Elettra Sincrotrone Trieste

Improving long-term stability and 1/f amplitude noise using pilot-tone compensation technique in Beam Position Monitors

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Elettra-Sincrotrone Trieste

Outline

- Introduction
- Pilot tone compensation technique
- eBPM system at Elettra
- Noise considerations
- Results and conclusions

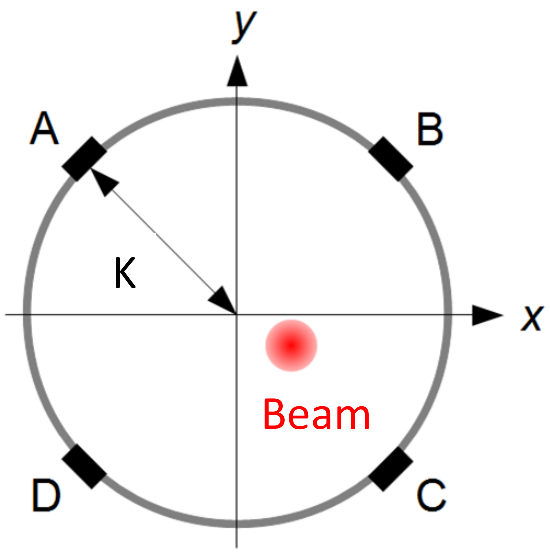
Beam Position Monitors: quick recap

- Beam induces EM field on pickups
- Information is encoded in signal amplitude (AM)

$$a(t) = A\cos(2\pi f_{RF} t)$$

- Amplitude signals mapped into positions by DoS equation

$$x = K_x \frac{(A + D) - (B + C)}{A + B + C + D}$$



- Resolution target for 4th gen. lightsources (ppm/bit/SNR):

$$\frac{\delta A}{A} \approx \frac{2\sigma_x}{K_x} \rightarrow$$

~100 nm resolution over 10 mm scale factor: 20 ppm
94 dB of SNR – 16 “real” bits – BW~10/20 kHz

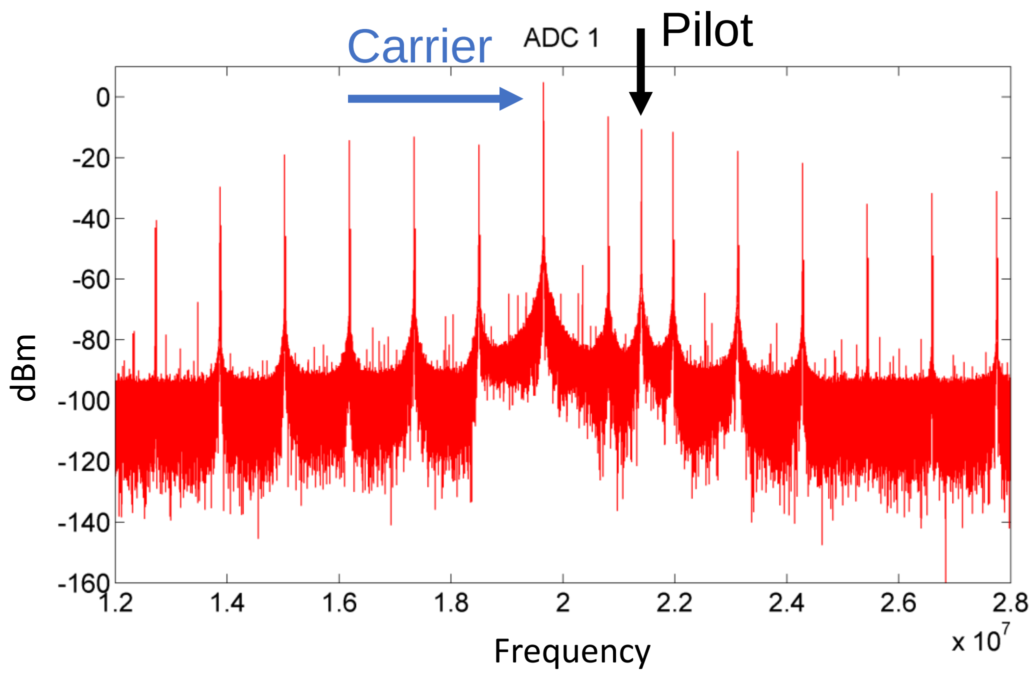
- Calibration/compensation is needed to discriminate between real beam movements and electronics’ drifts

  → Possible techniques: switching matrix, pilot tone

Pilot tone: implementation by Elettra

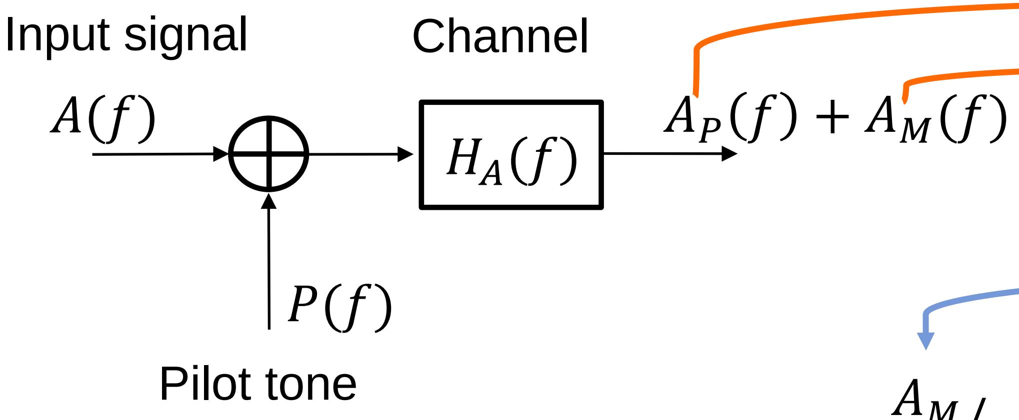
- A fixed sinusoidal tone (*pilot*) is added to the original signal coming from the beam (*carrier*)
- The 4 channels use the same tone as reference
- The pilot tone frequency has to fall near the carrier one without interfering with the latter

Typical spectrum of a eBPM button plus the pilot tone: Spaces between revolution harmonics are valid locations



Pilot tone: implementation by Elettra

Hypothesis: every channel variation affects in the same way both carrier and pilot



$$A_P(f) = H_A(f) \cdot P(f)$$
$$A_M(f) = H_A(f) \cdot A(f)$$

$$A(f) = \frac{A_M(f)}{A_P(f)} \cdot P(f)$$

$$x_C = K_x \cdot \frac{{A_M}/{A_P} - {B_M}/{B_P} - {C_M}/{C_P} + {D_M}/{D_P}}{{A_M}/{A_P} + {B_M}/{B_P} + {C_M}/{C_P} + {D_M}/{D_P}}$$

