Continuous high-precision gravity measurement over 5 months of a Portable Atom Gravimeter in field application

Chen-Yang Li[1,2,3],Jin-Bao Long[1,2],Ming-Qi Huang[1,2,3],Bin Chen[1,2],Yu-Meng Yang[1,2,3],Xiao Jiang[1,2,3],Chuan-Fang Xiang[4],Zhao-Li Ma[4],De-Qiang He[4],Luo-Kan Chen[1,2,3],Shuai Chen[1,2,3]

[1]Hefei National Research Center for Physical Sciences at the Microscale and School of Physical Sciences, University of Science and Technology of China, Hefei 230026, China
[2]Shanghai Research Center for Quantum Science and CAS Center for Excellence in Quantum Information and Quantum Physics, University of Science and Technology of China, Shanghai 201315, China
[3]Hefei National Laboratory, University of Science and Technology of China, Hefei 230088, China
[4]Zhaotong Earthquake Prevention and Disaster Reduction Administration, Zhaotong, Yunnan 657000, China

Key Points:

- Atom gravimeter can perform a long-term high-precision gravity measurement
- The vibration noise is effectively suppressed via a vibration compensation method
- The accuracy of atom gravimeter is comparable to the best commertial gravimeter FG-5(X), they are likely to play important roles in geophysics, geodesy, or geological disasters observation in the near future

Corresponding author: Luo-Kan Chen, `lkchen@ustc.edu.cn`

Corresponding author: Shuai Chen, `shuai@ustc.edu.cn`

Abstract

We report a portable and robust home-built atom gravimeter (USTC-AG11) continuously working in a seismic station over 5 months. Based on the principle of matter-wave interference, the atom gravimeter is very sensitive to the local gravity and can reach the precision of micro-Gal ($1\times10^{-8}\mathrm{m/s^2}$) level. With the technique of vibrational compensation, the sensitivity of the atom gravimeter reaches 38 $\mu\mathrm{Gal}/\sqrt{\mathrm{Hz}}$, which is almost immune to the ground vibration noise. The design of the atom gravimeter in the electronics and laser optics, especially the laser frequency and phase auto-relock technology, guarantees the long term continuous running. The long-term precision of the atom gravimeters is better than 2 μGal, which is comparable to the best classical gravimeter FG-5(X). Our work provides a novel application for the high precision atomic gravimeter based on modern quantum sensing technology in the field of geophysics and geodesy survey.

1 Introduction

Since the pioneering work started by Mark Kasevich and Steve Chu in 1991(Kasevich & Chu, 1991), atom interferometry has accessed to long-term development and grown into a successful tool for precision measurements. Nowadays, atom interferometer has been extensively used in the fields such as measurements of gravity acceleration(Peters et al., 1999, 2001; Hu et al., 2013; Freier et al., 2016; Farah et al., 2014; Ménoret et al., 2018), gradiometry(Snadden et al., 1998; Sorrentino et al., 2014; Duan et al., 2014),rotation(Gustavson et al., 1997; Canuel et al., 2006; Dutta et al., 2016; Yao et al., 2016) and tests of fundamental physical laws(Rosi et al., 2014; Parker et al., 2018; Chaibi et al., 2016; Müller et al., 2008; Schlippert et al., 2014; Tarallo et al., 2014; Duan et al., 2016; Overstreet et al., 2018). Atom gravimeter (AG), one of the most significant embranchment of atom interferometers, has attracted much attention as a result of its existing performance and potential(Gillot et al., 2014), since the precise gravity measurement is valuable in broad areas such as geophysics, geodesy and aided inertial navigation based on gravity reference map. At present, the research interests of atom gravimeter are most focused on applications. Portable atom gravimeters are developed towards field applications, which has become a research priority(Fang et al., 2016; Bongs et al., 2019).

