INTERLABORATORY COMPARISON OF NOISE-PARAMETER MEASUREMENTS ON CMOS DEVICES WITH 0.12 μm GATE LENGTH

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I. INTRODUCTION

The "Kelvin" Project:

- What is it?
  - Regular, small-group collaboration between IBM, RFMD and NIST to explore noise in IBM CMRF 8SF (0.13μm)
  - Aimed at developing working relationship, combining skills and allowing customer to gain experience with this technology
- Goals:
  - Develop new device, circuit and test structure designs over several MPWs
  - Explore means of improving data quality
  - Examine features and quirks of data to understand new physics and/or provide feedback to modeling
- Participants:
  - IBM: technology knowledge, device/modeling/RF test experience
    - David Greenberg, Susan Sweeney, Larry Wagner, Sebastian Csutak, Jack Pekarik
  - RFMD: Circuit design and test, modeling, product knowledge
    - Tom McKay, Ali Rezvani, Leonard Reynolds, Jon Tao, Judah Mendez
  - NIST: RF test innovation and standardization
    - Jim Randa, David Walker

Interest in CMOS:

- Relatively inexpensive: “mature” technology, extensive infrastructure (facilities, processes, models) already in place.
- Integration advantages: combine RF + digital on same chip
- Big IF is performance at higher frequencies.
- Several factors: speed, transmission line losses, difficulty getting good inductors …
- Also must characterize noise performance of CMOS devices at RF (and above), especially for very small devices (since that’s what will be used).

Measurement Challenges:

- Very low minimum noise figure or noise temperature
- Very poorly matched; $|S_{11}|$, $|S_{22}|$, and $|\Gamma_{opt}|$ can all be greater than 0.7, and are often greater than 0.9.
- Even probe contact to pads (Al) is potentially problematic if vibration present.

This Paper:

- Measure “same” device (different dies) at all three labs & compare
  - S-parameters
  - Noise parameters

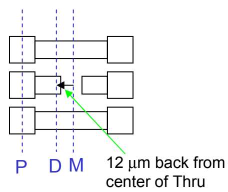
II. MEASUREMENTS

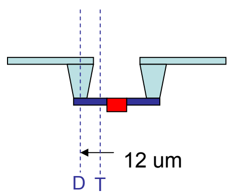
The Device

- 128×3×0.12 NMOS device
  - 128 fingers of polysilicon over
  - 3 µm wide active channel
  - 0.12 µm gate length
  - fabricated in 0.13 µm technology (by IBM)

