Low Noise InP HFET Receivers

NRAO Experience

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Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

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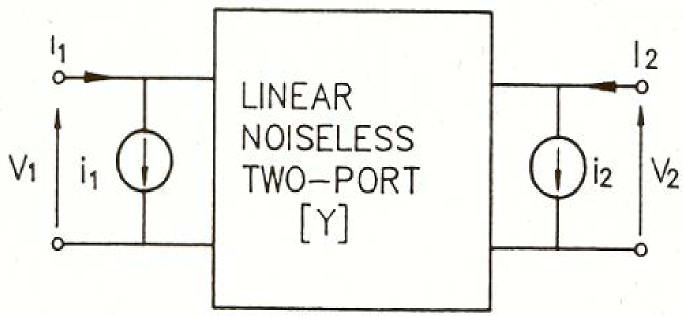
Outline

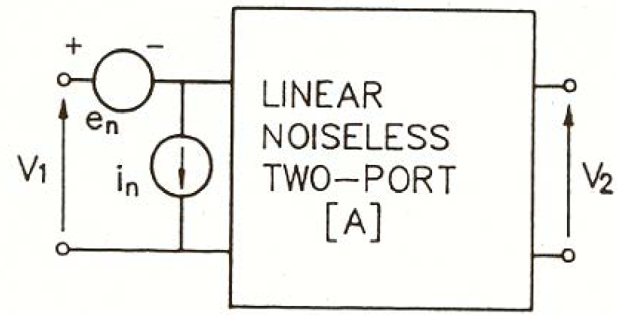
- Limits on noise parameters of microwave transistors
- Accuracy of model predictions
- Limits on noise performance of InP HFETs
- Practical limits on broadband noise matching: examples
- Other factors limiting noise performance of NRAO receivers
- Examples of performance of VLA receivers
- Expected trade-off in very broad band receiver performance

Noise Representations of 2-Ports



$$G_1 = \frac{\overline{|i_1|^2}}{4k\,T_o\,\Delta F}, \qquad G_2 = \frac{\overline{|i_2|^2}}{4k\,T_o\,\Delta F},$$

$$\rho_c = \frac{\overline{i_1^* i_2}}{\sqrt{\overline{|i_1|^2}\;\overline{|i_2|^2}}}$$



$$g_n = \frac{\overline{|i_n|^2}}{4k\,T_o\,\Delta F}, \qquad R_n = \frac{\overline{|e_n|^2}}{4k\,T_o\,\Delta F},$$

$$\rho = \frac{\overline{e_n^* i_n}}{\sqrt{\overline{|e_n|^2}\;\overline{|i_n|^2}}}$$

Allowed Values of Noise Parameters (1)

$$T_n = T_{min} + 4NT_o \frac{\left|\Gamma_g - \Gamma_{opt}\right|^2}{\left(1-\left|\Gamma_{opt}\right|^2\right)\left(1-\left|\Gamma_g\right|^2\right)}$$

$$\Gamma_{opt} = \frac{Z_{opt} - Z_o}{Z_{opt} + Z_o}$$

$$N = R_{opt}\, g_n$$

For all linear noisy two-ports for :

$$|\rho| \le 1$$ And therefore $$\frac{4NT_0}{T_{min}} \ge 1$$

which is equivalent to correlation matrix being Hermitian and non-negative definite.

Allowed Values of Noise Parameters (2)

$$T_{min} = T_0 \{2N + \mathrm{Re}\left(\rho\sqrt{R_n g_n}\right)\} \ .$$

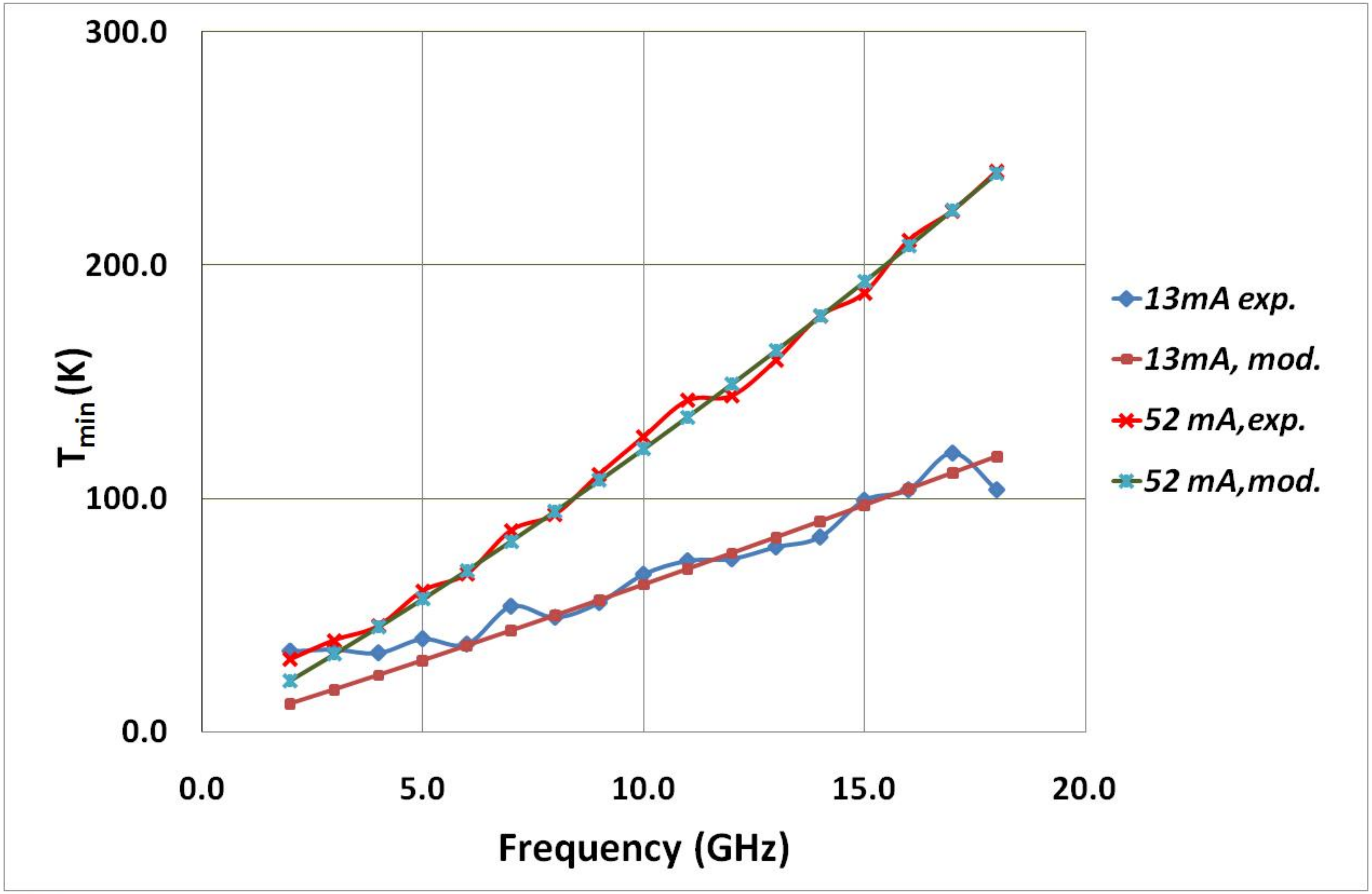
If therefore Re(ρ) **≥** 0 and correlation matrix is Hermitian and non-negative definite, than always

