm resistors connected to two differential LNA's with a gold-plated SS tubing quad transmission lines.



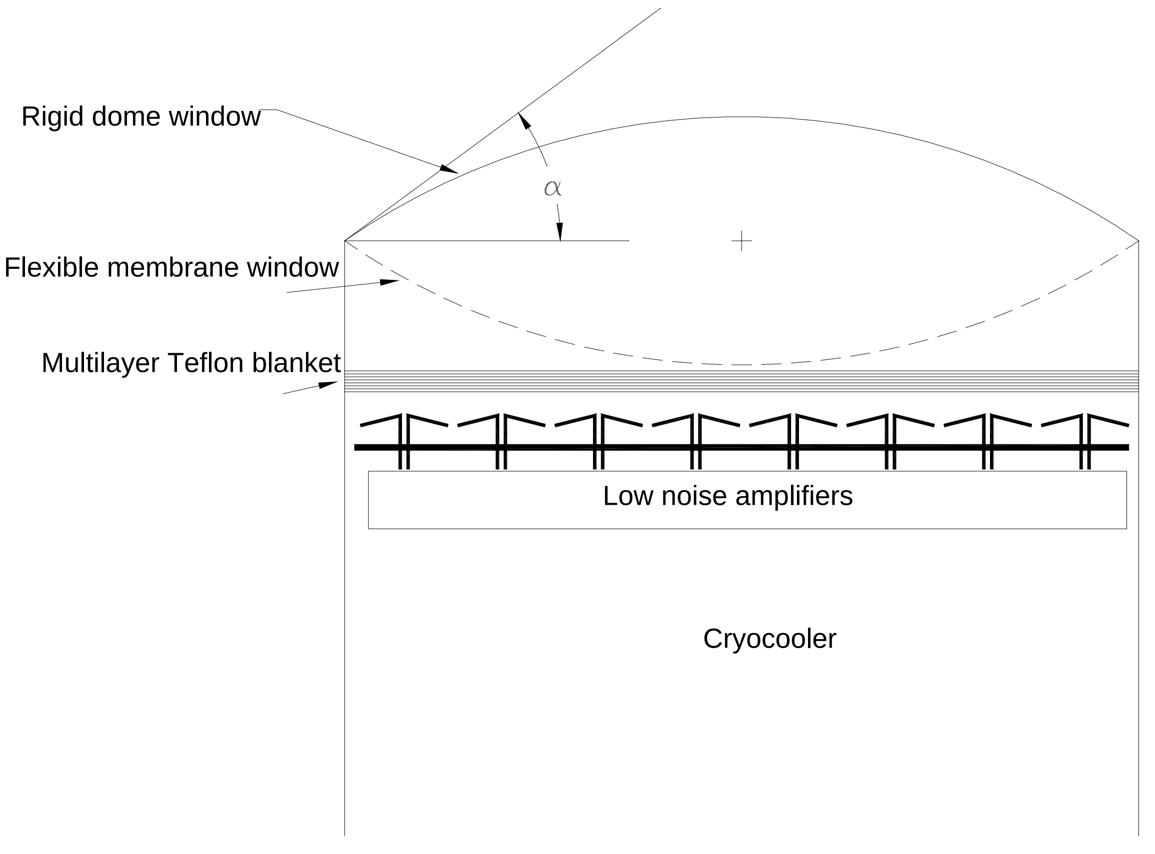
System Noise Budget for 1.2 – 1.5 GHz PAF

- Feed loss is largest unknown; not easy to measure. Need computations
- Window need study and tests
- LNA’s at 300K and 18K may improve by 5K t o 3K in the next few years

Component	Remarks	LNA 300K Feed 300K	LNA 18K Feed 300K	LNA 77K Feed 77K
Sky	Background + atmosphere	4	4	4
Spillover & Blockage	Compromise with efficiency	10	10	10
Window	Weather and vacuum	1	1	2
Feed loss	Estimate 0.10 dB	7	7	2
LNA to feed loss	10cm of 0.25” Cu coax, .04 dB at 300K	0	2	1
Vacuum feedthru	Special bead, 0.05 dB	0	2	0
Coax in dewar	6cm or .141 SS/BeCu .05 dB at 190K	0	2	0
LNA	Robust, LNA measured at connector	15	4	6
Total	**Estimate, +/- 5K**	**37**	**32**	**25**

Mechanical Stress and Infrared Heat for 1m Diameter Window

Two windows with dry air in-between are needed to prevent condensation



$$Stress = \frac{D}{4 \bullet t \bullet \sin\alpha} \bullet p$$

1500psi for D=1m, t=0.5cm, and α=30^{o}

18,850 lbs total force on window

IR Heat = 361 W through 1m diameter window. Must be reflected or re-emitted. N layer Teflon blanket reduces heat flow by N. With N=18 and cooled surface emissivity of .05, heat load is 1W.

