Corrections of systematic effects of FG5/X gravimeters

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Motivation and Methodology

Reference gravity values are strongly "FG5(X) dependent" !!! Any systematic error influences the reference itself.

How accurate is really an FG5/X?

Could be FG5(X) improved?

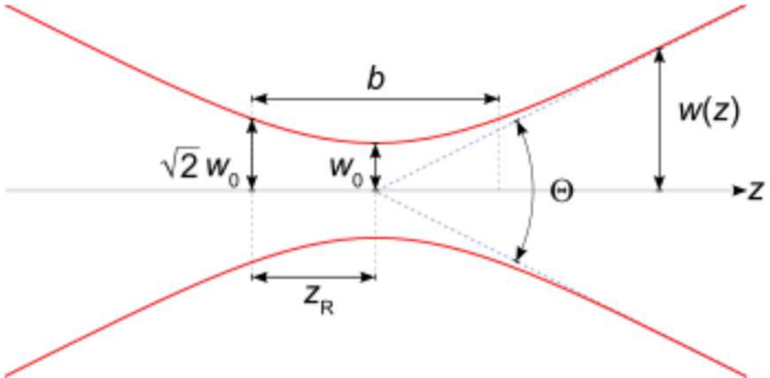
How to determine systematic errors?

Experiments on FG5-215 and FG5X-251:

- validation of measurement results (AGDAS)
- development of a new measurement system (HS5)
- determination of particular systematic errors

Diffraction correction

Monchalin et al. (1981) | Van Westrum et al. (2003) | Robertsson (2007)



FG5s spot size ($\pi\ w$)≈ **10 - 5 mm** ⇨ **width** (w)≈ **3.2-1.6 mm, Rayleigh range (z_R)=50-13 m**

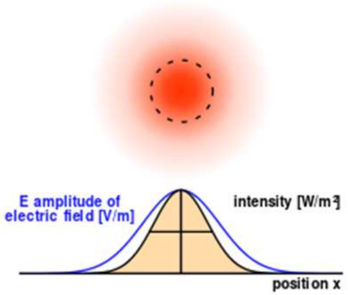
Diffraction correction (DC)

$$\Delta g = \frac{g\,\lambda^2}{4\,\pi^2 w_0^2} \Rightarrow 1.0 - 3.8\ \mu Gal$$

Usual DC: 1.0 – 1.6 μGal

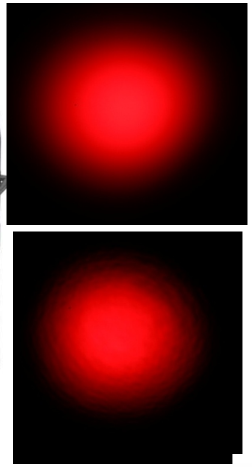
Beam waist should be here, but **beam width** w **is often measured**

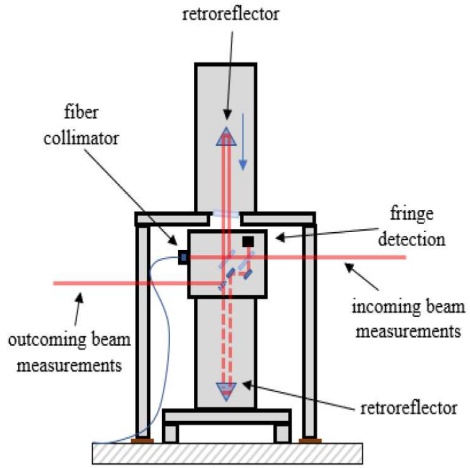
Validity only for Gaussian beam



New method (also for non-Gaussian beams)

Applied Optics 61, 1811-1817 (2022)



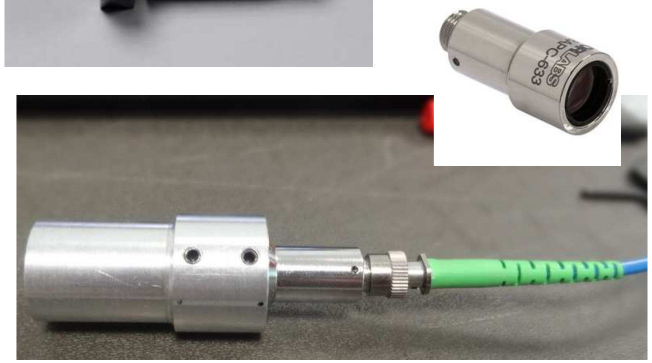


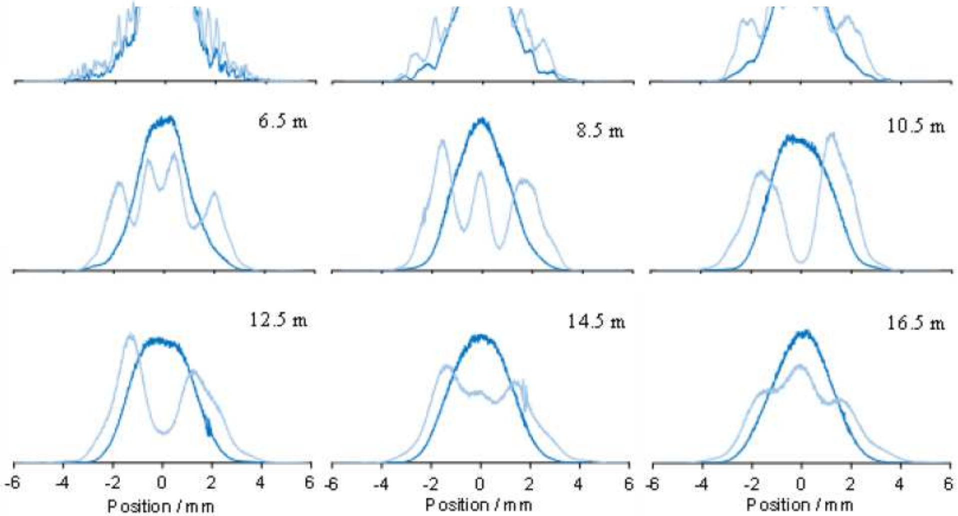
Intensity beam profile measurements by using a camera for test and reference beams at different distances (up to 17 m).

The method is valid also for non-gaussian beams.

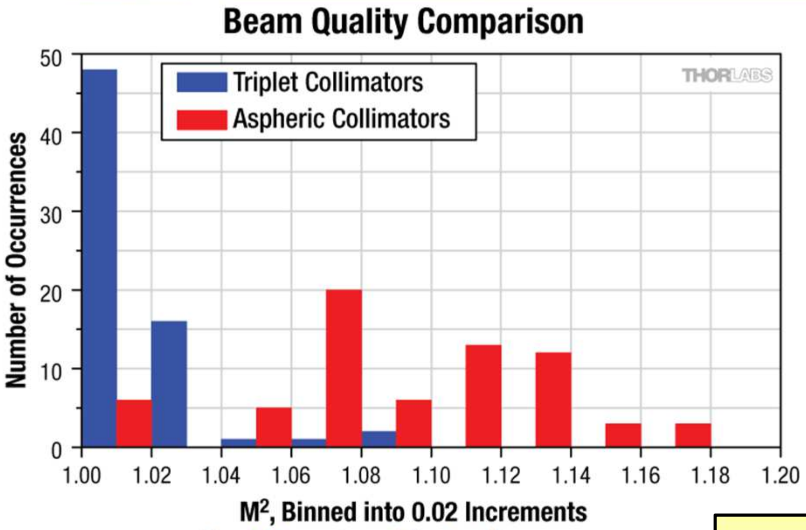
$$\delta k(x,y,z) \cong \mathrm{Re}\left\{\frac{\nabla_{\perp}^{2} E(x,y,z)}{2kE(x,y,z)}\right\}$$

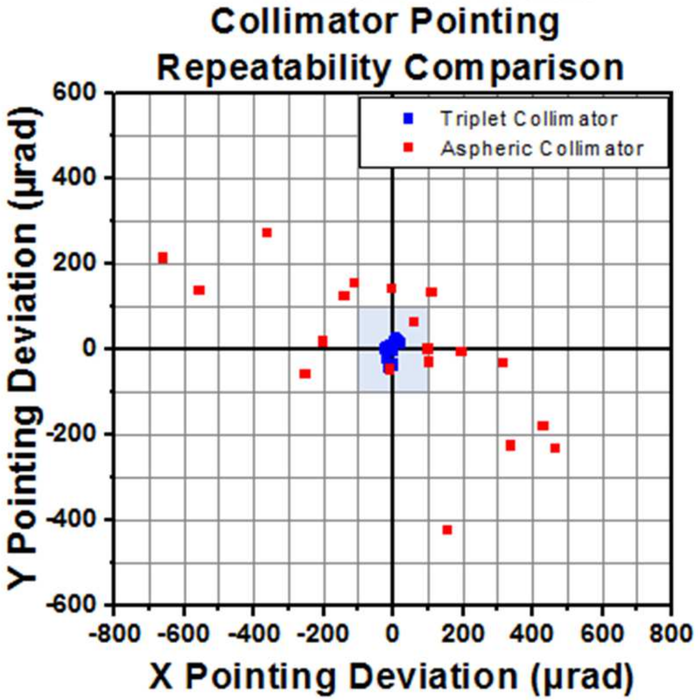
$$\theta_p(z_i) = \frac{1}{2}\left[\tan^{-1}\left(\frac{r_p(z_i)-r_p(z_{i-1})}{z_i-z_{i-1}}\right) + \tan^{-1}\left(\frac{r_p(z_{i+1})-r_p(z_i)}{z_{i+1}-z_i}\right)\right],$$





New method (also for non-Gaussian beams)