Compensated position in classical Difference-over-Sum (DoS) equation
“Deconvolution” between carrier and pilot

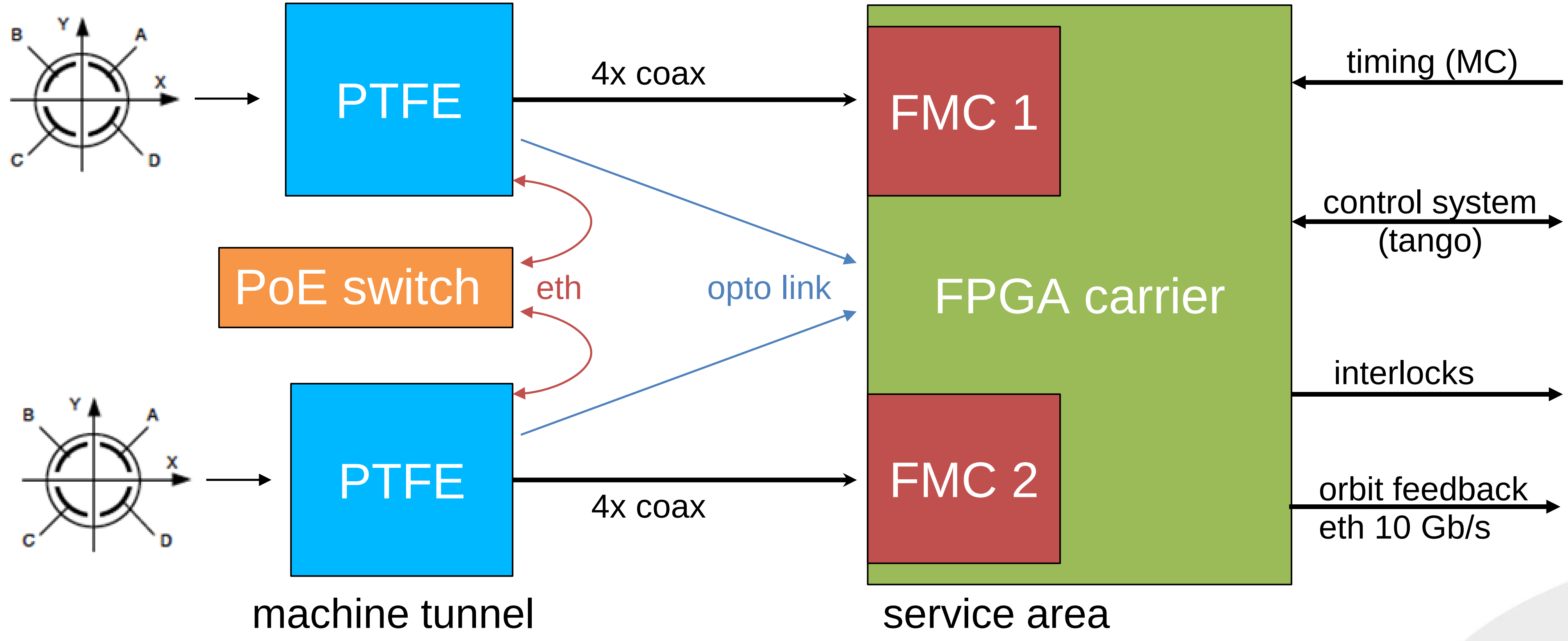
Pilot tone: implementation by Elettra

Advantages of this technique:

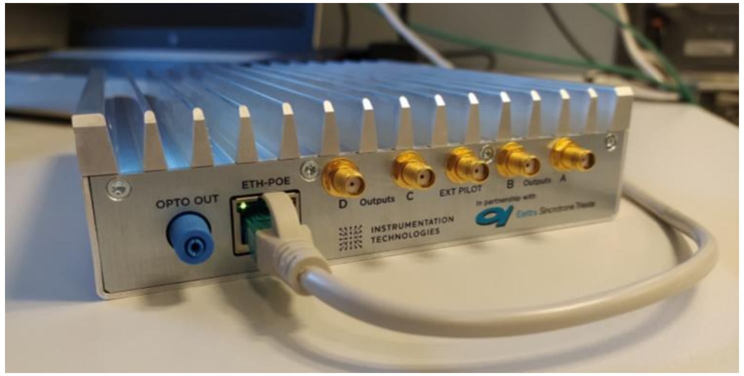
- Compensation of cables
  - Possible when the tone is injected near to the pick-ups
- No need for thermoregulation
  - Thermal drifts are the same for carrier and pilot
- Reduced current dependence
  - Pilot can be also used as a “dithering” with low beam currents
- The pilot position returns continuously a diagnostic of the system status
  - Hardware faults can be identified
- No switching harmonics compared to switching matrix

Block diagram of Elettra 2.0 eBPM system

- Result of a partnership signed between Elettra and Instrumentation Technologies
- Modular system: analog front end plus digitizer