References

Microwave noise reference: http://www.internationaleventconnection.com/mtt14/referencepage.html
For low noise work at Caltech: http://radiometer.caltech.edu
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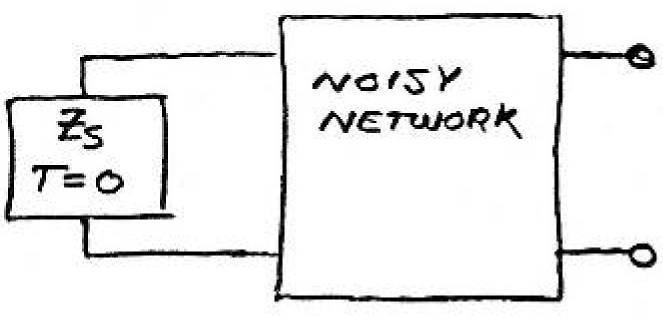
Backup Slides

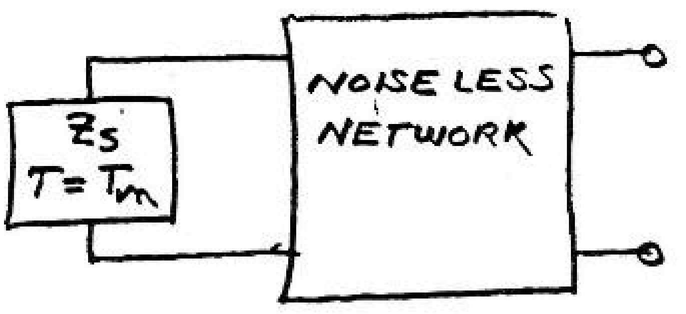
Most Common Microwave Noise Representation

- The noise of microwave amplifier is usually specified by the noise temperature, Tn, that must be added to the source generator to represent the noise in the amplifier. The noise figure is given by

$$NF = 10*\log(1+Tn/290)$$

- Tn is a function of the source impedance Zs and there is a noise parameter, Zopt, which minimizes Tn to give a key 3rd parameter, Tmin. A fourth number is needed to complete the 4 parameter set and this is usually Rn or N to specify the increase in noise if Zs ≠ Zopt.





Noise Parameters from S Parameters

- Noise parameters can be determined by measuring the noise temperature at several generator impedances. For very low noise transistors this is not easily done with sufficient accuracy especially if the Zopt for the transistor is far from 50 ohms and the noise parameters at cryogenic temperatures are desired.

- An alternative is to measure the S parameters and DC characteristics of the transistor as a function of frequency and find the equivalent circuit of the transistor from these S parameters. Then transistor device theory is applied to reduce the number of unknown noise variables to 2, 1, or 0 frequency-independent numbers. The number depends upon the type of device (i.e FET or bipolar) and required accuracy.

- Noise parameters of any linear passive network can be calculated from the S parameters and temperature of the network. Thus noise due to input and other circuits in a low noise amplifiers can be accounted for.

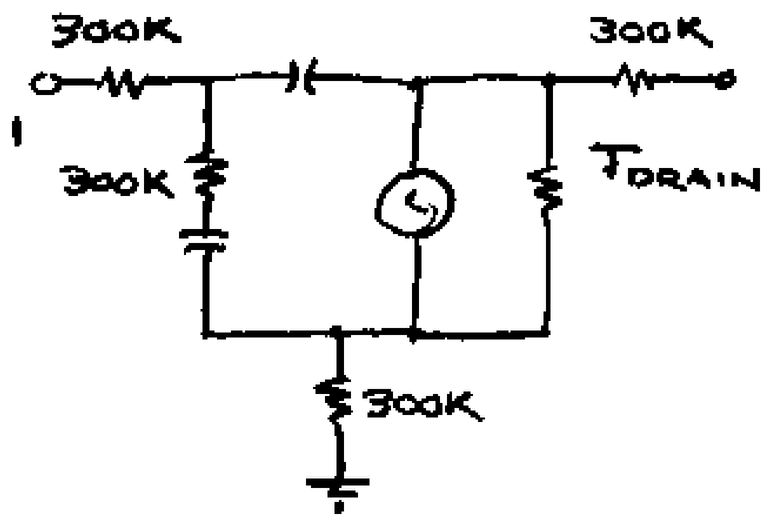
- All of the above calculations can be most easily performed with a circuit simulator such as Microwave Office.

