

Stability comparison of two absolute gravimeters: optical versus atomic interferometers

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Abstract.

We report the direct comparison between the stabilities of two mobile absolute gravimeters of different technology: the LNE-SYRTE Cold Atom Gravimeter and FG5X#216 of the Université du Luxembourg. These instruments rely on two different principles of operation: atomic and optical interferometry. The comparison took place in the Walferdange Underground Laboratory for Geodynamics in Luxembourg, at the beginning of the last International Comparison of Absolute Gravimeters, ICAG-2013. We analyse a 2h10 duration common measurement, and find that the CAG shows better immunity with respect to changes in the level of vibration noise, as well as a slightly better short term stability.

1. Introduction

Absolute gravimeters measure test body free fall acceleration. The most used is the state-of-the-art commercial gravimeter FG5 [1]. It measures the free fall of a corner cube with a Mach-Zehnder interferometer. Since the beginning of the 90's [2], laboratories started to elaborate gravimeters using cold atoms as a test mass [3, 4, 5]. This led to develop transportable instruments [6, 7, 8, 9] coming out on participation to International Comparisons of Absolute Gravimeters (ICAG) as the LNE-SYRTE Cold Atom Gravimeter (CAG) does since 2009 [10, 11].

Usually, free fall corner cube users and in particular FG5 operators, record gravity by sets consisting of a number of drops (of the order of 100), that get repeated every hour. The repetition rate is usually of order of one drop every 10 s, in order to wait for the damping of the vibrations due to the carriage free fall and to preserve the device from mechanical wear. In [12], one free fall per 30 s was chosen, leading to an Allan standard deviation about twice worse than if one drop per 10 s would have been chosen. On one hand, the FG5 dropping chamber [13] allows drops of 2 s which can improve notably the stability of FG5. On the other hand, alike the FG5, that uses a sophisticated super-spring system [14], various vibration rejection systems have been demonstrated and gradually improved over the last years to reject ground noise for atom sensors. They are based on the combination of a passive isolation and of a low noise seismometer [4, 15]. Eventually, it turned into an active system [16, 9, 5], by using the signal of the seismometer to even better stabilize the position of the reference mirror. Using such an optimized active system, a stability of $4.2 \mu\text{Gal}\ddagger$ in 1 s measurement time was demonstrated in [17]. Using a passive system, or set directly on the ground, the CAG demonstrated a stability of $1 \mu\text{Gal}$ in 100 s measurement time interval [18]. To compare the stability performances of both technologies it is desirable to perform measurements at the same place and at the same time, under the influence of the same vibration noise. We took advantage of the last ICAG which took place in the Walferdange Underground Laboratory for Geodynamics (WULG) in Luxembourg at the end of 2013 to test the capabilities of the FG5X#216 and CAG on a common view measurement.

2. Measurements

Both gravimeters were installed on the platform B of the WULG [11]. The common view measurements were performed during the night between the 24th and the 25th of october 2013. The drop interval of the FG5X was chosen at 3 s close to his best capability of 2 s. We decided to use 3 s over 2 hours to spare the moving mechanical part of the instrument. The CAG measured continuously, all night long, using the protocol already used in [18] which is based on two interleaved integrations leading to a measurement time of 720 ms. Measurements are represented on figure 1. It started at 20h15 for CAG and 15 minutes later for the FG5X. We realized only after the measurement was performed

\ddagger $1 \text{ Gal} = 1 \text{ cm.s}^{-2}$, $1 \mu\text{Gal} = 10^{-8} \text{ m.s}^{-2}$

that the seismic noise was relatively high initially, due to an earthquake of magnitude 6.7 that occurred in the East of South Sandwich Islands. This excess noise can be seen on the FG5X first half hour measurement as well as on the superconducting gravimeter OSG-CT040 that records gravity variation continuously a few meters only from platform B. Usually, FG5 users compute the "drop scatter" (the standard deviation of a set) to characterize the dispersion of the measurements. Here the drop scatter of the FG5X first half hour measurement is $21.7 \mu\text{Gal}$ and $9.1 \mu\text{Gal}$ after. A zoom on the first hours of the gravity signals corrected from tides and atmospheric pressure effects (Figure 1 b) shows that the CAG is almost not affected by the seismic wave. The vibration rejection system [4, 15] is good enough to suppress the effect of the earthquake. This can also be seen on figure 2.

