Comparison between two mobile absolute gravimeters: optical versus atomic interferometers

S Merlet\textsuperscript{1}, Q Bodart\textsuperscript{1}, N Malossi\textsuperscript{1,3}, A Landragin\textsuperscript{1}, F Pereira Dos Santos\textsuperscript{1}, O Gitlein\textsuperscript{2} and L Timmen\textsuperscript{2}

\textsuperscript{1} LNE-SYRTE, Observatoire de Paris, CNRS et UPMC, 61 avenue de l’Observatoire, 75014 Paris, France
\textsuperscript{2} Institut für Erdmessung, Leibniz Universität of Hannover, Scheinderberg 50, 30167 Hannover, Germany

E-mail: franck.pereira@obspm.fr

Received 9 April 2010, in final form 27 May 2010
Published 18 June 2010
Online at stacks.iop.org/Met/47/L9

Abstract

We report a comparison between two absolute gravimeters: the LNE-SYRTE cold atom gravimeter and FG5\#220 of Leibniz Universität of Hannover. They rely on different principles of operation: atomic and optical interferometry. Both are movable which enabled them to participate in the last International Comparison of Absolute Gravimeters (ICAG’09) at BIPM. Immediately after, their bilateral comparison took place in the LNE watt balance laboratory and showed an agreement of (4.3 ± 6.4) µGal.

1. Introduction

Over the last two decades inertial sensors based on atom interferometry have been realized. In particular, as described in [1], cold atom gravimeters can reach performances comparable to ‘classical’ corner cube gravimeters in terms of both sensitivity [2, 3] and accuracy. The first and only comparison between atomic and optical gravimeters [4] has shown agreement between the sensors ((7 ± 7) µGal\textsuperscript{4} difference). In this paper, we present the result of a comparison, realized between the cold atom gravimeter (CAG) developed by LNE-SYRTE in the framework of the French watt balance project [5] and the FG5\#220 of Leibniz Universität of Hannover (LUH) [6]. Both rely on the measurement of the trajectory of free falling bodies (corner cube for FG5 and \textsuperscript{87}Rb atoms for CAG). Unlike the situation described in [4], both sensors are mobile which makes regular comparisons at various sites possible. Such comparisons between instruments based on different technologies are of fundamental interest for accurate metrology of $g$. This motivated the participation of both devices in ICAG’09 and the subsequent bilateral comparison presented in this paper. For this purpose, both sensors were moved from BIPM to the gravimetry room (GR) of the LNE watt balance laboratory [7], where they performed simultaneous gravity measurements.

2. Experimental setups

The CAG is an improved version of a prototype described in [2] which reached a short term sensitivity to acceleration of 1.4 × 10^{-8}g at 1 s. It is composed of three parts: a dropping chamber on its isolation platform (figure 1), a compact optical bench (60 \times 90 cm\textsuperscript{2}) [8] and two 2 m lab racks for the electronic control. The measurement of the Earth’s acceleration is deduced from the phase difference between the two paths of an interferometer realized with cold atoms. The FG5 absolute gravimeter of LUH is a state-of-the-art commercial gravimeter which is essentially a modified Mach–Zehnder ‘in-line’ interferometer as described in [9].

3. Results

The gravimeters measured simultaneously the whole night in the well characterized GR room [7]. The FG5\#220 was located on point GR\textsubscript{29} with one drop per 30 s. The result transferred
Short Communication

Figure 1. Scheme of the CAG set-up. The drop chamber made of titanium is placed onto a passive isolation platform. Atoms are first trapped in a magneto-optical trap (MOT), cooled with optical molasses and released. During the free fall, the interferometer is realized with vertical Raman laser beams. The measurement is determined from the interferometer phase shift.

(This figure is in colour only in the electronic version)

Table 1. Gravity results at 120 cm height.

| Device     | Point | \(g/\mu\text{Gal}\) | \(U(k = 1)/\mu\text{Gal}\) | \(s_g/\mu\text{Gal}\) |
|------------|-------|----------------------|--------------------------|------------------|
| CAG        | GR40  | 980 890 744.8        | 5.9                      | 0.7              |
| FG5#220    | GR29  | 980 890 742.6        | 2.2                      | 1.0              |
| CG5        | GR40 – GR29 | 6.5 1.0 | 0.1 |
| CAG–FG5#220| GR40  | –4.3 6.4 1.6        |                          |                  |

at 120 cm is reported in table 1. The CAG was on point GR40, measuring at the high cycling rate of 3 Hz. Its result, also transferred at 120 cm, is reported in table 1. The two points GR40 and GR29 are 2.12 m apart and the tie between them, obtained with a Scintrex CG5, is \(g_{\text{GR40}} – g_{\text{GR29}} = (6.5 \pm 1.0) \mu\text{Gal}\) at the height of 120 cm [7]. Transferred on point GR40 at 120 cm, the difference between the devices is \((4.3 \pm 6.4) \mu\text{Gal}\). The \(g\) measurements uncorrected for tides are displayed in figure 2. The stability is characterized by the Allan standard deviation of the tide-corrected \(g\) measurements (figure 3).

