Workshop on « Quantum gravimetry in space and on ground »

Absolute gravity measurement for field applications based on quantum gravimeter

Qiang Lin

Zhejiang University of Technology

Email: qlin@zjut.edu.cn

27th May 2021

Outline

1. Background
2. Principle
3. Instrument
4. Applications
5. Conclusions

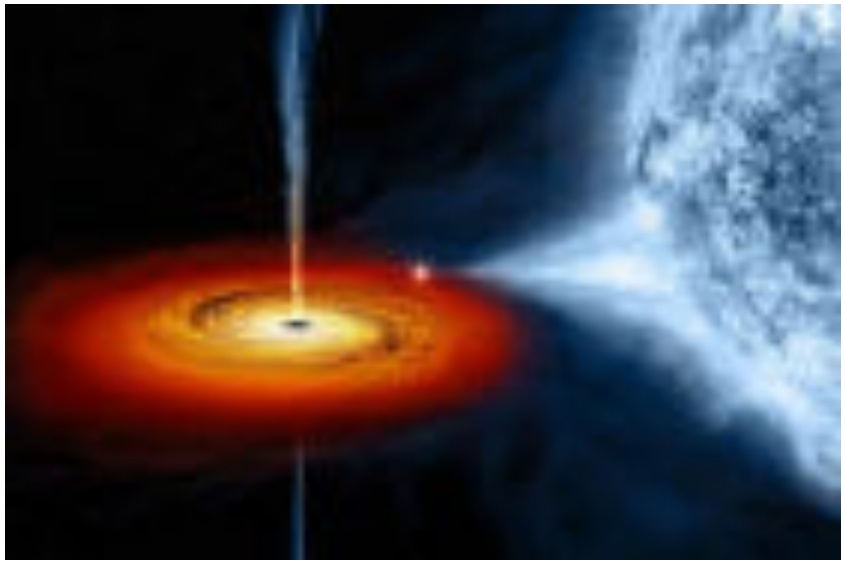
Outline

1. **Background**
2. Principle
3. Instrument
4. Applications
5. Conclusions

1. Background

Importance of the *g*

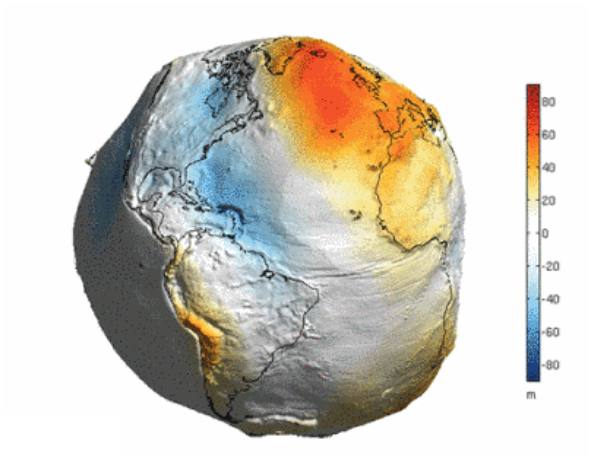
Gravitational wave—containing code of the Universe
LISA, TAIJI, TIANQIN
Gravity—containing the code of the Earth
Gravimeter—The key to solve the code of the Earth

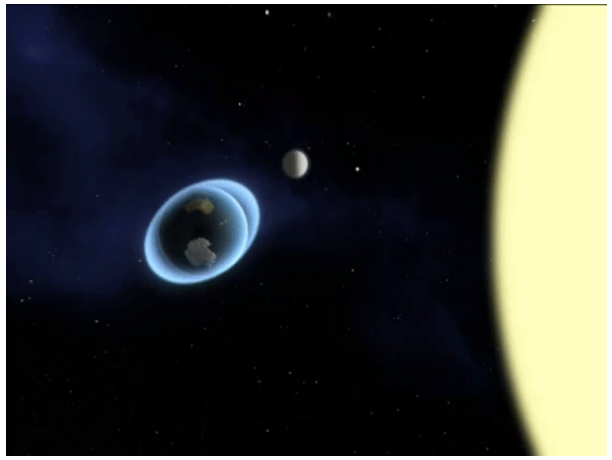


1. Background

Importance of the *g*

- The earth gravity field on the earth surface changes with space and time, because the earth is not an ideal sphere, and the moon revolves around the earth.
- Accurate measurement of the earth's gravity field has very important academic value and practical application value.





Changes with space： Vertical gradient of 300 μGal/m

Changes with time：tide≈280 μGal/day

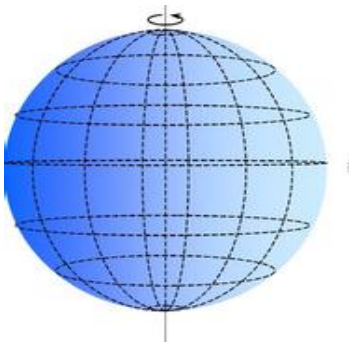
1. Background

Factors Affecting the *g*

1 Gal = 1 cm.s^{-2}

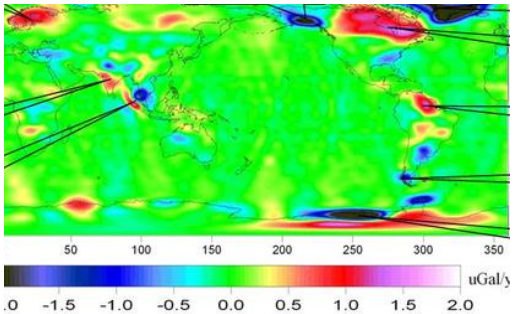
$$g = 979\ 341\ 114.3\ \text{mGal}$$

latitude



altitude

Local gravity anomaly

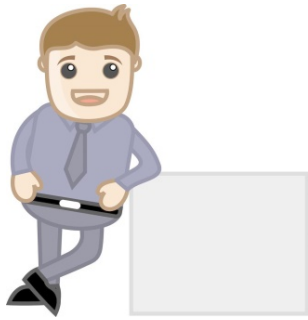


Earth tide

Atmospheric pressure

Polar movement

Human motion

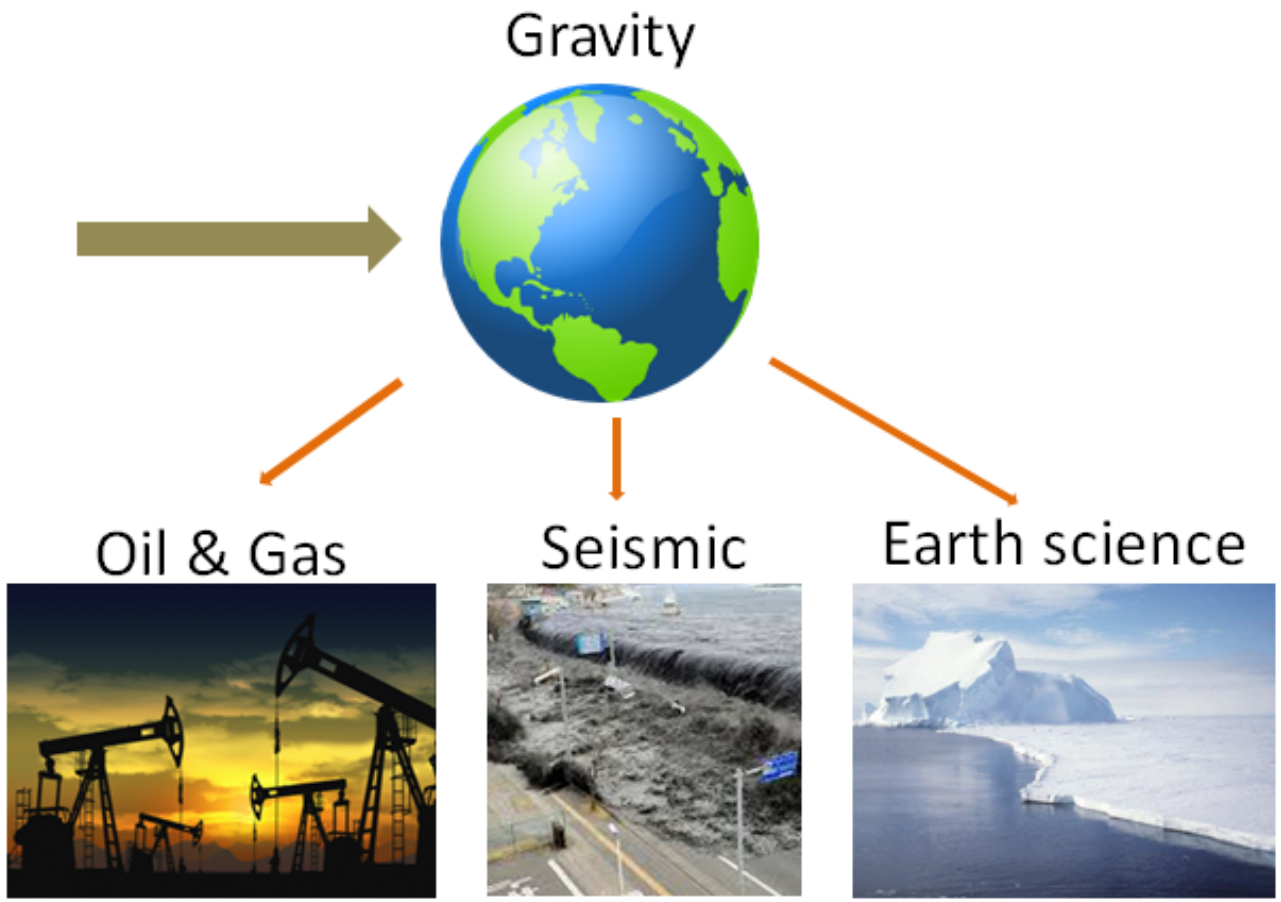


1. Background

Applications of the *g*

- **Resource Exploration**
- **Geophysics**
- **Seismology**
- **Metrology**
- **Hydrology**
- **Volcanology**
- **Geodesy**