$$1 \le \frac{4NT_0}{T_{min}} \le 2$$

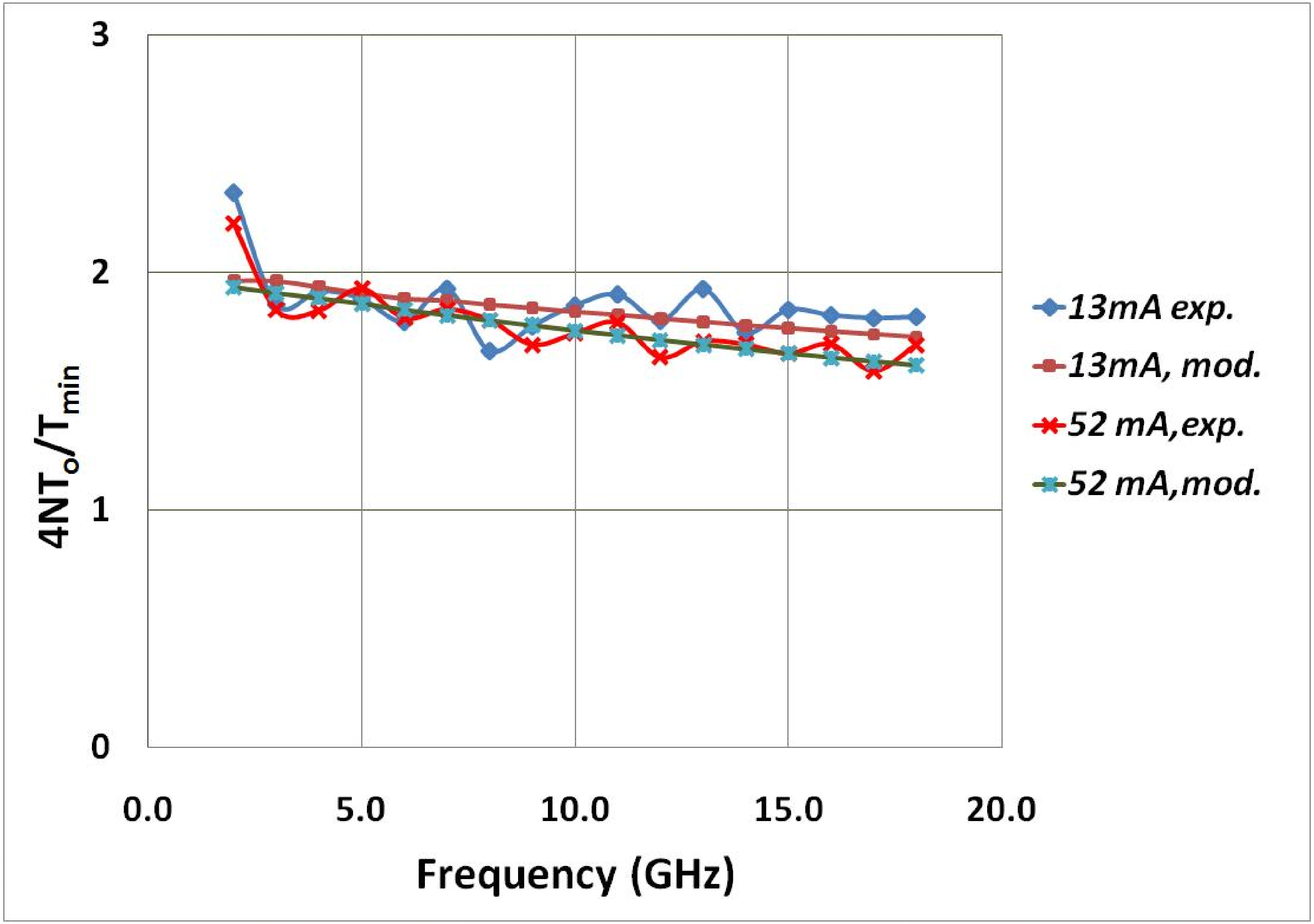
For all microwave transistors for useful frequency range :

