The LNE-SYRTE cold atom gravimeter

P. Gillot, B. Cheng, A. Imanaliev, S. Merlet, F. Pereira Dos Santos
LNE-SYRTE, Observatoire de Paris, PSL Research University
CNRS, Sorbonne Universités, UPMC Univ. Paris 06
61 avenue de l'Observatoire, 75014 Paris, France
Email: franck.pereira@obspm.fr

***Abstract*—We present results on the evaluation of the metrological performances of our second generation cold atom gravimeter, operating since 2009. This instrument uses free falling ^{87}Rb cold atoms, whose acceleration is measured thanks to atom interferometry techniques. This allows for a sensitive and absolute determination of the gravity acceleration. We present the results of various comparisons of our atomic sensor with high performance absolute or relative gravimeters based on other technologies.**

I. Introduction

Gravimeters are vertical accelerometers used to measure the local gravity acceleration or variations in the gravity field. They find applications in many fields, such as geophysics and geodesy, navigation, exploration of natural resources, detection of underground infrastructures and monitoring of reservoirs. The absolute measurement of gravity is obtained from the measurement of the motion of a free falling body. State of the art commercial absolute gravimeters are based on a free falling corner cube whose trajectory is tracked using a laser interferometer. These instruments have accuracies of a few μGal (1 μGal = 10^{-8}m/s^2) and their sensitivity depends on the environmental conditions, as they are usually limited by residual ground vibrations, despite the use of a sophisticated vibration isolation system based on the use of a super spring. They operate at a measurement cycle time of a few seconds, and require regular maintenance because of the wear of their mechanical parts.

Atomic sensors offer an attractive alternative to corner cube gravimeters. In these instruments, the test mass is an atom and its acceleration is measured by means of an atom interferometer realized with laser beamsplitters. Because the interaction with the lasers imprints the atoms position with respect to the lasers onto the atomic phase, the phase at the output of the interferometer finally allows for the measurement of the acceleration of the free falling atoms with respect to the setup (and to be more precise, in most cases, to the position of a mirror that reflects the interferometer laser beams). They have the great advantage of not suffering from mechanical wear and thus offer the possibility of performing continuous and high rate measurements over extended periods of time. Such continuous measurements are usually realized thanks to relative instruments, such as spring or superconducting gravimeters. But, these instruments need to be calibrated and suffer from drifts (of order of hundreds of μGal per day for spring gravimeters, to a few μGal per year only for superconducting gravimeters).

In this paper, we describe the cold atom gravimeter (CAG) we have developed and its measurement principle. We give details on its level of performance, and present the results of the various comparisons it participated to with other instruments, either absolute or relative gravimeters.

II. Description of the Gravimeter

In our experiment, ^{87}Rb atoms from a 2D-Magneto-Optical Trap (MOT) load a 3D-MOT for 80 ms [1]. Next, a molasses phase cools atoms down to a temperature of about 2 μK. The molasses beams are then switched off within 100 μs with a fast mechanical shutter. The atomic cloud is thus simply let to freely fall, over a distance of about 20 cm, before being detected at the bottom of the vacuum chamber.

The atoms are then velocity selected [2] along the vertical direction in the $|F = 1, m_F = 0\rangle$ state thanks to a combination of microwave, pusher and Raman pulses. After the selection, we drive a Mach-Zehnder interferometer, using a $\pi/2$-π-$\pi/2$ Raman pulse sequence, to respectively separate, redirect and finally recombine the two partial wave packets [3]. The two-photon Rabi frequency of the Raman pulse is of order of $2\pi \times$ 25 kHz at maximum. The single-frequency detuning of the Raman lasers is of order of -1 GHz, and the $1/e^2$ radius of the Raman beams is 12 mm. The first pulse of the interferometer occurs about 16 ms after the release from the molasses.

We exploit the state labelling of the Raman process [4] to measure the populations in the two output states, thanks to a fluorescence detection performed on the internal state. From the measurement of the populations N_1 and N_2 in the two hyperfine states, we calculate the transition probability $P = N_1/(N_1 + N_2)$. This transition probability P is given by $P = (1 + C\cos(\Delta\Phi))/2$, where C is the interferometer contrast and $\Delta\Phi$ the phase difference between the two different arms. In our geometry, with vertically aligned Raman lasers, this interferometer phase shift is given by $\Delta\Phi = k_{eff} g T^2$ [5]. k_{eff} is the effective Raman wavevector, given by the difference between the wavevectors of the two counter-propagating Raman lasers. g is the gravity acceleration and $T = 80$ ms is the time separation between consecutive pulses. The cycle time in our experiment is 380 ms.

