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# Noise contributions in eBPM systems

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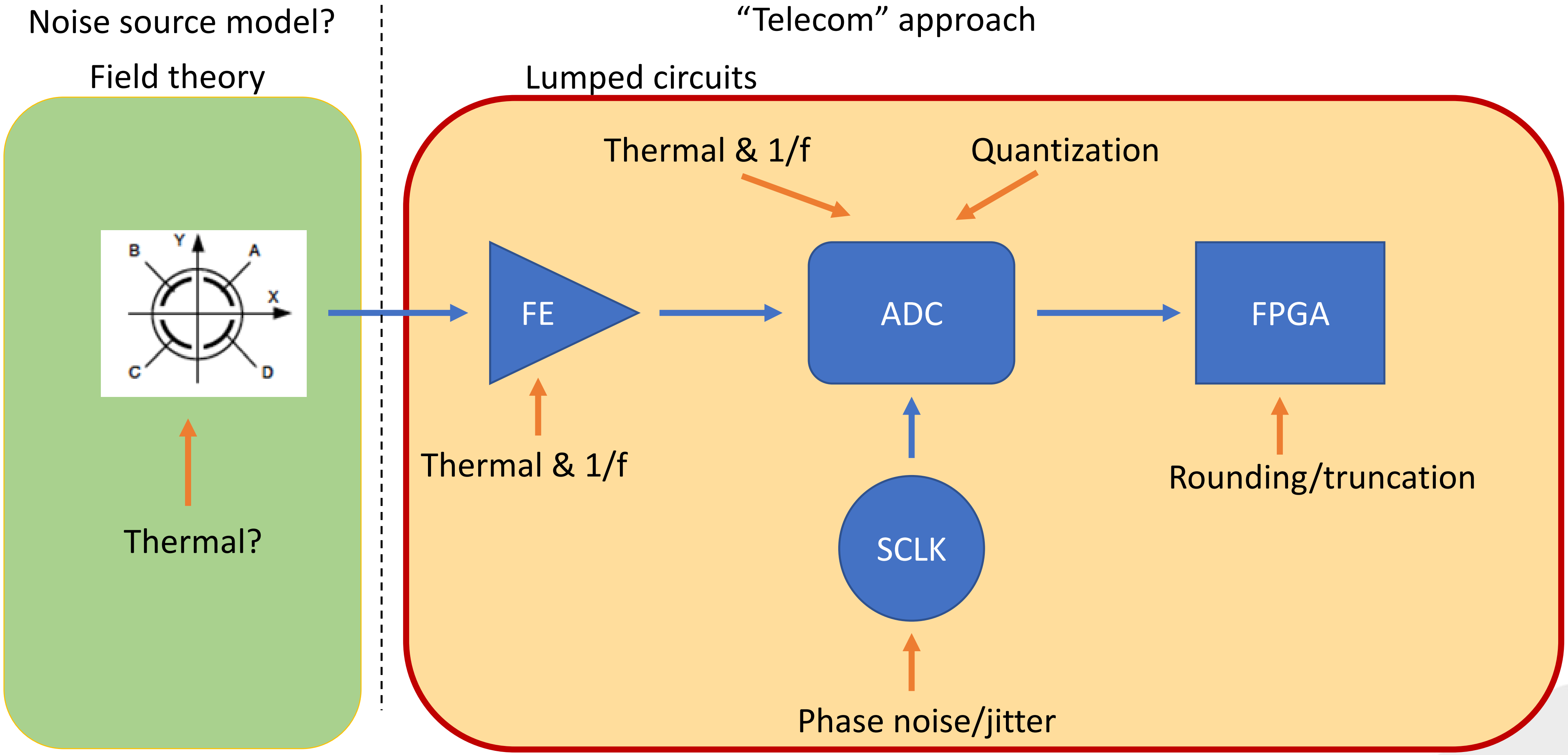
# Noise in passive/active devices

- We refer as noise as a random process that can be described only through statistical properties, such as:
  - distribution (mean, variance, probability density function)
  - autocorrelation function and its Fourier transform (Power spectral density, PSD)
- Noise power can be estimated integrating the PSD over the given bandwidth

