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RESEARCH ARTICLE

Development of an atom gravimeter and status of the 10-meter atom interferometer for precision gravity measurement

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Abstract Experimental realizations of cold ^{85}Rb atom interferometers in Wuhan are reviewed in this paper. The application of atom interferometers in local gravity measurement are reported. The resolutions of gravity measurement are 2.0×10^{-7}g for 1 s and 4.5×10^{-9}g for 1,888 s. The absolute g value was derived with a difference of 1.6×10^{-7}g compared to the gravity reference value. The tidal phenomenon was observed by continuously monitoring the local gravity over 123 h. A 10-meter atom interferometer designed for precision gravity measurement and the equivalence principle test is under construction, the latest status is reported for the first time.

Keywords Cold atom · Atom gravimeter · Precision measurement

1 Introduction

Gravitational waves (GW) should be generated either by the collision of giant mass objects (especially black holes), Big Bang, or by unknown components in the dark matter.

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Due to no observable electromagnetic radiations, these areas can only be observed through their gravitational wave radiation. Thus, observations of GW can bring us new information about the universe. In order to detect GW, United States of America, Europe, and Australia have launched a series of projects on large-scale gravitational wave detection facilities. Current large scientific facilities on GW are ground-based laser interferometers, such as LIGO [1], VIRGO [2] and AIGO [3]. A large space-based laser interferometer gravitational wave detector LISA [4] was also planned. Europe is planning a new generation of underground gravitational wave detector named ET [5]. On the other hand, it is possible to use matter wave interferometers to detect GW. Atom interferometer detectors are expected to exceed the sensitivity of laser interferometers in gravitational wave detection for certain frequency bands. Since Chu and Kasevich first demonstrated light pulse atom interferometry [6] for gravity measurement in 1991, atom interferometry has become a powerful tool for precision measurement in many fields [7–9]. Recently, due to the rapid development of new techniques and methods of atom interferometry, experimental schemes based on atom interferometry have been proposed to further test Equivalence Principle (EP) [10] and to detect GW [11–17]. The possibility of using atom interferometers to detect GW was investigated by Tino [11], the translational invariance of gravitational wave atom interferometers was evaluated by Yu [12], a new tool for gravitational wave detection by applying atom interferometry techniques to the rotational-vibrational states of molecules was shown by Wicht et al. [13], Dimopoulos et al. proposed a terrestrial and a satellite based atom interferometer gravitational wave detectors, which utilizing the core technology of the Stanford 10-meter atom interferometer presently under construction [14,15]. Relativistic models for detecting GW with atom interferometers are presented by Delva and Rasel [16], an orientational atom interferometer based on highly charged hydrogen-like atoms for GW detection was proposed by Lorek et al. [17].

On the way to GW detection with atom interferometers, we have recently demonstrated realization of cold atom interferometers, successfully measured the local gravity using a compact atom interferometer. Meanwhile, we designed a 10-meter fountain type atom interferometer for precise measurements of gravity, EP test, and gravitational wave detection. In this paper we summarize our works including the laboratory prototype of a laser-cooled ^{85}Rb atom interferometer [18,19], investigation of magnetic field dependence of coherent population transfer [20], precision measurements of quadratic Zeeman shift [21,22], and local gravity measurement using atom interferometer [23]. The design and the latest progress of the 10-meter atom interferometer are reported for the first time.

2 Measurement of local gravity by an atom gravimeter

In the gravity field, the path of atom interferometer is deformed due to the free falling of atoms, and that introduces a phase shift, the value of gravitational acceleration can be determined by gravitational phase shift. Both the Mach–Zehnder (M-Z) type atom interferometer and the Ramsey-Bordè type atom interferometer can be used as gravimeter.

Fig. 1 The vacuum system of the atom gravimeter for gravity measurement

We started cold atom interferometry experiment with ^{85}Rb atoms in 2003, and observed interference fringe in 2005. The first atom interferometer was in a horizontal configuration [18–22]. A stainless steel chamber with fourteen windows was used for magneto-optical trap (MOT), and a longer chamber combined with stainless steel cubes and nipples was used for the interference area. The whole experimental apparatus is mounted on a vibration isolated optical table (Newport RS-4000 floating on I-2000 legs) to reduce high frequency vibration. The detail information of experimental setup is described in Ref. [18,19].