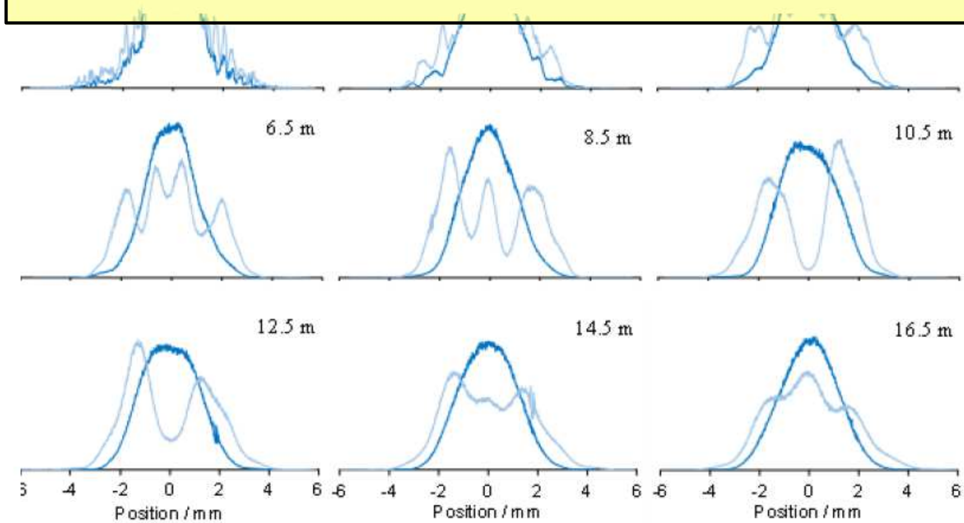




Beam difraction and divergence

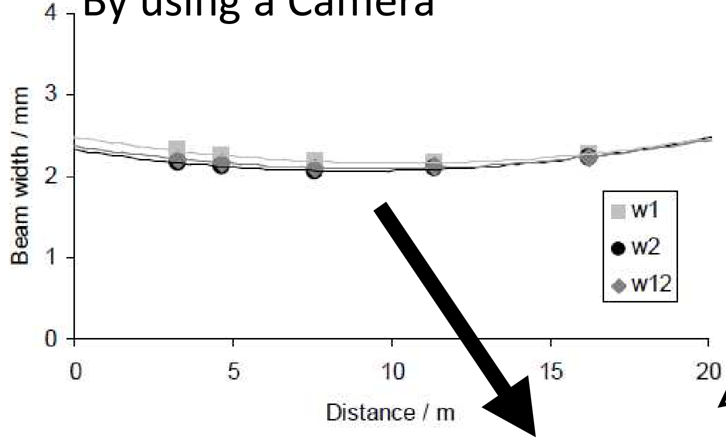
$$\delta k(x,y,z) \cong \mathrm{Re}\left\{\frac{\nabla_{\perp}^{2} E(x,y,z)}{2kE(x,y,z)}\right\}$$

$$\theta_p(z_i) = \frac{1}{2}\left[\tan^{-1}\left(\frac{r_p(z_i)-r_p(z_{i-1})}{z_i-z_{i-1}}\right) + \tan^{-1}\left(\frac{r_p(z_{i+1})-r_p(z_i)}{z_{i+1}-z_i}\right)\right],$$

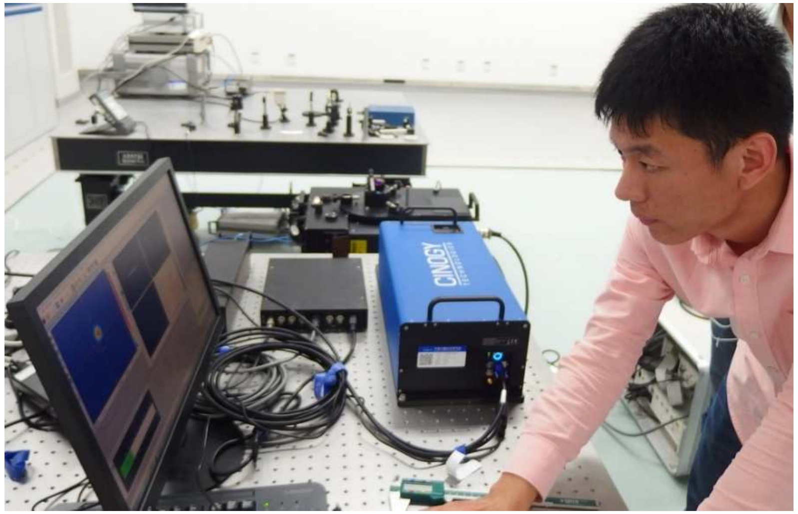


Common method (for Gaussian beams)

By using a Camera



By using a Beam profiler



Beam waist w_0 **…** $\Delta g = \frac{g\,\lambda^2}{4\,\pi^2\,w_0^2}$

DC / µGal	FG5X-251 gravimeter			FG5-101 gravimeter		
	original col.	**triplet col.**	difference	original col.	**triplet col.**	difference
common meth.	+1.3	**+2.3**	-1.0	+1.4	**+2.3**	-0.9
camera meth.	+3.8	**+2.8**	+1.0	+2.9	**+2.3**	+0.6
gravity meas.			**+0.6**			

We strongly recommend **to change the original collimator** of FG5/X gravimeters by a collimator with a higher quality (e.g. Thorlabs TC25APC-633).

New measurement system

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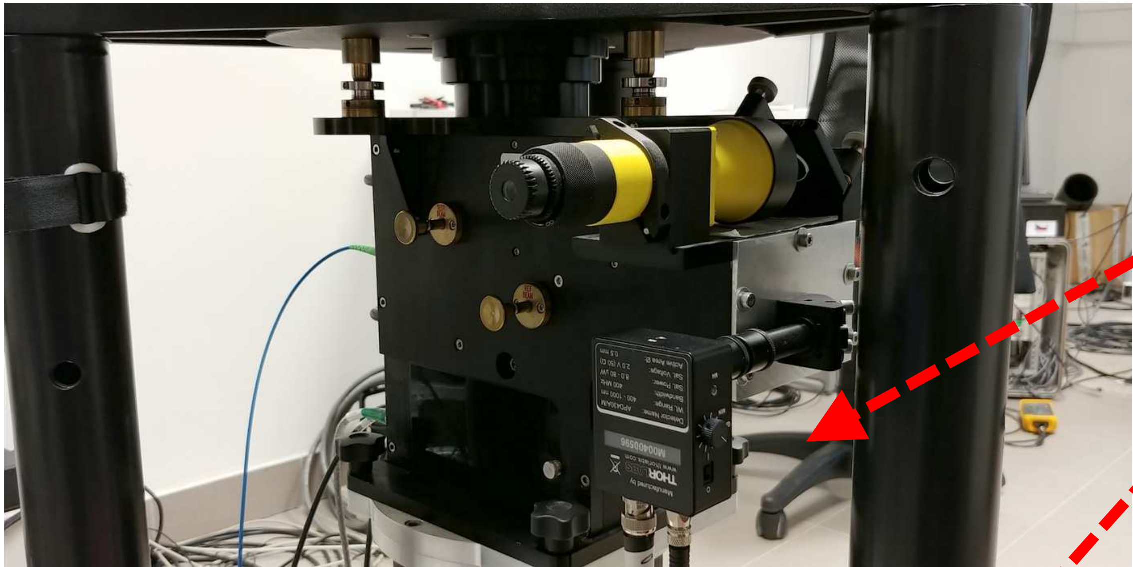
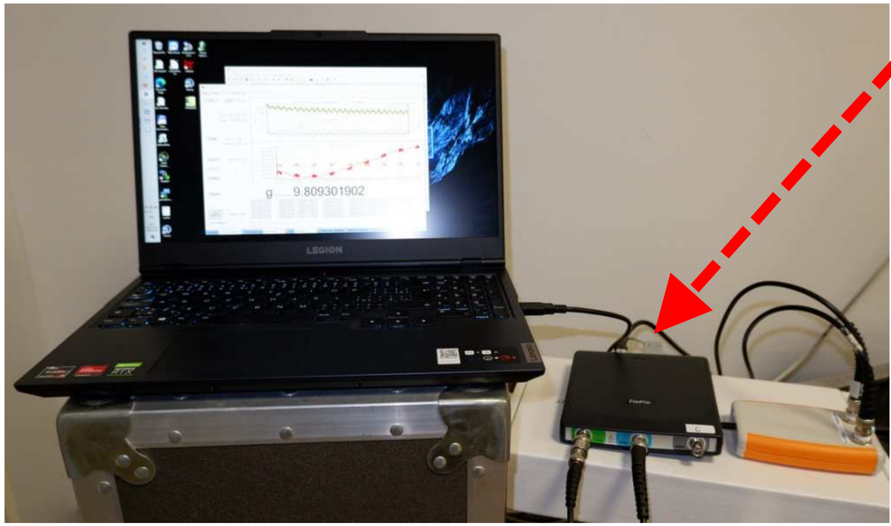


New APD on the viewport output

Analogue-to-digital converter **HS5** (TiePie Handyscope) digitizes the fringe signal with sample rate of 100 MHz/s – allows to analyze the complete **analogue** fringe signal without prescaling.

