Gravity surveys using a mobile atom interferometer

Xuejian Wu1, Zachary Pagel1, Bola S. Malek1, Timothy H. Nguyen1, Fei Zi1, Daniel S. Scheirer2, Holger Müller1,3*

Mobile gravimetry is important in metrology, navigation, geodesy, and geophysics. Atomic gravimeters could be among the most accurate mobile gravimeters but are currently constrained by being complex and fragile. Here, we demonstrate a mobile atomic gravimeter, measuring tidal gravity variations in the laboratory and surveying gravity in the field. The tidal gravity measurements achieve a sensitivity of 37 μGal/√Hz (1 μGal = 10 nm/s²) and a long-term stability of better than 2 μGal, revealing ocean tidal loading effects and recording several distant earthquakes. We survey gravity in the Berkeley Hills with an uncertainty of around 0.04 mGal and determine the density of the subsurface rocks from the vertical gravity gradient. With simplicity and sensitivity, our instrument paves the way for bringing atomic gravimeters to field applications.

INTRODUCTION

Light-pulse atom interferometers (1) have been used to measure inertial forces (2–6) and fundamental constants (7, 8), test fundamental laws of physics (9), and search for physics beyond the standard model (10). Gravimeters based on atom interferometry are among the most accurate and sensitive tools for measuring gravity (11, 12). By contrast to instruments based on springs (13), superconducting coils (14), microelectromechanical devices (15), or falling corner cubes (16), atomic gravimeters rely on matter-wave interferometry with a freely falling atomic cloud. Matter waves are directed into two interferometer arms by the momentum of photons, extremely well defined through the laser wavelength. Transportable atomic gravimeters are being developed toward metrology (17–22), airborne sensing (23), shipborne surveys (24), and field applications (25–29). They typically reach sensitivities around 5 to 100 μGalileo (μGal)/√Hz (1 μGal = 10 nm/s²) in the laboratory (17–21, 25, 27), but the only atomic gravimeter used in gravity surveys achieves a precision of only ~1 mGal on a ship (24). Meanwhile, precise mobile gravimetry is valuable in broad areas. Gravity measurements with an uncertainty of a few micro-Galileos are required for using the Watt balance to realize the definition of the kilogram (30). The use of gravity reference maps to aid inertial marine navigation requires onboard gravimeters with at least milli-Galileo accuracy (31). Seasonal aquifer fluctuations can be monitored by sensing micro-Galileo-scale gravity changes (32). These examples illustrate that atomic gravimeters must be not only sensitive but also mobile and reliable in field conditions.

Here, we demonstrate laboratory and field operation of a mobile atomic gravimeter. We achieve a sensitivity of 37 μGal/√Hz and a stability of better than 2 μGal in half an hour. Comparing the measured gravity with a solid Earth tide model, the atomic gravimeter is sensitive enough to reveal ocean tidal loading effects and to measure seismic waves of distant earthquakes. The atomic gravimeter measures absolute gravity in the laboratory with an uncertainty of 0.02 μGal, confirmed by a spring-based relative gravimeter referencing to a site with known absolute gravity. Furthermore, the mobility allows us to measure gravity in the field with a resolution of around 0.5 mGal/√Hz, depending on environmental noise. We implement gravity surveys in the Berkeley Hills along a route of ~7.6 km and an elevation change of ~400 m. At each static measurement location, it takes about 15 min to set up the gravimeter and a few minutes to measure gravity with an uncertainty of around 0.04 mGal. From the measured vertical gravity gradient (VGG), the density of subsurface rocks is estimated to be 2.0(2) g/cm³. Geodetic and geophysical studies—such as refining the geoid, resource exploration, hydrological studies, and hazard monitoring—can benefit from precise absolute gravity measurements using field-operating atomic gravimeters.

RESULTS

Mobile atom interferometer

The mobile atomic gravimeter is based on an atom interferometer, schematically shown in Fig. 1A. It features a magneto-optical trap (MOT) inside a pyramid mirror with a through-hole. This novel geometry offers many advantages. First, it acts as a differential pumping stage between the MOT and atom interferometry regions. A vapor pressure ratio of more than 10:1 (see fig. S1) accelerates atom-loading speed and decreases background noise in atom detection. We achieve a signal-to-noise ratio of 200:1 (see fig. S1) and reduce systematic effects from the refractive index of background atoms, particularly important when the laser is at a small detuning (see Materials and Methods). Second, it allows the MOT and interferometer laser beams to have different waists such that we can obtain both a large MOT volume and a high Raman beam intensity with the available laser power. Third, the atomic gravimeter takes advantage of retroreflection from a vibration-isolated mirror and is insensitive to vibrations of the pyramid mirror. Thus, the vibration isolation is simpler and more effective than in traditional pyramidal atomic gravimeters (26–28). Last, using a flat mirror as the retroreflector eliminates the systematic effects from imperfections in the pyramidal top angle and wavefront aberration due to the pyramid edges.

The MOT beam and its reflections off the pyramid mirror and the retroreflector trap ~5 × 10⁷ cesium atoms in a 150-ms loading time. Polarization gradient cooling, after switching off the MOT magnetic fields, further cools the atoms to ~2 μK. The atoms are then released to fall freely under gravity. A microwave pulse transfers ~5 × 10⁸ atoms from the state F = 4 and m_F = 0 into F = 3 and m_F = 0 (where F and m_F are the total spin quantum numbers). A resonant laser pulse clears away atoms left in F = 4.

