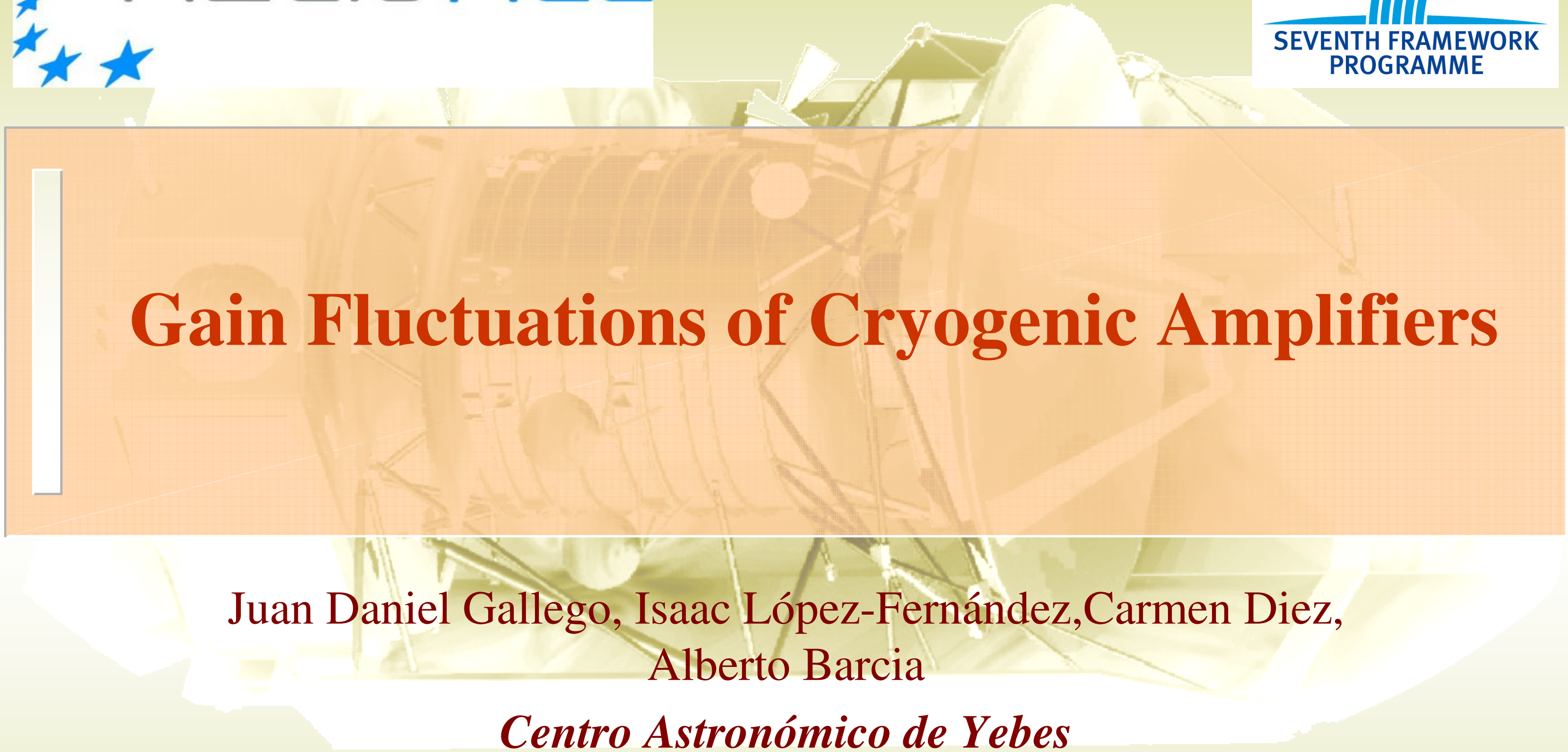

Gain Fluctuations of Cryogenic Amplifiers

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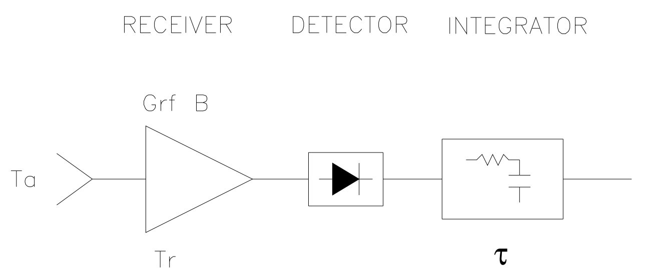
Contents

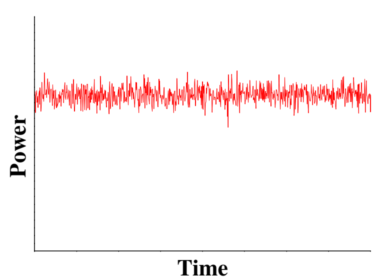
Radiometer Sensitivity

- Radiometer

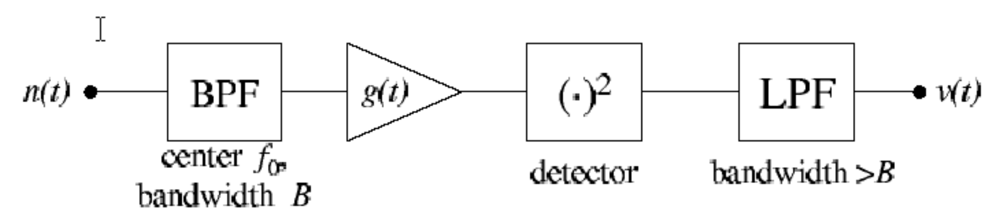
$$P_{out} = K \cdot G_{rf} \cdot B \cdot (T_a + T_r)$$

$$\frac{\Delta P_{out}}{P_{out}} = \frac{k}{\sqrt{B\tau}} + \frac{\Delta G_{rf}}{G_{rf}}$$





- Radiometer model



- Radiometer sensitivity (total power radiometer)

$$\left(\frac{S_v(f)}{V_0}\right)^2 = \delta(f) + \frac{2}{B} + \left(\frac{S_g(f)}{G_0}\right)^2, \quad |f| << B$$

Gain Stability Characterization

- Allan Variance of Normalized Gain (unitless):
  - Time domain
  - Astronomer's choice

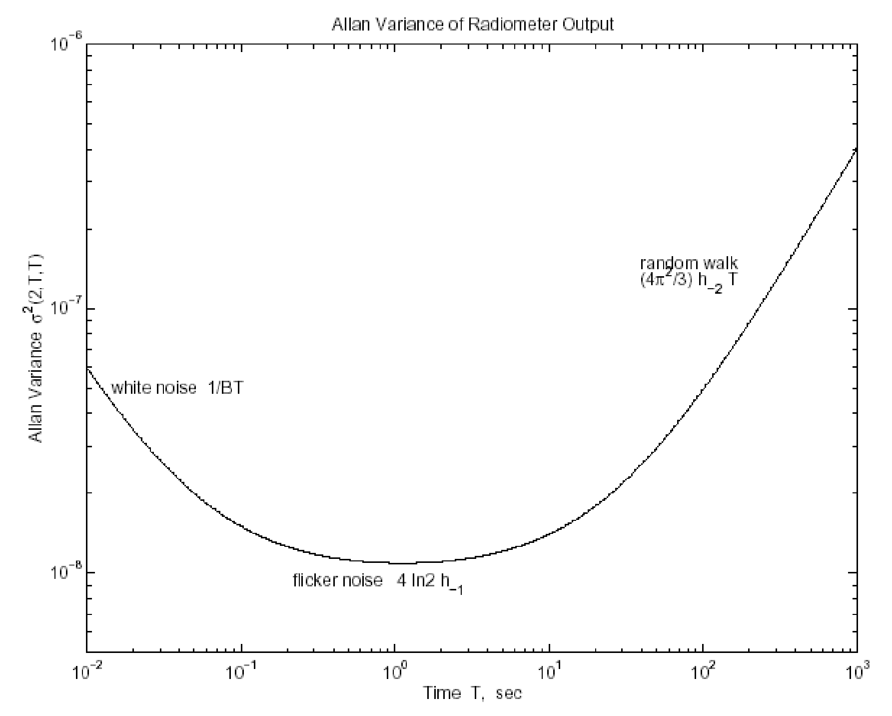
$$\sigma^2(\tau) = \frac{1}{2}\left\langle \left(\overline{G}(t+\tau) - \overline{G}(t)\right)^2 \right\rangle$$

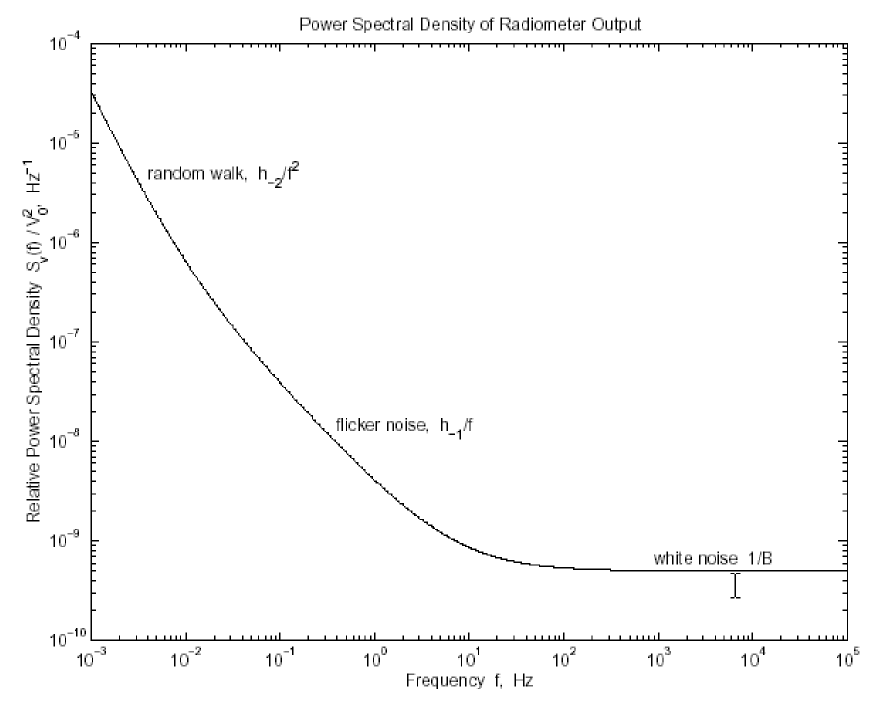
- SNGF (units: 1/√Hz, sometimes 1/Hz):
  - Spectrum of Normalized Gain Fluctuation
  - Frequency (video) domain
  - Engineer's choice

$$S(0) = \mathrm{mean}(G(t)) = 1$$

$$\int_{f_{\min}}^{f_{\max}} \left| S(f) \right|^2 \cdot df = \mathrm{var}(G(t))$$

Allan Variance vs. SNGF





$$\sigma^2(\tau) = \int_{-\infty}^{+\infty} S(\nu) \left| 4 \frac{\sin^4(\pi\tau\nu)}{(\pi\tau\nu)^2} \right|^2 d\nu$$