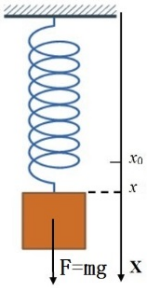
……

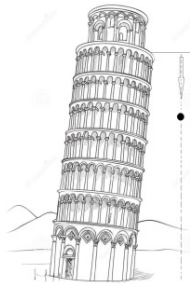


1. Background

Measurement of the *g*

Measurement type : relative and absolute gravity measurement

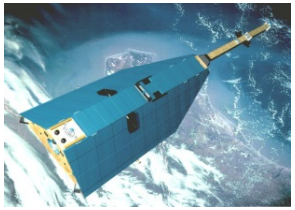




Measurement method : Static and dynamic gravimetry (mobile)



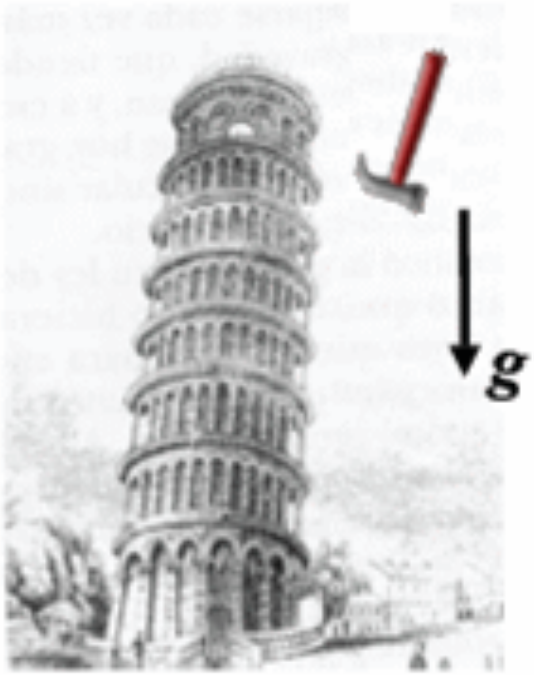


Measurement carrier: Vehicle gravity survey, marine gravity survey,
airborne gravity survey and satellite gravity survey

1. Background

Absolute Gravimeters



Classical method

FG-5

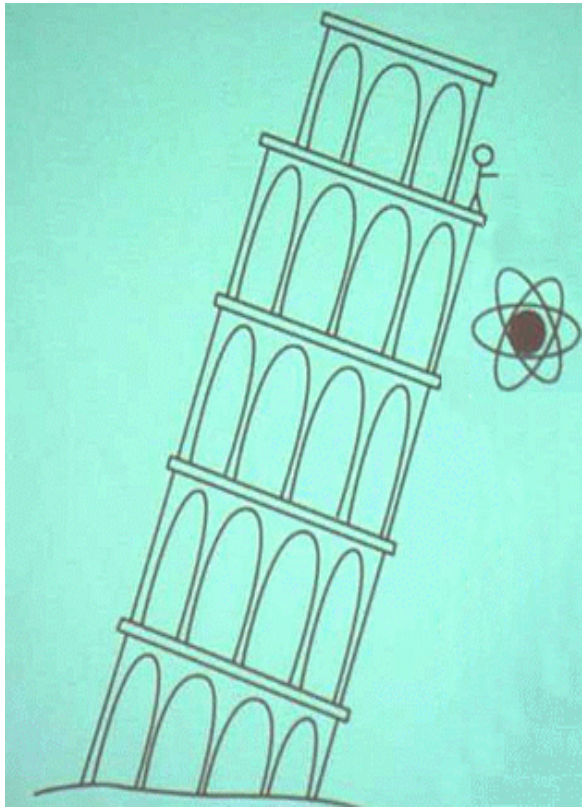
Accuracy: 2μGal

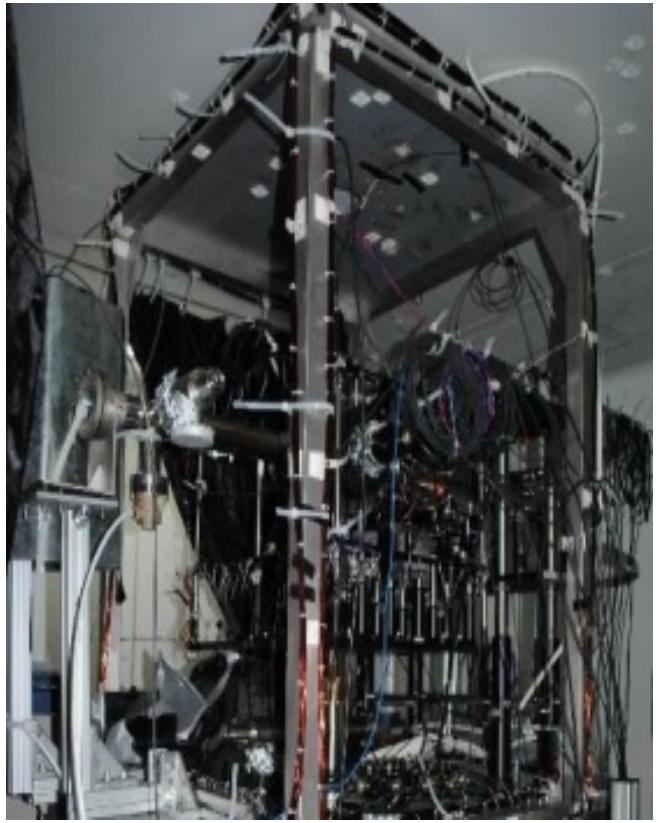
Sensitivity: 15μGal/$\sqrt{\text{Hz}}$

1. Background

Absolute Gravimeters

CAG

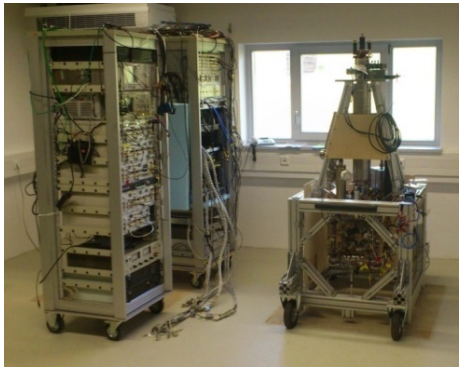




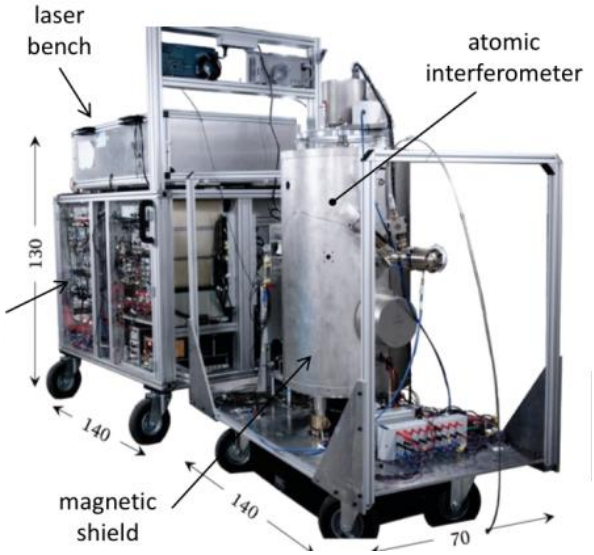
Advantages of quantum gravimeter: more precise, faster and can be worked in dynamic measurement method.