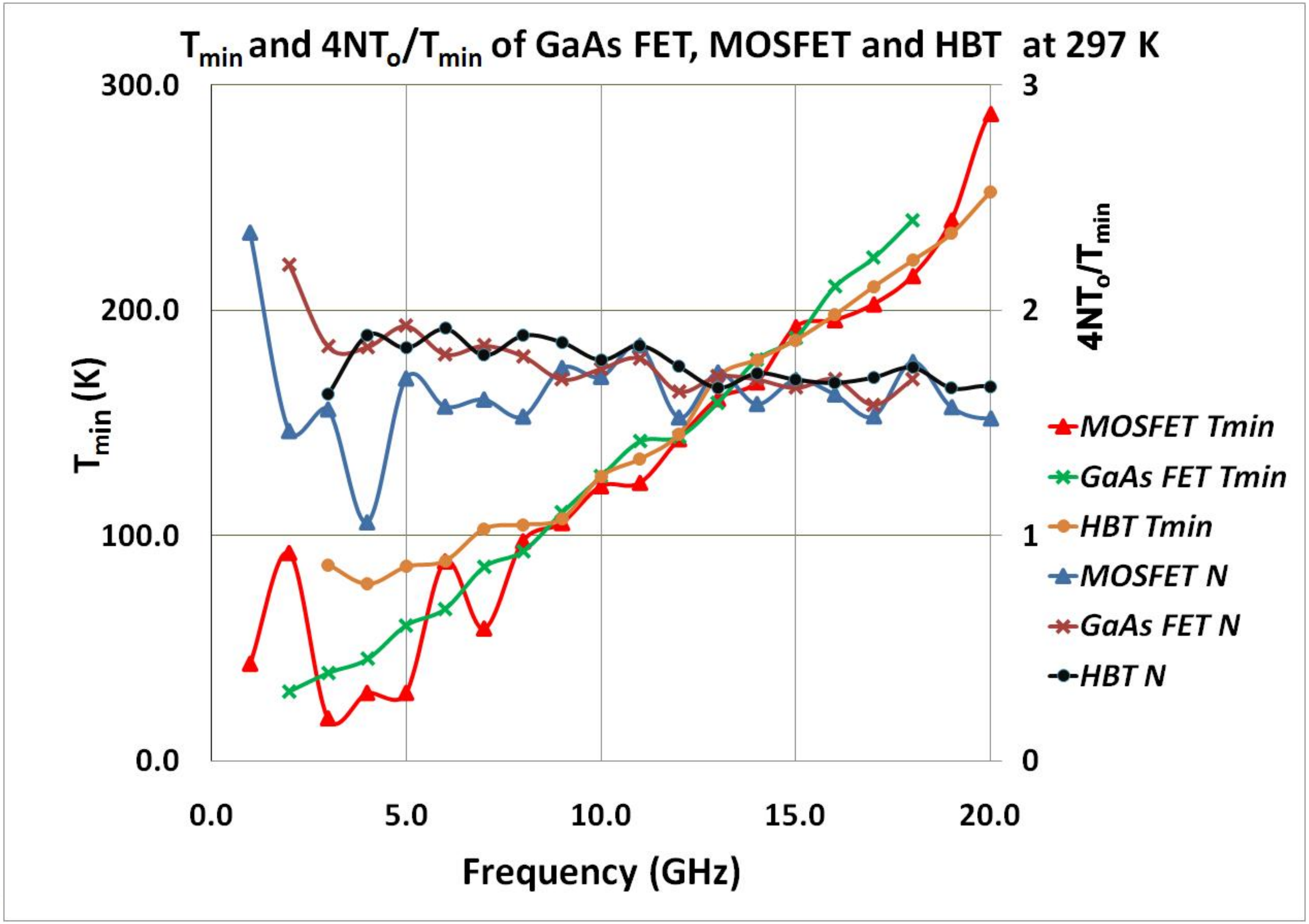
$$\frac{4NT_0}{T_{min}} \approx 2$$

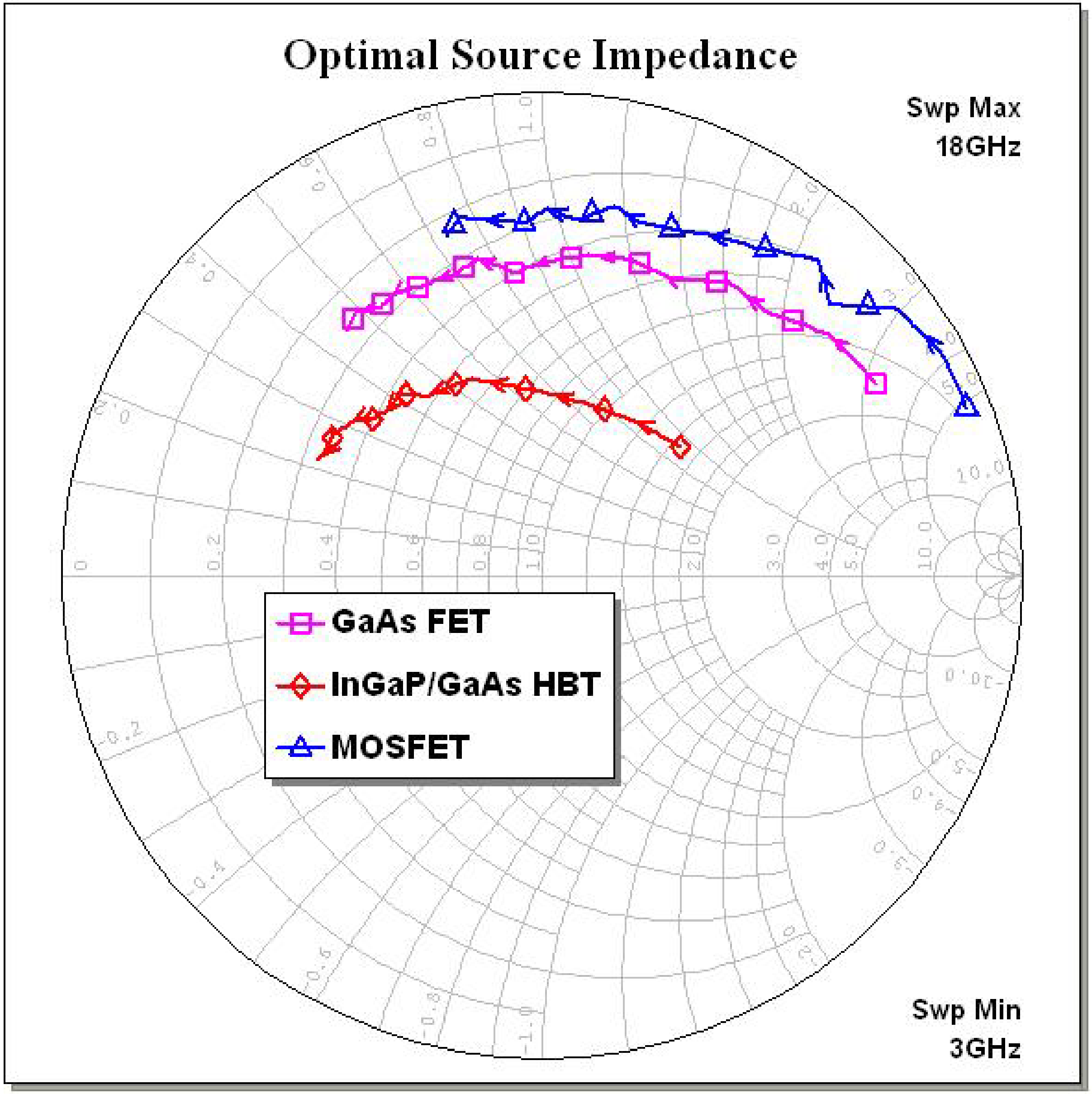
Measured and Modeled T_{min} of a FET



Measured and Modeled $4NT_0/T_{min}$ of a FET

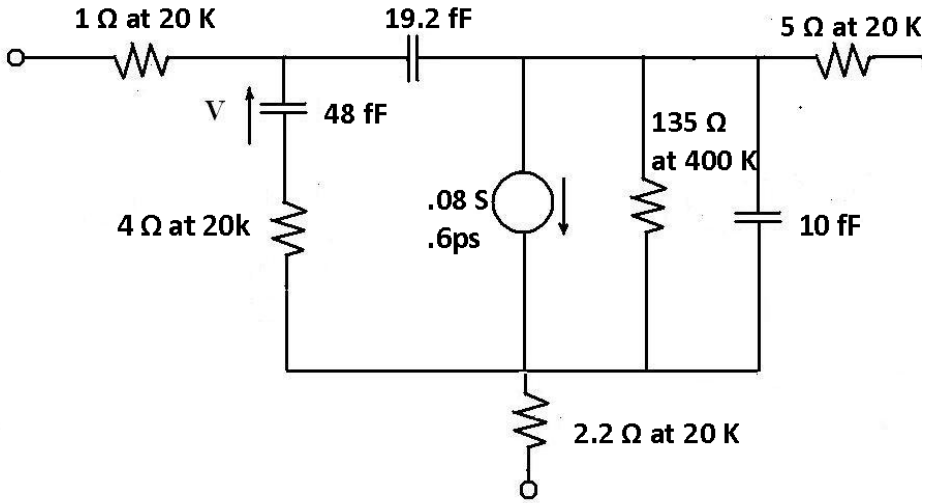



T_{min} and $4NT_o/T_{min}$ of GaAs FET, MOSFET and HBT at 297 K
300.0
200.0
100.0
0.0
T_{min} (K)
3
2
1
0
$4NT_o/T_{min}$
0.0
5.0
10.0
15.0
20.0
Frequency (GHz)
MOSFET Tmin
GaAs FET Tmin
HBT Tmin
MOSFET N
GaAs FET N
HBT N