Conversion of SNGF to Allan Variance

- SNGF in 1/√Hz units:

$$S(f) = b \cdot f^{-\alpha} \quad \Leftrightarrow \quad \sigma^2(\tau) = K_\alpha \cdot b^2 \cdot \tau^{2\alpha-1}$$

$$(\text{valid for} \quad -\tfrac{1}{2} < \alpha < \tfrac{3}{2})$$

$$K_1 = \frac{2}{3} \cdot \pi^2$$

$$K_{3/4} = \frac{32}{15} \cdot \pi \cdot \left(\sqrt{2} - 1\right)$$

$$K_{1/2} = 2 \cdot \ln(2)$$

$$K_{1/4} = \frac{4}{3} \cdot \left(2 - \sqrt{2}\right)$$

$$K_0 = \frac{1}{2}$$

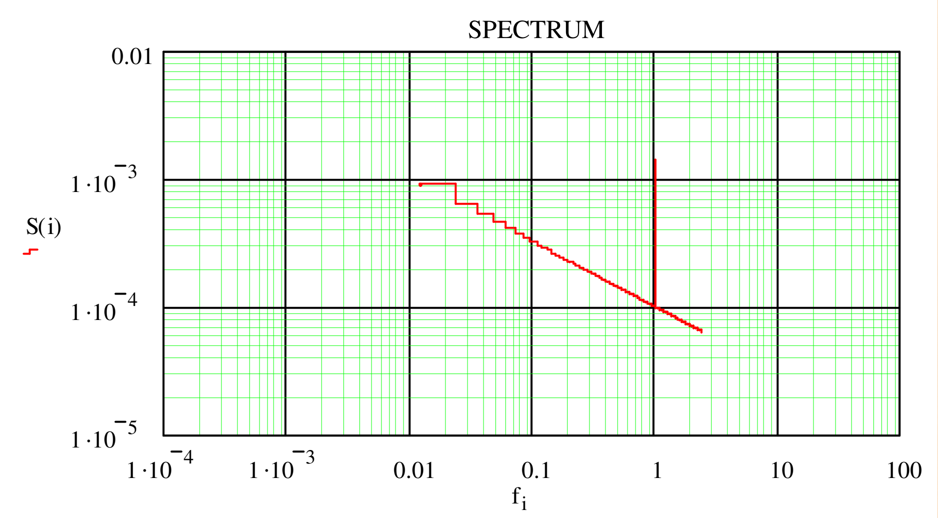
$$K_{-1/4} = \frac{1}{2\pi} \cdot \left(4 - \sqrt{2}\right)$$

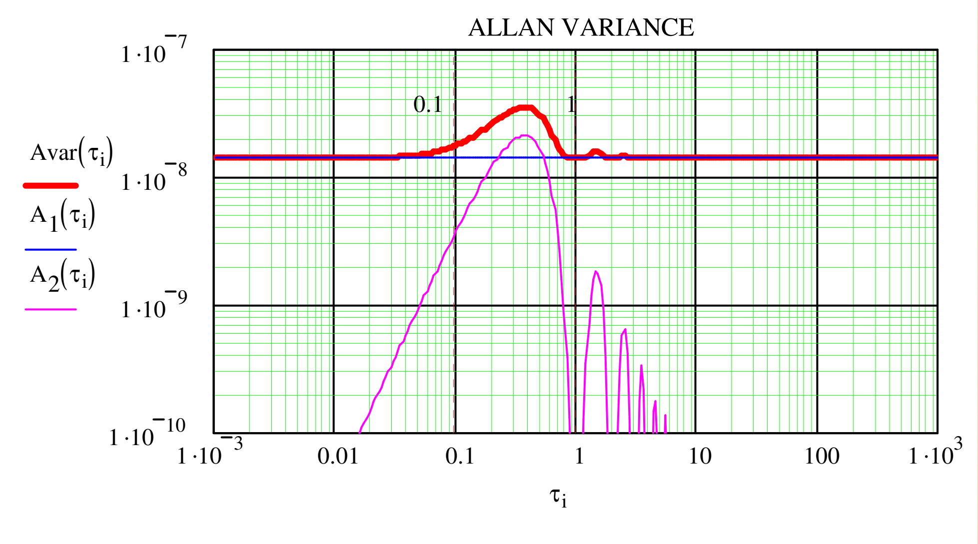
- Ambiguity:

  Note that the inverse mapping is not unique (more information in SNGF)

  However in practical cases with random signals the inverse conversion is "valid"

Why using SNGF ?

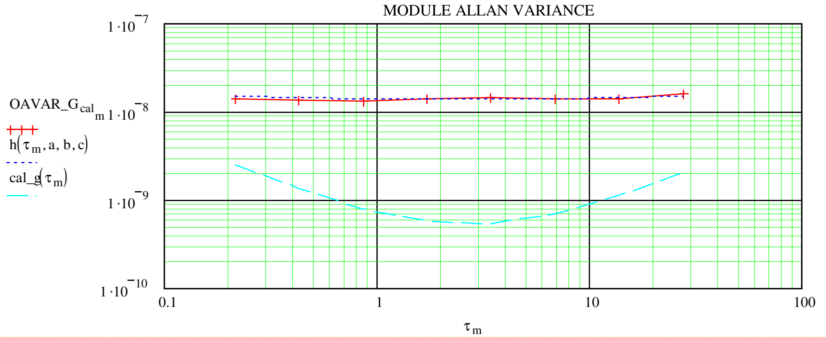




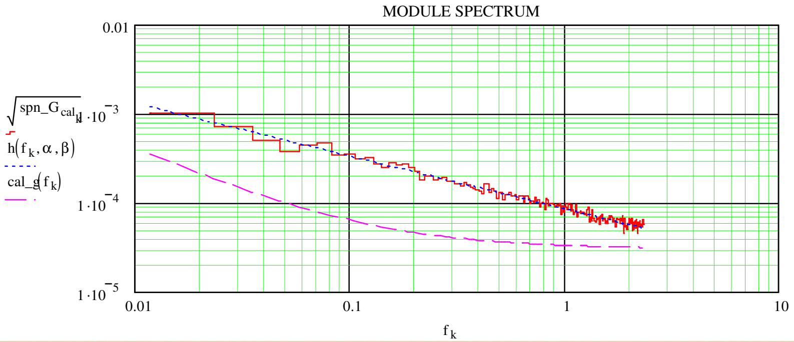
- Example:
  - 1 Hz gain oscillation (typical refrigerator cycle)
  - A=2E-4 (0.0017 dB pp)
  - Typical InP amplifier fluctuation
- Result:
  - Allan Variance “bump” spread over time (0.1-1 sec)

Why using SNGF ? (real world)

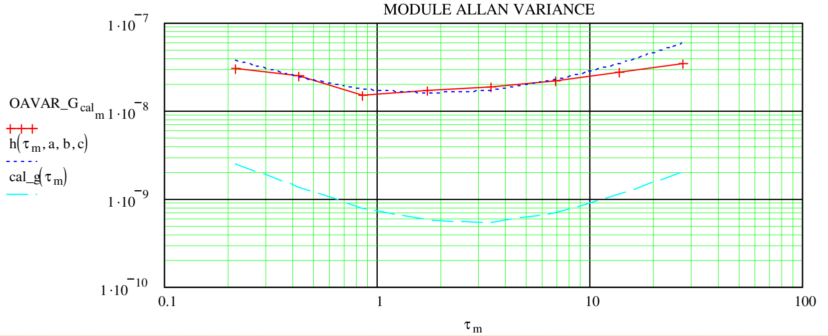
$a = 2.219\times10^{-10}$ $b = 1.386\times10^{-8}$ $c = 4.184\times10^{-11}$ Fit: $h(\tau) = a\cdot\tau^{-1} + b + c\cdot\tau$



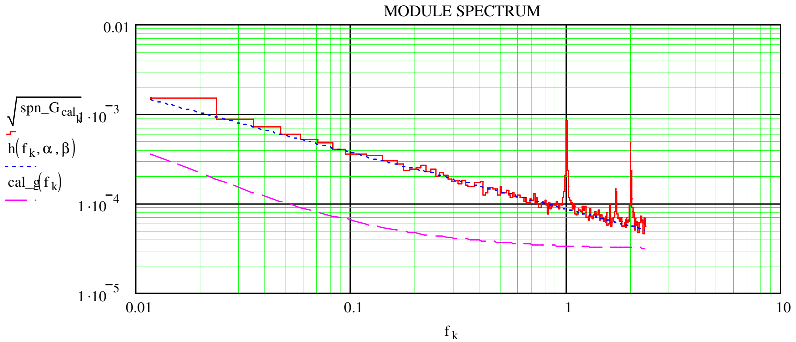
$\alpha = 0.59$ $\beta = 8.574\times10^{-5}$ Fit: $h(f) = \beta\cdot f^{-\alpha}$



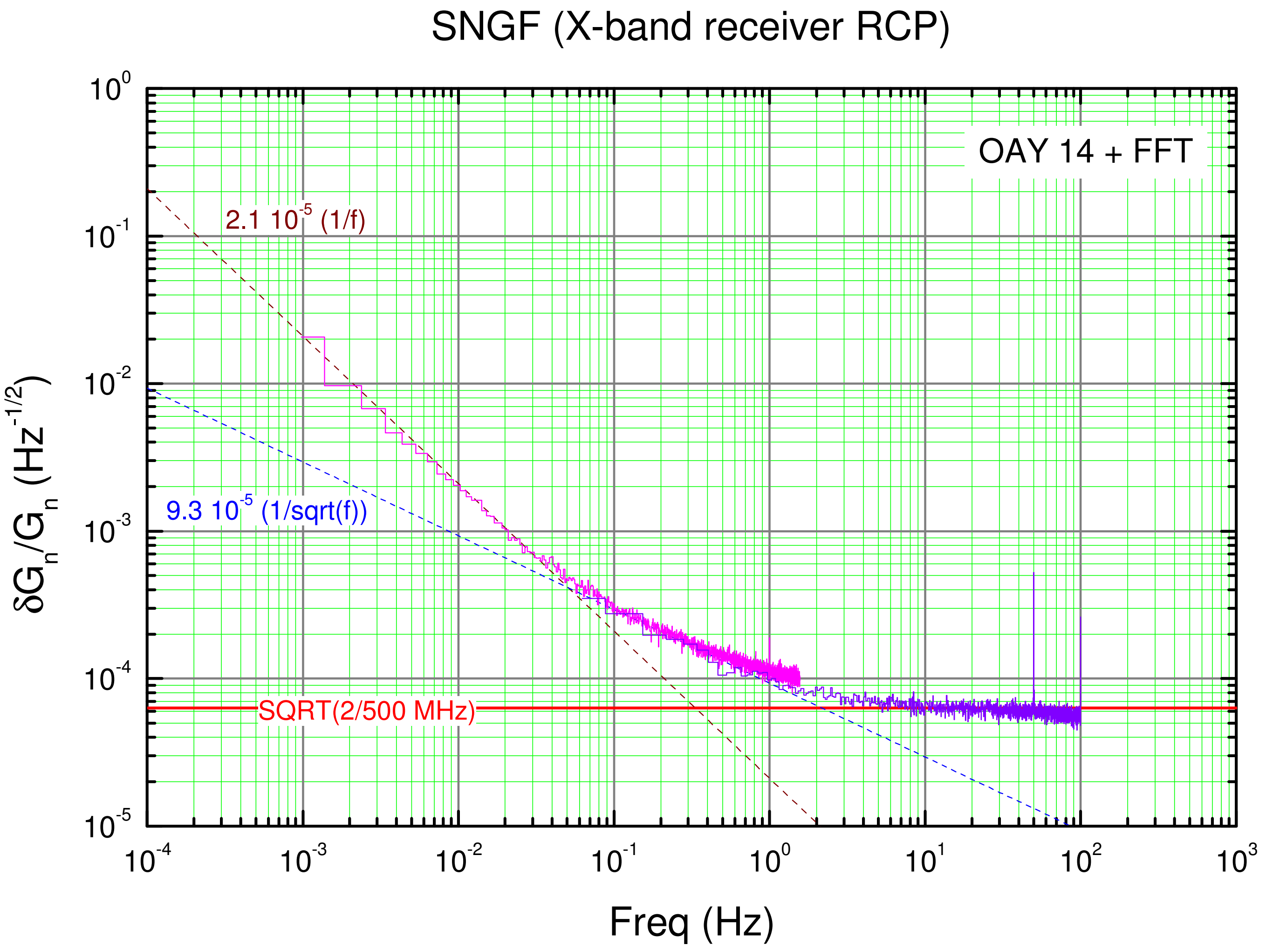
$a = 6.097\times10^{-9}$ $b = 9.063\times10^{-9}$ $c = 1.833\times10^{-9}$ Fit: $h(\tau) = a\cdot\tau^{-1} + b + c\cdot\tau$