1. Background

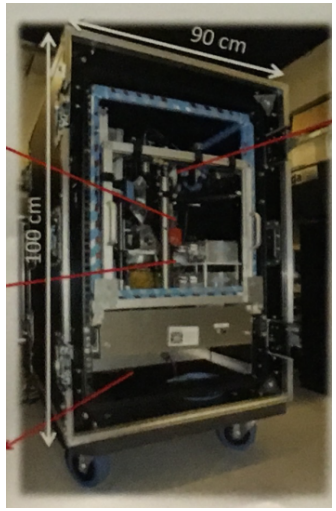
Transportable Quantum Gravimeters



Germen
Humboldt Universität
zu Berlin, GAIN



France
LNE-SYRTE
CAG-01



UK
University of
Birmingham

μQUANS

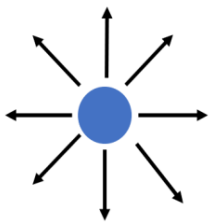
……

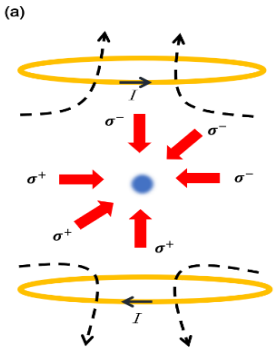
Outline

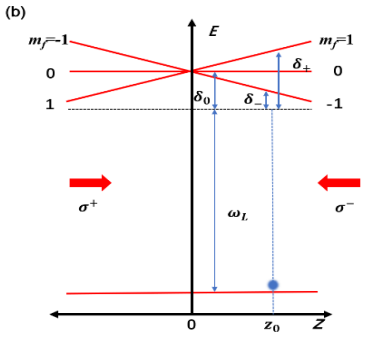
1. Background
2. **Principle**
3. Instrument
4. Applications
5. Conclusions

