Low frequency noise measurements in direct detection radiometers

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Receiver Gain Stability

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Why we test 1/f noise?

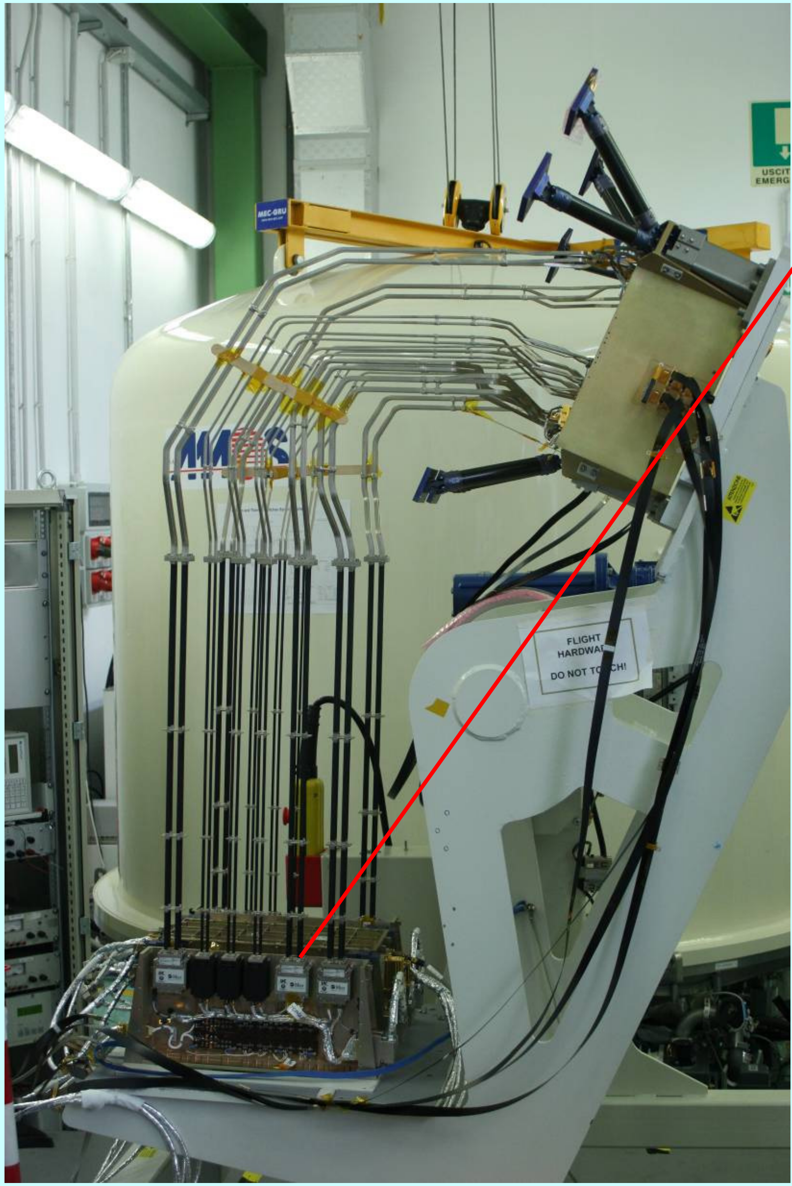
- Planck mission (ESA): Low Frequency Instrument (LFI)

- To map spatial anisotropy in the Cosmic Microwave Background (CMB)

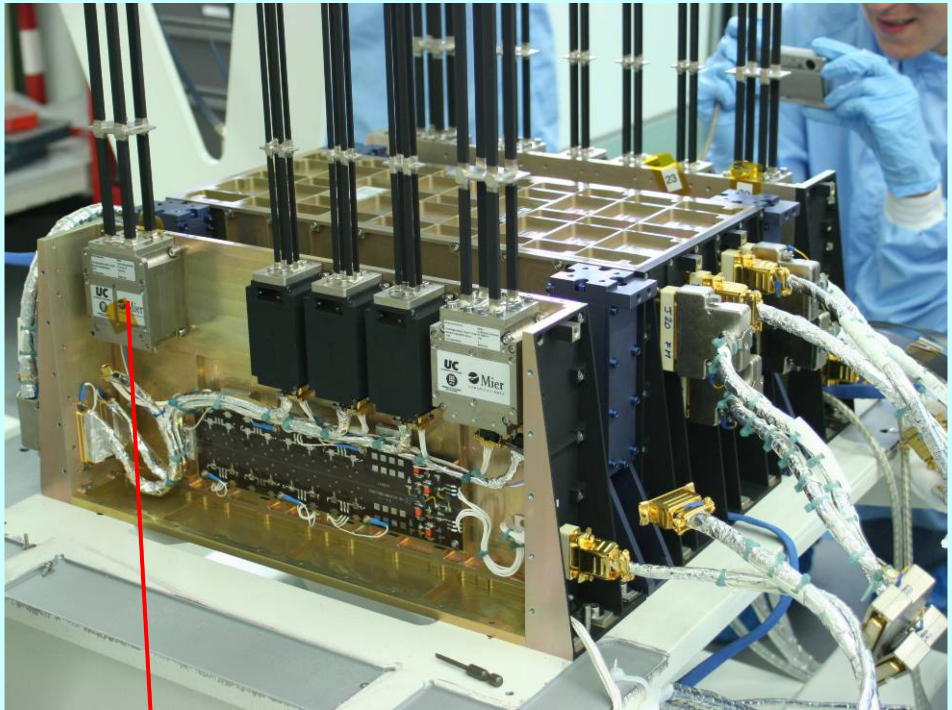
- Data with low 1/f noise to achieve scientific objectives

- Pseudo-correlation radiometers (to cancel 1/f noise)

Planck-LFI integration



Three Back End Modules at 44 GHz



Two Back End Modules at 30 GHz

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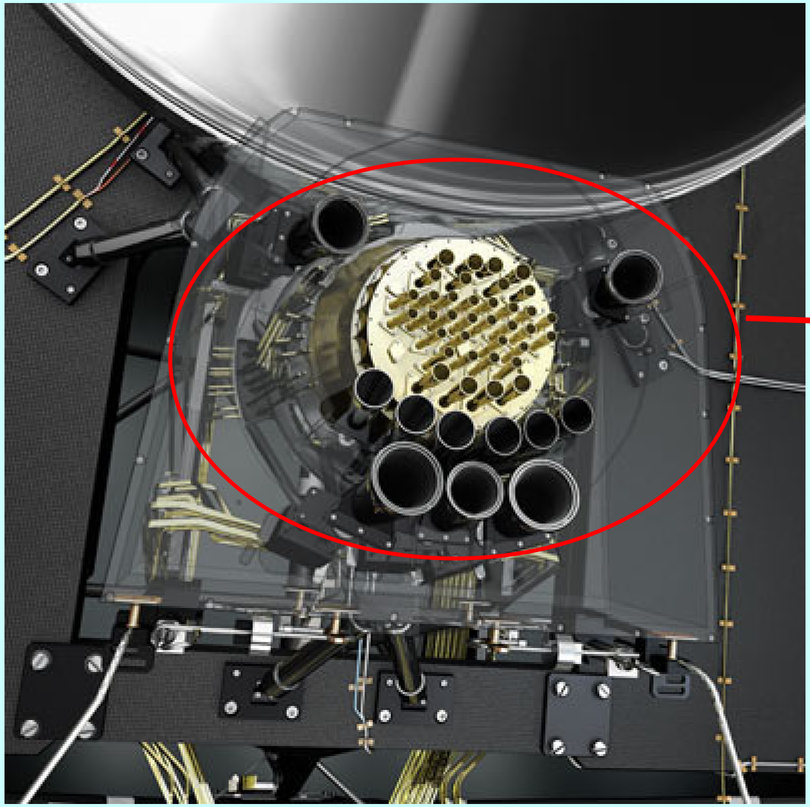
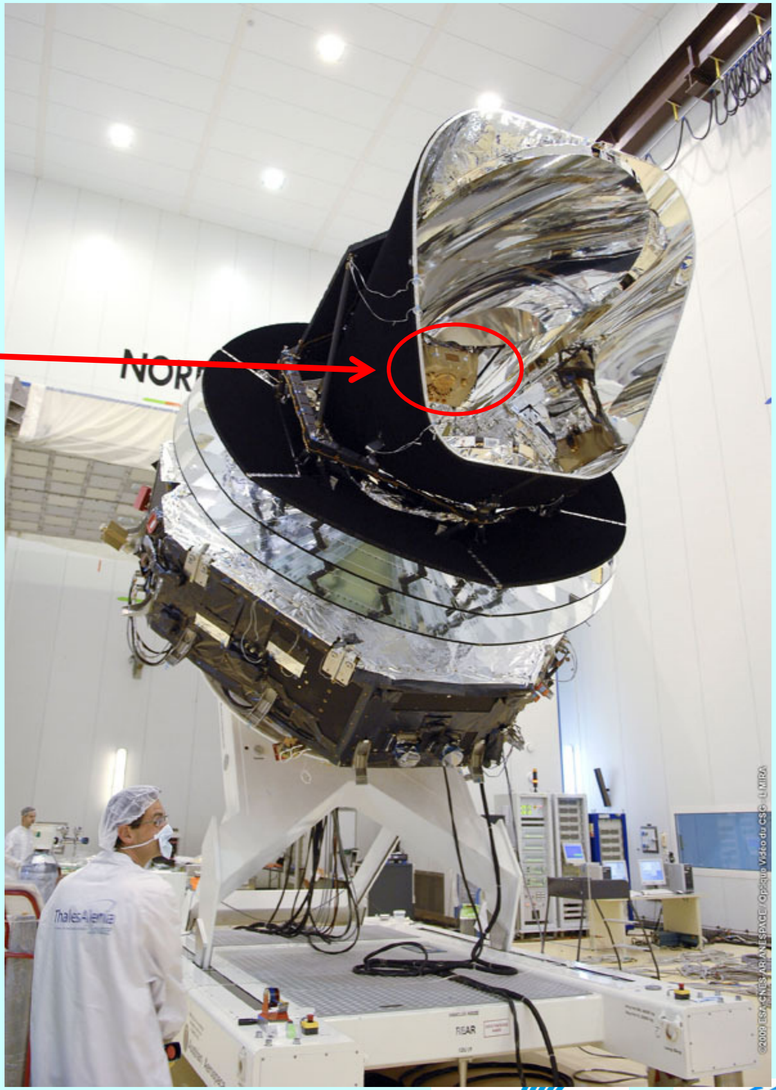
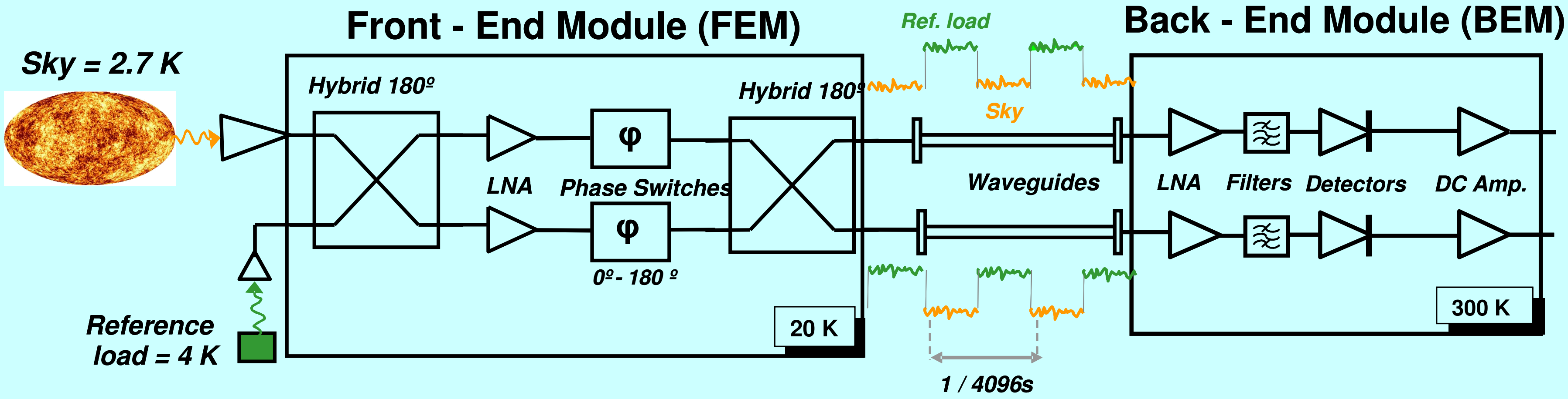
Planck receivers (LFI + HFI)