1Department of Physics, University of California, Berkeley, Berkeley, CA 94720, USA.
2U.S. Geological Survey, 345 Middlefield Road, MS 989, Menlo Park, CA 94025, USA.
3Molecular Biophysics and Integrated Bioimaging, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA.
*Corresponding author. Email: hm@berkeley.edu

Copyright © 2019 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. No claim to original U.S. Government Works. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC).
Atom interferometry is performed underneath the pyramid mirror using Doppler-sensitive two-photon Raman transitions between the $F = 3$ and $F = 4$ hyperfine ground states, driven by two laser beams with wave vectors $k_1$ and $k_2$. We use a Mach-Zehnder geometry, as shown in Fig. 1B. A $\pi/2$ pulse can place the atoms into a superposition of the two states. A $\pi$ pulse can fully transfer atoms from one state to the other. The three pulses are equally spaced by a pulse separation time $T$, and their durations are 4, 8, and 4 $\mu$s, respectively. Because the atoms move in free fall, they see a Doppler-shifted laser frequency. To compensate this effect, we linearly ramp the laser frequency difference between the two beams with a rate of $\alpha$.

The population fraction of the atoms in the two states can be used to estimate the phase difference $\Delta \phi$ between the two interferometer arms, $P = P_0 + (C/2)\cos(\Delta \phi)$, where $P_0$ is the normalized background population and $C$ is the contrast. For atomic gravimeters, the phase difference $\Delta \phi = (k_{\text{eff}} \cdot g - \alpha)T^2$, where $k_{\text{eff}} = k_1 - k_2$ is the effective wave vector of the interferometer beams and $g$ is the gravitational acceleration. By varying $\alpha$, the interference fringes, and thus the acceleration, can be obtained (Fig. 1C).

The $\cos(\Delta \phi)$ dependence of the fringes introduces an ambiguity in the gravity measurement that we resolve by using different pulse separation times. To measure absolute gravity, we start with a short $T$ of several milliseconds to obtain a unique but coarse measurement and process finer measurements with longer $T$. For each $T$, we reverse the wave vectors to reduce the systematic effects from the magnetic gradient and the first-order light shift (33). This procedure is performed automatically at the start of a new measurement (see fig. S2).

All laser beams necessary for the MOT, interferometry, and detection are generated from a single-diode laser using three acousto-optic modulators (AOMs) and one fiber-based electro-optic phase modulator (EOM) (see Materials and Methods and fig. S3). The 50-mW cooling beam has a waist of 13 mm ($1/e^2$ radius), and the 25-mW Raman beam has a waist of 5 mm. They are combined before entering the vacuum chamber. A liquid crystal retarder switches between circular and linear polarizations. For trapping atoms, counterpropagating $\sigma^+ / \sigma^-$ polarization pairs are formed inside the pyramid owing to the pyramidal geometry. For atom interferometry, lin $\perp$ lin polarization is used. The single-photon detuning of the Doppler-sensitive two-photon Raman transition is $-158$ MHz relative to $F = 4 \rightarrow F' = 5$. At this detuning, we obtain a $\pi$ pulse of as short as 8 $\mu$s. Owing to the fast Rabi frequency, more than 60% of the total atoms can be addressed without velocity selection of the atomic cloud. With an effect of all the Raman laser sidebands, this detuning can also cancel the differential AC Stark shift, strongly reducing systematic effects (28). For $T = 10$ ms, we obtain a fringe contrast higher than 30%. For $T = 120$ ms, we achieve fringe contrast of 16% (Fig. 1C), which may be limited by the broad velocity width of the atomic cloud and the inhomogeneous Rabi flopping of the interferometer pulses across the cloud.

**Fig. 1. Atomic gravimeter.** (A) Schematic. Cesium clouds are loaded in the novel pyramidal MOT and then freely fall into the region of fluorescence detection. $k_1$ and $k_2$ are the wave vectors of the interferometer beams. A magnetic shield and a solenoid (not shown) around the vacuum chamber create a uniform magnetic bias field. The retroreflector consists of a flat mirror and a quarter-wave plate. The vibration isolation stage includes a passive vibration isolation table, a seismometer, voice coils, and an active feedback loop. (B) Mach-Zehnder interferometer geometry. Three laser pulses (wavy green lines) split, redirect, and combine a matter wave (blue and orange lines). (C) Fringes with $T = 120$ ms and $C = 16\%$. The blue dots are single-shot experimental data, and the red curve is a sinusoidal fit.
Tidal gravity measurements

Figure 2 illustrates the long-term tidal gravity variation measured over 12 days by the atomic gravimeter. We operated the atom interferometer with $T = 130$ ms and active vibration isolation (see Materials and Methods and fig. S4). The cycle time was 0.481 s. Fitting an interference fringe with 16 drops, one gravity measurement took 7.696 s (see fig. S5 for the gravity data per fringe). Figure 2A shows the mean value of the gravity data over every 2 hours compared with a solid Earth tide model (34).

Because our laboratory is about 4.5 km east of the San Francisco Bay, the ocean tidal loading effect on gravity at our location is notable and is not accurately described in available models (35). Figure 2B shows that the residual gravity variation is correlated with the water level variation measured in the Bay. As shown in Fig. 2 (C and D), the ocean tidal loading leads to the peaks in the Allan deviation and the power spectral density in a period band between 6 to 24 hours. After correcting for the solid Earth tide, the sensitivity of the atomic gravimeter is $37 \mu\text{Gal}/\sqrt{\text{Hz}}$, and the stability in half an hour is better than $2 \mu\text{Gal}$ (see Fig. 2C and Materials and Methods).