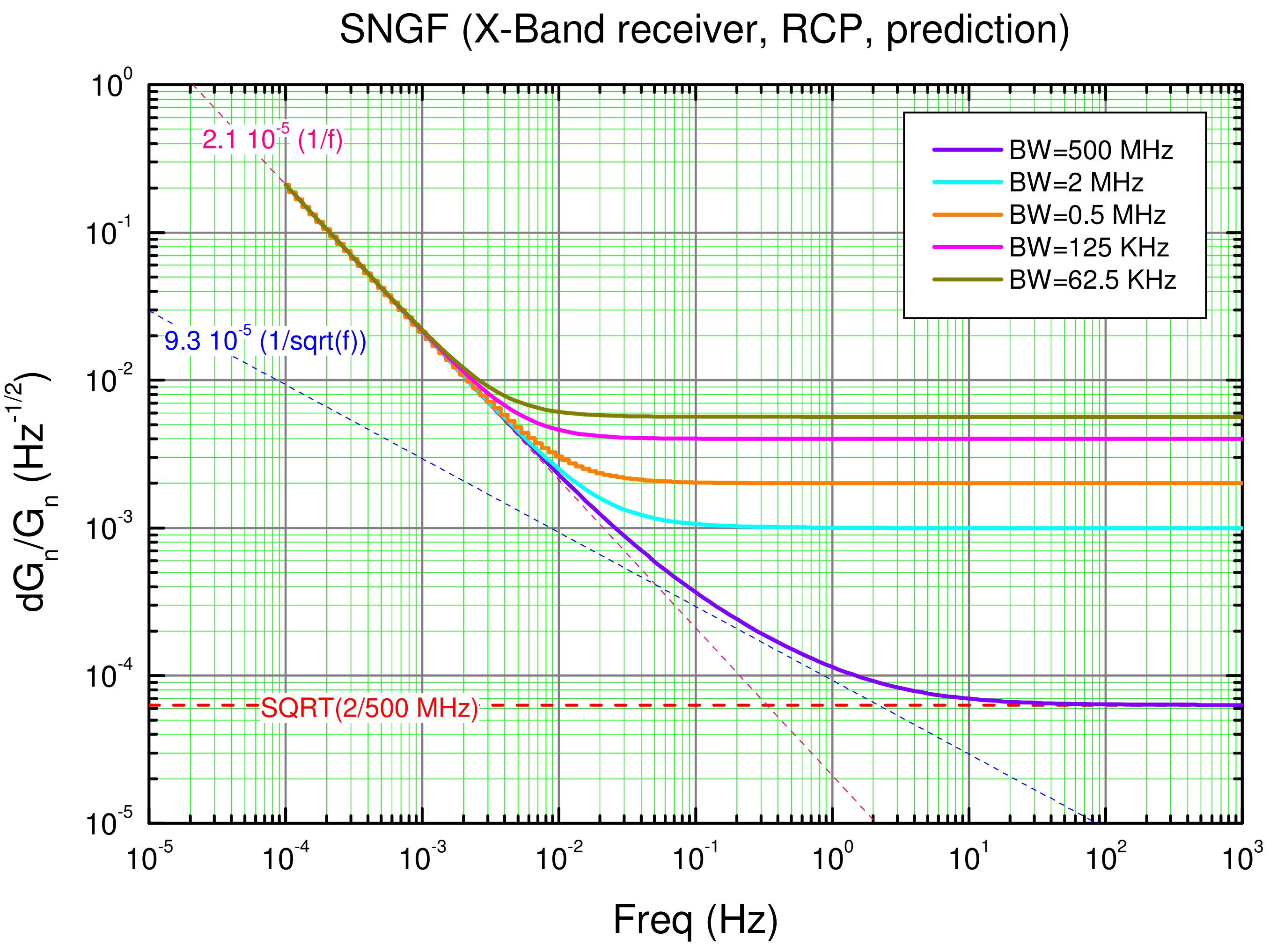
$\alpha = 0.633$ $\beta = 8.608\times10^{-5}$ Fit: $h(f) = \beta\cdot f^{-\alpha}$



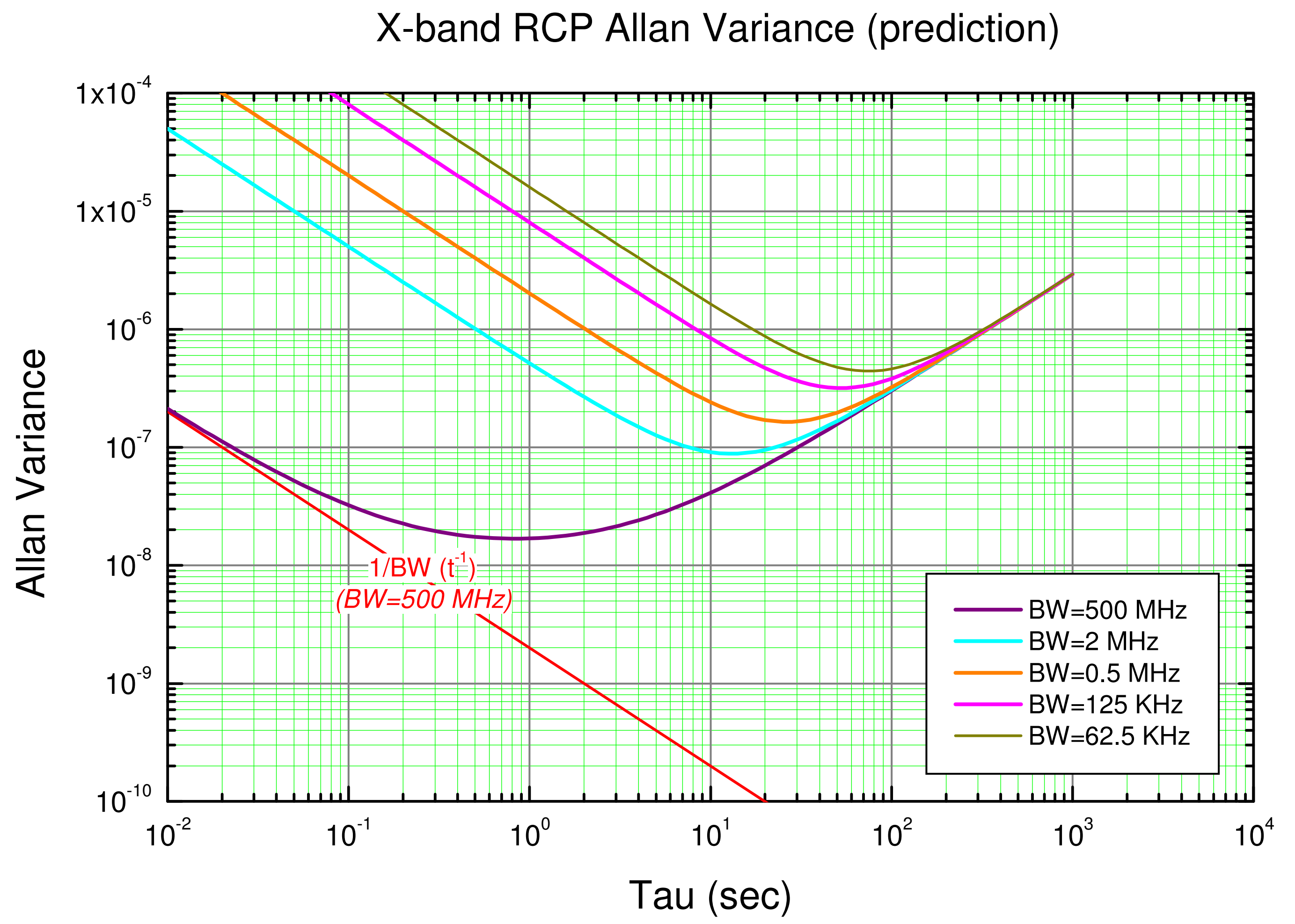
Real receiver: CAY 40m



Real receiver: CAY 40m VLBI



Real receiver: CAY 40m VLBI



Specs of Gain Fluctuations (examples)

- HERSCHEL:
  - Far Infrared and Submillimeter 3.5 m Telescope orbiting in L2 with 3 cryogenic instruments
  - HIFI: Heterodyne Instrument for the Far Infrared with 7 dual polarization submillimeter SIS and HEB receivers
  - Low noise, wide band 4-8 GHz cryogenic IF preamplifiers
  - Specification for cryo amplifiers:

$$\Delta G_n = 1.4 \cdot 10^{-4} \ {}^{1}\!/\!\sqrt{Hz} \quad @1 \cdot Hz$$

- ALMA:
  - Atacama Large Millimeter Array (USA, Europe, Japan), 64 Antennas, 35-850 GHz
  - 4-8 and 4-12 GHz cryogenic IF preamplifiers (bands 7 and 9)