Through the developments over two decades, the sensitivity and accuracy of atom gravimeters have reached the level of several μGal ($1\mu\mathrm{Gal} = 10^{-8}\mathrm{m/s^2}$), which is comparable with a high precision commercial classical gravimeter such as FG-5(X) and A10. In ICAG-2017, six atom gravimeters took part in the comparison, and four of their results are recorded into the official report(WU et al., 2020). Recently, a commercial atom gravimeter AQG-B from μQuants company is successfully installed on Etna Volcano, and used to observe the variation of the gravity caused by the underground dynamics(Antoni-Micollier et al., 2022). Not only for static gravity measurements, the atom gravimeters are also applied in different moving platforms. M*ü*ller's group from University of California performed a field gravity survey along a route of about 7.6 kilometers in Berkeley Hills using a mobile atom gravimeter(Wu et al., 2019); Huazhong University of Science and Technology (HUST) reported a car-based portable atom gravimeter that revealed the density distribution of a hill located in HUST campus(Zhang et al., 2021); Zhejiang University of technology (ZJUT) also performed a gravity survey with their atom gravimeter around the Xianlin reservoir in Hangzhou City(Wang et al., 2022). The French aerospace laboratory ONERA developed a marine atom gravimeter and implemented it in real sea condition with a measurement accuracy better than 1 $mGal$(Bidel et al., 2018), besides, they also loaded it on an airplane to perform the gravity survey in Iceland(Bidel et al., 2020); ZJUT and Innovation academy for precision measurement science and technology, Chinese Academy of Science, also reported their ship-borne atom gravimeter(Bing et al., 2021; Che et al., 2022).

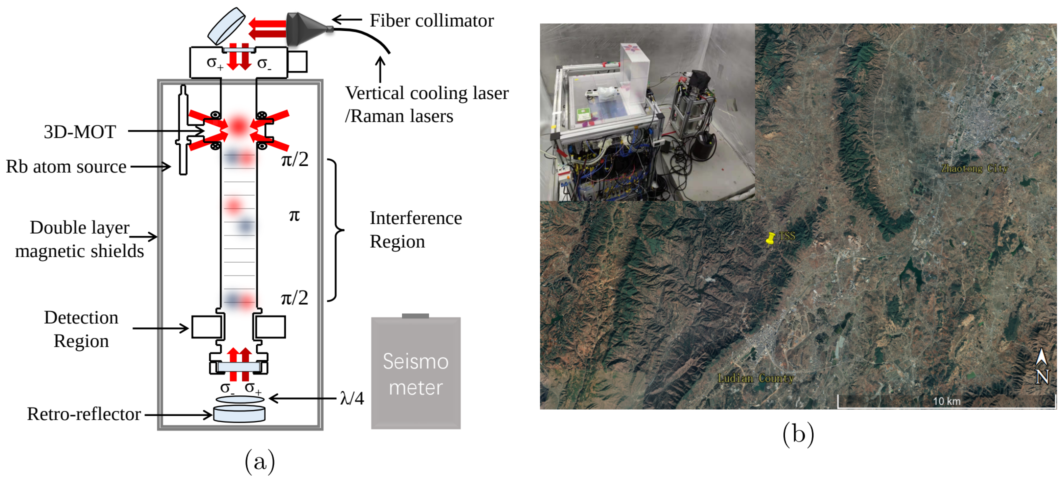

Figure 1. (a) The Schematic of sensor head, it presents the basic structure of sensor head. (b) The location of USTC-AG11 on satellite map, insert picture is the real field gravity measurement of USTC-AG11.

Compared to the classical gravimeter, the atom gravimeter use the laser cooled atoms as the test mass. It do not have any mechanical movement, therefore mechanical wear has avoided completely, this unique attribute brings AG excellent long term uninterrupted output performance. In this paper, aiming towards the precision gravity measurements for seismic station, we report a portable and compact atom gravimeter named USTC-AG11 based on matter wave interferometry. We transport the AG over 2200 Km from Shanghai to Zhaotong, Yunnan province, and deploy the AG in a local seismic station and carried out a long term g survey over five months. The sensitivity, the long-term stability and the overall accuracy of USTC-AG11 respectively are 38 μGal/$\sqrt{\text{Hz}}$, better than 1 μGal and about 2 μGal, which is same level as the best classical gravimeter FG-5(X). Our result implies that the atom gravimeter is an ideal instrument for long-term precise measurements of gravity acceleration g in the near future.

2 Setup of the atom gravimeter

The assembly of USTC-AG11 atom gravimeter consists of three parts, it is contains a miniaturized sensor head, a compact laser package and a electrical control system.

The miniaturized sensor head has a dimension of only 30cm×30cm×65cm. There are three regions in the sensor head: the atoms preparation region, the matters wave interferometry region and the quantum state detection region, as shown in Fig.1. The vacuum chamber was made by non-magnetic metal titanium with a 10^{-9}mbar level vacuum degree.