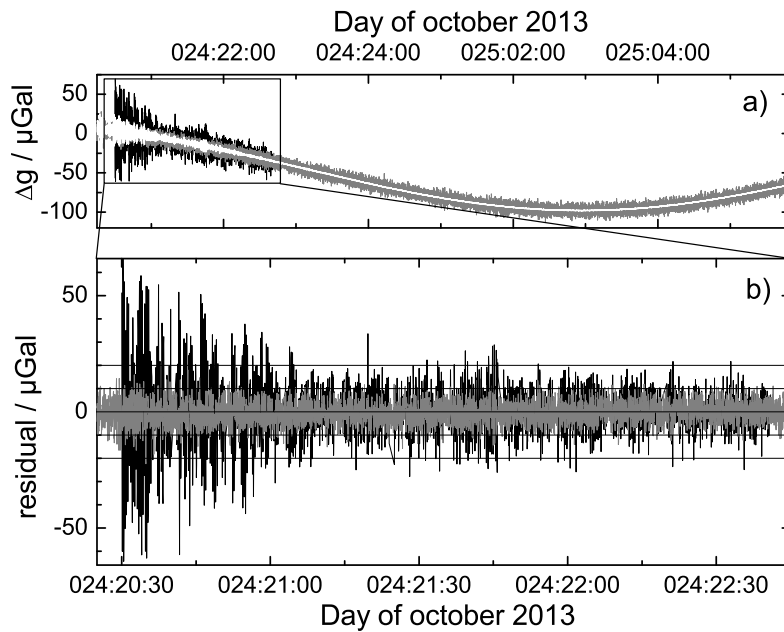


Figure 1. a) Earth's gravity variation during the night from the 24th to the 25th of October 2013 measured at Walferdange with FG5X#216 in black and CAG in grey. The gravity variations observed with the superconducting gravimeter OSG-CT040 is also plotted in white. b) FG5X#216 and CAG corresponding signals corrected for tides and atmospheric pressure effects, during the common view measurement.

In this paper, we choose to analyse the stabilities of the measurements using the Allan standard deviations [19] of the corrected gravity data (figure 2). Two analyses were performed for each gravimeter with and without the period during which the influence of the earthquake is significant. As we can guess from figure 1, the short term stability of the FG5X is about 30 % better when excluding the first half hour. After 200 s of measurement time the Allan standard deviation calculated with and without the earthquake noise are similar. The $1 \mu\text{Gal}$ level is obtained after 86 s of measurement and the Allan standard deviation continues to decrease down to $0.3 \mu\text{Gal}$ and maybe

even better. However the FG5X measurements would have to be longer to perform this analysis. For shorter averaging times, the Allan standard deviation decreases faster than a $\tau^{-1/2}$ slope. This behaviour is due to the averaging of the low frequency noise which is reasonably well sampled by the FG5X. As a consequence the statistical error se should not be estimated here using the standard formula $se = sd/\sqrt{N}$ where N is the number of free falls. In contrast, the CAG stability is not affected by the seismic wave. We find that the Allan standard deviation for the whole CAG measurements, displayed with open circles on figure 2 is superimposed with the grey circles representing the Allan standard deviation calculated when excluding the earthquake. The initial bump on the Allan standard deviation is due to our measurement technique: the CAG signal is locked onto the gravity acceleration thanks to an integrator with a time constant of a few cycles [15]. Then the Allan deviation decreases with a $\tau^{-1/2}$ slope up to 370 s (the 1 μ Gal level is obtained after less than 36 s of measurement) and continues to decrease down to 0.2 μ Gal. Such a long term stability had already been obtained in the LNE laboratory [20], by comparing the CAG with a superconducting gravimeter iGrav [21]. Performing the FG5X measurement every 2 s instead of 3 s would only slightly affect the Allan standard deviation by shifting the curve to the left and would be still above the CAG results. This can be inferred from a previous study on the uncertainty of the FG5 [22] showing that at high frequency (10^{-5} Hz $\leq \nu \leq 10^{-1}$ Hz) the noise of a FG5 is white. The same study reveals that the noise increases at lower frequencies due to gravity changes linked to environmental fluctuations, that are not modeled. Both Allan variance curves of the CAG and FG5X will thus overlap for an integration time greater than one fourth day.