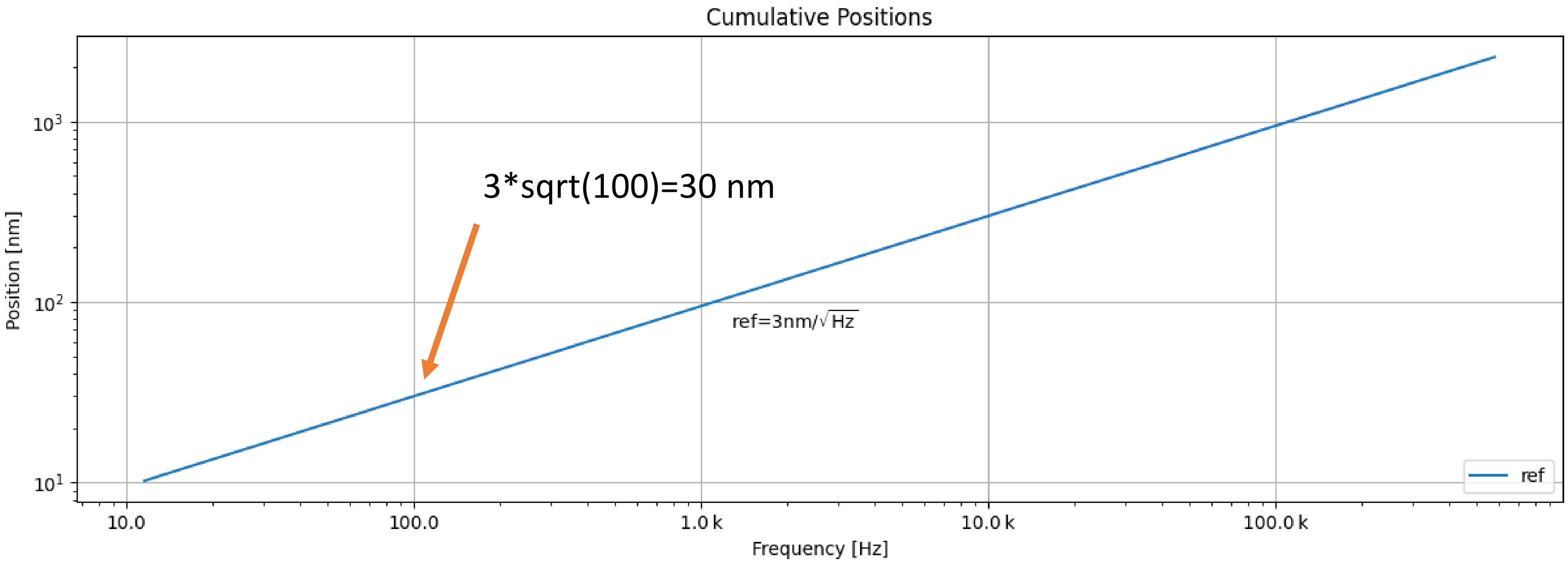
| Johnson – Nyquist (thermal) | Shot | Flicker or 1/f |
|---|---|---|
| • Generated by thermal agitation of charge carriers in a conductor (resistors, channel in a FET, etc)<br>• Usually modelled as a gaussian process<br>• No correlation between samples<br>• **PSD is flat** (white noise), value is 4kTR for voltage noise | • Generated by discrete charge particles that flow across barriers (e.g. p-n junction)<br>• Usually modelled as a Poisson process<br>• No correlation between samples<br>• **PSD is flat** (white noise), value is 2qI for current noise | • Generated by impurities or generation-ricombination of charges in electronic devices<br>• Different processes: gaussian or chi-distributed<br>• Correlation between samples<br>• **PSD is NOT flat**, value is inversely proportional to frequency |

# Noise in BPM acquisition chain



# Noise evaluation in BPMs

- Easier to refer to noise on calculated positions
- graphs: cumulative sum of PSD vs frequency



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# Noise evaluation in BPMs

- Test setup: RF gen + splitter (emulate a stable beam)
- Significant 1/f noise on our BPMs
- Pilot tone compensation can cancel it out
- Coming from ADCs?
  - No difference w & w/o front end -> PTFE has white noise
  - No difference at different frequencies -> not related to sampling clock jitter
  - Could be a ADC “signature”? -> different between various ADC models? (tests in progress)

# Cumulative Spectral Density

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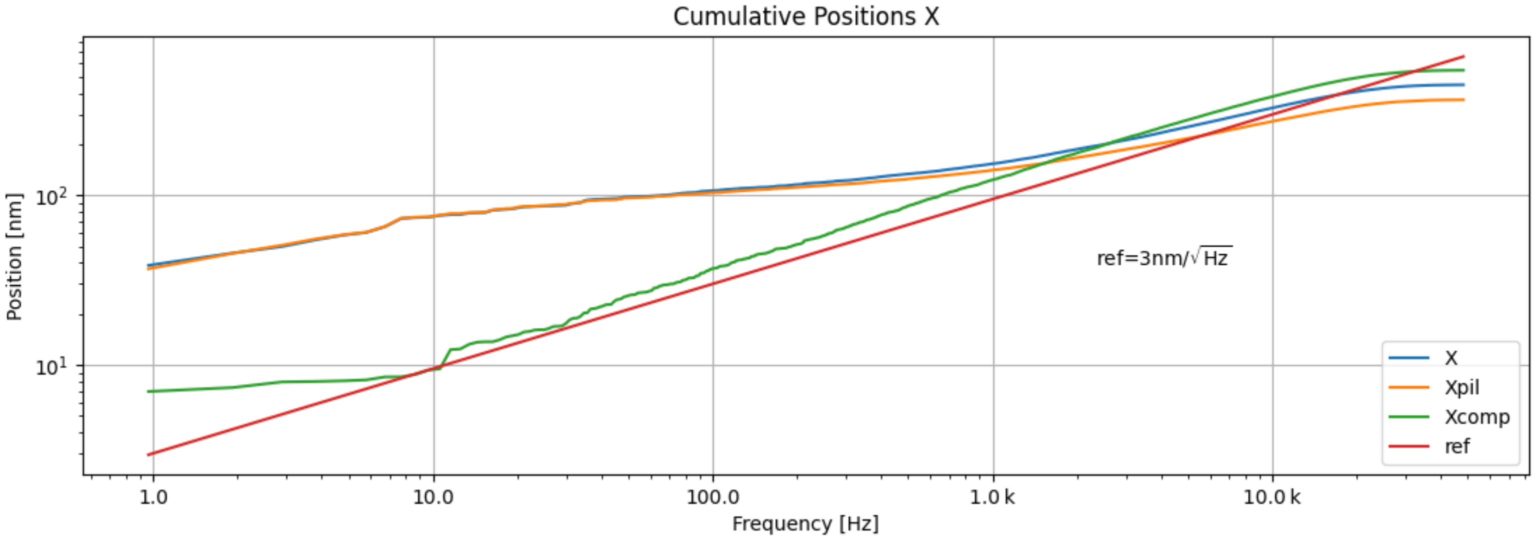
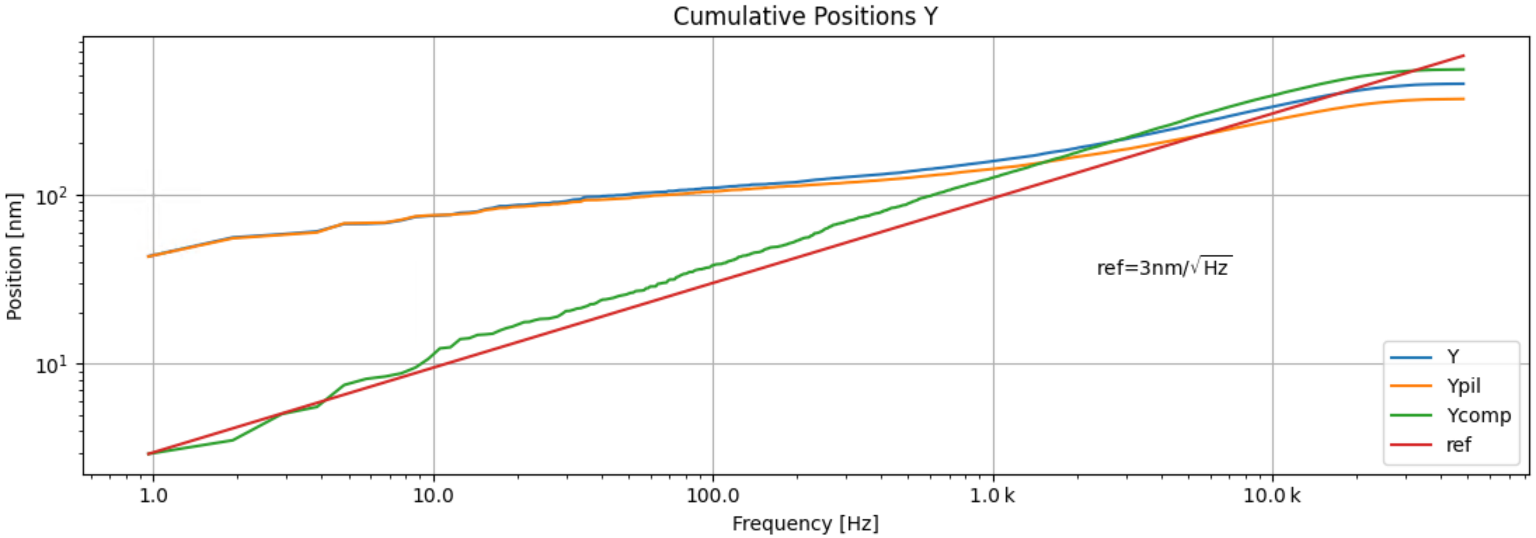



