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TOPICAL REVIEW — Ultracold atom and its application in precision measurement

Movable precision gravimeters based on cold atom interferometry*

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High precision atom interferometers have shown attractive prospects in laboratory for testing fundamental physics and inertial sensing. Efforts on applying this innovative technology to field applications are also being made intensively. As the manipulation of cold atoms and related matching technologies mature, inertial sensors based on atom interferometry can be adapted to various indoor or mobile platforms. A series of experiments have been conducted and high performance has been achieved. In this paper, we will introduce the principles, the key technologies, and the applications of atom interferometers, and mainly review the recent progress of movable atom gravimeters.

Keywords: atom interferometer, absolute gravimeter, precision measurement

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1. Introduction

The concept of matter wave was first proposed by de Broglie in 1923, which showed that particles have wave–particle duality.[1] Since Davisson and Germer experimentally demonstrated electron diffraction in 1927,[2] interferometry of matter wave has attracted attentions of physicists. Compared with optical interferometers, matter wave interferometers have their own advantages: particles can be electrons, neutrons, atoms or molecules. Because these particles have a rest mass and energy level structures, they can be used to measure external physical fields. Moreover, according to the relationship between the wavelength of the matter wave and the momentum of the particle, the matter wave interferometer has a much shorter wavelength than the optical one, which means that the potential sensitivity of the matter wave interferometer is higher. In the middle of 20th century, the matter wave interferometry based on neutron[3] and electron[4] was demonstrated in experiments. Atom interferometry was also observed by micro structure grating[5] and Yang's double silt experiment.[6,7] Because atoms have large mass and rich internal degrees of freedom, these experiments have great potential. But, due to technical limitations, the further development of these two schemes are limited.

With the development of technology on laser cooling and trapping of neutral atoms, the matter wave source has been extended to employ the cold atoms with a greater mass than Helium atoms, which greatly increased the coherent time. The cold atom interferometer demonstrated in 1991 by Chu *et al.*[8] paved the way for using atom interferometer for precision measurements. This kind of matter wave sensor was based on the two-photon stimulated Raman transition. Except for this technique, another way to manipulate matter wave packet based on Bragg scattering was also proposed and realized later.[9,10] This paper will only focus on movable gravimeters based on the mature Raman-type cold atom interferometry.

High-precision cold atom interferometry has been proven to be a powerful tool in science researches, such as testing of UFF[11–13] and general reality,[14,15] searching for dark energy[16,17] and gravitation wave detection,[18,19] determining the exact value of fine structure constant α[20,21] and the Newtonian gravitational constant G,[22] and measuring the Berry phase[23,24] and short range forces.[25] In addition, atom interferometry has also been demonstrated to be a promising way for inertial sensing. Sorrentino *et al.* built an atom interferometer to measure gravity gradiometer,[26] Xu *et al.* on site calibrated absolute frequency of laser[27] and Xu *et al.* measured tilt.[28] Another representative and successful application of cold atom interferometry is to measure the acceleration of particles. All setups on the ground are subject to the standard gravity so that accelerometers based on atom interferometry are always made to be gravimeters.

There are many groups pursuing researches in cold atom gravimeters. The group in Stanford University is a pioneer in cold atom interferometry. In 1991, they first developed a gravimeter based on sodium atom and obtained a resolution of 3×10^{-6} g within an interrogation time of 1000 s.[8] After some improvements, they achieved a measurement resolution

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of 1×10^{-10} g in 2001.[29] The group in LNE-SYRTE built a six-axis inertial sensor to simultaneously measure the rotation and the gravity.[30] A mobile gravimeter developed by Humboldt University for outdoor measurement has achieved a resolution of 5×10^{-11} g after 27-hours interrogation time in 2013.[31] After applying a series of key technologies in atom interferometry, such as the ultra-low frequency vibration isolation platform,[32] the low phase noise Raman laser[33] and the high signal-to-noise ratio detection, a lab-based ultra-high sensitivity gravimeter was built in 2013 in Huazhong University of Science and Technology (HUST),[34] whose sensitivity was 4.2 μGal/$\sqrt{\text{Hz}}$. Besides, there are many other groups that have made lots of efforts on atom gravimeters. Table 1 lists some reported state-of-the-art Raman-type cold atom gravimeters. In addition, some long baseline atom interferometers with a height of several meters have been built[35,36] or under construction.[37,38]

Table 1. State-of-the-art in gravimeters based on stimulated Raman transition (1 μGal $=10^{-8}$ m/s^2).