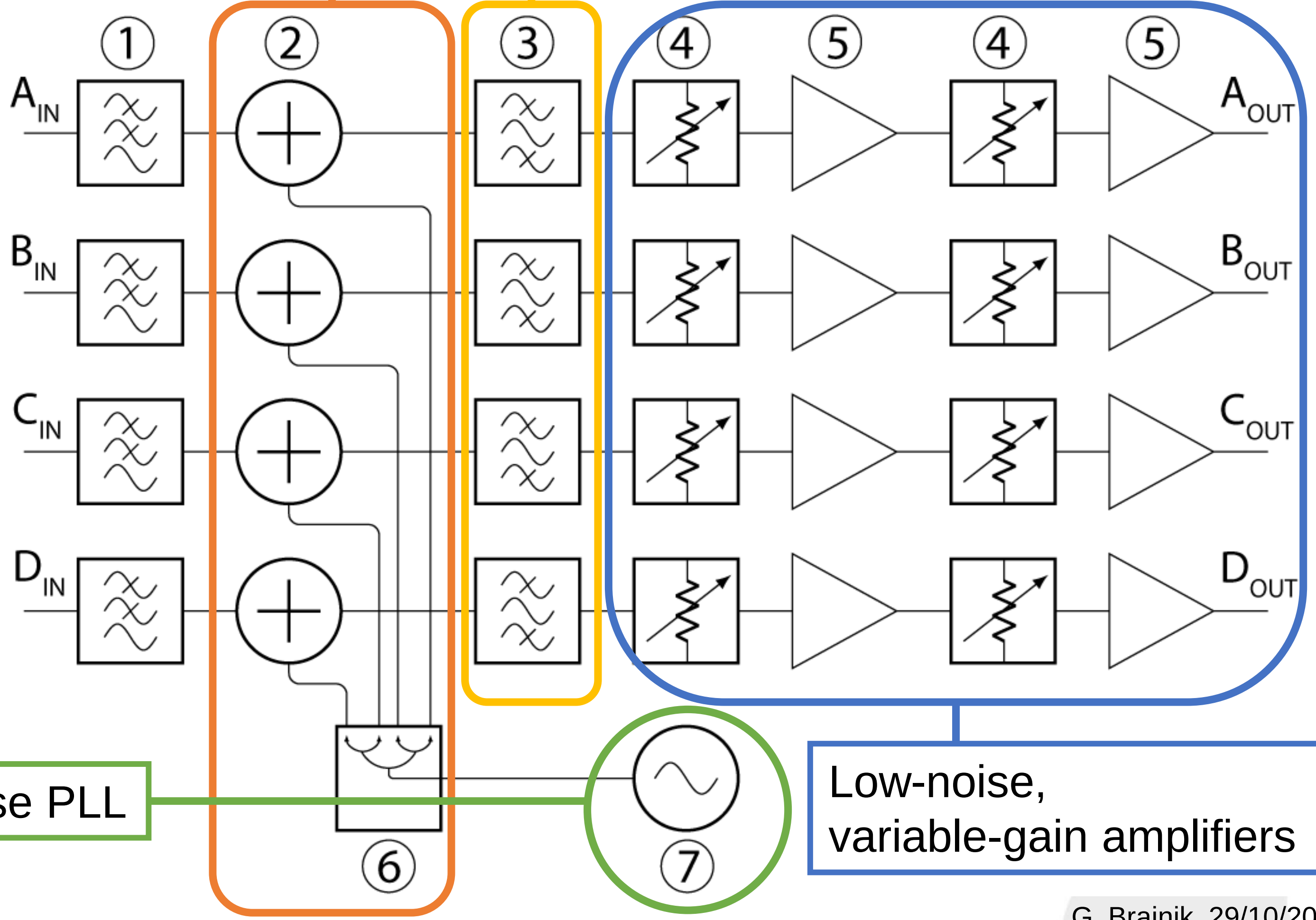
Pilot tone front end (PTFE)



Eth connectivity with POE

High isolation couplers

Bandpass filters, 500 MHz, BW~10MHz



Low phase-noise PLL

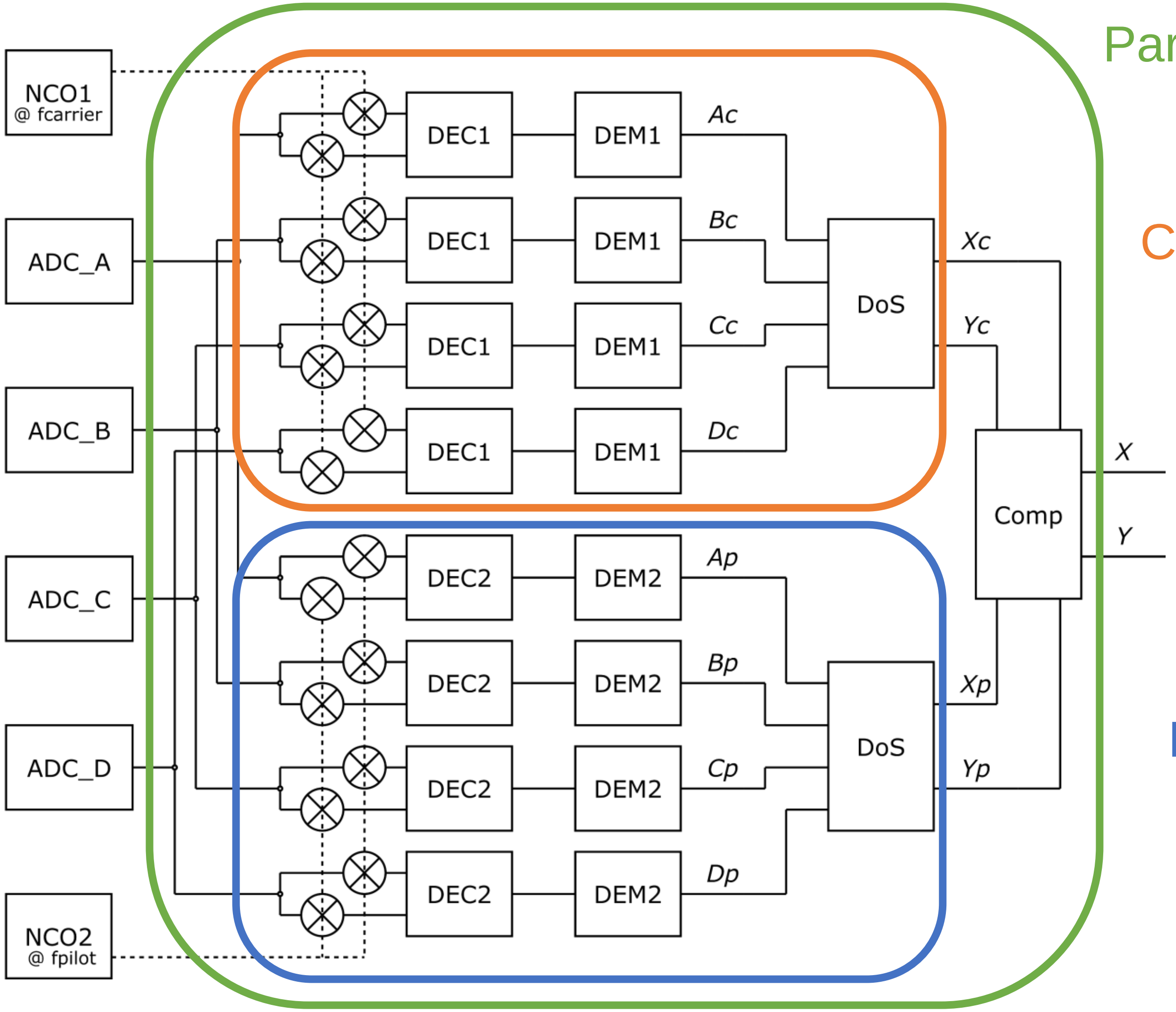
Low-noise,
variable-gain amplifiers

Digital board (DAQ)

