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Influence of instrumentation noise in magnetic measurements by induction method

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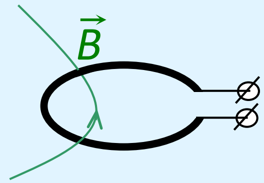
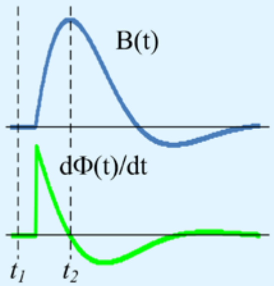
Introduction



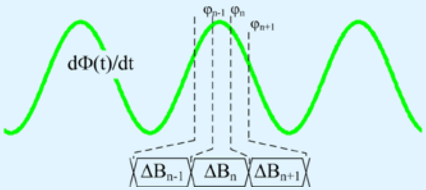
$$\varepsilon(t) = -\frac{\partial(\vec{B}\vec{S})}{\partial t}$$

Pulsed Measurements



Measurement of ramped magnets, BUMP, SEPTUM and others with pulse duration from microseconds to seconds.

Constant Field Measurements

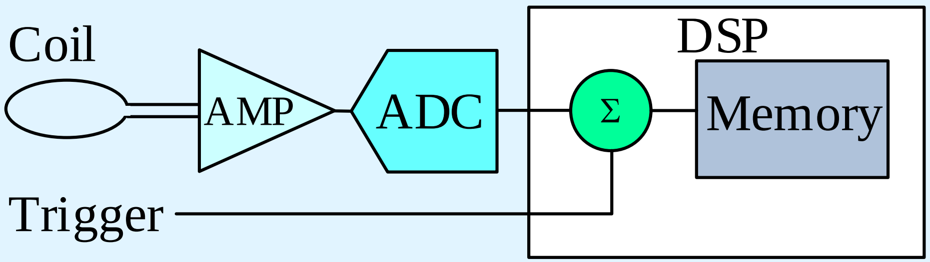


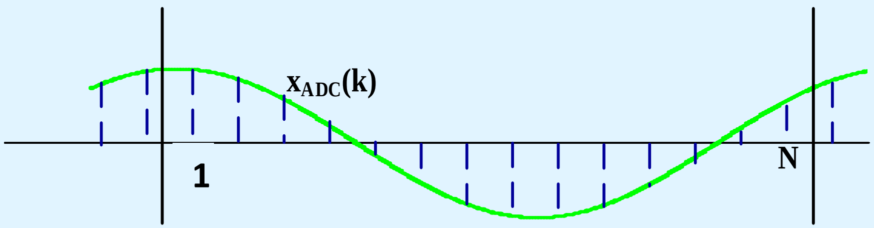
Rotating coils, Stretch wires, λ-coils, etc.

Repeatability of measurements is influenced by:

- Noise and ripples of PS current;
- Electrical interference (multiples of AC line frequency or induced by PS bars);
- Noise and errors of moving system and position sensors;
- Instability of integration interval;
- Noise of induction signal measuring electronics.
- and others…

Noise of the direct digital integration





$$Vs = \sum_{k=1}^{N} x_{ADC}(k) T_S$$

If noise of ADC sample statistically independent and its root-mean-square noise equals to δx_{ADC}:

$$\langle Vs \rangle = \left\langle \sum_{k=1}^{N} x_{ADC}(k) T_S \right\rangle = \delta x_{ADC} T_S \sqrt{N}$$

If introduce $T_S N = T$ – integration time, and $1/T_S = F_S$ – sampling frequency, than:

$$\langle Vs \rangle = \delta x_{ADC} T_S \sqrt{N} = \frac{\delta x_{ADC}}{\sqrt{F_S}} \sqrt{T} = \eta_{ADC} \sqrt{T},$$ where $$\eta_{ADC} = \frac{\delta x_{ADC}}{\sqrt{F_S}}$$

Noise spectral density of analog path

Comparison of ADC chips by noise spectral density

Shown that at given integration time T the noise of the integral is:

$$\langle Vs \rangle = \eta_{ADC}\sqrt{T}$$

η_{ADC} can be expressed via ADC chip parameters like full scale V_{FS}, F_S and SNR (dB):

$$\eta_{ADC} = \frac{V_{FS}}{2\sqrt{2F_S}}10^{-SNR/20}$$ and relative to full scale V_{FS}: $$D_{ADC} = \frac{10^{-SNR/20}}{2\sqrt{2F_S}}$$

Model	AD7177-2	AD7177-2	LTC2378-20	AD7960	LTC2387-18	LTC2216	AD9467
Fs, SPS	5	10k	1M	5M	15M	80M	250M
V_{FS}, V	10	10	10	10	8.192	2.75	2
Bits	32	32	20	18	18	16	16
SNR, dB	154	126	104	99	95.7	82.5	75
INL, ±ppm, typ	1	1	0.5	3	3	18	53
η_{ADC}, nV/$\sqrt{Hz}$	22.3	17.7	22.3	17.7	12.3	8.2	8.0
D_{ADC}, $10^{-9}/\sqrt{Hz}$	2.2	1.8	2.2	1.8	1.5	3.0	4.0

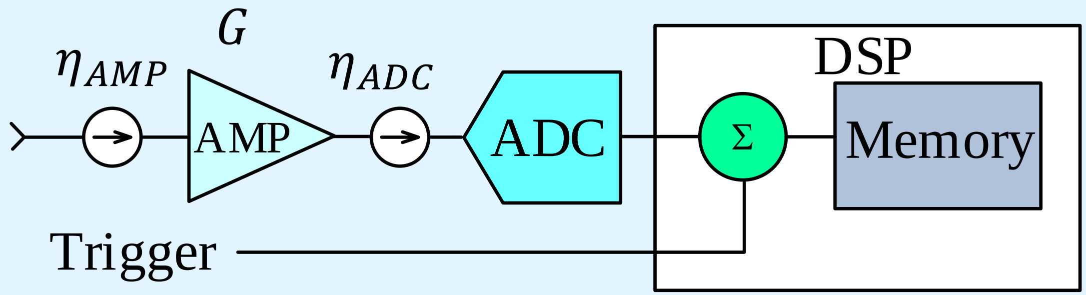
ADCs with middle range throughput, (10kSPS - 10MSPS, SAR-ADC or ∑Δ-ADC), demonstrate the best noise spectral density and quite good linearity for low noise digital integrators.