Group	T/ms	Sensitivity/(μGal/$\sqrt{\text{Hz}}$)	Uncertainty/μGal	Ref.
SYRTE	80	5.7	4.3	[39,40]
Stanford Uni.	400	8	3.4	[29,41]
Humboldt Uni.	260	9.6	3.2	[31]
Berkeley	130	37	15	[42]
ONERA	48	42	25	[43]
HUST	300	4.2	3.0	[34,44]
WIPM	200	28	9.0	[45,46]
NIM	70	44	5.2	[47]
ZJUT	60	90	19	[48]

Gravimeters have been widely used in the inertial navigation,[39,49] civil engineering,[50] archeology,[51] limiting the rate of uplift of mountain,[52] monitoring earthquake,[53] magmatic activity,[54] and groundwater,[55] resource exploration,[56] as well as other geophysic applications. These applications generally require that the instrument should be used in the field. The overall structure of this paper has five sections, including this introductory section. The second section discusses the principle of measurement based on the stimulated Raman transition. Section 3 introduces promising methods to make the gravimeter movable. Section 4 introduces some outdoor practical applications. The last section is a summary and discussion of the full text.

2. The theory of the atom gravimeter based on stimulated Raman transition

Considering an atom with two ground states $|1\rangle$, $|2\rangle$, and an excited state $|i\rangle$, as shown in Fig. 1(a), where ω_{12} is the energy splitting between the two ground states. The Raman beam is composed of two counter-propagating laser beams whose wave vectors are $\boldsymbol{k_1}$ and $\boldsymbol{k_2}$, respectively. As shown in Fig. 1(b), the atom first absorbs one photon from one laser and obtains a recoil velocity of $\hbar\boldsymbol{k_1}/m$. Then it will emit another photon with the same direction as the second beam and obtain a recoil velocity of $\hbar\boldsymbol{k_2}/m$. After this two-photon transition process, the atom will obtain a recoil velocity of $\hbar\boldsymbol{k}_{\text{eff}}/m$ ($\boldsymbol{k}_{\text{eff}}=\boldsymbol{k}_1-\boldsymbol{k}_2$). Suppose the atoms are initially in state $|1\rangle$, the probability of finding atoms in state $|2\rangle$ can be expressed as

$$|c_2|^2=[1-\cos(\Omega\tau)]/2,$$

where Ω is the Rabi frequency and τ is the duration time of pulse. When $\Omega\tau=\pi/2$, atoms have the equal probability in either ground state, which plays a role like beam splitter in optical interferometer. When $\Omega\tau=\pi$, atoms will be entirely transferred to state $|2\rangle$ and acts as a mirror. Given this situation, these two laser pulses are called $\pi/2$ pulse and π pulse.

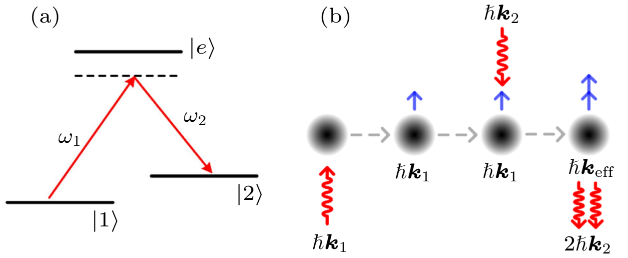

Fig. 1. (a) Stimulated Raman transition in three-level system and (b) momentum transfer in stimulated Raman transition.

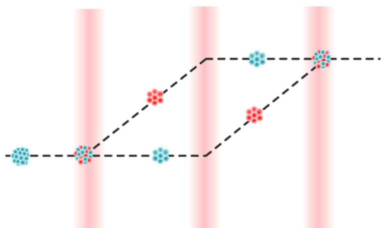

Fig. 2. Structure of Mach–Zender-type atom interferometry.

The structure of a typical Mach–Zender interferometer is shown in Fig. 2. Three Raman pulses $\pi/2-\pi-\pi/2$ are used to split, redirect and recombine mater wave and the whole process is similar to optical interferometers. The detailed calculation of phase shift can be found in Refs. [57,58]. The phase difference $\Delta\Phi$ accumulated by the two interference arms can be divided into two parts. One part is the free evolution phase $\Delta\Phi_{\text{FE}}$, which can be determined by Feynman's path integral approach and generally equals 0 for a closed path. The other part $\Delta\Phi_{\text{laser}}$ results from the laser-atom interaction. In order to keep atom resonant with the laser beams, an extra linearly sweep of laser frequency should be added to compensate for the gravity acceleration, so that the total phase shift becomes

$$\Delta\Phi=\boldsymbol{k}_{\text{eff}}gT^2-\alpha T^2,$$

where $\boldsymbol{k}_{\text{eff}}$ is the effective wave vector of Raman pulse, T is the time interval between two adjacent Raman pulses and α is frequency chirp rate. The sensitivity of an atom gravimeter is proportional to T^2, which means one way to improve the sensitivity is to increase the interrogation time T. When two terms on the right of the above equation are completely cancelled, we can obtain

$$g = \alpha_0 / \boldsymbol{k}_{\text{eff}}.$$

In experiments, frequency can be measured accurately and thus acceleration of gravity can be determined with high accuracy.