Planck-LFI radiometer scheme



1/f noise limitations in Planck-LFI

- Planck satellite rotation (scan): 1 rpm ≅ 0.0166 Hz = f_{spin}
- Post-detection knee frequency $f_k < f_{spin}$ (should be)
- For $f_k > f_{spin}$ ⇒ mitigate 1/f effects by "destriping and map making algorithms"
- Small residual knee frequency (of ~ 0.1 Hz)

1/f noise limitations in Planck-LFI

Strategies to mitigate 1/f noise:

- Gain modulation (r factor applied in software) compensates different temperatures of the reference load (4 K) and sky (2.7 K):

$$r = \frac{T_{sys} + T_{sky}}{T_{sys} + T_{ref}} \Rightarrow Vout = A\left(T_{sky} + T_{sys} - r\left(T_{ref} + T_{sys}\right)\right) \approx 0$$

- Fast phase switching ($f_{sw} \sim$ 4 kHz) reduces the impact of 1/f fluctuations of BEM amplifiers ($f_{sw} >> f_{kBEM}$):

$$f_{kBEM} << 4\ kHz$$

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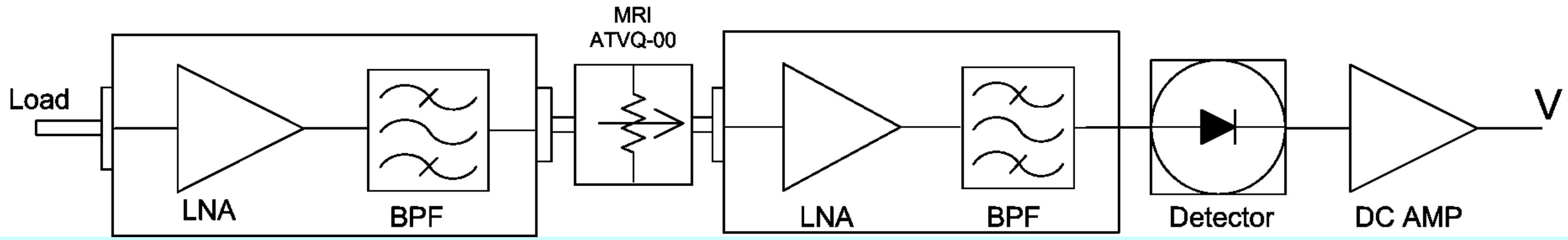
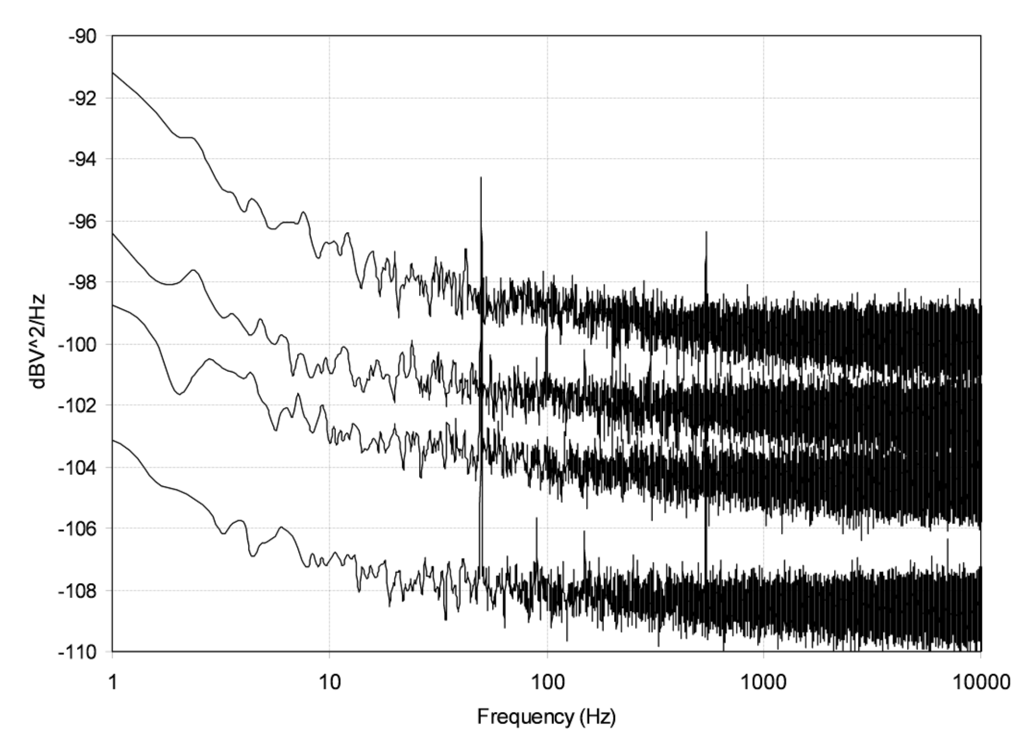
Example: Planck 44 GHz BEM 1/f noise results





Output spectra for RF relative input powers to the detector:

- 0 dB (bottom)
- 5.4 dB
- 8.2 dB
- 15 dB (top)

f_{kBEM} increases slightly

f_{kBEM} ~ 80 Hz << 4 kHz

Noise levels and test equipment

- Thermal noise spectral density (T_0 = 290 K; B = 1 Hz)

$$S_n = k\,T_0\,B = 4\,x10^{-21}\ (Watt/Hz) = -174\ \ (dBm/Hz)$$

- Signal Analyzer (HP 89410A) noise floor:
  typical ~ -165 dBm/Hz *at 1kHz*

- Lock In Amplifier (SR 830) typical input noise:

$$6\ \ nV/\sqrt{Hz}\quad at\,1kHz$$

Input impedance: 10 MΩ ⇒ Noise floor ≈ -204 dBm/Hz *at 1 kHz*

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Conversion between units

Noise voltage spectral density $v_n \; (V/\sqrt{Hz})$

Noise power spectral density $S_n \; (dBm/Hz)$

$$S_n \; (dBm/Hz) = 10 \log\left(\frac{v_n^2}{R_{in}}\right) + 30$$

Example:

$$v_n = 6 \; (nV/\sqrt{Hz}) \qquad S_n = -204.4 \; (dBm/Hz)$$

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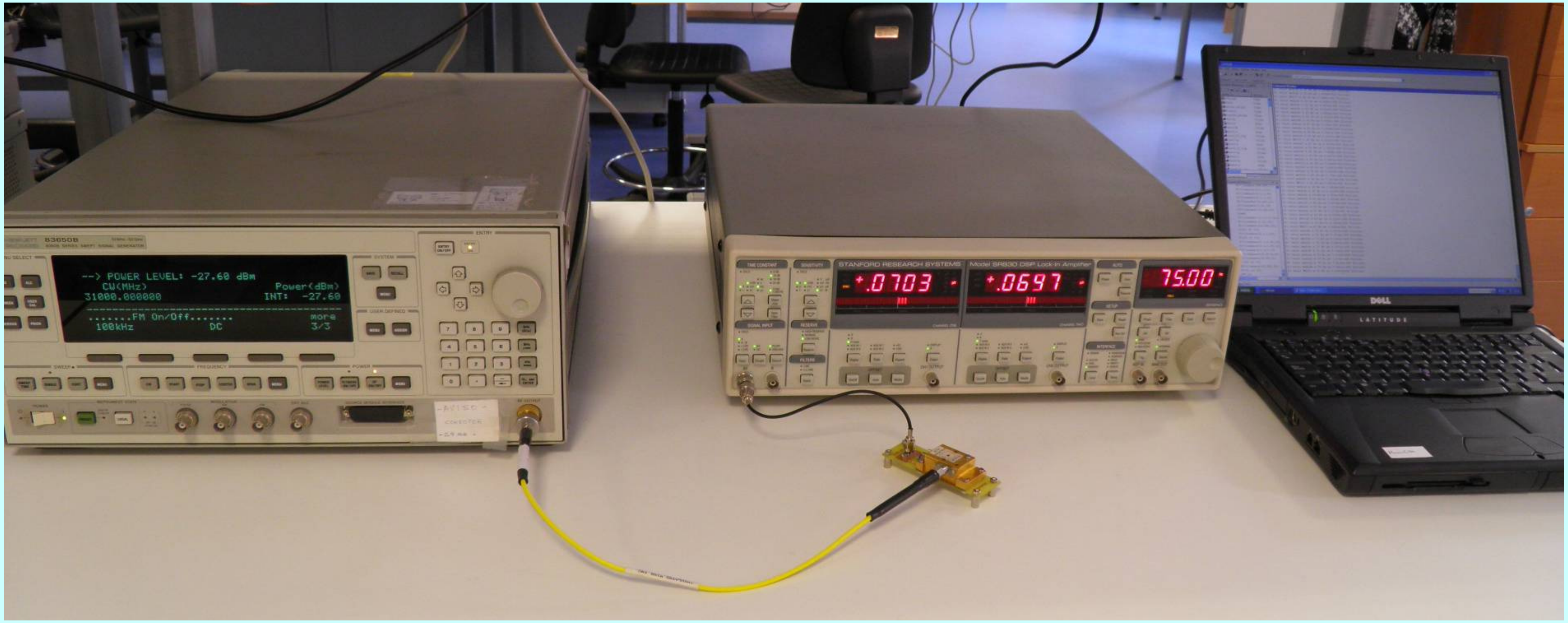
Testing 1/f Noise with a Lock-In Amplifier
SR830 (1 mHz - 102 kHz)