Figure 2. Earth’s gravity variation \(g\) during the night from the 1st to the 2nd of October 2009 on site GR at LNE. Dots represent average data over 2 min 30 s (black squares: FG5#220, grey circles: CAG). Tidal variation is plotted as a white line on the data.

Despite different vibration isolation systems and repetition rates, the signal dispersions are similar except during the first hours of the comparison, as can be seen in figure 3. Measurements are found to be less noisy after midnight due to the drastic reduction in human activity in the surrounding industrial area. At best, the FG5 drop scatter is 16 \(\mu\text{Gal}\). The CAG’s \(g\) determination is based on measurement in four successive configurations in order to reject bias due to the two-photon light shift [10]. This degrades the sensitivity by a factor \(\sqrt{10}\). Better sensitivity could also be obtained with the FG5 if performed with one drop per 10 s rather than 30 s chosen to preserve the device.

Rotating the CAG by 180\(^\circ\) around the vertical axis, we measured a Coriolis shift of \((6.5 \pm 0.5) \mu\text{Gal}\). Varying the temperature of the atoms enabled us to evaluate the bias due to wavefront aberrations [11] as \((3.0 \pm 3.0) \mu\text{Gal}\). During this comparison, the lack of rigidity of the mechanical structure resulted in a relatively large vertical alignment bias of \((4.5 \pm 4.5) \mu\text{Gal}\). The final accuracy was 5.9 \(\mu\text{Gal}\). In [9] an error analysis of the FG5 system led to a total uncertainty of 1.1 \(\mu\text{Gal}\). From numerous comparisons with other absolute gravimeters since 2002, the LUH group estimates the accuracy of their device to be 2.0 \(\mu\text{Gal}\) [6, 12]. The \(g\) result measured by FG5#220 on point GR29 agrees with the mean of previous measurements performed with other FG5s on the same point, in October 2006 [13] (difference of \((1.9 \pm 2.9) \mu\text{Gal}\)).

4. Conclusion and discussion

We have compared two different portable absolute gravimeters and found an agreement of \((4.3 \pm 6.4) \mu\text{Gal}\). More such
comparisons will be made in the future while striving to improve the accuracy of the CAG down to 1 µGal. Already, the vertical alignment bias has been reduced to (0.0 ± 0.5) µGal. Future comparisons will benefit from the mobility of atomic sensors as described here. Transportability is an important and original feature of the CAG, which is necessary for regular participation in comparison campaigns. Nevertheless, CAG is still a laboratory device but such comparisons as the ‘field’ gravimetric measurements would benefit from the development of a more compact gravimeter as described in [14].

Acknowledgments

The authors would like to thank IFRAF and ESF (EuroQUASAR) for financial support. QB thanks CNES for supporting his work.

References

[1] Kasevich M and Chu S 1992 Measurement of the gravitational acceleration of an atom with a light-pulse atom interferometer *Appl. Phys. B* **54** 321–32
[2] 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 interferometer *Appl. Phys. B* **92** 133–44
[3] Müller H, Chiow S W, Herrmann S and Chu S 2008 Atom-interferometry tests of the isotropy of post-Newtonian gravity *Phys. Rev. Lett.* **100** 031101
[4] Peters A, Chung K Y and Chu S 2001 High-precision gravity measurements using atom interferometry *Metrologia* **38** 25–61
[5] Genevès G et al 2005 The BNM Watt balance project *IEEE Trans. Instrum. Meas.* **54** 850–3
[6] Gu X (ed) 2010 *Sciences of Geodesy, Advances and Future Directions* 1st edn (Berlin: Springer) ISBN: 978-3-642-11740-4
[7] 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** 265–74
[8] Cheinet P, Pereira Dos Santos F, Petelski T, Le Gouët J, Kim J, Therkildsen K T, Clairon A and Landragin A 2006 Compact laser system for atom interferometry *Appl. Phys. B* **84** 643–6
[9] Niebauer T M, Sasagawa G S, Fuller J E, Hilt R and Klopping F 1995 A new generation of absolute gravimeters *Metrologia* **32** 159–80
[10] Guauguet A, Mehlstäubler T E, Lévéque T, Le Gouët J, Chaibi W, Canuel B, Clairon A, Pereira Dos Santos F and Landragin A 2008 Off-resonant Raman transitions impact in an atom interferometer *Phys. Rev. A* **78** 043615
[11] Fils J, Leduc F, Bouyer Ph, Holleville D, Dimarçq N, Clairon A and Landragin A 2005 Influence of optical aberrations in an atomic gyroscope *Eur. Phys. J. D* **36** 257–60
[12] Timmen L et al 2006 Geodetic Deformation Monitoring: From Geophysical to Engineering Roles, IAG Symp. vol 131 ed F Sanso and A J Gil (Berlin: Springer) pp 193–9
[13] Merlet S, Francis O, Palinkas V, Kostelecky J, Le Moigne N, Jacobs T and Genevès G 2007 *Absolute Gravity Measurement at LNE* (TG-SMM 2007) Symp. Proc. (St Petersburg, Russia) pp 173–4
[14] Bodart Q, Merlet S, Malossi N, Pereira Dos Santos F, Bouyer P and Landragin A 2010 A cold atom pyramidal gravimeter with a single laser beam *Appl. Phys. Lett.* **96** 134101