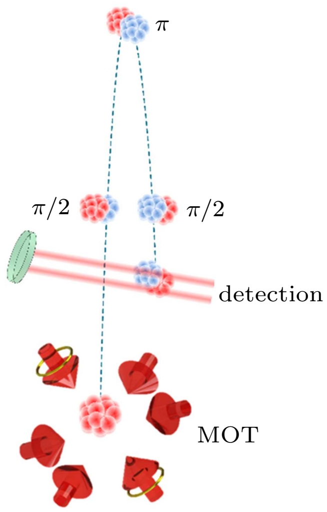

Fig. 3. Typical process of atom interferometer with parabolic trajectory.

The typical measuring process of atom gravimeters is shown in Fig. 3. Firstly, atoms are trapped in magneto–optical trap (MOT). Next, the atomic cloud is launched vertically by slightly detuned the frequency difference between upper and lower beams. Sometimes, the atomic cloud will also be released directly from the MOT and begin to fall freely. At the same time, the polarization-gradient cooling is applied so that the temperature of cloud is further reduced down to several μK. To prevent systematic errors caused by extra electric or magnetic fields, the atoms in magnetically insensitive state are selected. Then a set of $\pi/2$–π–$\pi/2$ Raman pules are applied to split, reflect, and recombine the atomic wave packet. Finally, the atoms are detected by a probe beam when they reach detection area, and the fluorescence signals of different atomic states are collected to get the gravity value.

3. Advanced technologies that enable the application of atom gravimeters from the laboratory to the field

In the laboratory, atom gravimeters have proven to perform well, and their accuracy and resolution can compete with classic ones. However, these high performance instruments still remain in lab where environmental factors can be well controlled. The field applications require that the atom gravimeters not only have high stability and reliability, but also have small size, compact structure, easy operation and low power consumption. To meet these requirements, some advanced techniques and reasonable structural changes were proposed by groups or companies.

3.1. Compact magneto–optical trap (MOT)

3.1.1. Single laser beam MOT

In 1996, Lee and his coworkers put forward a novel hollow pyramidal and conical trap with an apex angle of 90°, which trapped atoms by using only a single laser beam.[59] When a laser beam with circular polarization incident on a pyramidal mirror, the beams propagating along the axis of the MOT coils had same handness while beams propagating perpendicular to the axis are opposite. This geometry fully met the requirements of atom trapping and subsequent atom interferometry. The group in Imperial College London integrated an array of hollow pyramids with an apex angle of 70.5° on a silicon wafer and a PEEK holder, respectively.[60,61]