During the tidal gravity measurements, the atomic gravimeter recorded seismic wave trains from several distant earthquakes. Because the frequency of the seismic waves generated by the earthquakes was much lower than the resonant frequency of the active vibration isolation, the ground motion passed through linearly and vertically moved the retroreflector. Thus, the atomic gravimeter measured the vertical acceleration of the seismic waves. Figure 3 illustrates a comparison between the atomic gravimeter and one of the seismometers in the Berkeley Digital Seismic Network. On 5 January 2019, a 6.8-magnitude and 570-km-deep earthquake occurred in Brazil at 19:25 UTC. After about 20 min, body waves from this earthquake were detected by both the atomic gravimeter and the seismometer. On 6 January 2019, a 6.6-magnitude and 43-km-deep earthquake occurred in Indonesia at 17:27 UTC, and its dispersive Rayleigh surface wave arrived at Berkeley around 18:16 UTC. According to the measured acceleration as a function of time, the vertical component of the Rayleigh wave had a period of $\sim30$ s and a peak-to-peak amplitude of $\sim90 \mu\text{m}$.

Systematic effects and repeatability

To investigate the accuracy of the atomic gravimeter, we estimated the systematic effects. With major errors from the magnetic fields and the refractive index of background vapor, the total systematic
error is 0.015 mGal, and the measurement bias is −0.008 mGal (see Materials and Methods and the Supplementary Materials for details).

To verify the repeatability after transporting the atomic gravimeter, we measured gravity on different floors of Campbell Hall in the University of California (UC) Berkeley campus, comparing with the gravity differences measured by a spring-based relative gravimeter (CG-5, Scintrex). The atomic gravimeter measured 979 955.61(2) mGal on the floor of the basement (in the laboratory). This value matches one estimated by the relative gravimeter, 979 955.58(1) mGal, using standard gravity surveying techniques (36) and referencing to a gravity station with known absolute gravity, in the U.S. Geological Survey (USGS) campus in Menlo Park, CA.

We took fringes with $T = 70$ ms for the measurements on the upper floors. The measurement had an unambiguous range of 8.7 mGal, larger than the gravity variation in the building. Because the seismometer in the active vibration isolation needs several hours to warm up after transport, we did not use the active system but only the passive stage. The atomic gravimeter achieved a sensitivity of around 0.2 mGal/$\sqrt{\text{Hz}}$ depending on vibrational noise. Although the sensitivity on higher floors decreased because of stronger vibration noise, the gravimeter took data for several minutes on each floor and thus ensured a statistical uncertainty below 0.05 mGal. The experiment of measuring gravity on the floors of the building was carried out by only one person within 3 hours, most of the time spent on transporting and realigning to the vertical axis (see Materials and Methods).

Taking the basement floor gravity as a reference, Fig. 4 compares the gravity variation from the atomic gravimeter and the relative gravimeter (see table S2 for the absolute gravity on each floor). We excluded the gravity measured on the basement floor when fitting the gravity gradient because the gradient is expected to be significantly different below and above the ground level. The atomic gravimeter measures a VGG of $-0.289(3)$ mGal/m, and the relative gravimeter obtains $-0.285(1)$ mGal/m, matching within the statistical error. These gradients are smaller than the free-air gradient ($-0.3086$ mGal/m), indicating the gravitational effect of the mass of the building.

Gravity survey in Berkeley Hills

To demonstrate the use of the atomic gravimeter in the field, we measured absolute gravity in the Berkeley Hills. As shown in Fig. 5A, the route had a length of ~7.6 km and an elevation change of ~400 m. We operated the atomic gravimeter inside a vehicle using passive vibration isolation and measured gravity at six locations. At each location, it took about 15 min to set up the gravimeter, including powering up the instrument and aligning the interferometer beam to the gravity axis (see Materials and Methods). Because of increased vibrational noise in the field, the sensitivity of the gravimeter was around 0.5 mGal/$\sqrt{\text{Hz}}$. We first determined the absolute gravity with $T = 10$ ms and increased with steps of 10 ms and, lastly, took more fringes with $T = 70$ ms to reach a statistical uncertainty of around 0.03 mGal. A microcontroller system managed this procedure automatically (see Materials and Methods). Considering the systematic effects, the uncertainty of the gravity values was around 0.04 mGal (see Materials and Methods). The laser system required no realignment during the 7-hour survey, with air temperature changing by 12°C and significant transport vibrations.

The gravity changes by $-92.6$ mGal from the base to the peak of the Berkeley Hills (see table S3 for the absolute gravity at each measurement location). To determine the VGG, we corrected the measured gravity for solid Earth tides, latitude variations, and terrain effects (see Materials and Methods). Figure 5B illustrates the gravity anomaly as a function of the elevation. The VGG is $-0.225(10)$ mGal/m, a value that is $0.084(10)$ mGal/m smaller than the free-air gradient because of the mass of the rocks forming the Berkeley Hills. This gradient yields an average density value of the Berkeley Hills of 2.0(2) g/cm$^3$. The VGG and the average density match those calculated from USGS gravity stations (37) collected in 1998 along the same path (see Materials and Methods).