A compact laser package has been designed for providing all laser beams to manipulate the quantum states of ^{87}Rb atom. All laser beams are supplied via two diode lasers and a tapered amplifiers (TA). One of the Diode Lasers is locked with a magnetic-enhanced modulated-transfer spectral(ME-MTS)(Long et al., 2018), the other one is phase-locked using a optical-phase lock loop and amplified by TA. A laser frequency auto-relocked scheme is designed to ensure that the AG can work without long time interval. The lasers are all integrated in a 46cm × 42cm × 15cm solid module to achieve mechanical stability and compactness.

The electrical control system chassis for the laser controller, time or clock controller, as well as data acquisition modules are all integrated in three standard 3U 19 inches electronic boxes and mounted together with the optics module in a 56cm $\times$ 68cm $\times$ 72cm rack. The total power consumption is less than 250 Watt.

3 Performance of AG in a field seismic station

The analysis of long-term gravity anomaly provides an efficient method to help identify a incoming earthquake. Since AG can perform a continuous drift-free absolute gravity measurement, it may pave a new way to reveal a continuous record of gravity anomaly. To verify this, we move USTC-AG11 to the Tianhetai seismic station(TSS) located at Ludian, Zhaotong, Yunnan Province. Fig.1 shows the location of our AG on satellite map. The inset of Fig.1 shows the real field gravity measurement.

During the measurement of gravitational acceleration g, we utilize a high-sensitive seismometer G*ü*ralp-3ESPC to record the vibration data and calculate the phase shift ϕ_{vib} caused by fluctuation of Raman reflector. This phase shift is given by

$$\begin{aligned}\phi_{\text{vib}} \quad &= k_{\text{eff}}(z_{\text{g}}(0) - 2z_{\text{g}}(T) + z_{\text{g}}(2T)) \\ &= k_{\text{eff}} \int_0^{2T} g_{\text{s}}(t) v_{\text{g}}(t) dt \\ &= k_{\text{eff}} K_{\text{s}} \int_0^{2T} g_{\text{s}}(t) U_{\text{s}}(t) dt\end{aligned}$$

where T, k_{eff}, z_{g} (v_{g}), $U_s(t)$ and $K_s(t) = 2000\text{v/m/s}$ are respectively interaction time between each raman pulse, effective raman wave vector, the position (velocity) of Raman reflector of sensor head, the output voltage of the seismometer and the conversion factor of this seismometer, as well as the sensitive function $g_s(t)$ can expressed as

$$g_{\text{s}}(t) = \begin{cases} -1 & 0 < t < T, \\ 1 & T < t < 2T. \end{cases} \tag{1}$$

To demonstrate the validity of this vibrational post-correction method, we picked out a solid tide match from a whole day Sept. 25th 2020 to calculate the sensitivity before and after vibration noise post-correction. As shown in Fig.2, the black dot is the measured g data by USTC-AG11, the red line is the Earth solid tide model, which is calculated by $Tsoft$ software, a general tool to calculate the Earth tide model. Fig.2 (a) shows the solid tide match and the residue obtained by minus tide model from measured g value. During this day, we can clearly see the difference before and after vibration correction, especially at the working time such as nearly 9 to 12 o'clock and 14 to 19 o'clock in daytime. The straight distance between the TSS and the locally constructed roads is several kilometers, which may be the major source of the measurement noise.

To further explain the vibration correction method of our AG, we calculate the correlation factor between the phase shift caused by vibration noise and the population probability of atoms in $|F = 1\rangle$, as shown in Fig.2 (b). we find a correlation factor as high as 0.92, that means that most of the vibration noise can be effectively corrected.

To evaluate the noise level of our AG, the sensitivity of our AG is calculated by using standard Allan deviation, which is shown in Fig.2 (c). With vibration correction, the sensitivity has been improved significantly from 84 $\mu\text{Gal}/\sqrt{\text{Hz}}$ to 38 $\mu\text{Gal}/\sqrt{\text{Hz}}$, which improves the sensitivity by approximately 55%. At the same time, the stability can reach 1 μGal@1200 seconds with vibration correction. Thus, this method of suppressing vi-