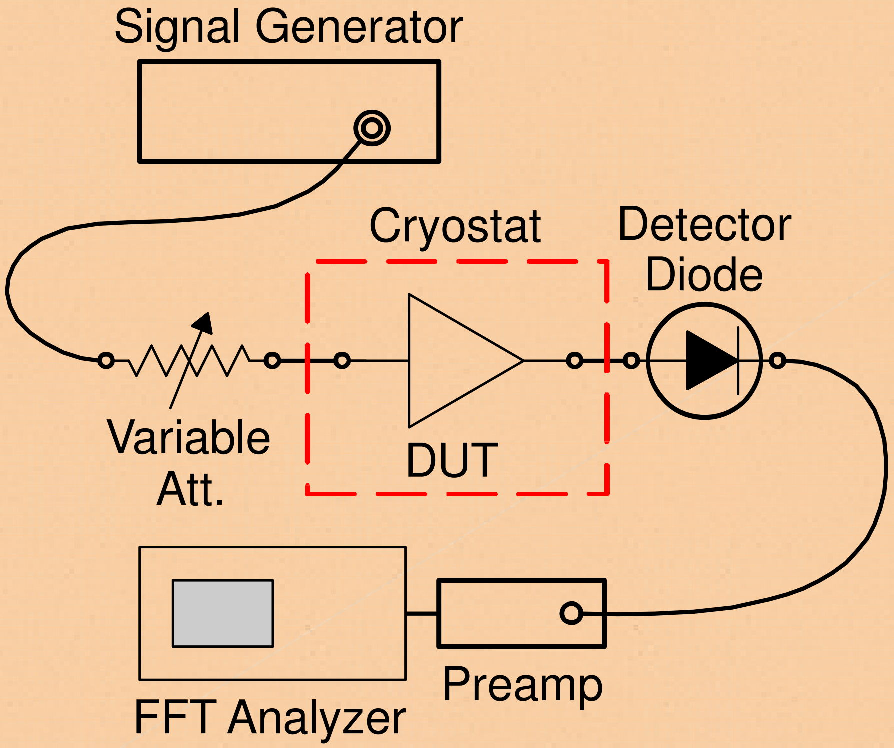
$$\begin{cases} \sigma^2(\tau) \le 2 \cdot 10^{-8} & 0.05 \le \tau \le 100 \quad (\text{sec}) \\ \sigma^2(\tau) \le 2 \cdot 10^{-7} & 100 < \tau \le 300 \quad (\text{sec}) \end{cases}$$