3. Conclusion

We compared the stabilities of two absolute gravimeters of different technology. Atom interferometry was already known for high cycling rate operation and the new FG5X for performing a free fall measurement every 3 s. During a quiet period the FG5X reaches a stability of 1 μ Gal after 86 s averaging time while the CAG needs only 36 s, even for higher level of vibration noise. Considering the current level of accuracy of such gravimeters, of order of a few μ Gal at best, a measurement time of only a few minutes is enough for the statistical uncertainty to be a negligible contribution to the combined uncertainty in the measurement.

The possibility to perform continuous measurements with atom gravimeters at high cycling rates, and to reach stabilities of 0.2 μ Gal in less than 2 000 s, now offer the opportunity to develop such instruments for permanent installation in geophysical observatories. Moreover, the sensitivity of atom gravimeters which scales as T^2 can be increased using taller vacuum chambers and larger time T between the three interrogating pulses [23]. As an example, the fountain configuration used in [17] allows to increase T up to 300 ms, to be compared with the 80 ms we use in the CAG.

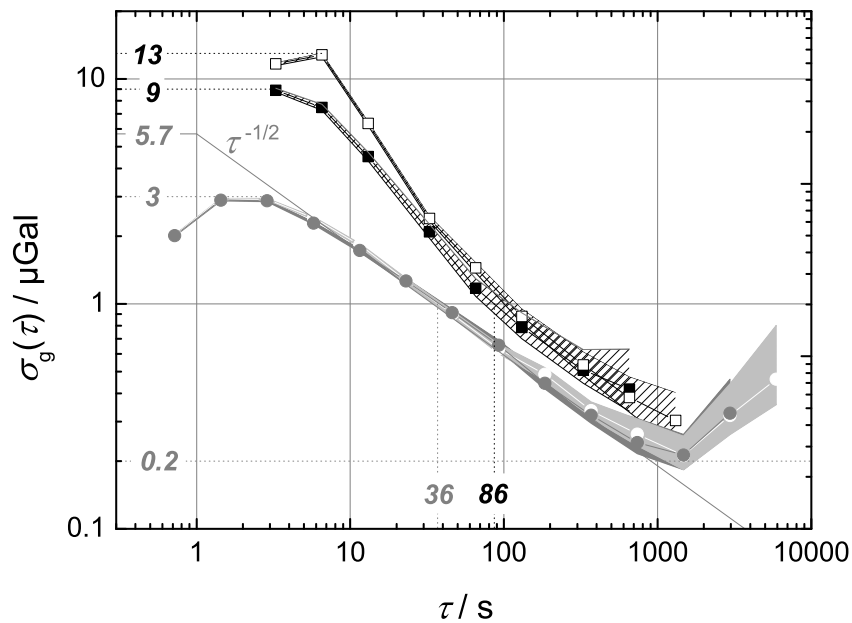


Figure 2. Allan standard deviation of the corrected gravity signals. FG5X#216: open squares take into account all the drops and black squares exclude the earthquake. CAG: open circles take into account all the drops and grey circles exclude the earthquake. The $\tau^{-1/2}$ slope represents the averaging expected for white noise, the filed areas surrounding the Allan standard deviations dots represent the confidence intervals of the analyzes.

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References

- [1] Niebauer T M, Sasagawa G S, Faller J E, Hilt R and Klopping F 1995 A new generation of absolute gravimeters *Metrologia* **32** 159-180
- [2] Kasevich M and Chu S 1992 Measurement of the Gravitational Acceleration of an Atom with a Light-Pulse Atom Interferometer, *Appl. Phys. B* **54** 321-332 .
- [3] Peters A, Chung, K Y and Chu S 2001 High-precision gravity measurements using atom interferometry, *Metrologia*, **38**, 25-61
- [4] Le Gouët J, Mehlstäubler T E, Kim J, Merlet S, Clairon A, Landragin A and Pereira Dos Santos F 2008 Limits to the sensitivity of a low noise compact atomic gravimeter, *Appl Phys B*, **92**, 133-44