100 kS/s data rate

Red trace: white noise reference of 3nm/sqrt(Hz)

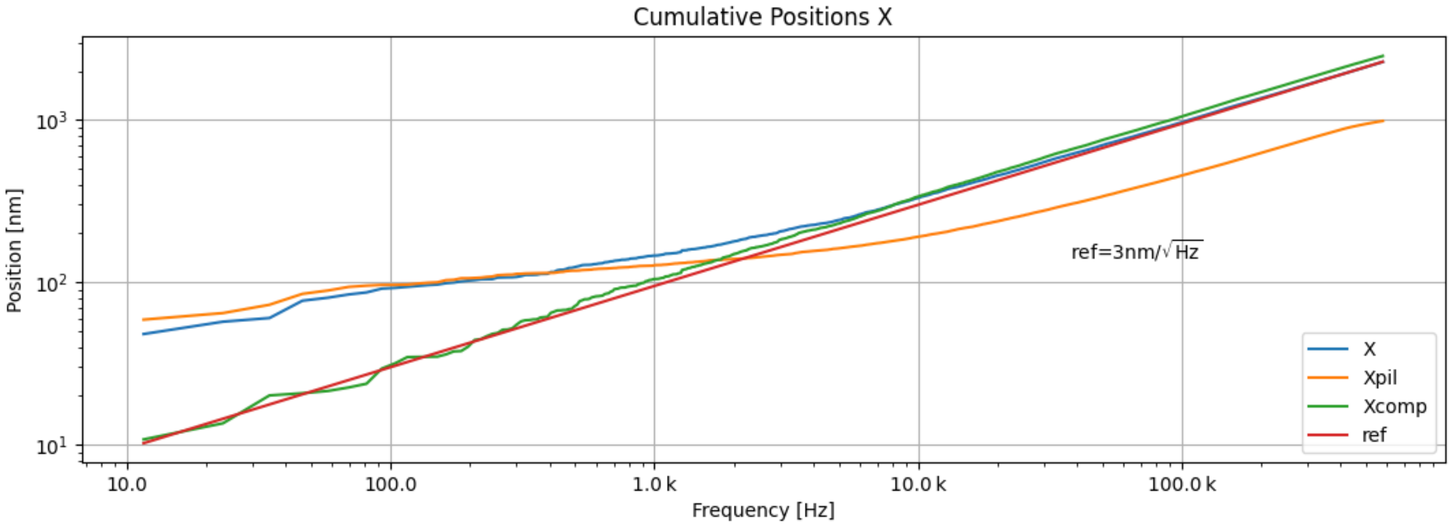
Blue trace: carrier
Orange trace: pilot
Green trace: compensated position