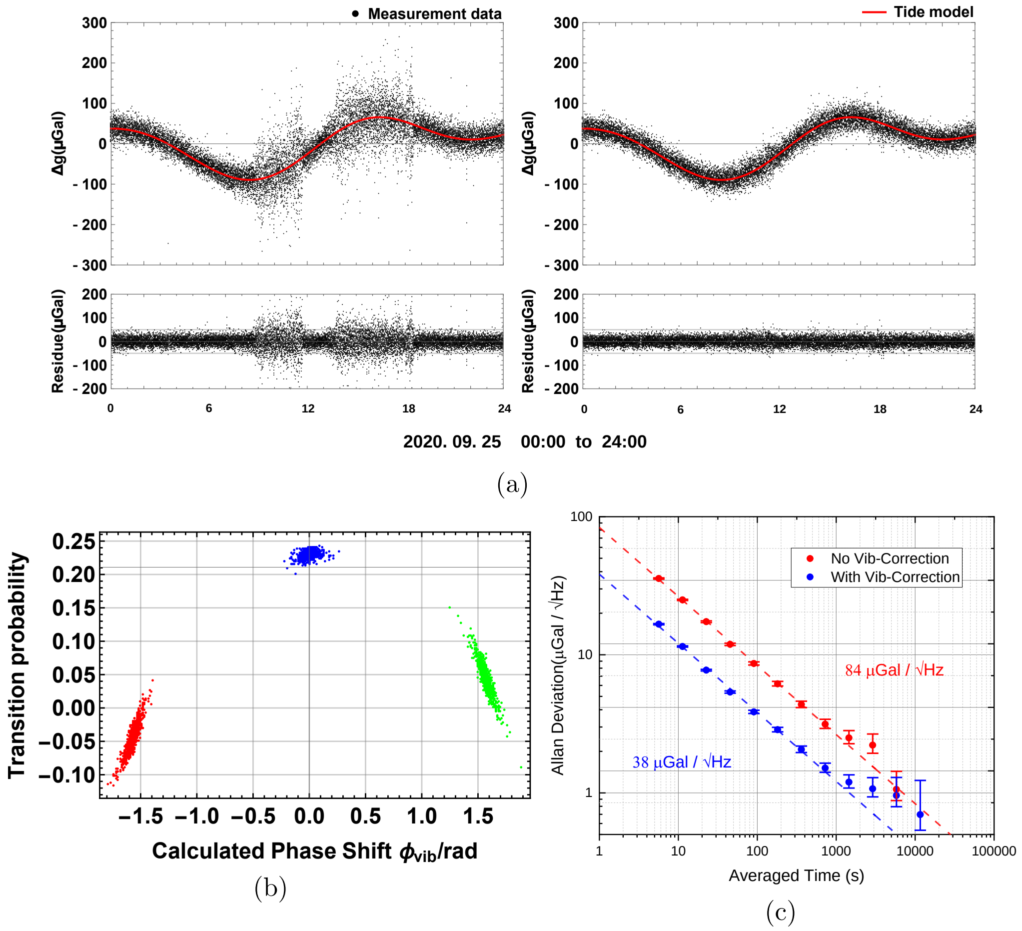

Figure 2. (a) The experimental data of the gravitational constant g (the black dot) measured by USTC-AG11 from 0 o'clock to 24 o'clock, on Sept. 25 2020. The red curve is calculated by *Tsoft* software based on the earth solid tide model. The original data (left) measured directly by USTC-AG11 is processed by a efficient vibration noise correction (right). (b) The correlation factor between the phase shift caused by vibration noise and the population probability of atoms in $|F = 1\rangle$, 0.92 correlation factor. (c) The standard Allan deviation with vibration correction. The sensitivity has been improved significantly from 84 μGal/$\sqrt{\text{Hz}}$ to 38 μGal/$\sqrt{\text{Hz}}$, which improves the sensitivity by approximately 55%.