High sensitivity tests ⇒ Large time constant (τ) ⇒ Large waiting and average times ⇒ typical ~ 9 hours for 55 freq. (0.1 to 100 Hz): 550 samples

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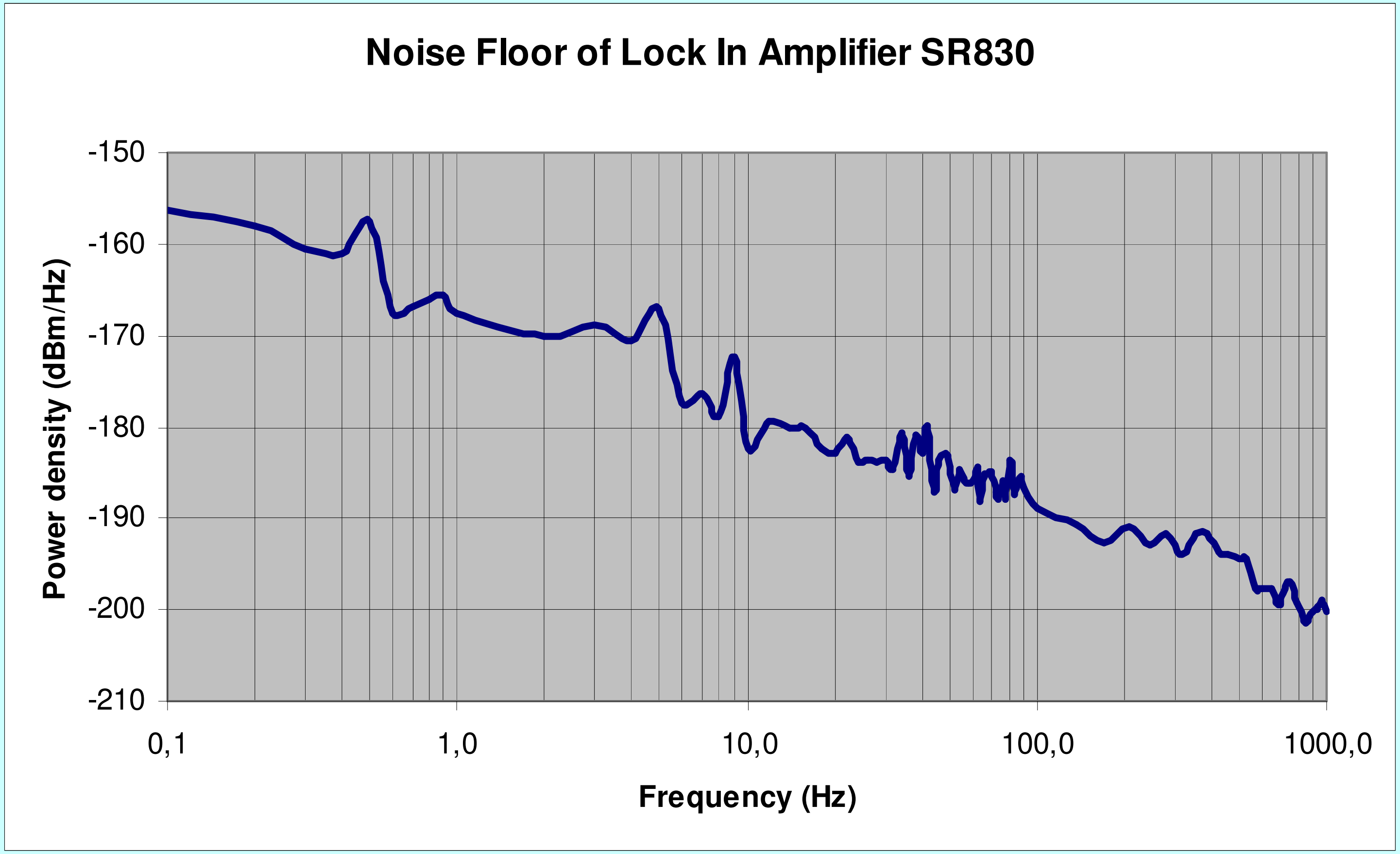
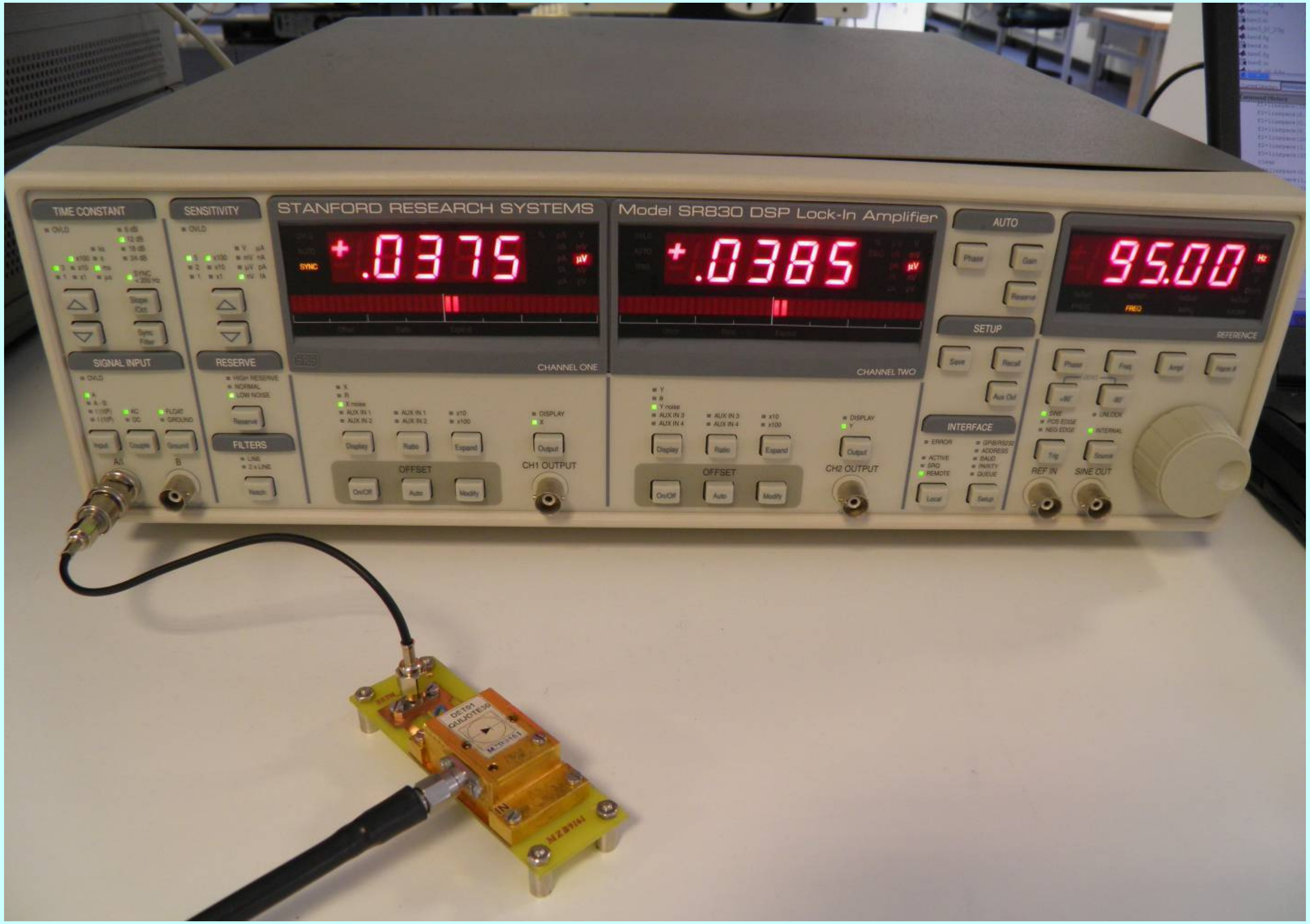
Noise floor of Lock-In Amplifier system



