NOISE MEASUREMENTS AND REMOTE-SENSING RADIOMETRY (AT NIST)

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Outline

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- Microwave networks
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- Uncertainties

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- Noise-parameter measurements
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- (Cryogenic amplifier noise figure measurement)

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- Calibration target

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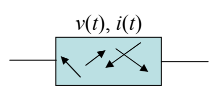
I. INTRODUCTION & FOUNDATION

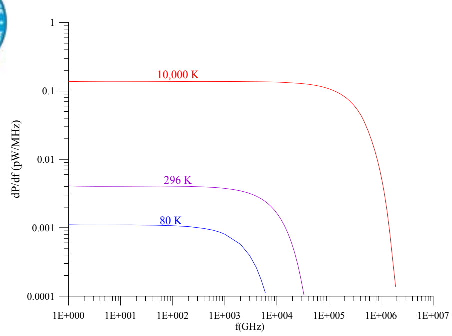
Nyquist Theorem & Noise Temperature [1 – 4]

- Thermal motion of charges in a resistor gives rise to random fluctuations of current & voltage

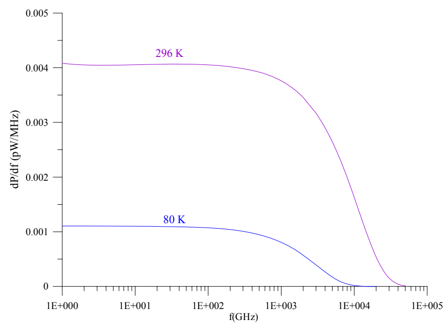


- For passive device, at physical temperature T, with small Δf,

$$\langle P_{avail}(f) \rangle = \frac{hf}{e^{hf/(k_B T)} - 1} \Delta f$$



$$\left\langle P_{avail}(f)\right\rangle = \frac{hf}{e^{hf/(k_B T)} - 1}\Delta f$$



Note: very small powers.

- Limits
  - small f: $<P_{avail}> \approx k_B T\, \Delta f\, [1 - hf/(2k_B T)]$
    $\approx k_B T\, \Delta f$
  - large f: $\to 0$
  - knee occurs around f(GHz) ≈ 20 T(K)
- Quantum effect
  - h/k_B = 0.04799 K/GHz
  - So at 290 K, 1 % effect at 116 GHz
    at 100 K, 1 % effect at 40 GHz
    at 100 K, 0.1 % effect at 4 GHz
    30 K @ 40 GHz → 6.4%, 0.26 dB

- What about active devices? Can we define a noise temperature?
- Several different definitions are used: [5]
  - delivered vs. available power
  - with or without quantum effect
    i.e., does $T_{noise} \propto P_{avail}$ ("power" definition), or is T_{noise} the physical temperature that would result in that value of P_{avail} ("equivalent-physical-temperature" definition)?

- We (I) will use the "power" definition,
  noise temp ≡ available spectral noise-power divided by Boltzmann's constant.
- It is the common choice in international comparisons [6] and elsewhere [7].
- It is much more convenient for amplifier noise considerations, at least for careful ones. (See discussion below, under Noise Figure and Parameters.)

- So $P_{avail} \equiv k_B T_{noise} \Delta f$
- And for passive devices,

$$T_{noise} = \frac{1}{k_B}\left[\frac{hf}{e^{hf/(k_B T)} - 1}\right] \approx T_{phys}$$

- Convenient to define "Excess noise ratio"

$$ENR_{avail}(dB) \equiv 10\log_{10}\left(\frac{T_{avail} - T_0}{T_0}\right) \qquad T_0 = 290 \text{ K}$$

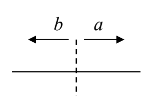
T=9500 K $\Rightarrow$ ENR ≈ 15.02 dB

T=1000 K $\Rightarrow$ ENR ≈ 3.89 dB

No matter what definition of noise temperature you choose, it is helpful to state your choice.

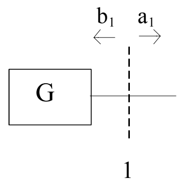
MICROWAVE NETWORKS & NOISE [8,9]

- Assume lossless lines, single mode.
- Travelling-wave amplitudes *a*, *b*.



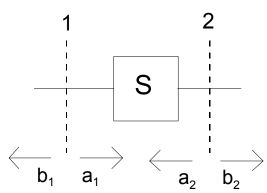
- Normalized such that $P_{del} = |a|^2 - |b|^2$ is the spectral power density.

- Describe (linear) one-ports by



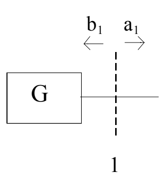
$$a_1 = \Gamma_G b_1 + \hat{a}_G$$

- And (linear) two-ports by



$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} + \begin{pmatrix} \hat{b}_1 \\ \hat{b}_2 \end{pmatrix}$$

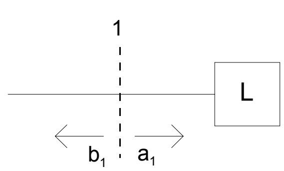
- Available power:



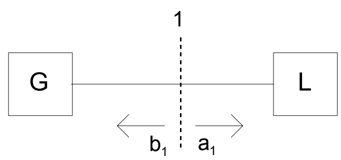
$$P_G^{avail} = \frac{|\hat{a}_G|^2}{1-|\Gamma_G|^2}$$

Relation to noise temp: $\langle |\hat{a}_G|^2 \rangle = (1-|\Gamma_G|^2)\, k_B T_G$

- Delivered power:

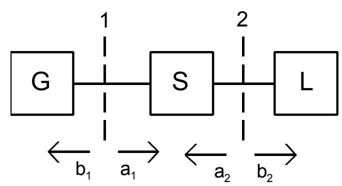


$$P_1^{del} = |a_1|^2 - |b_1|^2 = |a_1|^2 \left(1-|\Gamma_L|^2\right)$$



Mismatch Factor

$$M_1 = \frac{P^{del}}{P^{avail}} = \frac{\left(1-|\Gamma_L|^2\right)\left(1-|\Gamma_G|^2\right)}{|1-\Gamma_L\Gamma_G|^2}$$



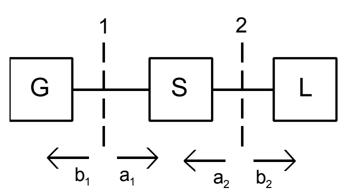
Efficiency

$$\eta_{21} = \frac{P_2^{del}}{P_1^{del}} = \frac{|S_{21}|^2\left(1-|\Gamma_L|^2\right)}{|1-\Gamma_L S_{22}|^2\left(1-|\Gamma_{SL}|^2\right)}$$

$$= \frac{|S_{21}|^2\left(1-|\Gamma_L|^2\right)}{|1-\Gamma_L S_{22}|^2 - |(S_{12}S_{21}-S_{11}S_{22})\Gamma_L + S_{11}|^2}$$

- Available power ratio (available gain):

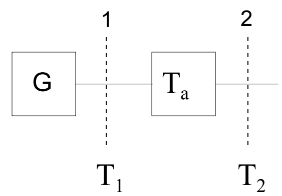
$$\alpha_{21} \equiv \frac{p_{2,avail}}{p_{1,avail}} (\hat{b}_1 = \hat{b}_2 = 0)$$



$$\alpha_{21} = \frac{|S_{21}|^2\left(1-|\Gamma_G|^2\right)}{|1-\Gamma_G S_{11}|^2\left(1-|\Gamma_{GS}|^2\right)}$$

$$\Gamma_{GS} = S_{22} + \frac{S_{12}S_{21}\Gamma_G}{1-\Gamma_G S_{11}}$$

- Temperature translation through a passive, linear, 2-port (attenuator, adapter, line, ...)



$$P_2^{avail} = \alpha_{21} P_1^{avail} + f_0(T_a)$$
$$T_2 = \alpha_{21} T_1 + f(T_a)$$

Say $T_1 = T_a$, then T_2 must $= T_a$, so

$$T_2 = T_a = \alpha_{21} T_a + f(T_a)$$
$$f(T_a) = (1 - \alpha_{21}) T_a$$

and therefore

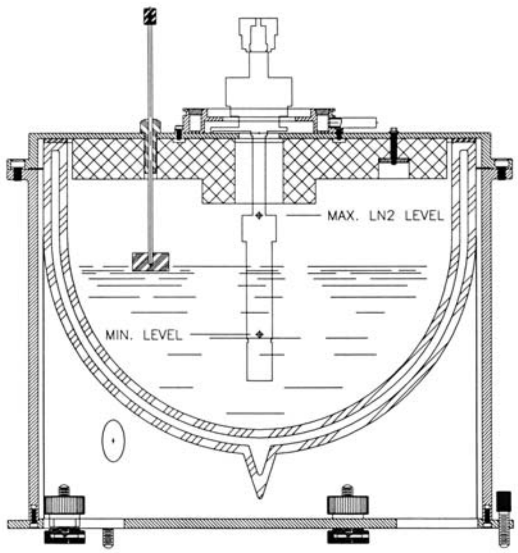
$$T_2 = \alpha_{21} T_1 + (1 - \alpha_{21}) T_a$$

Noise Standards [10 – 13]

- Ambient standard: matched load, water jacket, thermistor, thermal paste.
  $u_{Ta} = 0.1$ K

- Cryogenic standards: liquid nitrogen, both coaxial & waveguide.

- Coaxial standards: 30 MHz, 60 MHz, 1 – 12.4 GHz. $u_{TC} \approx 0.6$ K (coaxial)



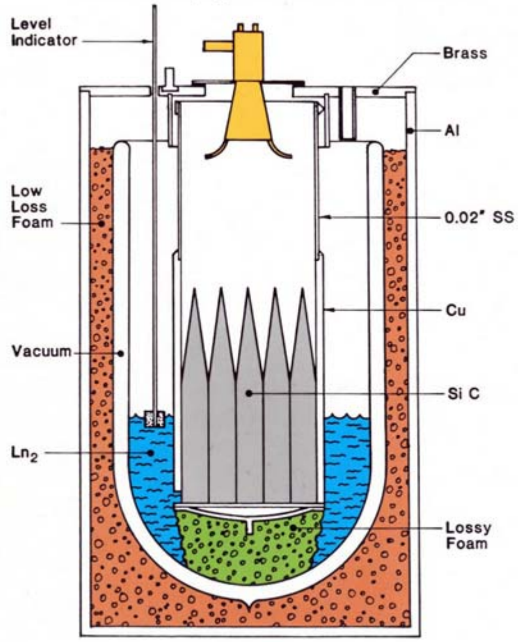
- Waveguide standards: 8.2 – 110 GHz, in 7 bands. (But radiometers only to 65 GHz.)