- Board based on Intel Arria 10 SoC FPGA with ARM processor inside
- Onboard memory: 8 GB of DDR3 (buffers, postmortem, collection of raw adc data, etc)
- Connectivity: control system ethernet plus 6 SFP+ capable up to 10 Gb/s (feedbacks)
- Mezzanine support: two FMC HPC slots with 400 pins each
- Double DDC converter in FPGA (carrier + pilot) for each channel
- Position calculation at different data rates (TbT, 100 kHz, 10 kHz, 10 Hz, etc)

Simplified FPGA block diagram

16 bits ADCs
@ 150 MS/s
Bandpass sampling



Parallel data processing

Carrier demodulation

Pilot demodulation

UDP stream
to SFP interfaces

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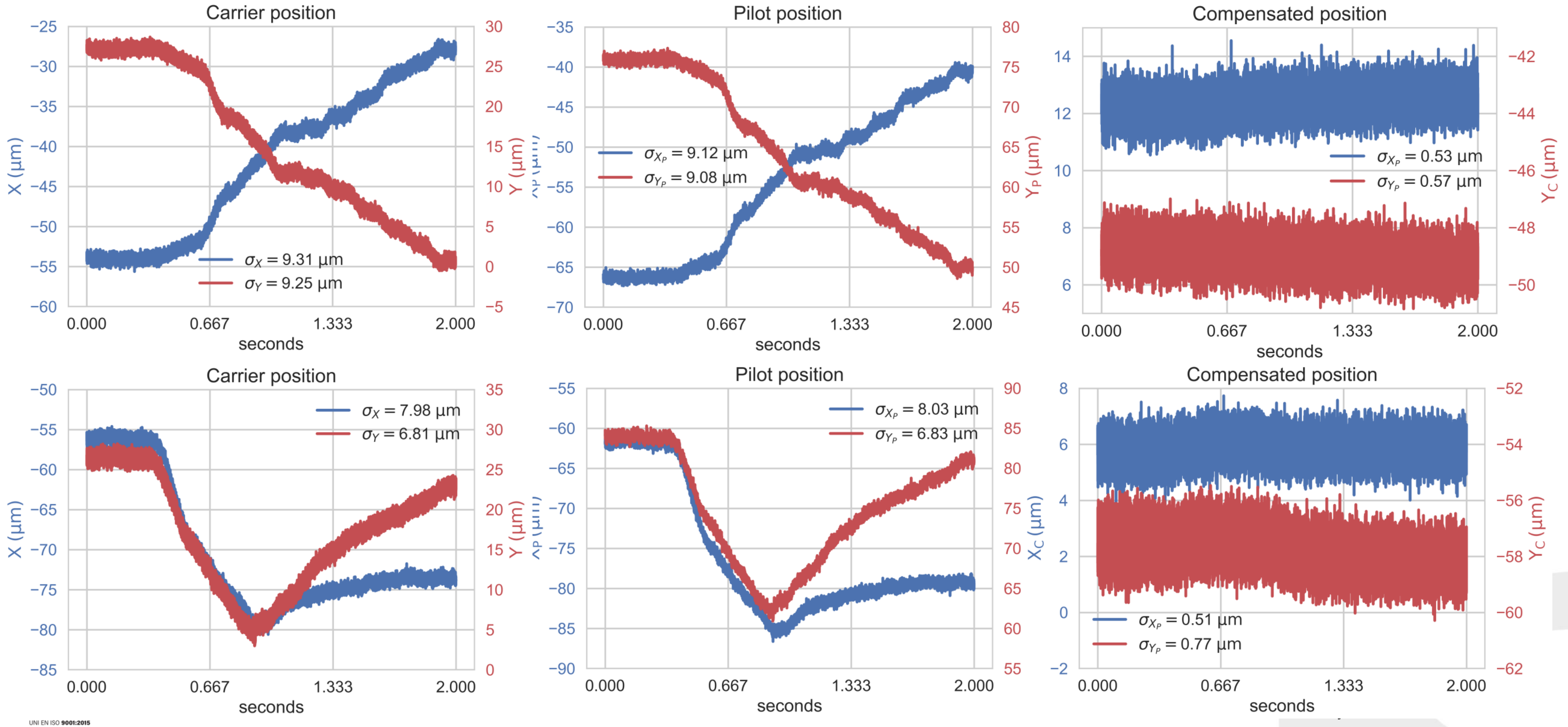
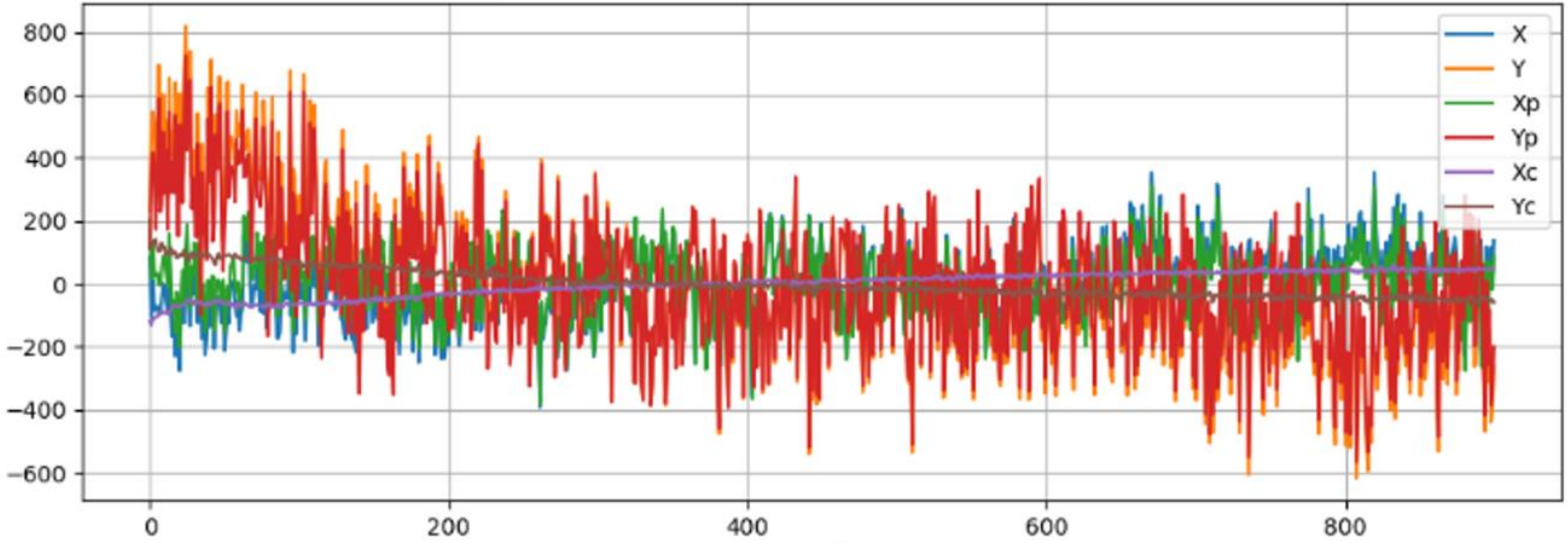
Temperature compensation (ADC, PTFE)



