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Tests with commercial classical gravimeters in preparation for tests of quantum prototype

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Foreword

This note describes experiments with commercial gravity meters carried out in 2016 and 2017 at the outdoor test facility at Ispra by researchers from University of Birmingham (UoB) with the aim of establishing a test bed suitable for assessing the performance of novel quantum gravimeters, and comparing them with conventional classical devices. In these preparatory measurements, no quantum device was used.

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Authors

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Abstract

Preliminary tests with commercial spring-mass gravimeters have been carried out on the outdoor test field at Ispra in order to establish a test-bed suitable for testing a cold-atom quantum gravimeter. In 2016, the background on a single device was measured. In 2017, measurements of the field above a buried 5 ton lead mass were carried out, using two gravimeters mounted vertically one above the other. A clear indication of the gravitational field of the test mass with seen, with good signal-to-noise ratio. It was concluded that the general layout is satisfactory, given that the quantum prototype should have sensitivity similar to or better than the conventional instruments. Practical experience gained is helpful for understanding the requirements for mounting and positioning the quantum instrument.

1 Introduction

This note describes experiments with commercial gravity meters carried out in 2016 and 2017 at the outdoor test facility at Ispra by researchers from University of Birmingham (UoB) with the aim of establishing a test bed suitable for assessing the performance of novel quantum gravimeters, and comparing them with conventional classical devices. In these preparatory measurements, no quantum device was used. In 2016, the background on a single device was measured. In 2017, a differential measurement of the field above a buried 5 ton lead mass was carried out, using two gravimeters mounted vertically one above the other.

Background

The work forms part of work package 5, Tasks 5.4 and 5.5 of the MSC-RISE project Q-SENSE. Engineers from the University of Birmingham (UoB) and industrial partner e2v were planned to be seconded to JRC to carry to these tasks. To date, two engineers have come, both from UoB. It was originally hoped to complete the tasks by end 2017, but it has taken longer than expected to develop the portability of the cold-atom gravimeter to the point where it can be relying transported to Ispra, so tests on it are delayed until 2018.

The objective is to examine application scenarios for quantum sensors. This will be driven by feasibility studies targeted at each of domain. The focus is to understand the range of opportunities and deliver targeted suggestions for the clearest routes to impact. The terrestrial work will be supported through characterisation of specific civil engineering application scenarios at the JRC, such as underground detection and demining. The outdoor test site at Ispra was originally established in 1999-2000 for testing apparatus for detection of land mines in humanitarian demining, and can also be used for test of detection of larger objects and so is well-suited for the purpose. JRC senior management has agreed that the test site will be kept available until the end of the project (31st December 2019).

- Task 5.4: Feasibility study for terrestrial application scenarios (lead UoB, secondments include from e2v and UoB to JRC) A joint effort between the UoB civil engineering and cold atoms groups, and e2v all seconded to the JRC will be employed to create a feasibility study with input from cold atom physicists, industry and end-users. This activity will bring cold atom systems into policy discussions. This will be coupled with more specific expertise in optical clocks through a secondment of INRIM to UDUS.
- Task 5.5: Demonstration of civil engineering applications (lead UoB, secondments from UoB and e2v to JRC) Test series to determine performance of atom interferometer in civil engineering applications at JRC, including characterisation of noise and signal parameters at JRC site.

Physical principle of classical and quantum gravimeters

Classical gravimeters may be divided into spring-mass types and falling mass types. The first consists of a test mass suspended by a carefully made spring whose extension is measured by optical or electronic means. The superconducting gravimeter is a variant in which the mechanical spring is replaced by magnetic levitation of a superconducting sphere. In the falling mass type of gravimeter, the test mass is allowed to fall in a vacuum and its acceleration measured optically.

Tilt, drift, temperature and tidal errors are corrected by software. The difference in signal between two vertically separated gravimeters may be used to measure the gradient, reducing or eliminating errors caused by barometric, tidal, vibrational and seismic effects and making the reading independent of location and height.