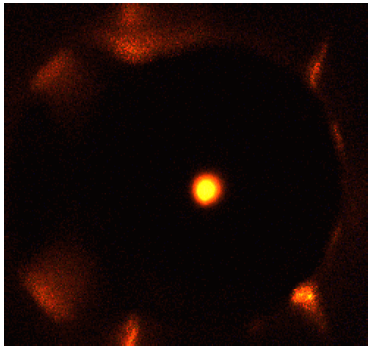
2. Principle

Doppler cooling and magneto-optical trap technology









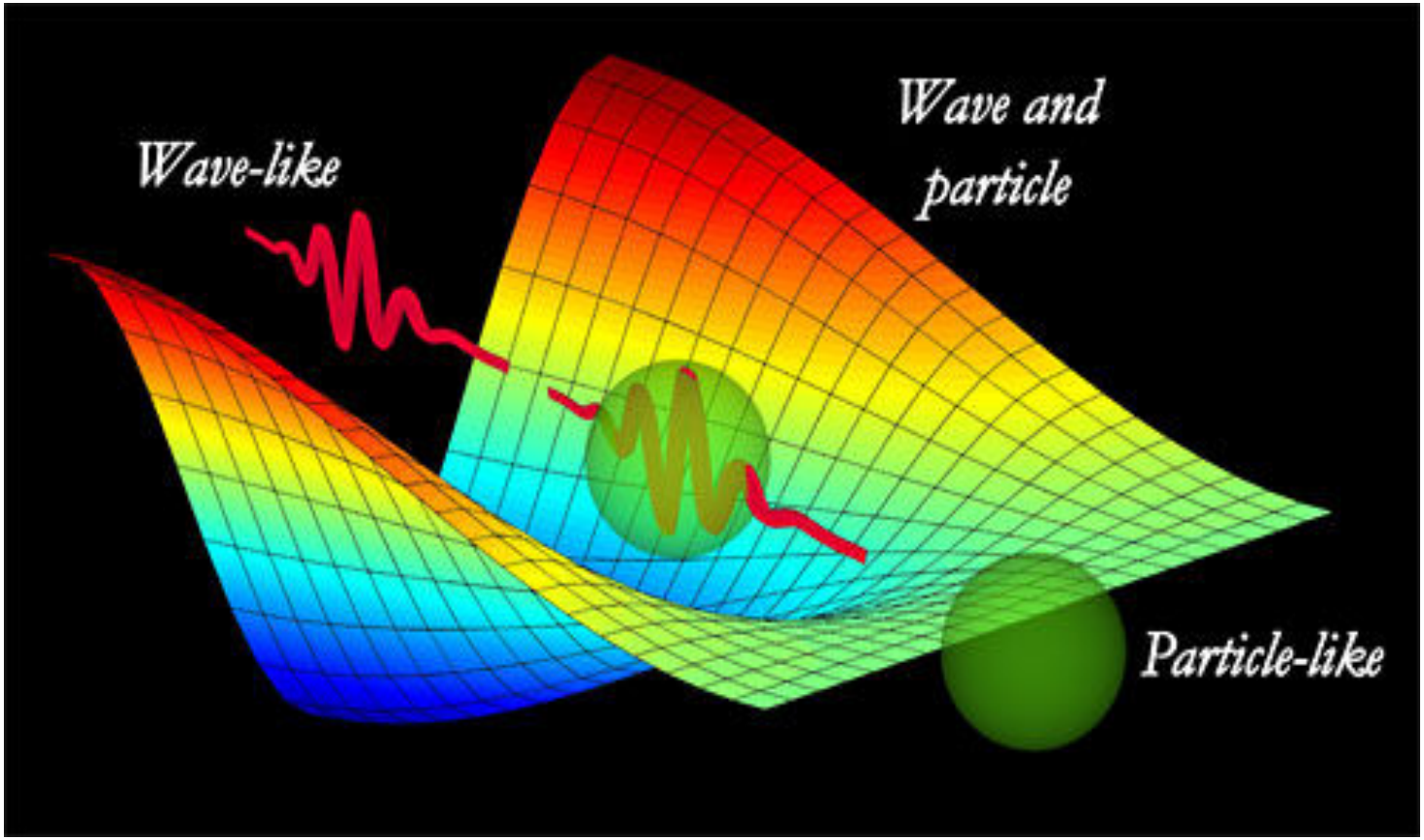
Doppler cooling

MOT

Trapped cold atom cloud

2. Principle

Cold atom interferometer based on particle wave duality

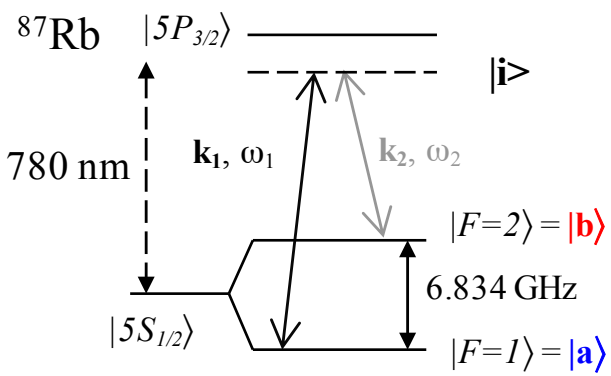


Wave particle duality of real particles

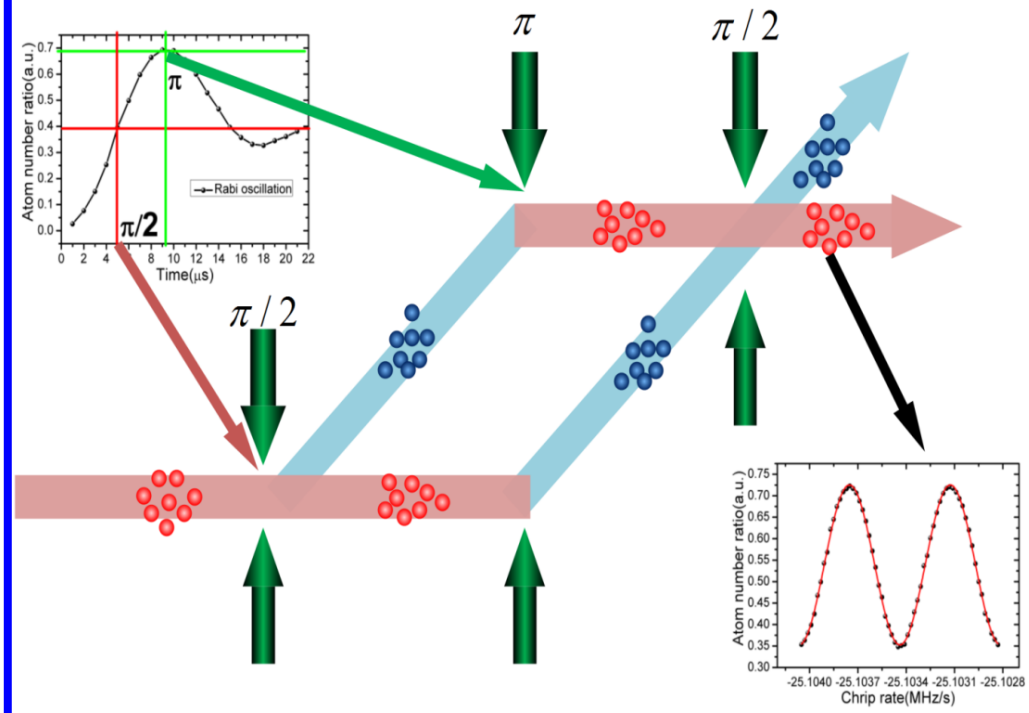
2. Principle

Atom interferometer

^{87}Rb simplified atomic level scheme



Two Photons Raman transition

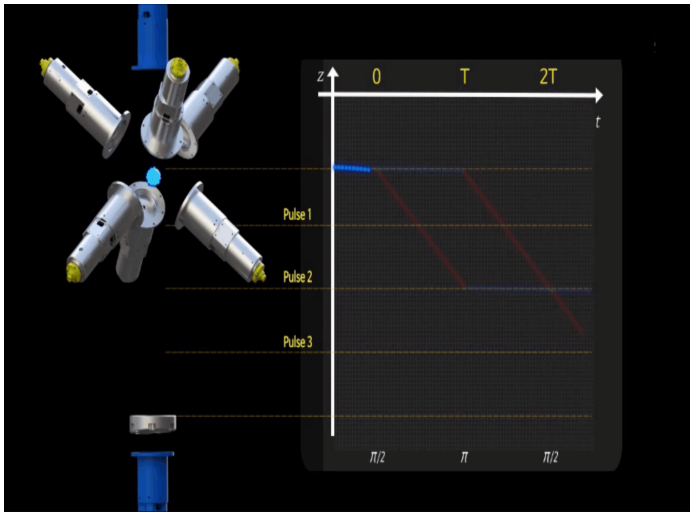


Mach-Zehnder Interferometer

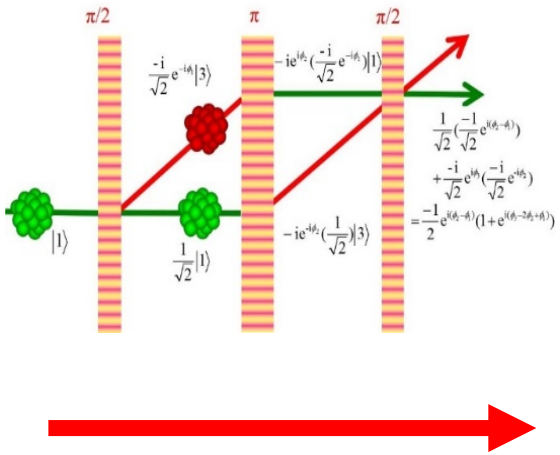
2. Principle

Quantum gravimeter

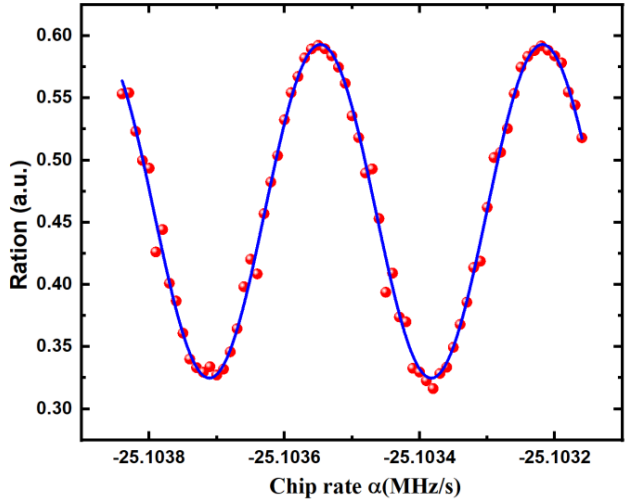
➢Quantum gravimeter is a new generation of ultra-high precision gravity detection device, which combines laser cooling and quantum state interference technology.



Working process of quantum gravimeter



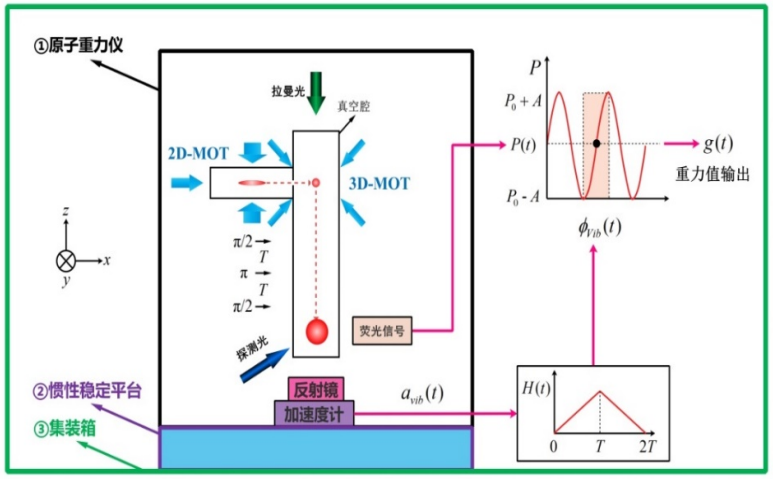
The atomic interference process

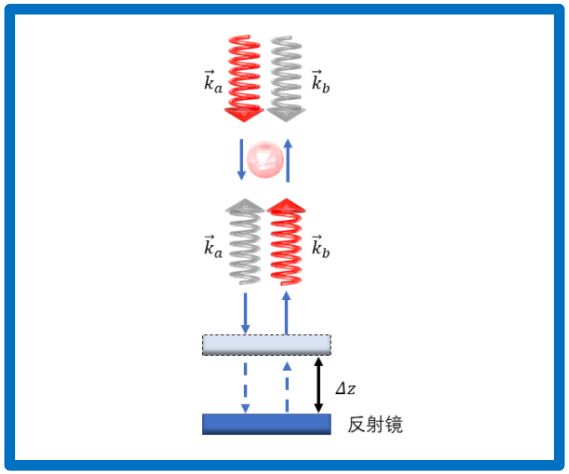


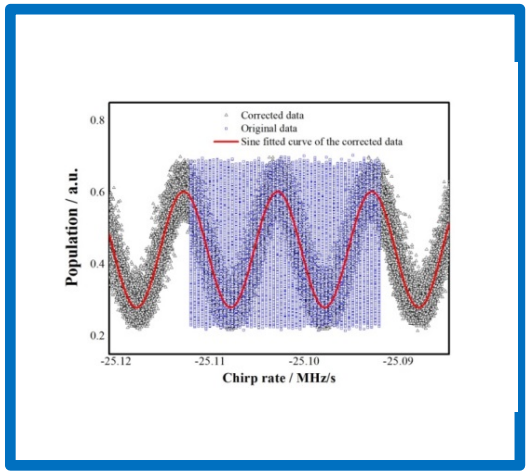
Atomic interference fringes

2. Principle

Dynamic absolute gravity measurement







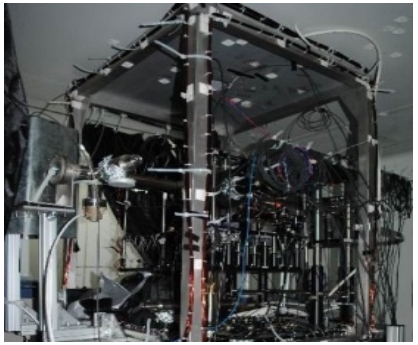
The suppression of the external acceleration, the influence of vibration phase and the compensation of vibration phase.