Uncertainties in Waveguide Standards

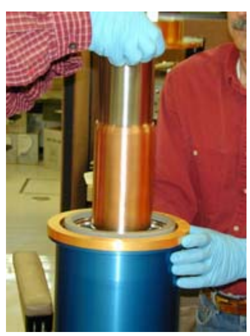
Band	Frequency (GHz)	Uncertainty (K)
WR-90	8.2 – 12.4	0.14
WR-62	12.4 – 18	0.18
WR-42	18 – 26.5	0.21
WR-28	26.5 – 40	0.14
WR-22	33 – 50	0.31
WR-15	50 – 75	0.38

94 GHz Cryogenic Noise Standard

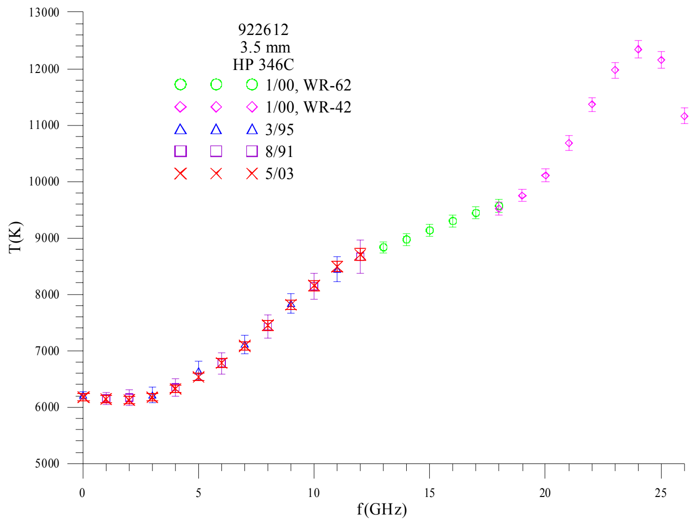
NIST NOISE



NIST NOISE



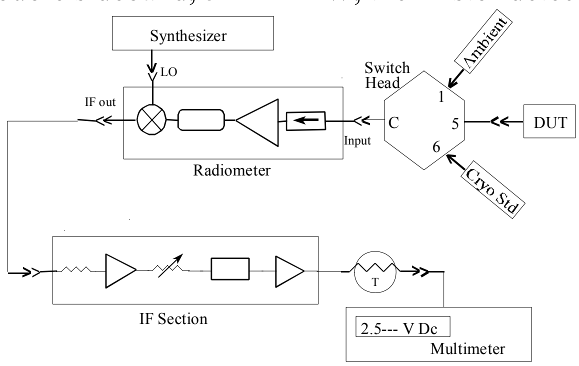
- Overlap is a good check:



Total-Power Radiometer [14 - 17]

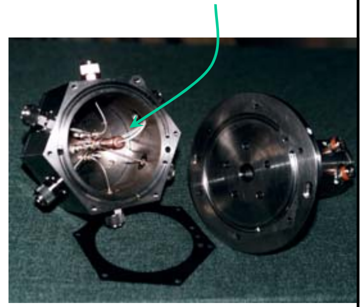
- Radiometer: measures "radiated" power. For us, measures delivered power (in w.g. or transmission line), & we convert to available power & therefore to noise temperature.
- Two principal types of radiometer for noise-temperature measurements are Dicke radiometer and total-power radiometer [14].
- Total-power radiometer is most common for lab use, & that's what we'll discuss.

- NIST Coaxial Radiometer [17], General Features:
  - Total-power radiometer, isolated (60 dB), baseband IF, double sideband, 5 MHz BW, thermistor detector.

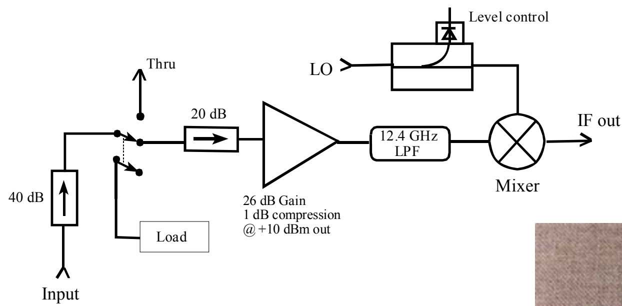


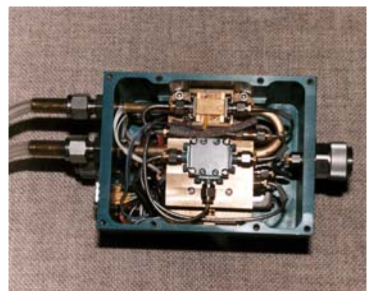
  - Radiometer eqn: $$T_x = T_a + \frac{M_{Cryo}\eta_{Cryo,0}}{M_x\eta_{x,0}} \frac{(Y_x - 1)}{(Y_{Cryo} - 1)} (T_{Cryo} - T_a)$$

- Coaxial Radiometer "NFRad" [17]



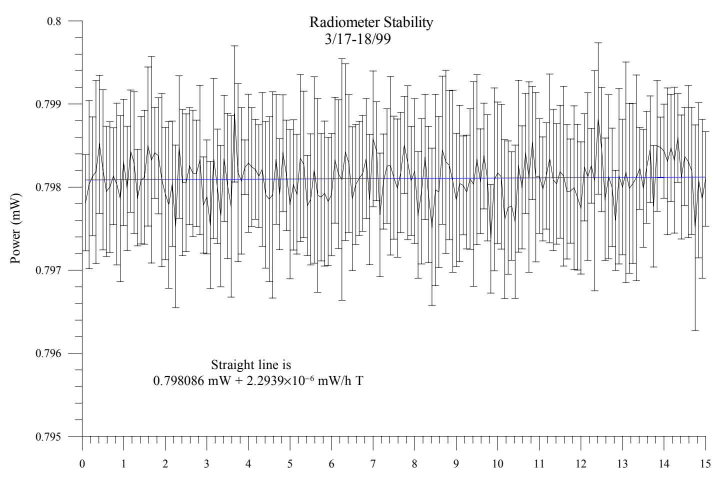
- RF Section (8 - 12.4 GHz unit):



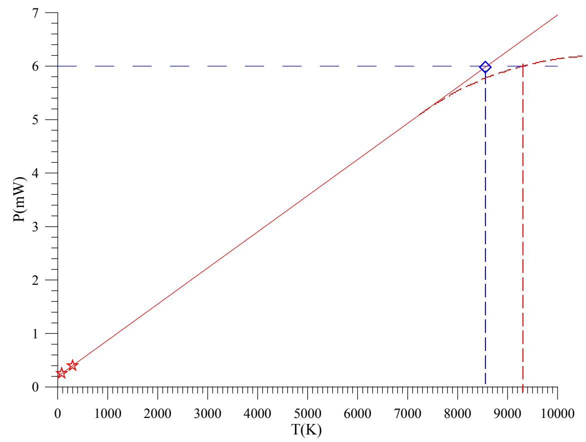


Some Characteristics & Tests

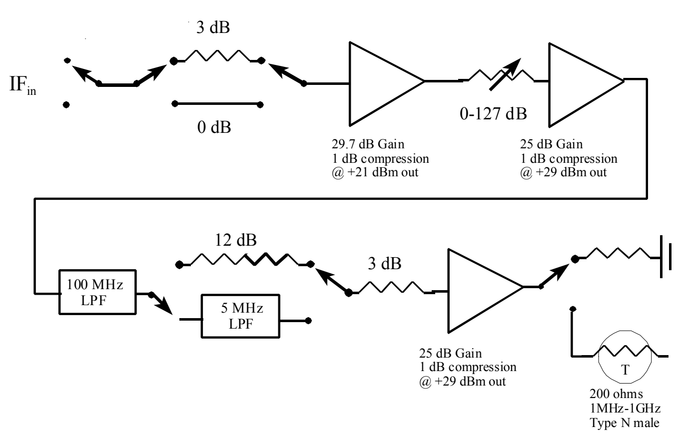
- Stability



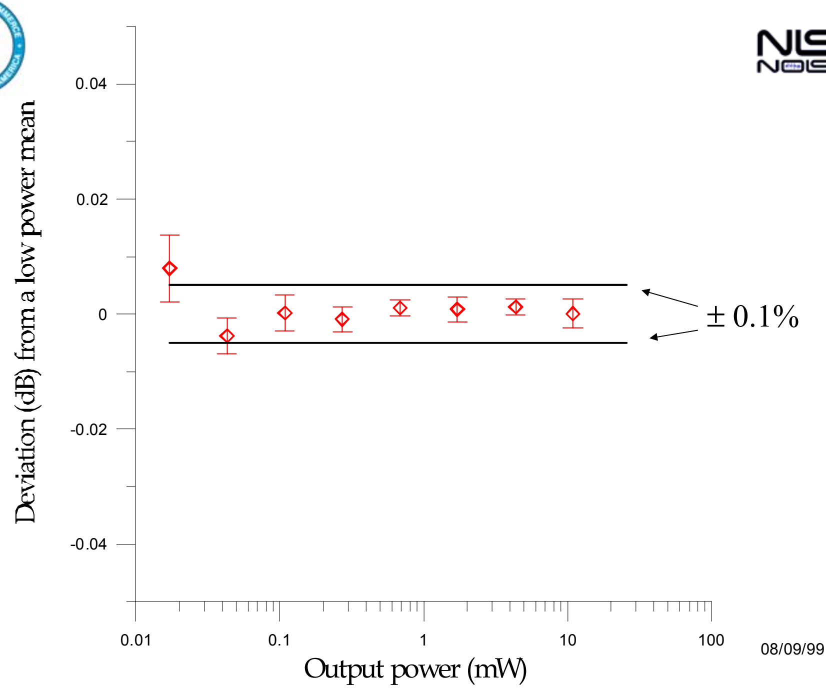
- Linearity is critical



IF Section

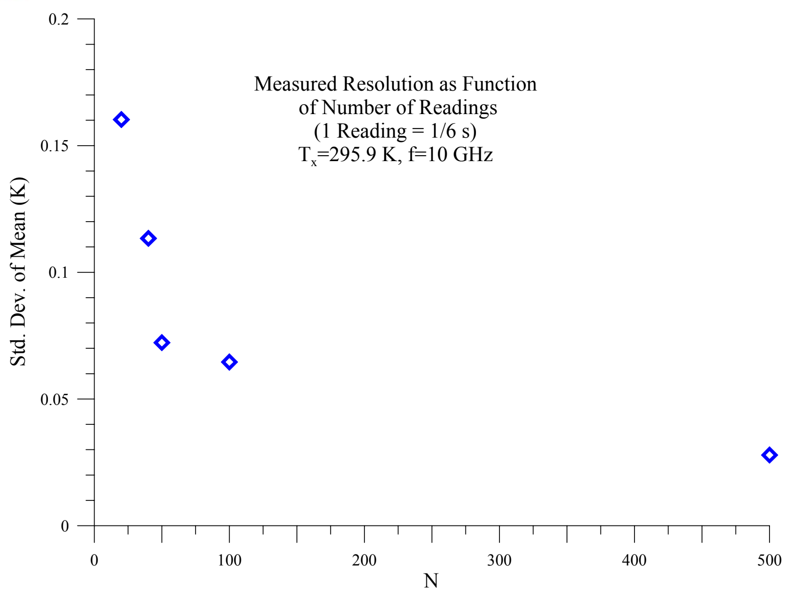


IF Linearity Test: measure with 3 dB attenuator in & out for range of 127 dB attenuator.