For gravity measurement purpose, we rearranged the experimental setup from a horizontal configuration to a vertical one as shown in Fig. 1. The new setup is actually an atom fountain. The propagation direction of Raman beams and atom cloud are parallel to the direction of gravity. Three pairs of cooling and trapping laser beams also act as launching beams for atom fountain. The Raman beams enter the vacuum chamber from the top window and are retro-reflected by a mirror located under the bottom window.

Atoms were cooled and trapped in the MOT within 900 ms, the number of cold atoms is about 1×10^8. 10 ms later, these atoms were launched upward to form a fountain. Moving molasses techniques was used during launch phase. Atoms were launched to a height of 410 mm at a velocity of 2.8 m/s. Time of flight (TOF) signal was used to measure the temperature of the atom cloud, and the average temperature of atoms at launch point was 30μK. During the time of atom free falling in interference region, the blow away beam, Raman beams, and probe beam were applied successively. Laser induced fluorescence was recorded by a photon detector.

M-Z atom interferometer was realized by applying $\pi/2$, π, $\pi/2$ Doppler insensitive Raman beams (Fig. 2) to atoms. An electro-optical modulator (EOM) was used to

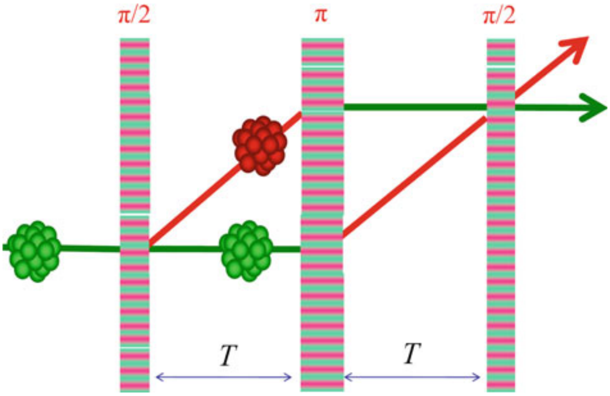

Fig. 2 A Mach-Zehnder interferometer configuration. Doppler insensitive Raman beams $\pi/2$, π, $\pi/2$ was applied to atoms; the freely propagating time of atoms between Raman beams is 150 ms

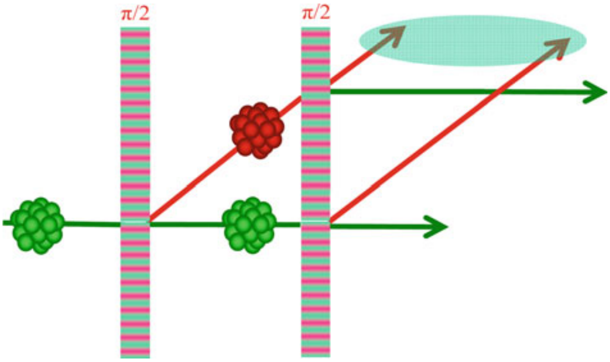

Fig. 3 A Ramsey-Bordè interferometer configuration. Doppler insensitive Raman beams $\pi/2$, $\pi/2$ was applied to atoms

change the phase difference of the second $\pi/2$ Raman beams. We changed the phase shift of the Raman beams by adjusting the voltage applied to the EOM. Dependence of population of state $F = 3$ on voltage was showed as M-Z interference fringes.

Ramsey-Bordè atom interferometer was formed by applying $\pi/2, \pi/2$ Doppler insensitive Raman beams to atoms (Fig. 3). Atoms in state $F = 2, m_F = 0$ were driven by the first $\pi/2$ Raman beams, and the second $\pi/2$ Raman beams interacted with atoms after free propagation. Dependence of population of state $F = 3$ on frequency detuning between two Raman beams revealed a typical Ramsey interference fringes.