- Bias:
  - drain voltage $V_{ds} = 1.2$ V
  - $J = 25$ µA/µm

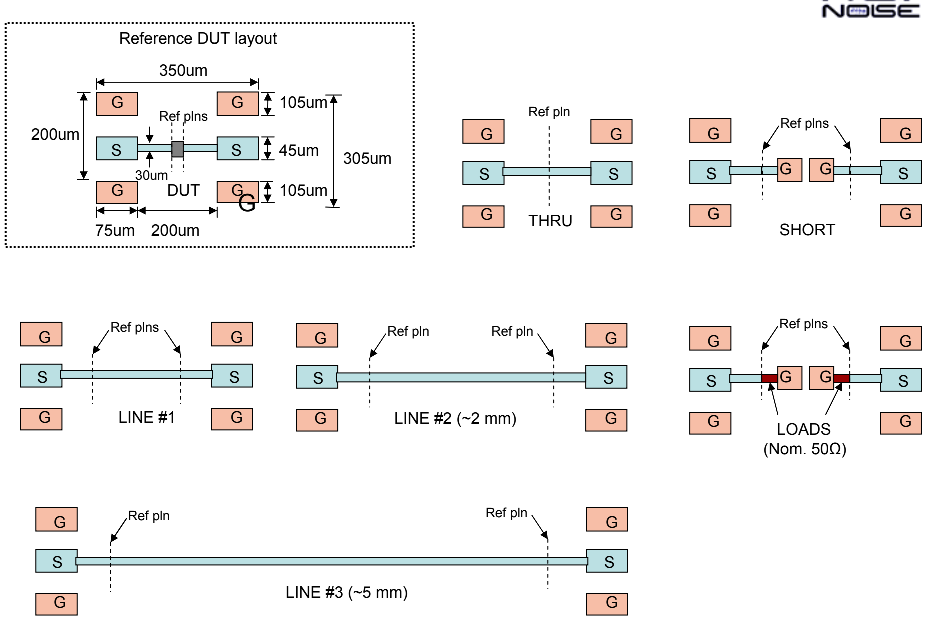
Calibration & Reference Planes





- RFMD & IBM:
  - Probe-tip cal at ref planes P with off-wafer standards + deembed to planes T
  - Also multiline TRL with on-wafer standards at planes D
- NIST:
  - multiline TRL with on-wafer standards at planes D

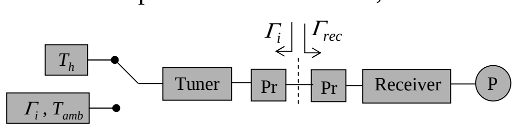
MPW1 TRL Calibration Set



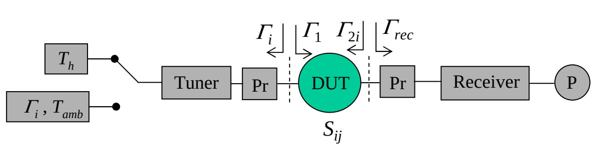
Noise Measurements

- RFMD (Maury) & IBM (ATN) use commercial systems.

First measure noise parameters of receiver,

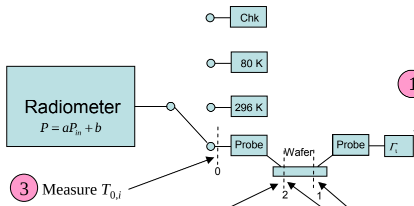


Then measure DUT + receiver



and extract DUT noise parameters.

•NIST uses a radiometer-based method similar to its method for packaged amplifiers:



① Series of different terminations i

② $\Gamma_{1,i}$, $\Gamma_{2,i}$, and S_{ij} measured with on-wafer cal, $T_{1,i}$ measured on wafer

③ Measure $T_{0,i}$

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} = 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

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

- The X's are essentially the elements of the noise matrix in the wave representation,

$$k_B X_1 \equiv \left\langle |c_1|^2 \right\rangle, \quad k_B X_2 \equiv \left\langle |c_2 / S_{21}|^2 \right\rangle, \quad k_B X_{12} \equiv \left\langle c_1 (c_2 / S_{21})^* \right\rangle$$

  They can be written in terms of the conventional IEEE noise parameters (& vice versa).

- The NIST uncertainties are evaluated with a Monte-Carlo routine developed for amplifiers & modified to accommodate large $|S_{11}|$, $|S_{22}|$, and $|\Gamma_{opt}|$.

<u>X's → IEEE</u>

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

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

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

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

<u>IEEE → X's</u>

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

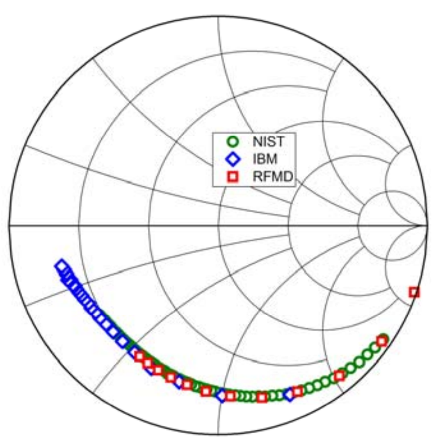
$$X_2 = T_{e,\min} + \frac{t|\Gamma_{opt}|^2}{|1+\Gamma_{opt}|^2},$$