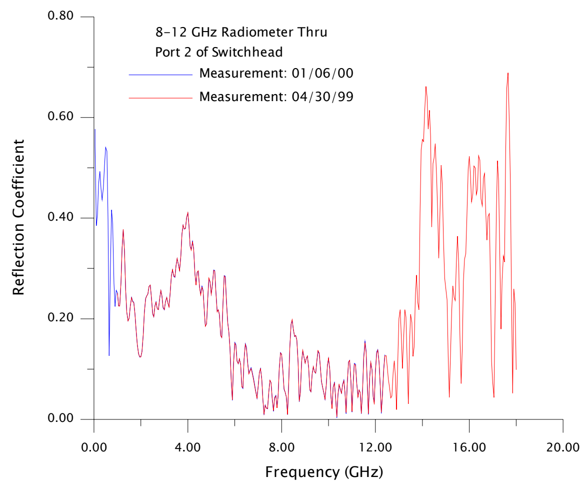
0.04
0.02
0
-0.02
-0.04
Deviation (dB) from a low power mean
± 0.1%
0.01
0.1
1
10
100
Output power (mW)
08/09/99

- Resolution



Measured Resolution as Function
of Number of Readings
(1 Reading = 1/6 s)
T_x=295.9 K, f=10 GHz
0.2
0.15
0.1
0.05
0
Std. Dev. of Mean (K)
0
100
200
300
400
500
N

- Repeatability of connections; stability of reflection coefficients.



Uncertainties

- Simple case (matched):

$$T_x = T_a + \frac{(Y_x - 1)}{(Y_S - 1)}(T_S - T_a)\frac{M_h \eta_h}{M_x \eta_x}$$

Uncert "should" be negligible

small uncert, but linearity is a concern

about 1 or 2%

typically around 1 %

For the ENR, this $\Rightarrow u(\text{ENR}) \approx 0.10$ dB to 0.15 dB

- Simple-case uncerts (cont'd)
  - drift: temperature stability/control important (effect minimized by frequent switching to standards)
  - connector variability: hard to do much better than 0.1%, easy to do considerably worse.
  - ΔG_{rad}, ΔT_{rad} (due to $\Delta\Gamma$): depends on details of system, can make a crude estimate:

$T_{rev} \sim T_e$, $|\Delta\Gamma| \sim 0.05$ or 0.1

So $\Delta T_{in} \sim 0.05$ or $0.1 \times T_e$

- Uncertainties (more careful case)
  (Numbers are for NIST case) [17,18]
  - Radiometer equation:

$$T_x = T_{amb} + \frac{M_S \eta_S}{M_x \eta_x} \frac{(Y_x - 1)}{(Y_S - 1)} (T_S - T_{amb}) + (negligible)$$

  - Ambient standard:

$$\frac{u_{amb}(T_x)}{T_x} = \left|\frac{T_x - T_S}{T_a - T_S}\right| \frac{T_a}{T_x} \varepsilon_{T_a}, \quad \varepsilon_{T_a} = \frac{0.1K}{296K} = 0.034\%$$

– Cryogenic standard:

$$\frac{u_{T_S}(T_x)}{T_x} = \left|1 - \frac{T_a}{T_x}\right| \left|\frac{T_S}{T_a - T_S}\right| \frac{u(T_S)}{T_S}, \quad \frac{u(T_S)}{T_S} = 0.2\% (NIST\ W.G.), 0.8\% (NIST\ coax)$$

– Path asymmetry: (zero if connect to same port)

$$\frac{u_{\eta/\eta}(T_x)}{T_x} = \left|1 - \frac{T_a}{T_x}\right| u(\eta/\eta), \quad u(\eta/\eta) = 0.2\% \ to\ 0.56\%$$

– Mismatch:

$$\frac{u_{M/M}(T_x)}{T_x} = \left|1 - \frac{T_a}{T_x}\right| u(M/M), \quad u(M/M) \approx 0.2\%$$

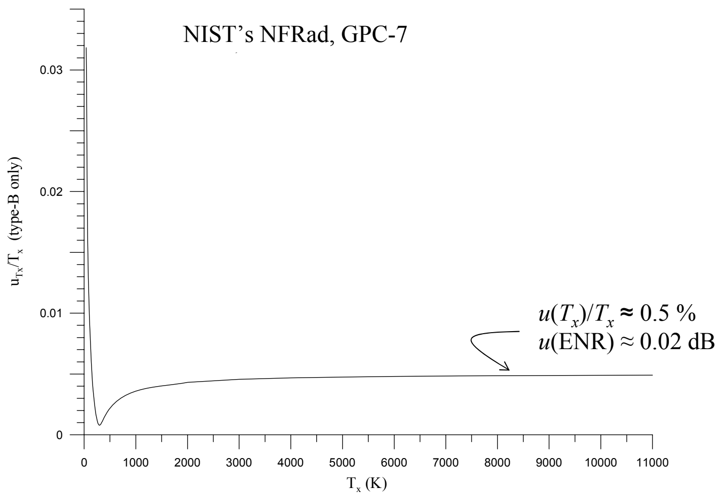
– Connectors:

$$\frac{u_{conn}(T_x)}{T_x} = u_0 \left|1 - \frac{T_a}{T_x}\right| \sqrt{f(GHz)}, \quad u_0 \approx 0.053\% \ to\ 0.069\%$$

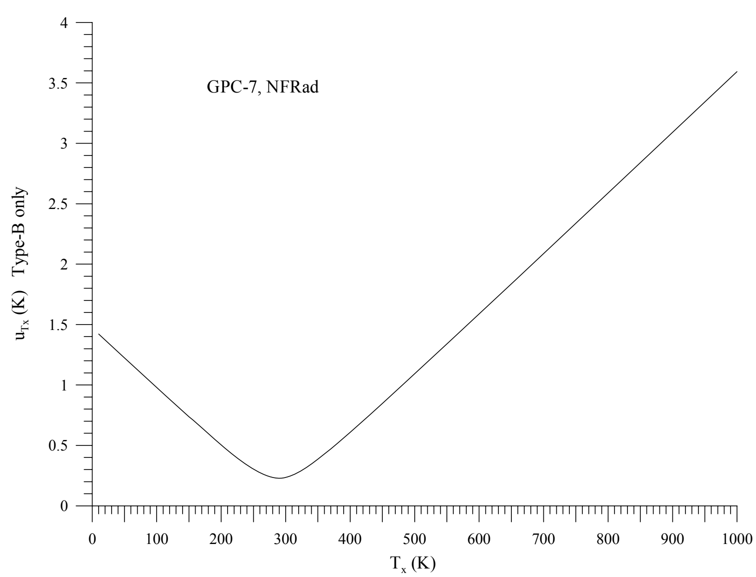
(depending on connector type)

– Other: Nonlinearity, imperfect isolation, power ratio measurement, and broadband mismatch/frequency offset all lead to small (<0.1%) uncertainties for T_x around 10 000 K (for us/NIST).

- $u_B(T)/T$ as a function of T
  Standard relative uncertainty (1σ)



- Uncertainties (Type-B)



II. AMPLIFIER & TRANSISTOR NOISE MEASUREMENTS

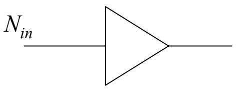
Noise Figure Defined

- Want a measure of how much noise an amplifier adds to a signal or how much it degrades the S/N ratio.
- Define Noise Figure, IEEE [19]: (at a given frequency) the ratio of total output noise power per unit bandwidth to the portion of the output noise power which is due to the input noise, evaluated for the case where the input noise power is $k_B T_0$, where T_0 = 290 K. (vacuum fluctuation comment)
- Noise figure & signal to noise ratio[20]:

$$\frac{(S/N)_{in}}{(S/N)_{out}} = \frac{S_{in}/290K}{GS_{in}/(G\times 290K + N_{amp})} = \frac{G\times 290K + N_{amp}}{G\times 290K} = F$$

- Effective input noise temperature:

S_{in} , N_{in}



$S_{out} = G\,S_{in}$

$N_{out} = GN_{in} + N_{amp} = Gk_B\boldsymbol{T_{in}} + \boldsymbol{N_{amp}}$

Define $N_{amp} \equiv Gk_BT_e$

So $N_{out} = Gk_B(T_{in} + T_e)$

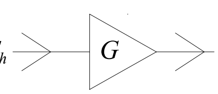
So Noise Figure becomes

$$F = \frac{Noise\ out}{G \times Noise\ in} = \frac{G(T_0 + T_e)}{GT_0} \qquad F(dB) = 10\log_{10}\left(\frac{T_0 + T_e}{T_0}\right)$$

Note: G, F, T_e all depend on Γ_{source}.

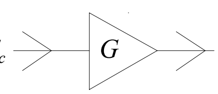
Simple Case Measurement, all Γ's equal

T_h



$N_{out,h} = Gk_B(T_h + T_e)$

T_c



$N_{out,c} = Gk_B(T_c + T_e)$

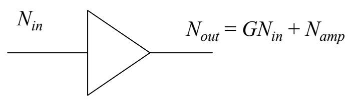
Combine & solve:

$$G = \frac{N_{out,h} - N_{out,c}}{k_B(T_h - T_c)} \qquad T_e = \frac{N_{out,c}T_h - N_{out,h}T_c}{N_{out,h} - N_{out,c}} = \frac{T_h - YT_c}{Y-1} \quad \text{where } Y = N_{out,h}/N_{out,c}$$

$$F = 1 + \frac{T_e}{T_0} = 1 + \frac{T_h - YT_c}{(Y-1)T_0}$$

Noise-Temperature Definition Revisited

- Quantum I: Equivalent black-body definition vs. "power" definition.



"Power" definition: $N = kT$,

then $N_{in} = kT_{in}$, $N_{out} = kT_{out}$, $N_{amp} = kGT_e$,

so $kT_{out} = kG(T_{in} + T_e)$

and $T_{out} = G(T_{in} + T_e)$

"Equivalent black-body temperature" definition: $N = \dfrac{hf}{e^{hf/kT} - 1}$

so $N_{out} = GN_{in} + N_{amp}$ becomes (after dividing by k)

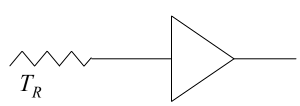
$$\frac{hf}{e^{hf/kT_{out}} - 1} = G\left(\frac{hf}{e^{hf/kT_{in}} - 1} + \frac{hf}{e^{hf/kT_e} - 1}\right).$$

Solving for T_{out} , we would get

$$T_{out} = \frac{hf}{k}\left\{\ln\left[1 + \frac{1}{G}\left(\frac{1}{\left(e^{hf/kT_{in}} - 1\right)} + \frac{1}{\left(e^{hf/kT_e} - 1\right)}\right)^{-1}\right]\right\}^{-1}$$

- Quantum II: Vacuum-fluctuation contribution
  - Continual “sea” of virtual particle-antiparticle pairs everywhere.
  - Cannot extract energy from them (from the vacuum), but they can effect physical processes; & in particular they add noise to active electronic devices [21 – 23].
  - They result in an additional effective input noise temperature of $hf/2k_B$ at the inut of an amplifier.
  - This is very small, *usually* negligible at microwave freqeuncies, T_{vac} = 0.24 K at 10 GHz, but it is there, & there are some cases where it is not negligible [24].
  - It results in a minimum possible output noise from an amplifier, $N_{out,min} = Ghf/2$.

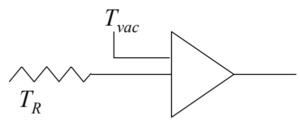
- Not yet a general agreement on how to include T_{vac} in definition of noise temperatures.
- Can include it in T_e (blame it on the amp)



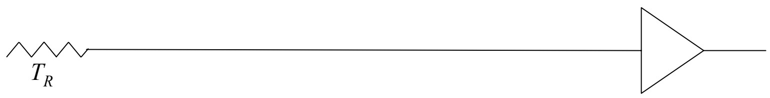
$$T_{out} = G(\underbrace{T_R + T_{vac}}_{T_{in}} + T_e) \quad \text{with } T_e' = T_{vac} + T_e$$

  or can include it in T_{in} .
- We’ll include it in T_{in} [7, 24].
- Also a question of whether to include T_{vac} as part of the source T_R (as in [7]) or as a separate input source [24].