Do we need high gain?

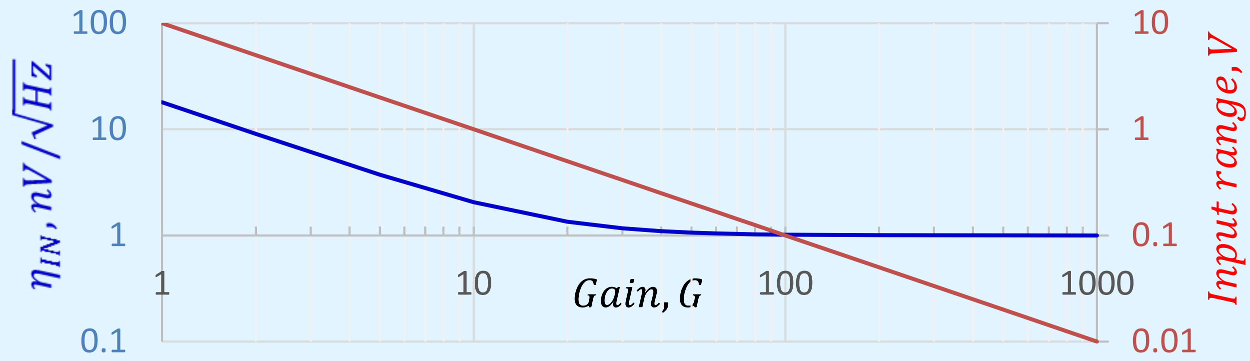
After choosing of ADC-chip let's consider the noise spectral density of full analog path for simple case:

Relative to input:

$$\eta_{IN} = \sqrt{\frac{\eta_{ADC}^2}{G^2} + \eta_{AMP}^2}$$



ADC Chips has $14 - 18\, nV/\sqrt{Hz}$ Low noise Op. Amps has $\sim 1\, nV/\sqrt{Hz}$



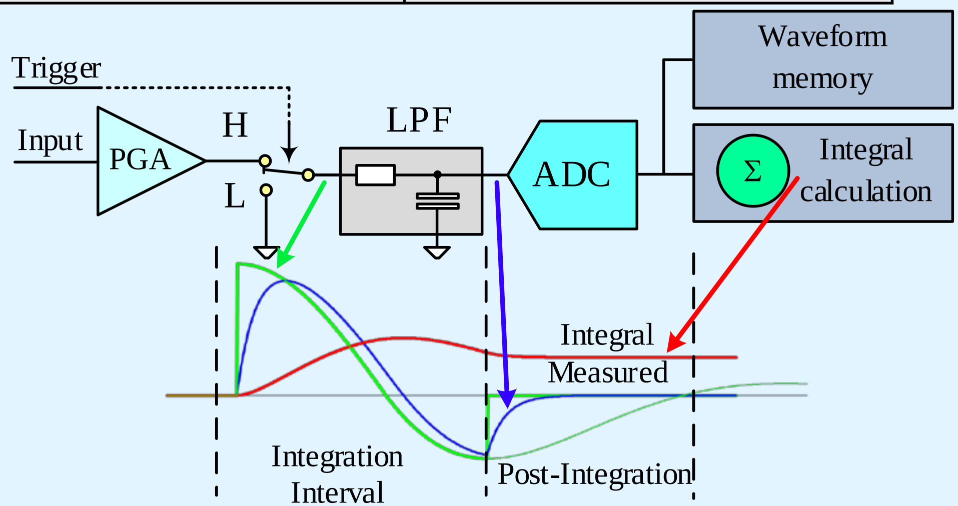
High amplifier gains (G>20) don't influence on relative to input noise but lowers the input voltage range, therefore they are not actually required.