$$\Delta G_n = 8.4 \cdot 10^{-5} \ {}^{1}\!/\!\sqrt{Hz} \quad @1 \cdot Hz$$

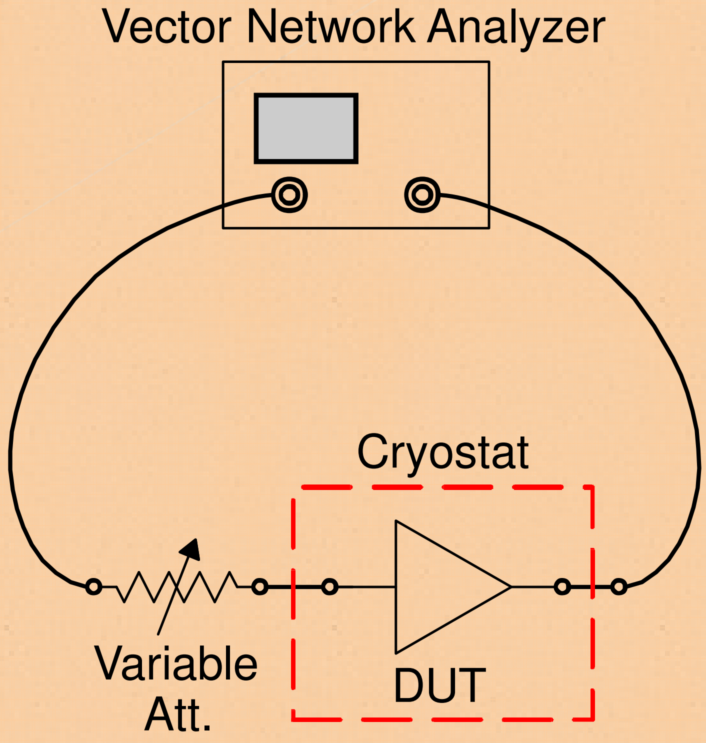
Gain Fluctuation Measurements

Measurement of individual amplifiers

System A

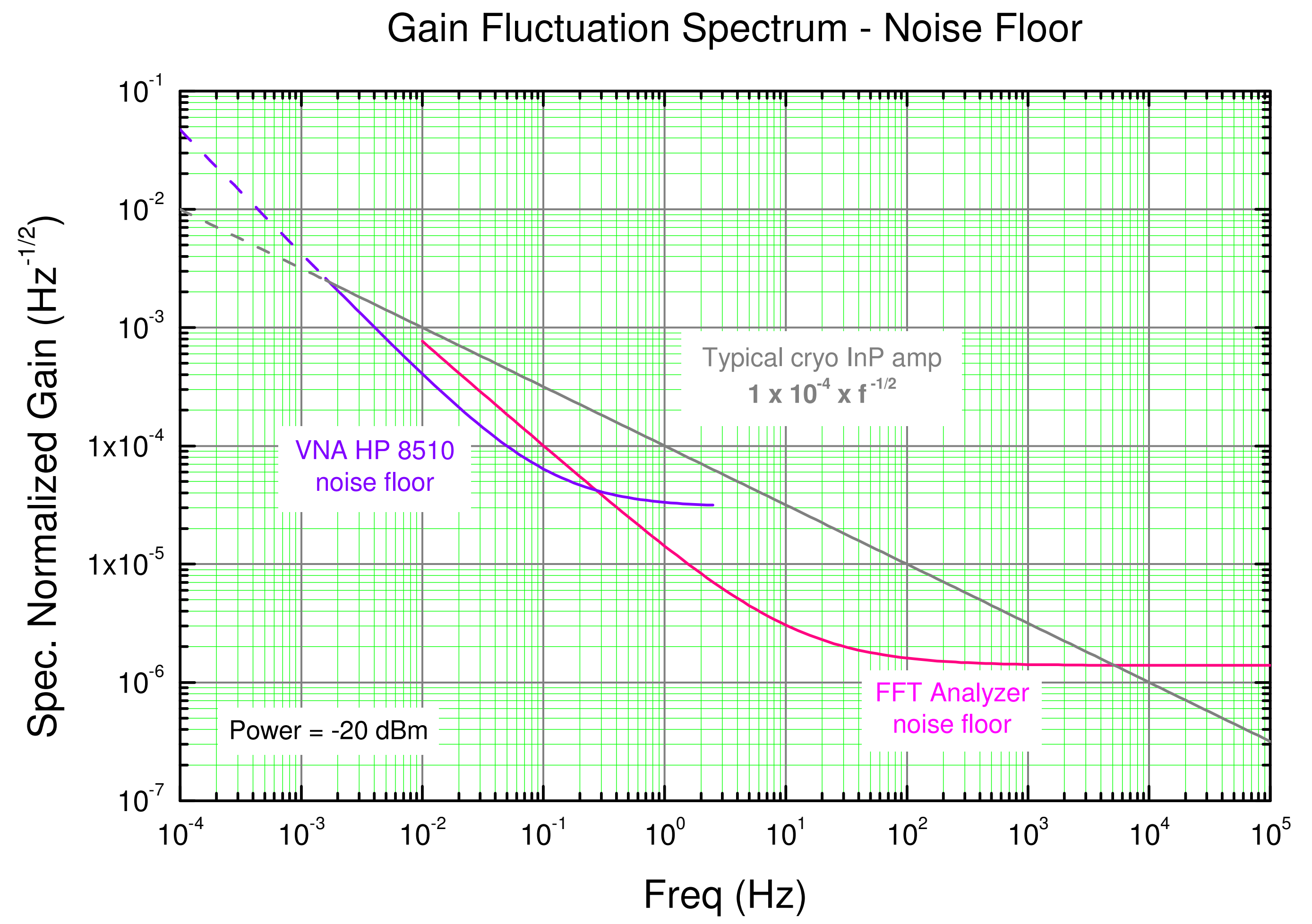


System B

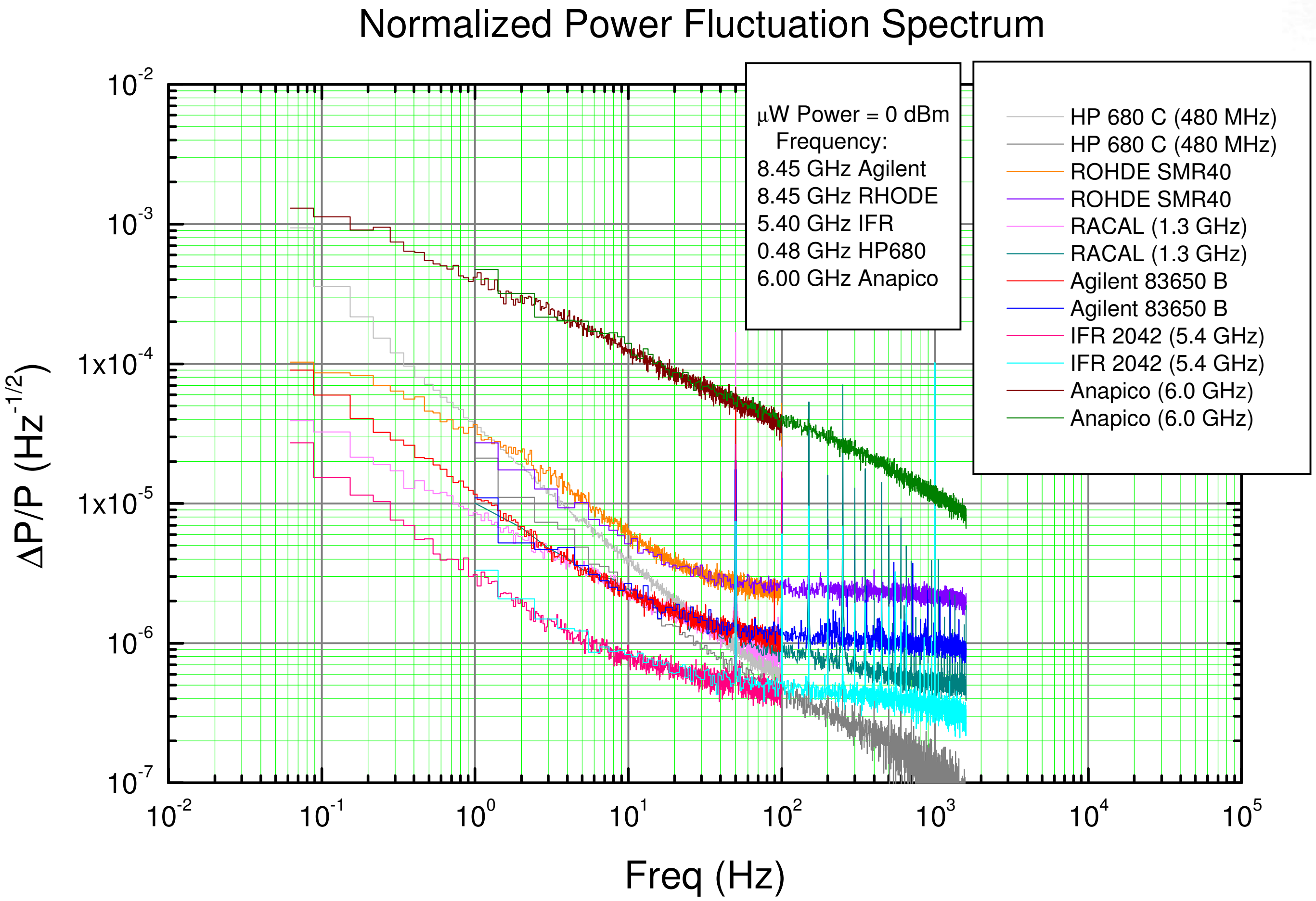


Details in ALMA memo 560

Measurement Systems

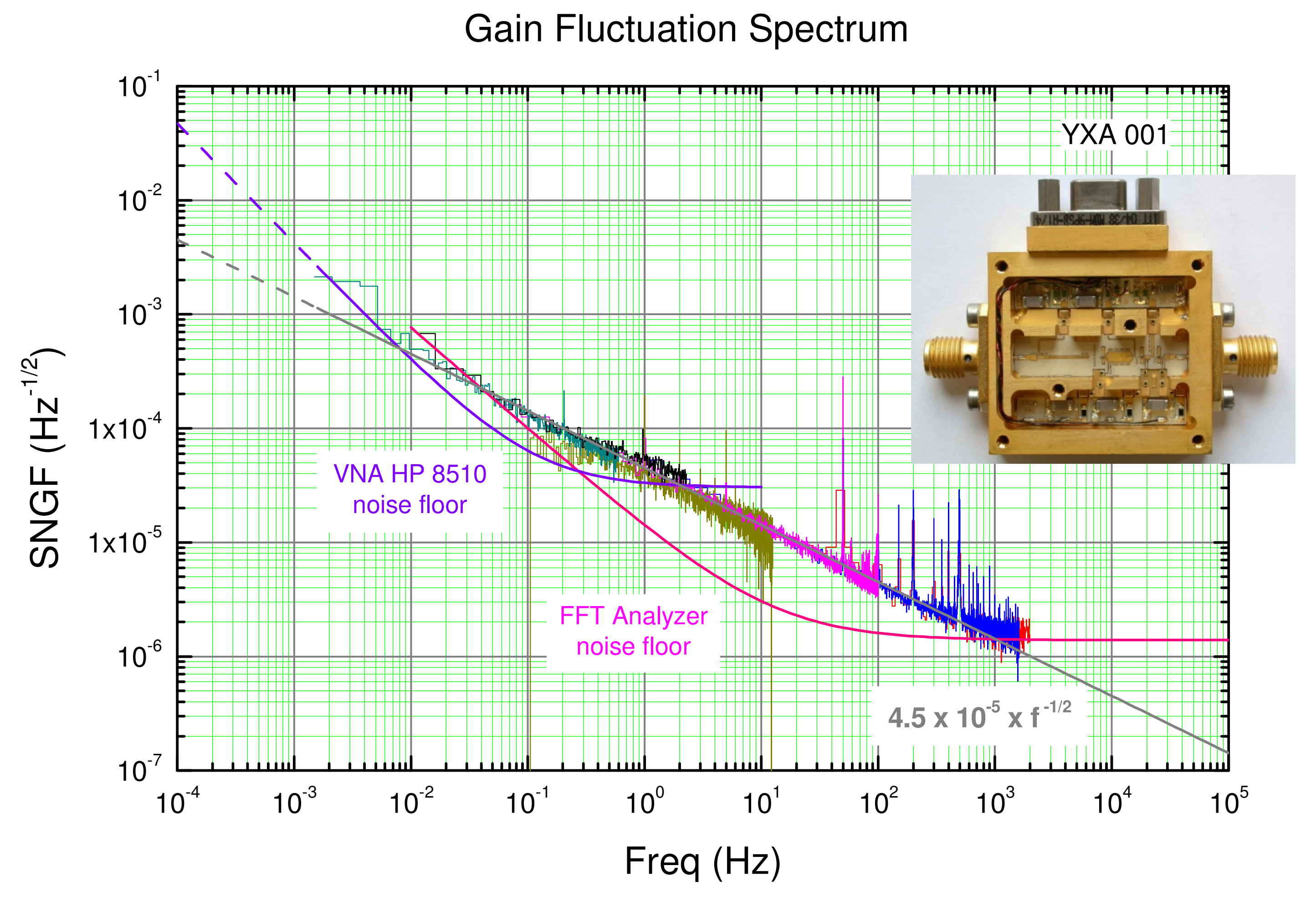


Performance of Signal Generators



µW Power = 0 dBm
Frequency:
8.45 GHz Agilent
8.45 GHz RHODE
5.40 GHz IFR
0.48 GHz HP680
6.00 GHz Anapico

Measurement example



Lessons Learned

- Classical approach: noise input
  - High MW gain needed (many amp. stages or complete radiometer)
  - Sensitivity limited at high audio frequencies (noise bandwidth)
- This approach: single tone
  - Good generator or VNA needed
  - Characterization of individual amplifiers (even a single stage!)
  - Information at different input frequencies in the band
  - Good sensitivity at high audio frequency (generator + FFT)
  - Highly immune to interferences (VNA)
  - Information on phase noise possible (VNA)
    - ➔ New VNAs (PNA) not as good as old models (8510) for stability measurements
- Measurements are slow and should be done very carefully
  - Stable temperature in the lab
  - No cell phones!

Gain Fluctuation Origin

- Origins
  - External
    - ➔ Power supply
    - ➔ Temperature variations (refrigerator cycle)
    - ➔ Microphonics (vacuum pumps)
  - Internal
    - ➔ Intrinsic to the devices
- Typical Intrinsic Spectrum of Cryogenic Amplifiers

$$S(f) = b \cdot \left(\frac{1 \cdot Hz}{f} \right)^{\alpha}$$

$\alpha \approx 1/2$

Is the Power Supply important?

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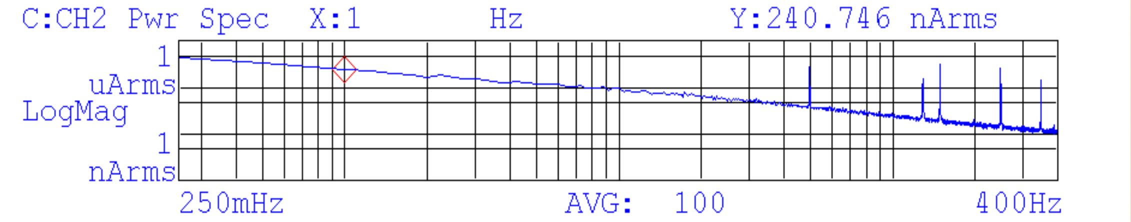
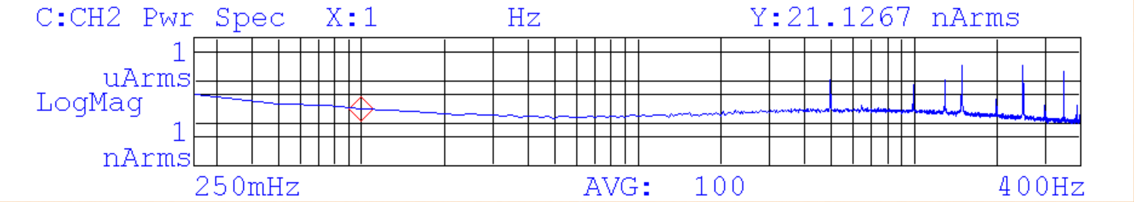
- Possibilities:
  - Constant Vd, Vg
  - Constant Id, Vg (variable Vd)
  - Feedback: Constant Vd, Id (controlled Vg)
- Power supply must be low noise
  - Examples: Agilent N3280 or classical NRAO feedback supply
  - Typically the gain fluctuation caused by noise from the power supply is more than two orders of magnitude below the observed values in cryogenic amplifiers
- Best results always obtained with feedback supply
  - but not much improvement at cryogenic temperature
- Worst results obtained with constant Id, Vg

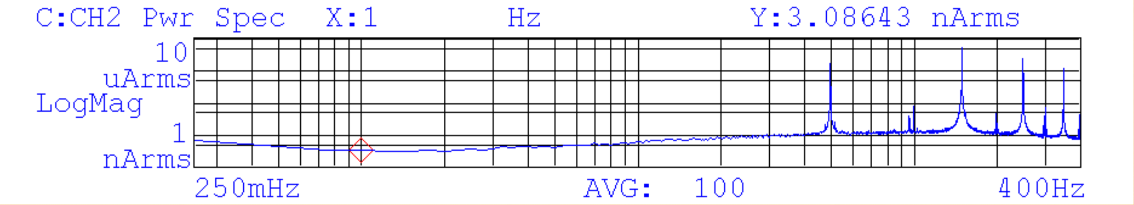
Illustration of the reduction of Id fluctuation with Feedback Power Supply at T=15 K



YCF 4001 Vd=1.10
Id=3 Rd=172 T=14 K,
Constant Vd, Vg



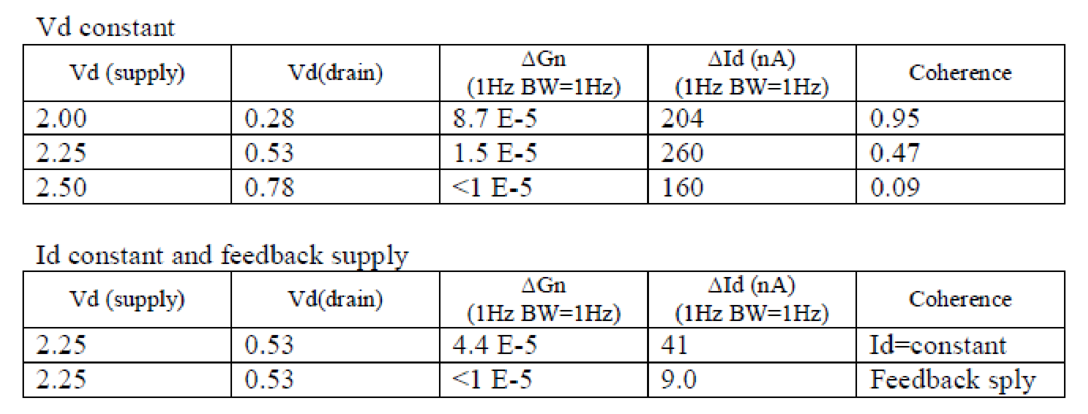
YCF 4001 Vd=1.10
Id=3 Rd=172 T=14 K,
Constant Id, Vg



YCF 4001 Vd=1.10
Id=3 Rd=172 T=14 K,
Feedback Supply

Coherence of Gain-Id fluctuations (ambient)

Measurements on 1 stage amplifier (YCF4001)



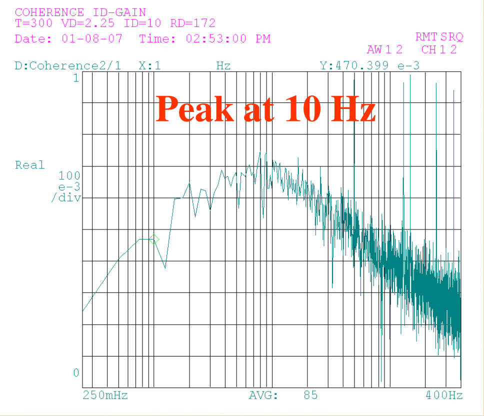
Vd constant

Vd (supply)	Vd(drain)	ΔGn (1Hz BW=1Hz)	ΔId (nA) (1Hz BW=1Hz)	Coherence
2.00	0.28	8.7 E-5	204	0.95
2.25	0.53	1.5 E-5	260	0.47
2.50	0.78	<1 E-5	160	0.09

Id constant and feedback supply

Vd (supply)	Vd(drain)	ΔGn (1Hz BW=1Hz)	ΔId (nA) (1Hz BW=1Hz)	Coherence
2.25	0.53	4.4 E-5	41	Id=constant
2.25	0.53	<1 E-5	9.0	Feedback sply