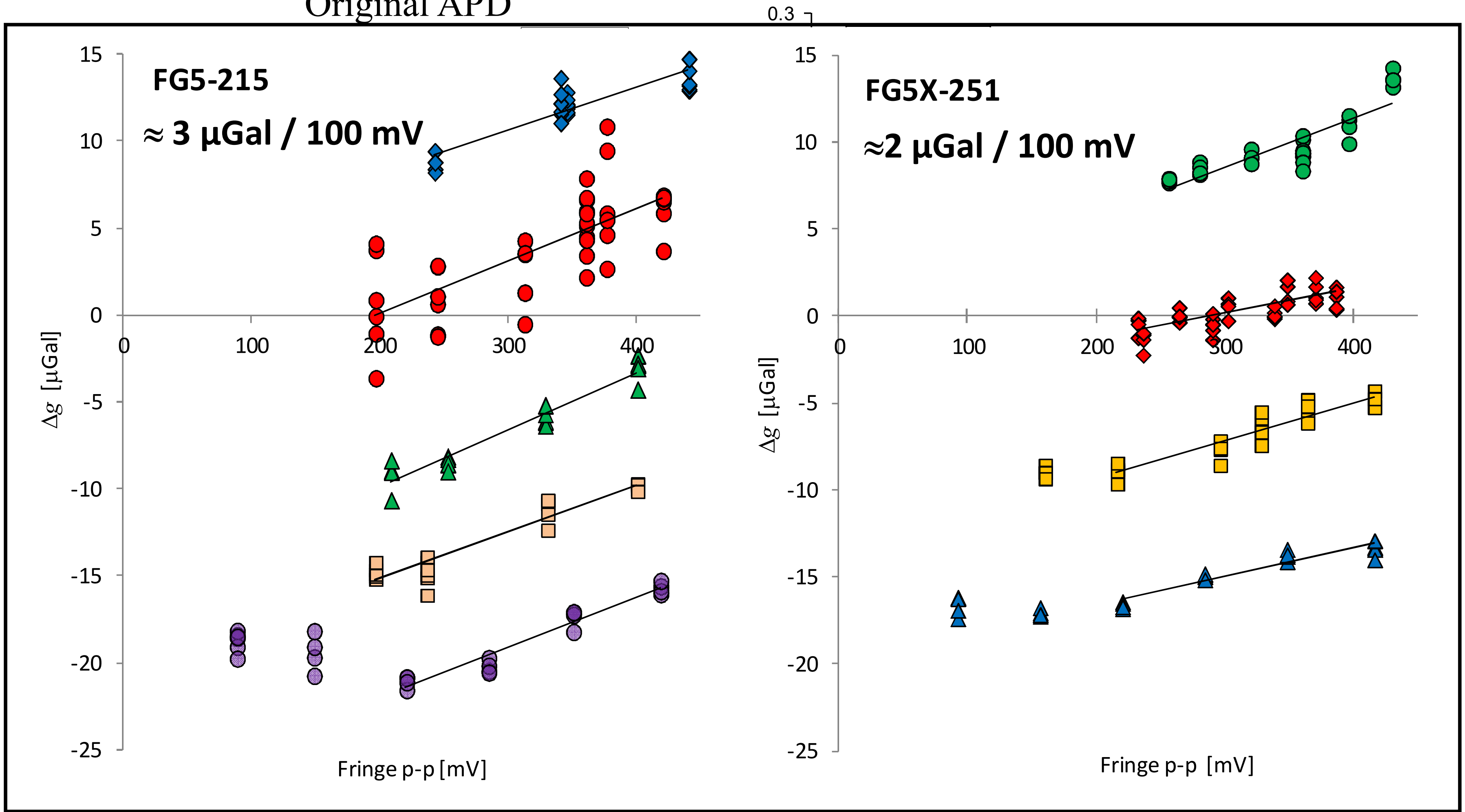
Data are recorded through drops triggered by g-software or by HS5 with the help of **Trigger box**

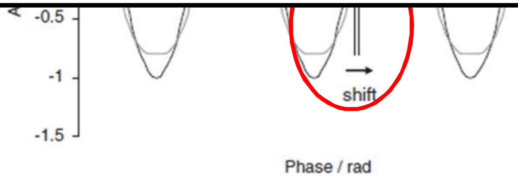


Software Gravity for detection of zero-crossings, g-determination

Electronic distortion

Original APD





FFT swept method of fringe signal processing should be used

Journal of Geodesy 93 (2019) 27-40

Differences between systems

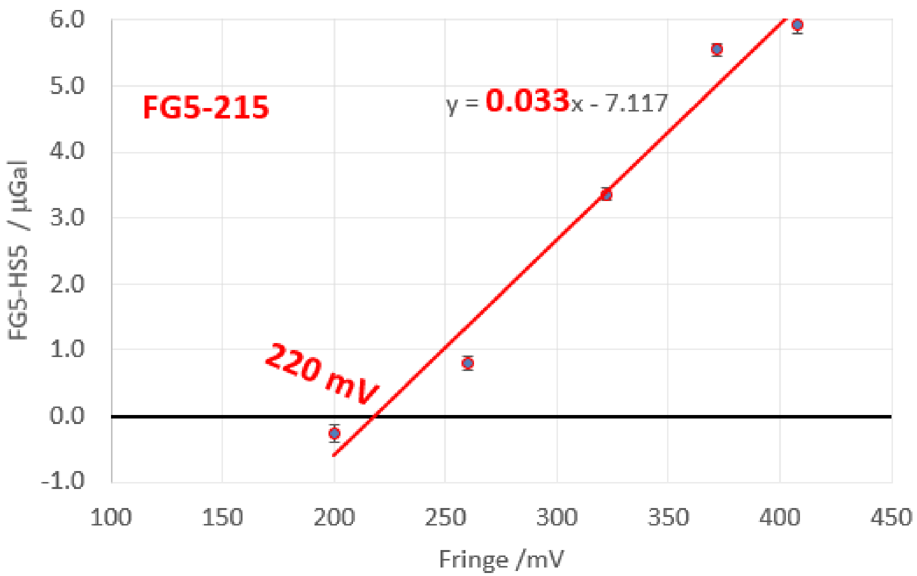
Two (FG5 and HS5) evaluation systems could run in parallel!!!

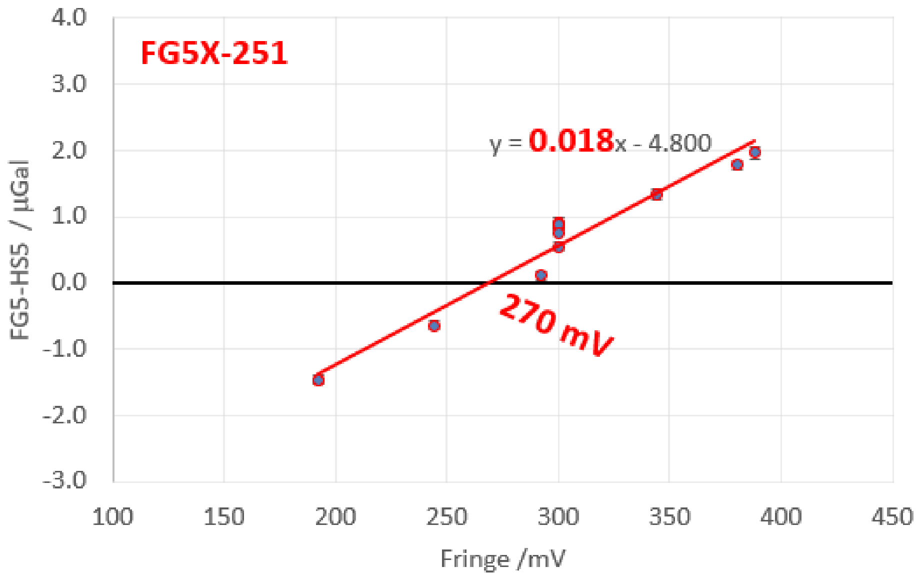
Advantages:

- significant reduction of noise in differences – excellent for tests

- validation of the original FG5(X) systems – the electronic part

„Fringe size effect“ from 100-200 drops in the range of 200-400 mV

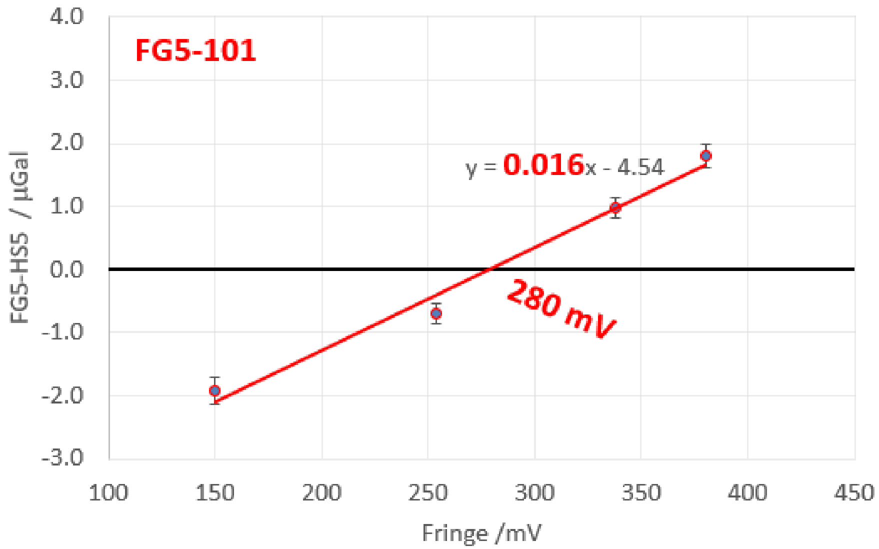


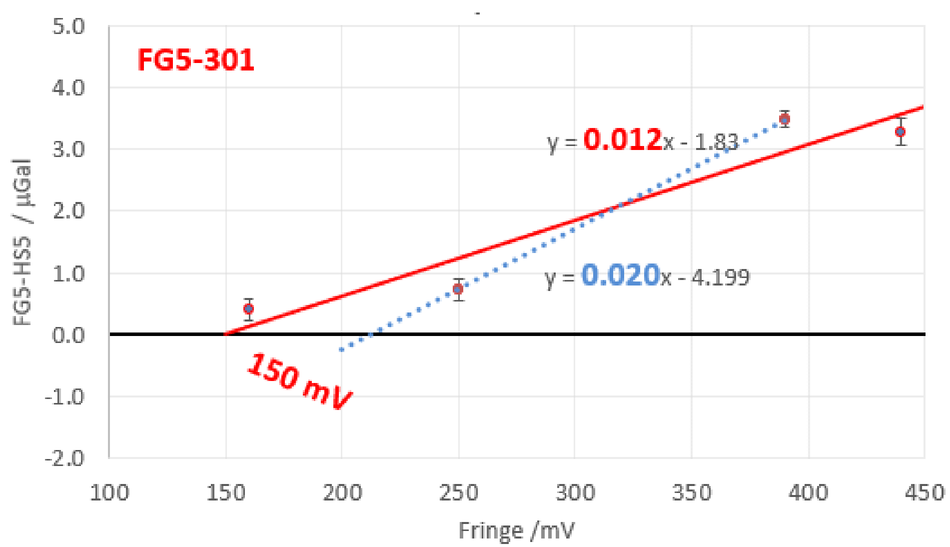


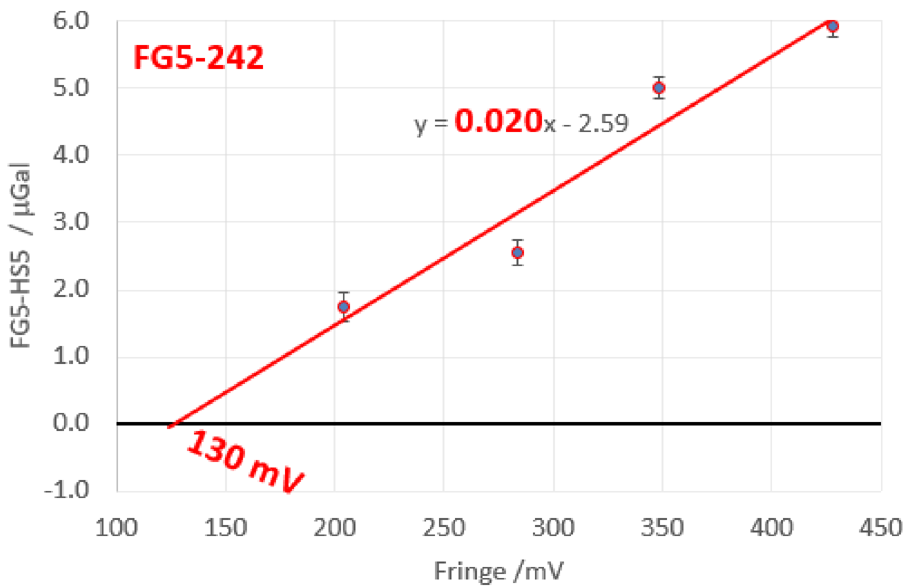
Confirmation of the fringe size effect: 2-3 µGal / 100 mV

Where is the „zero“ difference between systems?... at ≈ 250 mV?

