Traceability of the Hannover FG5X-220 to the SI units

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Abstract

The absolute measurement of g is currently realized through the laser interferometric measurement of a free falling retroreflector. The Micro-g LaCoste FG5X is a free-fall gravimeter with a laser interferometer in Mach-Zehnder configuration which uses simultaneous time and distance measurements to calculate the absolute value of g. The instrument itself contains the necessary standards of length and time and operates independent of external references. The timing is kept with a 10 MHz rubidium oscillator with a stability of 5×10^{-10}. The length standard is provided by a iodine stabilized Helium Neon Laser with a wavelength of 633 nm and accuracy of 2.5×10^{-11}. In 2012 the FG5-220 was upgraded to the FG5X-220. The upgrade included a new dropping chamber with a longer free fall and new electronics including a new rubidium oscillator. The traceability to the Système International d'unités (SI unit) is ensured by two complementary and successive approaches: the comparison of frequencies with standards of higher order and the comparison of the measured g to a reference. Since the upgrade of the absolute gravimeter the instrument participated in several international comparisons, which showed no measuring offset between the instrument prior and after the upgrade. Measurements at well observed stations and the comparison with specific instruments, however, point to an offset of about 20 nm s^{-2}. A number of experiments to test the rubidium oscillator were performed. The oscillator showed a linear drift of 0.2×10^{-3} Hz per month (=0.3 nm s^{-2} per month) in the first 18 months of use. A jump in the frequency of 0.01 Hz (=20 nm s^{-2}) was revealed recently and the drift rate changed to -0.5×10^{-3} Hz per month.

Traceability Chain in Gravimetry

As described by the *CCM - WGG* [5]

- Independent calibration of time and frequency
- Calibration by comparison in a variety of configurations, e.g.:
  - CIPM Key Comparisons (National Metrology Institutes/Designated Institutes)
  - Regional, Bilateral/Additional Comparisons (linked to KC by common participants)