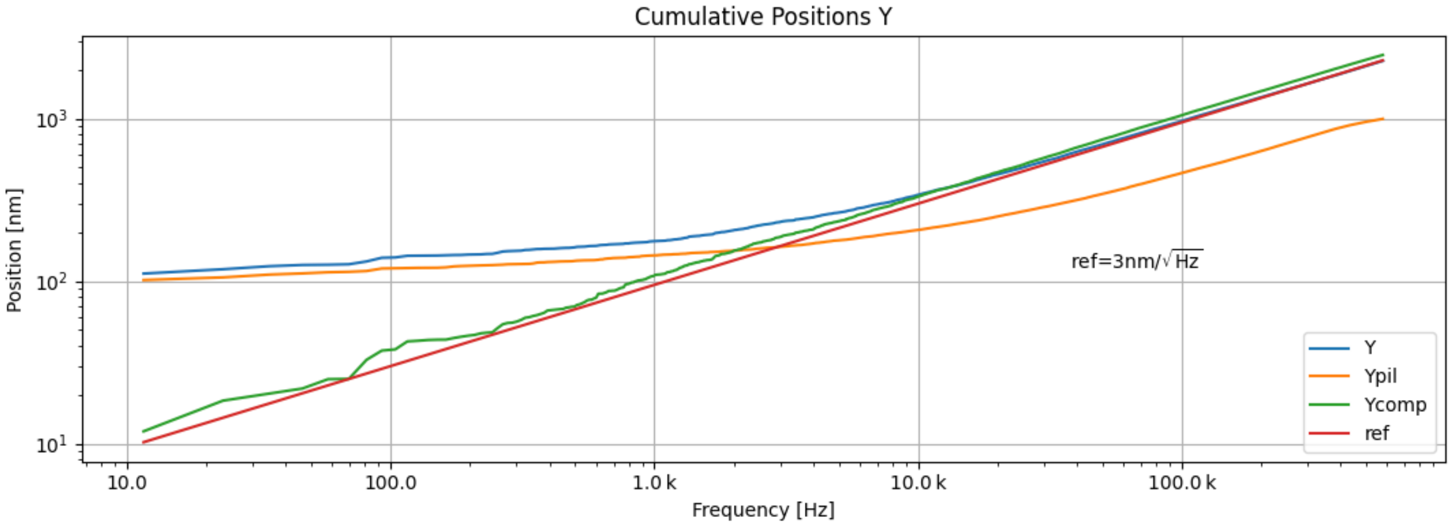
**Noise of non-compensated position higher than expected**