Noise Parameters of a FET or HEMT

• Procedures exist to find the equivalent circuit from measurements of the S parameters vs frequency. The elements in the equivalent circuit have a physical basis; they can be identified with regions of the transistor. Regions with resistive loss generate thermal noise with noise power proportional to physical temperature.

• As suggested by Pospieszalski [1989] the noise due to turbulence in DC current flow within the transistor channel can be modeled by assigning a temperature, Tdrain, to the shunt drain resistor determined by the model..

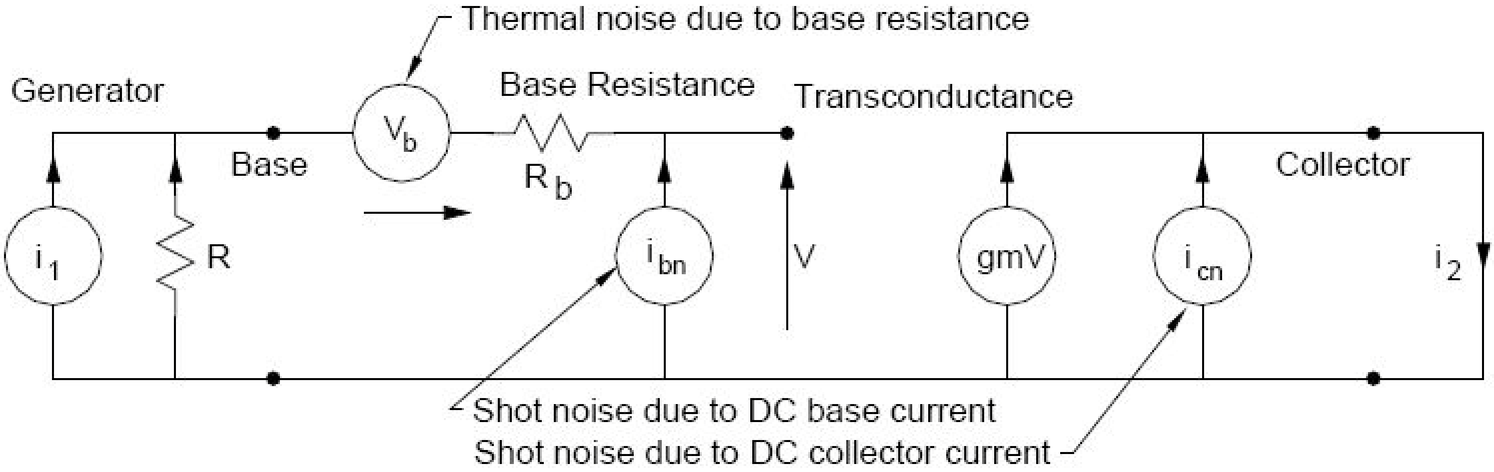
• Tdrain is independent of frequency and thus one measurement of noise temperature at one frequency can be used for find Tdrain. Then all 4 noise parameters as a function of frequency can be calculated.



Noise of SiGe Bipolar Transistors

• Noise in SiGe transistor consists of thermal noise plus shot noise due to base and collector currents. The shot noise power is proportional to the DC base and collector currents and is thus determined by DC measurements.