To extract the information of local gravity, we need to scan the frequency difference between the last $\pi/2$ Raman beams. Define the frequency detuning amount per second as chirp rate, α, for a cycle fringe with 4π phase shift, we recorded 40 data with different chirp. The chirp rate, corresponding to phase difference between Raman beams, was changed by controlling the signal generator 33250A. Series of M-Z interference fringes under different free evolution time T (from 60 ms to 160 ms) were obtained. A typical M-Z interference fringes is shown in Fig. 4, the resolution for gravitational acceleration measurement is 6.4×10^{-9} g at the integration time of 944 s. We evaluated the

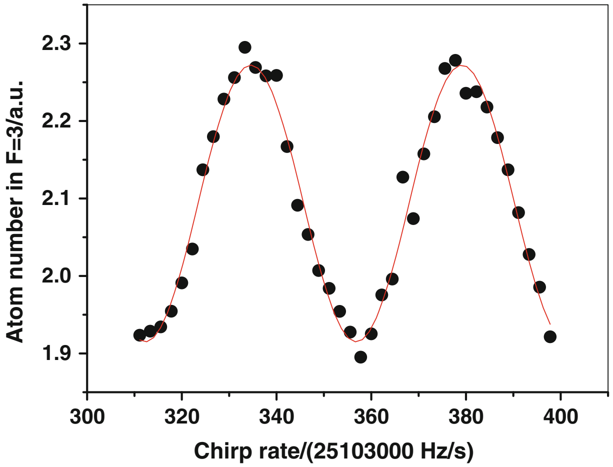

Fig. 4 A typical M-Z interference fringes at the integration time of 944 s, the resolution for gravitational acceleration measurement is 6.4×10^{-9} g

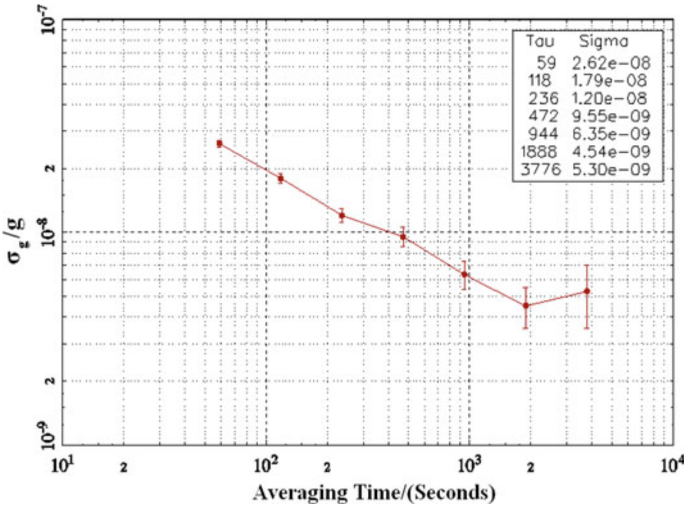

Fig. 5 Stability evaluation of gravity measurement

measurement stability from above data, as shown in Fig. 5, the short term stability is 2.0×10^{-7} g/Hz$^{1/2}$, and the typical stability is 4.5×10^{-9} g for an integration time of 1888 s.

The gravitational phase shift of interference fringes exactly compensates the phase shift of Raman beams if the chirp rate equals to the Doppler shift due to the gravity. M-Z fringes for $T = 80, 90, 100$ ms are shown in Fig. 6, and typical M-Z fringes for $T = 2, 3, 4$ ms are shown in Ref. [23]. Since the total phase shift $\Delta\Phi$ depends on the chirp rate, α, the effective wave vector of Raman laser, k_{eff}, and the absolute gravitational acceleration, g, the absolute value of g can be obtained by setting the total phase shift $\Delta\Phi$ to zero [24],

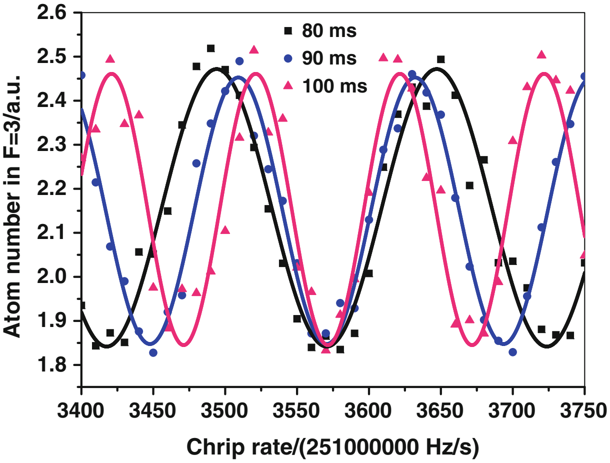

Fig. 6 M-Z type atom interference fringes for $T = 80$ms (black square), 90 ms (*blue dot*), and 100 ms (*red triangle*)