Differences between systems





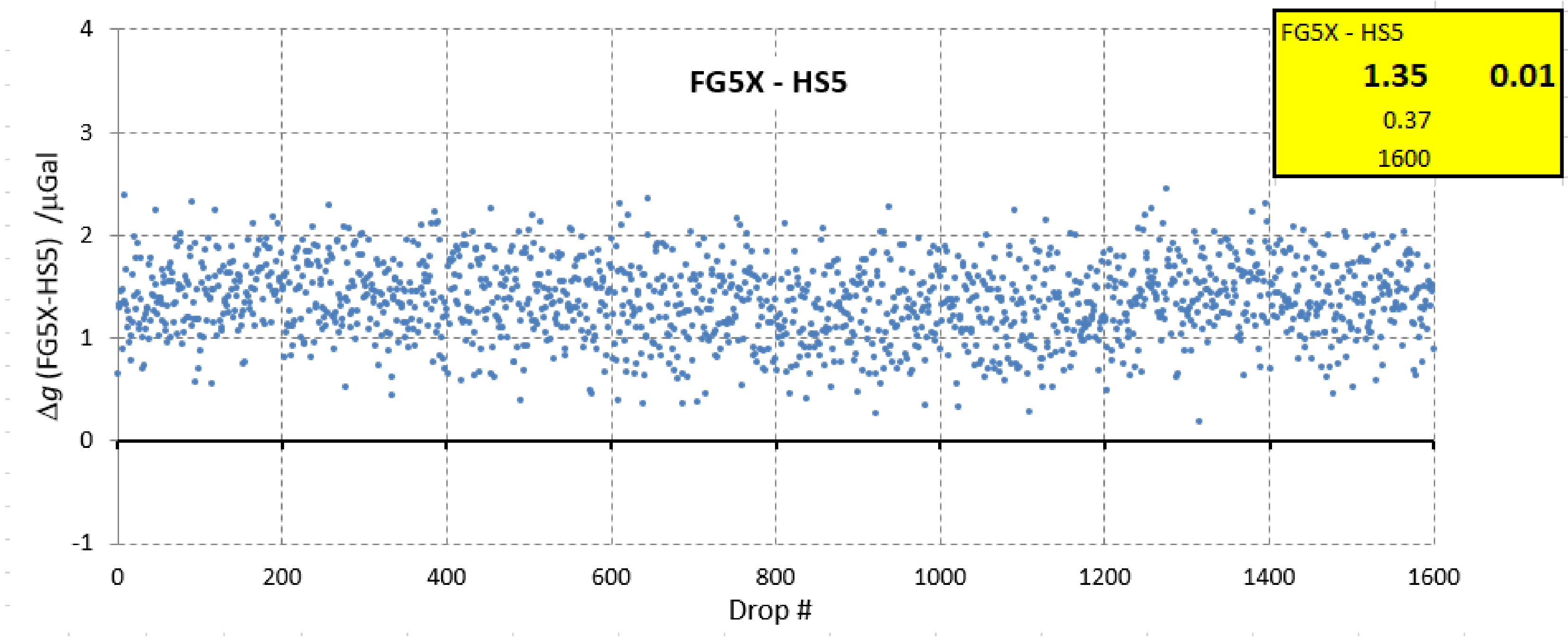


≈ 2 µGal / 100 mV seems to be clear

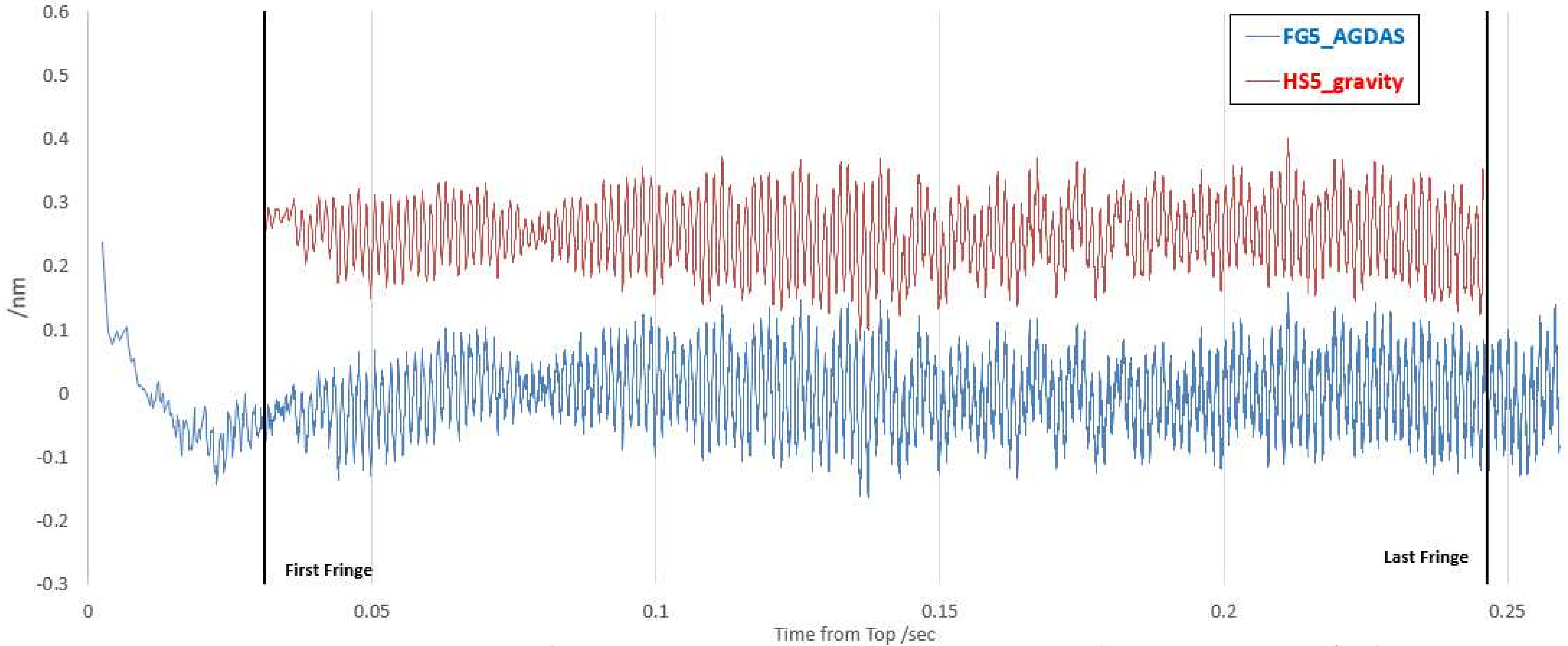
„zero“ difference is more uncertain

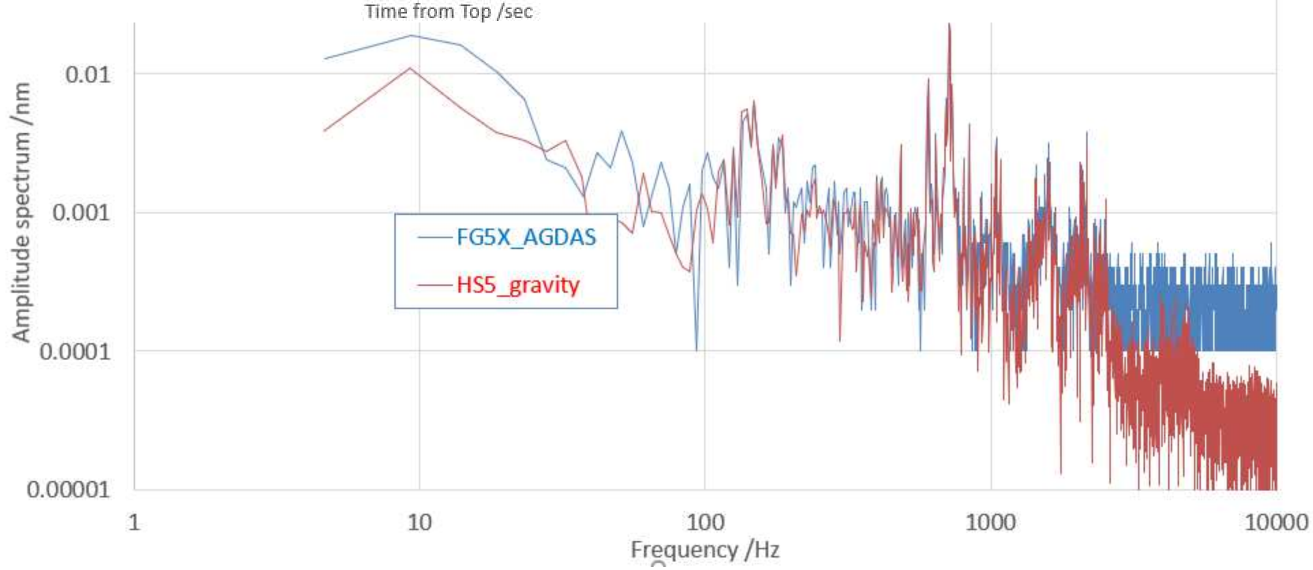
Another effects have to be also considered: polarization or the impedance mismatch effect.

Difference between residuals

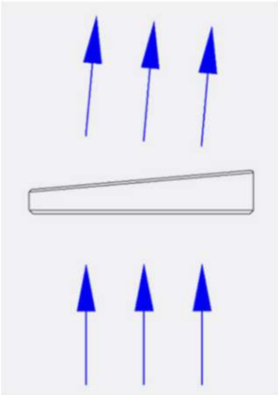


Difference between residuals

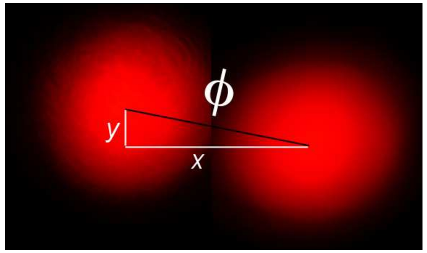




Verticality and Eötvös/Coriolis effects

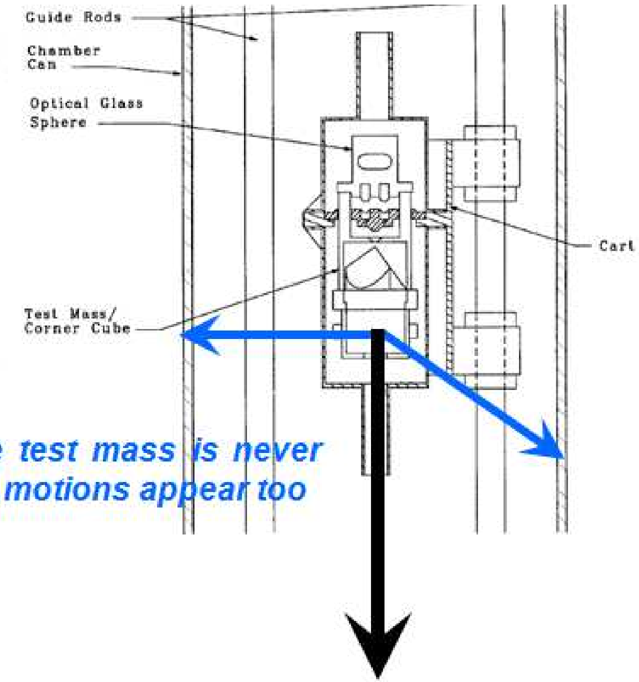


Imperfect optical elements between the alcohol pool, the free-falling retroreflector and the telescope (a window to the dropping chamber, the compensator plate, the beam splitter, the attenuator) are introducing angular deviations (e.g. due to glass wedges) $\Rightarrow$ **The alignment seeing in the telescope is apparent only**



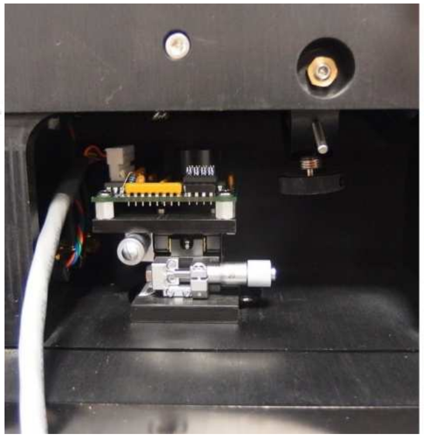
$$\Delta g_{Ve} = g\,\phi^2 / 2$$

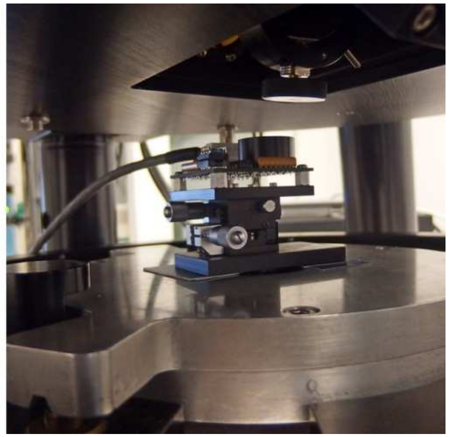
The Eötvös effect (vertical component of the Coriolis effect) representing the change in centrifugal acceleration resulting from the east-west velocity of the test mass during the free-fall.



Release of the test mass is never perfect, lateral motions appear too

Monitored by Position Sensitive Detector





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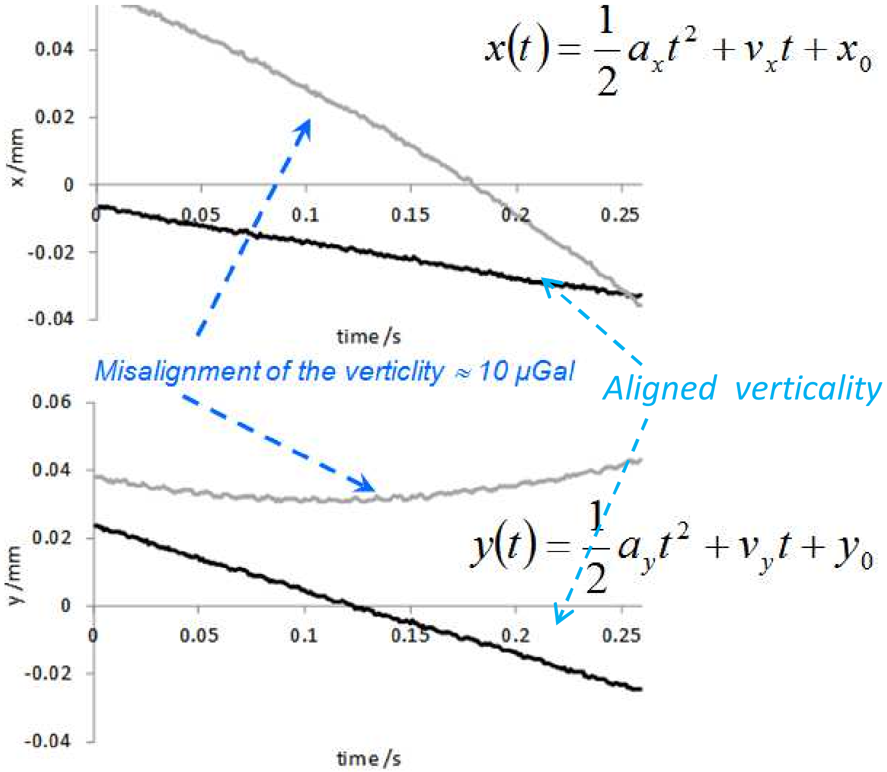
Verticality and Eötvös effects