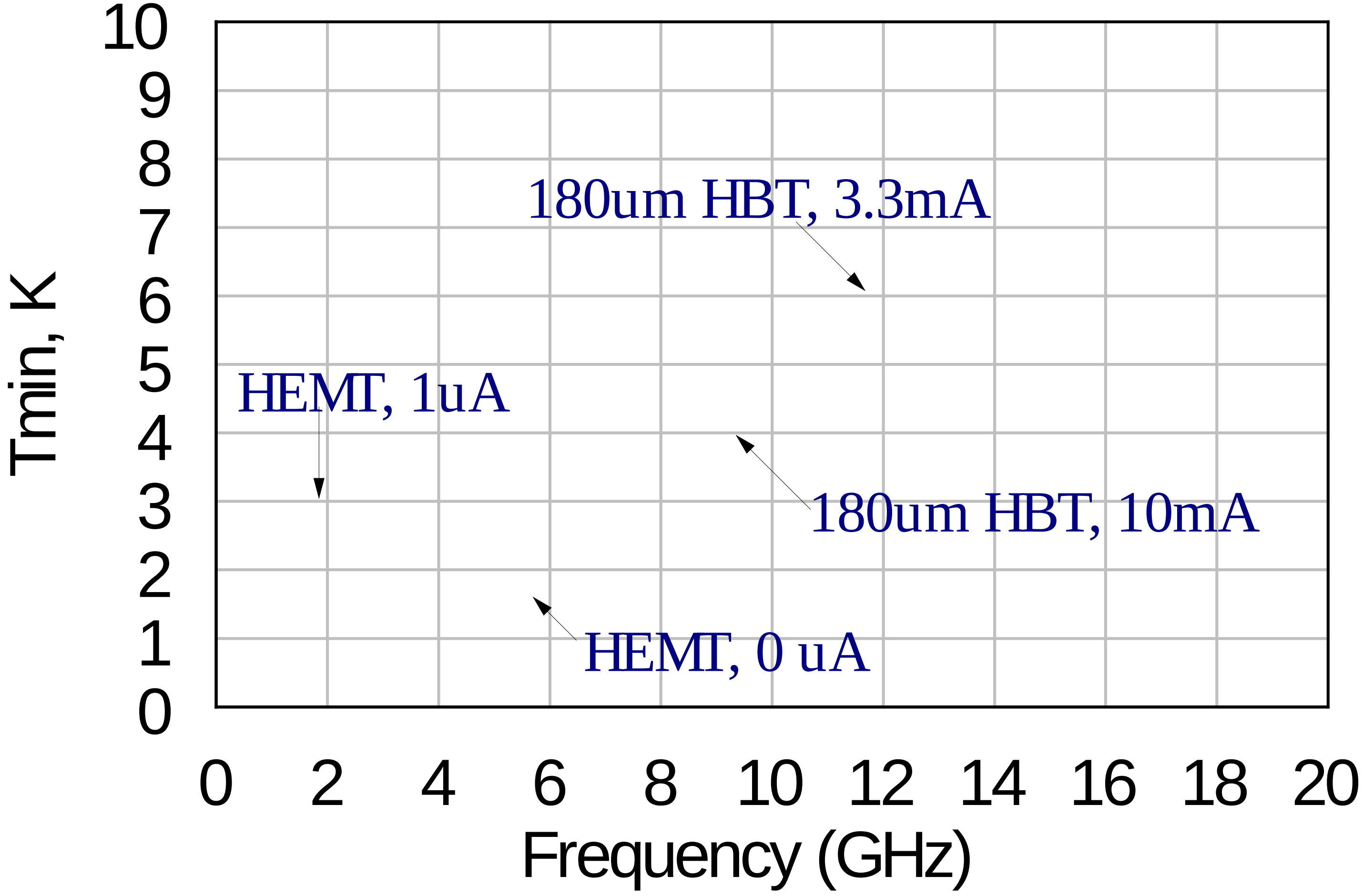
•A simple model which gives Tmin ~ 290K / $\sqrt{\beta}$ where β is the DC current gain. This approximation holds for all temperatures at frequencies below a few GHz. [See Weinreb and Bardin, Nov 2007, IEEE MTT Transactions]



• A complete noise theory is given in the J. Bardin Ph.D. thesis, Caltech, 2009.

SiGe HBT and InP HEMT Minimum Noise at 15K

Results below are modeled. As a confirmation of the model an HBT single-stage cascode amplifier has been measured with 2K noise temperature and 28 dB gain at 1 GHz.



Understanding Waves

- At any reference plane voltage and current are related to forward wave complex amplitude, a, and backward wave b, by:

$$V = (a+b) * \sqrt{Zn} \qquad I = (a-b) / \sqrt{Zn}$$

where Zn is the normalization impedance

- Zn is usually equal to the interconnection transmission line characteristic impedance, Zo, often 50 ohms, or for differential connections 200 ohms. When Zn = Zo, a and b only change phase if the reference plane is changed.
- Wave noise parameters (i.e. (E) and (F) in previous figure) change when Zn is changed but Tn does not change.
- An important case for (E) it that the input-to-output noise wave correlation coefficient, $\rho_{io} = 0$ when an amplifier has been designed for both noise and gain matched to Zn. [see Wedge, et al, 1992]. To be discussed further in a subsequent slide.