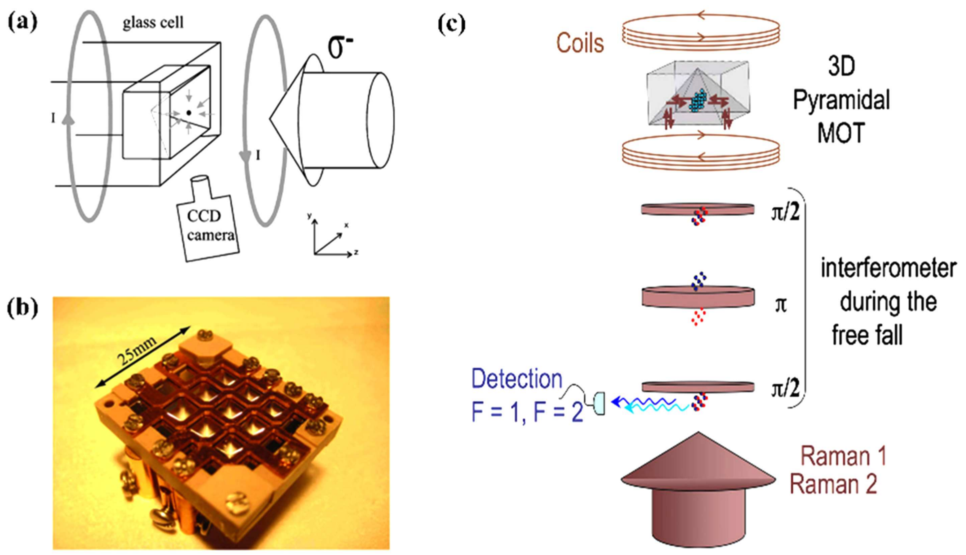

Fig. 4. (a) Polarization configurations in a hollow pyramidal MOT. (b) MOT array in Imperial College London. (c) Experiment setup of pyramidal atom gravimeter using single laser beam in LNE-SYRTE. Panel (a) reprinted with permission from Ref. [59] of the Optical Society. Panel (b) reprinted with permission from Ref. [60] of the Optical Society. Panel (c) reprinted from Ref. [61], with the permission of AIP Publishing.

In 2011, the group in LNE-SYRTE realized an atom gravimeter based on hollow pyramidal trap.[62] The experimental setup is shown in Fig. 4(c). They used only one laser beam to realize atom trapping, state selection, atom interferometry and atomic state detection, which greatly simplified the structure of atom gravimeter and thus reduced the device volume. Inspired by this innovative structure, some groups also used this hollow pyramidal trap to construct their mobile atom gravimeters.[42,50,63]

3.1.2. Atom chip

The atom chip has already been proved to be a micro structure that can capture atoms, and its characteristics make it widely used in various fields. Atom chip integrates tiny copper wires, and it can generate a sufficiently large magnetic gradient even if the power consumption is very small. Atom chip always acts as a mirror-MOT (Fig. 5(a)) which uses four laser beams instead of the six beams in the traditional MOT. In this structure, tens of millions of atoms are trapped nearby the mirror.[64,65] Although the atom chip is small enough, the spatial structure of the four laser beams is not compact. Researchers proposed a 'flat' pyramid structure (Fig. 5(b)) based on diffraction grating, which proved to have the equivalent ability of conventional MOT to trap up to about 10^8 atoms.[66,67]

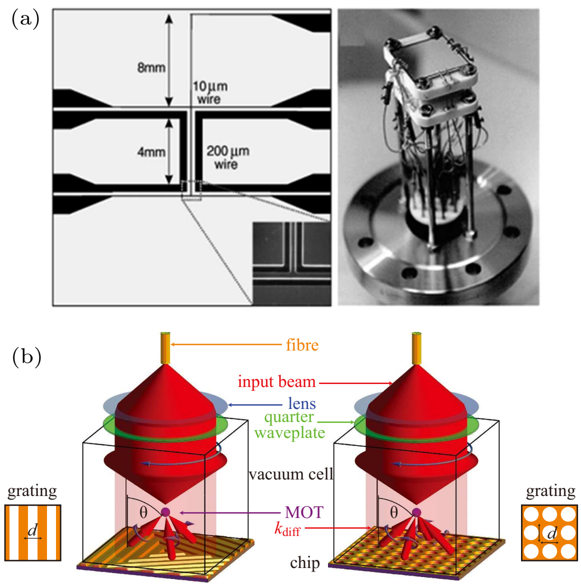

Fig. 5. Atom chips reported by (a) University of Innsbruck and (b) University of Strathclyde. Panel (a) reprinted with permission from Ref. [65] Copyright (2000) by the American Physical Society. Panel (b) reprinted by permission from Ref. [67] Copyright (2013) by the Springer Nature.

3.2. Integrated optical system

Optical system is another vital subsystem in atom interferometer, which provides laser beams with appropriate frequency and power. This subsystem in lab always occupies large space and is not easy to move. The most direct way to miniaturize an optical system is to replace the bulky and heavy optical mounts with miniaturized one.[68] However, the free-space system is sensitive to external environment such as the vibration noise and the temperature fluctuation. By contrast, fiber optics based on the C-band and second harmonic generation of mature telecom is an alternative method to obtain a stable and compact optical system.[69,70] This system usually needs only one seed laser and few fiber components, which greatly simplifies the system and is insensitive to misalignment.