Compensated position follows theoretical prediction

CERTIFIED MANAGEMENT SYSTEM CQY CERTIQUALITY UNI EN ISO 9001:2015 UNI ISO 45001:2018

# Cumulative Spectral Density



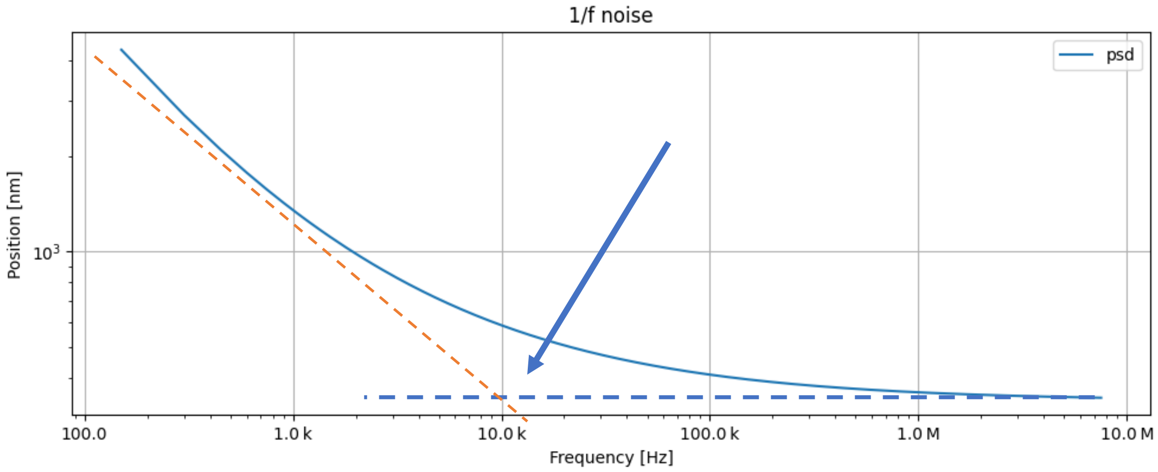

1.156 MS/s data rate - TbT

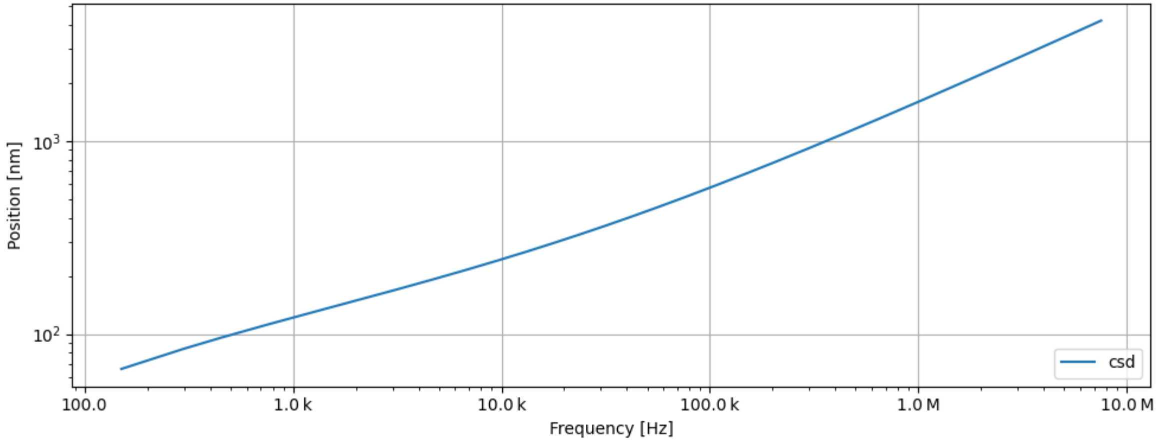
Noise PSD is flat over 7/10 kHz

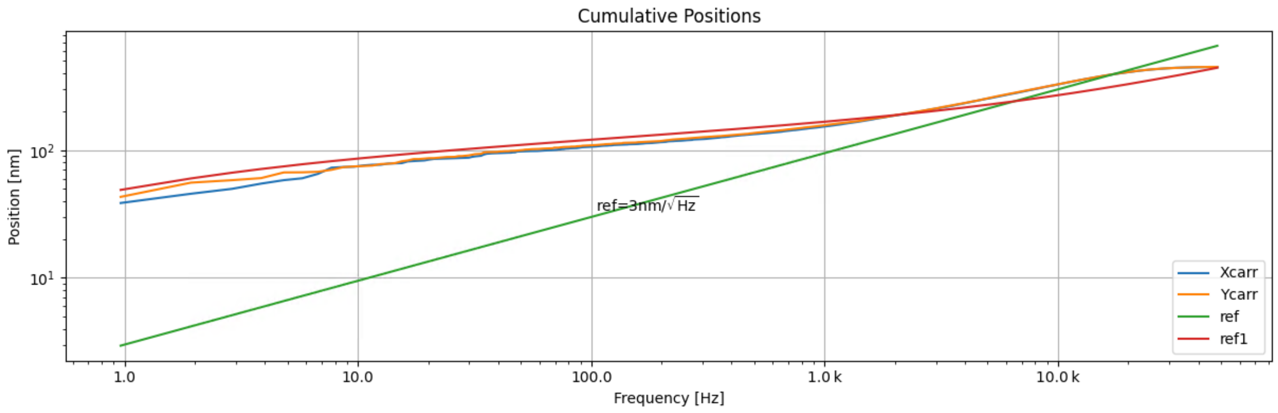
Expanding bandwidth helps to understand the phenomena

Noise on pilot positions is lower due to enhanced filtering (reduced BW)

# 1/f fitting



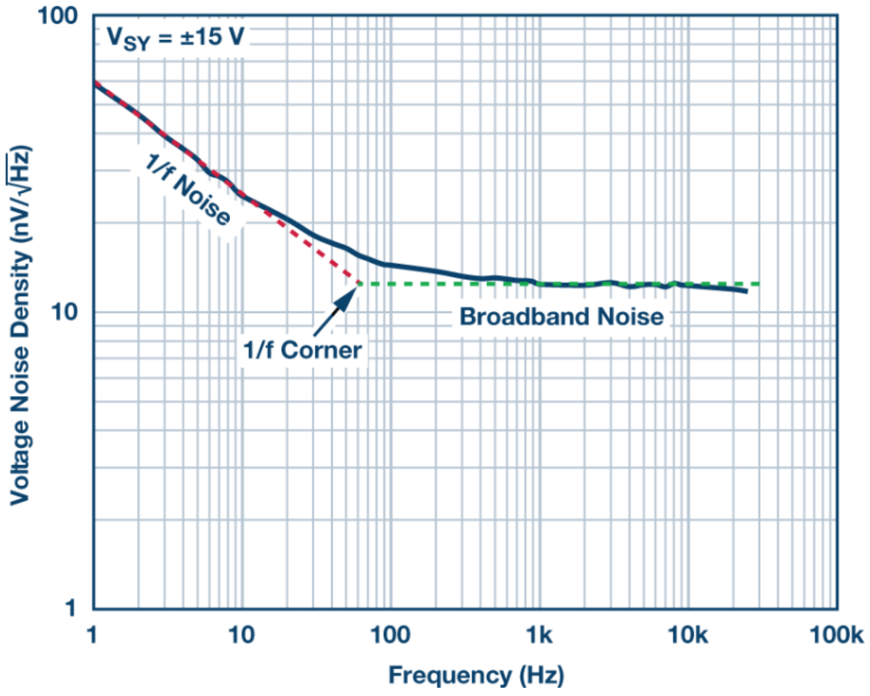



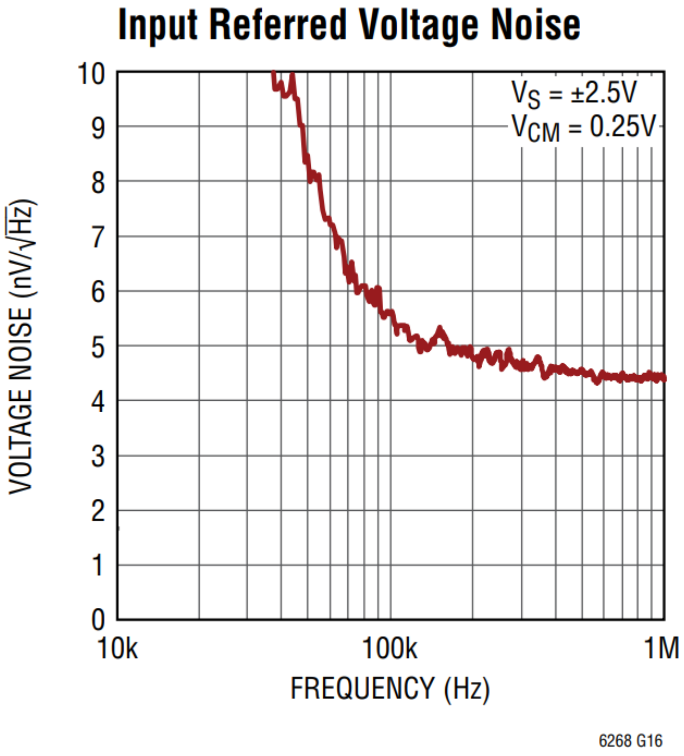

Fit 1/f noise (red trace):