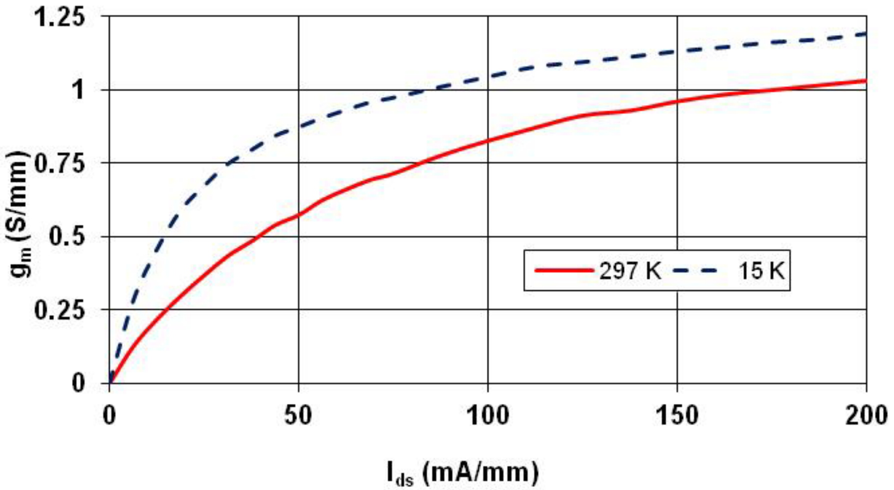

Optimal Source Impedance
Swp Max
18GHz
Swp Min
3GHz
GaAs FET
InGaP/GaAs HBT
MOSFET

Example of Equivalent Circuit and $g_m(I_{ds})$ Characteristics of Cryo3 InP HFET