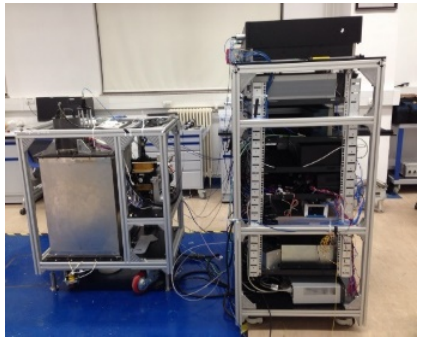
Outline

1. Background
2. Principle
3. **Instrument**
4. Applications
5. Conclusions

3. Instrument

History of our group





2006 start experiment

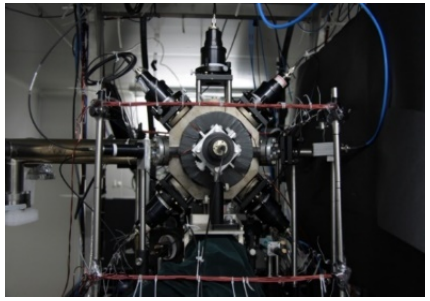
2011 lab setup

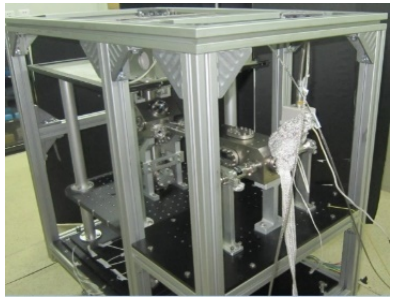
2016 portable Asia Pacific comparison

2017 International Comparison

2018 compact instrument

2019 Field applications

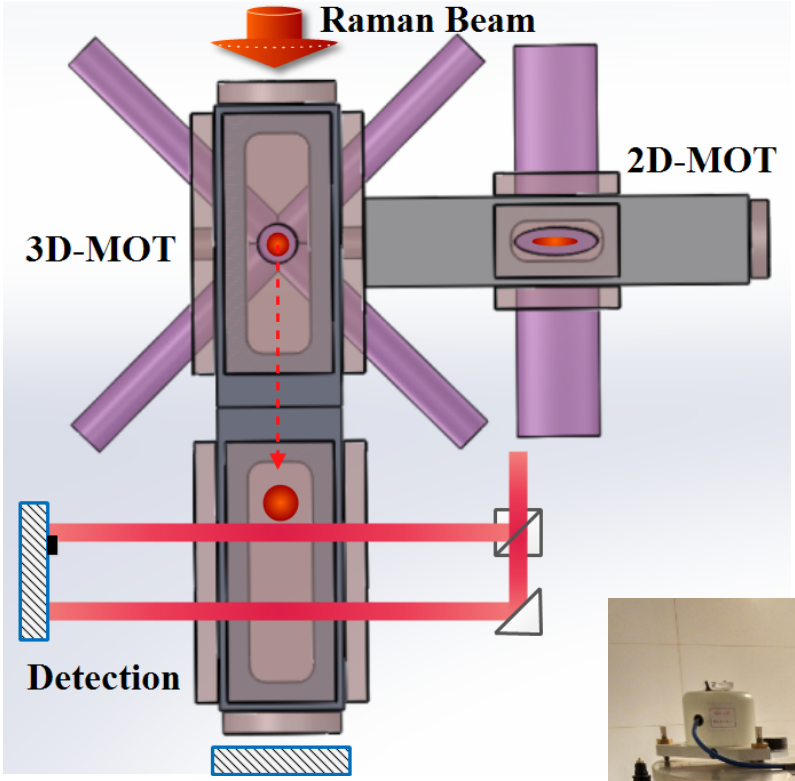


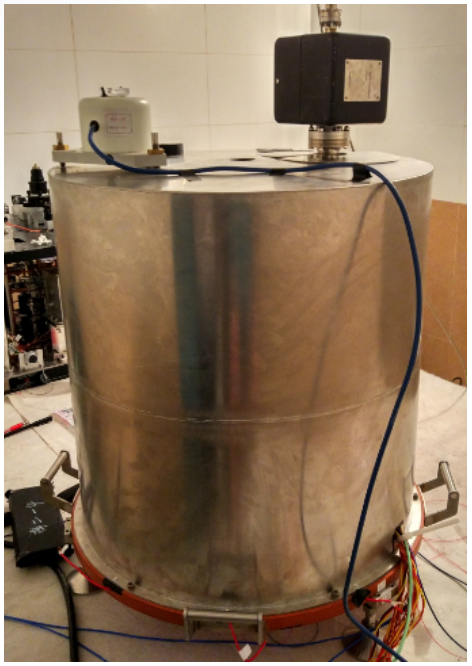


3. Instrument： Key Technology (1)

Vacuum Chamber

- All-glass cell
- Improved optical access
- Compact design
- No eddy currents
- Low He permeability
- Less than 10^{-7}Pa





The sensor head with
Single layer magnetic field shield

3. Instrument： Key Technology (2)

Electronic System

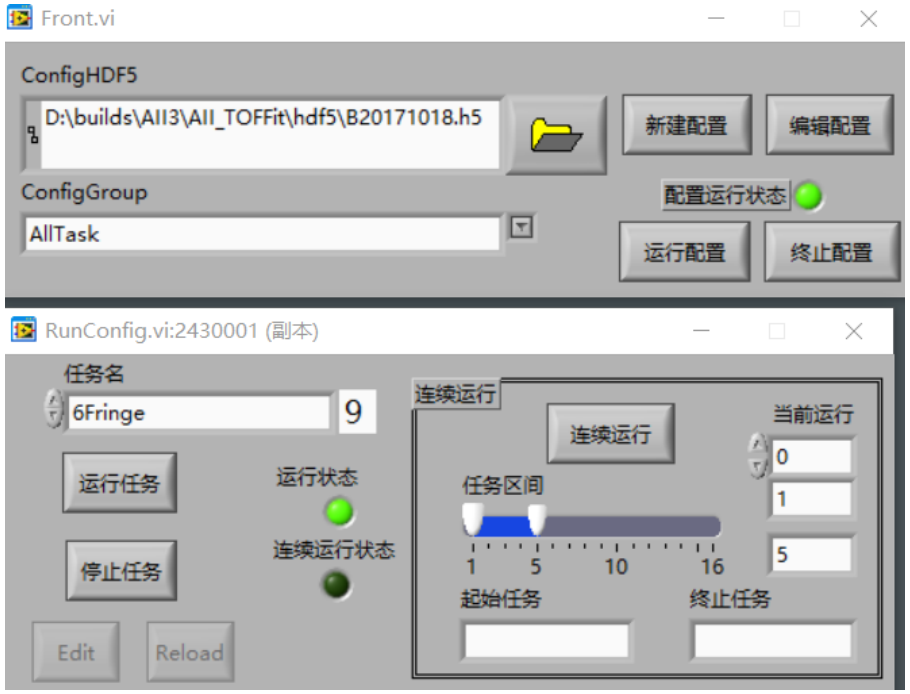
- Modular design
- Low power consumption
- Few cables to plug

$0.6 \times 0.9 \times 0.7 m^3$

3. Instrument： Key Technology (3)

Control System

- Parallel control
- Less time consuming
- Simplified program interface



3. Instrument： Integration

Technical Parameters

1. Performances	
Accuracy	5~10 μGal
Sensitivity	50-100 μGal / $Hz^{1/2}$
Repeatition	2 Hz
2. Physical package	
Dimensions	Sensor Module: h=0.52 m， D=0.55 m Laser Module: 0.9×0.6×0.7 m^3 Control Module: 0.9×0.6×0.7 m^3
Mass	70kg (Sensor Module only)
Power Consumption	150W

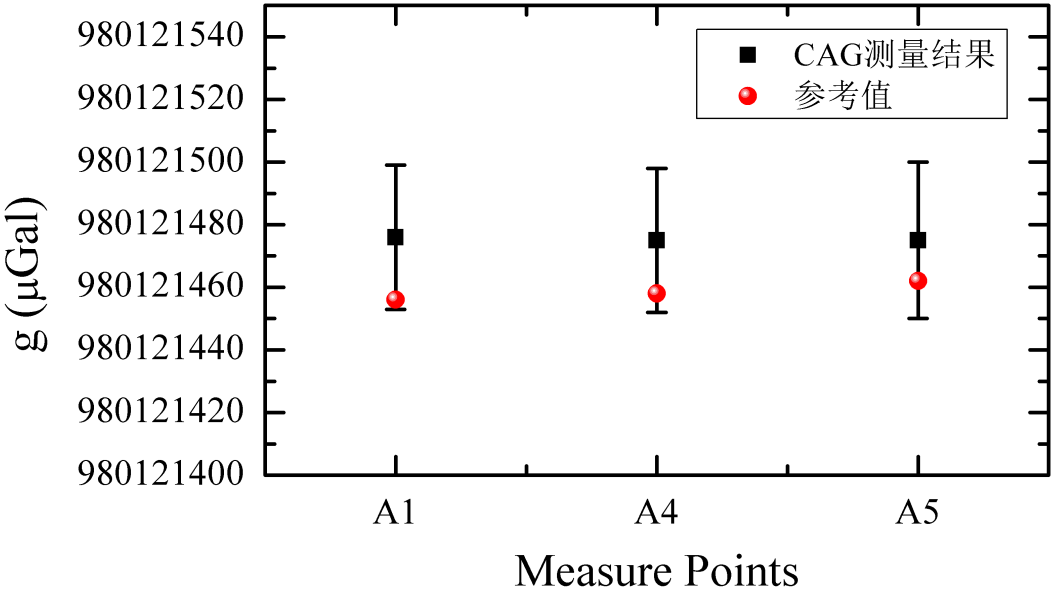
Outline

1. Background
2. Principle
3. Instrument
4. **Applications**
5. Conclusions

4. Applications: Asia Pacific comparison

APMP.M.G-K1 in 2016

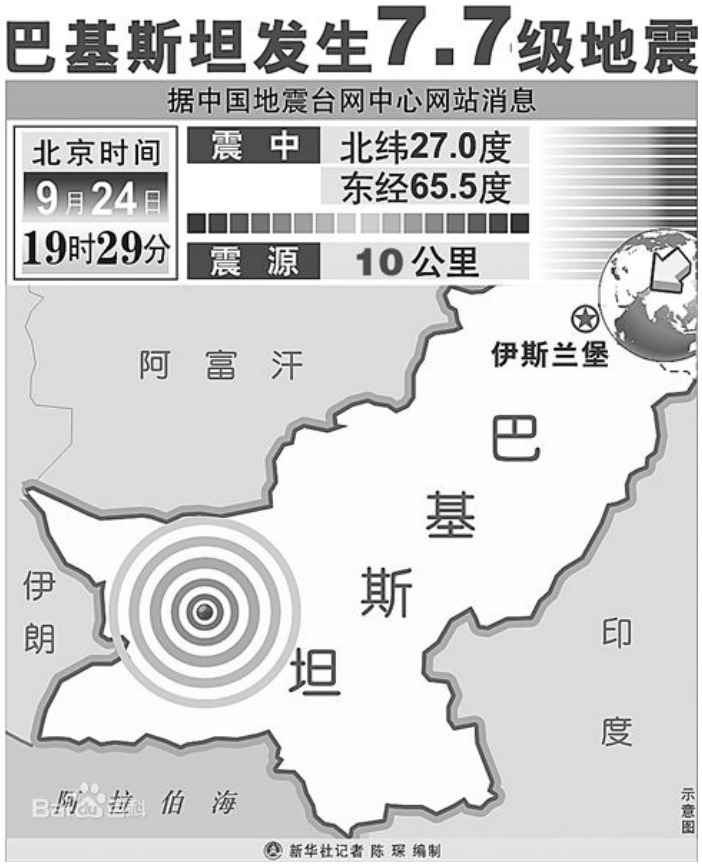
- Accuracy： 20μGal
- Sensitivity : 100μGal@1s