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

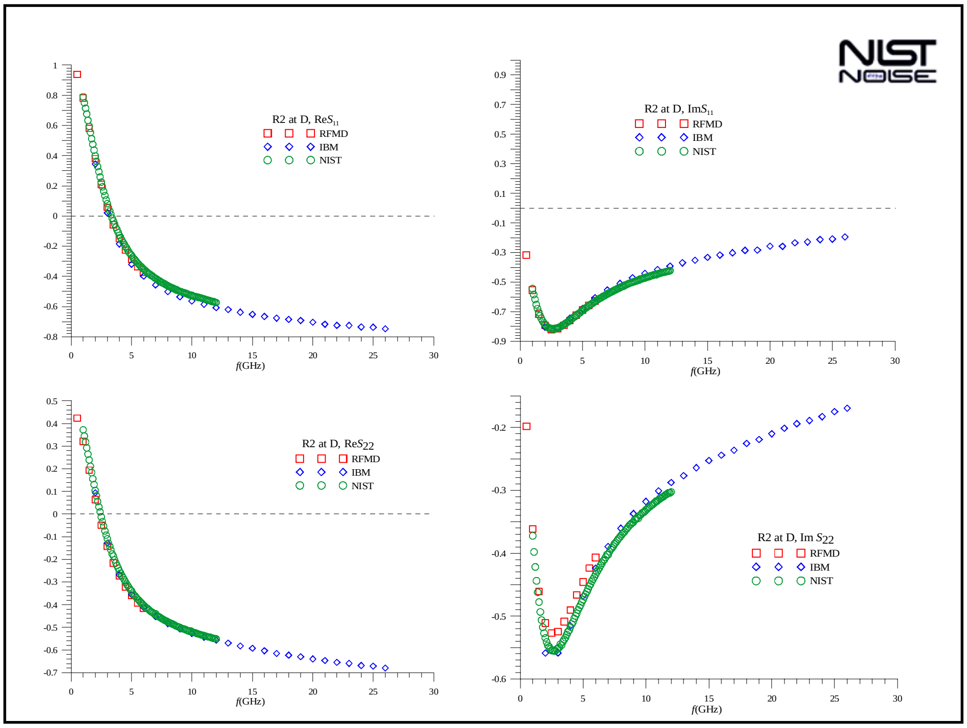
Notes:
$X_2 = T_{e,0}$
Bound implied by $X_1 \geq 0$

<u>III. RESULTS</u>

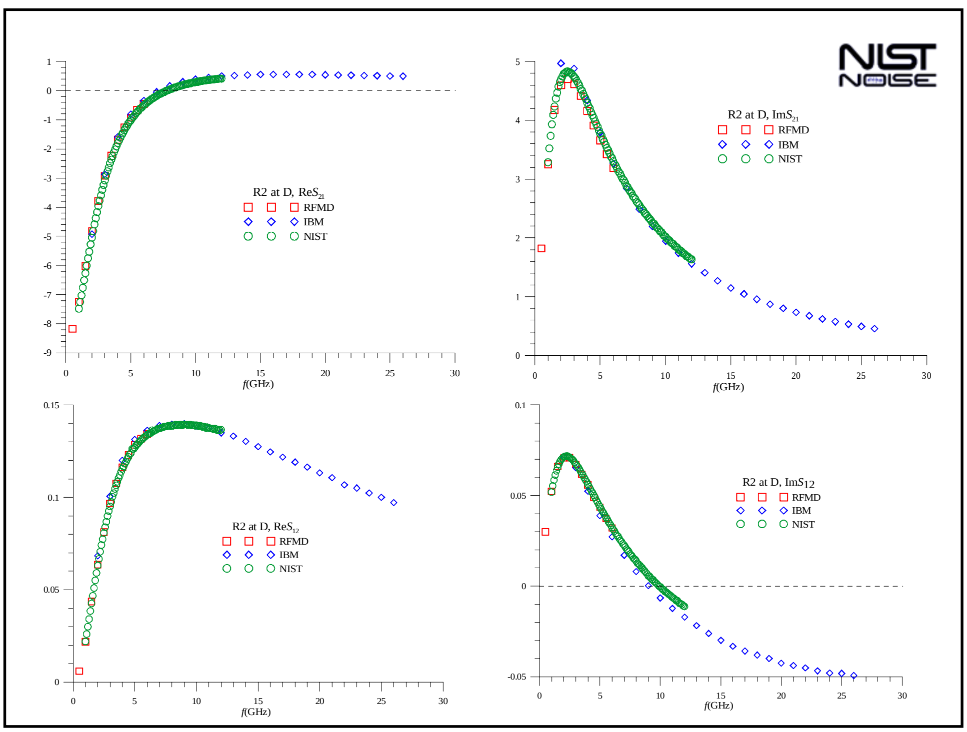
S Parameters:



S_{11} at plane D

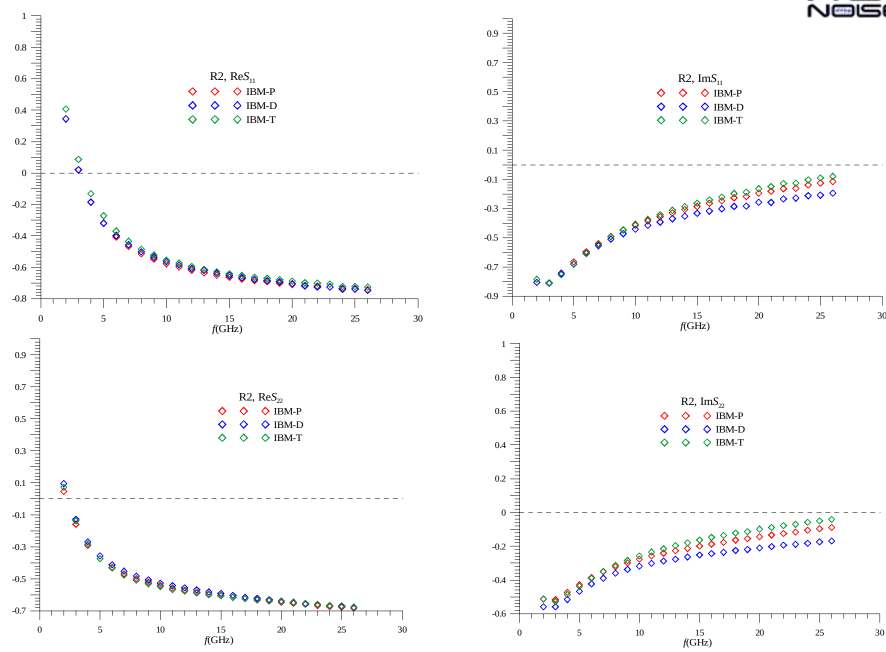


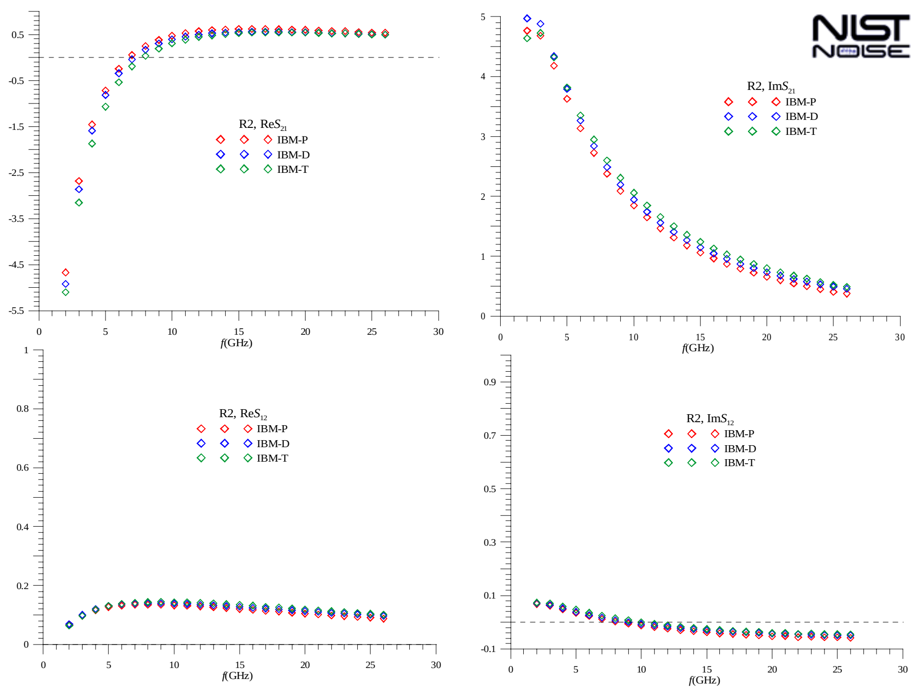
NIST NOISE
R2 at D, ReS11
RFMD
IBM
NIST
f(GHz)
R2 at D, ImS11
RFMD
IBM
NIST
f(GHz)
R2 at D, ReS22
RFMD
IBM
NIST
f(GHz)
R2 at D, Im S22
RFMD
IBM
NIST
f(GHz)



