Quantum gravimetry going toward real applications

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GRAVIMETRY AND ATOM INTERFEROMETERS

Gravimetry techniques play significant roles in the fields of metrology, geology, and industrial-related applications such as resource exploration and navigation. Classical absolute gravimeters and absolute gravity gradiometers have long been limited by mechanical wear and lower sampling rate, which make them powerless for long-term continuous observations and applications on moving platforms. At the end of the last century, the inception of atom interferometers (AIs) brought a new technical solution. In AIs, laser pulses are employed to manipulate atom groups in a vacuum to achieve splitting, redirection, and recombination. However, different from photons in optical interferometers, atoms have static masses, which make their trajectories to be deflected in a gravitational field. Since different laser phases are picked up in different magnitudes of gravitational field during the interference process, the gravity can be evaluated by measuring the phase of the interferometer fringes. Because there are no macroscopic moving components in AIs, they are well suited for long-term continuous measurements and high sampling rate operations due to the avoidance of thermal and wear effects, which seriously decrease the measurement precision in classical instruments. Additionally, the reference of atom standards (i.e., energy levels and related transitions) gives the instruments the same potential precision and stability as the atom clocks.

ATOM GRAVIMETERS (AGs)

In 1991, M. Kasevich at Stanford University realized the first AI and achieved gravity measurement, which set off an international wave of AI technology research. In the following 30 years of development, AGs have achieved a measurement sensitivity of up to 4.2 μGal/Hz1/2,1 and a resolution of up to 0.05 μGal.2 In 2017, six AGs took part in the 10th International Comparison of Absolute Gravimeters. The results from Huazhong Univ. Sci. Tech., National Institute of Metrology, Innovation Academy for Precision Measurement Science and Technology, CAS (APM), and Zhejiang Univ. Tech. (ZJUT) were accepted by the committee and showed performances competing with classical corner cube gravimeters. In terms of dynamic measurement, the gravimeter GIRAFE from ONERA have realized marine and airborne measurements in 2018 and 2020, respectively. A measurement precision of 0.2–0.6 mGal has been achieved under the condition of 4 sea state. This result is beyond 0.8–2.9 mGal that was achieved by a referenced spring gravimeter. In China, two mobile AGs from APM and ZJUT also completed the first round of lake test in 2021. Up to now, AGs have achieved such a high maturity that

Figure 1. Typical signal sizes of gravity gradient anomaly generated by different gravity sources (Practical signal size varies with the dimensions, densities, and detection distance of the objects.)
many commercial products have appeared on the market, such as those from Muquans, CASColdatom, and Mugaltech.

**ATOM GRAVITY GRADIOMETERS (AGGs)**

Gravity gradiometers are sensitive to short-wave gravity fields and can distinguish the mass distribution in the surrounding environment with higher spatial resolutions. Furthermore, due to the differential measurement mode, gravity gradiometers are highly immune from acceleration noises, which makes them useful in harsh environments. Especially in AGGs, simultaneous AIs are manipulated by a common series of Raman laser pulses, which bring an additional advantage of common-mode rejection for many internal noises. In 1998, Kasevich’s group demonstrated the first measurement of local gravity gradient with dual AIs. In the following years, many AGGs have been developed for measurement of gravitational constant G. In 2007 and 2014, the groups in Stanford and in Florence measured G using AGGs and achieved precision of 4,000 and 150 ppm respectively.

At the same time, research works on practical AGGs have also been carried out. In 2008, Kasevich’s group developed the first transportable AGG with a resolution of about 2 E (1 E ~ 0.1 μGal/m) and performed an outdoor measurement of horizontal gravity gradient. A reciprocating measurement was performed in the range from 4 m inside to 8 m outside the door of the four-story building’s loading bay, and a change of the horizontal gravity gradient of 300 E with a precision of 7 E was observed. In the second generation of this AGG, the baseline was reduced from 70 cm to 20 cm, which led to a volume of the sensor head close to 200 L. However, this reduction of the baseline also decreased the measurement sensitivity by 4–5 times.