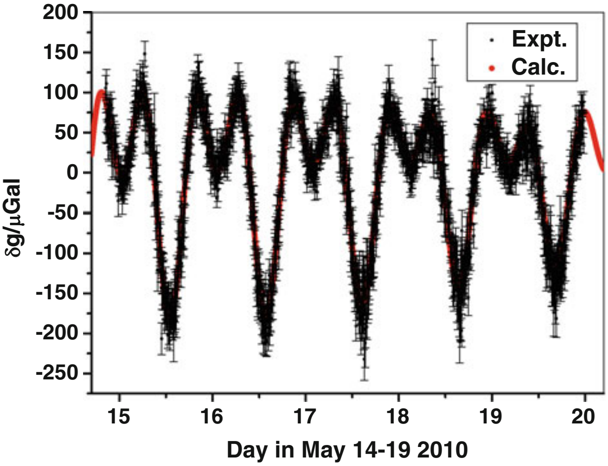

Fig. 7 Measurement of the variation of local gravity by atom interferometer in May of 2010, and the periodical fluctuation of g due to the solid tidal effect. *Black dots line* with *error bars* are experimental data and *red line* is theoretical calculation results

$$\Delta\Phi = \mathbf{k}_{eff} \cdot \mathbf{g}T^2 - \alpha T^2 = 0 \tag{1}$$

In our experiments, the wavelength of Raman laser is 780 nm, and the effective wave vector $k_{eff} = 1.61056930 \times 10^7$ rad/m. Series of fringes for different T (from 60 to 150 ms) were used to measure the absolute gravity, and the chirp rate determined from the experimental data is $\alpha = 25.103$ MHz/s. According to Eq. (1), the absolute value of local gravitational acceleration is $g = 9.7935 \pm 0.0001$ m/s^2.

The uncertainty is mainly caused by systematic errors, such as the dependence of Raman transition on magnetic field, and the quadratic Zeeman shift. The total

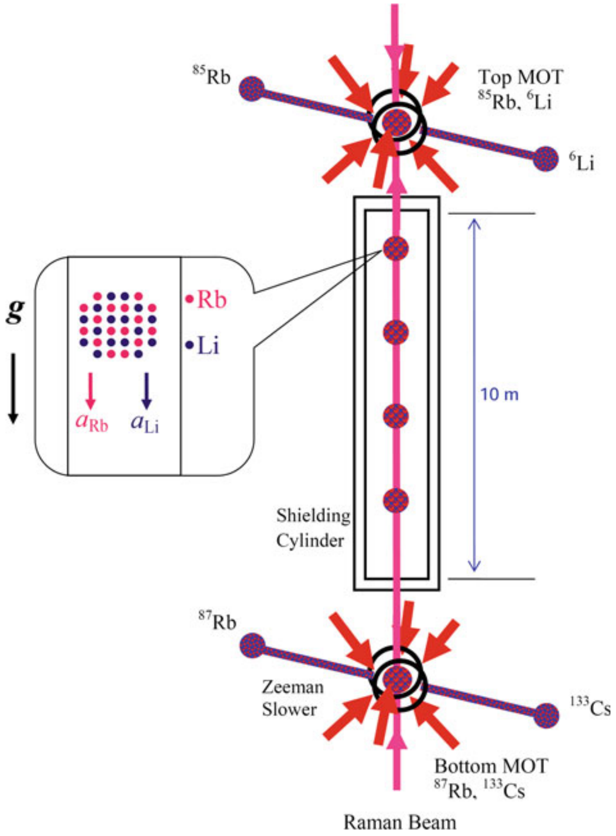

Fig. 8 The experimental schematic of 10-meter fountain type atom interferometer. The effective height of free falling chamber is 10 m, Rb, Cs, and Li atoms will be adopted in this interferometer

systematic errors mentioned above are less than 10^{-7} g. Comparison measurement of the absolute gravity was carried out via a commercial gravimeter (Scintrex CG-5) between the site of our laboratory and a reference point in Wuhan Institute of Seismology, the difference of measurement value between the atom gravimeter and CG-5 is $\Delta g = 1.6 \times 10^{-7}$g.