DISCUSSION

We have developed a mobile atomic gravimeter and performed tidal gravity measurements and gravity surveys. Our instrument uses a
novel pyramidal MOT that takes advantage of single-beam atom interferometry and offers differential pumping, simple laser-to-gravity alignment, and enhanced vibration isolation. Our atomic gravimeter is mobile, compact, and robust over transport in the field while maintaining comparable sensitivity to other transportable atomic gravimeters (17–29). These features make it a candidate for

Fig. 4. Gravity variation on different floors of Campbell Hall. The data at 0 m are the gravity measured on the floor of the basement, and the others are from floors 1 to 5. The error bars are 1 − σ statistical and systematic errors. The height of the floors is obtained from the building design. The free-air gradient of −0.3086 mGal/m is removed from the data to emphasize deviations of the VGG from the free-air value. The solid line is a linear fit of the gravity variation measured by the atomic gravimeter from floors 1 to 5 and determines a VGG of −0.289(3) mGal/m. Similarly, the dashed line is a linear fit of the relative gravimeter, determining a VGG of −0.285(1) mGal/m.

Fig. 5. Gravity survey in Berkeley Hills. (A) Measurement route. The blue curve depicts the route, and the white pin drops are the six measurement locations. (B) Gravity anomaly as a function of the elevation. Elevations are from Google maps. The error bars are 1 − σ statistical and systematic errors. The dashed line indicates a VGG of −0.225(10) mGal/m. (C) The atomic gravimeter apparatus. (D) Field operation of the atomic gravimeter inside a vehicle. [Photo credit for (A): Google Maps; photo credit for (C) and (D): Xuejian Wu, UC Berkeley].
geodetic and geophysical applications requiring precise mobile gravimetry (38).

Although spring-based gravimeters and falling corner cube gravimeters are popular transportable instruments, atomic ones are developing rapidly. Atomic and classical gravimeters have been compared in the laboratory (17, 18, 20, 27). Spring-based gravimeters can measure gravity variations with a sensitivity of tens of μGal/√Hz, but their accuracy depends on the compensation of spring drifts and reference to gravity stations with known absolute gravity. Falling corner cube gravimeters can measure the absolute value of the local gravity, but their mechanical dropping and lifting system may not be suitable for continuous long-term operations. By contrast, atomic gravimeters can continuously measure absolute gravity with sensitivity and accuracy that are comparable to classical gravimeters. In the future, a field campaign of different types of gravimeters would provide more perspectives on the strengths and weaknesses of different gravimeter technologies with regard to particular applications.

The sensitivity of our atomic gravimeter is currently limited by vibrational noise. However, the sensitivity as a function of the pulse separation time indicates that we can further improve the sensitivity by dropping the atomic cloud longer (see fig. S4). To increase the gravity measurement rate, we can sample the fringes with fewer points, such as by alternating the laser phase around the rising and falling slopes. Because the local gravity is affected by the tidal effects, the inaccurate tide model at our location constrains the accuracy of the long-term stability measurement and the systematic effect evaluation. A gravity comparison at a geophysical observatory would allow us to characterize them more accurately (39). With these improvements, a more accurate measurement of the ocean tidal loading effect may be useful for investigating Earth’s mass structure and its variation with time at levels beyond current precision (35, 38). In addition, atomic gravimeters with mobility, sensitivity, and accuracy may find more applications in detecting tunnels, sensing underground water storage, and monitoring earthquake and volcano activity.

### Materials and Methods

#### Apparatus

The atomic gravimeter was installed in a cart of 1 m by 0.8 m by 1.7 m (L × W × H) (Fig. 5C). It weighs around 100 kg, mostly because of the lithium battery power supply, vibration isolation stage, and cart. The cart has two columns, one for the electronic system and the other for the vacuum system. The laser unit consists of two optical breadboards of 60 cm by 46 cm placed at the top level of the cart. The total power consumption is about 250 W. For field operation, the gravimeter was powered by a 1450-W-hour lithium power station (Yeti 1400, Goal Zero). A gas generator was used as a backup power supply. The vehicle used for the gravity surveys is a 15-feet truck (Fig. 5D).

#### Pyramid mirror

The pyramid mirror is in a glass cube of 40 mm by 40 mm by 40 mm (Fig. 1A). The diameter of the center hole is 10 mm. Its inner faces were coated with protected gold to generate equal phase shift between two orthogonal polarizations for the reflections. The pyramid mirror was attached to an aluminum holder and fixed to the bottom vacuum flange by rods. Its outside dimension was designed to fit within the vacuum chamber with a tolerance of ±0.5 mm.

#### Vacuum chamber

The vacuum chamber is a 0.6-m-long glass cylinder with an outside diameter of ~60 mm (fig. S1). The glass cylinder has two 0.1-m-long rectangular cells in the middle. They are separated by about 0.3 m. The pyramid mirror is in the top cell, and the atoms are detected in the bottom cell. The pressure in the interferometry region is 1 × 10^{-9} torr, measured by the ion pump (5S, Gamma Vacuum), of which ~3 × 10^{-10} torr is cesium vapor (when the dispenser is off, the residual pressure is 7 × 10^{-10} torr). The cesium pressure in the MOT region is ~1 × 10^{-8} torr, estimated by fluorescence detection.