Input load: Short (R_L = 0); τ = 300 ms; slope = 12 dB/oct; sensitivity = 1 µV

Testing noise with the Lock-In Amplifier



Noise testing with Signal Analyzers

Signal Analyzer
HP 89410A

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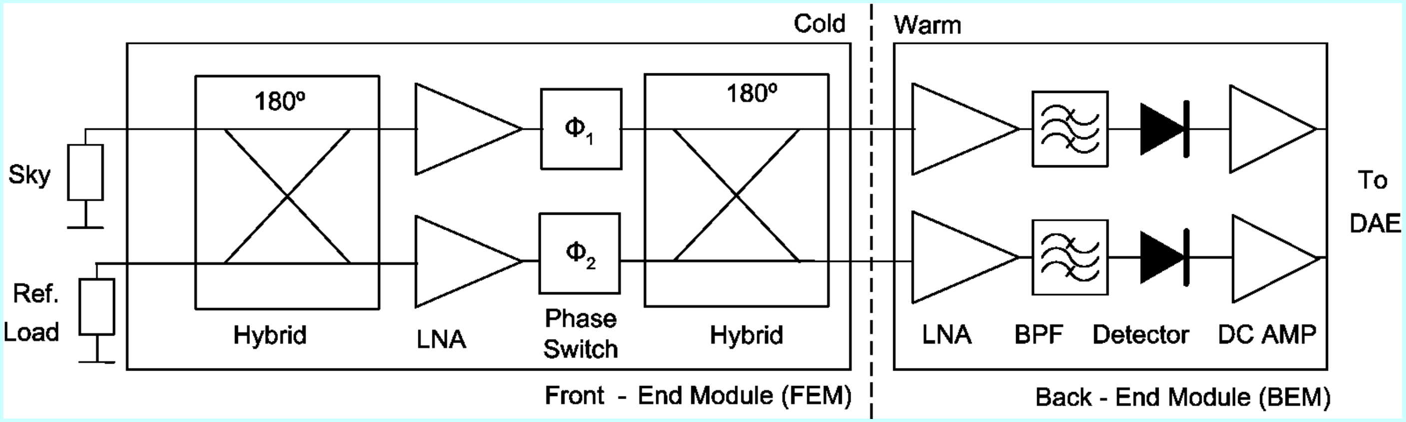
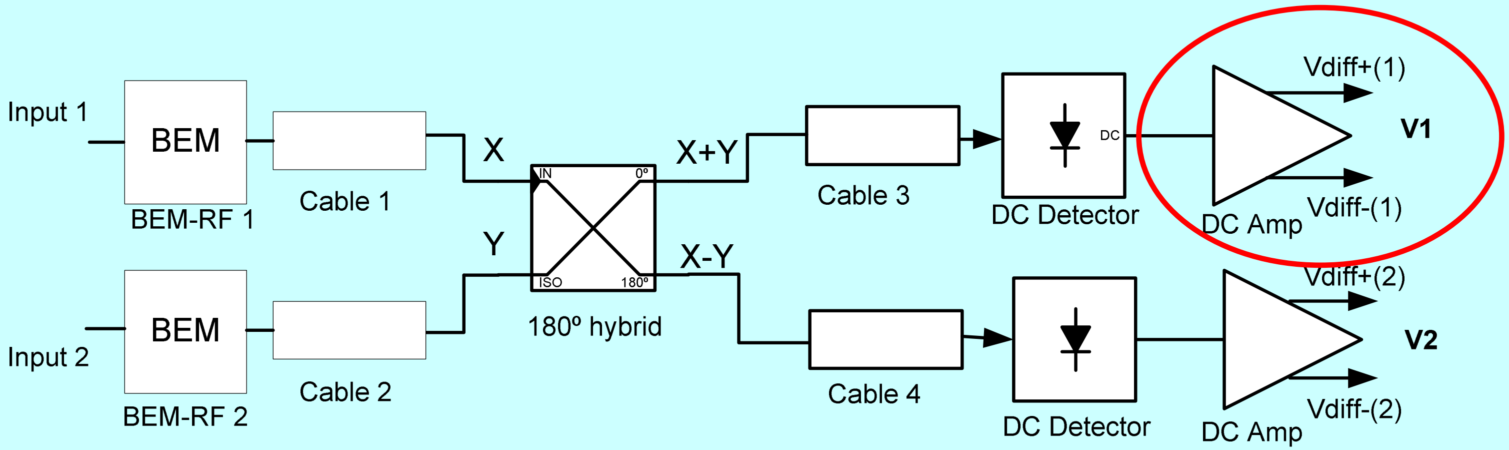
1/f noise contribution of radiometer subsystems

- DC amplifier
- Schottky diode detector (zero bias)
- LNA (Back End Module at RT)
- LNA cryogenic (Front End Module)



DC amplifier (in BEM QUIJOTE-1 radiometer)

Bandwidth: 26 to 36 GHz



Output voltages are differential signals
to meet EMC requirements and grounding integrity

Voltage balanced gain = 580

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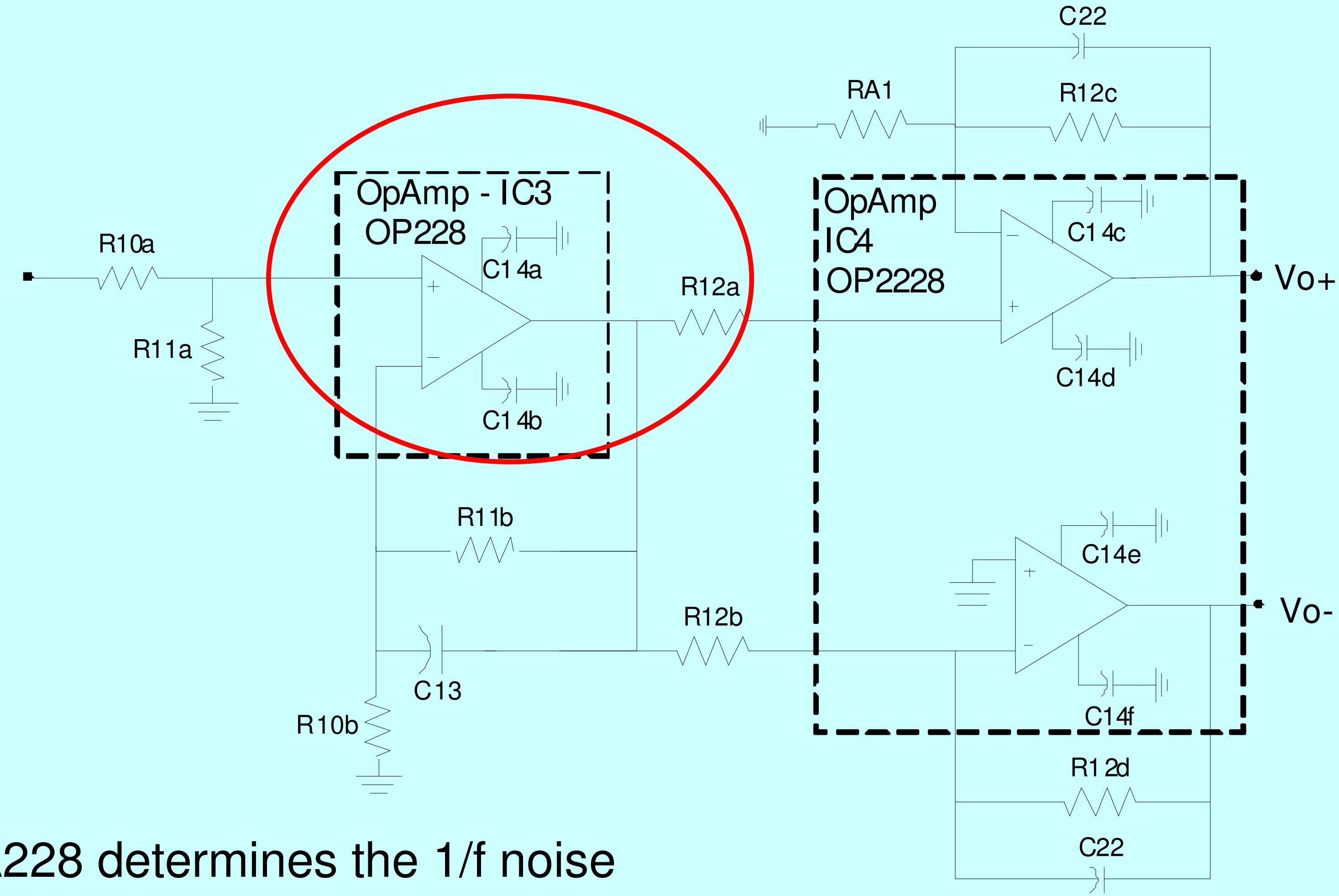
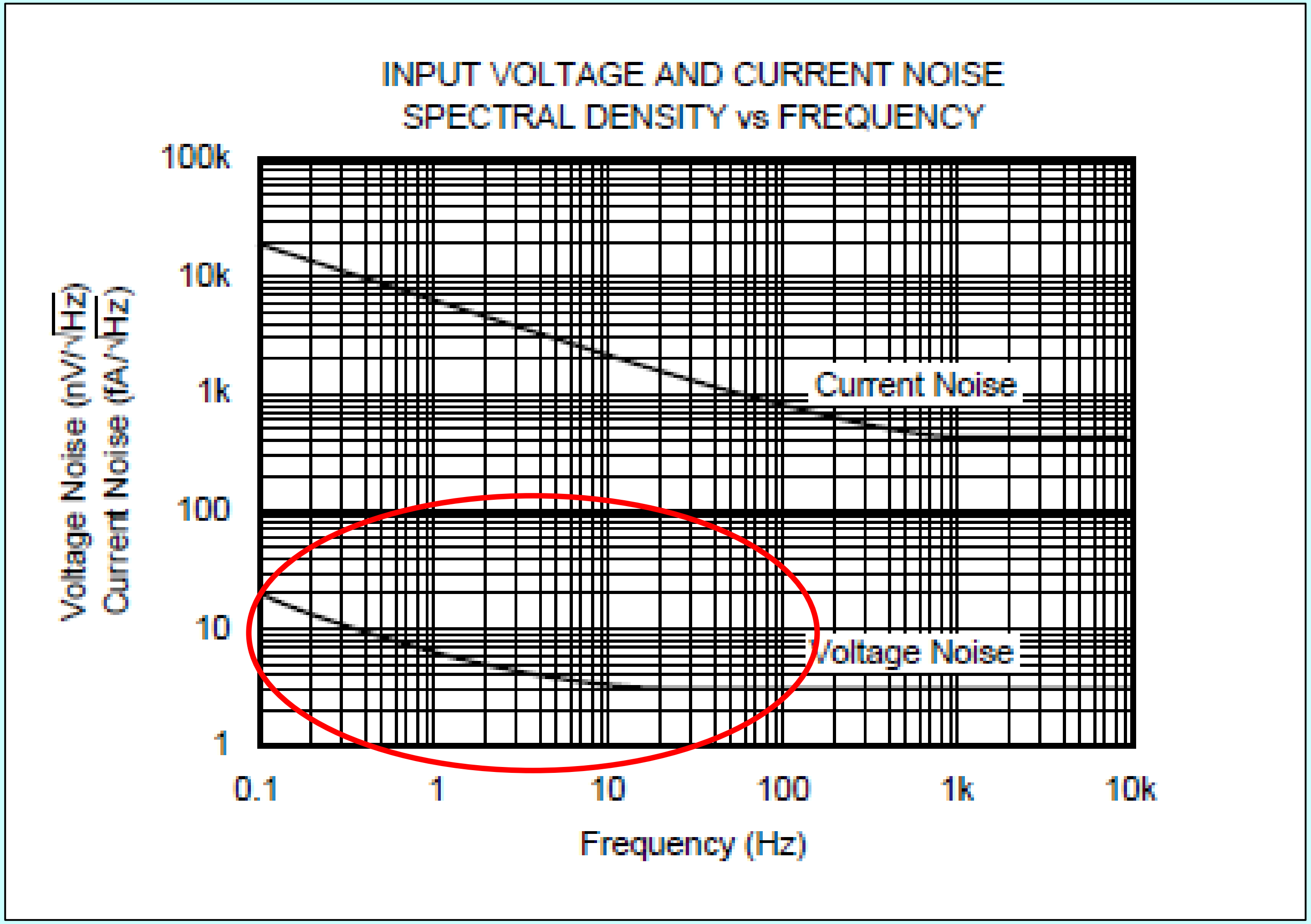
DC amplifier scheme