Due to the tidal effects, the absolute value of gravitational acceleration of a certain site on the earth will fluctuate over time. Atom interferometers can be used to monitor this kind of solid tidal phenomenon by continuously measuring the gravity. We demonstrated a 5-days' measurement of the variation of local gravity by atom interferometer in May of 2010, and observed the periodical fluctuation of g due to the solid tidal effect. The continuous measurement data of 123 h with error bars are shown in Fig. 7, same results without error bars are shown in Ref. [23]. The experimental data agree well with the prediction of the theoretical model, which indicates that the atom gravimeter works well. The difference between the experimental data and the calculation results are plotted, and the uncertainty is less than 10 μGal in the midnights, while in the later morning and early afternoon the uncertainty is around

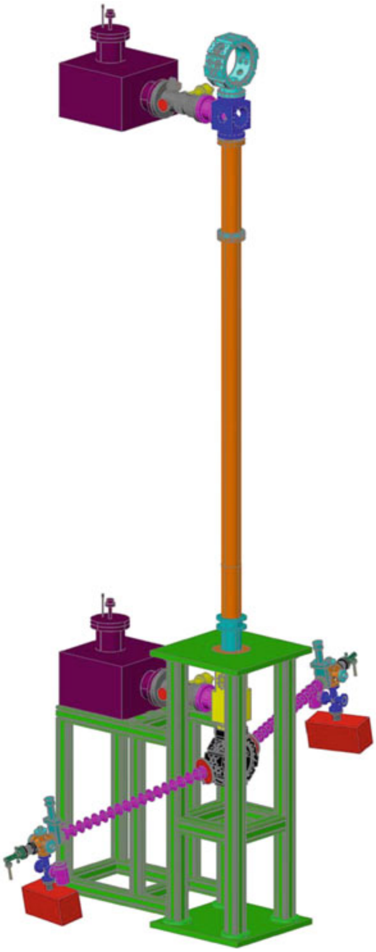

Fig. 9 The design renderings of vacuum system. Ion pumps, aluminum mounting framework, Zeeman slower for bottom MOT, and fountain tube are shown in *different colors*

30 μGal. That means the major error source is the random noise due to the human activities near the laboratory.

3 Design and installation of the 10-meter atom interferometer

The main parameters, which limit the measurement accuracy of atom interferometers, include the velocity (corresponding to the temperature) of atoms, υ; the effective laser wave vector, k_{eff}; the free flight time (the time interval between Raman pulses) T. These experimental parameters can be precisely controlled. Usually, the maximum duration of T is around 100–150 ms for a typical 1-meter-high fountain type atom interferometer. Although, the present 100–150 ms limit is not due to the chamber length, but the shorter chamber will be a limitation for the future experiments. Suppose the effective height of fountain chamber is 10 m, then the maximum free falling

Fig. 10 The fountain tube and magnetic shielding cylinder are mounted between two MOTs

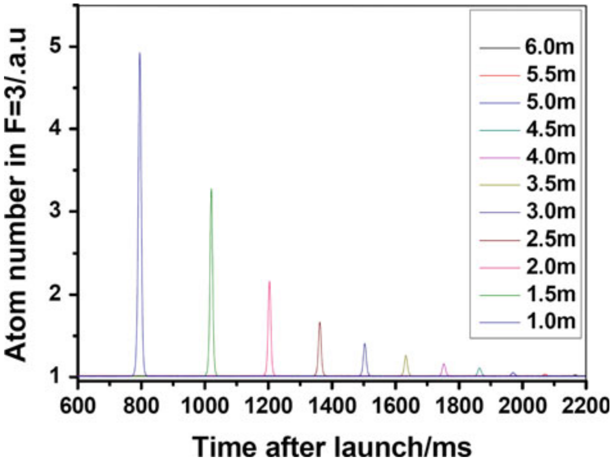

Fig. 11 Fountain signals with different launch height. Peaks from *left* to *right* correspond to launch height of 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, and 6.0 m, respectively

time of atoms from the top of fountain to the bottom, or from the bottom to the top is more than 1.3 s, this time is equivalent to the transmission time of light between the Earth and the Moon. The resolution of the atomic interferometer with 1s free-fall time is higher than that of 100 ms by 2 orders of magnitude. For this purpose, a 10-meter atom fountain is being built in Stanford University [14,15], two species of atoms, ^{85}Rb and ^{87}Rb, will be adopted to precisely measure the gravitational acceleration and to test EP. Theoretical analysis showed that the accuracy of gravity measurement using 10-meter fountain type atom interferometer can reach 10^{-15} [10]. Due to the potential high sensitivity in gravity measurements, this kind of large interferometer is not only a good facility for EP test, but also a possible detector for gravity wave. For comparison measurements and network link purpose in future, it is necessary to