Multifunction Digital Integrators VsDC2 and VsDC3

VsDC – **V**olt-second to **D**igital **C**onverter

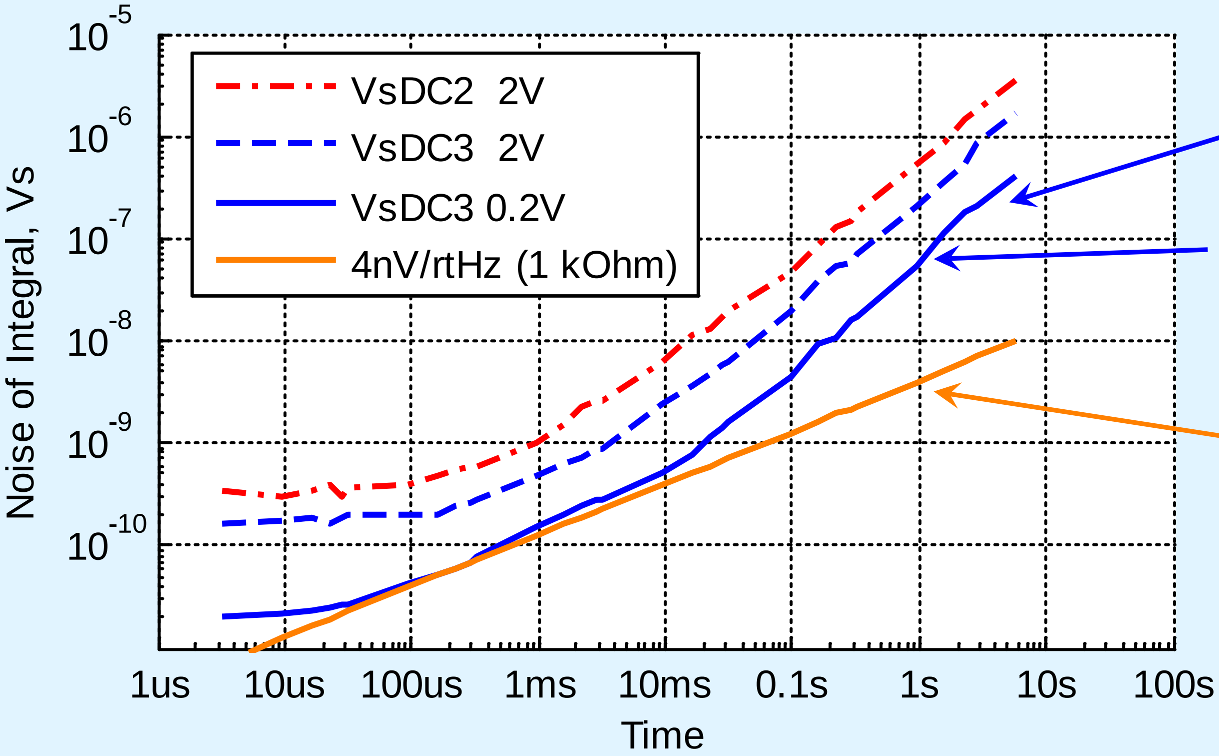
Intended for constant and pulsed field measurements

	VsDC2 (CAN version)	**VsDC3** (VME version)
# of channels	2	2
Input voltage ranges	±0.2V; ±0.5V; ±1V; ±2V; ±5V; ±10V	±0.2V; ±2V
ADC	AD7763, 24bit, 3.2 (1.6) mks/sample	
Footprint	3U 4HP Eurocard	6U 4HP Eurocard



Details in IMMW19: "The precise digital integration from microseconds to seconds: theory and implementation"

Measured noise of VsDC2 and VsDC3 Integrators



Slope~T

Measured noise of integral 60nV*s @ 1s !!!

Expected noise of integral:

$$\langle Vs \rangle = \eta_{ADC}\sqrt{T}$$

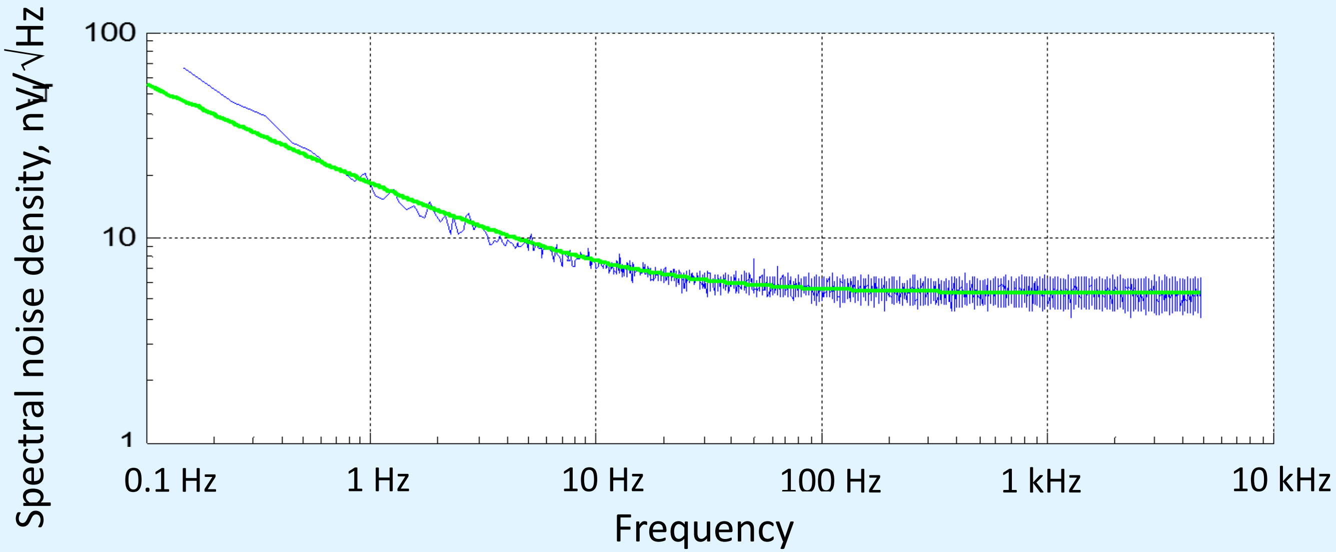
Should be 4nV*s @ 1s

Knowing the area of the measuring coil, such plot allows one to estimate the resolution of the system at a given integration time.

Influence of 1/f noise on the noise of integral

$\langle Vs \rangle = \eta_{ADC}\sqrt{T}$ obtained under assumption of constant noise spectral density.

Actual spectral density is influenced by 1/f noise: $\eta_{ADC}\sqrt{1+(f_C/f)}$ giving linear rise of the noise of integral at high $T_{INTEGRATION}$.