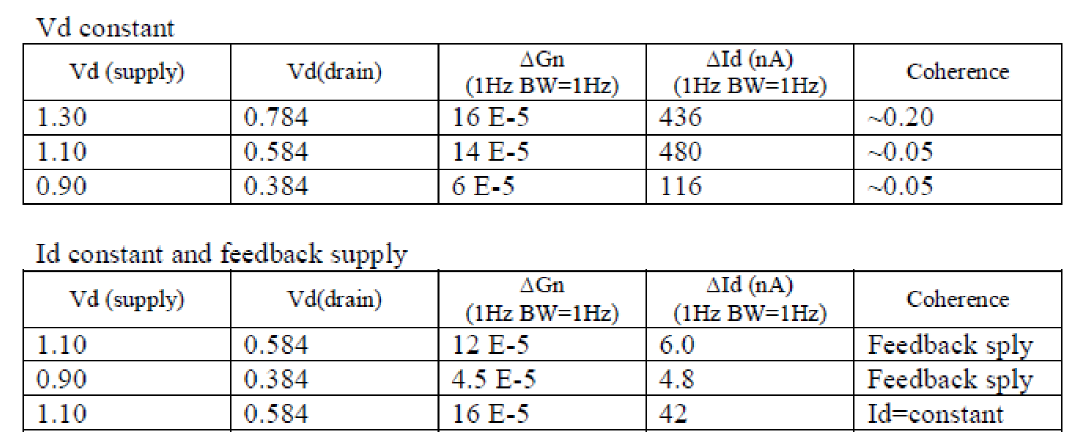
- Very **strong coherence at low drain voltage** (linear part of Id-Vd curve)
- Only **partial coherence at the “optimum” bias**
- The DC current fluctuation does not follow the same pattern
- **Worst results** obtained with **constant Id** and Vg
- **Best results** obtained with **feedback supply**



Peak at 10 Hz

Coherence of Gain-Id fluctuations (cryogenic)

Measurements on 1 stage amplifier (YCF4001)



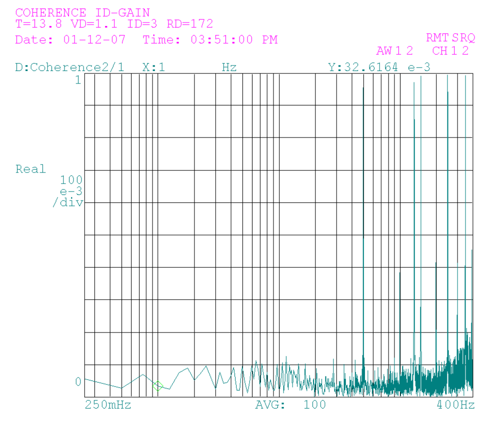
Vd constant

Vd (supply)	Vd(drain)	ΔGn (1Hz BW=1Hz)	ΔId (nA) (1Hz BW=1Hz)	Coherence
1.30	0.784	16 E-5	436	~0.20
1.10	0.584	14 E-5	480	~0.05
0.90	0.384	6 E-5	116	~0.05

Id constant and feedback supply

Vd (supply)	Vd(drain)	ΔGn (1Hz BW=1Hz)	ΔId (nA) (1Hz BW=1Hz)	Coherence
1.10	0.584	12 E-5	6.0	Feedback sply
0.90	0.384	4.5 E-5	4.8	Feedback sply
1.10	0.584	16 E-5	42	Id=constant

- **Low coherence** (only observed at high Vd)
- **Higher values** of gain fluctuation and Id fluctuation at cryogenic temperature
- **No (significant) improvement with feedback supply**



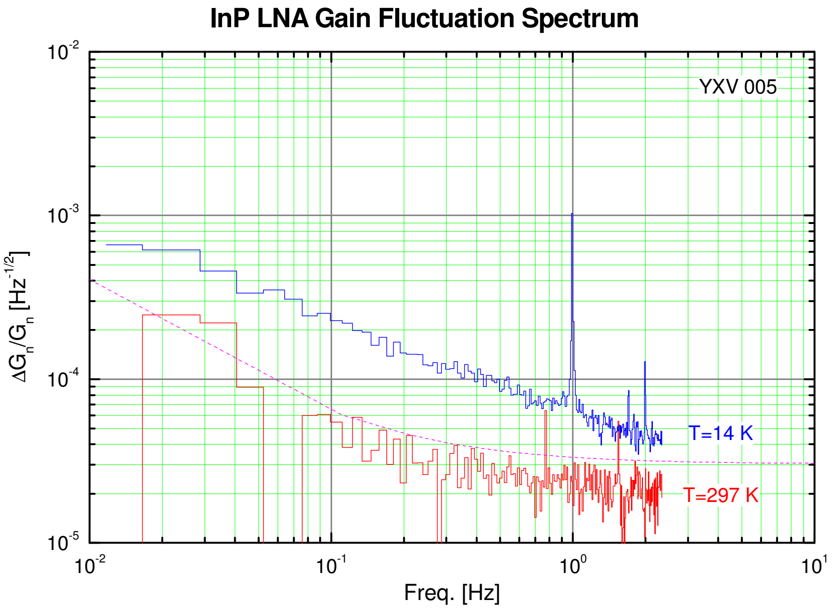
What can be done?

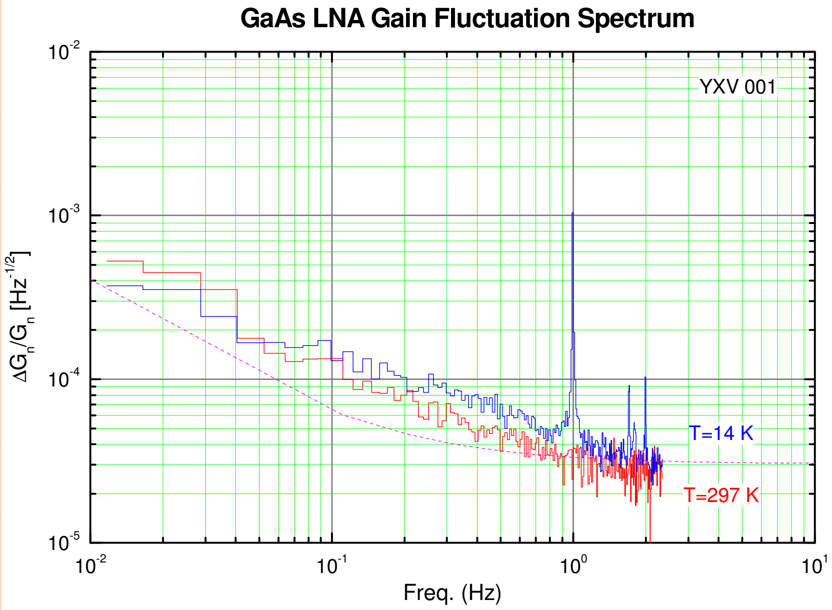
- Unfortunately DC and MW fluctuation appear to be non-coherent at optimum bias and cryo temperature → power supply does not help much
- Similar to problem with Rds and Gm (different values at low and MW, related with trap time constants)
- Use of "pilot" signals has been suggested sometimes (E. Wollak 1995, S. Weinreb)
- In this work: modulation at audio frequency of bias supply (low level, ~60 KHz, cryogenic temperature) for sampling Gm was tried. A coherence of 0.3 with was found
- More work needed

Intrinsic Gain Fluctuations Dependence

- Improvements in Noise
  - Shorter gate length
  - HEMTs
  - InP substrate
  - Cryogenic Temperature
- Improvements in Gain Stability
  - Larger gate area
  - Non HEMT
  - GaAs substrate
  - Ambient Temperature
- Conclusion:
  - Advances in the reduction of Noise Temperature have contributed to increase Gain Fluctuations

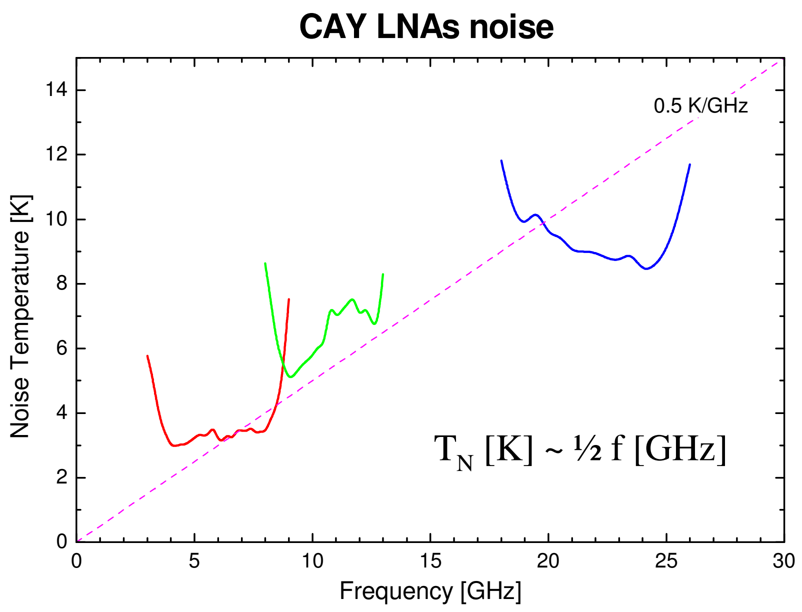
Material (InP vs. GaAs) and Temperature (amb. vs. cryo.)

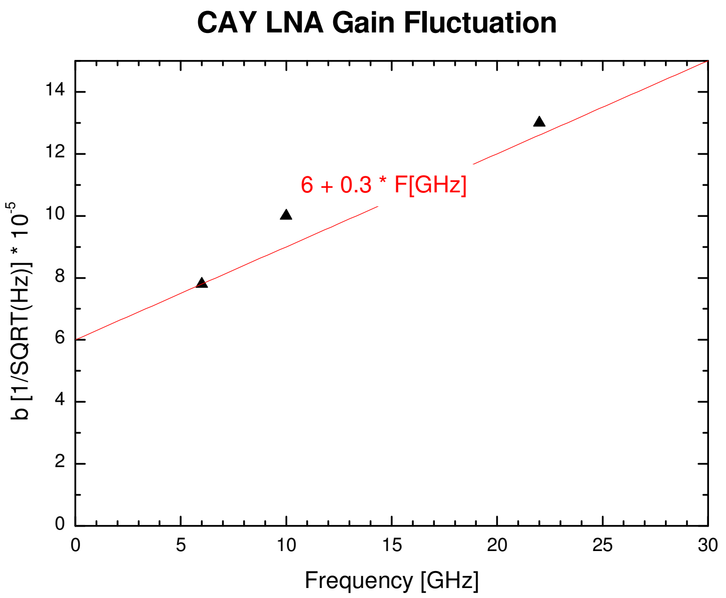




DEVICES		NOISE TEMPERATURE [K]			GAIN FLUCTUATIONS [$Hz^{-1/2}$]		
TECHNOLOGY	MODEL	297 K	14 K	VARIATION	297 K	14 K	VARIATION
GaAs	FHX13X 200×0.25µm	99	13.6	**÷ 7.3**	2.0E-5	3.4E-5	**× 1.7**
InP	NGST 160 160×0.1µm	96	6.5	**÷ 14.8**	(1.3E-5)	9.4E-5	**× (7.2)**
	ETH 200 200×0.2µm	108	6.7	**÷ 16.1**	(1.0E-5)	7.0E-5	**× (7.0)**
GaAs – InP Variation [times]		None	**÷ 2.1**	–	÷ (1.7)	**× 2.8**	–