Principle of Light Interferometer Absolute Gravimetry

FG5-220 upgrade to FG5X-220

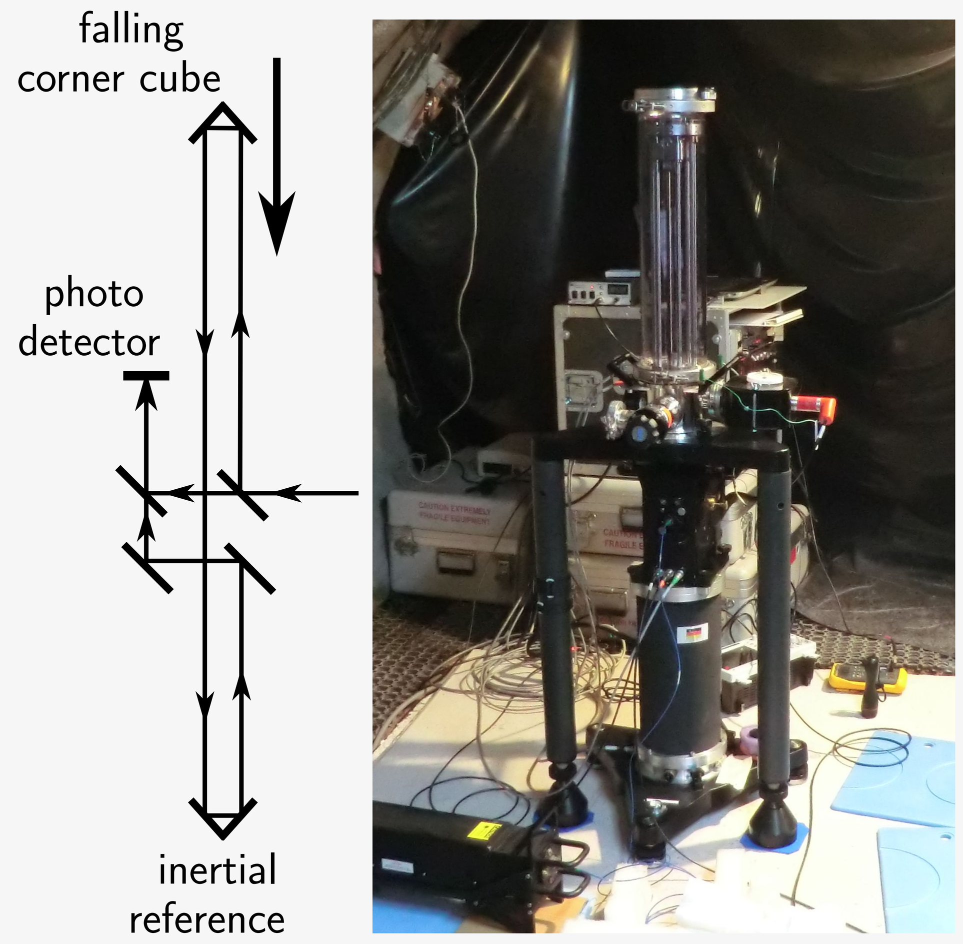

Fig. 1: Interferometer scheme and FG5X-220 at Black Forest Observatory, Schiltach (Germany). A photodiode detects interferometer fringes between a reference beam and a beam reflected by a falling object and an inertial reference.

- First major update for FG5-220 since 2003
- Updated electronics; no changes to laser system
- Dropping distance 31 cm → Reference height +4 cm
- Drag free cart with counter weights and lighter test mass for reduced vibrations

Laser interferometer observations

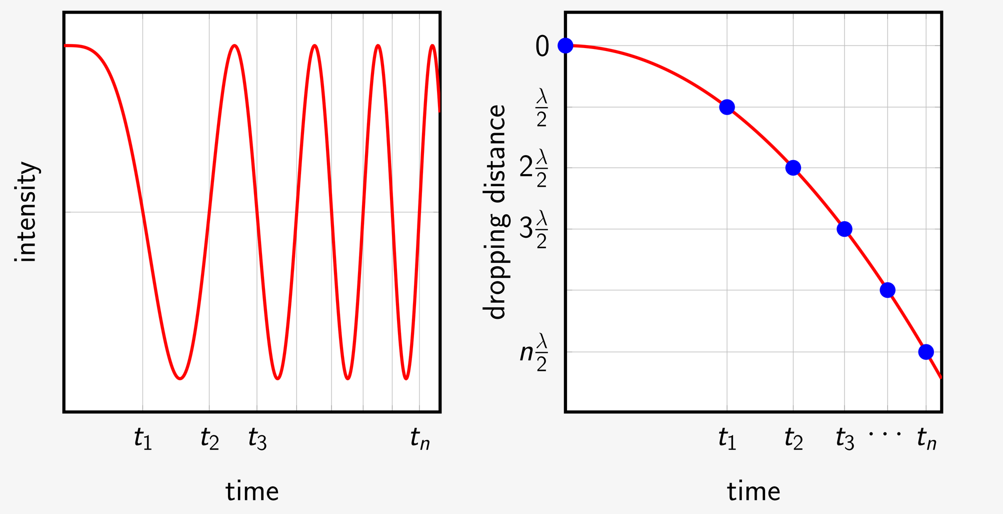

Fig. 2: *left*: The photodiode measures changes in light intensity with a phase shift due to the acceleration of the falling mass. *right*: Observations plotted with respect to distance traveled in multiples of half wavelengths.