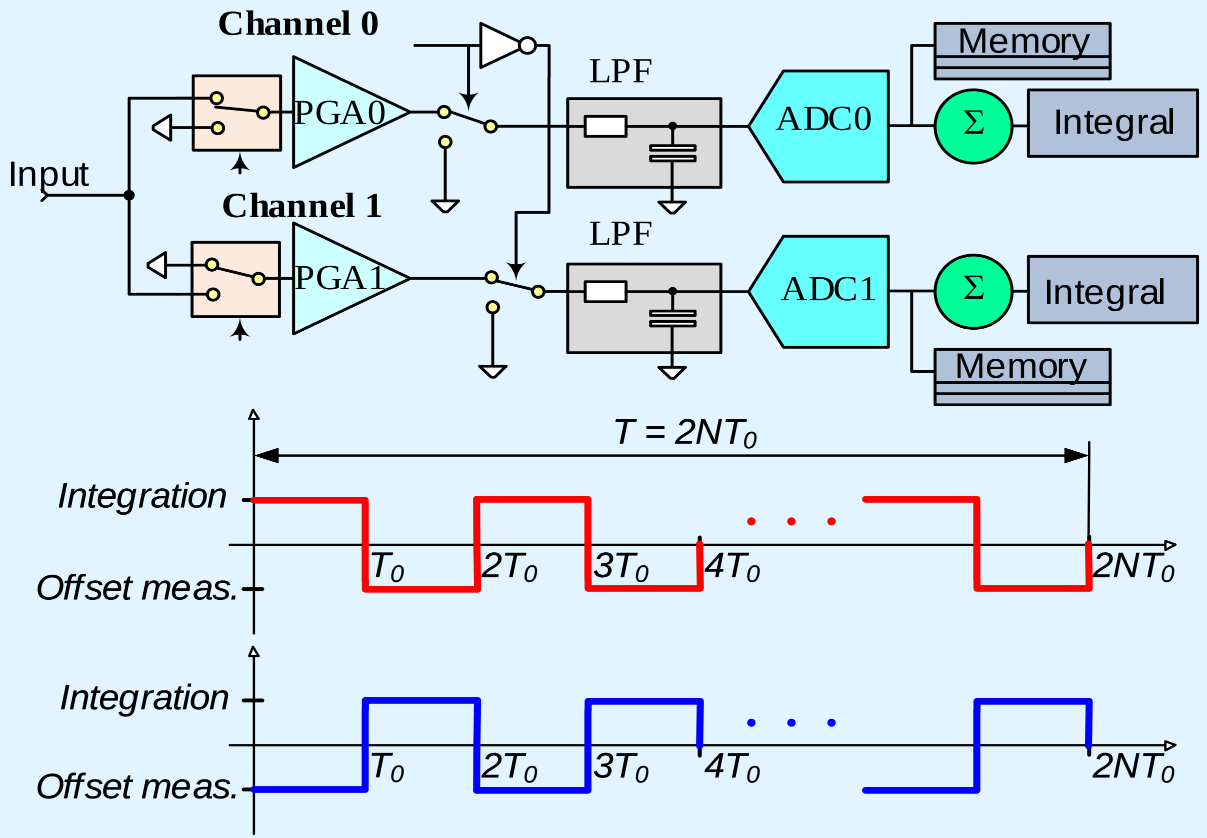


VsDC3 analog path (ampls+ADC) voltage noise spectral density at 200mV range:

- η_{ADC} = 4,5 nV/√Hz.
- f_C=20 Hz.

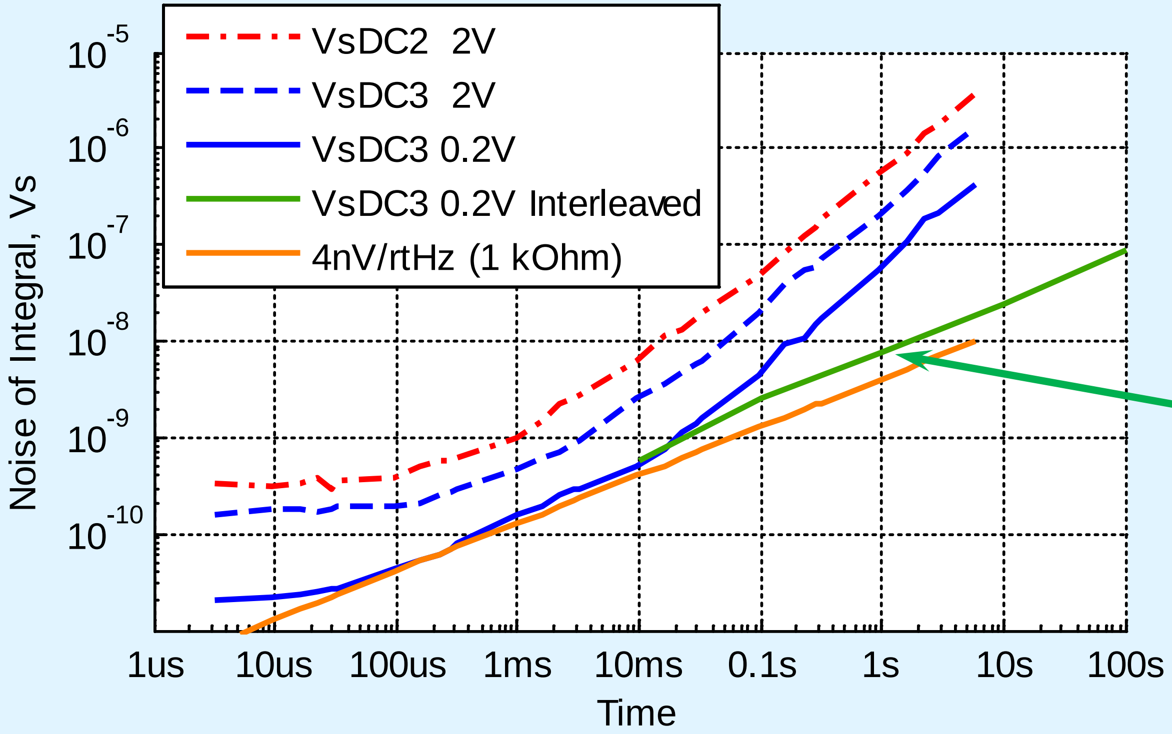
Cancellation of 1/f noise by combining of two channels