– I prefer keeping it as a separate input [24].



– One reason: case of large separation distance (especially in remote sensing, for example)

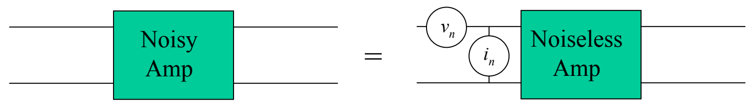


– Note: get same/consistent results, independent of which way you group things.

Noise Parameters, IEEE Representation

- Simple case was $T_e = \dfrac{T_h - YT_c}{Y-1}$, $Y = \dfrac{N_{out,h}}{N_{out,c}}$
- But that's just for one value of Γ_{source}. Want to determine F or T_e for any Γ_{source}. So parameterize dependence on Γ_{source}.
- Several parameterizations in use; most common are variants of the IEEE [25] form.

- Equivalent circuit:



- (Noise out)/(Noise in) depends on impedance of input termination, $NF = NF(Z_S)$ or $NF(\Gamma_S)$, & $T_e = T_e(Z_S$ or $\Gamma_S)$,

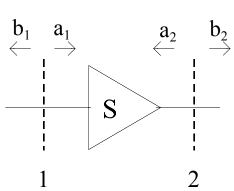
$$NF = NF_{\min} + \frac{4R_n}{Z_0} \frac{|\Gamma_{opt} - \Gamma_S|^2}{|1+\Gamma_{opt}|^2 (1-|\Gamma_S|^2)} \qquad T_e = T_{e,\min} + t \frac{|\Gamma_{opt} - \Gamma_S|^2}{|1+\Gamma_{opt}|^2 (1-|\Gamma_S|^2)}$$

4 parameters: $T_{e,min}$, $t = 4R_nT_0/Z_0$, and complex Γ_{opt} .

Note: many equivalent forms of IEEE representation; this one is from [26].

Wave Representation of Noise Matrix

- For microwave radiometry, wave representation [26 – 31] provides more flexibility.
- Linear 2-port:



$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} + \begin{pmatrix} \hat{b}_1 \\ \hat{b}_2 \end{pmatrix}$$

- Noise correlation matrix is defined by

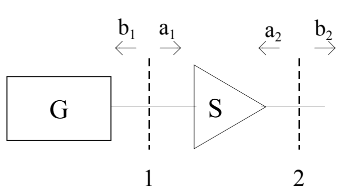
$$N_{ij} = \langle b_i b_j^* \rangle$$

or $\hat{N}_{ij} = \langle \hat{b}_i \hat{b}_j^* \rangle$ for intrinsic noise matrix

- Four real noise parameters:

$$\langle |\hat{b}_1|^2 \rangle, \langle |\hat{b}_2|^2 \rangle, \langle \hat{b}_1 \hat{b}_2^* \rangle$$

- Output noise temperature T_2



$$k_B T_2 = \frac{|S_{21}|^2}{\left(1 - |\Gamma_{GS}|^2\right)} \left[N_G + N_1 + N_2 + N_{12}\right]$$

$$N_G = \frac{\left(1 - |\Gamma_G|^2\right)}{|1 - \Gamma_G S_{11}|^2} k_B T_G$$

$$N_1 = \left| \frac{\Gamma_G}{1 - \Gamma_G S_{11}} \right|^2 \langle |\hat{b}_1|^2 \rangle$$

$$N_2 = \langle |\hat{b}_2 / S_{21}|^2 \rangle$$

$$N_{12} = 2 \operatorname{Re}\left[\frac{\Gamma_G}{(1 - \Gamma_G S_{11})} \langle \hat{b}_1 (\hat{b}_2 / S_{21})^* \rangle \right]$$

- So for T_e we have

$$T_e = \frac{|\Gamma_G|^2}{(1-|\Gamma_G|^2)} X_1 + \frac{|1-\Gamma_G S_{11}|^2}{(1-|\Gamma_G|^2)} X_2 + \frac{2}{(1-|\Gamma_G|^2)} \mathrm{Re}\left[(1-\Gamma_G S_{11})^* \Gamma_G X_{12}\right]$$

where $k_B X_1 \equiv \left\langle |\hat{b}_1|^2 \right\rangle$, $k_B X_2 \equiv \left\langle |\hat{b}_2 / S_{21}|^2 \right\rangle$, $k_B X_{12} \equiv \left\langle \hat{b}_1 (\hat{b}_2 / S_{21})^* \right\rangle$

- Whereas IEEE parameterization is

$$T_e = T_{e,\min} + t \frac{|\Gamma_G - \Gamma_{opt}|^2}{\left(1-|\Gamma_G|^2\right)|1+\Gamma_{opt}|^2}$$

- Can relate the two:

X's → IEEE

$$t = X_1 + |1+S_{11}|^2 X_2 - 2\,\mathrm{Re}\left[(1+S_{11})^* X_{12}\right],$$

$$T_{e,\min} = \frac{X_2 - |\Gamma_{opt}|^2 \left[X_1 + |S_{11}|^2 X_2 - 2\,\mathrm{Re}\left(S_{11}^* X_{12}\right)\right]}{\left(1+|\Gamma_{opt}|^2\right)},$$

$$\Gamma_{opt} = \frac{\eta}{2}\left(1 - \sqrt{1 - \frac{4}{|\eta|^2}}\right),$$

$$\eta = \frac{X_2\left(1+|S_{11}|^2\right) + X_1 - 2\,\mathrm{Re}\left(S_{11}^* X_{12}\right)}{(X_2 S_{11} - X_{12})}.$$

IEEE → X's

$$X_1 = T_{e,\min}\left(|S_{11}|^2 - 1\right) + \frac{t|1 - S_{11}\Gamma_{opt}|^2}{|1+\Gamma_{opt}|^2},$$

$$X_2 = T_{e,\min} + \frac{t|\Gamma_{opt}|^2}{|1+\Gamma_{opt}|^2},$$

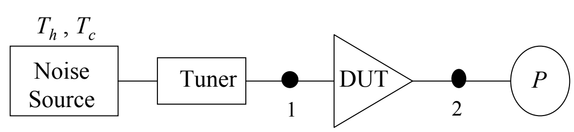
$$X_{12} = S_{11} T_{e,\min} - \frac{t\Gamma_{opt}^*\left(1 - S_{11}\Gamma_{opt}\right)}{|1+\Gamma_{opt}|^2}.$$

Notes:
$X_2 = T_{e,0}$
Bound implied by $X_1 \geq 0$

Measuring Noise Parameters

- Many different methods [26, 28, 30, 32 – 43]. Most are based on IEEE parameterization.
- Basic idea of (almost) all methods is
  - present amplifier (or device) with a variety of different known input terminations (Γ & T),
  - have an equation for the "output" in terms of the noise parameters and known quantities (Γ's, T's, S-parameters),
  - determine noise parameters by a fit to the measured output.
  - Need good distrib. of Γ's in complex plane.

- Can fit for noise figure [32]

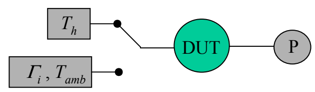


$$NF = NF_{\min} + \frac{4R_n}{Z_0} \frac{\left|\Gamma_{opt} - \Gamma_1\right|^2}{\left|1 + \Gamma_{opt}\right|^2 \left(1 - \left|\Gamma_1\right|^2\right)}$$

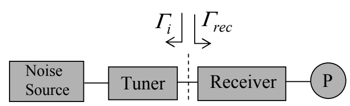
Notes:

- Use tuner to get different Γ_1, measure with T_h and T_c for each Γ_1 to get NF for that Γ_1.
- Must correct for tuner to get T_{in} at 1. Must calibrate receiver for each value of Γ_2 (or have isolator in front of receiver).

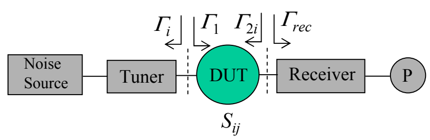
- Or can fit for output power [33, 44, 45]. This is the most popular method now.



In practice, first measure noise parameters of receiver,

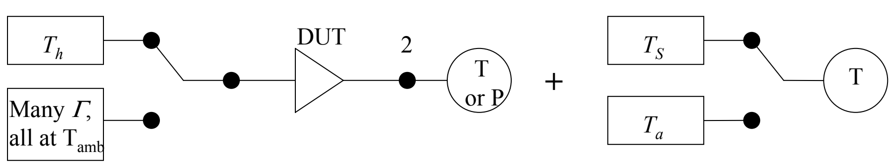


Then measure DUT + receiver



and extract DUT noise parameters.

- Noise-matrix approach [30, 31, 40, 46] to measuring noise parameters:



$$k_B T_2 = \frac{|S_{21}|^2}{\left(1-|\Gamma_{GS}|^2\right)}\left[N_G + N_1 + N_2 + N_{12}\right]$$

$$\Gamma_{GS} = S_{22} + \frac{\Gamma_G S_{12} S_{21}}{(1-\Gamma_G S_{11})}$$

$$N_G = \frac{\left(1-|\Gamma_G|^2\right)}{|1-\Gamma_G S_{11}|^2} k_B T_G$$

$$N_1 = \left|\frac{\Gamma_G}{1-\Gamma_G S_{11}}\right|^2 k_B X_1$$

$$N_2 = k_B X_2$$

$$N_{12} = 2\,\mathrm{Re}\left[\frac{\Gamma_G}{(1-\Gamma_G S_{11})} k_B X_{12}\right]$$

- Noise-Parameter Uncertainties
  - Monte Carlo method is probably the most practical [35, 46 – 49]
  - Some general approximate features [46]:
    - Uncerts in G and $T_{\min}$ (& $F_{\min}$) are dominated by uncert in T_{h}. 0.1 dB uncert in $T_h \to \sim$ 0.1 dB uncert in G and $F_{\min}$.
    - Uncerts in Γ_{opt} are dominated by uncerts in Γ_G's. Uncert in Re or Im Γ_{opt} is ~ 3 or 4× uncert in Re or Im Γ_G (for 13 terminations).
    - t (or R_n) is sensitive to just about everything.
    - T_{amb} is not a major factor, because it is known much better than T_h. Note, however, that it could affect T_h or the amplifier properties.

Measuring Noise Parameters on Wafer

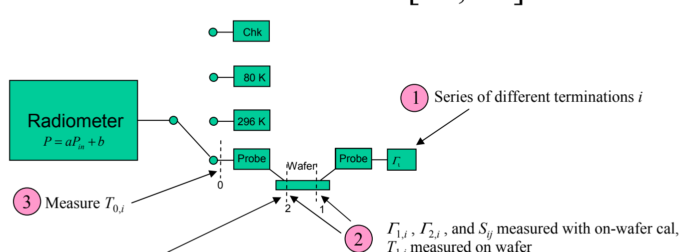
- Just like amplifier noise parameters—only harder.
- Harder due to probes and to device properties.
- Complications due to Probes:
  - Must characterize probes: on-wafer standards ⇒ larger uncertainties for Γ's, S-parameters, T_{in}, T_{out}.
  - Restricted range of Γ's (due to loss in probe).
  - Potential contact problems, vibrations.