The Essence of N

• The dimensionless noise parameter, N, has some interesting properties

• N, as well as Tmin, is invariant to lossless input networks. The N of a packaged transistor is the same as the N of a chip. It is not changed by a length of transmission line. [Lange, 1967]

• N is not changed by putting transistors in parallel or changing the width of the transistor

• N is known to within a factor of 2 if Tmin is known (To = 290K).

$$\frac{T\min}{4 \bullet To} \leq N \leq \frac{T\min}{2 \bullet To}$$

[See Pospieszalski for proof.]

•For the SiGe bipolar transistors investigated by Bardin, N is close to the upper limit in the above equation

• Noise parameters (usually using Rn) are sometimes published which violate the lower limit above due to errors in the measurements

The Noise Parameters of a FET Chip Have Simple Frequency Dependence

- Linear dependence upon frequency used to extrapolate noise parameters of commercial GaAs FETs many years ago.
- The linear dependence of Tmin allows a Tmin measurement at a higher frequency (say 4 GHz or 12 GHz) to be extrapolated to a lower frequency where the Tmin is too small to be accurately measured.

NOISE CONSTANTS A, B, C, D FOR CHIP

$T_{MIN} = A \cdot f \qquad R_{op} = B/f \qquad X_{op} = C/f \qquad N = D \cdot f$

TRANSISTOR	TEMP °K	V_D	I_D	A K/GHz	B Ω·GHz	C Ω·GHz	D /GHz	REFERENCE
FHR01	297	2	10	9.1	250	526	.011	POSPIESZALSKI OCT 25, 1989
	12.5	2	5	1.2	65	513	.0014	
MGF1412	297	3	7.5	12.0	237	499	.029	NRAO EDIR 259 p. 28
	15	3	7.5	2.1	147	534	.0065	
NE045	300	3	10	10.0	358	1105	.012	NRAO EDIR 260 p. 11
	15	1.5	5	2.3	175	1198	.0026	

With Cooled LNA's Most of the System Noise is Not in the LNA

- Assume feed for 0.3 to 1.4 GHz is at 300K.
- Feed for 1.4 to 10 GHz must be cooled or partially cooled.
- No calibration signal coupling is assumed.

Component	**Remarks**	**2009, K LNA at 300K**	**2009, K LNA at 60K**	**2011, K LNA at 300K**	**2011, K LNA at 60K**
Sky	Background + atmosphere	4	4	4	4
Spillover & Blockage	Reduce with offset antenna	12	12	6	6
Feed loss	Estimate, measure by 2010	7	7	5	5
LNA to feed loss	10cm of 0.141 Cu coax, .04 dB at 300K	4	4	3	3
Vacuum feedthru	Glass/Kovar bead, 0.1 dB	0	7	0	5
Coax in dewar	10cm or .141 SS/BeCu .09 dB at 190K	0	4	0	3
LNA	Robust, differential LNA measured at connector	40	12	25	5
Total	**Estimate, +/- 5K**	**67**	**50**	**43**	**31**

S. Weinreb, Jun 2009

Correlation of What?

- Note that correlation depends upon which two sources we are referring to. Thus the correlation coefficients between input and output currents in the previous figure does not imply correlation between input and output voltages or waves.

$$\rho_i \neq \rho_v \neq \rho_{io}$$

- The term “correlated noise” is often confused. We must specify which two variables we are referring to.