#### Laser system

The laser system (fig. S3) used only one 240-mW distributed Bragg reflector diode laser (PH852DBR, Photodigm) with 852-nm wavelength and 500-kHz line width. The laser was frequency-stabilized by polarization spectroscopy in a cesium vapor cell, nominally to the \( F = 4 \rightarrow F' = 4/F = 4 \rightarrow F' = 5 \) crossover line. An AOM can vary the laser frequency relative to the spectroscopy by ±15 MHz to switch between frequencies needed for trapping the atoms and for detecting them after interferometry. A 125-MHz frequency change was available by adding a bias voltage to the spectroscopy signal, which changed the lock point to the \( F = 4 \rightarrow F' = 4 \) line. This was used to generate a ~140-MHz red detuning for polarization gradient cooling. Another AOM acts as an overall on/off switch for the beam and shifts it to about ~10 MHz from \( F = 4 \rightarrow F' = 5 \) to act as the cooling beam. The beam was coupled into a polarization-maintaining fiber. A fraction of the beam was deflected by another AOM and sent through a fiber-coupled EOM, which generated the repumping frequency as a sideband. Although the repumping beam has a smaller waist than the cooling beam, we did not observe a decrease in the number of atoms. For interferometry pulses, most power was directed through the EOM, and the carrier and one sideband served as the frequency pair to drive Raman transitions. The high peak power does not degrade the EOM lifetime because of the short pulse time. Fluorescence detection was performed using the MOT laser.

#### Electronic system

The electronic system includes a microcontroller system, drivers for the laser and modulators, and a microwave frequency chain. The microwave frequency chain is a phase-lock loop that stabilizes the microwave frequency of a dielectric resonant oscillator to the high-order harmonic of a phase-locked radio frequency oscillator. By varying the offset frequency, the microwave frequency chain can produce the frequency of the cesium clock transition, as well as ramp frequency, to compensate for the Doppler shift of the freely falling atomic clouds. The electronic system refers to a 10-MHz Rubidium clock (PRS10, Stanford Research Systems). The microcontroller system generates all the controlling digital and analog signals and measures the analog signal from the photodetector to obtain an interference fringe. A detailed implementation of the microcontroller system can be found in (40).

#### Vibration isolation

The vibration isolation stage includes a passive vibration isolation table (25BM-10, Minus K), a broadband seismometer (MBB-2, Metrozet), two voice coils inside the table, and a digital feedback loop. The digital feedback loop is a finite impulse response (FIR) filter based on a field-programmable gate array (FPGA). The output from
the seismometer was amplified by a factor of 200 and then sampled into the FPGA (StemLab 125-14, Red Pitaya) with a rate of ~3.8 kS/s and a resolution of 14 bit. On the basis of (41), the FIR filter was designed to suppress vibrations around the resonance frequency of the Minus K stage, roughly around 1 Hz. Around this frequency, the transfer function of the digital filter includes elements to enhance the gain of the feedback loop. Additional filter elements were added to provide stability near the 0.01-Hz unity gain point, as well as mechanical resonances above 100 Hz. An in-loop measurement shows a 500-fold suppression in vibration noise around 1 Hz (fig. S4).

Alignment procedure
Before measuring gravity, we first adjusted the leveling feet of the cart using a bubble level on top of the vacuum chamber. Second, we adjusted the leveling feet under the vibration isolation table using a bubble level on the seismometer. Third, we adjusted the retroreflector using an electronic tilt sensor (700-series, Applied Geomechanics) with a resolution of 1 μrad. Fourth, we aligned the interferometer beam to be perpendicular to the retroreflector by adjusting the pair of mirrors after the telescope. We achieved this by overlapping the reflection beam and the incident beam through a pinhole, with an accuracy of about 50 μrad. Last, we adjusted the cooling beam to center the atomic cloud with respect to the pyramid hole.

Systematic effects
The total systematic error of our mobile atomic gravimeter is \( \sim 8 \pm 15 \) μGal (table S1). Here, we briefly discuss those contributions that produce an error larger than 1 μGal.

Magnetic fields
The cesium ground state hyperfine splitting exhibits a quadratic Zeeman effect of 0.43 kHz/G². A homogenous magnetic field has no influence on the phase of a Mach-Zehnder atom interferometer, but a magnetic field gradient \( B' \) on top of a bias field \( B_0 \) can add an effective force that is proportional to \( B_0 B' \). To characterize the shift, we varied \( B_0 \) and found that the gravity measurement was modified by \( \sim 1.8 \) mGal/G. Wave vector reversal reduces this to \( \sim 9 \pm 28 \) μGal/G (fig. S6). At a nominal bias field of 0.3 G, this systematic is \( \sim 3 \pm 9 \) μGal.

Refractive index of background vapor
Operating with small detunings, we had to check whether the refractive index \( n \) of cesium background atoms generates a substantial systematic error. It is related to the atomic polarizability \( \alpha \) and thus to the AC Stark shift \( \omega_{AC} \), by \( (n - 1) = 2\pi\alpha_0 = 2\pi\rho n\omega_{AC} / I \), where \( \rho \) is the number density of atoms, \( c \) is the speed of light in vacuum, and \( I \) is the laser intensity. The calculation of the AC Stark shift can be found in our previous paper (28). This refractive index is averaged over the \( F = 3 \) and \( F = 4 \) ground states (background atoms are equally distributed in either state), the two Raman frequencies, and the 270-MHz-wide thermal distribution of the Doppler shifts. With a cesium partial pressure of \( (3 \pm 3) \times 10^{-10} \) torr, the index of refraction is \( (n - 1) \approx -7 \pm 7 \times 10^{-9} \), corresponding to an error in the gravity measurement of \( \sim 7 \pm 7 \) μGal.

Coriolis effect
The Coriolis effect causes an extra phase shift of \( 2\Omega \times k_{eff} / \tau^2 \) and thus an error \( \Delta g / g \approx 2\Omega / \tau^2 k_{eff} \), where \( \tau \) is the initial velocity of the atoms and \( \Omega \) is the Earth’s rotation (42). The Earth’s rotation at the latitude of Berkeley has a horizontal component of 58 μrad/s. For a transverse velocity component of the atoms of \( \pm 1 \) mm/s, the systematic is \( \sim 0 \pm 6 \) μGal.