Equivalent circuit of cryo3 device



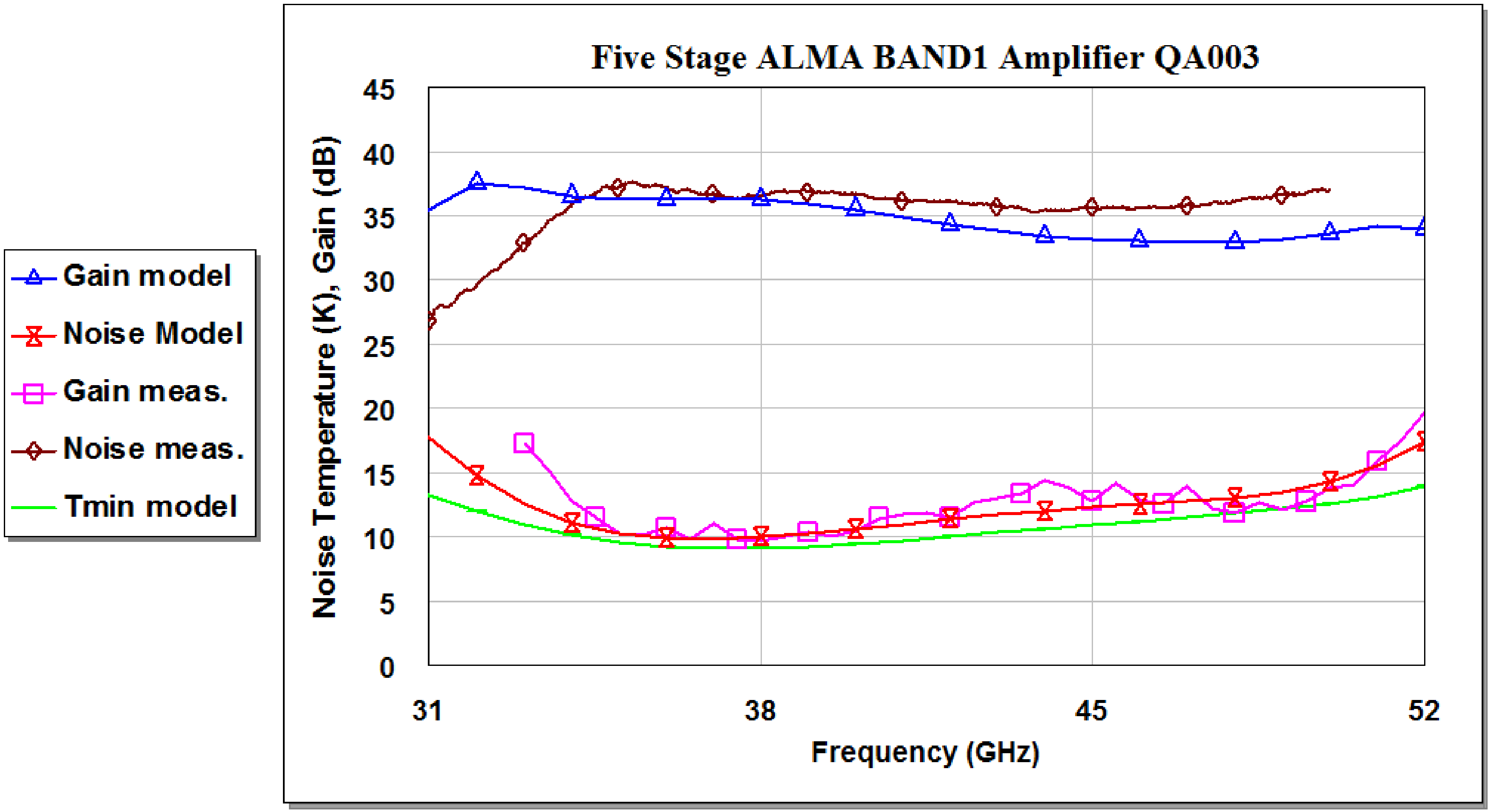
$g_m(I_{ds})$ characteristics



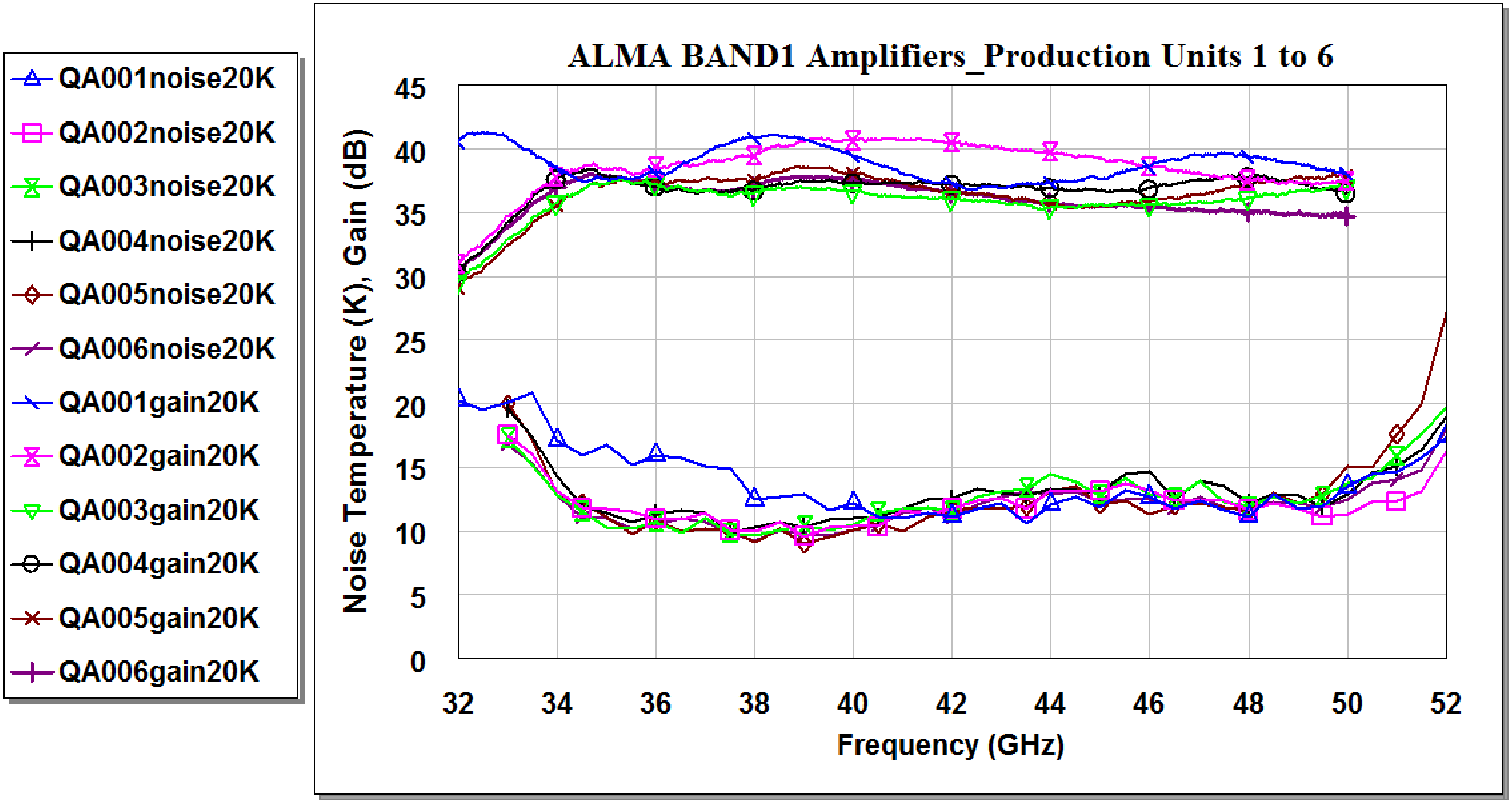
L_g=80nm, W_g=80μm

$$T_{min} \cong 2\frac{f}{f_t}\sqrt{g_{ds}\, T_d\, r_t\, T_g} \cong \frac{f}{f_{max}}\sqrt{T_d T_g}$$

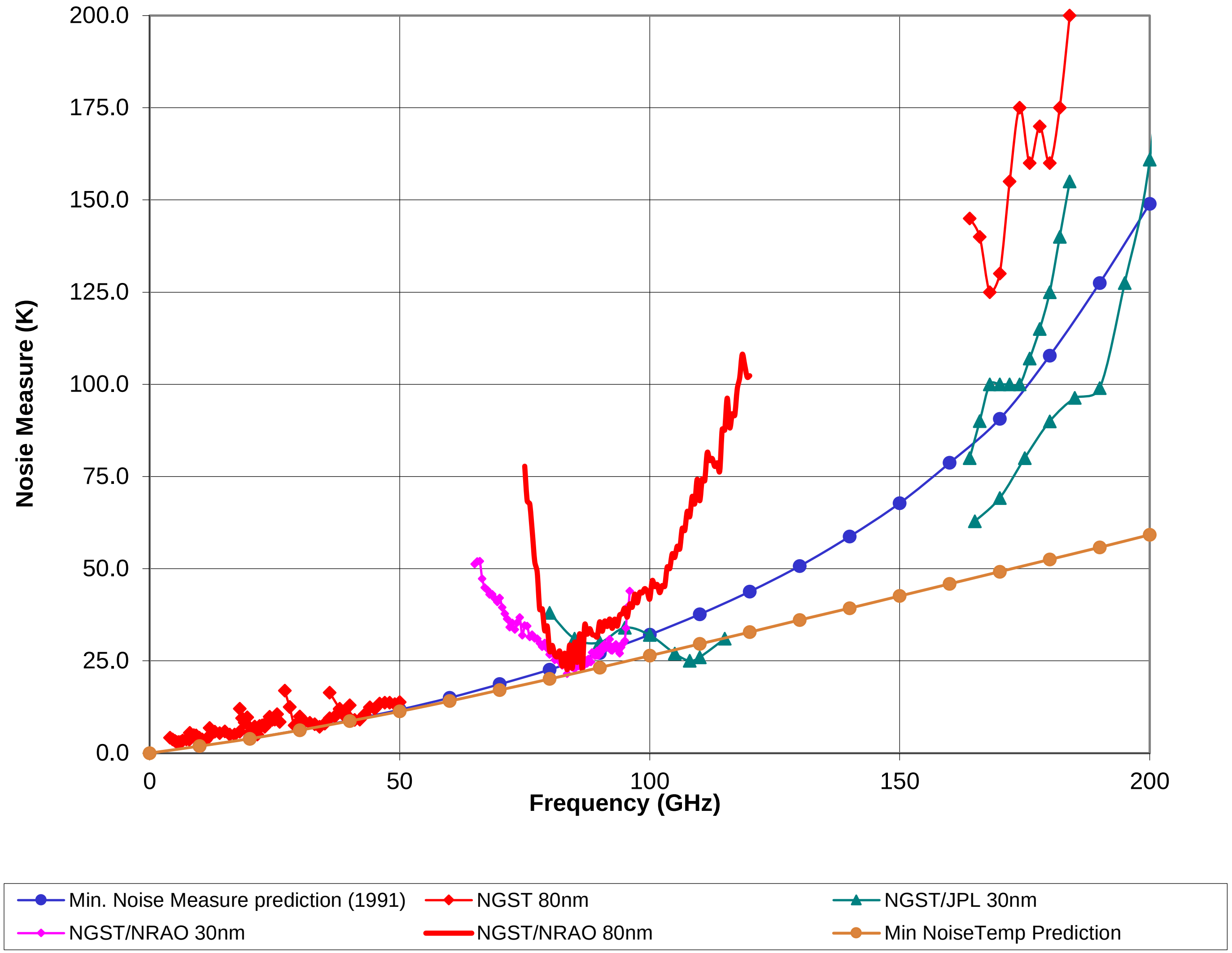
5 stage 33-52 GHz amplifier: model and measured results at 20 K



33-52 GHz amplifiers: First Six Units at 20 K



Noise Temperature Summary of Cryogenic HEMTs



Device Scaling: Gate Length (1)

$$T_{min} \cong 2\frac{f}{f_t}\sqrt{g_{ds}\,T_d\,r_t\,T_g} \cong \frac{f}{f_{max}}\sqrt{T_d T_g} \qquad f_t \cong \frac{g_m}{2\pi(C_{gs}+C_{gd})}$$

$$L_g \downarrow \quad f_{max} \uparrow \quad T_{min} \downarrow \quad \text{if } T_d \approx \mathit{const.}$$

$T_g \cong$ **Ambient temp.** T_d **depends on gate length, channel structure, and current density I_d/mm but mostly not on ambient temperature**

For every device structure there must exist a lower limit on T_{min} upon further device scaling. Exact dependence of T_d on device structure and properties of electron transport in the channel is not known, but …..