REASONS FOR LARGE ERRORS IN MM WAVE TRANSISTOR NOISE MEASUREMENTS

1) COMPARABLE CIRCUIT AND DEVICE NOISE

2) 300K GENERATOR NOISE » DEVICE NOISE

3) DEVICE HAS LOW GAIN AND SECOND STAGE NOISE IS HIGH

4) LOW FREQUENCY OSCILLATION

5) CHIP MEASUREMENT PLANE POORLY DEFINED

6) OPTIMUM NOISE IMPEDANCE IS FAR FROM 50 OHMS

7) UNKNOWN NOISE FROM SEMICONDUCTOR VARIABLE TUNERS

Coaxial 50 Ohm Noise Source Calibration

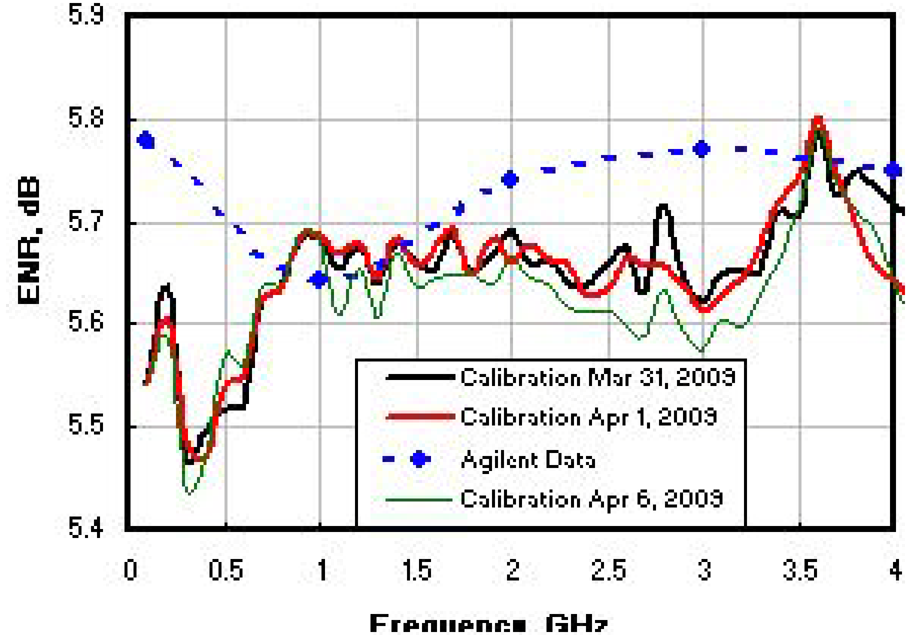
• The specified uncertainty of the ENR of Agilent noise sources is +/-0.15dB. For LNA noise temperatures under 100K this results in a a noise temperature uncertainty of +/-10K

• The noise source uncertainty limits the accuracy of transistor manufacturer's data at low frequencies where the data sheet noise figures are of the order 0.2 dB at 2 GHz. This is 14K +/- 10K

Noise source ENR can be calibrated with LN2 terminations such as the one at right developed at NRAO in 1983. The noise temperature at the SMA connector is believed to be known to +/- 1K. LN2 terminations are also available from Maury Microwave.

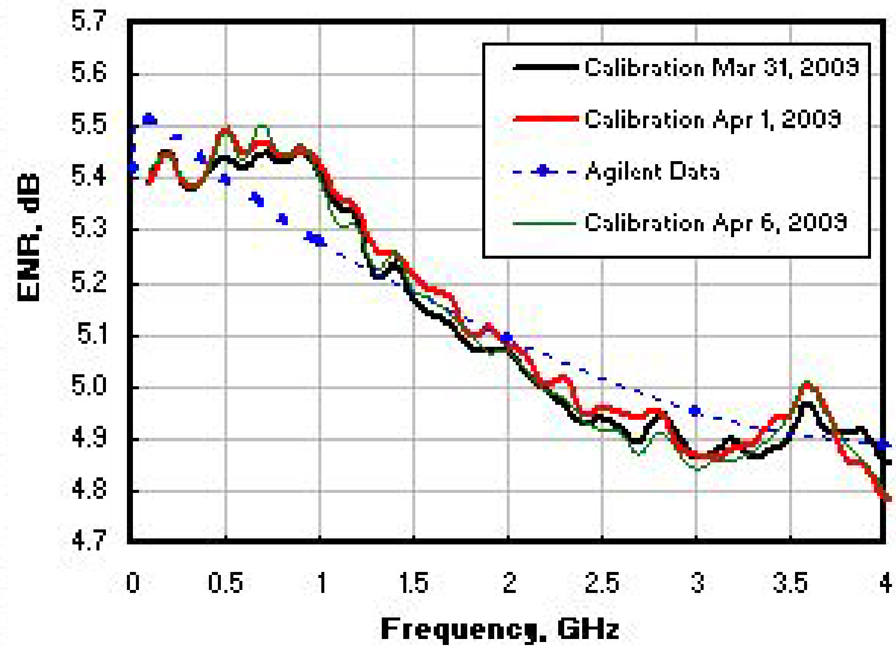
Calibration of Two Agilent Noise Sources with NRAO LN7 Noise Standard

by Hamdi Mani, Apr 6, 2009



Top Graph is for N4000A

Bottom graph is for 346A



Red, black, and green curves show repeatability within +/- .05dB on 3 days.

Agilent values in blue dashed.

Conclusions:

In the 0.1 to 4 GHz range the N4000A differs from the LN7 by as much as 0.2 dB.

The peak difference for the 346A is 0.15 dB