Frequency Band

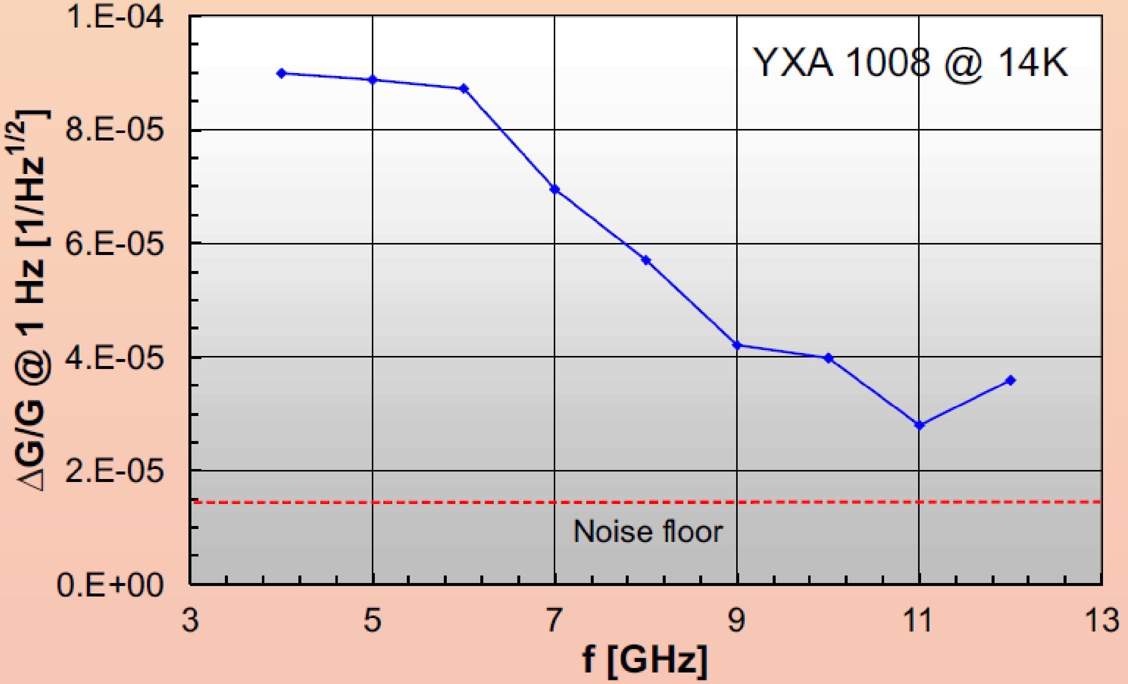




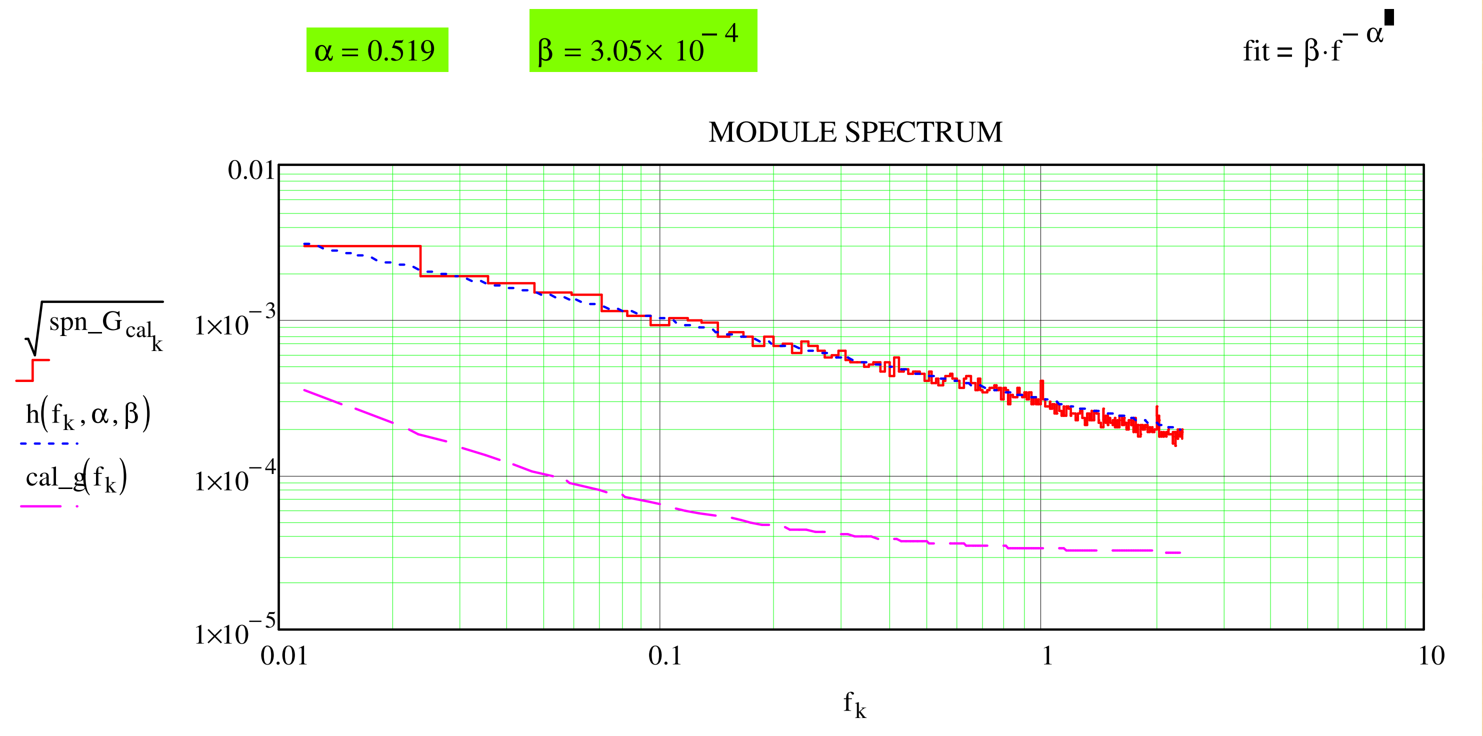
AMPLIFIER	BAND [GHz]	STAGES	DEVICES	NOISE [K]	GAIN [dB]	GAIN FLUCTUATIONS	
						b [$Hz^{-1/2}$]	α
YCA 2	4 - 8	3	2 × NGST CRYO4	3.5	39.2	7.8E-5	0.64
YXF 0	8-12	2	NGST 160 + FHX13X	6.5	21.9	10E-5	0.58
YK22	18 - 26	3	NGST CRYO3 + 2 × NGST 160	8.9	26.1	13E-5	0.43

Different Frequencies in the Band

Frequency dependence: Fluctuations @ 1 Hz measured with CW vary significantly with the input frequency. This may be due to the dominant role of the transistors transconductance gm in the gain fluctuations. Monte Carlo simulations performed show that variations of gm produce variations of gain with similar frequency dependence. Cgs will produce gain variations in the opposite sense.



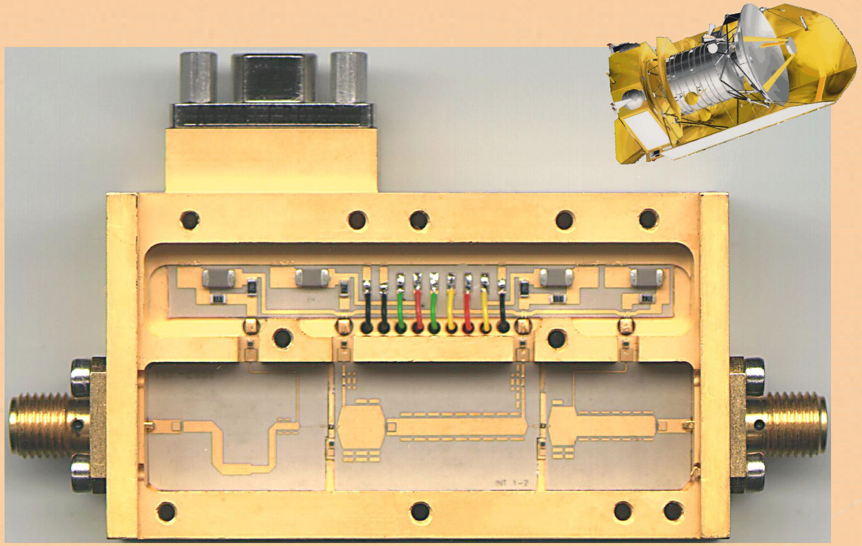
Defective Materials

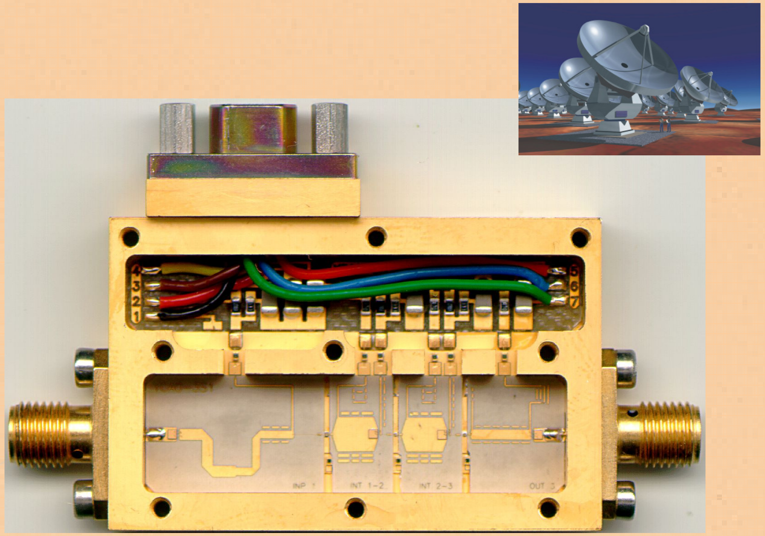


$\alpha = 0.519$ $\beta = 3.05\times 10^{-4}$ $\mathrm{fit} = \beta \cdot f^{-\alpha}$

- Manchester 0.13×200 µm Run March 2011
- Bad material, ~ <u>4 times</u> more fluctuation
- Noise was almost normal

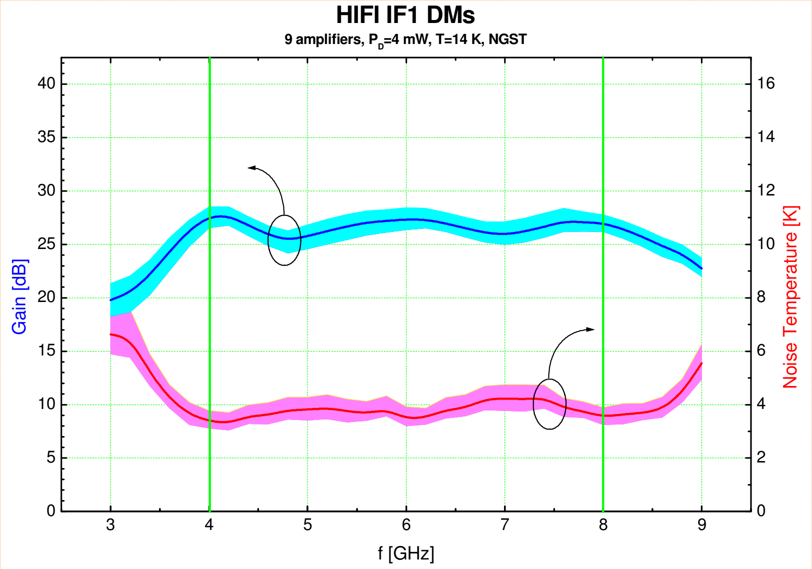
Statistical Analysis: Results of long series (1)