Device Scaling: Gate Length (2)

within a measurement error no device demonstrated T_{min} lower than that predicted in MMA Memo #67 (1991)

The best cryogenic wafers: Chalmers (130 nm), NGSTCryo3 (80-100 nm), NGST (35 nm) exhibit progressively better f_{max} and M_{min}

but about the same minimum $\mathbf{T_{min}}$ because T_d increases for deep submicron gate lengths.

The reasons:

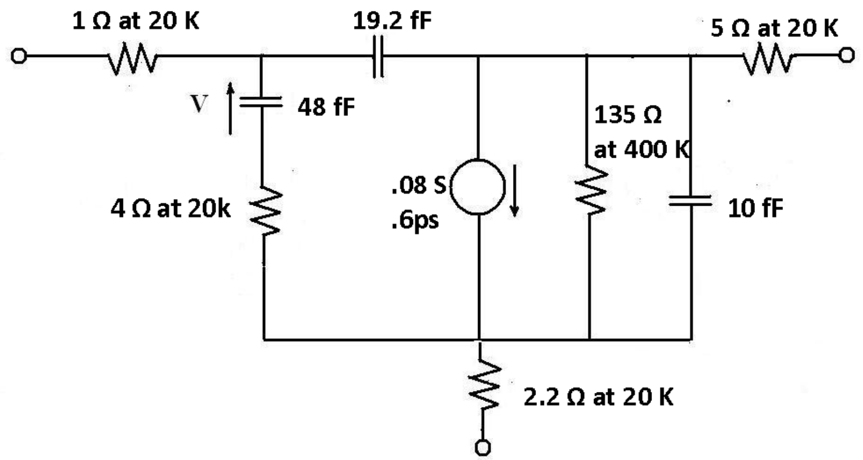
- Noise optimal bias minimizing the value of : $f(V_{ds}, I_{ds}) \approx \frac{\sqrt{I_{ds}}}{g_m}$ increases for (shorts channel effects).
- Also T_d increases for the same value of I_d/mm (no explanation yet).

For f_{max}=const. and constant bias:

$$T_{min} \propto \sqrt{T_a}$$

Plausible Explanation ?

Equivalent circuit of cryo3 device



L_g=80nm, W_g=80µm, V_{ds} =.8V, I_{ds}=3 mA

Shot noise in the drain?

Assume:
$4kT_d=2qI_d$
Than for I_d=3mA
$T_d \approx 4700$ K

$$T_{min} \cong 2\frac{f}{f_t}\sqrt{g_{ds}\, T_d\, r_t\, T_g} \cong \frac{f}{f_{max}}\sqrt{T_d T_g}$$

Device Scaling: Gate Width

$$T_{min} \cong 2 \frac{f}{f_t} \sqrt{g_{ds}\, T_d\, r_t\, T_g}$$

$$R_{opt} \cong \frac{f_t}{f} \sqrt{\frac{r_t\, T_g}{g_{ds}\, T_d}}$$

$$r_t = r_{gs} + r_g + r_s$$

Width $\nearrow$ R_{opt} $\searrow$

T_{min} $\rightarrow$ in principle

T_{min} $\nearrow$ in practice

Important Notes:

$$T_n = T_{min} + 4NT_o \frac{\left|\Gamma_g - \Gamma_{opt}\right|^2}{\left(1-\left|\Gamma_{opt}\right|^2\right)\left(1-\left|\Gamma_g\right|^2\right)}$$

$$\frac{4\,NT_0}{T_{min}} \cong 2 \qquad \Gamma_g = 0 \quad \Longrightarrow$$

$$T_n \cong T_{min} \frac{\left|\Gamma_{opt}\right|^2}{\left(1-\left|\Gamma_{opt}\right|^2\right)}$$

For a given frequency range chose Γ_{opt} close to SC center.

In practice, for a given frequency range average T_n is:

$$\frac{1}{f_{max} - f_{min}} \int_{f_{min}}^{f_{max}} T_n df \approx M_{min}(f_{max})$$