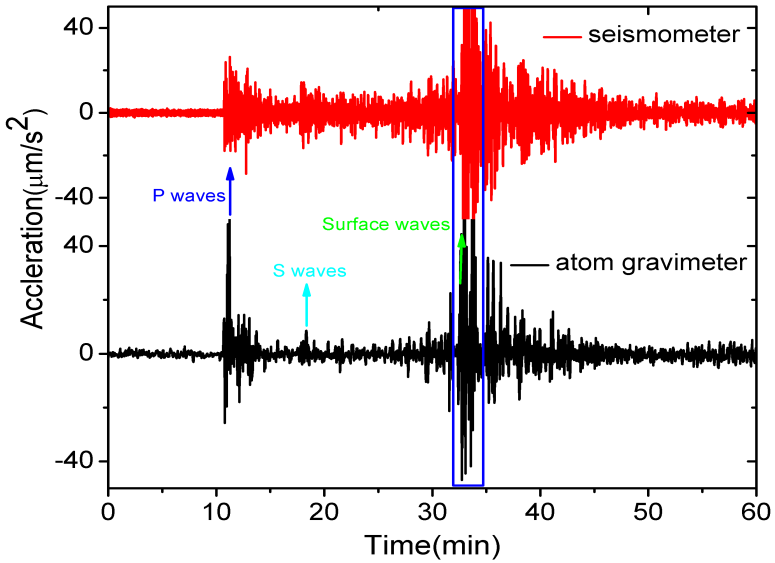


4. Applications: International comparison

The 10th International Comparison of global absolute gravimeters in Beijing in 2017 , Organized by Chinese Academy of Metrology

4. Applications: Earthquake monitoring





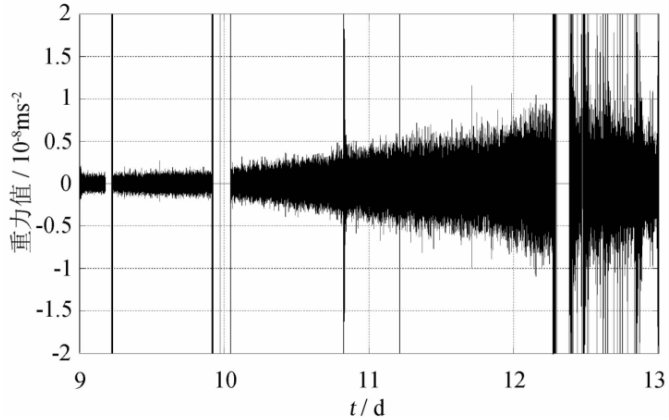
Time: 2013-09-28 15:34

Earthquake magnitude : 7. 2

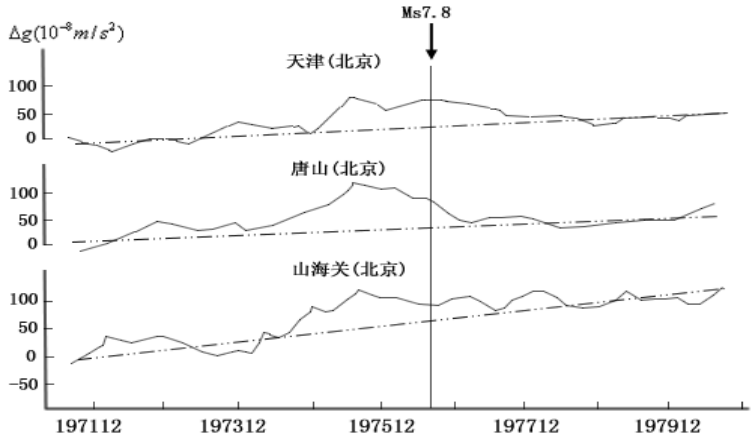
Source: Pakistan

4. Applications: Earthquake monitoring

On May 12, 2008, at 14:28:04, Wenchuan County, Sichuan Province, with a magnitude of 8.0, many people were killed.



Variation of gravity during Wenchuan Earthquake



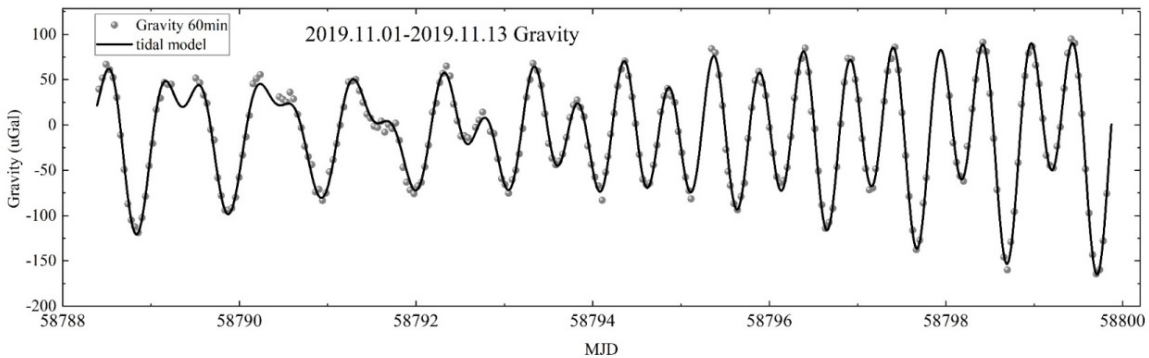
Time: 1976-07-28
Earthquake magnitude : 7. 8
Source: Tangshan, China
Change of gravity 100μGal

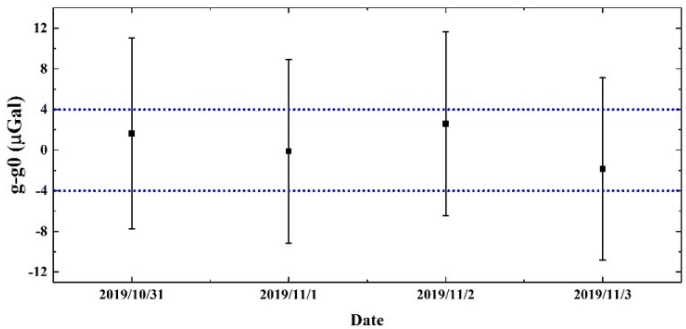
4. Applications: Long term monitoring

Long-term precise monitoring of the absolute gravity data

Location: Sichuan seismic station

Duration：14 days（November 2019）



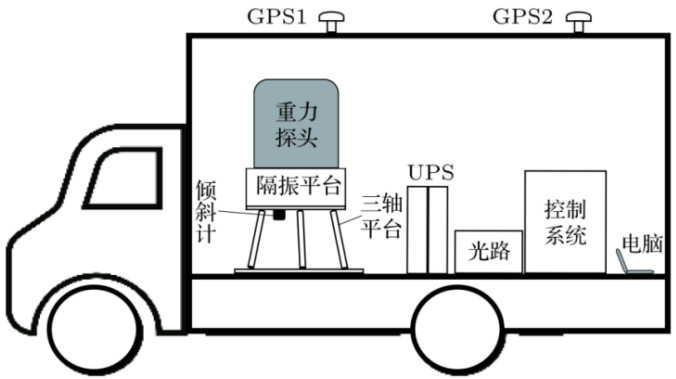


Accuracy：5μGal

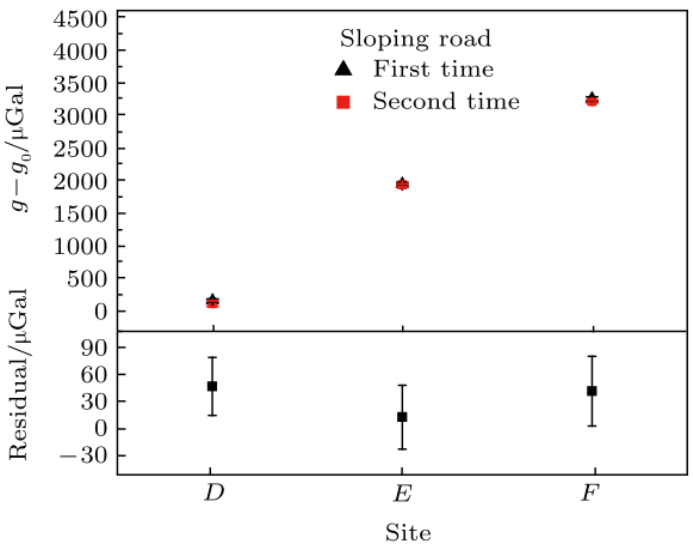
4. Applications: Vehicular gravity survey