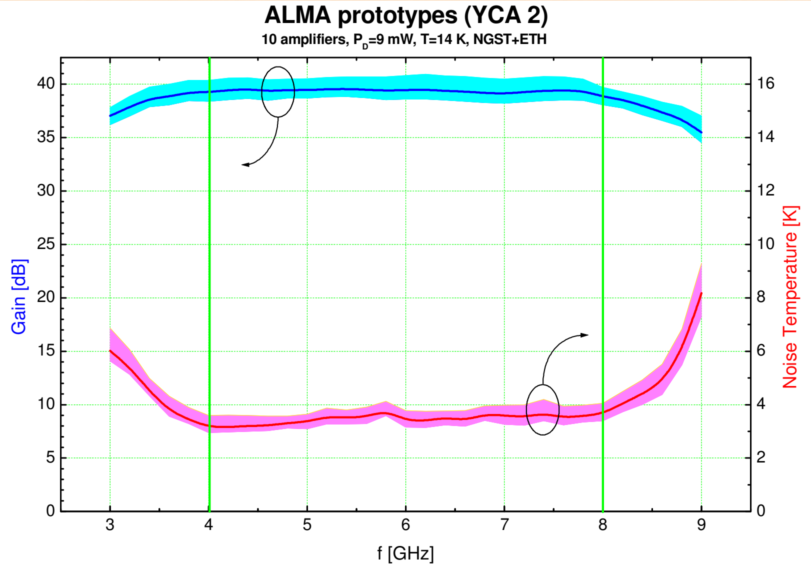




- Analyzed two series of 9 and 10 state-of-the-art 4-8 GHz cryogenic amplifiers designed and built at CAY with microstrip hybrid technology:
  - Development models for Herschel space telescope (all cryogenic LNAs for HIFI)
    - ➔ 2 stages of InP NGST transistors
    - ➔ Design constrained by space qualification
  - Pre-production phase of ALMA (cryogenic LNAs for the European contribution)
    - ➔ 3 stages of InP NGST and ETH transistors.
    - ➔ Based on HIFI design, with more degrees of freedom

Statistical Analysis: Results of long series (2)





AMPLIFIER YCF	GAIN FLUCT. @ 1 HZ (b)	SPECTRAL INDEX (α)
6004	8.62E-05	0.754
6005	8.88E-05	0.706
6006	8.58E-05	0.332
6007	14.5E-05	0.430
6009	10.0E-05	0.726
6010	8.69E-05	0.415
6011	11.4E-05	0.324
6012	9.03E-05	0.429
6014	10.2E-05	0.762

AMPLIFIER YCA	GAIN FLUCT. @ 1 HZ (b)	SPECTRAL INDEX (α)
2003	7.43E-05	0.668
2004	7.65E-05	0.690
2005	7.91E-05	0.606
2006	7.51E-05	0.731
2007	7.04E-05	0.640
2008	8.72E-05	0.647
2009	8.61E-05	0.633
2010	8.39E-05	0.588
2011	7.21E-05	0.639
2012	7.13E-05	0.606

Statistical Analysis: Results of long series (3)

HIFI AMPLIFIERS

x	MIN.	MAX.	$\bar{x}$	$\sigma / \bar{x}$
T_N [K]	3.4	4.2	**3.78**	**0.076**
b [Hz$^{-1/2}$]	8.58E-5	14.5E-5	**9.99E-5**	**0.194**
α	0.321	0.762	0.542	0.351

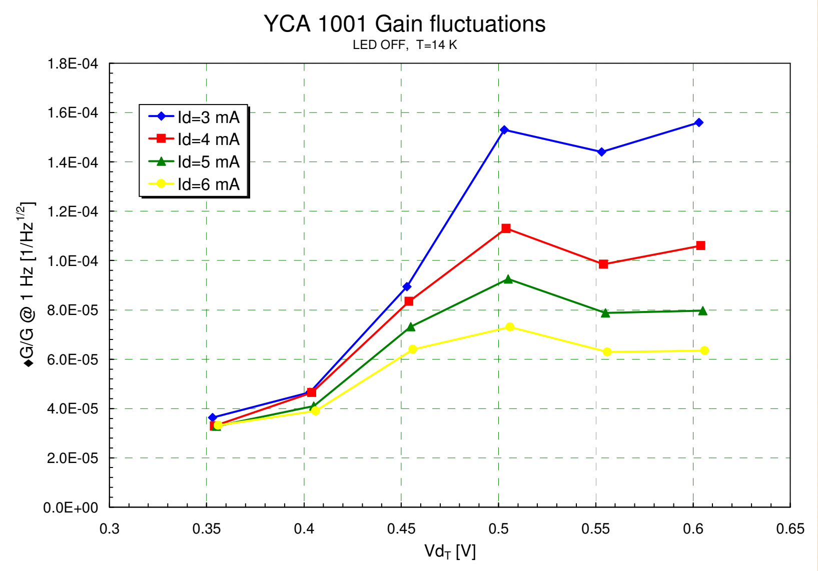
ALMA AMPLIFIERS

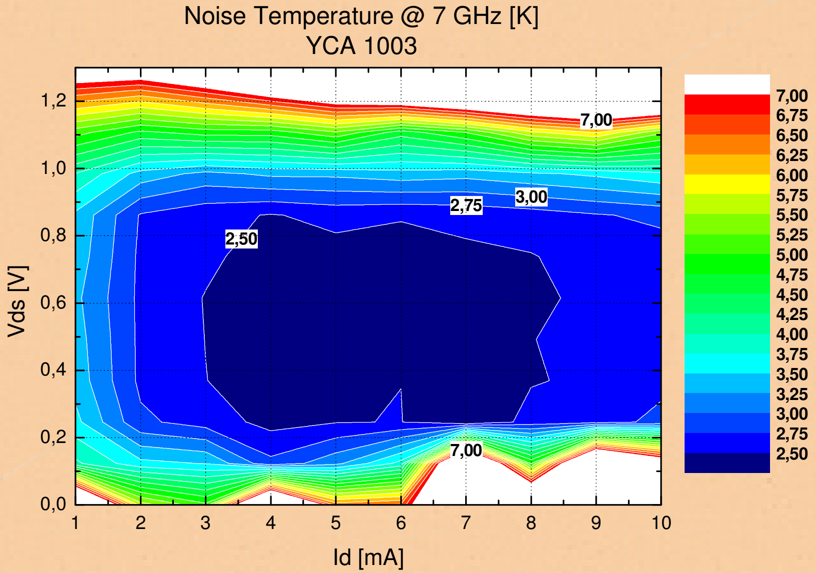
x	MIN.	MAX.	$\bar{x}$	$\sigma / \bar{x}$
T_N [K]	3.2	3.8	**3.46**	**0.051**
b [Hz$^{-1/2}$]	7.04E-5	8.72E-5	**7.76E-5**	**0.080**
α	0.588	0.731	0.645	0.066

- Mean values of noise and fluctuations are similar in both series
- Excellent repeatability in noise and gain
- Greater dispersion of gain fluctuations results (value @ 1 Hz and spectral index)
- HIFI dispersion in fluctuations significantly wider than ALMA
  - Bias conditions homogeneous for both series
  - Different transistor batch used for each series of amplifiers

- **Some transistor batches exhibit high scattering of gain fluctuations within devices of the same batch not shown in noise results**
- **Observed also a significant batch to batch variation**

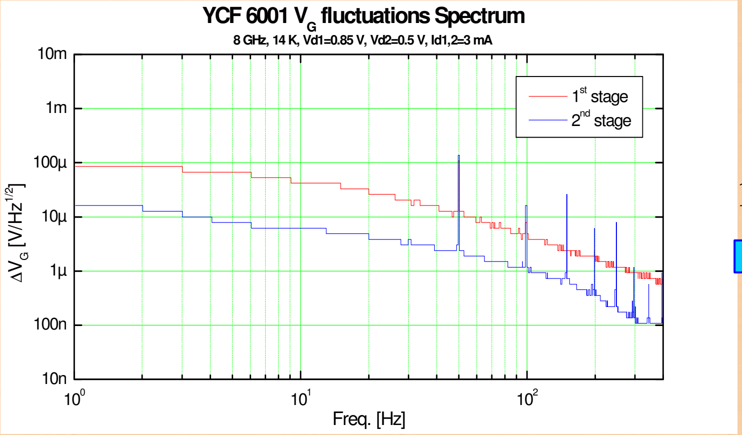
Bias Point (1)



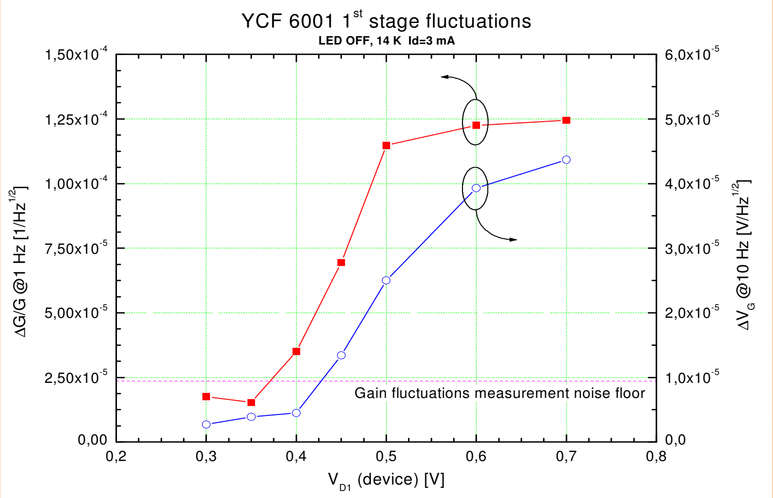


- Tested the variation of gain fluctuations and noise with Vd, Id
  - Found a steep change in gain fluctuations around 0.4-0.5 V
  - Noise (and gain) are much more insensitive to bias changes
  - High fluctuation zones could be avoided with no penalty in noise or gain
- Gain fluctuations ↑ when Id ↓

Bias Point (2)

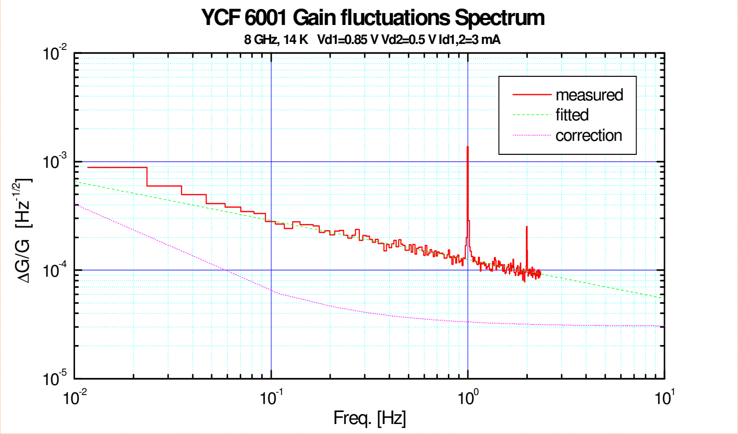


10 Hz



- Tested also fluctuations of gate voltage with HP35670A
  - Found similar bias dependence
- Simple measurements of voltage fluctuations may help detecting sensitive bias regions
- Correlation with gain fluctuations for different devices useful for pre-selecting least fluctuating devices from a batch

1 Hz



Conclusions

- The reduction in noise and the increase in bandwidth of modern cryogenic amplifiers have made more prominent the problem of gain fluctuations
- Data on gain fluctuations of cryogenic amplifiers collected over the years
- Systematic measurement with a VNA are possible, although very time consuming
- The reduction (or at least some control) of the gain fluctuations is possible with an adequate selection of devices and bias
- Lack of theoretical model

END