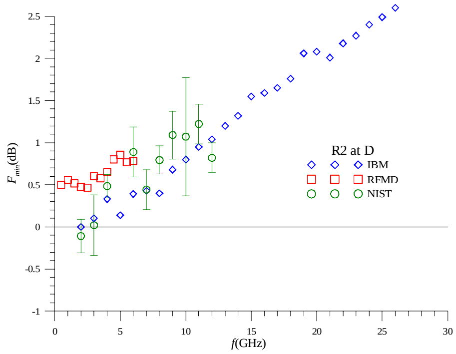
NIST NOISE
R2 at D, ReS21
RFMD
IBM
NIST
f(GHz)
R2 at D, ImS21
RFMD
IBM
NIST
f(GHz)
R2 at D, ReS12
RFMD
IBM
NIST
f(GHz)
R2 at D, ImS12
RFMD
IBM
NIST
f(GHz)

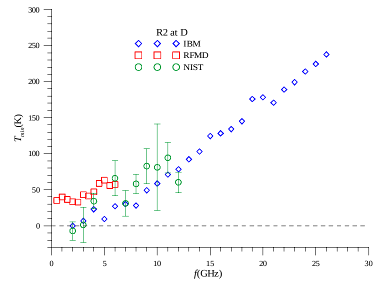
Comparison of different reference planes:

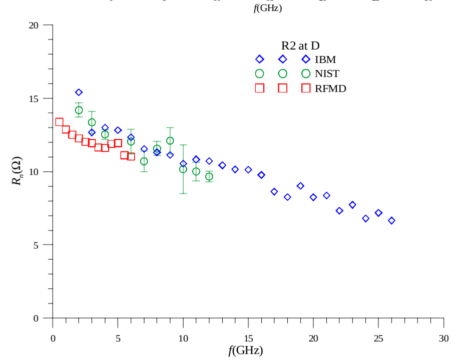




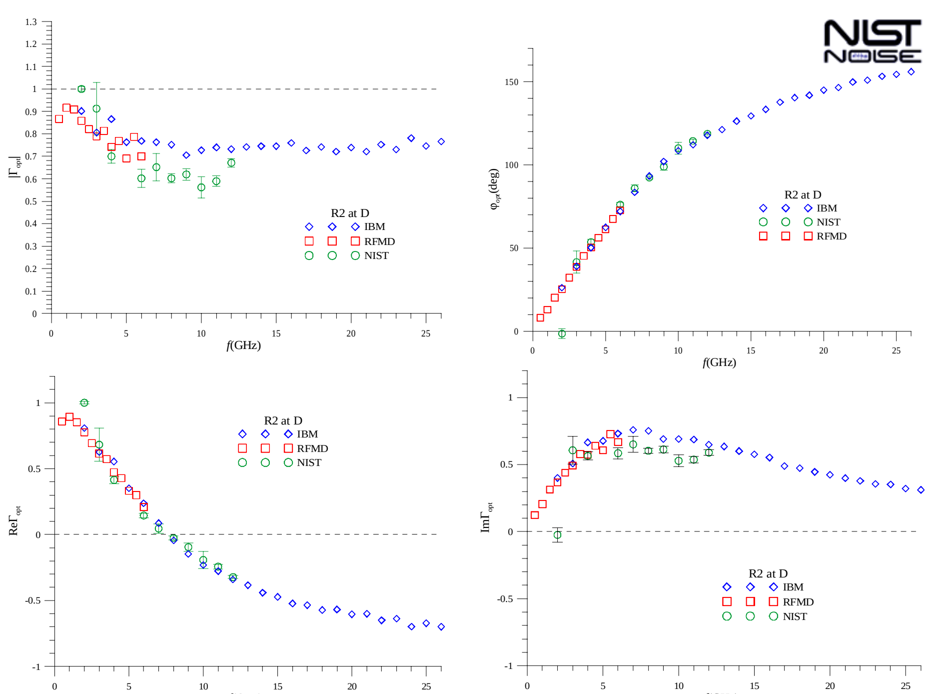
Noise Parameters (at D):



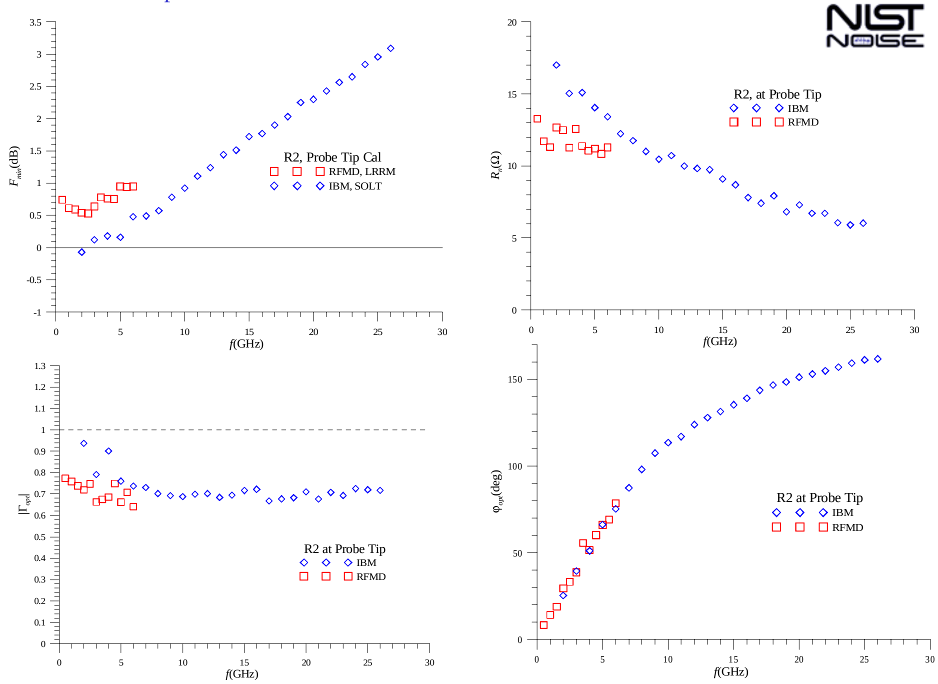




All labs used TRL cal at D.



With Probe-Tip Cal:



IV. DISCUSSION

Conclusions:

- S-parameter measurements are in good agreement.
- Noise-parameter agreement is not as good
  - no really egregious conflicts
  - agreement probably within uncertainties
  - need smaller uncertainties, improved methods

Possible Improvements:

- Better calibration of hot noise source (RFMD & IBM)
- Input terminations (NIST)
  - bigger & better set
  - switch rather than manually change
- Use cold noise source on input (all)
- Additional reverse measurements
- Monte Carlo uncertainty analysis for RFMD & IBM