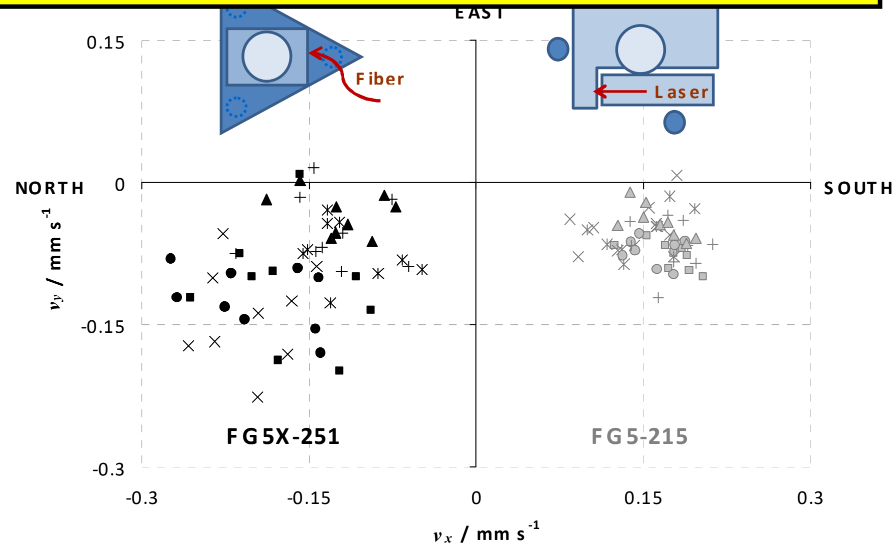
Lateral motions in two perpendular directions (*x* and *y*) during the free fall



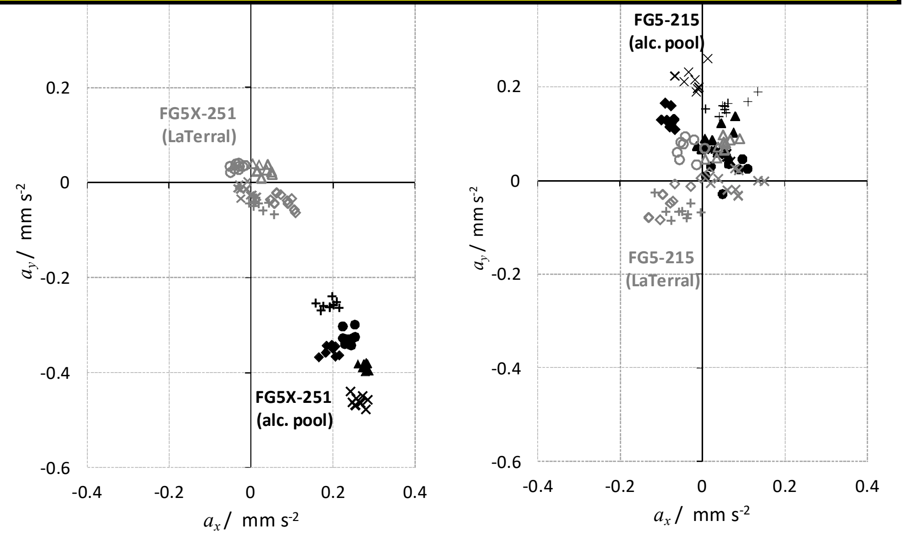
$$x(t) = \frac{1}{2} a_x t^2 + v_x t + x_0$$

$$y(t) = \frac{1}{2} a_y t^2 + v_y t + y_0$$

Eöt. effect: -0.8 μGal -0.4 μGal



Vert. effect: -1.0 μGal -0.2 μGal



Verticality error	Eötvös error
$a_L = \sqrt{a_x^2 + a_y^2}$ $\delta g_V \approx -\frac{a_L^2}{2g}$	$v_L = \sqrt{v_x^2 + v_y^2}$ $\alpha_v = \arctan \frac{v_y}{v_x}$ $\delta g_E \approx 2\Omega v_{EW} \cos \varphi$

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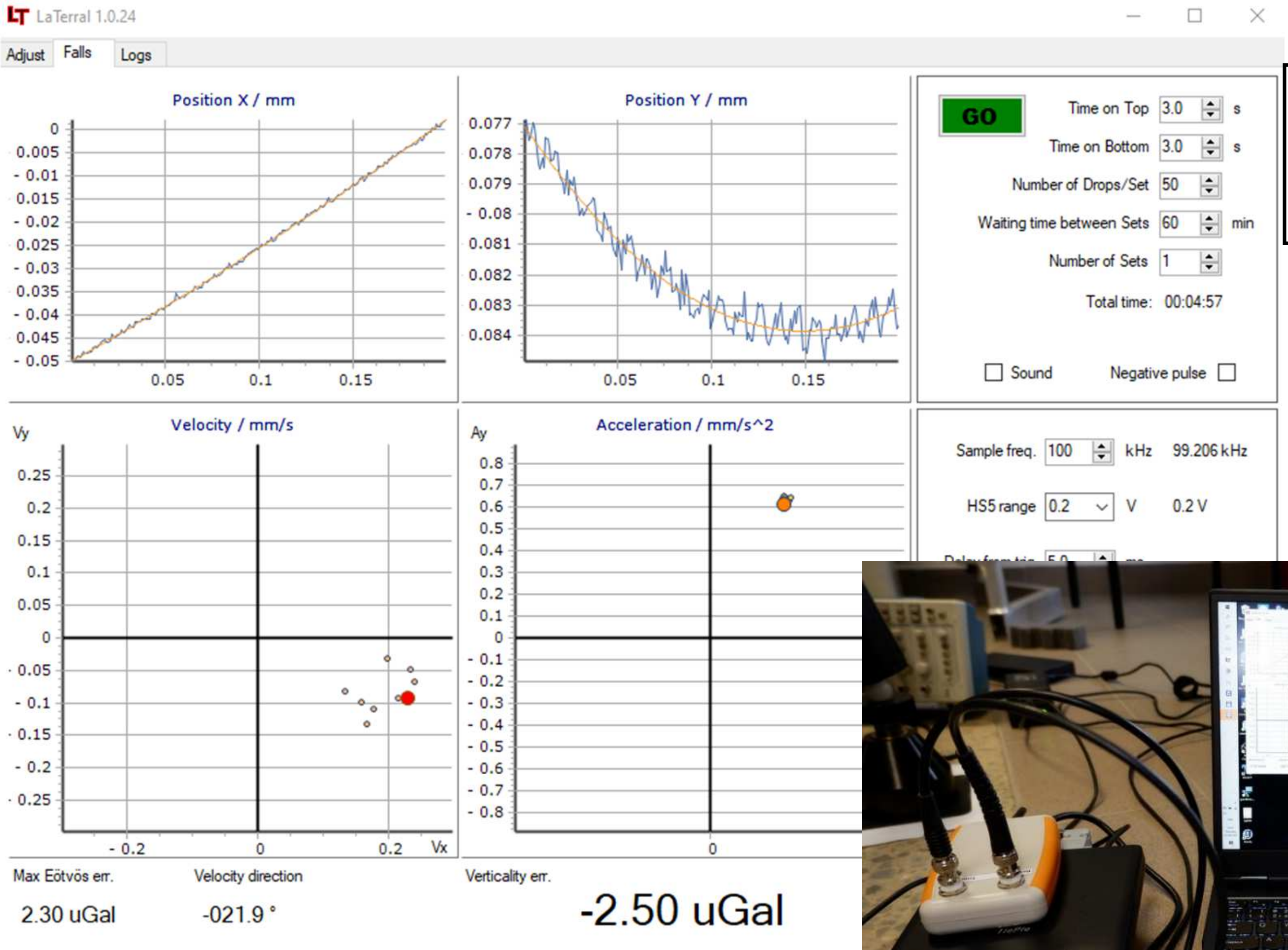
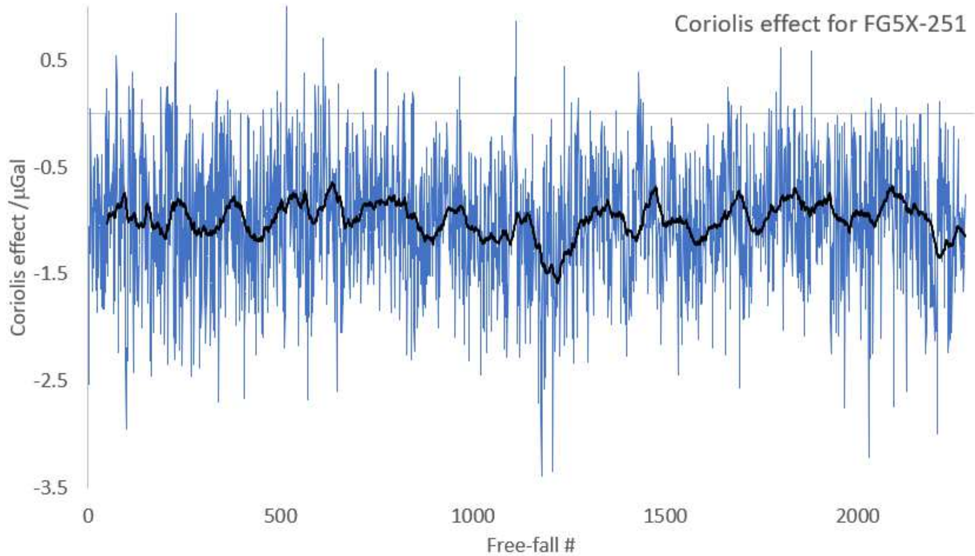
Software LaTerral