$$\text{If } T_0 \ll 1/(4\ln(2)f_C) \Longrightarrow \langle Vs \rangle = \sqrt{2}\eta_{ADC}\sqrt{T}$$



Input signal integration in one channel is coupled with self offset measurements in the other channel providing continuous integration of input signal and offset cancellation.

Measured noise of integral with 1/f cancellation

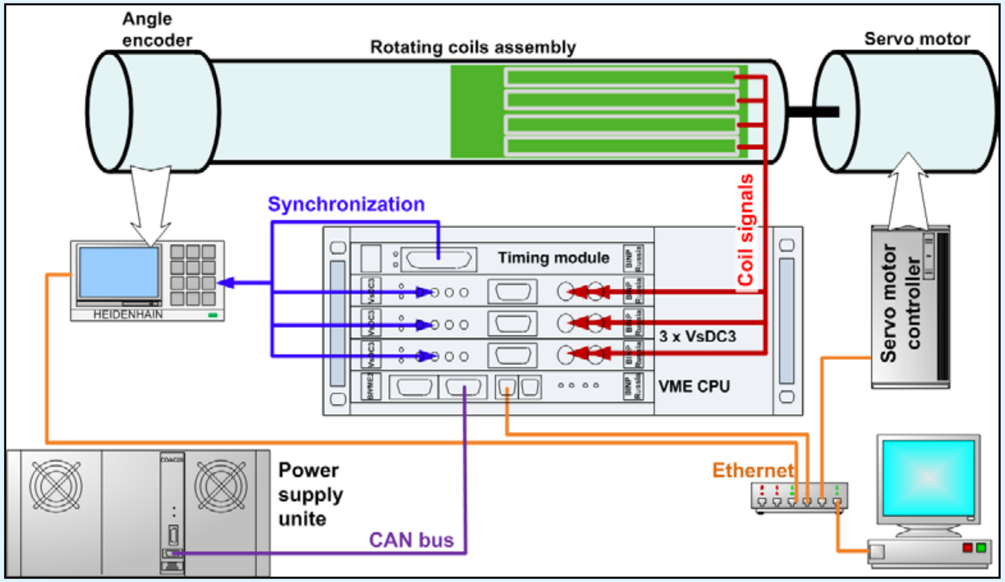


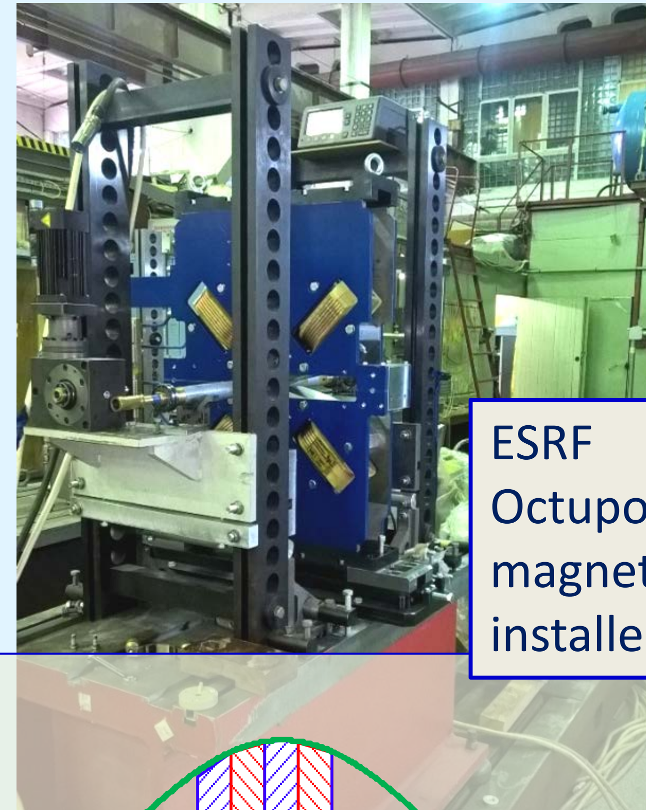
With 1/f cancellation noise of integral behaves as expected:

- 7nV*s @ 1s
- 90nV*s @ 100s

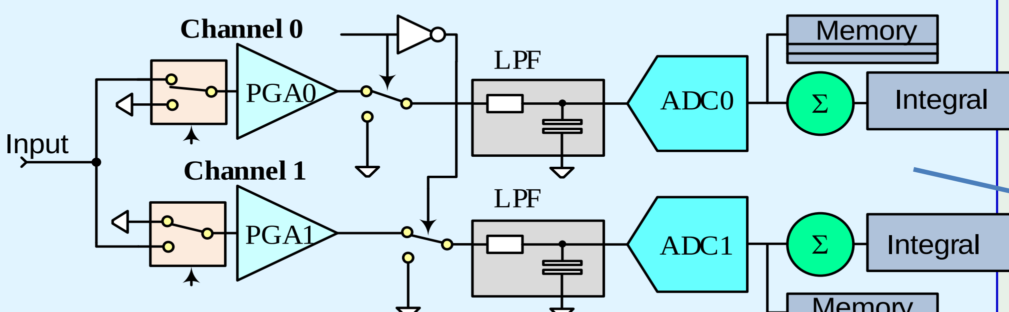
The possibility of obtaining a low noise in the electronics imposes strict requirements on the level of electrical interference, mechanical vibrations, temperature gradients, etc.