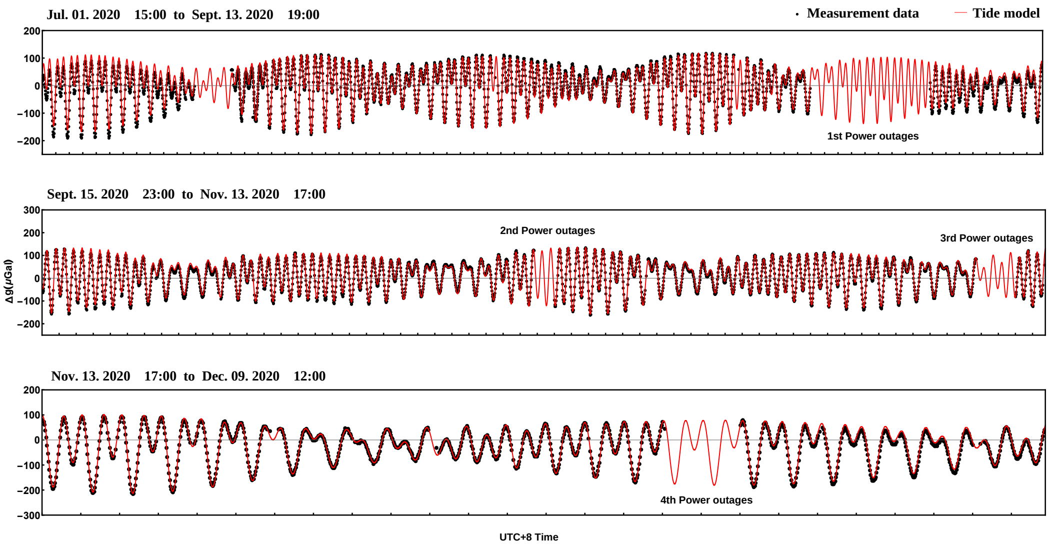

Figure 3. Continuous stable unattended gravity measurement carried out by USTC-AG11 lasting for more than five months in TSS. The black points are the gravity values measured by USTC-AG11, each black point is averaged by half hour; The red solid line is the solid tide model calculated by $Tsoft$. There exist four prolonged power outages marked in the Figure, and the other intervals were caused by laser auto-relock.

bration noise is very efficient for stability and long-term measurements of our atom gravimeter.

To verify the long-term stable working ability of our AG, USTC-AG11 performs a continuous running from Jul. 1st to Dec. 9th 2020 under an unattended mode. Fig.3 shows the continuous solid tide observation over five months. The black points are the gravity values measured by USTC-AG11, each black point is averaged by half hour; The red solid curve is the solid tide model. During the measurement of g, there exist four prolonged power outages, marked in the Fig.3. After the first power outage, we went to the TSS to restore the measurement of g. Meanwhile, we added the vibration noise correction method mentioned above. For the remaining three power outages, the non-professional duty officer in TSS helped us to restore the electricity, then g-measurements start after frequency auto-relock. Fig.3 not only exhibits that a good match between the measured data and the tide model, but also illustrates the robustness, the long-term stable and drift-free working ability of USTC-AG11.

To characterize the stability of our AG, we randomly pick out two consecutive 48-hour periods in each month during the whole measurement. As shown in Fig.4, the red dots is the residue data obtained from the measured gravity data minus the theoretical solid tide data, each dot is averaged by half-hour, the error bar represents the uncertainty of the half-hour measured gravity data, about 1μGal. Meanwhile, we also calculate the uncertainty between each half-hour measured gravity data, the standard deviation of each consecutive 48-hour is marked in this figure, the long-term stability of USTC-AG11 is only about 1.3 μGal to 2.2 μGal. This performance is comparable to the best commercial gravimeter FG-5(X). Actually, considering the other environment variations, such as the atmospheric pressure, polar motion and groundwater subsidence, the performance of our AG would even be better. During this long-term measurement period, there are