PSD: $S(f) = \frac{k^2 F_c}{f} + k^2$ , k = 3nm/sqrt(Hz)

Corner frequency: about 10 kHz

# Examples of 1/f noise in opamps



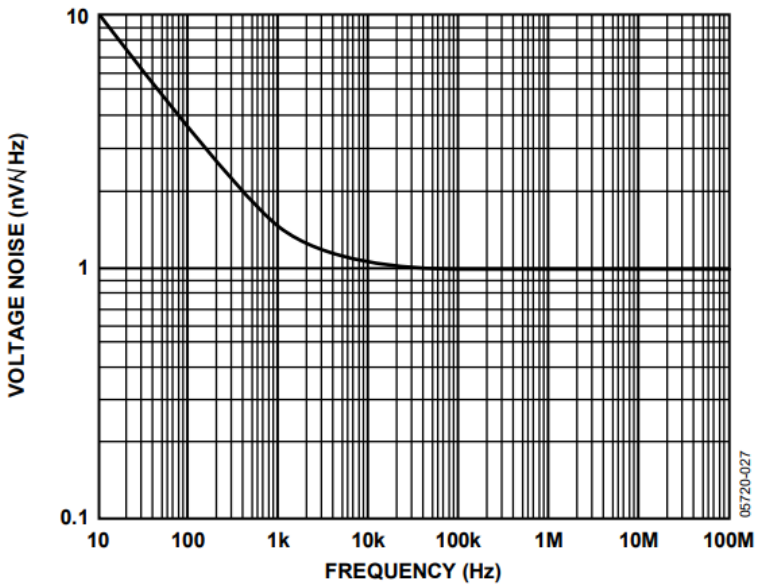
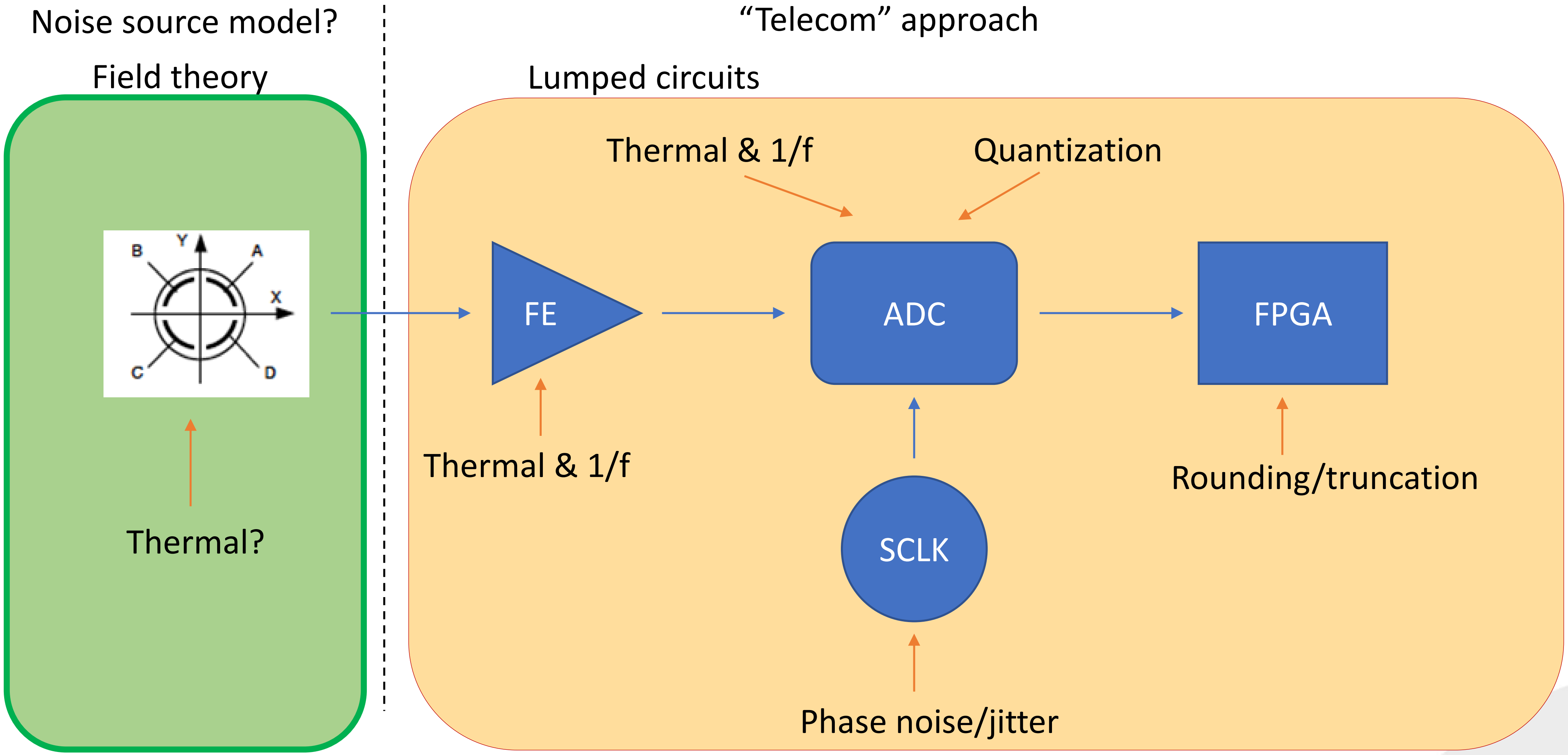