Vertical alignment after correction
To calibrate the alignment to the gravity axis, we measured gravity with different tilt angles of the retroreflector and fit the data with a bivariate quadratic function to obtain the gravity correction (fig. S7). The SE of the fit residual is \( \pm 5 \) μGal. For each measurement, the gravity values were corrected on the basis of the real-time tilt and the fit function. After correction, the systematic is \( 0 \pm 5 \) μGal.

Differential AC Stark shift
A differential AC Stark shift between the hyperfine ground states \( a \) and \( b \) during Raman transitions adds a phase \( \Delta\phi_{AC} = (\delta_{13} / \Omega_1 - \delta_{13} / \Omega_2) \) to the interferometer, where \( \delta_{13} = \omega_{4} - \omega_{6} \) are the differential AC Stark shifts during the first and the third pulses, and \( \Omega_{1,3} \) is the two-photon Rabi frequencies (11). We worked at a red detuning of 158 MHz relative to four to five transitions and a modulation index \( \beta \) of 1.1, close to the zero crossing of the differential AC Stark shift (28). Moreover, the AC Stark shift systematic was suppressed by cancellation between the first and the third pulses and by wave vector reversal. In principle, the AC Stark effect systematic can be eliminated by varying the power of the interferometer beam and extrapolating the measured gravity value to zero power.

Raman frequency offset
Off-transition Raman frequencies can result in interferometer phase shifts (43). In a similar atomic gravimeter, Gillot et al. (43) reported \( \Delta g \) corresponding to \( \sim 1.4 \) μGal/kHz due to the offset from the Raman frequencies. We scanned the Raman frequencies and found that the resonance has a bandwidth of \( \sim 70 \) kHz. Setting the Raman frequency to the peak has an error of \( \pm 2 \) kHz. The systematic error to gravity is \( \sim 0 \) μGal.

Two-photon light shift
Off-resonant Raman transitions can cause an additional phase shift (33). For \( T = 130 \) ms, the Doppler shift at the first Raman pulse is about 0.46 MHz and gets to about 6.44 MHz for the third pulse. A π pulse of 8 μs corresponds to a Rabi frequency of 62.5 kHz. Using equation 8 of (33), the two-photon light shift leads to a phase shift of 32 μrad, corresponding to a down correction to \( g \) by 3 μGal. We estimated the error with the same magnitude of the correction. The systematic effect of two-photon light shift is \( 3 \pm 3 \) μGal.

Wavefront aberrations
Wavefront aberrations combined with transverse motion of the atomic cloud lead to systematic phase shifts (42). Upon retroreflection, the interferometer laser beam passes a λ/4 plate and a vacuum viewport (λ/4) twice; each pass causes wavefront aberrations proportional to \( 1 - n \), where \( n \approx 1.5 \) is the index of refraction. The mirror itself has λ/10 flatness. Added in quadrature, the three elements cause 0.4λ total aberration. According to equation 6 of (42), if this aberration has a parabolic shape over a 25.4-mm diameter, then the optical phase change can be described as \( \phi = K_\sigma \omega_0^2 / \lambda^2 \), with \( K_\sigma = K_{eff} / R \approx 1.5 \times 10^4 \) m² (\( R \) is the radius of curvature) and a horizontal velocity spread of \( \sigma_v = 1 \) mm/s (an upper limit obtained by detecting the cloud with a camera). It predicts a systematic effect of \( \Delta g = 2K_\sigma \sigma_v k_{eff} \approx 2 \) μGal. Because the wavefront aberrations do not have a well-defined shape, we did not correct for this effect but treated it as an error estimate. Thus, the systematic effect of wavefront aberrations is \( 0 \pm 2 \) μGal.

Vertical gravity gradients
VGGs are of the order of 3 μGal/cm, which cause an error if the effective measurement height of the instrument is unknown. The instrument
was mounted on adjustable feet, which contributed a change of ±0.5 cm in the effective height when leveling the instrument. Other than that, the effective height is known with better than millimeter precision relative to the pyramid mirror. This systematic error is 0 ± 2 μGal.

**Gouy phase**

The gradient of Gouy phase causes a relative decrease of $\Delta k_{\text{eff}}/k_{\text{eff}} = \lambda^2/(2\pi w_0^2)$ to the wave number and thus a scale factor error that depends on the waist $w_0$ of the laser beam. For $w_0 = 5$ mm, it amounts to $\Delta k_{\text{eff}}/k_{\text{eff}} = 1.47$ parts per billion, so that the measured value of $g$ needs to be corrected up by ~1 μGal. We estimated the error with the same magnitude of the correction. Thus, the systematic effect of Gouy phase is about ~1 ± 1 μGal.

**Laser frequency stability**

Laser frequency drift leads to an error to the wave number $k_\Delta$.

**Gal.** phase is about $-1 \pm 1$ magnitude of the correction. Thus, the systematic effect of Gouy phase causes a relative decrease of $k_\Delta$.

**Self-gravity**

Self-gravity of the instrument is dominated by the metal vacuum components, vibration isolation stage, and pyramid mirror. The metal vacuum components and vibration isolation stage attract the atomic cloud downward, while the pyramid mirror attracts it upward. The total self-gravity is less than 1 μGal, so that we can neglect it.