- [5] Zhou M-K, Hu, Z-K, Duan, X-C, Sun, B-L, Chen, L-L, Zhang, Q-Z and Luo, J 2012 Performance of a cold-atom gravimeter with an active vibration isolator *Phys Rev A* **86** 043630
- [6] Q Bodart, S Merlet, N Malossi, F Pereira Dos Santos, P Bouyer, and A Landragin 2010 A cold atom pyramidal gravimeter with a single laser beam, *Appl Phys Lett* **96**, 134101
- [7] Louchet-Chauvet A, Farah T, Bodart Q, Clairon A, Landragin A, Merlet S and Pereira Dos Santos F 2011 Influence of transverse motion within an atomic gravimeter, *New J Phys*, **13**, 065025
- [8] Bidel Y, Carraz O, Charrière O, Cadoret M, Zahzam N and Bresson A 2013 Compact cold atom gravimeter for field applications *Appl Phys Lett*, **102** (14):144107
- [9] Hauth M, Freier C, Schkolnik V, Senger A, Schmidt M and Peters A 2013 First gravity measurements using the mobile atom interferometer GAIN, *Appl Phys B*, **113**, Vol 1, 49-55
- [10] Jiang Z et al 2012 The 8th International Comparison of Absolute Gravimeters 2009 - The First Metrological Key Comparison CCMG-K1, *Metrologia*, **49**, 666-684
- [11] Francis O et al 2013 The European Comparison of Absolute Gravimeters 2011 (ECAG-2011) in Walferdange, Luxembourg: results and recommendations, *Metrologia* **50**, 257-268
- [12] Merlet S, Bodart Q, Malossi N, Landragin A, Pereira Dos Santos F, Gitlein O and Timmen L 2010 Comparison between two mobile absolute gravimeters: optical versus atomic interferometers, *Metrologia* **47** L9-L11
- [13] Niebauer T M, Billson R, Ellis B, Mason B, van Westrum D and Klopping F 2011 Simultaneous gravity and gradient measurement from a recoil-compensated absolute gravimeter, *Metrologia* **48**, 154-163
- [14] Nelson P G 1991 An active vibration isolation system for inertial reference and precision measurement, *Rev Sci Instrum* **62**, 2069-75
- [15] Merlet S, Le Gouët J, Bodart Q, Clairon A, Landragin A, Pereira Dos Santos F and Rouchon P 2009 Operating an atom interferometer beyond its linear range *Metrologia*, **46**, 87-9
- [16] Hensley J M, Peters A, Chu S 1999 Active low frequency vertical vibration isolation, *Rev Sci Instrum* **70** (6), 2735-41
- [17] Hu Z-K, Sun B-L, Duan X-C, Zu M-K, Chen L-L, Zhang Q-Z and Luo J 2013 Demonstration of an ultrahigh-sensitivity atom-interferometry absolute gravimeter, *Phys Rev A* **88**, 043610
- [18] Farah T, Guerlin C, Landragin A, Bouyer Ph, Gaffet S, Pereira Dos Santos F and Merlet S 2014 Underground operation at best sensitivity of mobile LNE-SYRTE Cold Atom Gravimeter, *accepted to Gyroscopy and Navigation, Arxiv 1404.6722*
- [19] Allan D W 1987 Time and frequency (time domain) characterization, estimation, and prediction of precision clocks and oscillators *IEEE Trans. Ultrason., Ferroelect, Freq. Control* **UFFC-34** 647-54
- [20] Merlet S, Kopaev A, Diament M, Genevès G, Landragin A and Pereira Dos Santos F 2008 Micro-gravity investigations for the LNE watt balance project *Metrologia*, **45**, 265-274
- [21] <http://www.gwrinstruments.com>
- [22] Van Camp M, Simons S D P and Francis O 2005 Uncertainty of absolute gravity measurements *Journal of Geophysical Research* **110** B05406 doi:10.1029/2004JB003497
- [23] Bordé Ch J 2001 Theoretical tools for atom optics and interferometry *C R Acad Sci Paris, t2, Série IV*, 509-30