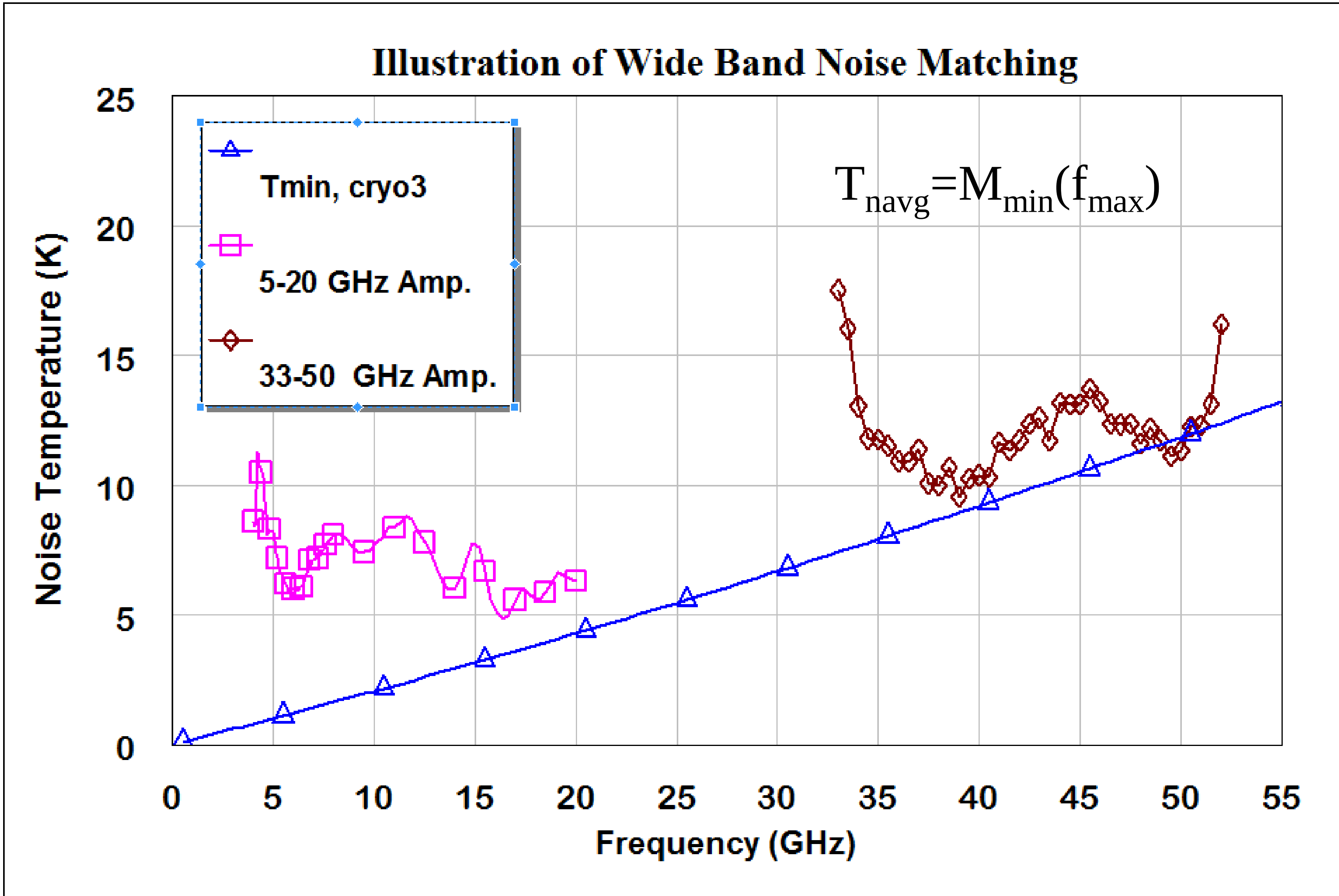
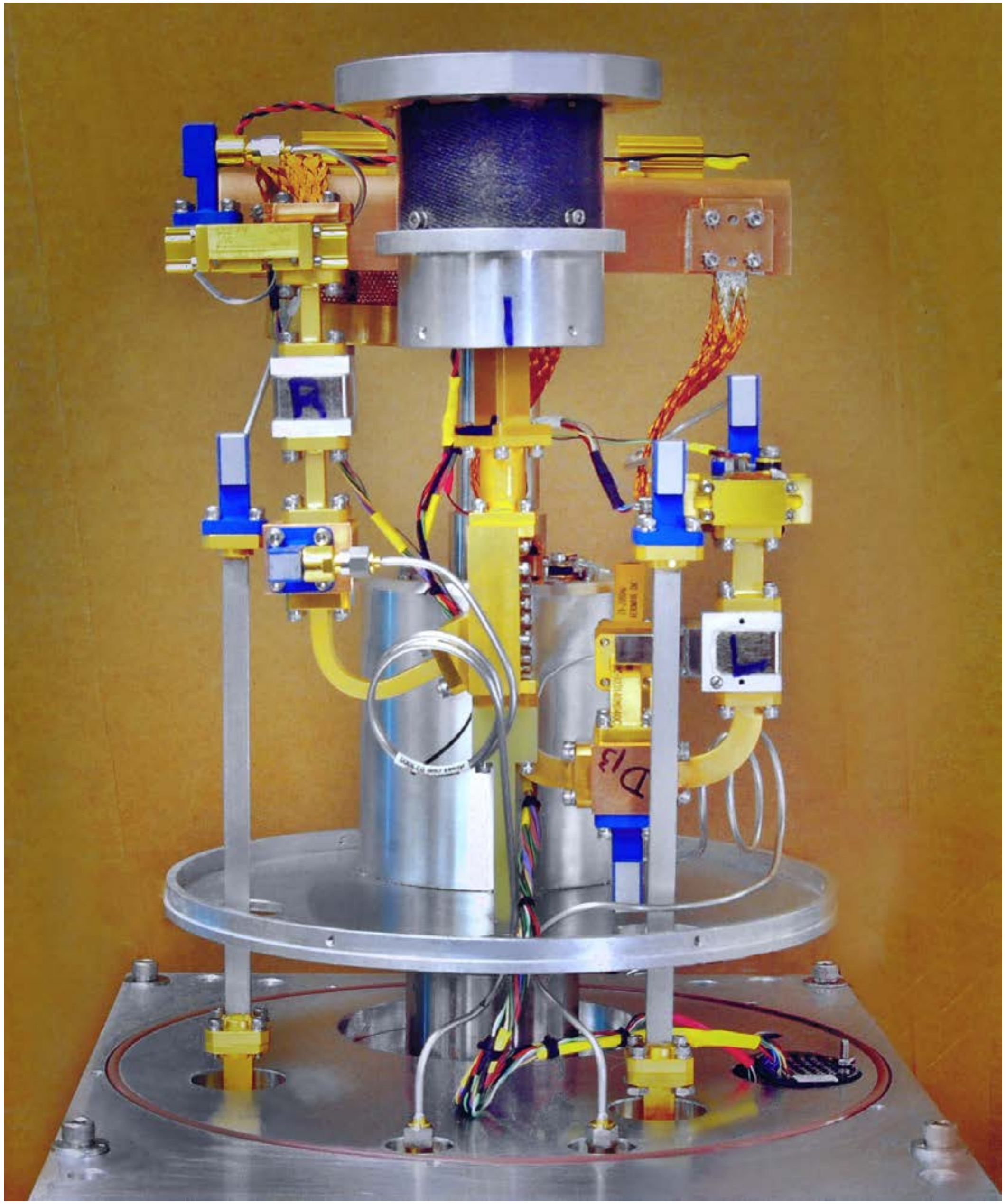


Illustration of Wide Band Noise Matching
Noise Temperature (K)
Frequency (GHz)
Tmin, cryo3
5-20 GHz Amp.
33-50 GHz Amp.
$T_{navg}=M_{min}(f_{max})$
0
5
10
15
20
25
30
35
40
45
50
55