**Aperture effect**

The intensity variation of the interferometer beam caused by an aperture effect of the pyramidal hole is about 5% with a correlation length in the range of 100 to 200 μm, measured by a beam profiler. This effect on the accuracy of atomic gravimeters has been analyzed for 15% intensity variations and a similar correlation length (44). It shows that these effects decrease rapidly to below $10^{-3}$ as the thermal atom velocity exceeds a few millimeters per second because atoms average over high- and low-intensity spots. The thermal expansion speed of our atomic cloud is about 1 cm/s, so that the potential position-dependent phase shifts caused by the intensity ripple can be negligible.

**Evaluation of gravity measurement**

First, we characterized the short-term sensitivity and long-term stability of the atomic gravimeter by the Allan deviation of the measured residual gravity variation (Fig. 2C). The short-term sensitivity was calculated from fitting the Allan deviations from about 7 to 200 s using a function scaling with $\sqrt{\text{Hz}}$. The short-term sensitivity indicates how the measurement precision improves with longer averaging time. The long-term stability is the Allan deviation at an averaging time of about 2000 s, reflecting the best measurement precision. Second, we used standard uncertainty to evaluate the accuracy of the absolute gravity measurement. The value of the absolute gravity at each location is the mean value of more than 60 repetitive measurements. The uncertainty is the square root of a sum of statistical error and systematic error. We estimated the statistical error using the SEM. We investigated the systematic error according to the measurement method. We expressed the uncertainty of gravity values as a 1 − σ (68%) confidence interval.

**Latitude and terrain correction**

We corrected the gravity values collected in the Berkeley Hills for latitude variations using the WGS84 ellipsoidal gravity formula (45) to create latitude-corrected gravity anomalies. Furthermore, we corrected these gravity anomalies for the effects of terrain using a National Elevation Dataset 1–arc sec (~30 m) digital elevation model and the Plouff approach (46). The terrain correction was calculated in an annulus around a gravity station, with an inner radius of 50 m and an outer radius of 166.7 km, per standard practice. Most of the variability in the terrain correction among these stations arises from the terrain variability within 5 to 10 km of the stations. The local terrain is rougher at higher elevations in the Berkeley Hills than near their base, and local terrain effects always add to gravity (36). Hence, accounting for the terrain will yield a VGG that is smaller than the measured gradient and that can be used to estimate the density of the terrain via the Nettleton method (47).

To verify the measurement accuracy, we referenced to the gravity stations that were collected in 1998 by the USGS at 10 sites (37) along the same roads in the Berkeley Hills as our mobile atomic gravimeter. In (37), the 10 stations have the prefix of “98rp” and are numbered 094, 095, 096, 097, 149, 150, 151, 152, 161, and 162. The VGG and estimated terrain density values from these stations are 0.221(10) mGal/m and 2.1(2) g/cm³, respectively, which are equivalent within uncertainties to the values determined from the mobile atom gravimeter.

**Supplementary Materials**

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/5/9/eaax0800/DC1

Fig. S1. Cesium fluorescence inside the glass vacuum chamber.

Fig. S2. Measuring absolute gravity with different pulse separation time.

Fig. S3. Schematic of the laser system.

Fig. S4. Vibration isolation.

Fig. S5. Tidal gravity variation.

Fig. S6. Evaluation of systematic effects.

Fig. S7. Calibration of alignment to gravity axis.

Table S1. Systematic effects.

Table S2. Gravity survey in Campbell Hall in UC Berkeley campus.

Table S3. Gravity survey in Berkeley Hills.

**References and Notes**

1. Atom Interferometry, in Proceedings of the International School of Physics “Enrico Fermi,” Course CLXXVIII, G. M. Tino, M. A. Kasevich, Eds. (Societa Italiana di Fisica and IOS Press, 2014).

2. A. V. Rakhola, H. J. McGuinness, G. W. Biedermann, Dual-axis high-data-rate atom interferometer via cold ensemble exchange. Phys. Rev. Appl. 2, 054012 (2014).

3. K. S. Hardman, P. J. Everitt, G. D. McDonald, P. Manju, P. B. Wigley, M. A. Sooriyabandara, C. C. N. Kuhn, J. E. Debs, J. D. Close, N. P. Robins, Simultaneous precision gravimetry and magnetic gradiometry with a Bose-Einstein condensate: A high precision, quantum sensor. Phys. Rev. Lett. 117, 138501 (2016).

4. G. W. Hoth, B. Pelle, S. Riedl, J. Kitching, E. A. Donley, Point source atom interferometry with a cloud of finite size. Appl. Phys. Lett. 109, 071113 (2016).

5. M. Xin, W. S. Leong, Z. Chen, S.-Y. Lan, An atom interferometer inside a hollow-core photonic crystal fiber. Sci. Adv. 4, e1701723 (2018).

6. D. Savoie, M. Altorio, B. Fang, L. A. Sidorenkov, R. Geiger, A. Landragin, Interleaved atom interferometry for high-sensitivity inertial measurements. Sci. Adv. 4, eaau7948 (2018).

7. G. Rosi, F. Sorrentino, L. Cacciapuoti, M. Prevedelli, G. M. Tino, Precision measurement of the Newtonian gravitational constant using cold atoms. Nature 510, 518–521 (2014).

8. R. H. Parker, C. Yu, W. Zhong, B. Estey, H. Müller, Measurement of the fine-structure constant as a test of the standard model. Science 360, 191–195 (2018).