The field vehicle gravity survey around a reservoir was done,

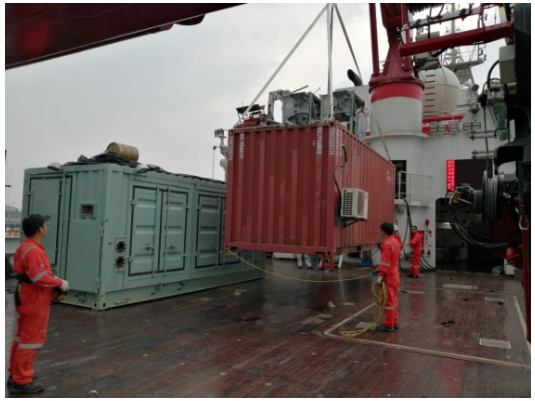
The accuracy is 30 μ Gal

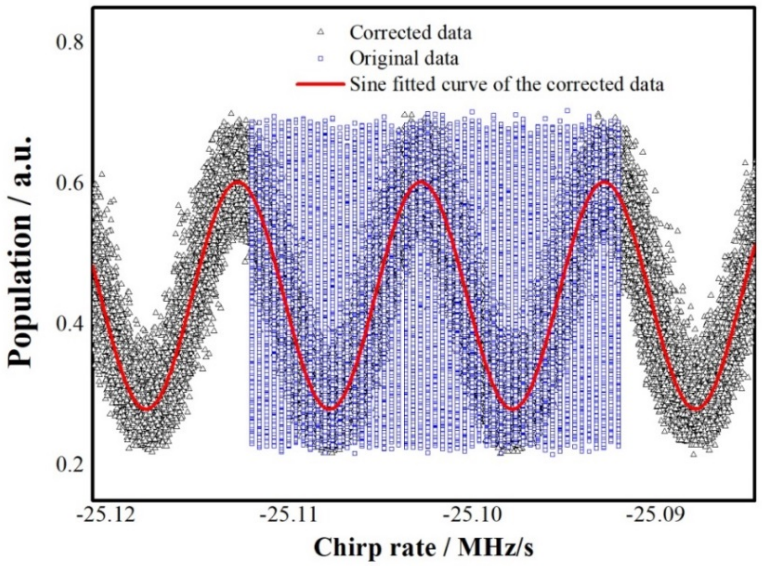


Field test route of atomic gravimeter

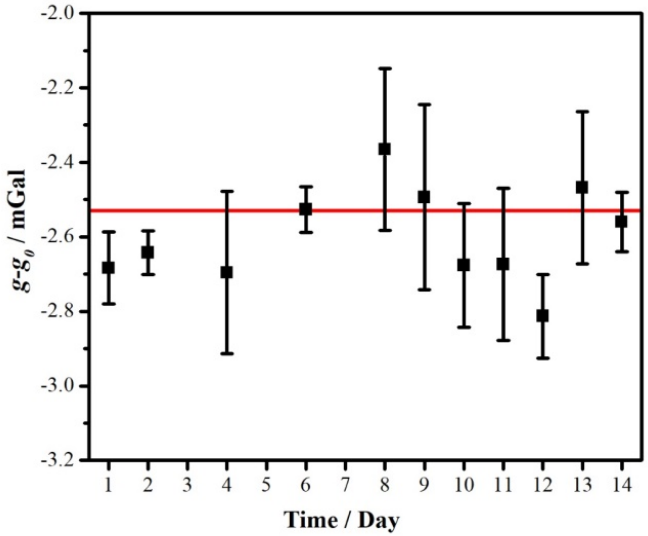


4. Applications: Shipboard mooring status





Vibration compensation



Accuracy：<1mGal

Outline

1. Background
2. Principle
3. Instrument
4. Applications
5. **Conclusions**

5. Conclusions

We have developed a compact quantum gravimeter, which is suitable for field applications, and can be transported for a long distance.

Measurement method	Accuracy
Laboratory static absolute gravity measurement[1]	**5-10 μGal**
Vehicle absolute gravity measurement [2]	**30 μGal**
Gravity measurement under shipboard mooring[3]	**134 μGal**

References:

[1] Fu Z, et al., A new type of compact gravimeter for long-term absolute gravity monitoring, Metrologia 56 025001, (2019).

[2] Wu B, et al. Static measurement of absolute gravity in truck based on atomic gravimeter, *Acta Phys. Sin.* 69(6): 060302, (2020)

[3] Cheng B, et al. Absolute gravity measurement based on atomic gravimeter under mooring state of a ship, *Acta Phys. Sin*. 70(4), 040304, (2021)

5. Conclusions : References

Research Article

applied optic

Active vibration isola
LADRC algorithm for

Yin Zhou,[1,†] Dongyun Luo,[1,2,†] Bin W
[1]Institute of Optics, Zhejiang Provincial Key Laboratory of Q
Technology, Hangzhou 310023, China
[2]College of Electronics, Jiujiang University, Jiujiang 332005,
[†]e-mail: bingcheng@zjut.edu.cn
*Corresponding author: qlin@zjut.edu.cn

Received 12 February 2020; revised 16 March 2020; acce
published 9 April 2020

A new, to the best of our knowledge, method
algorithm is proposed to design and build a v
This system combines the control system tha
a seismometer and a voice coil that is used to
form. When the feedback is on, the vertical vi
5 Hz, while the system has a steady oscillation
LADRC is an effective control algorithm for th
filters in our case. In addition, there are fewe
feedback gain of the system state error for its a

https://doi.org/10.1364/AO.390168

1. INTRODUCTION

The isolation of ultralow-frequency vibrational noise
cal issue in precise gravitational acceleration meas
using atomic interferometry (AI) [1–4]. In AI, the
of the mirror reflecting the Raman beam is the most
factor contributing to the interferometer phase noise
sequently reducing the sensitivity of the AI. Le Gou
used a passive isolation platform to sustain the interf
and adopted an efficient technique of vibration co
tion, which improved the sensitivity of the measure
rejecting residual vibrational noise with the help of a l
seismometer [5]. According to the vibration sensitivity
proposed by Cheinet *et al.* [6], the amplitude of the
function decreases proportionally to ω^2 (where ω is t
tion angular frequency), whereas at higher frequencies
corner frequency of the transfer function is $1/T$ (where
interferometer pulse spacing), and thus when the AI fu
used as a second-order low-pass filter, it is more sensiti
vibrational frequencies [7–9].

Lautier *et al.* [10] and Merlet *et al.* [11] adopted a
correction of the atomic interferometer phase by t
from a classical accelerometer, which allows it to opera
best performance without any isolation platform. Farah *et al.*
reported the best short-term sensitivity ever obtained without
any ground vibration isolation system with such an instrument:

Research Article Vol. 37, No

Journal of the Optical Society of America B

Compact magneto-optical tr
vacuum chamber for miniatu

Kanxing Weng,[1,†] Bin Wu,[1,†] Jiahong Lin,[1] Yin Zh
[1]Institute of Optics, The Zhejiang Provincial Key Laboratory of Quantum Precision
Zhejiang University of Technology, Hangzhou 310023, China
[2]e-mail: bingcheng@zjut.edu.cn
[3]e-mail: qlin@zjut.edu.cn

Received 13 February 2020; revised 22 March 2020; accepted 7 April 2020; pc

The realization of a compact magneto-optical trap (MOT) with
cooling laser is reported. The dependence of the properties of th
gated. The efficiency of capturing atoms of the novel MOT is com
compact quartz vacuum chamber can achieve a maximum rubidi
with less than 60 mW of the total power of cooling lasers, while
loading rate of about 3×10^9/s with more than 240 mW of the t
tus avoids undesired effects found in a metal chamber, such as hig
current effect. This compact MOT is helpful in the design of mir

https://doi.org/10.1364/JOSAB.390512

1. INTRODUCTION

The cold atom gravimeter developed in recent decades with
ultra-high sensitivity has shown its importance for precision
measurement [1–6]. The preparation of a sufficient amount
of cold atoms is the basic process of the atom gravimeter [7–9],
and it is the same for quantum information [10] and quantum
simulation [11,12]. Meanwhile, the invention and utilization
of magneto-optical trap (MOT) technology have greatly sim-
plified the technology of capturing cold atoms. So far, there
have been many excellent reviews on the basic theories of MOTs
[13–16]. With the progress of MOT technology, the structure of
MOTs has become diversified, from simple three-dimensional
MOTs (3D-MOTs) to two-dimensional MOTs (2D-MOT)
combined with 3D-MOTs [17], as well as the latest grating
MOT (G-MOT) [18], pyramid MOT (P-MOT) [19], and
mirror MOT (M-MOT) [20]. Among all these methods, the
2D-MOTs are used to produce a continuous slow atom flux
[21–23], which can effectively increase the loading rate and
atomic number in 3D-MOTs. It has become standard MOT
technology for trapping atoms and molecules. However, most
of the vacuum chambers of MOTs are made of metal, which is
bulky and unsuitable for miniature atomic sensors. In addition,
they often need the strong power of a cooling laser, and it is hard
to avoid the magnetic-field eddy current effect [24–27].