- Complications due to Device:
  - If measuring an on-wafer amplifier, no additional device-related problems (assuming it's well matched).

  But for a transistor:

  - Matching problems, large S_{11}, S_{22} $\Rightarrow$ larger corrections & therefore larger uncertainties.
  - Large Γ_{opt}, near edge of Smith chart.
  - Smaller noise figures/noise temps than amps.

•Procedure used at NIST [50, 51]:



4 Compute $T_{2,i}$: $T_0 = \alpha_{02} T_2 + (1-\alpha_{02}) T_{amb}$ so $T_{2,i} = \dfrac{T_{0,i} - (1-\alpha_{02,i}) T_{amb}}{\alpha_{02,i}}$

where $\alpha_{02.i} \equiv \dfrac{P_0^{avail}}{P_2^{avail}} = \dfrac{|S_{21}(02)|^2 \left(1 - |\Gamma_{2,i}|^2\right)}{|1 - \Gamma_{2,i} S_{11}(02)|^2 \left(1 - |\Gamma_{0,i}|^2\right)}$

5 Measure $T_{rev} = \mathrm{T}_1$ in reverse configuration

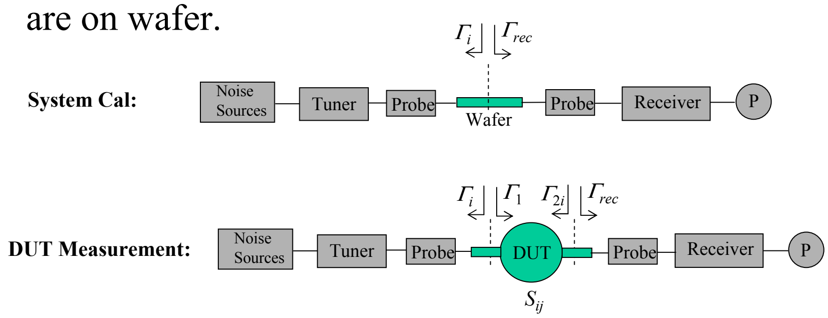
6 (Weighted) Fit to

$$T_{2,i} = \frac{|S_{21}|^2}{\left(1 - |\Gamma_{2,i}|^2\right)} \left\{ \frac{\left(1 - |\Gamma_{1,i}|^2\right)}{|1 - \Gamma_{1,i} S_{11}|^2} T_{1,i} + \left| \frac{\Gamma_{1,i}}{1 - \Gamma_{1,i} S_{11}} \right|^2 X_1 + X_2 + 2\,\mathrm{Re}\left[\frac{\Gamma_{1,i} X_{12}}{1 - \Gamma_{1,i} S_{11}} \right] \right\}$$

and

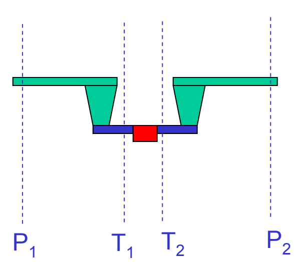
$$T_1(rev.config) = \frac{1}{\left(1 - |\Gamma_1|^2\right)} \left\{ \frac{|S_{12}|^2 \left(1 - |\Gamma_{2,L}|^2\right)}{|1 - \Gamma_{2,L} S_{22}|^2} T_{2,L} + \left| \frac{S_{12} S_{21} \Gamma_{2,L}}{1 - \Gamma_{2,L} S_{22}} \right|^2 X_2 + X_1 + 2\,\mathrm{Re}\left[\frac{S_{12} S_{21} \Gamma_{2,L} X_{12}{}^*}{1 - \Gamma_{2,L} S_{22}} \right] \right\}$$

- Commercial Systems [e.g., 44, 45]: similar to general noise parameters (above), except that reference planes are on wafer.

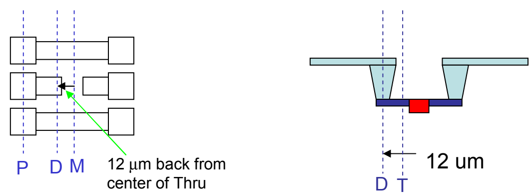


- Must therefore calibrate at those reference planes on wafer. Commonly done at probe tip, with an "off-wafer" cal set.

- To get properties of device itself, must remove effects of lines between the calibration reference planes (P_1 and P_2) and the device reference planes (T_1 and T_2). To do so, measure auxiliary standards (short, open) between planes T_1 and T_2, and "deembed" [52].



- NIST on-wafer calibration (Statistical) calibrates at center of through (M) and translates back (to D). Would still need to “deembed” to get down to T.



Noise-Parameter Checks and Verification

- So how do we convince ourselves that our noise-parameter measurement results might be correct?
- Will give three tests:
  - measure noise parameters of passive device, such as attenuator
  - measure T_{rev}
  - Cascade test

Attenuator Test

- Noise matrix of a passive device (such as an attenuator) is given by Bosma's theorem,

$$\left\langle \hat{b}_i \hat{b}_j^* \right\rangle = kT\left(\mathbf{1} - \mathbf{SS}^+\right)_{ij}$$

- So for an attenuator at (noise) temperature T_a,

$$X_1 = \left(1 - |S_{11}|^2 - |S_{12}|^2\right)T_a$$

$$X_2 = \frac{\left(1 - |S_{22}|^2 - |S_{21}|^2\right)}{|S_{21}|^2}T_a$$

$$X_{12} = -\frac{\left(S_{21}^* S_{11} + S_{12} S_{22}^*\right)}{S_{21}^*}T_a$$

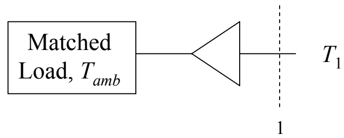
- So, measure noise parameters of an attenuator & see if you get the correct answers.

- Other passive devices as tests (especially on a wafer):
  - Cold FET [53]
  - Lange Coupler [54]

  These have the advantage of being poorly matched, & therefore more similar to the devices of interest.

T_{rev} Test [36, 40, 55]

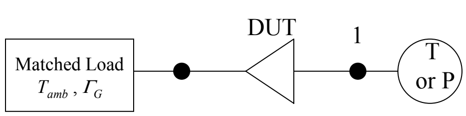
- T_{rev} test: Measure noise temp from input of amplifier, when output is terminated in a matched load.



- Can show that for $\Gamma_L S_{21} S_{12}$ small,

$$T_{rev} \approx \frac{X_1}{\left(1-|\Gamma_1|^2\right)}$$

- Full form is:



$$T_1 = \frac{1}{\left(1-|\Gamma_1|\right)}\left[N_G + N_1 + N_2 + N_{12}\right]$$

$$\Gamma_1 = S_{11} + \frac{\Gamma_G S_{12} S_{21}}{(1-\Gamma_G S_{22})}$$

$$N_G = \frac{|S_{12}|^2\left(1-|\Gamma_G|^2\right)}{|1-\Gamma_G S_{22}|^2} k_B T_{amb}$$

$$N_1 = k_B X_1$$

$$N_2 = \left|\frac{S_{12} S_{21} \Gamma_G}{1-\Gamma_G S_{22}}\right|^2 k_B X_2$$

$$N_{12} = 2\,\mathrm{Re}\left[\frac{S_{12} S_{21} \Gamma_G}{(1-\Gamma_G S_{22})} k_B X_{12}^*\right]$$

- So measure T_{rev}, compare to value predicted from the value of X_1 from the noise-parameter determination.
- If working in terms of IEEE parameters, convert, using

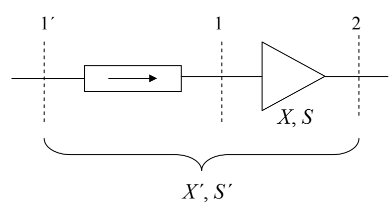
$$X_1 = T_{e,\min}\left(|S_{11}|^2 - 1\right) + \frac{t\left|1 - S_{11}\Gamma_{opt}\right|^2}{\left|1+\Gamma_{opt}\right|^2},$$

$$X_2 = T_{e,\min} + \frac{t\left|\Gamma_{opt}\right|^2}{\left|1+\Gamma_{opt}\right|^2},$$

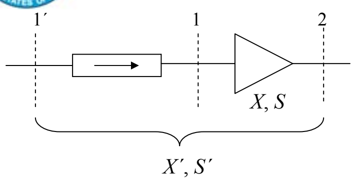
$$X_{12} = S_{11}T_{e,\min} - \frac{t\Gamma_{opt}^*\left(1 - S_{11}\Gamma_{opt}\right)}{\left|1+\Gamma_{opt}\right|^2}.$$

Cascade Test [55]

- Connect an isolator (or other passive 2-port) to amplifier input & measure noise parameters of combination.



- X' parameters can be written in terms of X parameters (amp alone) and the S-parameters of amp and isolator.
- Using Bosma's theorem and standard S-parameter algebra, can show



$$X_1' = \left|\frac{S^I_{12}}{1 - S_{11}S^I_{22}}\right|^2 X_1 + T_I(A_1 - A_2),$$

$$A_1 = \left\{\left(1 - |S^I_{11}|^2 - |S^I_{12}|^2\right) + \left|\frac{S_{11}S^I_{12}}{1 - S_{11}S^I_{22}}\right|^2 \left(1 - |S^I_{21}|^2 - |S^I_{22}|^2\right)\right\},$$

$$A_2 = 2\,\mathrm{Re}\left[\frac{S^I_{12}S_{11}}{(1 - S_{11}S^I_{22})}\left(S^I_{21}S^{I*}_{11} + S^{I*}_{12}S^I_{22}\right)\right],$$

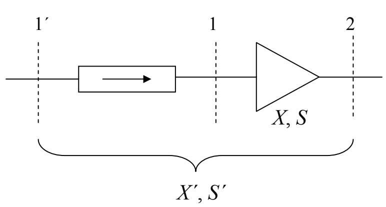
$$X_2' = \frac{1}{|S^I_{21}|^2}\left\{|1 - S_{11}S^I_{22}|^2 X_2 + |S^I_{22}|^2 X_1 + 2\,\mathrm{Re}\left[S^I_{22}(1 - S_{11}S^I_{22})^* X_{12}\right] + T_I\left(1 - |S^I_{22}|^2 - |S^I_{21}|^2\right)\right\},$$

$$X_{12}' = \frac{S^I_{12}(1 - S_{11}S^I_{22})^*}{S^{I*}_{21}(1 - S_{11}S^I_{22})} X_{12} + \frac{S^I_{12}S^{I*}_{22}}{S^{I*}_{21}(1 - S_{11}S^I_{22})} X_1 - T_I A_3,$$

$$A_3 = \left[\left(\frac{S^{I*}_{21}S^I_{11} + S^I_{12}S^{I*}_{22}}{S^{I*}_{21}}\right) - \frac{S^I_{12}S_{11}}{S^{I*}_{21}(1 - S_{11}S^I_{22})}\left(1 - |S^I_{22}|^2 - |S^I_{21}|^2\right)\right],$$

Note: could instead use an attenuator (for on wafer).