In a quantum gravimeter, the test masses are atoms in a high vacuum container, trapped and slowed almost to a halt ("cooled") by laser beams. The atoms are put in a superposition of two momentum states by additional laser pulses, with paths such that one of the states accelerates under gravity for longer than the other, so their final momenta are different. Since, in quantum mechanics, the momentum is proportional to the wave number of the state, comparison of their final wavelengths by interferometry gives a measurement of the gravitational field. The vacuum containment and laser cooling are necessary because otherwise collisions and thermal motion would completely obscure the effect. Although the technique is called cold-atom interferometry, no bulk refrigeration is employed: it is only a relatively small number of trapped atoms which are cooled. The device under development at UoB [Hinton e al., 2017] employs a magneto-optical trap which can hold 10^7 rubidium 87 atoms, and a frequency-doubled telecommunications-wavelength laser operating at 780nm, in the gradiometer configuration.

2 Experiments

Apparatus

Scintrex CG5 and CG6 spring-mass gravimeters (UoB)

Gantries, mounting frames, Leica TP 1200 total station theodolite, 5 ton lead test mass, Venieri S23F back-hoe excavator (JRC)

Fig. 1 CG5 gravimeter mounted vertically above CG6, suspended from gantry over test lane, adjacent to the test mass pit covered by the plywood lid. Theodolite prism is visible on top of the CG5. Yellow tripod of the total station is visible at the back of the hangar.

Fig. 2 Lower two sections of the test mass, each consisting of a double layer of lead bricks on a steel plate with screw holes for handling rings. The upper section, not shown, consists of a single layer.

Method

In the first visit (3rd -7th October 2016), only one instrument was used, a CG5.

The site was inspected and the condition of the separate soil plots was assessed for suitability. Soil samples from the different plots were taken for analysis in Birmingham and JRc provided UoB with soil-chemistry data for the test site, from an analysis made by GGA Institut Hannover [Igel and Preetz, 2005]. Topographic measurements of the site were made using the total station.

The *x-y* scanner instrument was inspected and some simple tests done to see if the gravimeter could be mounted easily and remain sufficiently free of movement. It was found that the vibration was excessive but a stable reading could be obtained by lightly bracing the mounting frame against the ground.

Long measurements were made overnight (>6 hours) with the CG5, for comparison with similar measurements taken in Birmingham and Troyes, France. Further sequences of measurements were made over approximately one hour with the instrument placed first on the *x-y* scanner and then repeated with it placed on the ground, to see if it was possible to detect extra noise in the measurements due to the *x-y* scanner structure. Some disturbances were seen which were apparently from passing trains.

In the second visit, 4th-5th July 2017, lead bricks of the type used for radioactivity shielding were assembled into an approximately 1m square to see if it would be feasible to construct a 5 ton test mass. Based on this, during August an arrangement of 5 layers of bricks on 3 square steel sheets (2 layers-2 layers-1 layer) was assembled (Fig.2). Each plate had threaded holes in the corners into which rings could be screwed for handling. A practice pit was excavated to the side of the test lane and it was confirmed that it was possible to lower the test mass into it by suspending it on slings from the bucket of the excavator. A mounting frame was constructed from 20mm mild steel square section tube, with holes drilled to allow platforms to be set at various heights. It was suspended from one of the gantries so it could be positioned by hand over the required point in the test lane.

In the third visit (28th August – 1st September 2017) the lead mass was positioned in a pit excavated in the test lane a few metres in front of the hangar, lined with plywood shuttering, with a lid. The soil in this position is unmodified natural soil, sandy in texture.

Arrangements had been made to ship the gravimeters in advance, so they could be switched on and stabilise over the weekend. Unfortunately, the shipment was delayed and did not arrive until the first day of the campaign. It had also been hoped originally to have two identical instruments for the gradiometer configuration, but it proved difficult to get them for the date planned, so one CG5 and one more recent model CG6 had to be used.

The gravimeters were mounted on the frame, with the CG5 above the CG6, and measurements made at various points over the centre of test mass. Differential and single-instrument measurements were attempted. The exact relative position was measured with the total station, to precision of a few mm. The measurement spacing was 0.2m (except at the centre where it was 0.1m either side). The vertical distance from the CG6 sensor to the anomaly was 0.36m.

All data stored on the gravimeters was transferred to computer for post-processing. Due to inadequate warm-up following the shipping delay, the CG5 stability was too poor for a good differential measurement. Later data from the CG6 only are shown in Fig. 3 and 4.

During the measurements there were some temperature fluctuations due to changing cloud cover of the sun. Wind was negligible. The sporadic train passage encountered in 2016 was less frequent or absent. No other environmental factors were identified which might contribute to errors.