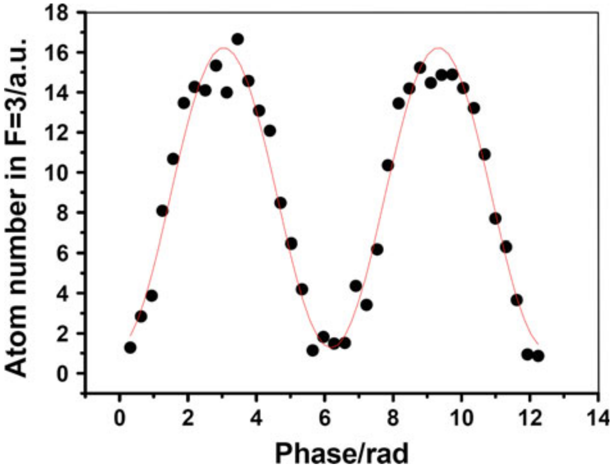

Fig. 12 Interference fringes exhibited as a function of relative population to the phase of Raman lasers. Interrogation time between pulses is T = 100 ms, and the visibility of it is 86%

build several similar atom interferometers around the world as laser interferometers do (LIGO, VIRGO, and AIGO).

We started to build a 10-meter atom interferometer in our laboratory in 2007. The experimental schematic is shown in Fig. 8. The main design includes several aspects: (1) The height of the whole interferometer is 13 m, and the effective height of free falling chamber, which is inside the magnetic shielding cylinder, is 10 m; (2) Three kinds of atoms, Rb, Cs, and Li, will be adopted in this interferometer. (3) There are two MOT chambers, one is on the top of the fountain chamber, and the other is at the bottom of fountain chamber. (4) The top MOT is designed for cooling, trapping and dropping ^{6}Li and ^{85}Rb atoms simultaneously for EP test purpose; (5) The bottom MOT is designed for cooling and trapping ^{87}Rb/^{85}Rb and ^{133}Cs atoms respectively, ^{85}Rb will be used for fountain type interferometer as a gravimeter, ^{87}Rb and ^{133}Cs will be used to build dual fountain atom clocks; (6) Zeeman slower is used for pre-cooling different atom beams before they enter the MOT chambers. The renderings of the vacuum system is shown in Fig. 9, ion pumps, aluminum mounting framework, two sets of Zeeman slowers for bottom MOT, and fountain tube are shown in different colors.

The vacuum system was made in May of 2009; the installation site was ready in February of 2010. The installation and testing of the entire 10-meter system was gradually carried out since the end of April of 2010. Interferometer facility is mounted vertically in the middle of the special laboratory. There are two underground floors in the lab, the top floor is 4.5 m below the ground, and there is a movable cover on the surface, which is designed for equipment installation. The bottom floor is 12 m below the top floor. A crane was used during the installation of fountain tube and magnetic shielding cylinder. The top MOT chamber is installed in the middle of top floor, the bottom MOT chamber is seated at the middle of bottom floor, and the fountain tube and magnetic shielding cylinder are mounted between two MOTs (Fig. 10).

This facility is under commissioning, the first MOT signal of ^{85}Rb was observed in October of 2010, and first fountain of ^{85}Rb was realized and the maximum launch height is 6 m. Fountain signals with different height is shown in Fig. 11. To realize the designed 10 m high fountain, experimental parameters need to optimize. M-Z interference fringe based on 2.5 m fountain condition was observed recently, and the best visibility of it is 86% as shown in Fig. 12. More work will be followed step by step.

4 Conclusions

In summary, we demonstrated a precision measurement of gravity by a cold atom interferometer; the resolutions are 2.0×10^{-7} g for 1 s and 4.5×10^{-9} g for 1,888 s. The absolute g value was derived with a difference of 1.6×10^{-7} g compared to the gravity value of reference site. We demonstrated a 5-days' measurement of the variation of local gravity by atom interferometer, and observed the periodical fluctuation of g due to the solid tidal effect. A 10-meter atom interferometer is standing at our laboratory; test for it is right under way. It will be used to EP test experiments and precision measurement physics.

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