- Approximate expressions (for isolator case):



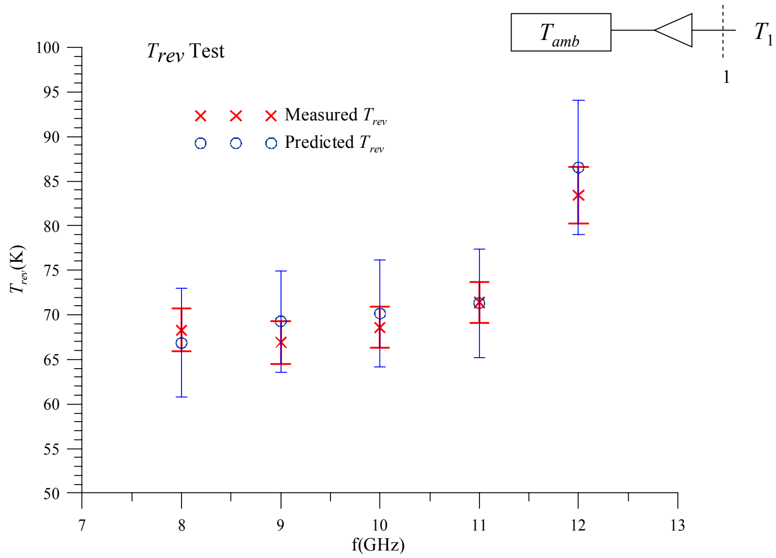
$$X_1' \approx T_I,$$

$$X_2' \approx \frac{\left(X_2 + T_I\left(1 - |S^I_{21}|^2\right)\right)}{|S^I_{21}|^2},$$

$$X_{12}' \approx \frac{S^I_{12}}{S^{I*}_{21}} X_{12} - T_I S^I_{11},$$

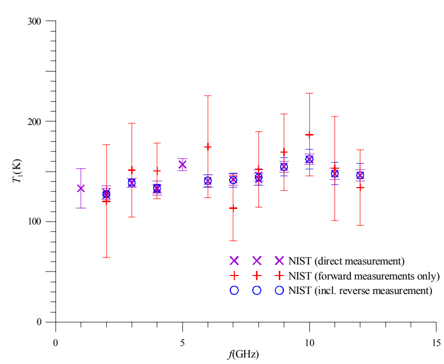
X_{12}' is small and (approximately) independent of amplifier; excellent verification test.

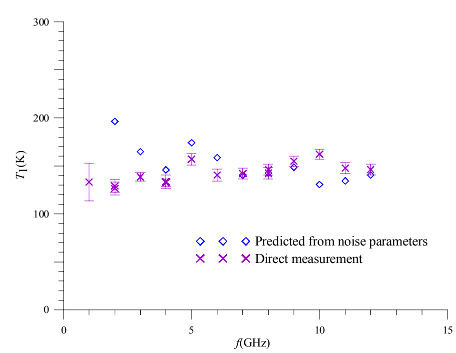
Samples of Test Results [55]



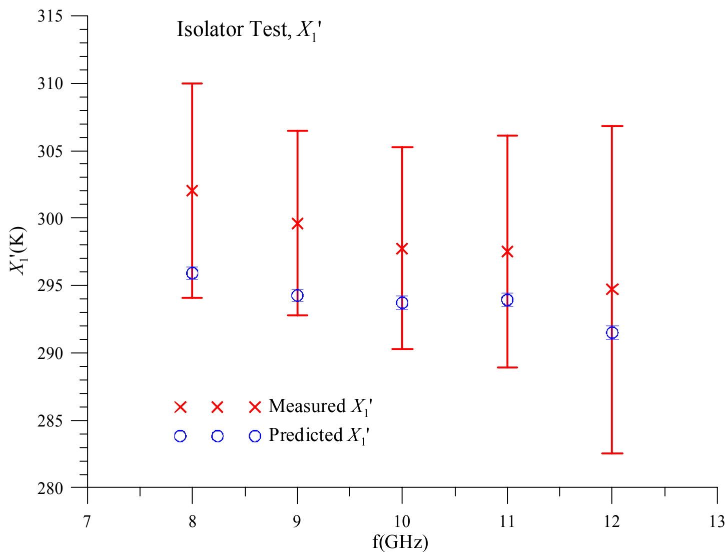
Error bars are standard uncertainties (1σ).

T_{rev} test on wafer [56]

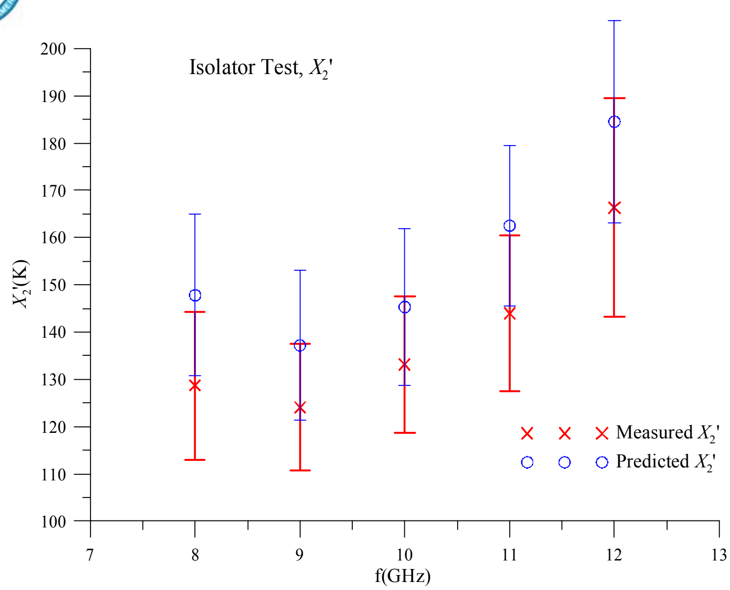




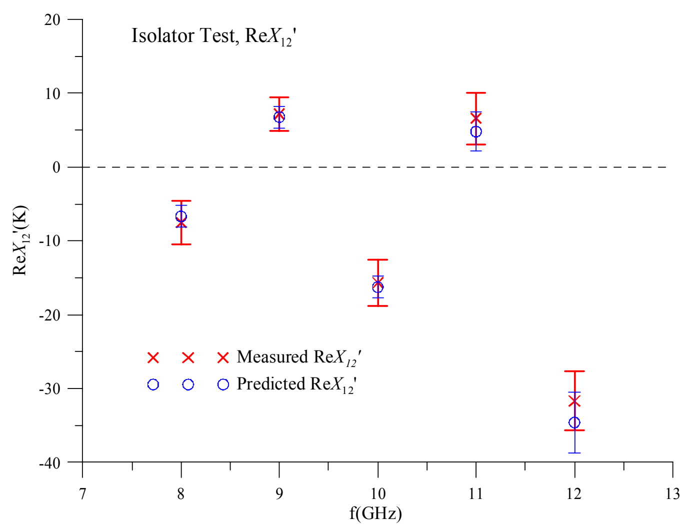
Error bars are standard uncertainties (1σ).



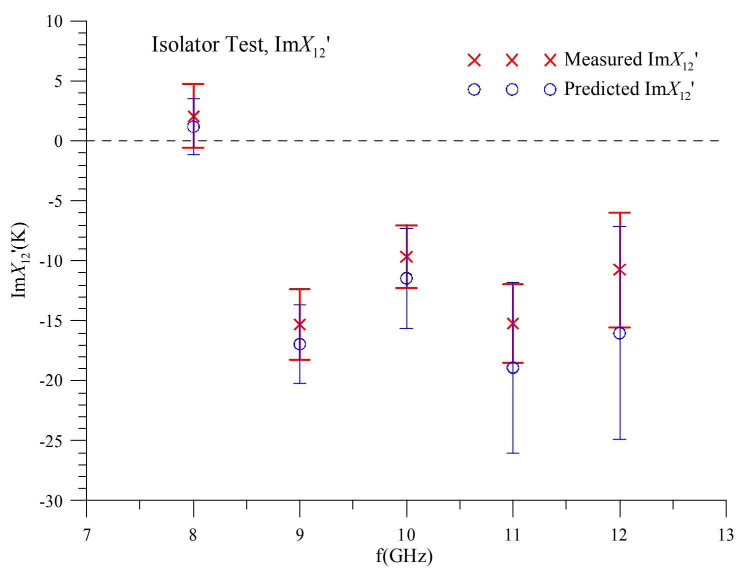
Error bars are standard uncertainties (1σ).



Error bars are standard uncertainties (1σ).



Error bars are standard uncertainties (1σ).



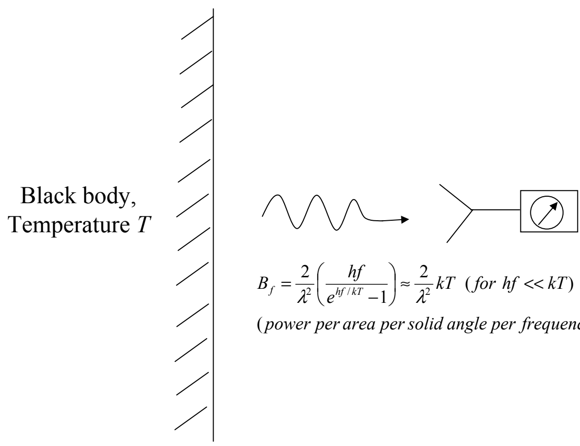
Error bars are standard uncertainties (1σ).

III. REMOTE-SENSING RADIOMETRY: MICROWAVE BRIGHTNESS-TEMPERATURE STANDARDS

Background

- NIST microwave radiometry effort
  - Noise & antenna metrology have been conducted separately for over 30 years
  - Recently began doing remote-sensing radiometry, combining the two
- NIST Optical Tech. Div. has such a program for UV, Visible, & IR [57]
- Need to develop analogous capabilities at microwave & mm-wave frequencies, providing a link between microwave remote-sensing measurements & NIST measurements & standards

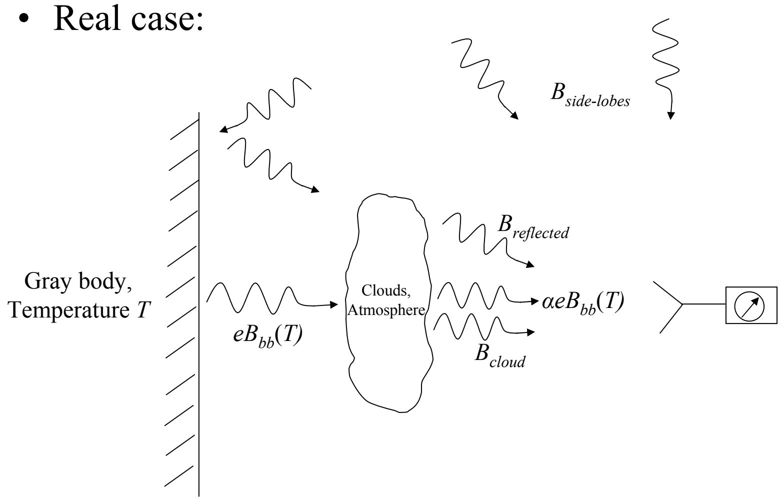
- Microwave remote sensing, ideal case:



$$B_f = \frac{2}{\lambda^2}\left(\frac{hf}{e^{hf/kT}-1}\right) \approx \frac{2}{\lambda^2}kT \quad (for\ hf << kT)$$

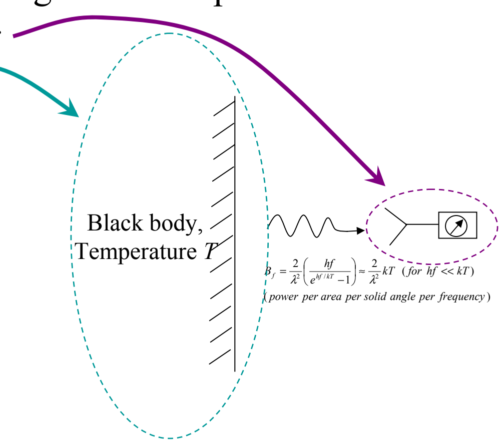
(*power per area per solid angle per frequency*)

- Real case:



- Calibration
  - linear radiometers ⇒ need (≥) two standards for calibration
  - need independent cal of targets, comparison to other radiometers, traceability
- Develop (& transfer) a standard for microwave brightness temperature
- Still in early stages, but some progress made

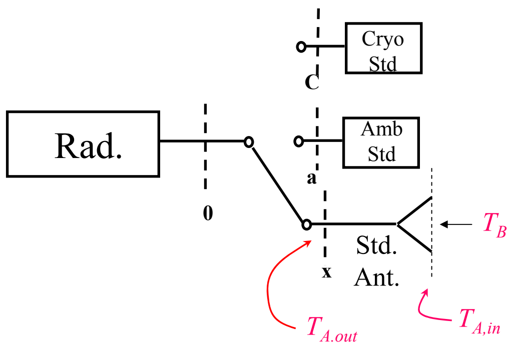
- Two approaches to brightness-temperature standard:
  - Standard radiometer
  - Standard target



- We have worked on both approaches.