A typical fiber system is shown in Fig. 6. The output of a 1560-nm seed laser is divided into two parts. One part is used to lock the frequency of the seed laser, and the other part passes through a phase modulator (PM) to generate the second laser with a different frequency. The two laser beams are amplified by a erbium-doped fiber amplifier (EDFA) and then their frequencies are doubled by a periodically poled lithium niobate crystal-wave guide (PPLN-WG). The microwave source driving the PM can be changed in different steps, and all the required frequencies can be achieved. In addition, an all-fiber system based on 780-nm seed laser was also demonstrated by Fang *et al.*[71]

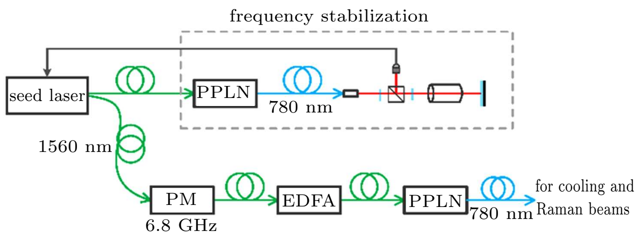

Fig. 6. Fiber optical system using single laser source based on telecom C-band.

3.3. Simplified vibration rejection method

The acceleration measured by the atom gravimeter is the acceleration between atom cloud and reference Raman mirror, which consists of two parts: the gravity acceleration and the vibration of the Raman mirror. These two parts cannot be distinguished experimentally according to the Equivalence principle. To reduce the influence from vibration, researchers usually placed Raman mirror on an isolation platform.[29,72–74] But this method needs complicated vibration isolator, which is not convenient to transport in practical applications. An alternative way is using mechanical sensors to record vibration data and then compensate this extra vibration phase by combining the corresponding transfer function. The seismometer,[75] the force balance accelerometer[76–78] and the opto-mechanical resonator[79] could be ideal candidates for mechanical sensors. All of these sensors have shown good performance in either improving short-term sensitivity or reconstructing the fringes, which are washed out by harsh vibration noise.

4. Status of movable atom gravimeters dedicated to various tasks

4.1. Participate in gravity comparison

The accuracy is a core indicator to assess the performance of an absolute measurement instrument. Some private[29,80] and international comparisons were held between absolute gravimeters to find possible systematic errors. International comparison of absolute gravimeters (ICAG) is an official and international comparison, which is held every four years from 1981 and, till now, 10 sessions have been successfully held. In 2009, a transportable atomic absolute gravimeter developed by SYRTE participated in ICAG.[81] This is the first time that an absolute gravimeter employs atomic ensemble as test mass rather than the macroscopic corner-cube only. In 2017, six atom gravimeters participated in the 10th-ICAG held in Beijing and exhibited well.[82] The uncertainty of the best atom gravimeter was 3 μGal, which was developed by HUST.[44] The gravity measured by two kinds of gravimeters showed a good agreement with each other, which directly demonstrated that atom gravimeter have the same outstanding performance in gravity measurement as commercial gravimeters, which laid a solid foundation for atom gravimeters to give full play in future field application.

4.2. Resource exploration and geophysics

Resource exploration and other field constructions also need to measure gravity in a large area while traditional measurement requires lots of manpower and time. A movable and reliable absolute gravimeter can meet this requirement without regular calibration. The movable absolute atom gravimeter developed by HUST achieved a sensitivity of 53 $\mu\text{Gal}/\sqrt{\text{Hz}}$ and its resolution can reach 1 μGal in an interrogation time of 3000 s. This atom gravimeter can be used for resource exploration.[70] Besides, a more compact atom gravimeter is under construction for field application. The researchers in UC Berkeley have developed an atom gravimeter which can be transported by a vehicle site to site.[42] In the laboratory, the sensitivity of this gravimeter could reach 37 $\mu\text{Gal}/\sqrt{\text{Hz}}$ and the stability was better than 2 μGal when $T = 130$ ms. To demonstrate field application capabilities, they measured gravity at six locations in Berkeley Hills with a span of 7.6 km and an elevation change of nearly 400 m (see Fig. 7). Using the measured data, the average density of the hills was calculated to be 2.0(2) g/cm^3, which was in good agreement with the data collected in 1998. Besides, Lin's group also integrated their compact atom gravimeter on a truck and measured gravity on both a flat road and a slope road.[83]

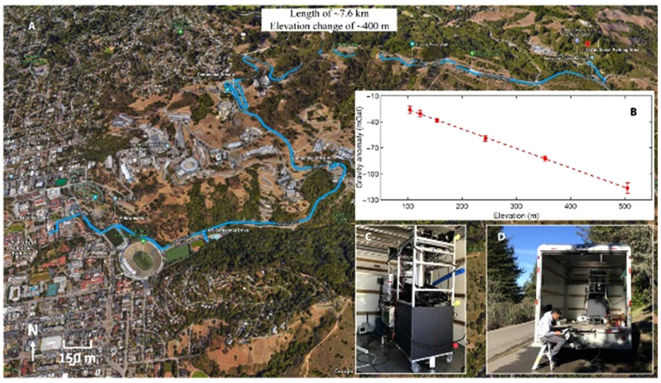

Fig. 7. (A) Measurement route, (B) gravity anomaly as a function of the elevation. (C) Atomic gravimeter inside a vehicle. (D) The atomic gravimeter apparatus. Reprinted by permission from Ref. [42]. Copyright (2019) by the AAAS. (© The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC) http://creativecommons.org/licenses/by-nc/4.0/).