*Figure 13. Voltage Noise vs. Frequency*

# Noise in BPM acquisition chain

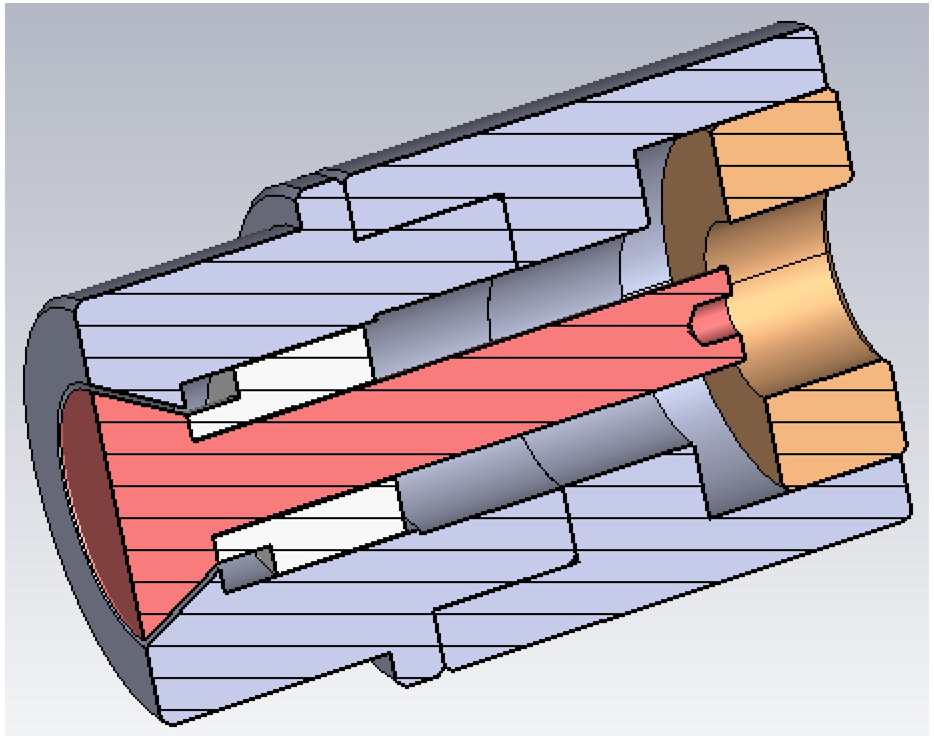


# S/N and position resolution

- Measurements are limited by (thermal) noise
- Signal power: TEM mode propagation implies that voltage and current concepts for lumped circuits can be defined at the signal port of the Pickup
- Noise power: what kind of electric source model matches the Pickup?
- Several articles/papers assume a thermal noise generator (Thevenin equivalent circuit)
- Thermal movement of electrons, independently from each other, in conducting material ($\sigma > 0$)

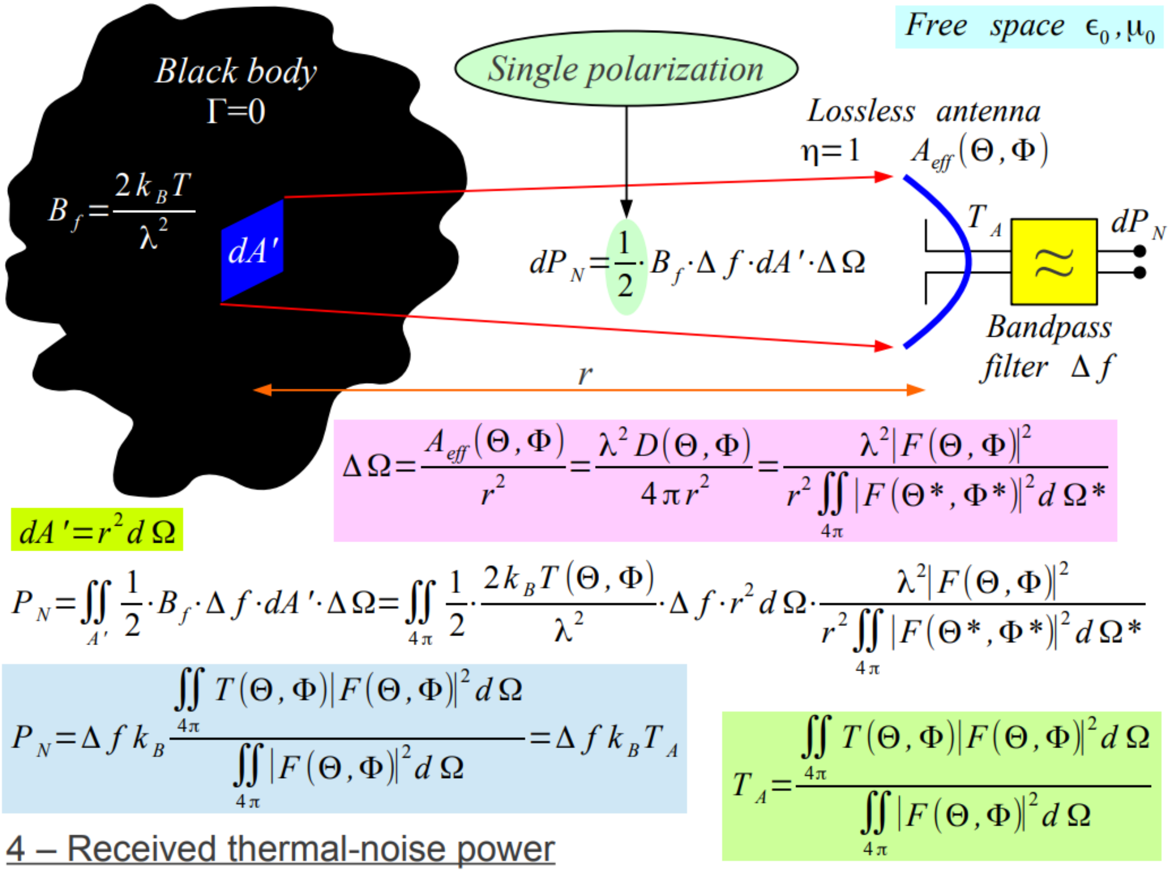
# Button type pickup

- Button type PU: what is R? How a coaxial propagation path can be modeled as a noise source?