Standard Radiometer [58 – 60]

- Radiometer measures $T_{A,out}$; want to determine T_B (assume far field conditions)



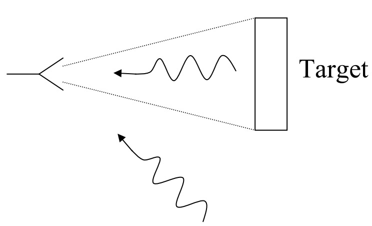
$$T_{A,out} = \alpha T_{A,in} + (1-\alpha) T_a$$

$$T_B(\theta,\phi) \equiv \frac{\lambda^2 B_f(\theta,\phi)}{2k}$$

$$T_{A,in} = \frac{\int_{4\pi} T_B(\theta,\phi) F_n(\theta,\phi) d\Omega}{\Omega_p}$$

$$\Omega_p = \int_{4\pi} F_n(\theta,\phi) d\Omega$$

- Break up $T_{A,in}$:



$$\overline{T_T} = \frac{\int_{\text{target}} T_B(\theta,\phi) F_n(\theta,\phi) d\Omega}{\int_{\text{target}} F_n(\theta,\phi) d\Omega}$$

$$\overline{T_{BG}} = \frac{\int_{\text{other}} T_B(\theta,\phi) F_n(\theta,\phi) d\Omega}{\int_{\text{other}} F_n(\theta,\phi) d\Omega} .$$

$$\eta_{AT} \equiv \frac{\int_{\text{target}} F_n(\theta,\phi) d\Omega}{\Omega_p}$$

$$T_{A,in} = \eta_{AT} \overline{T_T} + (1-\eta_{AT}) \overline{T_{BG}}$$

- So,

$$T_{A,out} = \alpha\eta_{AT}\overline{T}_T + \alpha(1-\eta_{AT})\overline{T}_{BG} + (1-\alpha)T_a$$

- Control the background, $\overline{T}_{BG} = T_a$
- Then

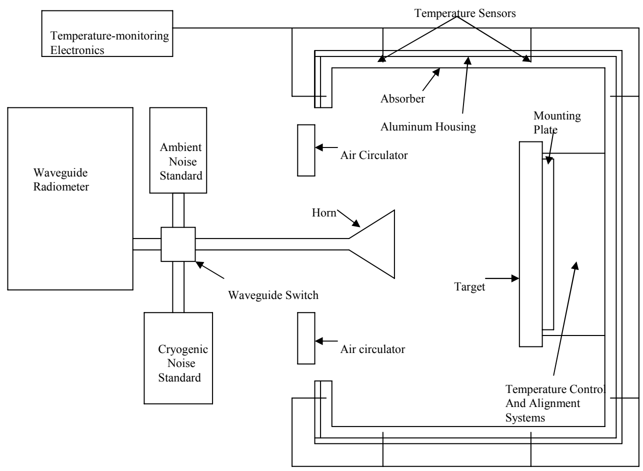
$$\overline{T}_T = T_a + \frac{1}{\alpha\eta_{AT}}\left(T_{A,out} - T_a\right)$$

- So we need $\alpha \approx 1/L$ and η_{AT}

$$\eta_{AT} \equiv \frac{\int_{\text{target}} F_n(\theta,\phi)d\Omega}{\Omega_p}$$

- Environment
  - not thermal-vac
  - must control $\overline{T}_{SL} = \frac{\int_{other} T_B(\theta,\phi)F_n(\theta,\phi)d\Omega}{\int_{other} F_n(\theta,\phi)d\Omega}$.
  - Do so by controlling/knowing T_B in the side lobes.

- Will need a chamber to control background



- Approximate achievable uncertainties:

$$u^2(\overline{T}_T) = \left(1 - \frac{1}{\alpha\eta_{AT}}\right)^2 u^2(T_a) + \left(\frac{1}{\alpha\eta_{AT}}\right)^2 u^2(T_{A,out}) + (\overline{T}_T - T_a)^2 \left(\frac{u^2(\eta_{AT})}{\eta_{AT}^2} + \frac{u^2(\alpha)}{\alpha^2}\right)$$

$u(T_a) \approx 0.2$ K
$u(T_{A,out}) \approx 0.3 - 0.5$ K (for $T_{A,out}$ = 200 to 300 K, 18 – 26.5 GHz)
$u(\eta_{AT}) \approx 0.003$
$u(\alpha) \approx 0.005$

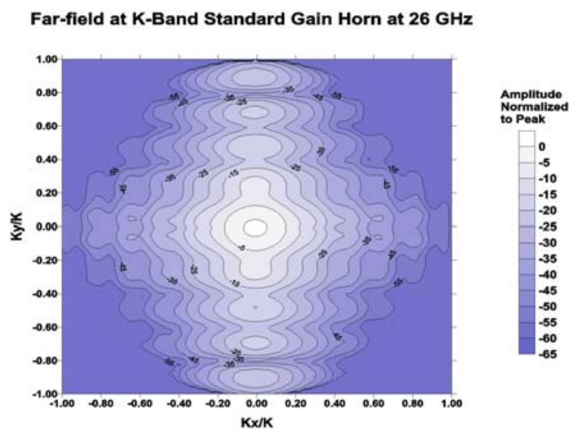
- So should be able to get

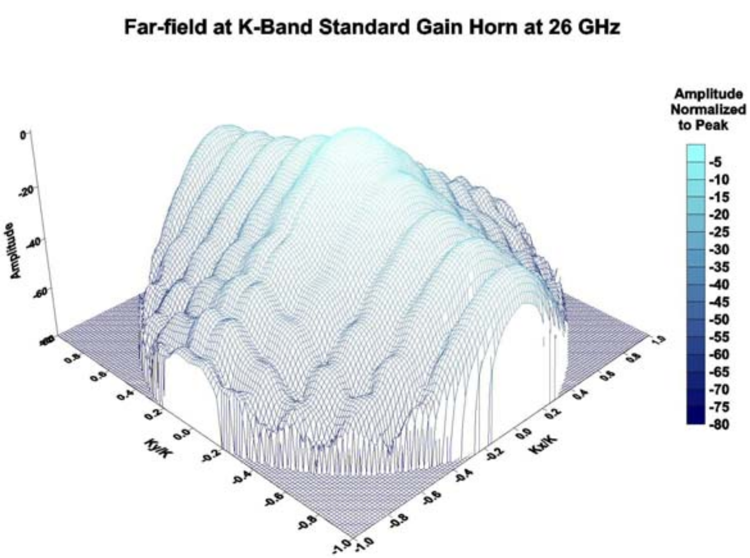
$u(\overline{T}_T) \approx 0.3$ K to 0.7 K

for $T_{A,out}$ = 200 to 300 K, 18 – 26.5 GHz

Demonstration Measurements

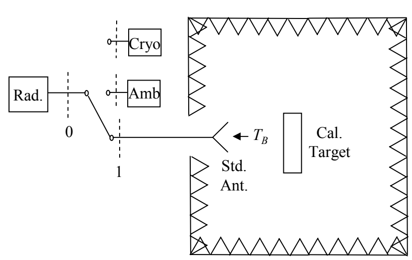
- Measured antenna pattern for a standard-gain horn (SGH) on the near-field range

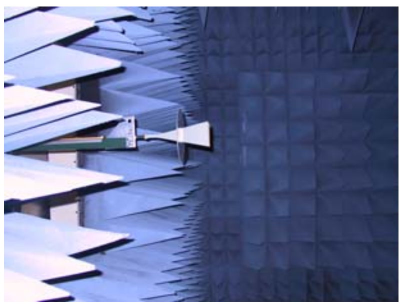


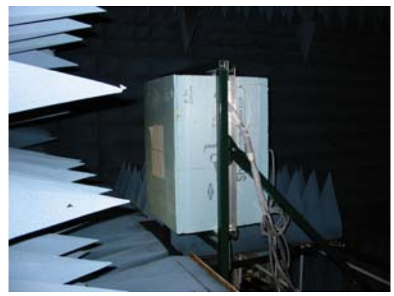


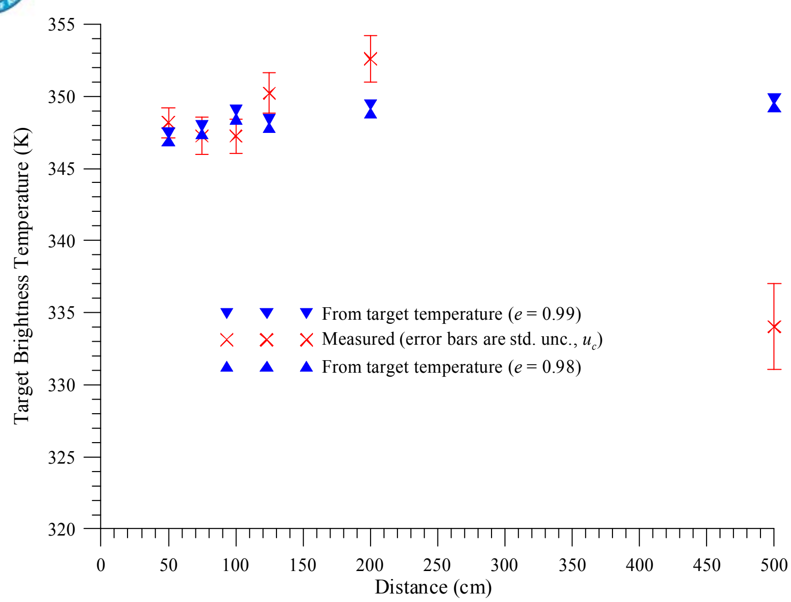
- Integrate pattern to get η_{AT}; value depends on frequency & distance. At 26 GHz, η_{AT} = 0.980 at 50 cm, η_{AT} = 0.301 at 5 m
- Compute α from conductivity. $\alpha = 0.9954 \pm 0.0023$ at 26 GHz
- Connected SGH to the DUT plane of the WR-42 (18 – 26.5 GHz) waveguide radiometer