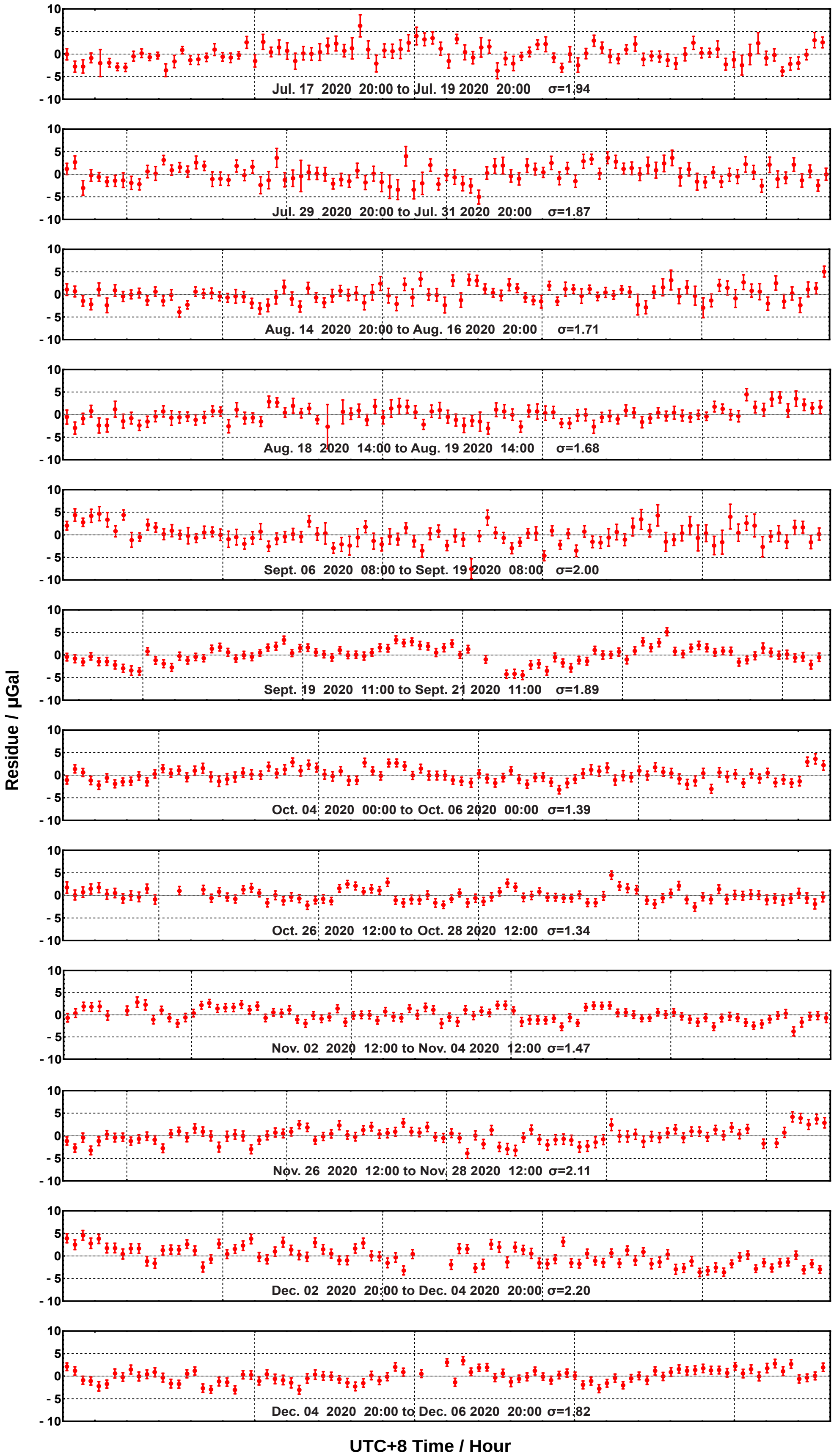

Figure 4. Typical residue data from a consecutive 48-hour period in each month. Each red point is obtained by a half hour averaged, and error bars represent the uncertainty (about 1 μGal) during the half measured gravity data. At the same time, we calculate the standard deviations of a consecutive 48-hour period picking up randomly from each month, and the uncertainty is 1.3 μGal to 2.2 μGal.

no professionals on site and any extra protection. Even more surprising, after several prolonged power outages caused by local infrastructure, we are still able to restart the measurement of g via remotely accessing to the host computer when the electric supply is restored.

4 Conclusion and Prospect

In this paper, we report the performance of a continuous running of a compact atom gravimeter USTC-AG11. It is transported over 2200 kilometers from Shanghai to Yunnan province, and deployed in a seismic station with unattended mode. We realized the continuous gravity measurement over five months from Jul. 1st to Dec. 9th, 2020. The robustness and stability of our atom gravimeter is well verified. We established a compact optical package and laser frequency auto-relock module, and the tight fit between them in control timing offers the possibility of long-term gravity measurement. By using the efficient vibration correction method, we obtained a good sensitivity of 38 μGal/$\sqrt{\text{Hz}}$, about 1 μGal for 1200 seconds. We present an excellent performance of this atom gravimeter in a field application, the measured g values and the tide model data shows a good match during whole measurement, with the uncertainty for only about 2 μGal. This performance is comparable to or even better than the best commercial gravimeter FG-5(X). Atom gravimeters are expected to become the priority for long-term precision absolute gravity measurements, they are likely to play important roles in geophysics, geodesy, or geological disasters observation in the near future.

Data Availability Statement

All of the values measured by our cold atom gravimeter are publicly accessed https://data.mendeley.com/da
The software for calculating the Earth solid tide model data is here: https://seismologie.oma.be/en/downloads/ts
The software for Allan standard deviation is here: https://alavar.software.informer.com/5.2/.

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