# Antenna theory

- Some references (M. Vidmar, Noise in Radio/Optical Communications, IBIC 2108; thanks to B. Roche for pointing it out)

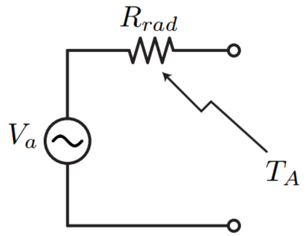



4 – Received thermal-noise power

Power radiated by a physical object: $P_N = kT_NB$

Power collected by a **lossless** antenna: $P_A = SA_eB = kT_AB$, depends on solid angles of source and receiver (radiation pattern) - $T_A$ is **not related** to physical temperature of the antenna

Equivalent noise circuit: we shall consider the radiation resistance of the antenna (ratio between E and H):

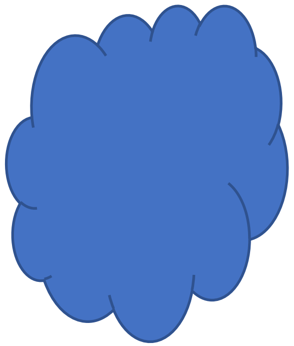



$$V_a^2(f) = 4kT_AR_{rad}B$$

With matched load: $P_L = kT_AB = P_A$

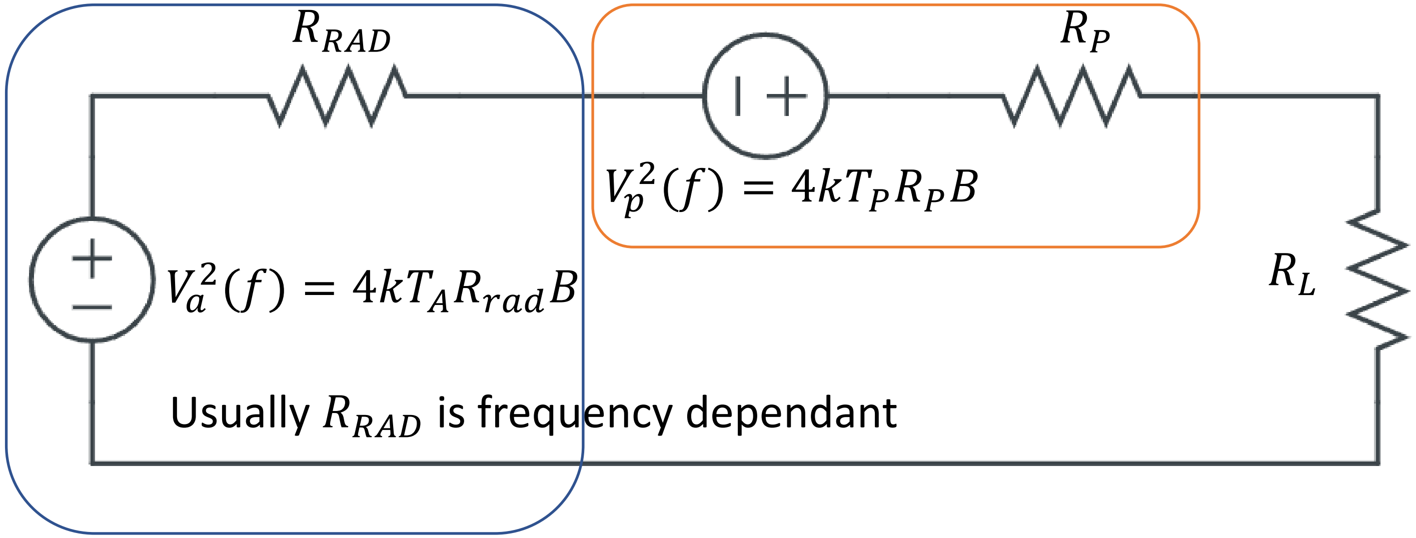
# Pickup – proposed equivalent circuit

Vacuum chamber (is it radiating noise power? At which temperature? $T_C$)



Pickup (antenna with a narrow directivity, $T_A$ and a given $R_{RAD}$)

Pickup losses from conductor and dielectric? $T_P$?




Load impedance – usually very different from $R_{RAD}$ (coax cable omitted)

Voltage noise on $R_L$: $V_L^2 = V_a^2 \left(\frac{R_L}{R_L+R_{RAD}+R_P}\right)^2 + V_p^2 \left(\frac{R_L}{R_L+R_{RAD}+R_P}\right)^2$

Depends on:
- Temperatures (real and equivalent)
- Ratio between impedances

# Thermal noise standards (NIST)

- Johnson noise thermometry based on available power: T=Pa/kB
- The power density is assumed constant in the measurment bandwidth
- For the evaluation of the noise along the BPM acquisition chain a coaxial thermal noise generator could be used as noise source.

# Questions

- Have you ever observed 1/f noise on calculated positions from BPMs? Could you define a clear “electronic” source?

- How can be modelled the noise from the pickups? Or can they be considered “noiseless” at the end?
  - References in “traditional” articles/papers take for granted the thermal noise behaviour with matched impedances (available power P=kTB)

# Thank you!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