OPA228 determines the 1/f noise

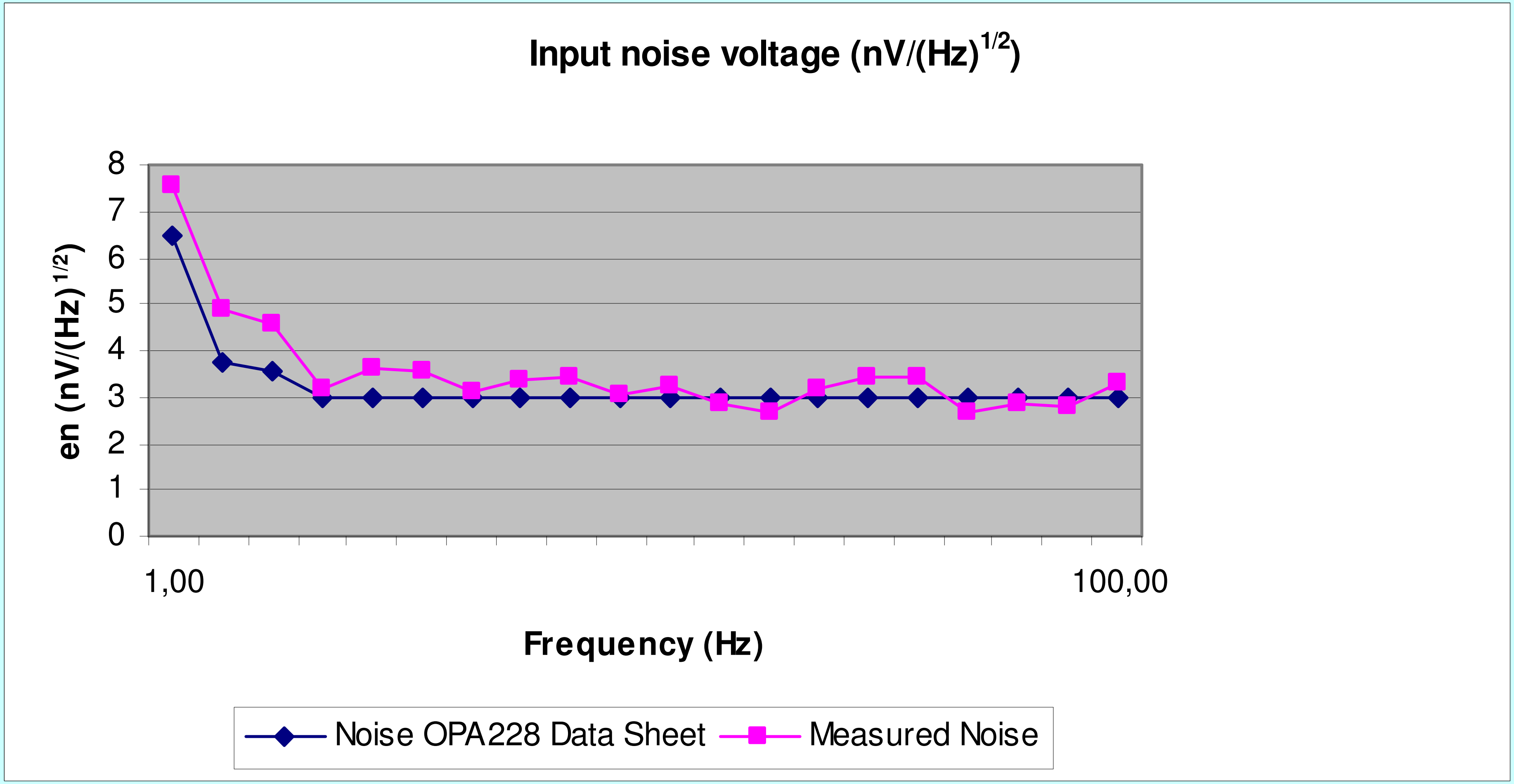
($Z_{in} \cong 50.6$ kΩ; $Z_{out} < 1$ Ω; $G_{DC} = 580$)

From OPA228 data sheet

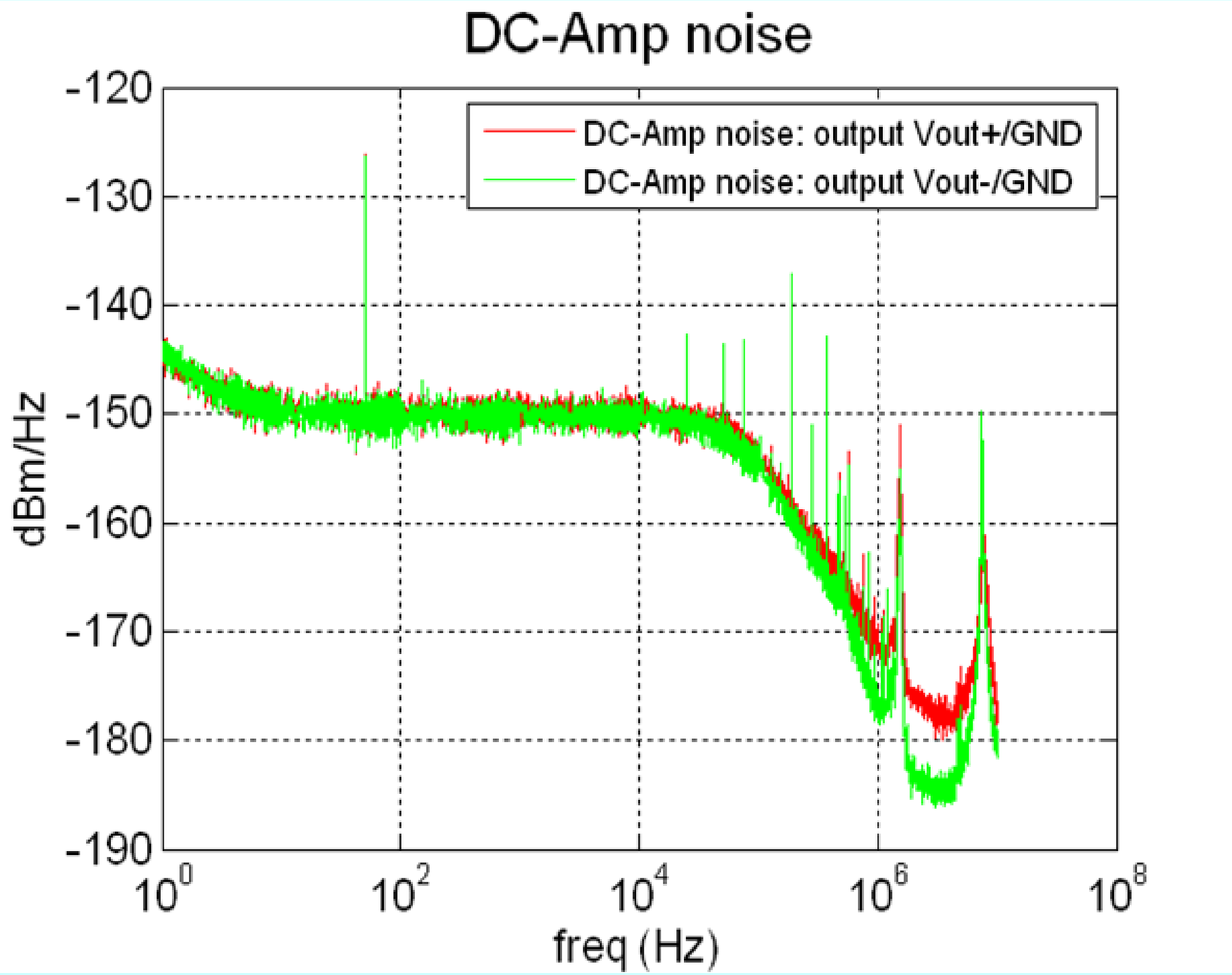


$3\ nV/\sqrt{Hz}$

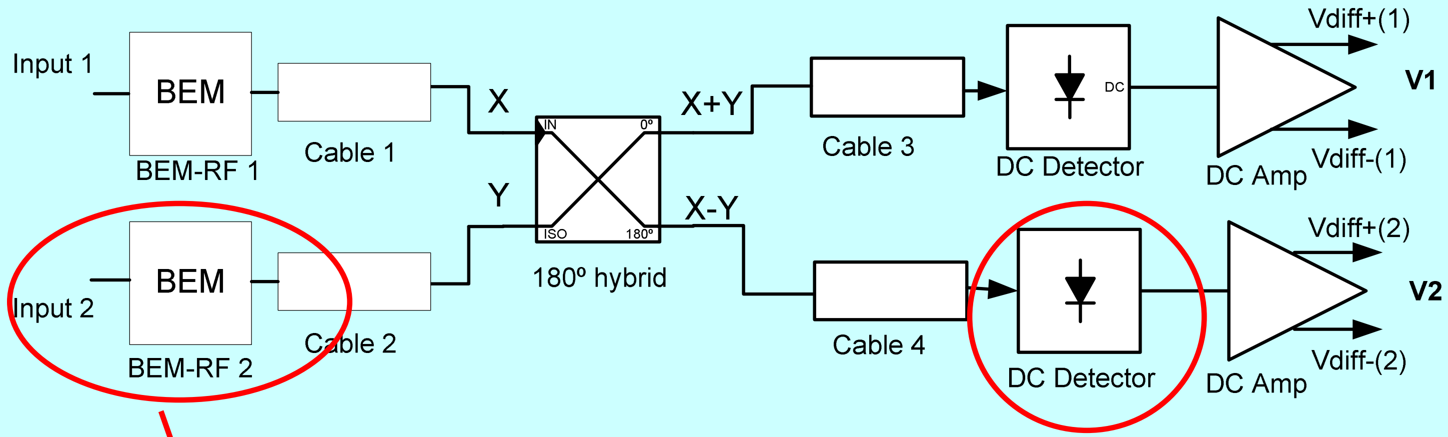
Comparison OPA228 – Test with Lock-In Amp.