**LATEST PROGRESS IN PRACTICAL AGGs**

Several important works were published at the beginning of 2022. Based on studies on environmental adaptability, a group in Birmingham has designed and implemented a highly robust vertical gravity gradiometer with a resolution of 20 E. The core scheme of this AGG is the fabrication of two hourglass configuration AIs, which enables robust coupled differential measurements on two clouds of atoms. In each AI, two pairs of horizontal laser beams for atom trapping are derived from one large-scale vertical propagating beam by right-angle prisms in vacuum, which makes the parameter fluctuations of the four beams completely synchronized. So, the initial position and flight trajectory of the atom cloud have extremely high stability and are immune from the variation of environmental conditions. By this scheme, this AGG could properly work under outdoor conditions of 0℃ – 30℃. To demonstrate its potential for gravity cartography, the group carried out measurements with a spatial resolution of 0.5 m on an 8.5 survey line above a tunnel with an internal cross-section of 2 × 2 m. Consequently, an anomalous signal of gravity gradient of about 170 E was observed with a signal-to-noise ratio of 3. It is of great significance for AGGs to verify the capability in a real application, and the resolution is enough to play important roles in many fields such as archaeology.

In comparison, another work from ixblue has become a good complement with respect to the resolution. The researchers have developed a transportable AGG that reaches the quantum projection noise limit by means of the double-phase-locking and two-state simultaneous detection techniques. Both interference fringes are locked at the mid-fringe phase, where the interferometers are maximally sensitive to the phase variations. The double-phase-locking scheme leads to a much higher sensitivity to gravitational accelerations, as the two-state simultaneous detection significantly rejects the common-mode detection noise caused by the intensity and frequency fluctuations of the detection laser. These techniques lead to an unprecedented resolution up to 0.15 E after an integration time of 110,000 s, and this is the first AGG in the world with a resolution better than 1 E. This resolution corresponds to the gravity gradient anomaly generated by a 1-L cubical void in the ground 37 cm under the instrument, as shown in Figure 1.

In addition to robustness and measurement resolution, the compactness and the measurement accuracy of the absolute value are also two very important technical indices of an AGG. A compact gravity gradiometer can be integrated with an inertial stabilized platform and take vehicles to efficiently map the gravitational field over a wide area. An absolute gravity gradiometer could calibrate gravimeters and accelerometers and measure the vertical deflection during the moving process, which are of great significance in the field of navigation. Researchers in APM have recently reported an absolute AGG with a high degree of compactness. While achieving a sub-E resolution as well, the volume of the sensor head has reached an unprecedented level of 92 L. In comparison with the two AGGs mentioned before, whose heights are 1.87 and 1.75 m respectively, the compactness will bring great convenience in matching with inertial platforms and applying in carriers where space is at a premium. Additionally, comprehensive investigations of the systematic errors of the AGG have been performed, and the error budget table for absolute gravity gradient measurement of AGG is shown for the first time, which enables it to operate as a real absolute gravity gradiometer.

**CHALLENGES TO AGGS IN DYNAMIC MEASUREMENT**

Dynamic high-precision measurement is the ultimate goal of practical AGGs. However, comparing with the signal size of gravity anomaly, that of gravity gradient derived from the same object is relatively small and attenuates drastically as the detection distance increases. To become a useful and competitive dynamic gravity gradiometer, AGGs first have to solve the problem of the scale factor in dynamic conditions. The measurement sensitivity of AIs is proportional to the square of the interrogation time, but longer interrogation time also corresponds to higher susceptibility to environmental noise. In typical dynamic conditions, AIs can only implement an interrogation time of about 20 ms, which decreases the AG’s resolution from μGal (in static conditions) to mGal. Therefore, to achieve a resolution of 10 E in AGGs with the interrogation time as short as 20 ms, a large momentum transfer technique, which could magnify the scale factor by tens of times, should be necessary. The second problem is about phase extraction. In moving platforms, different data points correspond to measurements at different positions. Hence the conventional phase extraction method of ellipse fitting, with which a gravity gradient is evaluated from dozens of data points, will bring large noise due to the forced connection between data points. In contrast, the phase extraction technique based on the shear imaging may be a promising solution, by which the phase can be derived through a single measurement, and the amplitude noise could also be rejected. After solving the preceding two technical problems, the AGGs will have a fantastic prospect in the conditions of dynamic measurement.

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**DECLARATION OF INTERESTS**

The authors declare no competing interests.