Therefore, some research groups have shown interest in inves-
tigating quartz vacuum chambers. Altin *et al.* [28] trapped
approximately 10^8 atoms (loading cycle of 500 ms) via a

An isolator that has a simpler and robust structure based on
a two-stage beam structure was proposed and demonstrated
[18]. A prototype system used an external sensor rather than

Participation in the absolu
compact cold

Zhijie Fu (付志杰)[1,2], Qiyu Wang (王启宇)[1],
Bing Cheng (程 冰)[4],
[1]Institute of Optics, Department of Physics
[2]Center for Optics and Optoelectronics Research,
Hangzhou
*Corresponding author: zhaoyingwang@zju.e

Received October 27, 2018; accepted Noven

The first Asia-Pacific Comparison of Absolute Grav
Institute of Metrology (NIM) of China from Decemb
compact cold atom gravimeter (CCAG) was transport
1200 km to participate in this comparison. The CCAC
on the principle of atom interferometry among all the
sites has been measured as requested by the orga
90 μGal/$\sqrt{\text{Hz}}$, even when the measurements are car
curacy of this gravimeter has been evaluated to be al
Our results show a good agreement with the given r

OCIS codes: 120.3180, 120.3940.
doi: 10.3788/COL201917.011204.

High-precision measurement of absolute gravity has a
wide application in geophysics, geology, hydrology, vol-
canology, etc. Accurate gravity measurement of a several
micro-gal (μGal)-level could reveal subtle changes in geo-
logical activities. For example, gravity values increasing
by 4 μGal can indicate 1 m elevation rising of volcanic lava
level[1]; scientists make this conclusion after long-time
precise gravity monitoring around the Kilauea Volcano.
Besides, volcanic activities may be predicted by continu-
ous absolute gravity measurements. Scientists found that
quick gravity decreasing and recovering of about 10 μGal
occurred before most volcanic eruption events[2]. On
the other hand, accurate absolute gravity measurements
also play an important role in hydrological observations.
Recent reports indicate that the changes of local water
storage are strongly correlated to local gravity variance.
When the water storage level rises by 100 mm, the gravity
value will increase about 4 μGal[3].

The accuracy of an absolute gravimeter (AG) is hardly to
be verified by itself, because the local absolute gravity value
is always changing with time and position. The only way to
verify its accuracy is to make comparisons with other high-
precision AGs, such as bilateral comparison[4–7], regional
comparison[8–9], and international comparison[10–11]. Since a
free-falling corner cube (FFCC)-type AG is based on differ-
ent working principles compared with atom interferometry
(AI)-type AG, bilateral comparison between them will be
beneficial for both instruments. For example, the research
group from the National Institute of Metrology (NIM)
of China demonstrated their cold atom AG (CAAG),
boasting with many advantages, such as high transmittance
(both sides of the quartz are AR coated), low coefficient of
thermal expansion, lack of magnetic field, and low helium per-
meability. Therefore, it can effectively avoid the system error
caused by the magnetic-field eddy current and other effects

Research Article Vol. 27, No. 8 | 15 Ap

Optics EXPRESS

Dependence of the sensitivity o
orientation for a free-fall atom g

Bin Wu,[1,4] Dong Zhu,[1,4] Bing Cheng,[1,5] Liming
Zhaoying Wang,[2] Qing Shu,[3] Rui Li,[3] Helin Wa
and Qiang Lin [1,6]
[1]Institute of Optics, College of Science, Zhejiang University of Techno
[2]Institute of Optics, Department of Physics, Zhejiang University, Hang
[3]China Aero Geophysical Survey and Remote Sensing Center for Natu
[4]These authors contributed equally to this work.
[5]bingcheng@zjut.edu.cn
[6]qlin@zjut.edu.cn

Abstract: The cold atom absolute gravimeters are intrinsically
to the Coriolis effect, which should be understood clearl
applications. The sensitivity on the orientation for a free-fall a
in this paper. The apparatus is simplified and improved a lot
measurement could be carried out within 20 minutes. From
found that the orientation angle has a dominant influe
measurement, especially when the horizontal velocity of atoms
magnitude and direction of average horizontal velocity of the
this experiment. In particular, the direction of East–West ha
gravimeter itself, such that gravity bias arising from Coriolis ef

1. Introduction

Mobile absolute gravimeters are of great interest for a wide r
instance, mobile absolute gravimeters could increase the eff
surveys, which are helpful for geophysics and seismic investig
0.02 mGal is required for the mobile gravimetric survey. For
compact absolute gravimeter on a truck allows the fast mea
gravity so that the flexibility and efficiency could be improve
absolute gravimeter with small size, light weight, and capabil
unavailable.

The cold atom absolute gravimeters (CAAG) could be
mentioned applications. In the past decades, the performances
substantially. In terms of sensitivities, a few μGal/$\sqrt{\text{Hz}}$ have b
higher than the classical FG5s. As for the accuracy, about 3-5
by operating these gravimeters in absolute gravity comparis
worse than that of FG5s (the best accuracy is about 2 μ
technology maturity of CAAG has been improved remarkably
compact and robust CAAGs have been developed [9–12]. Th
been produced [13] and the marine absolute gravimeter has bec

Intrinsically, the CAAG is sensitive to its orientation, wh
and may be a problem for field applications. Basically, the or
the horizontal velocity of atom along the East–west direc
interferometer sensitive to Earth's rotation through the Sagnac
as the Coriolis effect, which would yield a phase shift at the

#358808
Journal © 2019 Received 28 Jan 2019; revised 23 Mar 2019; accept

has wide applications in both the fields of fundamental
physics and applied physics, such as the measurement
of fundamental physics constants[22–23], the tests of the gen-
eral relativity[24], the equivalence principle[25], and the ex-
ploration for gravitational waves[26]. The test of the
equivalence principle at 10^{-8} level has been accomplished
by the Wuhan Institute of Physics and Mathematics with

IOP Publishing Metrologia
Metrologia 56 (2019) 025001 (8pp) https://doi.org/10.1088/1681-7575/aafcc7

A new type of compact gravimeter for long-term absolute gravity monitoring

Zhijie Fu[1,2], Bin Wu[2], Bing Cheng[2], Yin Zhou[2], Kanxing Weng[2], Dong Zhu[2], Zhaoying Wang[1] and Qiang Lin[2] 林强
[1] Department of Physics, Institute of Optics, Zhejiang University, Hangzhou 310027, People's Republic of China
[2] Center for Optics and Optoelectronics Research, College of Science, Zhejiang University of Technology, Hangzhou 310023, People's Republic of China
E-mail: wubin@zjut.edu.cn and qlin@zjut.edu.cn

Received 18 June 2018, revised 31 December 2018
Accepted for publication 9 January 2019
Published 8 February 2019

Abstract

Long-term absolute gravity monitoring has a wide range of applications in the field of geodesy, geophysics, seismology, volcanology, hydrology, etc. The traditional method of long-term absolute gravity monitoring is realized by the combination of absolute gravimeter and relative gravimeter. Here we report on a new type of compact gravimeter based on atom interferometry used for long-term absolute gravity measurements. The long-term absolute gravity monitoring could be carried out with only a single instrument. Over the course of a month we took long-term absolute gravity measurements in a seismic station. With an interrogation time of 120 ms and a repetition rate of 2 Hz, the sensitivity of our cold atom gravimeter reaches 300 μGal $\sqrt{\text{Hz}}^{-1}$ without any vibration isolation system, and the gravity residual fluctuations are within ±60 μGal.

Keywords: compact gravimeter, atom interferometry, long-term absolute gravity monitoring

(Some figures may appear in colour only in the online journal)

1. Introduction

Gravity field variations on the Earth's surface arise from a variety of geodynamic activities associated with mass redistribution. The long-term high-precision measurement of time-variable gravity provides a useful tool to investigate the dynamics of Earth [1]. It is also important to the study of other subjects, such as geology, geophysics, hydrology, seismology, volcanology, etc. The applications of long-term gravity measurement are growing considerably in recent years, and cover studying of the gravity tide model [2, 3], improving of the accuracy of relative gravimeters [3, 4], understanding of volcanic activity [5, 6], monitoring of seasonal groundwater variations [7, 8], and detecting of sea level changes [9], etc. For example, volcanic activities usually relate to gravity variance. Scientists find that most volcanic eruptive events are associated with precursory gravity decreases occurring over 5–6 h followed by quick recoveries lasting 1–2 h [10]. The amplitude of absolute gravity changing before volcanic eruption could be 10 μGal[3]. Other research shows a strong correlation with volcanic lava level and local gravity [11]. This research indicates that a one-meter elevation of the lava level will cause 4 μGal increase of gravity. Besides, long-term gravity monitoring also plays an important role in hydrology investigations. Another research paper identifies the hydrological models and karstic hydrological process with the help of three years' worth of long-term gravity measurements, which shows an underground water level rising of 24 mm will lead to a gravity increase up to 5 μGal [7]. The Caspian Sea level has been investigated by using both satellite radar altimetry and satellite gravity data, where the two results are corresponding [12].

With the rapid development of sophisticated gravimeters, include the free-falling corner-cube (FFCC) absolute gravimeters (such as the FG5 type) [13], superconducting relative

[3] 1 μGal = 10^{-8} m s^{-2}.

Many Thanks!

Email: qlin@zjut.edu.cn