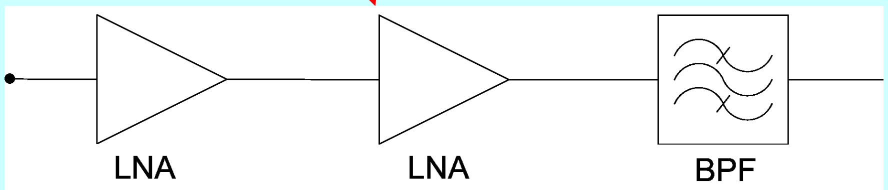


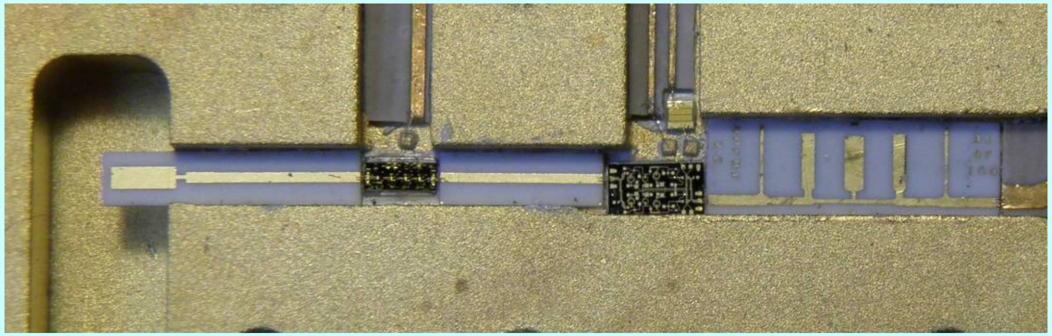
DC amp Noise tests with Signal Analyzer HP-89410A



Complete BEM 1/f noise tests (QUIJOTE-1: 26-36 GHz)







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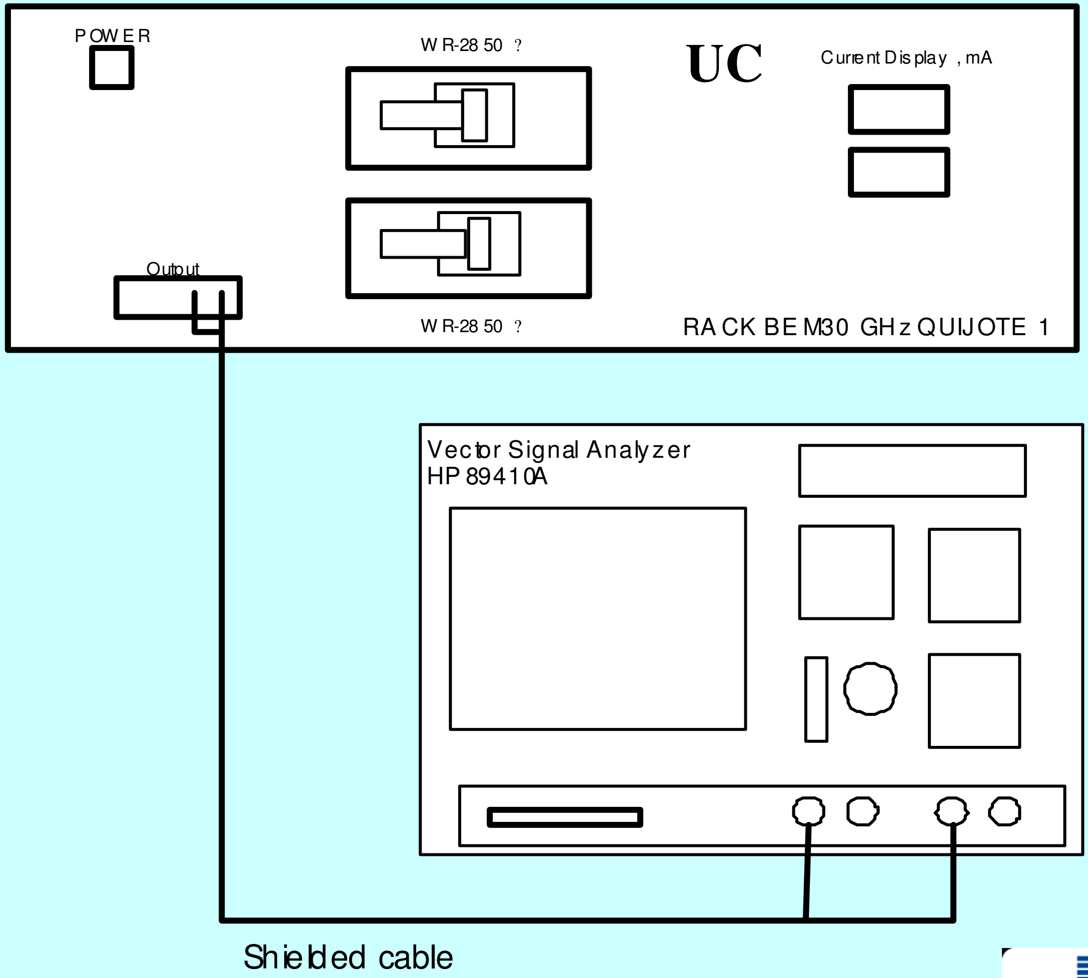
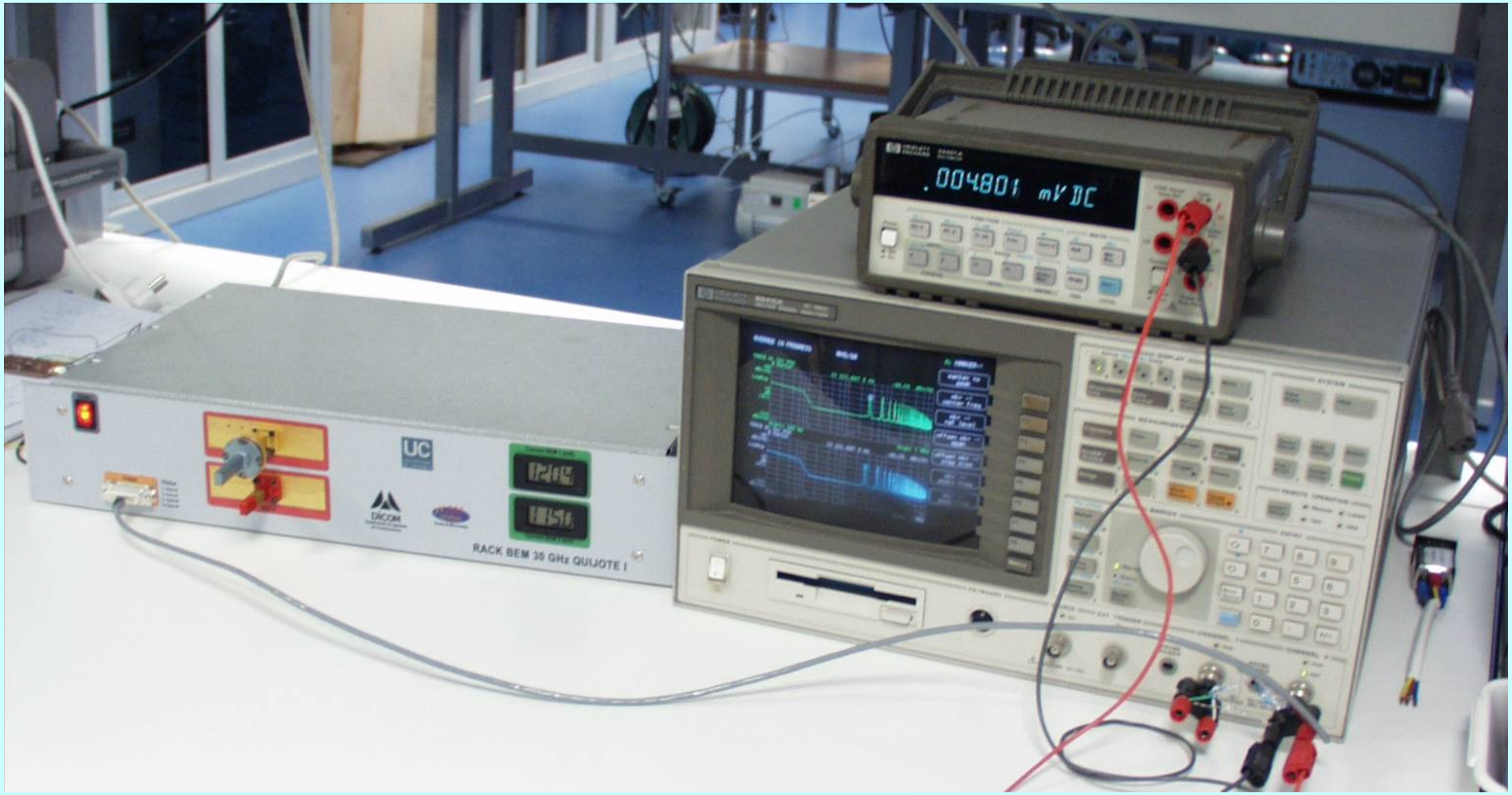
Test set-up for BEM low frequency noise



QUIJOTE-1
26-36 GHz

Low frequency noise test with Signal Analyzer



Low frequency noise in zero bias Schottky diode detector

Flicker and shot noise power spectral densities (A^2/Hz):

$$S_{if} = k_f \frac{I_{DC}^a}{f^b} \qquad S_{ishot} = 2q(I_{DC} + 2I_S)$$

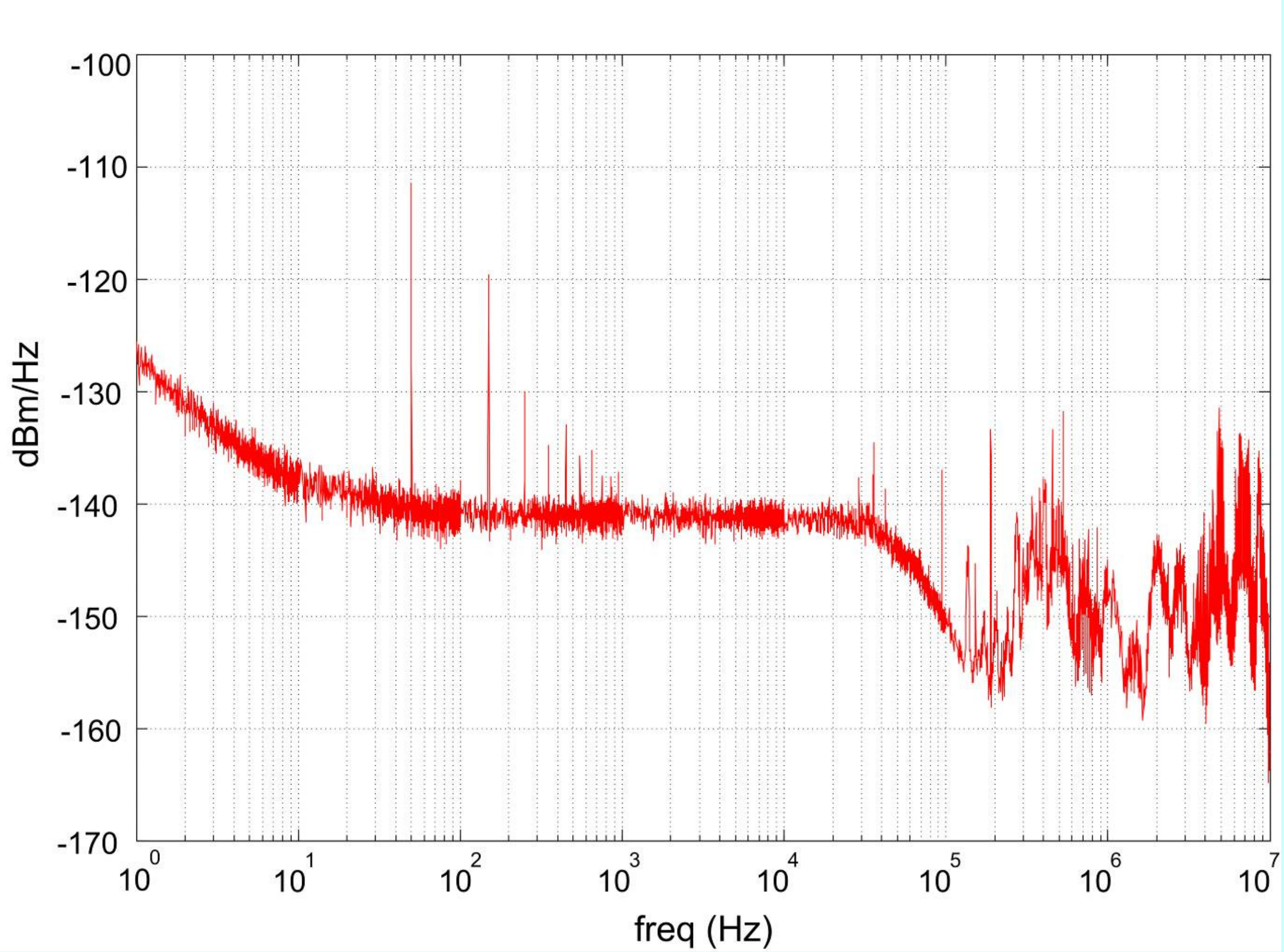
I_{DC} = rectified DC forward current (proportional to RF power)