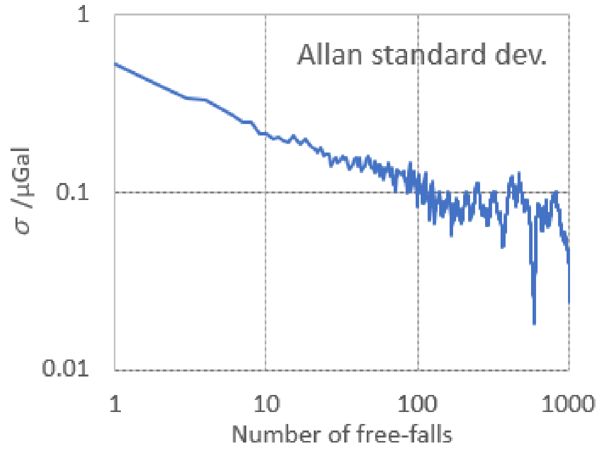


Additional drops controlled by the software

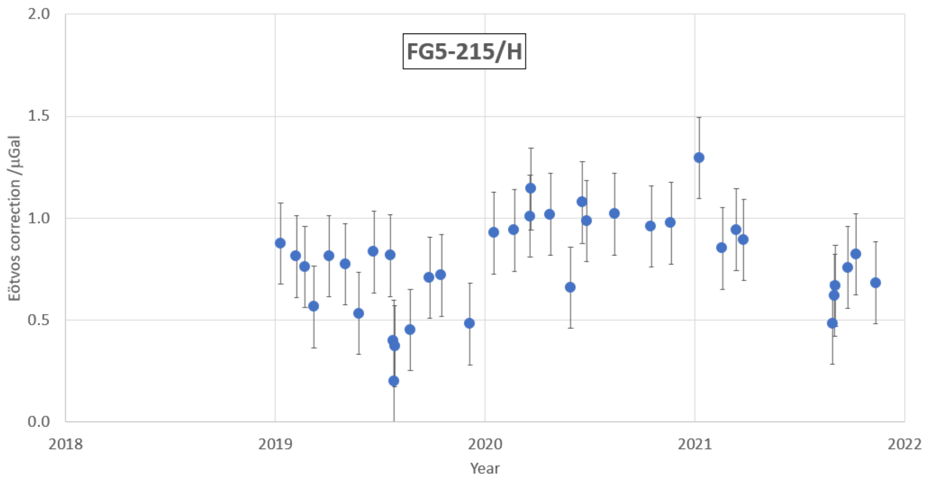
HS5 oscilloscope and **trigger box** is needed
Verticality aligned below 0.05 µGal error

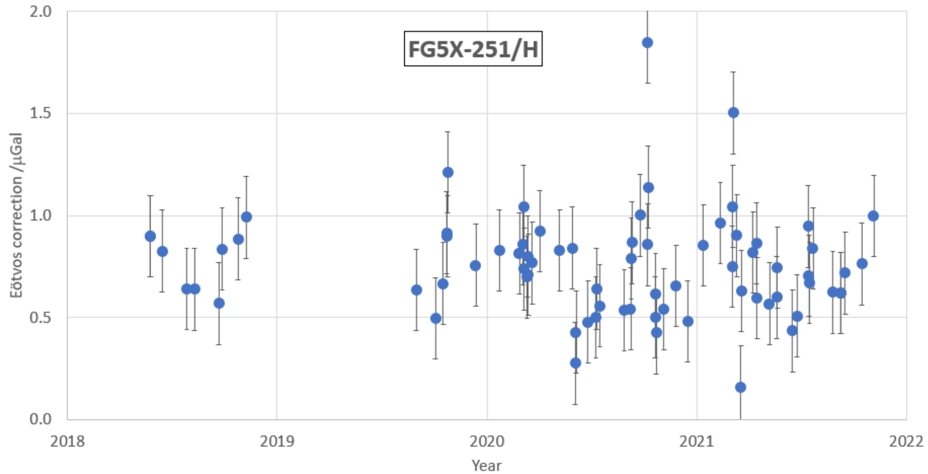
Stability of Eötvös/Coriolis effects





Coriolis effect of about ±0.1 µGal from ≈100 drops





Long-term stability of about ±0.4 µGal from ≈100 drops

Effects of coaxial cable length

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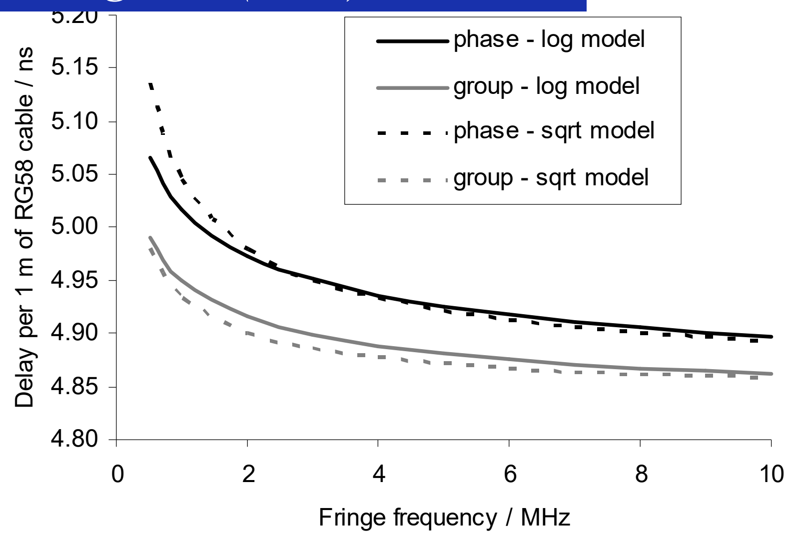


$$\{\tau_{ph}\} = \{l\}\left(173.6 + 8/\sqrt{\{f\}}\right)/36 \qquad \{\tau_{g}\} = \{l\}\left(173.6 + 4/\sqrt{\{f\}}\right)/36$$

Dispersion in the cable (transffering the fringe signal) generates *different time delays for different signal frequencies* that sweep up to:

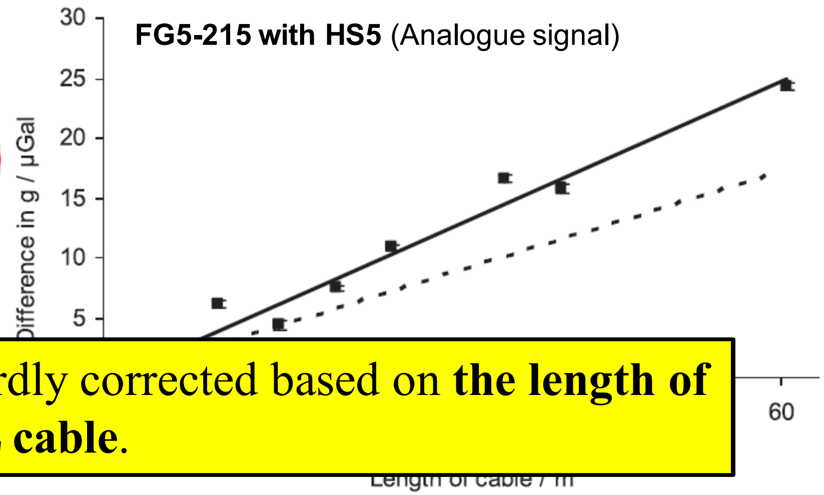
6.3 MHz for FG5, 7.8 MHz for FG5X, 4.0 MHz for A-10.

The electronic dispersion **simulates an additional acceleration** within the computed ***g*.**

Model

Measurement

gravimeter	z_1 / m	z_2 / m	Analogue signal **/ µGal/m**	TTL signal **/ µGal/m**
A10	0.005	0.08	**0.53**	**0.37**
FG5	0.010	0.20	**0.30**	**0.18**
FG5X	0.005	0.31	**0.25**	**0.16**



Meas

FG5 system (

The dispersion effect should be standardly corrected based on **the length of the TTL cable**.

Effects of impedance mismatch

Impedance mismatch of 20 Ω were found for FG5-215 and FG5X-251!!!

The electric **impedance mismatch** between the detector electronic circuit and the coaxial cable used for transmitting the fringe signal and between this cable and the timing electronics (evaluating time of occurrence of zero-crossings) causes **reflections of the transmitted signal**.