The figure 1 displays a picture of the instrument. At the forefront, the drop chamber, enclosed in a cylindrical two layer magnetic shield, is installed on a thick aluminium plate. This plate lies on a passive isolation platform, which we use to reduce the impact of parasitic vibrations. A low noise seismometer is installed on top of the chamber, which measures the residual vibration noise not filtered by the platform. At the back, the electronic control system and the power supplies are installed in a rigid frame made of aluminium bars. The laser breadboard is placed at the top of this frame, in a

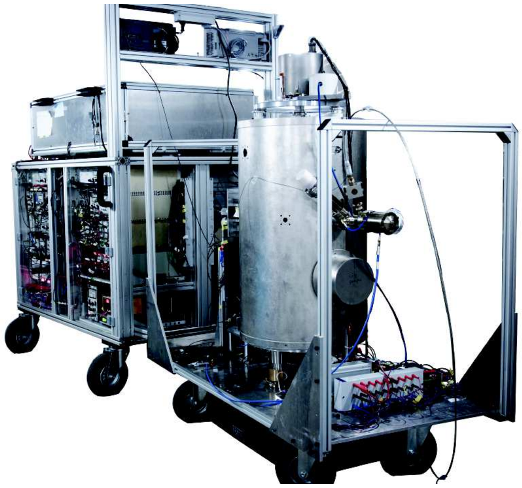

Fig. 1. Picture of the instrument. At the forefront, the drop chamber. Behind, the control electronics and laser system.

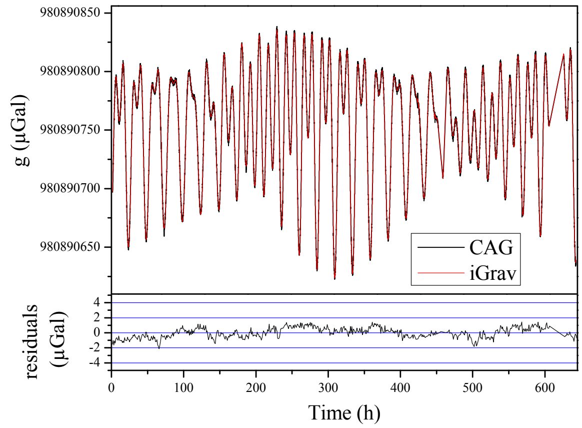

Fig. 2. Continuous measurement over 25 days of the CAG and the superconducting gravimeter iGrav, and the residuals of the difference between the two signals.

dedicated aluminium box. The two parts, vacuum chamber and electronic-optics frame, are connected via optical fibres and electrical cables. Both the drop chamber and the frame can be equipped with wheels, so that they can be moved out separately from the laboratory, be placed in a truck and be transported to a dedicated measurement site. In the normal conditions of operation, the wheels under the drop chamber are removed, so that the isolation platform rests on the floor.

III. Measurement principle

Usually, the absolute measurement of g is performed in our experiment by alternating measurements in four different configurations [1]. This protocol allows removing many of the systematic effects, except Coriolis acceleration and phase shifts due to wavefront distortions. It comprises two pairs of configurations in which the wave-vector k_{eff} is reversed ($k_\uparrow$ and $k_\downarrow$). The half difference of a single pair of configuration ($k_\uparrow$ and $k_\downarrow$) provides a $g_{\uparrow\downarrow}$ measurement in which most of the effects related to hyperfine frequency shifts and from radio-frequency phase shift are suppressed [6]. The second pair is performed with half the Raman power, which allows correcting for the two-photon light shift [7].

IV. Long term measurements and comparison with a superconducting gravimeter

We start by presenting in figure 2 continuous measurements of the gravity acceleration performed in April 2015, for almost a month, with two different instruments operating simultaneously, the CAG and an iGrav superconducting gravimeter installed in the same laboratory, just a few meters away. The superconducting gravimeter uses as a test mass a superconducting sphere which is levitated using a magnetic force that exactly balances the force of gravity. The CAG and iGrav data points are both averaged over the same duration of about 3 minutes. Both instruments record the expected fluctuations of gravity of order of a few hundreds of μGal which are due to Earth tides. For these measurements, which are performed in an industrial area in Trappes, the short term sensitivity is 10μGal at 1s. We have obtained at best a short term sensitivity twice better when operating in the more quiet environment of the underground laboratory at Walferdange [8], where the 2011 and 2013 comparisons took place.

The bottom plot on figure 2 displays the residuals obtained by subtracting the two signals. Note that in order to obtain these residuals, one has to have a precise determination of the calibration factor of the iGrav, ie the link between a change in its output current and the change of gravity, and also to account for eventual time delays in its response. This is in fact realized by correlating the two signals. Once this calibration is done, we are left with residuals which fluctuate by about $\pm 1\mu$Gal. We attribute these residuals to uncontrolled fluctuations of the systematic effects of the CAG.