4.3. Ocean and airborne gravimetry

The ocean occupies 70% of the Earth's area. A more detailed understanding of the structure of the ocean's gravity field can help to accurately study the shape and internal structure of the Earth. Surface ship based marine gravimetry is one of the high precision methods in marine gravity survey. Bidel and his coworkers introduced an absolute marine gravimeter which has been successfully implemented in real sea condition.[76] As shown in Fig. 8, the whole gravimeter was placed on a gyro-stabilized platform on ship to ensure the sensitive axis remained vertical at all times. To test their gravimeter, three different strategies were applied. Firstly, they measured the gravity along a known calibration profile, the reproducibility was < 0.5 mGal and the difference of mean value between the test data and known data was < 0.6 mGal. Last two measurements were measuring regional gravity along a grid or circles and inverting the local gravity model. The result not only showed that this atom gravimeter for marine gravimetry can derive a more accurate gravity model than satellites, but also demonstrated that the satellites altimetry may have an offset. For comparison, a relative gravimeter was placed next to atom gravimeter in first measurement and the result showed that atom gravimeter had a better performance in terms of repeatability and stability.

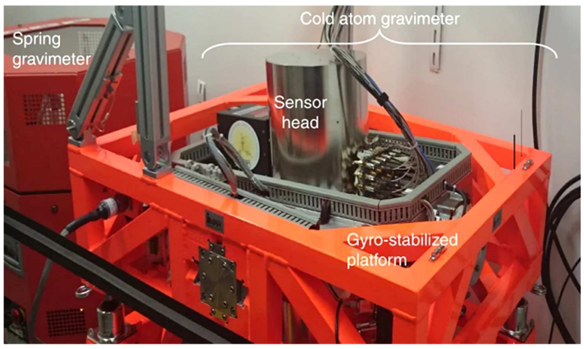

Fig. 8. Picture of cold atom gravimeter installed on a gyro-stabilized platform next to a spring gravimeter. Reprinted by permission from Ref. [76]. Copyright (2018) by the Springer Nature.

After this successful application, Bidel and his coworkers used the gravimeter to achieve a quantum absolute airborne gravimetry in Iceland with a spatial resolution of 10.5 km,[84] as shown in Fig. 9. The research strategy was the same as the one on ship. In the first step, they measured gravity back and forth along a straight line between two locations, which showed that repeatability of gravimeter was better than 3.9 mGal. In the second step, they also measured the gravity disturbance in another area where ground gravity data can be obtained. Compared with the results of the two models, the standard deviations and the mean differences were smaller than 6.2 mGal and −1.9 mGal, respectively.

Another atom interferometry experiment based on plane is the ICE project,[85] which dedicates to test the universality of free-fall (UFF) in microgravity environment. This project plans to simultaneously perform two atom interferometers based on ^{87}Rb and ^{39}K to test the UFF at 10^{-11} level by plane and 10^{-15} for space mission in future. In 2009, they obtained the Ramsey fringes based on ^{87}Rb with an interrogation time of 75 ms, which was much longer than $T = 20$ ms under standard gravity using same setup.[86] Two years later, they conducted an atom interferometry with MZ configuration on plane.[87] In this experiment, the interferometry was performed using only ^{87}Rb atoms with a temperature of 10 μK. A sensitivity level of 2×10^{-4} $(\mathrm{m/s^2})/\sqrt{\mathrm{Hz}}$ was achieved in 0 g, which was 300 times weaker than the vibration of plane. An improved sensitivity of 3.4×10^{-5} g/shot was obtained during 0 g flight in 2016,[88] and the interferometry fringe recorded was shown in Fig. 10.