I_S = diode saturation current

q = electron charge

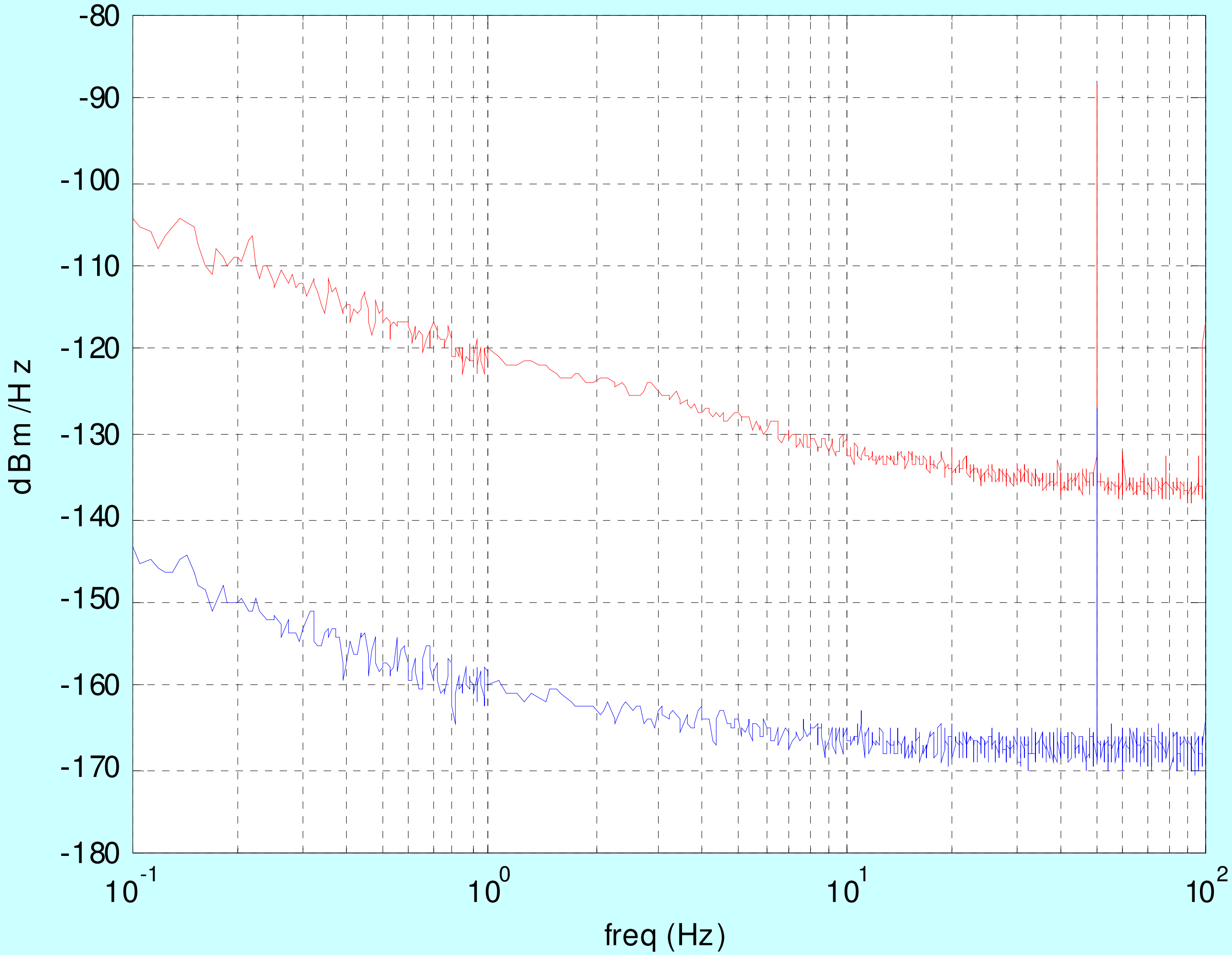
k_f, a, b are fitting variables

BEM (QUIJOTE-1) output noise



1/f knee frequency ~ 20 Hz

BEM (QUIJOTE-1) output noise and noise floor



red = BEM test

blue = noise floor

Test equipment: Signal Analyzer HP 89410A

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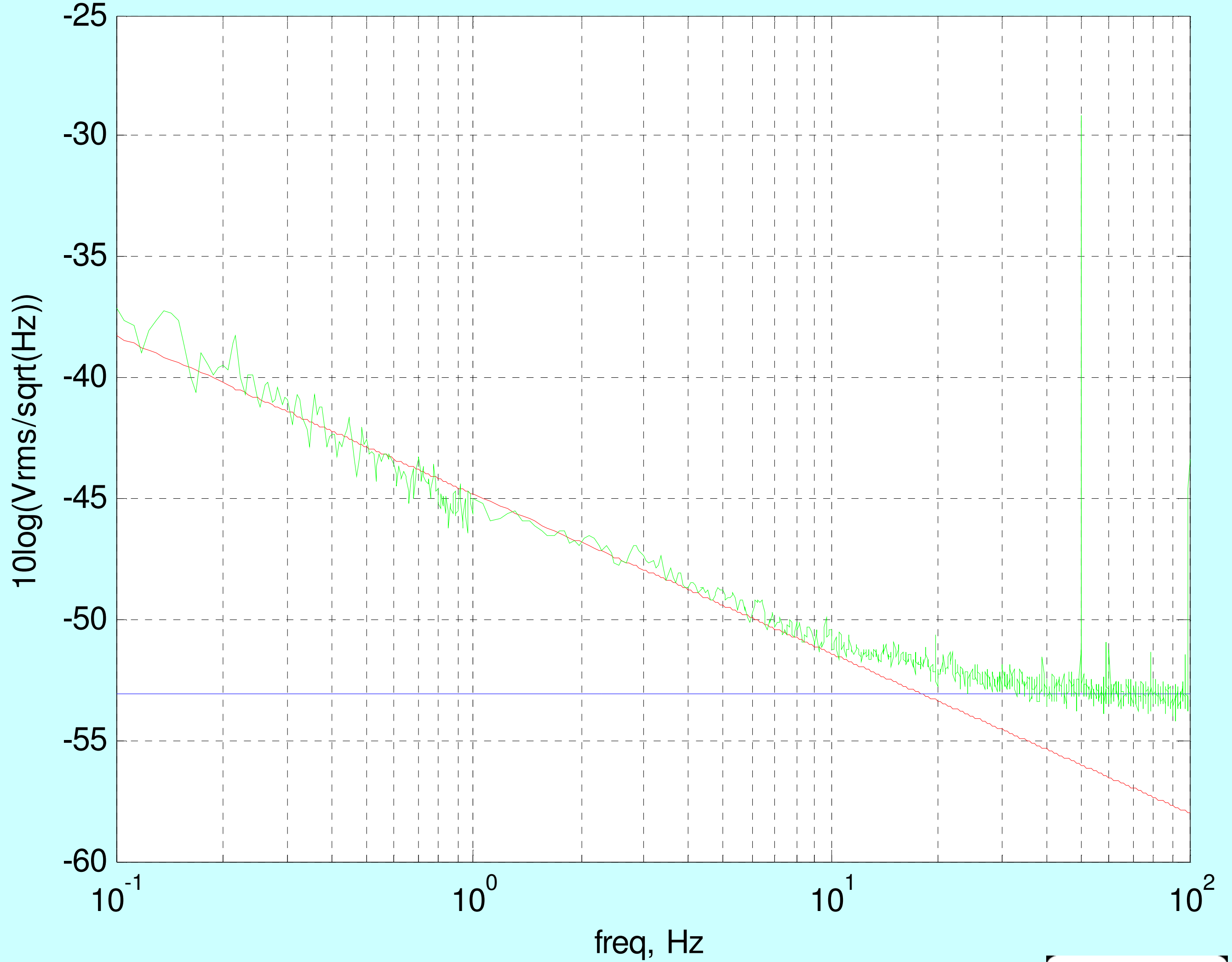
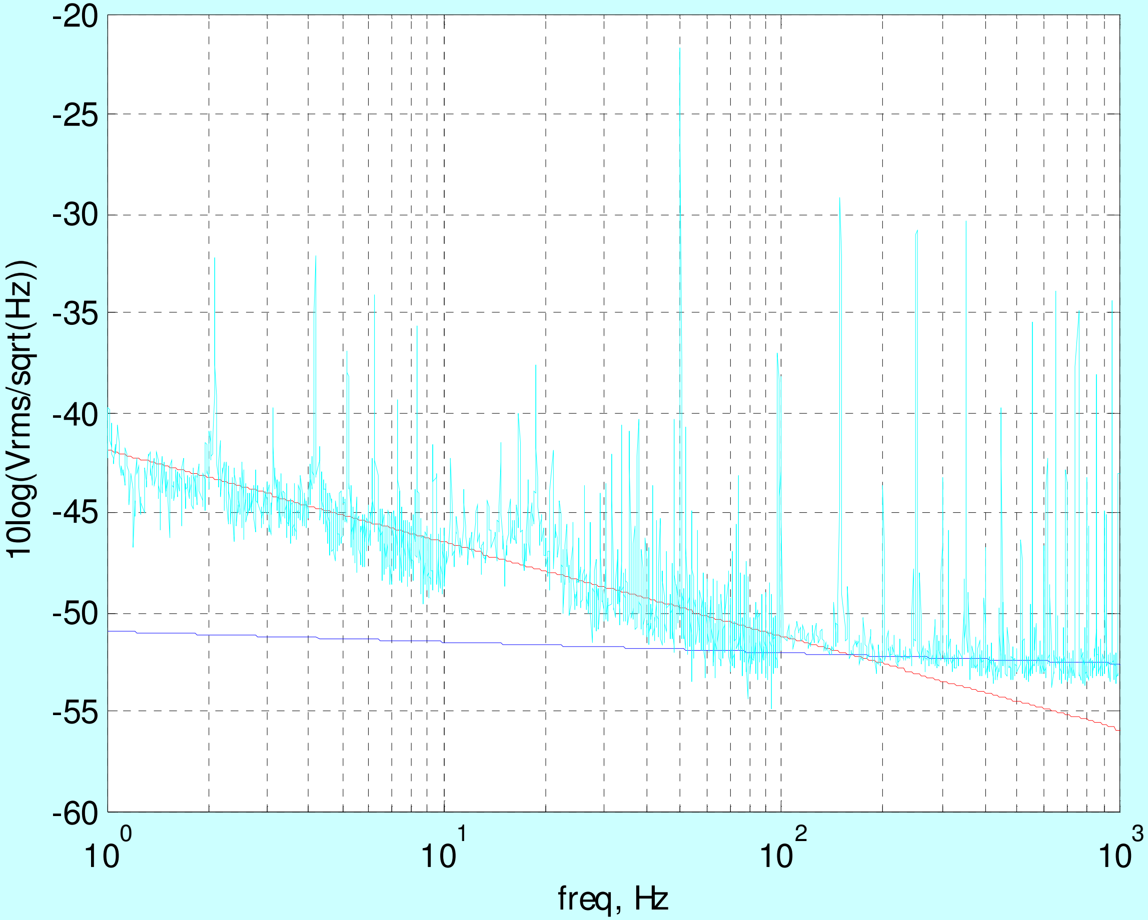
Knee frequency estimation by straight lines