Long-term stability

- Drifts reduction by a factor of 4 (from ~200 to ~50 nm)
- No thermoregulation – initial heating of the electronics

Compensated vs Uncompensated positions

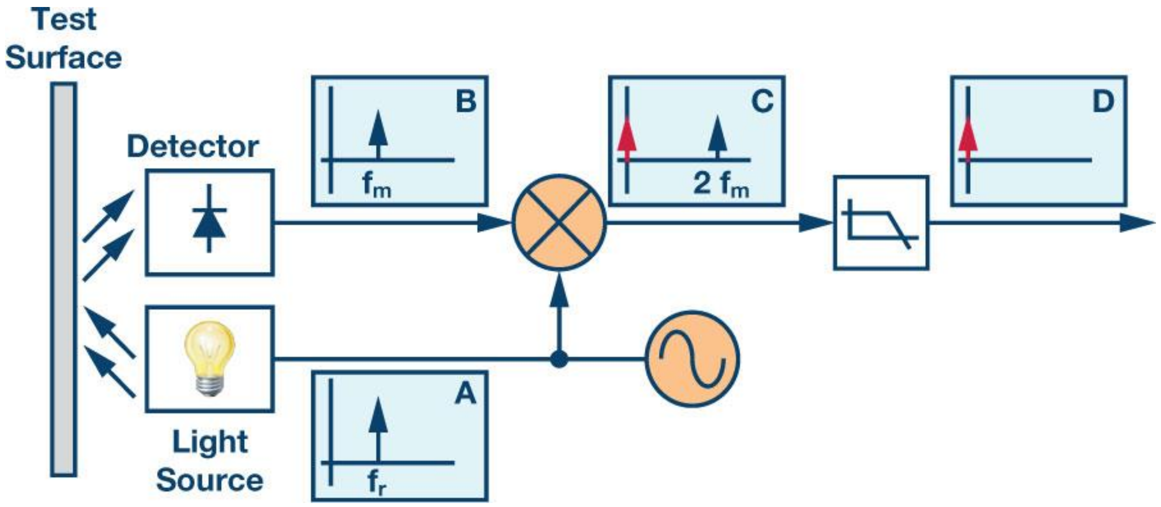


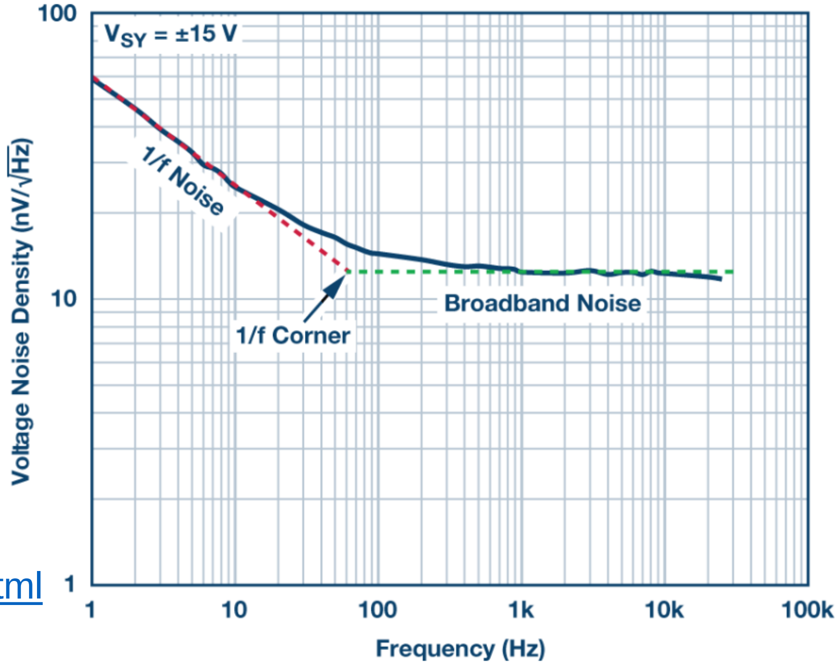
Positions [nm]

Acquisitions [minutes]

Noise considerations

- Can pilot tone compensation be useful not only in mitigating long-term drifts, but also in noise reduction?
- Answer: yes, if we are talking about 1/f noise (flicker)
- PSD of 1/f noise is not flat, there's correlation between consecutive samples
- Techniques for 1/f noise cancellation: modulation (lock-in amps, sigma-delta ADCs)