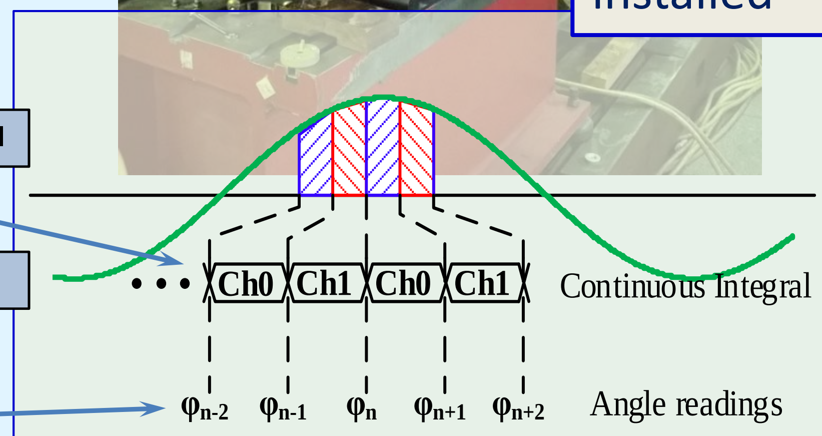
Noise sources in rotating coil bench: bench overview





ESRF Octupole magnet is installed





Heidenhain ND287 + RCN228 Encoder

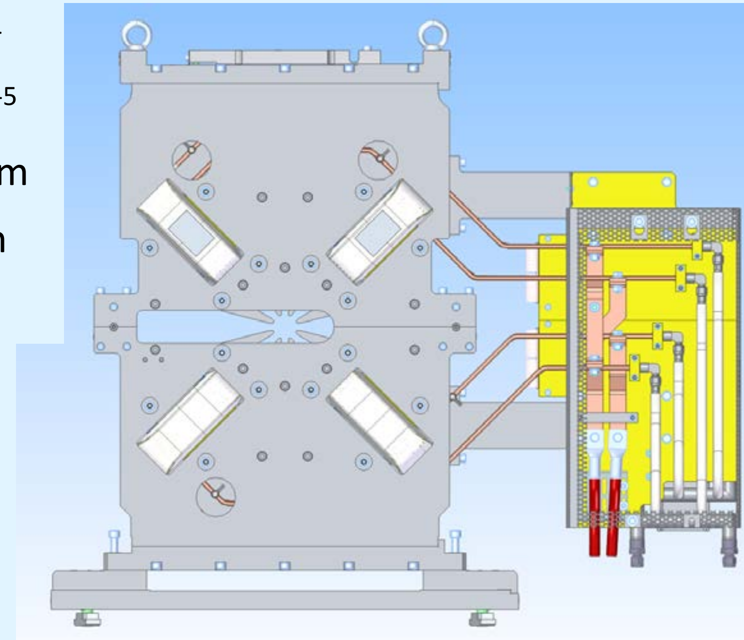
Noise sources in rotating coil bench: recent measurements

ESRF Octupole magnets:

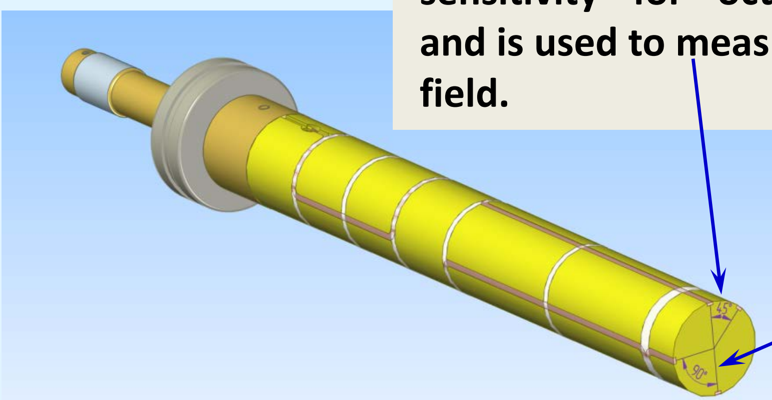
- Bore radius: 18,6 mm
- Yoke length: 90 mm
- Nominal gradient: $3.6 \cdot 10^4$ T/m^3
- Nominal current: 54 A

Measurement requirements:

- Harmonics abs error: $\sigma<10^{-4}$
- Harm. repeatability: $\sigma<2 \cdot 10^{-5}$
- Magnetic center shift: ±50μm
- Meas. repeatability: $\sigma<5$ μm
- Roll angle: ±50μrad



"45-degree" coil has maximum sensitivity for octupole component and is used to measure tilt angle of the field.