9. T. Kovachy, P. Asenbaum, C. Overstreet, C. A. Donnelly, S. M. Dickerson, A. Sugarbaker, J. M. Hogan, M. A. Kasevich, Quantum superposition at the half-metre scale. Nature 528, 530–533 (2015).
10. M. Jaffe, P. Haslinger, V. Xu, P. Hamilton, A. Upadhye, B. Elder, J. Khoury, H. Müller, Testing sub-gravitational forces on atoms from a miniature in-vacuum source mass. Nat. Phys. 13, 938–942 (2017).

11. A. Peters, K. Y. Chung, S. Chu, High-precision gravity measurements using atom interferometry. Metrologia 38, 25–61 (2001).

12. Z.-K. Hu, B.-L. Sun, X.-C. Duan, M.-K. Zhou, L.-L. Chen, S. Zhan, Z.-Q. Zhang, J. Luo, Demonstration of an ultrahigh-sensitivity atom-interferometer absolute gravimeter. Phys. Rev. A 88, 043610 (2013).

13. M. Lederer, Accuracy of the relative gravity measurement. Acta Geodyn. Geomater. 6, 383–390 (2009).

14. J. M. Goodkind, The superconducting gravimeter. Rev. Sci. Instrum. 70, 4131–4152 (1999).

15. R. P. Middlemiss, A. Samarelli, D. J. Paul, J. Hough, S. Rowan, G. D. Hammond, Measurement of the Earth tides with a MEMS gravimeter. Nature 531, 614–617 (2016).

16. T. M. Niebauer, G. S. Sasagawa, J. E. Faller, R. Hilt, F. Kloopeg. A new generation of absolute gravimeters. Metrologia 32, 159–190 (1995).

17. P. Gillot, O. Francis, A. Landragin, F. Pereira Dos Santos, S. Merlet, Stability comparison of two absolute gravimeters: Optical versus atomic interferometers. Metrologia 51, L15–L17 (2014).

18. C. Freier, M. Hauth, V. Schkolnik, B. Leykauf, M. Schilling, H. Wziontek, H.-G. Scherneck, H. Müller, Off-resonant Raman transition impact in an atom interferometer. Optica 5, 88 (2018).

19. B. Fang, I. Dutta, P. Gillot, D. Savioe, J. Lautier, B. Cheng, C. L. Garrido Alzar, R. Geiger, S. Merlet, F. Pereira Dos Santos, A. Landragin, Metrology with atom interferometry: Inertial sensors from surface to field applications. J. Phys. Conf. Ser. 723, 012050 (2016).

20. X. Zhang, J. Zhong, B. Tang, X. Chen, L. Zhou, P. Huang, J. Wang, M. Zhan, Compact portable laser system for mobile cold atomic gravimeters. Appl. Optics 57, 6545–6551 (2018).

21. Z. Fu, Q. Wang, Z. Wang, B. Wu, B. Cheng, Q. Lin, Participation in the absolute gravity comparison with a compact cold atom gravimeter. Chin. Opt. Lett. 17, 011204 (2019).

22. R. Geiger, V. Ménotret, G. Stern, N. Zahaam, P. Cheinet, B. Battelier, A. Villing, F. Moron, M. Lours, Y. Bidel, A. Bresson, A. Landragin, P. Bouyer, Detecting inertial effects with airborne matter-wave interferometry. Nat. Commun. 2, 474 (2011).

23. Y. Bidel, N. Zahaam, C. Blanchard, A. Bonnin, M. Cadoret, A. Bresson, D. Rouxel, M. F. Lequemec-Lalancette, Absolute marine gravimetry with matter-wave interferometry. Nat. Commun. 9, 627 (2018).

24. Y. Bidel, O. Carraz, R. Charière, M. Cadoret, N. Zahaam, A. Bresson, Compact cold atom gravimeter for field applications. Appl. Phys. Lett. 102, 144107 (2013).

25. Q. Boudart, S. Merlet, N. Malossi, F. Pereira Dos Santos, P. Bouyer, A. Landragin, A cold atom pyramidal gravimeter with a single laser beam. Appl. Phys. Lett. 96, 134101 (2010).

26. V. Ménotret, P. Vermeulen, N. Le Maigne, S. Bonvalot, P. Bouyer, A. Landragin, B. Desruelle, Gravity measurements below 10−9 g with a transportable absolute quantum gravimeter. Sci. Rep. 8, 12300 (2018).

27. X. Wu, F. Zi, J. Dudley, R. J. Bilotta, P. Canoza, H. Müller, Multiaxis atom interferometry with a single-diode laser and a pyramidal magneto-optical trap. Optica 12, 1545–1551 (2017).

28. F. Zi, X. Zhang, M. Huang, N. Li, K. Huang, X. Lu, A compact atom interferometer for field gravity measurements. Laser Phys. 29, 035304 (2019).

29. J. O. Liard, C. A. Sanchez, B. M. Wood, A. D. Inglis, R. J. Silliker, Gravimetry for Watt balance measurements. Metrologia 51, 352–354 (2014).

30. H. Wang, L. Wu, H. Chai, L. Bao, Y. Wang, Location accuracy of INS-gravity-integrated navigation system on the basis of ocean experiment and simulation. Sensors 17, 2961 (2017).

31. X. Wu, C. Huang, L.-C. Chang, C.-C. Ke, Short-time geodetic determination of aquifer storage coefficient in Taiwan. J. Geophys. Res. 123, 10987–11015 (2018).

32. X. Wu, Z. Pagel, B. S. Malek, T. H. Nguyen, F. Zi, D. S. Scheirer, H. Müller, Gravity surveys using a mobile atom interferometer. Sci. Adv. 5, eaax0800 (2019).