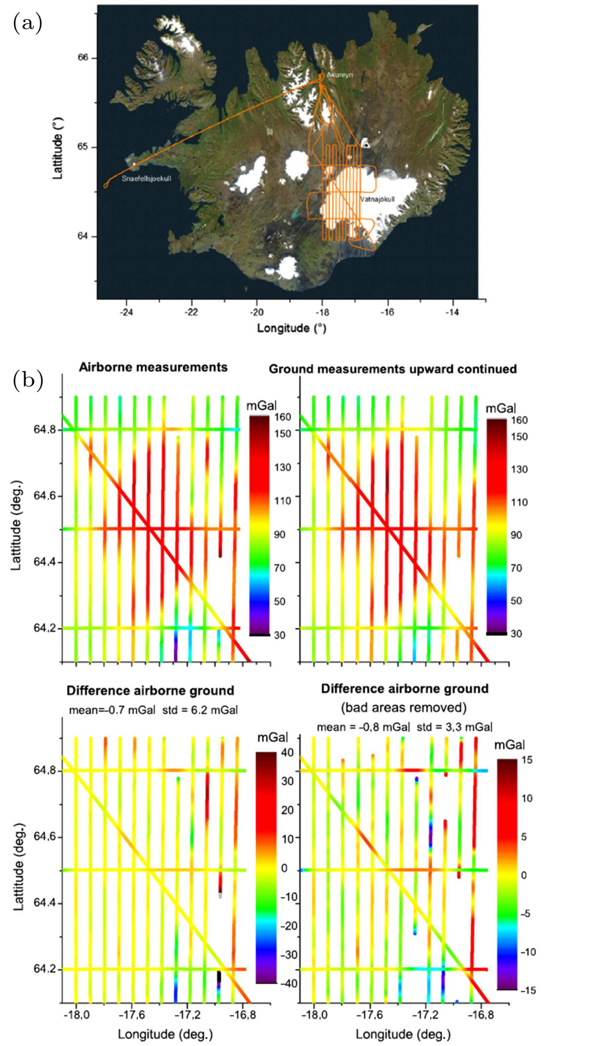

Fig. 9. (a) Flight plan of Iceland gravity campaign. (b) Comparison between airborne measurements and ground measurements upward continued. Reprinted by permission from Ref. [84]. Copyright (2020) by the Springer Nature.

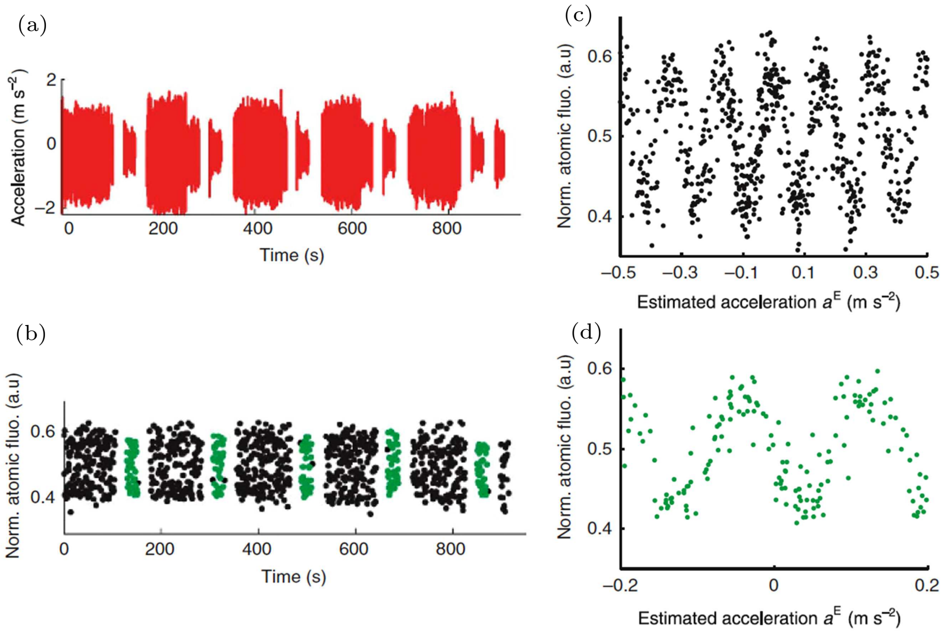

Fig. 10. (a) Acceleration signal recorded by the MAs. (b) AI discrete measurements. Corresponding to the atomic fluorescence of the ^{87}Rb atoms in the $F = 2$ state, normalized to the fluorescence of all the atoms. (c) and (d) Atomic measurements plotted *versus* the signal stemming from the MAs at 1 g (c) and 0 g (d). Reprinted by permission from Ref. [87]. Copyright (2011) by the Springer Nature.

4.4. Space programs

Experiments in space exhibit abundant physical phenomena, which attract more and more researchers' attention. In recent years, a lot of cold atom experiments,[89,90] especially the space projects based on cold atom interferometry[91–95] are proposed. Recently, the BEC (Bose–Einstein condensation) was observed in the international space station,[96] which offered a reliable platform in space. It is foreseeable that the performance of the atomic interferometer will be greatly improved.