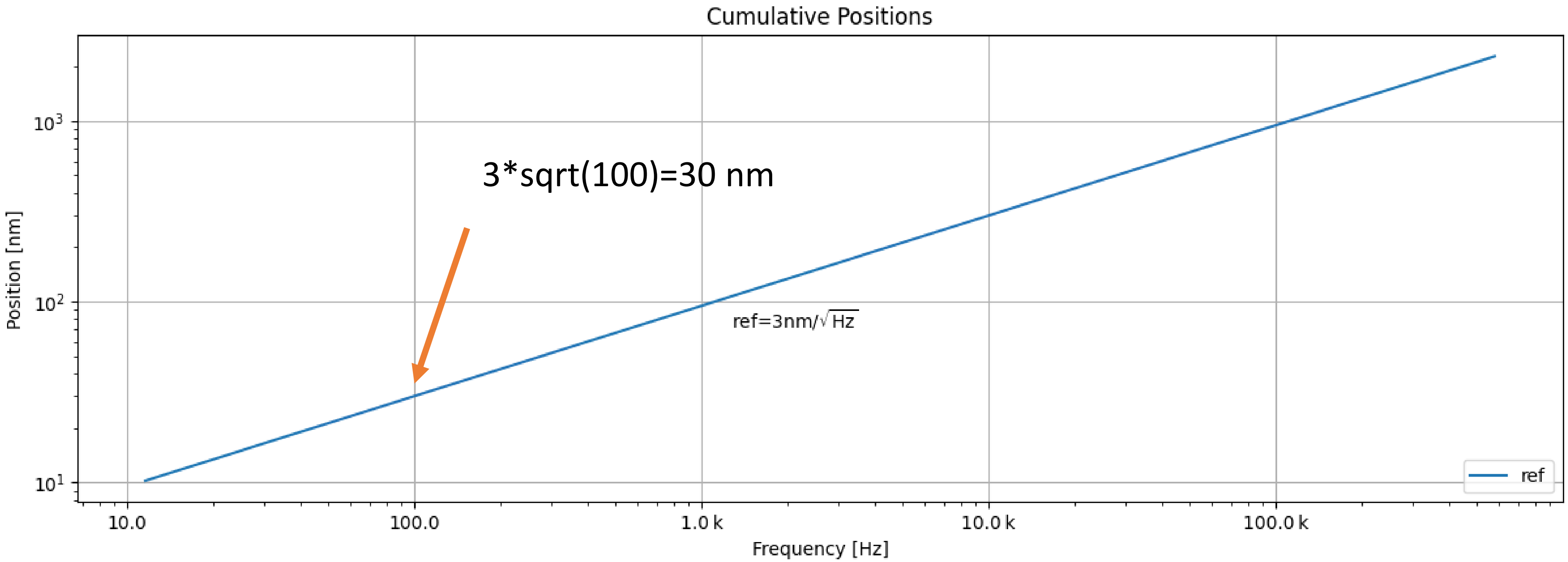
https://www.analog.com/en/resources/analog-dialogue/articles/understanding-and-eliminating-1-f-noise.html

Noise evaluation in BPMs

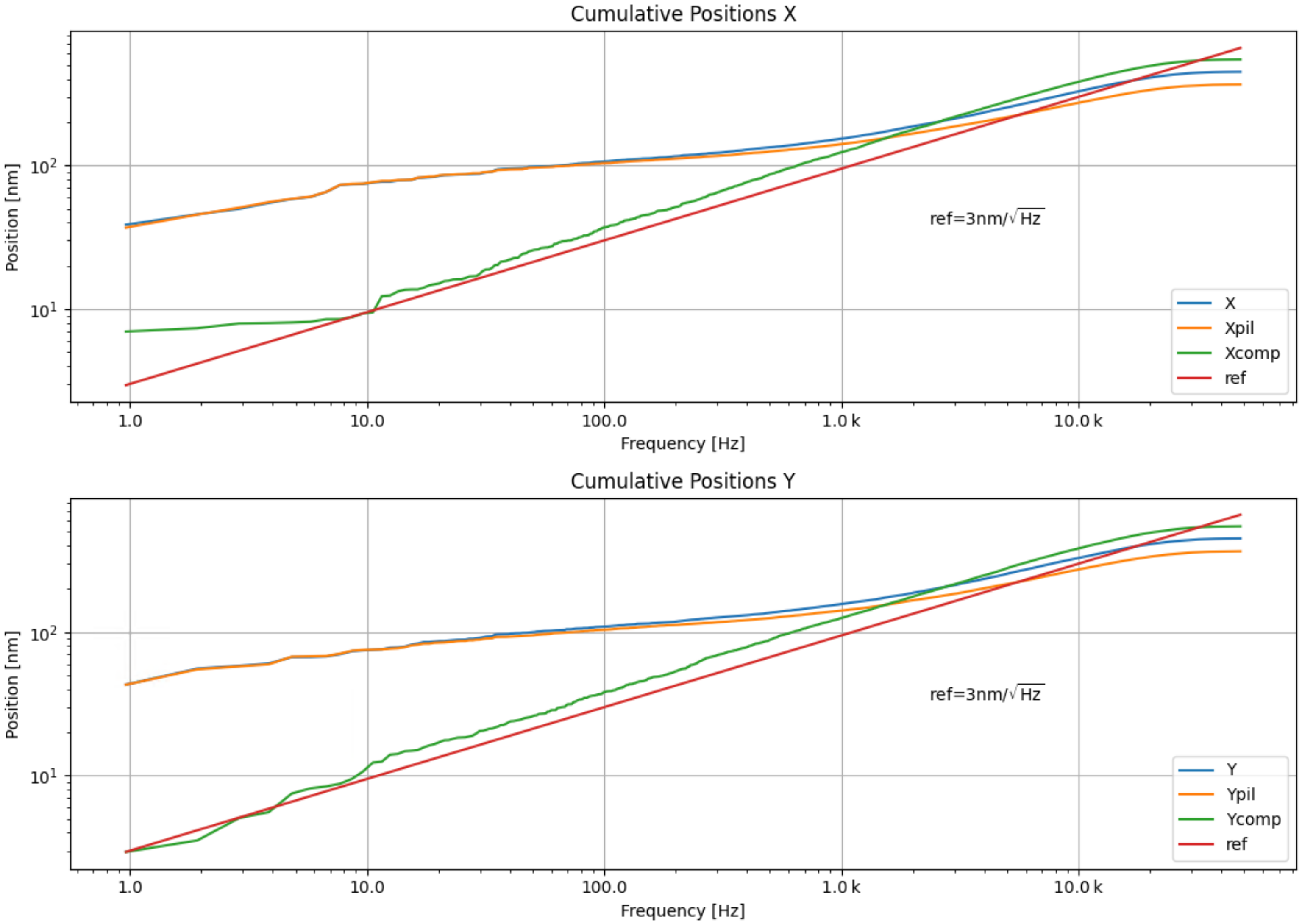
- Test setup: RF gen + splitter (emulate a stable beam)
- Significant 1/f noise on our BPM system
- Pilot tone compensation can cancel it out
  - Good correlation between amplitude variations due to 1/f on pilot and carrier
- Noise source: coming from ADCs?
  - No difference w & w/o front end → PTFE has white noise
  - No difference at different frequencies → not related to sampling clock jitter
  - Probably caused by sample & hold stage inside ADC

Noise evaluation in BPMs

- Easier to refer to noise on calculated positions
- graphs: cumulative sum of PSD vs frequency
- Example with white noise (flat PSD integrated over bandwidth):