- Mach-Zehnder type interferometer
- Fringe *zero-crossings* result in time-distance pairs
- Least squares adjustment of ≈ 1250 *zero-crossings*

Simplified observation equation with time t corrected for speed of light and accounting for a fixed linear gradient in gravity:

$$z(t) = z_0\left(1+\frac{\gamma}{2}t\right) + v_0\left(t+\frac{\gamma}{6}t^3\right) + \frac{1}{2}g_0\left(t^2+\frac{\gamma}{12}t^4\right)$$

z_0, v_0, g_0 : initial position, velocity, gravity
γ : vertical gradient in gravity

Comparison of Instruments

International comparisons of absolute gravimeters (AG)

- No AG of higher order available → key comparisons (KC) with large number of AGs
- AGs measure simultaneously on several stations for multiple setups
- Participants from national metrology institutes and designated institutes determine Key Comparison Reference Value (*KCRV*) with accompanying uncertainty for each measuring position
- Other AG are compared in a pilot study (PS) against KCRV → *Degree of Equivalence* $DoE = \frac{\sum_{i=1}^{n} x_i - x_{KCRV}}{n}$ [2] and compatibility index/normalized error E_n [8]

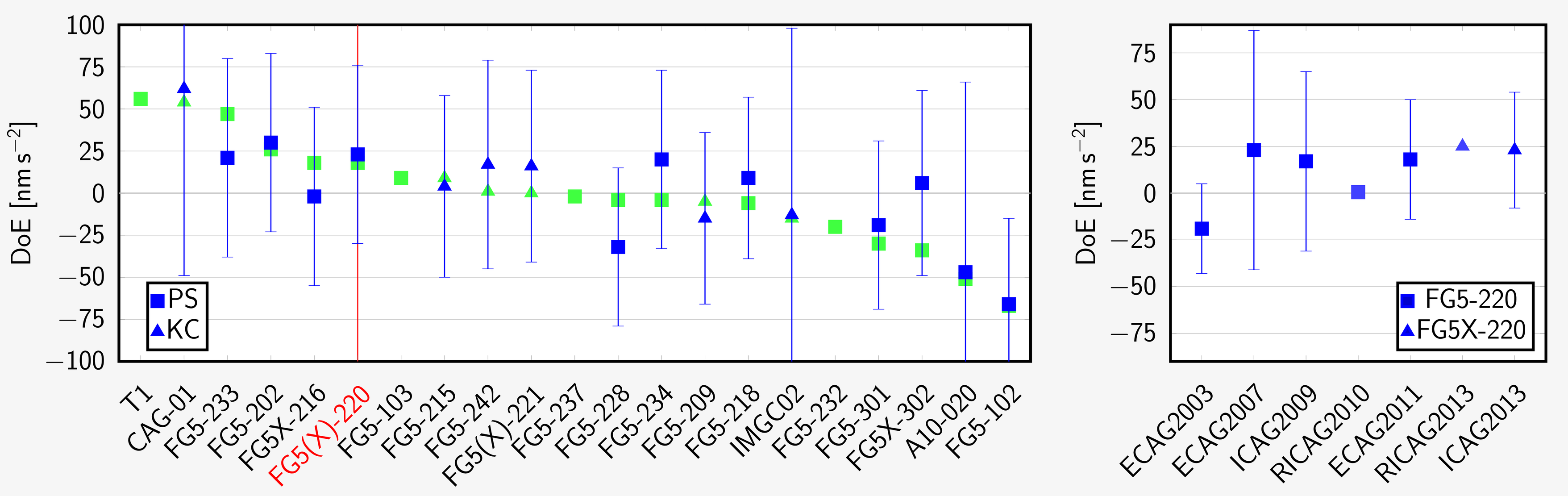

Fig. 3: *left*: Result of ECAG-2011 (all participants) and ICAG-2013 (common instruments only, 4KC/4PS omitted) in Walferdange (Luxembourg) [4, 3]. Errorbars represent the RMS of the expanded uncertainties of three setups of the AG. The expanded uncertainty of the KCRV is in the range of 26 nm s^{-2} to 39 nm s^{-2} for ICAG-2013. FG5 with a (X) were upgraded in between comparisons. The DoE of the FG5X-220 changed by 5 nm s^{-2}. *right*: Regional and international comparisons of the FG5(X)-220 with uncertainties according to the respective final report (standard deviations of expanded uncertainties of multiple setups). After ECAG-2003 a hardware defect was found on the FG5-220 probably causing the low DoE compared to later comparisons. RICAG are organized by the German Federal Agency for Cartography and Geodesy (BKG) in Wettzell with 6 participating AG. The FG5(X)-220 Results of RICAG are deviations to mean of participants.