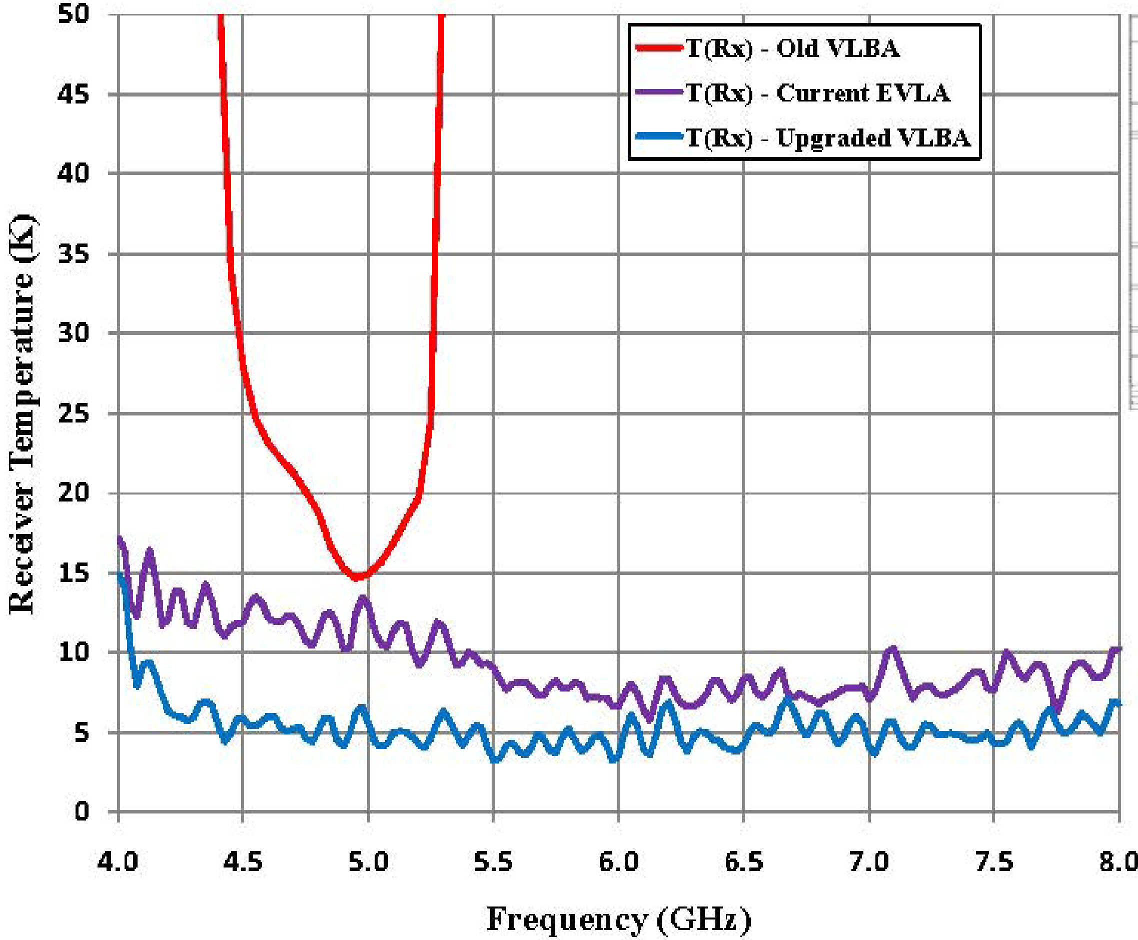


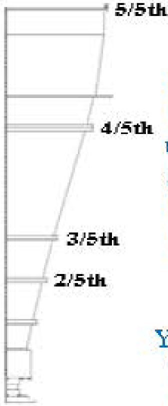
JVLA K_a- Band Receiver

Courtesy: R. Hayward, P. Harden, NRAO

Prototype VLBA C-Band (S/N 11) Sensitivity

Old VLBA vs. New VLBA vs. EVLA Receivers





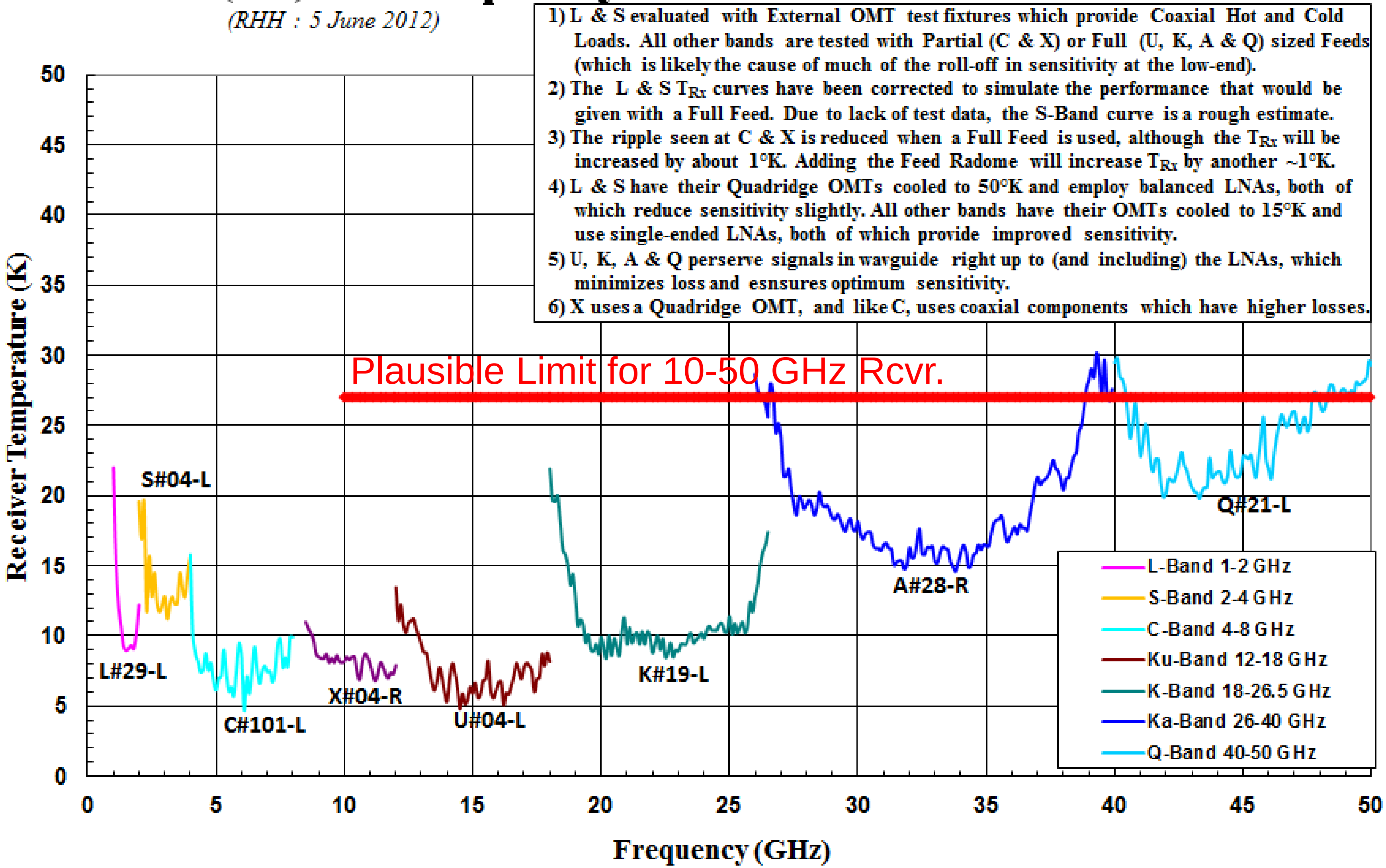
The ripple seen in the baseline of the EVLA & new VLBA receivers come from using only the 3 lower sections of the 5 piece EVLA feed so that a smaller 12" diameter Cold Load can be utilized for the Y-Factor measurements. The full feed will add 1-2°K to the T(Rx)..

Installing the Goretex RA3T20 radome over the mouth of the feed would add <1°K to the noise temperature.

The new upgraded VLBA C-Band receiver has better sensitivity over the receiver now in use on the EVLA thanks to a new improved Thermal-Gap assembly.

Courtesy: R. Hayward

T(Rx) vs. Frequency for JVLA Receiver Bands



Courtesy: R. Hayward

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Summary

- Only three wafer runs of InP discrete devices (NRAO/HRL, WMAP/HRL, NGST/JPL cryo3) have been used in construction of great majority of radio astronomy instruments: VLA/EVLA,VLBA, GBT, ALMA band6, CBI, SZ-Array, WMAP, Planck LFI (K_a and Q), VSA, AMI, MPI, JPL/DSN and others
- No single wafer devices have ever been fully understood
- There has been no significant progress in the low noise performance of cryogenic HFET's in the past 15 years; Are we approaching the limits?
- Amplifier noise temperature is no longer the dominant component of the system noise for radio astronomy instruments with cryogenic receivers
- Very broadband receivers will suffer loss of sensitivity which can be well predicted, with accuracy satisfactory for the assessment of possible benefits