Cumulative Spectral Density



Positions @ 100 kS/s

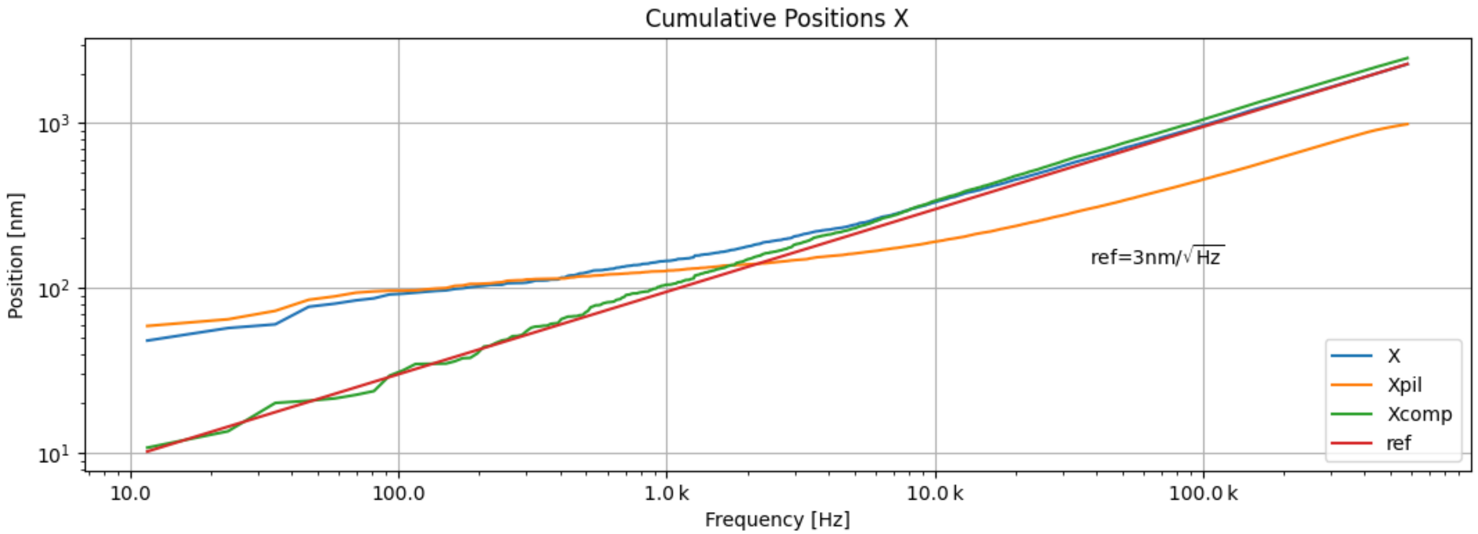
Red trace: white noise reference of 3nm/sqrt(Hz)

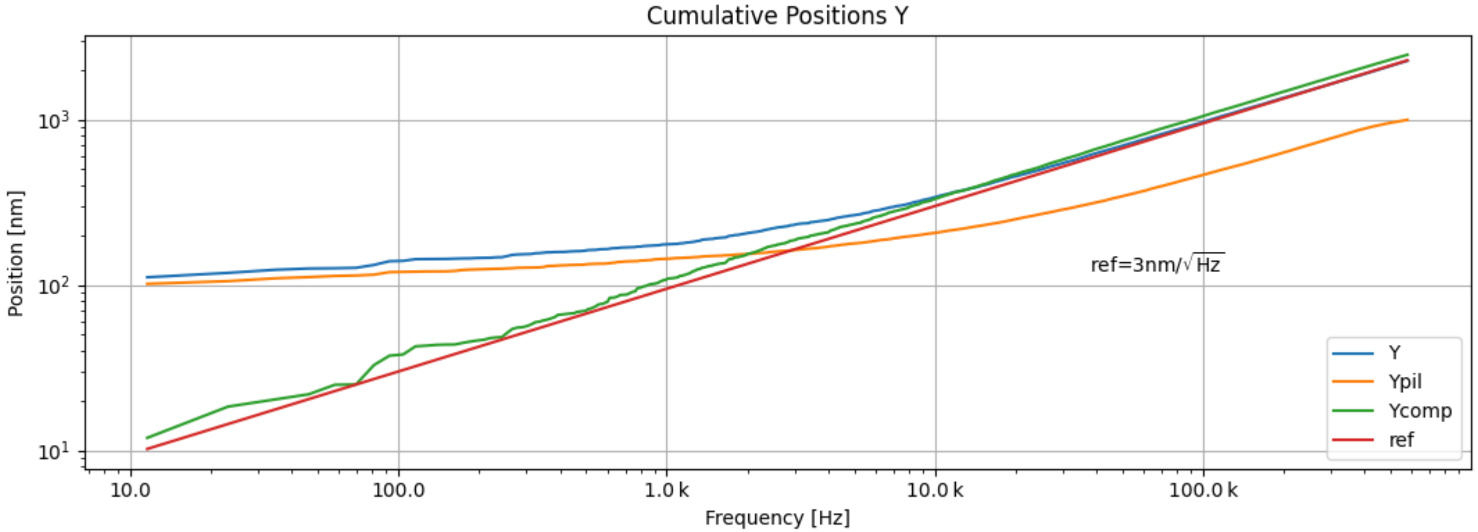
Blue trace: carrier
Orange trace: pilot
Green trace: compensated position