Comparison of FG5(X)-220 at well described station and with selected instruments

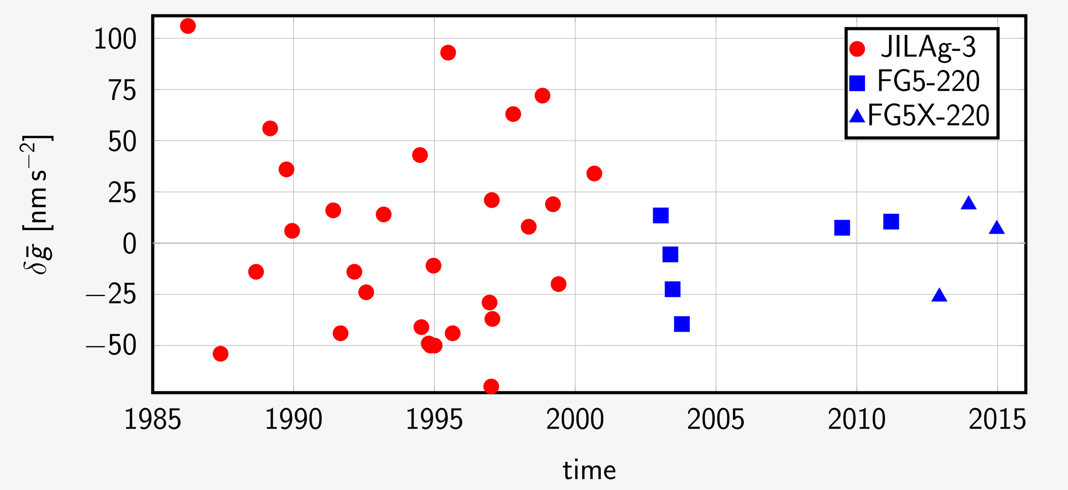

Fig. 4: Measurements of IfE AGs at TU Clausthal since 1986. Clausthal is located in the Harz mountains in northern Germany. The pillar is connected to bedrock and no gravity-trend has been discovered. Results shown refer to a height of 1.05 m, the middle height between JILAg and FG5X reference height.

Tab. 1: Difference of FG5(X)-220 and FG5-215 (VÚGTK, Czech Republic) and FG5-233 (Lantmäteriet, Sweden). The results are shown from measurements before and after the upgrade in 2012.

	ΔFG5-233 [nm s^{-2}]	ΔFG5-215 [nm s^{-2}]
RICAG 2010	−25	−3
ECAG 2011	−29	9
FG5X-220 upgrade		
RICAG 2013	−6	20
ICAG 2013	1	20
Onsala 2014	7	

Comparisons of AG

- FG5-220 and FG5X-220 are in equivalence within the uncertainty of each comparison
- Degree of Equivalence before and after upgrade within 20 nm s^{-2} to 25 nm s^{-2}

Combination of FG5(X)-220 with other AG

- Time series at otherwise stable station shows variation in g within instrumental uncertainty
- Offset between selected AG changed by 10 nm s^{-2} to 20 nm s^{-2}

⟹ AG offsets need consideration

Standards of Length and Time

10 MHz Rubidium oscillator [6]

- Frequency uncertainty 3.4×10^{-10}
- Drift 4×10^{-11}/month →0.4×10^{-3} Hz/month
- Effect of frequency $\Delta f = 5 \times 10^{-3}$ Hz → 10 nm s^{-2} in gravity
- Determination of absolute frequency and drift by comparison with reference clock

Comparison with GPS stabilized rubidium clock

- Meinberg GRP portable frequency reference
- Accuracy
  - $\pm 2 \times 10^{-12}$ with GPS locked
  - $\pm 1.5 \times 10^{-11}$/day and $\pm 5 \times 10^{-11}$/month without GPS