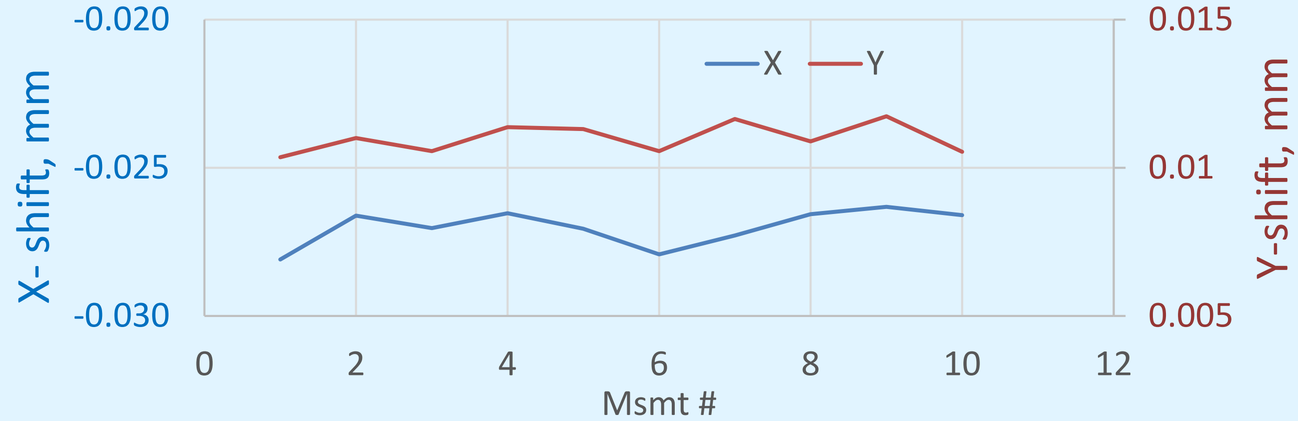


"90-degree" coil provides compensation of octupole component and is used to measure X and Y axis shifts.
Both coils are used to calculate field harmonics a_n and b_n

Fiberglass measurement shaft contains "axial" coils.

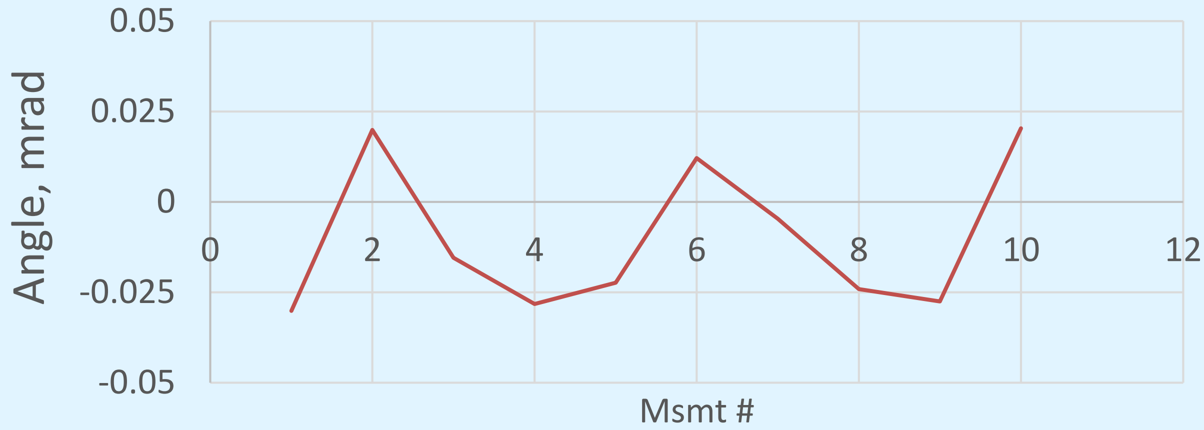
Noise sources in rotating coil bench: noise of measurements

Repeatability (caused by the system noise) obtained over a set of consecutive measurements.