1/f knee frequency ~ 18 Hz

FEM-cryo + BEM (QUIJOTE-1) output noise



1/f knee frequency ~ 120 Hz

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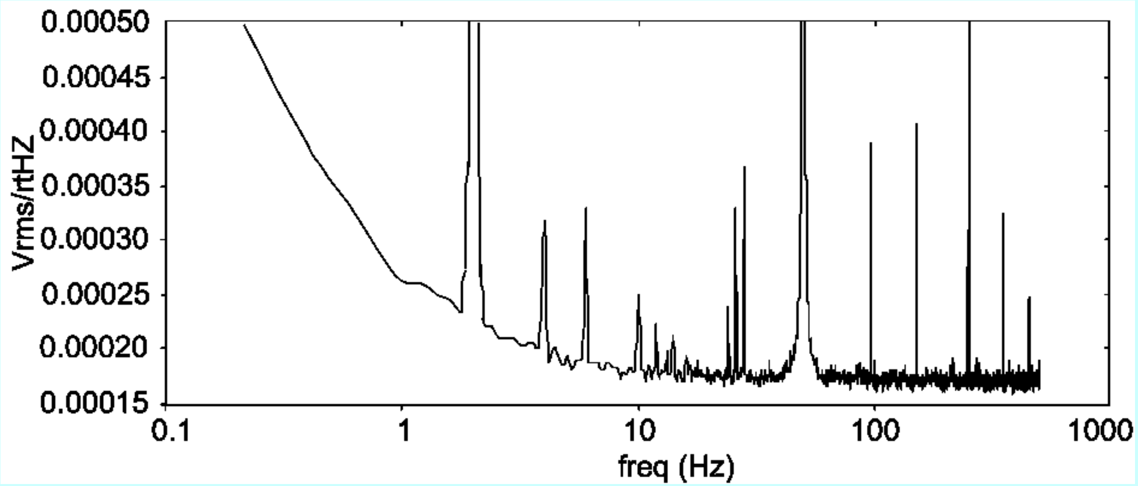
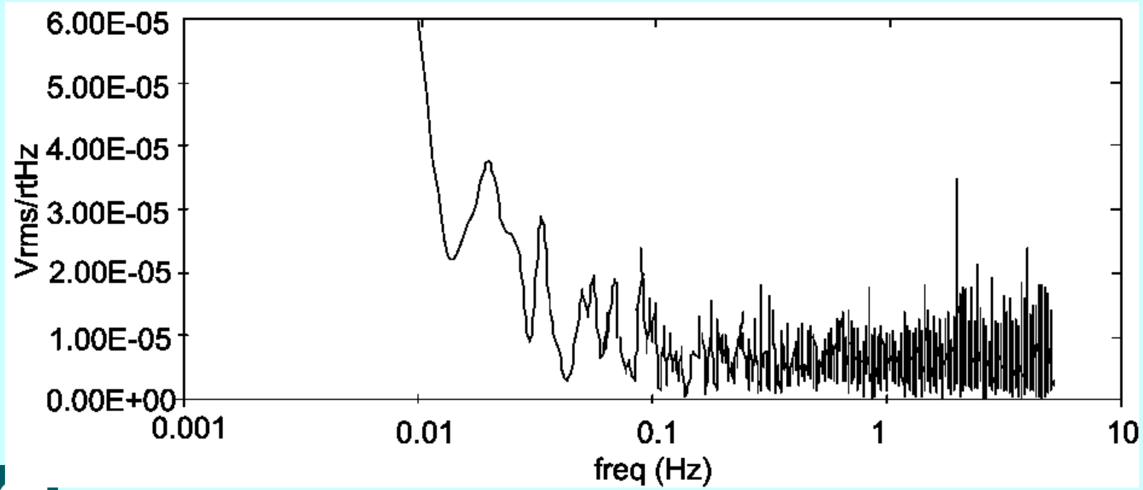
Planck radiometer 30 GHz (prototype)



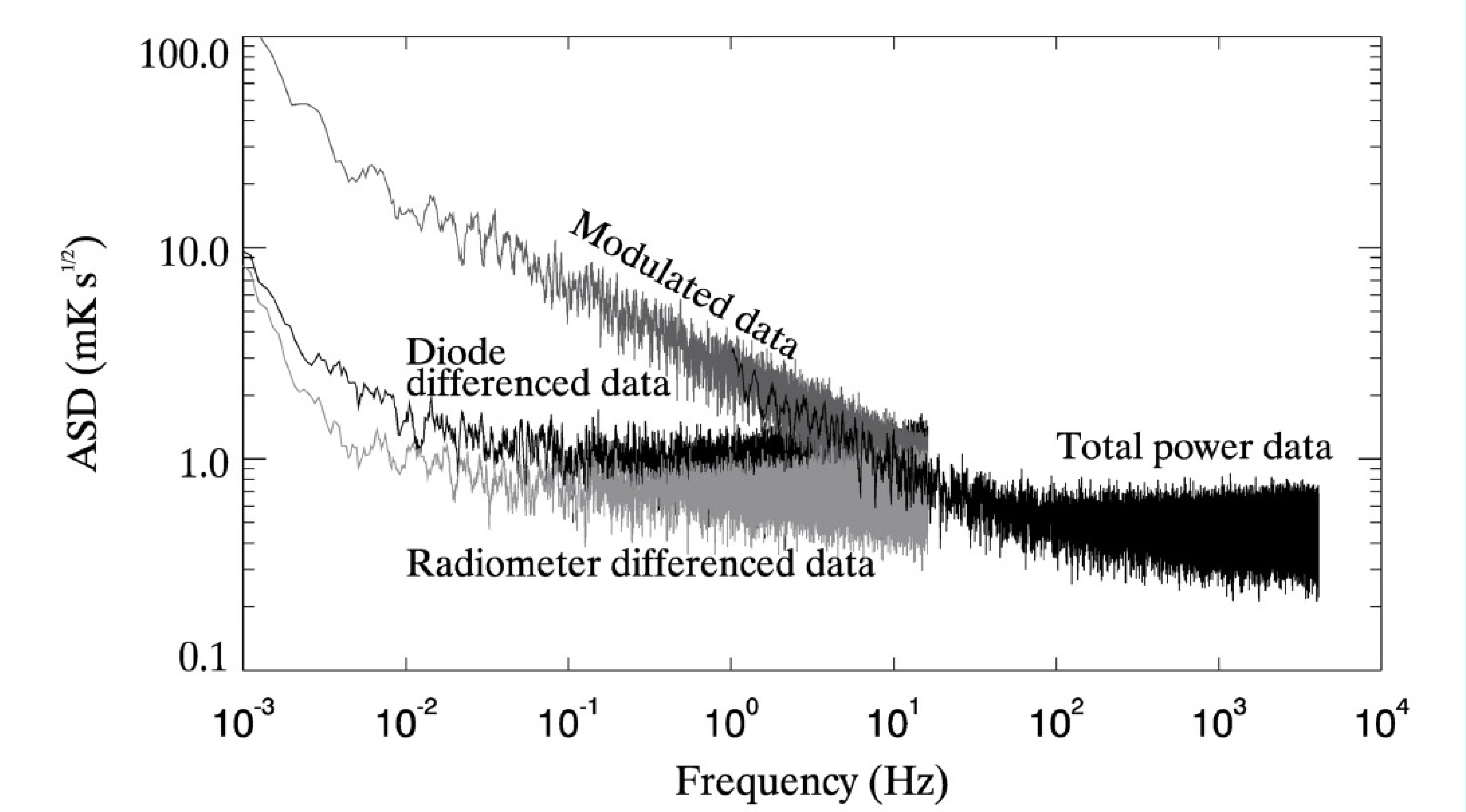
Unswitched



Switched

fknee ~ 50 mHz

1/f noise reduction in Planck radiometers



Amplitude Spectral Densities of unswitched and differenced data streams.
Reduction by 3 orders of magnitude of the 1/f knee frequency.
(A. Menella et al., 2010, A&A, 520, A5)

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Conclusions

- 1/f noise degrades the quality of measured data.
- Cryogenic HEMT amplifiers (gain and noise temperature fluctuations) are the major source of 1/f noise.
- Pseudo-correlation differential radiometers can reduce the 1/f knee frequency by 3 orders of magnitude.

References

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