WEO 100 Laser

- Iodine stabilized Helium-Neon laser (λ = 633 nm)
- Frequency reproducibility ±5 kHz [1]
- Realisation of the definition of SI meter by CIPM [7]
- Determination of wavelengths of iodine peaks by manufacturer
- Currently no further calibration performed on regular basis

Comparison of FG5X-220 10 MHz Rubidium oscillator

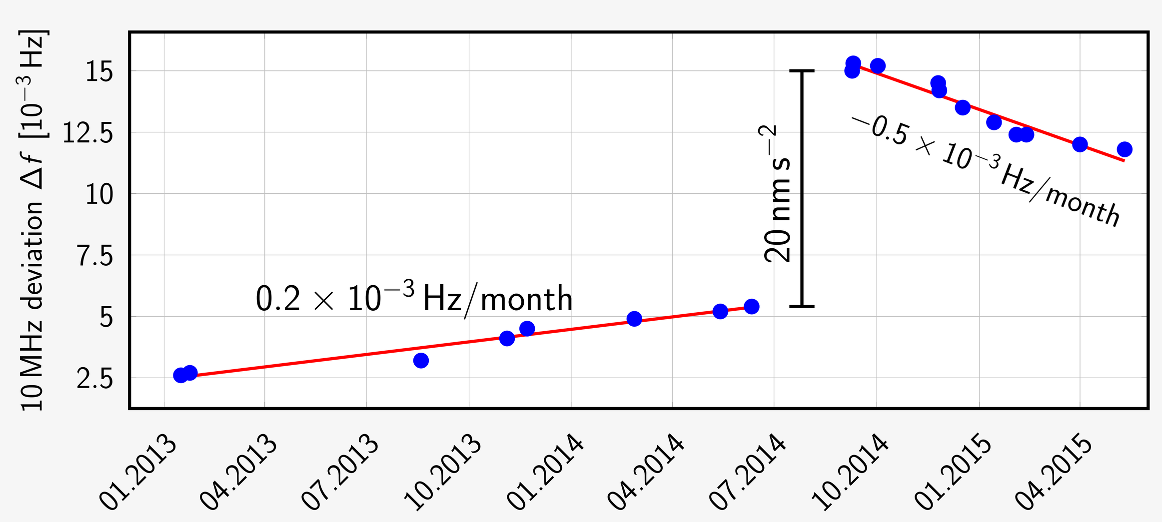

Fig. 5: Frequency comparisons of FG5X-220 rubidium with 10 MHz reference clocks. These comparisons are performed before and after measurement campaigns with the Meinberg GRP portable clock with GPS stabilization. Additionally comparisons are performed during long campaigns in the field. During measurements at metrology institutes comparisons are performed with local frequency standards. During the first 18 months a drift of 0.2×10^{-3} Hz/month was observed, which is well within limits published by the manufacturer [6]. After measurements at the Black Forest Observatory (Germany) for the calibration of the local Superconducting Gravimeter a jump in the frequency of the FG5X-220 rubidium clock of 10×10^{-3} Hz, which is equivalent to 20 nm s^{-2}, was observed. An intrusion of atmospheric helium into the rubidium cell may cause a positive frequency shift. The FG5X was located close to the SG in the underground laboratory, exposing the rubidium cell to a higher concentration of helium. The current drift of -0.5×10^{-3} Hz/months is expected to return to the previous rate with time.

Conclusions

- Frequent control of absolute frequency and drift of 10 MHz oscillator with portable clock and its influence
- Rubidium oscillator of FG5X-220 susceptible to Helium events
- Laser frequencies controlled indirectly by AG comparisons
- Repeatability of FG5(X)-220 measurements within 10 nm s^{-2}
- Systematic effects of FG5X-220 within 25 nm s^{-2}
- Agreement with KCRV within instrumental uncertainty

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