- Borrowed hot calibration targets from NOAA GSR (Al Gasiewski & Marian Klein, NOAA ETL) and NASA Goddard (Paul Racette)
- Measured it in the NIST anechoic chamber at 18, 22, & 26 GHz for several distances

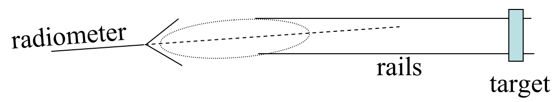




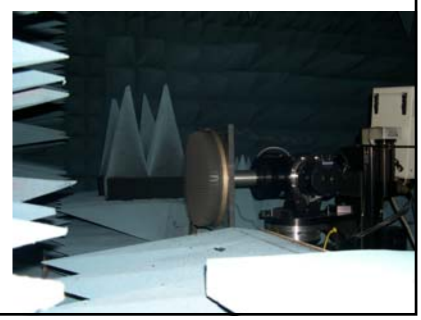



Target Brightness Temperature (K)
355
350
345
340
335
330
325
320
0
50
100
150
200
250
300
350
400
450
500
Distance (cm)
From target temperature (e = 0.99)
Measured (error bars are std. unc., u_c)
From target temperature (e = 0.98)

- 5 m results discrepancy probably just due to (mis)alignment



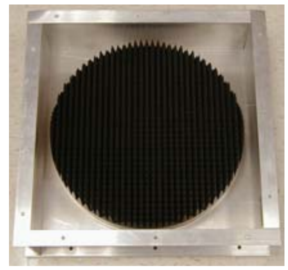
- Uncertainty large due to large $u(\eta_{AT}) = 0.0153$. Would be $u(\eta_{AT}) \approx 0.003$ if we knew target location better.



- Summary (standard radiometer)
  - Have developed framework and performed preliminary measurements
  - Expect uncertainties of about 0.5 – 0.7 K for T_B = 200 to 300 K, f = 18 – 26 GHz (Larger uncerts for higher/lower temperatures and/or higher frequencies)
  - Connection to thermal-vac testing must still be established.

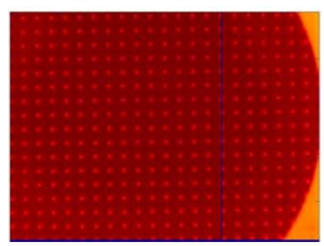
Standard Target & Hybrid Standard

- Most microwave remote sensing programs use a standard target, a blackbody radiator.

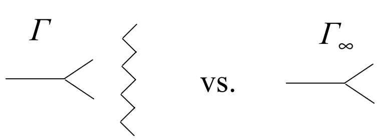


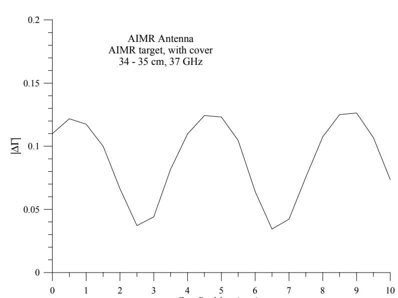
- Need to know
  - surface temperature and uniformity (thermometers embedded at a few locations in *back* of target)
  - emissivity (no generally accepted standard measurement method)
  - pattern (or near-field effects)

- Surface temperature & uniformity can be measured by IR imaging. [61]



- Reflectivity of target can have significant effect (a few kelvins) for small separation distance. [62]





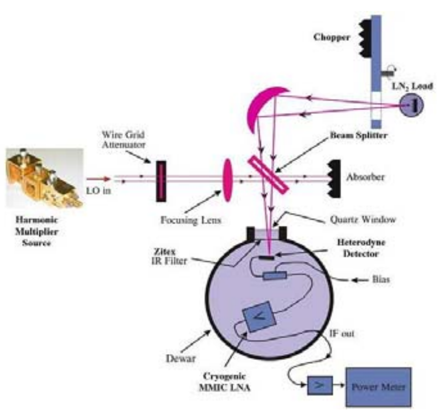
- Have also investigated
  - Material properties measurements [63]
  - Antenna near-field effect (preliminary) [64]
- Suggest a “hybrid” standard, which would consist of a standard radiometer + a standard target. [60]
  - Would reduce uncertainties somewhat
  - Greater flexibility
  - More robust (and credible).

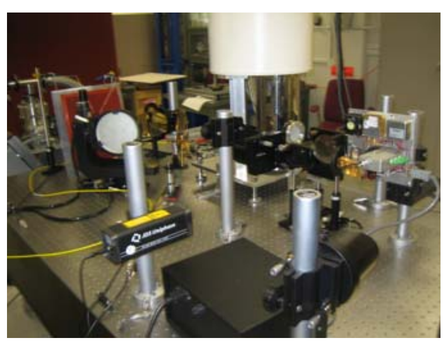
IV. TERAHERTZ NOISE

Approach

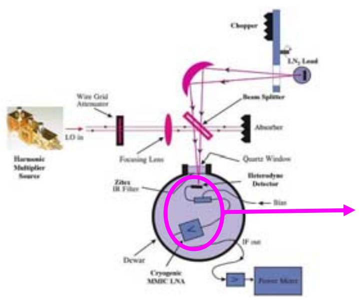
- Unlike the microwave case, we do not have a history of noise measurements at terahertz frequencies. Need both a standard and a detector/receiver.
- The NIST Terahertz Technology Project has developed a terahertz receiver built around a hot electron bolometer (HEB) mixer, which they use in an imaging system. [65]
- So, use or copy that receiver, and develop a terahertz noise standard.

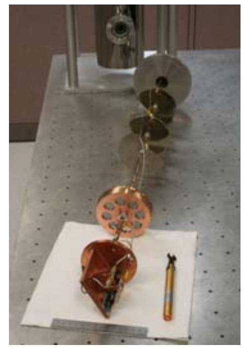
Full System [66]

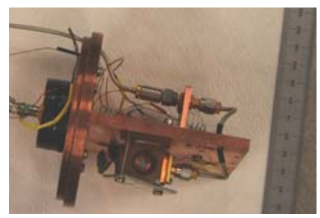




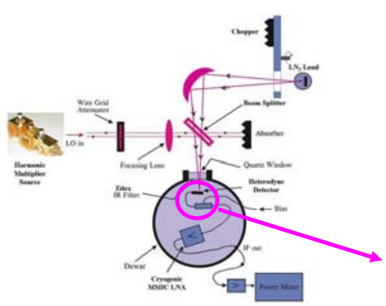
Inside the Cryocooler

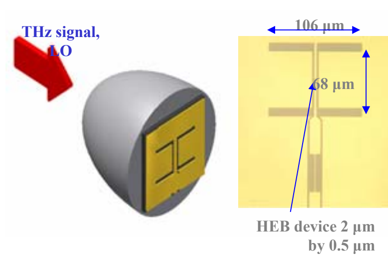




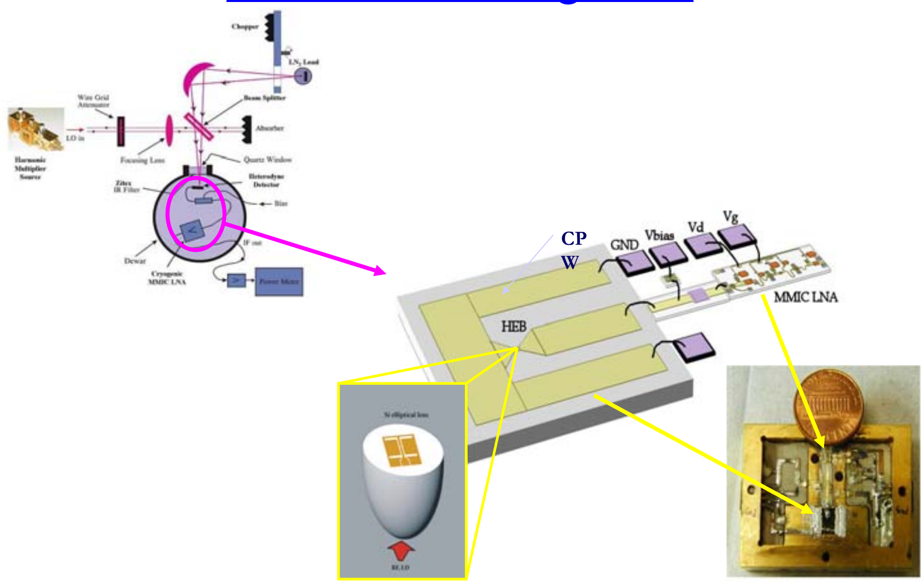


Adapter & Detector



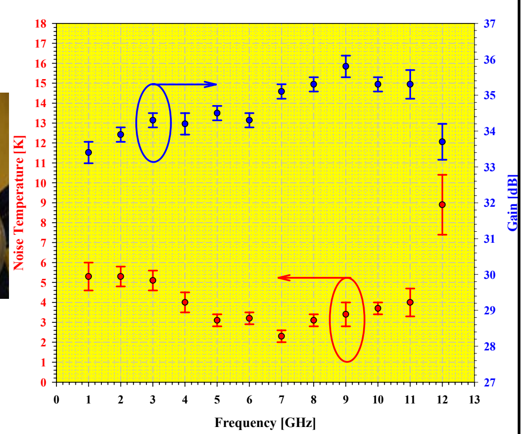


Mixer Block Integration

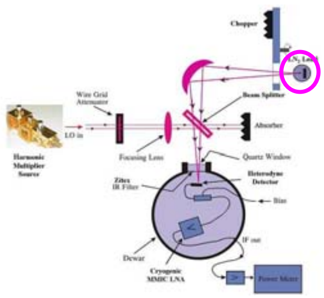


LNA Performance [24]

Developed by Dr. Sander Weinreb's group at JPL/Caltech



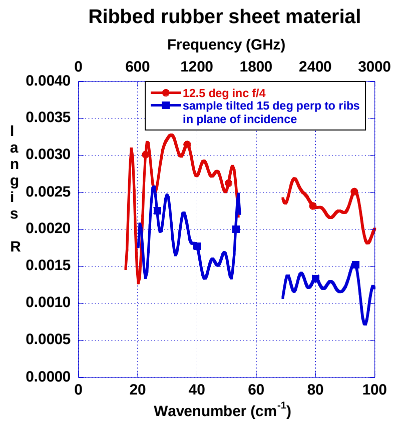
Variable-Temperature Standard



- Hot circulating oil, ~ 23 ˚C – 240 ˚C
- Surface will be instrumented with thermistors surrounding image area.
- NIST Physics Lab will measure the total reflectance (= 1 – emissivity)

NIST NOISE

- Initial measurements, specular reflectance (by L. Hanssen & S. Kaplan, NIST Physics Lab):



NIST NOISE

V. STATUS & PLANS

- Noise-temperature measurements & calibrations continue: 30 & 60 MHz, 1 – 65 GHz.
- Working to improve & verify noise-parameter measurements for LNAs and for transistors on wafers.
- Microwave remote-sensing radiometer-calibration effort has been suspended. If funding becomes available, we will proceed with the standard-radiometer development, and possible the hybrid standard work.
- The terahertz noise work is proceeding. We expect to make the first measurements later this year.

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(+1) 303-497-3150

NIST Noise publications & slides from talks: links at
http://boulder.nist.gov/div818/81801/Noise/index.html

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