V. Accuracy budget and comparisons with absolute gravimeters

TABLE I. Accuracy budget

Systematic effect	Correction μGal	U μGal
Alignement	1.2	0.5
Frequency reference	3.2	0.1
RF phase shifts	0	< 0.1
Gravity gradient	-13	< 0.1
Self gravity effect	-2.1	0.1
Coriolis	-5.3	1
Wavefront distortions	0	4
1 photon Light shift	0	< 0.1
Zeeman	0	< 0.1
2 photon Light shift	-7.7	0.4
Detection offset	0	0.5
Optical power	0	1.0
Refraction index	0.4	< 0.1
Cold collisions	0	< 0.1
TOTAL	-23.2	4.3

Table I displays the accuracy budget of our instrument. The inaccuracy of our measurement, of order of 4μGal is dominated by our imperfect knowledge of the effect of wave-front distortions. This accuracy budget has been validated by comparing our instrument with state of the art corner cube gravimeters.

We have participated to three international comparison campaigns of absolute gravimeters. They took place at BIPM in Sèvres in 2009, and in the Underground Laboratory for Geodynamics in Walferdange, Luxembourg, in 2011 and 2013. The 2009 comparison at BIPM was the first Key Comparison (KC) as defined by the CIPM MRA, organized by the Consultative Committee for Mass and Related Quantities (CCM) and designated as CCM.G-K1. Our instrument has been the first and remains so far the only atomic sensor which has ever participated to such official comparisons. In addition, we have organized a few comparisons in our laboratory, located in the Watt balance (WB) laboratories of the Laboratoire National de Métrologie et d'Essais, in Trappes, a city in the suburb of Paris (France).

Table II summarizes the results of these comparisons. Our instrument was in agreement within our claimed uncertainty with the reference value provided by the other sensors, this value being, depending on the comparison, an average over many, a few, or a single instrument.

TABLE II. RESULTS OF THE COMPARISONS WITH OTHER ABSOLUTE GRAVIMETERS

Date	Place	Number of Instruments	g(CAG)-g(other) (μGal)
2009	BIPM	22	-1.6(7.8)
2009	Trappes	2 FG5-220	-4.3(6.4)
2010	Trappes	3 FG5-209, IMGC-02	+11(6.5)
2011	LUX	22	+5.4(5.7)
2013	LUX	25	+6.2(5.5)
2014	Trappes	2 FG5X-220	0(5)

VI. Gravity Measurements at the WB Laboratory

Finally, we display in figure 3 the results of repeated gravity measurements performed at Trappes for the last 7 years. The red points correspond to measurements performed after changing the orientation of the experiment by 180 degrees. The difference of 15-20 μGal between two opposite orientations is due to Coriolis acceleration. The dispersion of the data decreases with time, which reflects the improvement of the long term stability and of our control of the systematic effects. Note that the measurements over the first three years were not taken for identical measurement parameters (such as Rabi frequency, power in the MOT beams, interferometer duration 2T ...), so that the dispersion is partly linked to these changes, which were necessary to investigate the systematic effects. Since 2012, we have tried to repeat the measurements with a set of fixed parameters. During the last year, we have implemented a lock of the power in the Raman beams and in the cooling beams, which improves even further the repeatability. The rms fluctuations of the gravity value over the last year is 2.5 μGal.

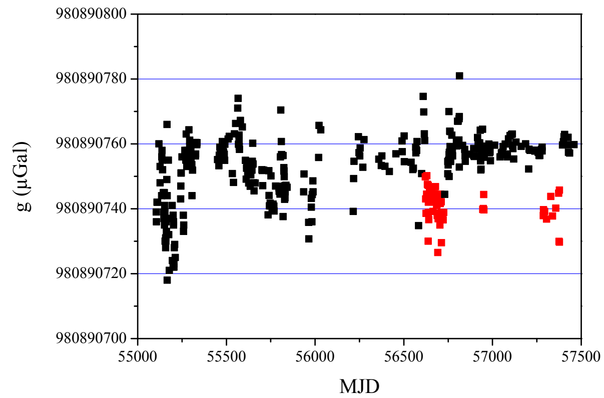

Fig. 3. Gravity measurements performed with the CAG in the Watt balance laboratory in Trappes since 2009.

VII. Conclusion

We have presented the main features our cold atom gravimeter and its level of performances. Limits on its long term stability and its accuracy have been identified. They are related to the fluctuations of the initial position of the atomic source and its residual expansion in the profile of the Raman beams. To reduce these effects, we plan to use a source of ultracold atoms produced by evaporative cooling in a crossed dipole trap, which will provide a better stability of the atoms initial position and a reduced expansion. We expect to push the accuracy and long term stability below the μGal level.

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