Y_{RMS}= 0,5 µm
Y_{p2p} = 1,4 µm

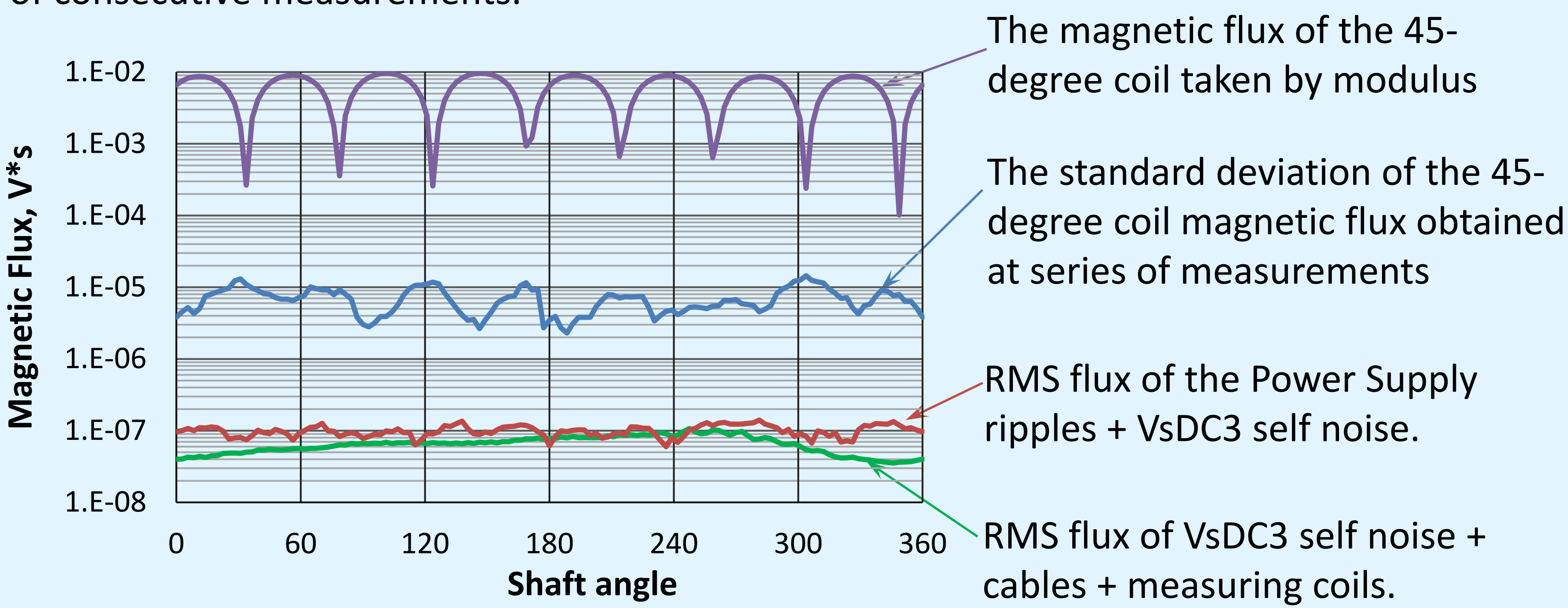
X_{RMS}= 0,6 µm
X_{p2p} = 1,8 µm



$\phi_{RMS}= 2\cdot10^{-5}$ rad
$\phi_{p2p} = 5\cdot10^{-5}$ rad

Noise sources in rotating coil bench

The standard deviation of the magnetic flux is calculated at each angular position using set of consecutive measurements.

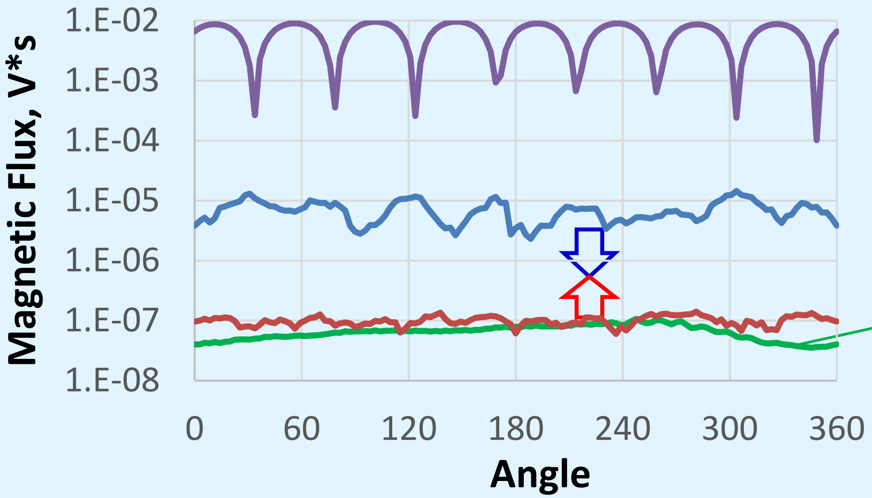


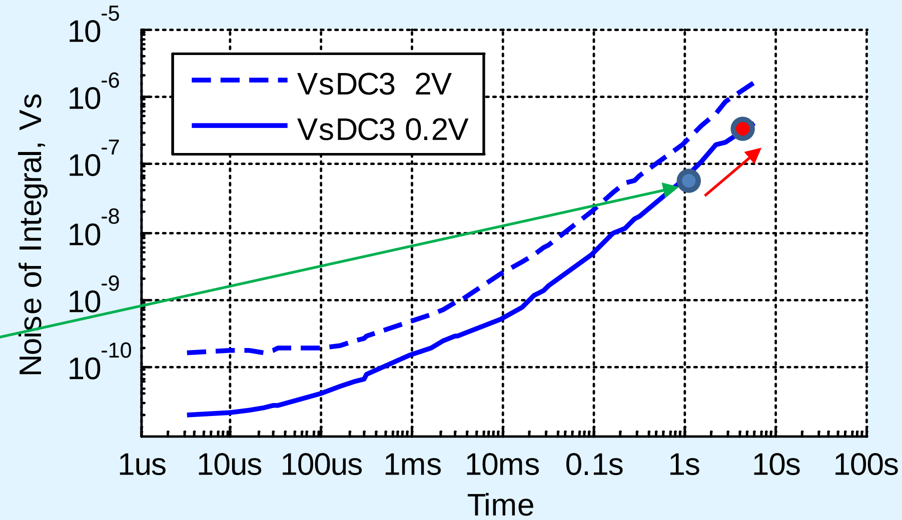
Main influence on measurement system noise is made by “jitter” of angle measurements due to imperfect synchronization (at Heidenhain ND287 + mechanical issues) with external pulses. The estimated jitter value is ±40 μs.

The search for the reasons for poor synchronization will be continued.

Noise sources in rotating coil bench

Noise from synchronization jitter is proportional to the signal amplitude and to the rotation speed.





To improve measurements in non-compensated channel there are two options:

- Slow down rotation speed (In addition to 2.56s/turn it is added 5.12s/turn and 10.24s/turn speed). It would decrease synchronization error, but increase measurement time and integrators self noise.
- Improve angle measurement synchronization mechanism (ND287 would be replaced with self design interface card to RCN228 Encoder).

Summary

- Methods to reduce noise of integral at high integration times have been realized and tested. At the integration time 100 s the noise is less then 10^{-7} V·s. The possibility of obtaining such a low noise in the electronics imposes strict requirements on the level of electrical interference, mechanical vibrations, temperature gradients, etc.

- Limiting factors for repeatability of angle measurements of our rotating coil bench are found and further improvement would be done in order to obtain noise of angle less then 10 μrads.

THANKS FOR YOUR ATTENTION!