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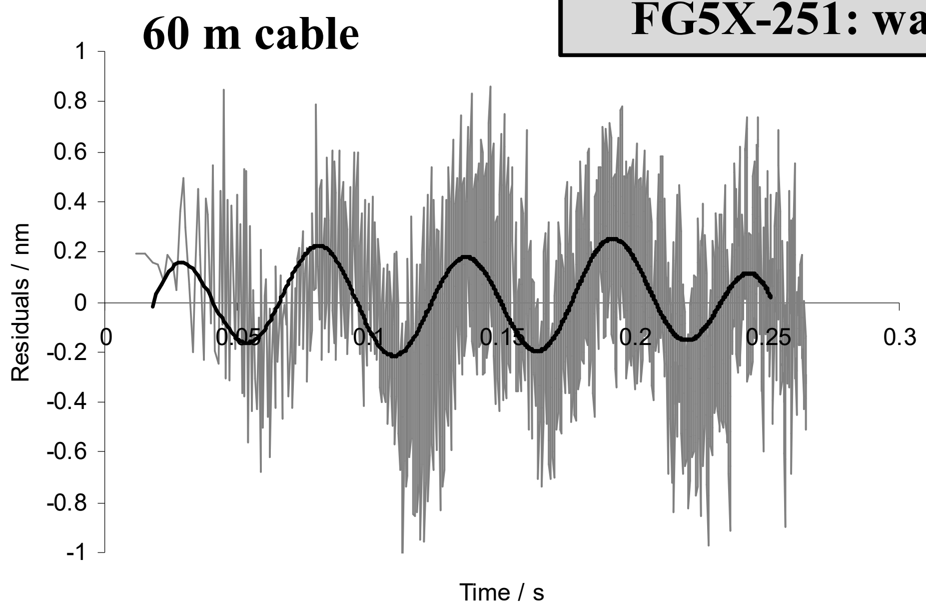
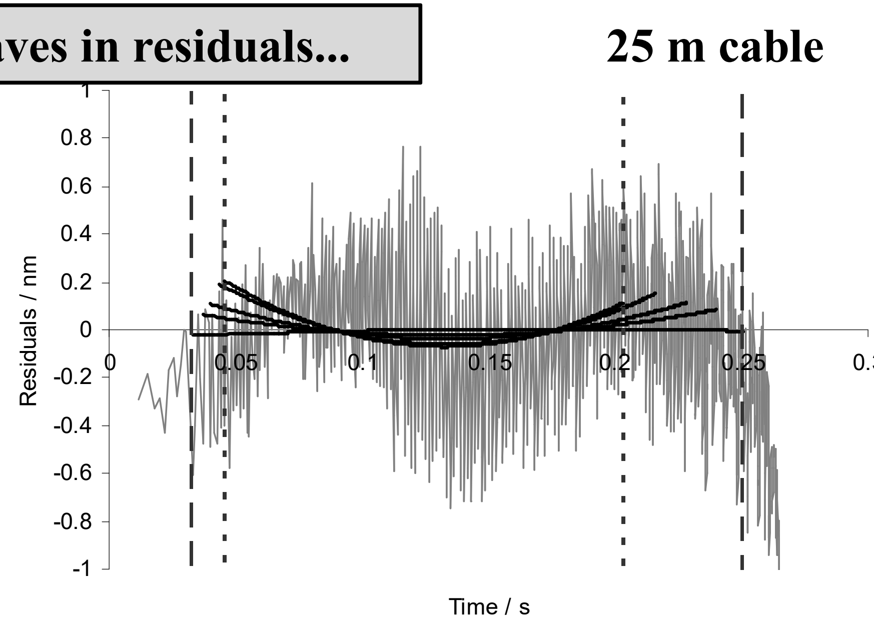
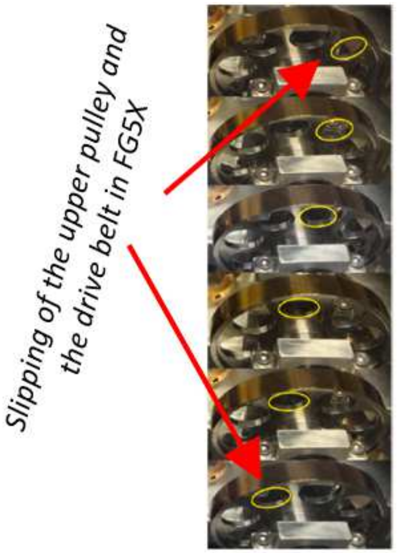
FG5X-251: waves in residuals...

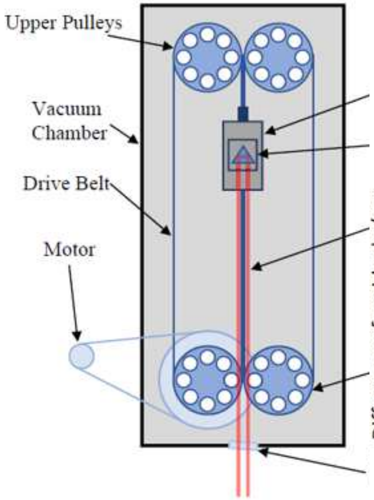


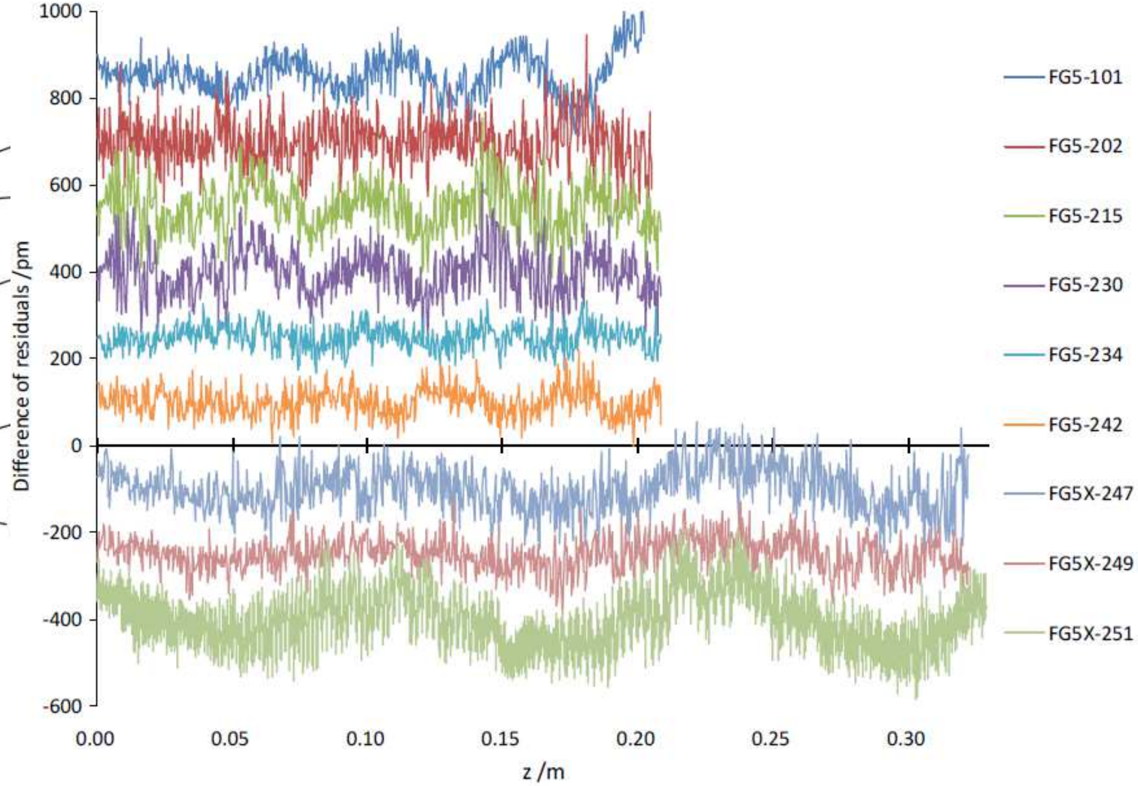


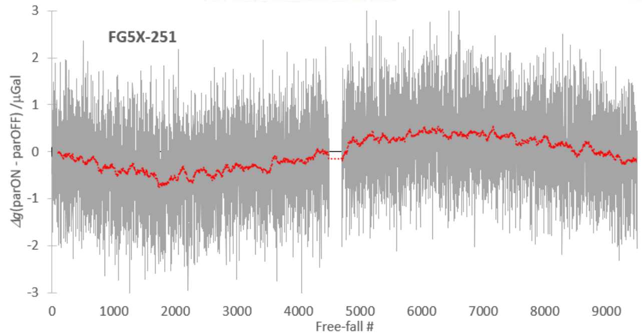
The errors caused by the **impedance mismatch of 20 Ω with 5 m** cable might cause errors within the range of **±1.4 μGal for FG5(X).** We strongly recommend **to use 2 m long TTL cable for** FG5/X gravimeters to decrese the uncertainty due to the impedance mismatch effect to about 0.2 μGal.

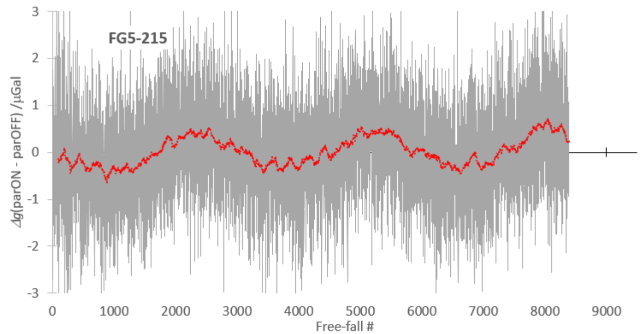
Parasitic wave correction











Periods: FG5/FG5X corresponds to the circumferences of pulleys

Effects up to 1 µGal

Can be included to the measurement model

Measurement 171, 108739 (2021)

FG5(X) Original system bias

Corrections / µGal	**Standardly applied**	**New corrections**	**Difference**
Self-attraction	-1.2	-1.2	0.0
Diffraction	+1.2	+2.4	+1.2
Distortion (350 mV fringes)	N/A	-2.2	-2.2
Cable length (5 m)	N/A	-1.0	-1.0
Impedance mismatch	N/A	-1.4 / +1.4	?
Verticality	N/A	+0.2 / +1.0	+0.6
Eötvös/Coriolis	N/A	-1.0 / +1.0	?
Rotation of pulleys	N/A	-0.6 / +0.6	?
Sum			**-1.4**

According to present estimates, the g-values of FG5/X should be too high at present and decreased by -1.4 µGal in average. However few next effects have to be estimated.

Conclusions

- Avoid to use low quality collimators in FG5/X gravimeters. For **good quality collimators**, the diffraction correction could be estimated from the beam waist estimation.
- The HS5 measurement system is free from errors due to **fringe signal distortion** and impedance mismatch.
- For the original FG5/X system, at least, a correction based on the fringe size could be applied – correct direction of the polarization has to be ensured, **short (2 m) RG58CU** coaxial cable should be used for the TTL signal.
- Dispersion effect in TTL cable should be reduced based on the length of the cable.
- **Verticality and Coriolis**/ Eötvös effects should be determine for an FG5/X based on a measurement of **lateral motion** of freely-falling body by using a Position Sensitive Detector.
- **Improved measurement model** is avoiding errors due to the rotation of pulleys.

Thank you for your attention!

Project of Czech Science Foundation (2016-2018) no. 16-14105S :
Advanced processing of absolute gravity measurements and investigation of systematic instrumental effects

Project of Ministry of Education, Youth and Sports(2019- 2023) LTT19008:
Research related with International Gravity Reference System