Noise of non-compensated position higher than expected

Compensated position follows theoretical prediction

Cumulative Spectral Density





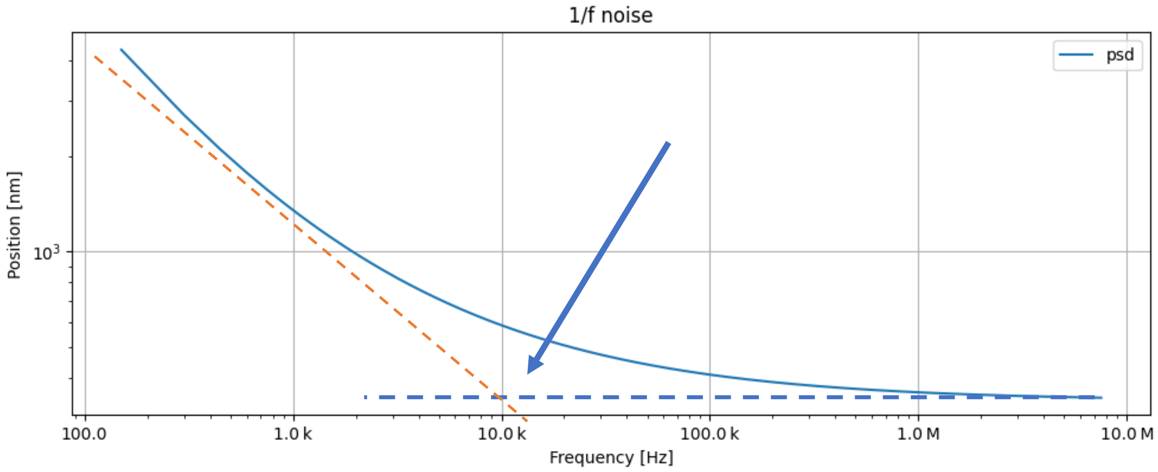
Positions @ 1.156 MS/s - TbT

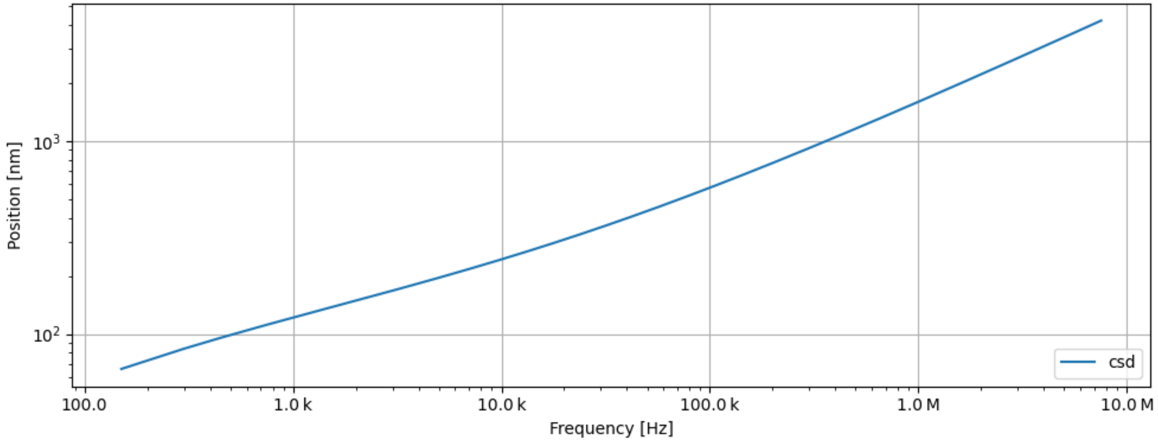
Expanding bandwidth helps to understand the phenomena

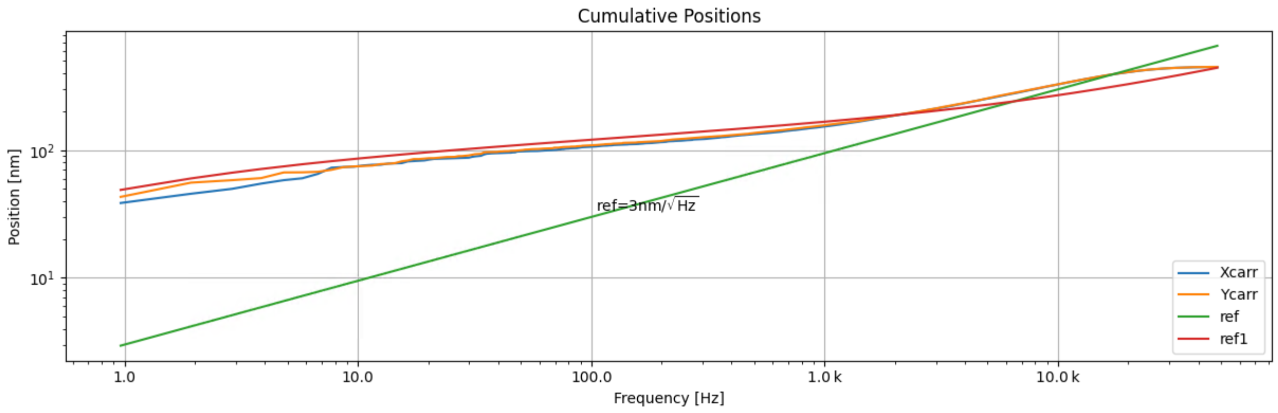
Noise PSD is flat above 7/10 kHz

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

1/f fitting







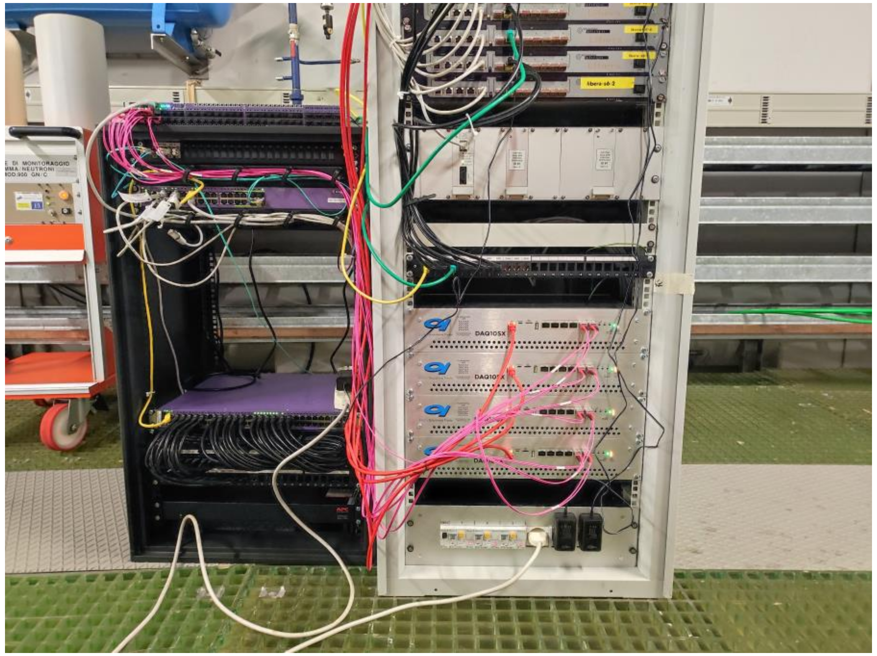
Fit 1/f noise (red trace):

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

Corner frequency: about 10 kHz

Integration in current machine

- Currently, a complete section of Elettra storage ring (8 BPMs) is working with the new eBPM system since August ’24
  - No issues reported
  - Extreme flexibility due to in-house developed firmware
  - Continuous (1 kHz) tune measurements thanks to higher data rate
  - Control system and Global Orbit Feedback integration thanks to DPDK framework (feedback freq. 10 kHz, bpm acq. freq. 1.15 MHz)



Conclusions

- Pilot tone is a useful technique to enhance both long-term stability and 1/f noise performance
- The new system is working well on the present machine
- Fine-tuning enhancements ongoing
- Target: increase reliability and usability for a easier deployment on the new machine

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Thank you!

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