As we all know, the cost of a launch mission is high. To meet the requirement, the Center of Applied Space Technology and Microgravity (ZARM) in the University of Bremen constructed a drop tower, which can provide a weightlessness environment for various space experiments. An outstanding performance of this tower is a relative low residual acceleration below 10^{-6} g, which is much less than 0-g platforms. The total height is 141 m and the maximum free-fall time allowed is 9.4 s.[97] In 2007, a joint team based on the project QUANTUS successfully realized BEC in microgravity in ZARM.[98] Seven years later, they demonstrated atom interferometry with an improved BEC source, whose temperature drops to 1 nK, thus obtaining a longer expansion time.[99] In the interferometry, an asymmetric Mach–Zender interferometer was applied. Even if the total time was larger to 0.5 s, the contrast was obtained to be greater than 40% (see Fig. 11).

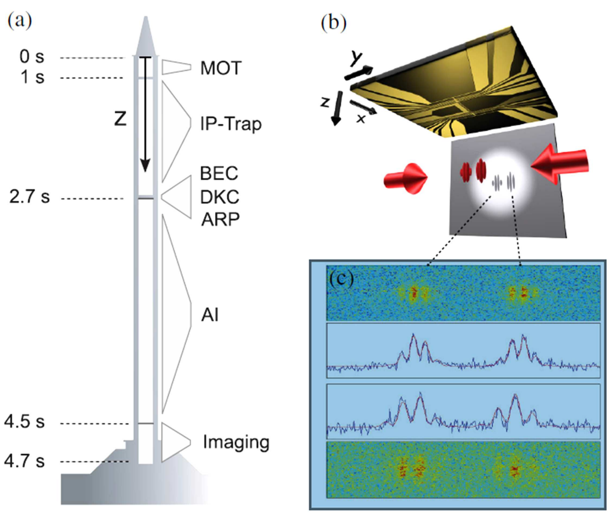

Fig. 11. Mach–Zehnder interferometry of a BEC in microgravity as realized in the ZARM drop tower in Bremen (a), where absorption imaging (b) brings out the interference fringes (c). Reprinted with permission from Ref. [99]. Copyright (2013) by the American Physical Society.

The cold atom platform, which is compatible with sounding rockets, is another good choice. It extends the time for free evolution to about 6 minutes. In addition, the entire process of sounding rocket can simulate the environment like the one on the satellite as realistically as possible, which will lay a firm foundation for future space projects. Some groundbreaking experiments on atomic optics have been carried out on rockets.[100,101] Both of them demonstrated the validity of the autonomous frequency stabilization on rocket, which is not easy to accomplish under the condition where peak acceleration is up to 12.1 g and vibration is 8.1 g_{rms}. On 23 January 2017, the mission MAIUS-1 was launched and a series of experiments were accomplished.[102] They studied the phase transition from thermal ensemble to a BEC and applied 110 experiments to atom interferometry. Although there are few public reports on atom interferometry, this is the first time that a sounding rocket has been used to demonstrate atom interferometry in microgravity.

5. Discussion

In the past 30 years or so, atom interferometry has made breakthroughs, and accelerometers based on this potential technique had also led innovations in this field. Although some prototypes have been developed and some tests have been implemented, many challenges still need to be solved to further improve the instrument performance in real-world application. First of all, the movable gravimeters mentioned in Section 4 are all confirmatory experimental instruments rather than commercial ones. Though commercial products have been developed by some companies,[103,104] wide applications and high technology maturity instruments are still urgently needed. Next, one of the biggest advantages of quantum sensors is that there are no moving parts in the sensor head, but mechanical parts are still likely to move under harsh vibration conditions, which may induce serious systematic errors. Last but not least, in some mobile platform-based applications, the gyro stabilization platform plays a vital role in ensuring that the sensitive axis of the quantum sensor remains vertical. In order to pursue higher accuracy, a high-performance gyro stabilization platform is essential.

As for further improvements, people can use other common techniques to improve the performance. The Bragg interferometer [105,106] manipulates atom's momentum states that are not sensitive to external electromagnetic field. It can transfer more momentums and is more sensitive to acceleration. Moreover, a cavity-based atom interferometer holding atoms up to 20 s was demonstrated recently,[107] which showed potential applications for high-precision measurement within a limited length. If it is possible to combine the atomic chip and the cavity, then the "on hand" accelerometer may become a reality.

Acknowledgment

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