Results

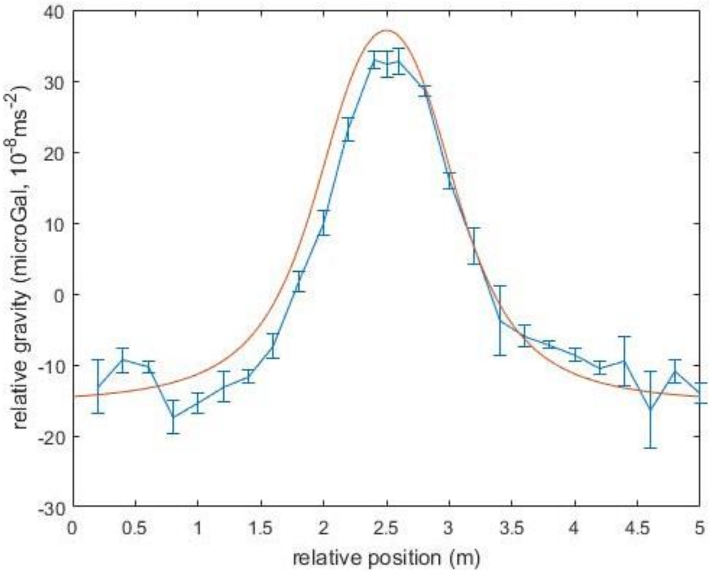

Fig. 3 Signal from CG6 as a function of horizontal displacement.

Experimental data are shown in blue, numerical model data in brown.

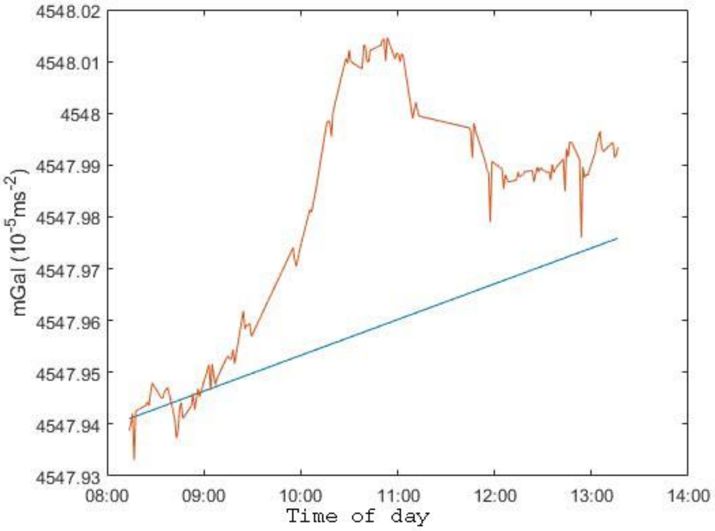

Fig. 4 Total drift over approximately 5 hours.

The straight blue line represents the calculated instrument drift.

The brown curve is the instrument reading

Discussion

The signal size from the 5 ton test mass is around 0.47×10^{-6} ms^{-2} with a signal to noise ratio of the order of 10 (Fig.3). The data are in fairly good agreement with the numerical model, the model overestimating the peak height by only about two standard errors, and the peak width by only about 0.1 m.

Drift of up to over 0.7×10^{-6} ms^{-2} over about 3 hrs was observed, which would be sufficient to mask the signal unless precautions are taken (Fig.4). In practice, it is possible to allow for this by fitting and compensation.

3 Conclusions

The test mass could be detected with the classical gravimeters with sufficiently good signal-to-noise ratio that the set-up can be used with confidence as a test bed for comparing the quantum prototype with the commercial classical instruments.

The mounting arrangement was found largely satisfactory, with vibrations reduced to an acceptable level, although some bracing was still needed. For the quantum instrument, a version of the mounting frame will be needed made from a non-magnetic material e.g. austenitic stainless steel, which would not affect the magneto-optical trap.

Environmental protection note

An inspection was conducted by JRC site directorate after the test to determine if there was a risk of soil contamination from the lead test mass. By covering the area in a tarpaulin, rain water ingress was minimized. It was agreed that the test mass would be removed at the end of the work, before the wooden shuttering could decay. Subject to these precautions, the risk was deemed minimal.

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