Cold-Atom Absolute Gravimetry

Franck Pereira dos Santos[1] and Sylvain Bonvalot[2,3]
[1]LNE-SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, Paris, France
[2]Bureau Gravimétrique International (BGI), Toulouse, France
[3]IRD/Geosciences Environnement Toulouse (GET), Toulouse, France

Definition

Cold-atom absolute gravimetry: Measurement of the gravitational acceleration based on laser-cooled atom interferometry.

Introduction

The principle of measurement of the gravitational acceleration by dropping atoms rose up in the 1990s. The first applications quickly revealed the promising alternative of cold-atom gravimetry to classical free-fall techniques currently used to perform accurate and absolute measurements of the Earth gravity field (see Kasevich and Chu, 1992; Peters et al., 2009). Over the last two decades, practical realizations of instrumental devices based on atomic interferometry (cold-atom gravimeters) have thus been developed by different research laboratories in the world (Bodart et al., 2010; Charriere et al., 2012; Poli et al., 2010; Zhou et al., 2011; Altin et al., 2013; Bidel et al., 2013; Hauth et al., 2013; Hu et al., 2013; Wu et al., 2014). Based on the simple principle that measuring the acceleration of a freely falling mass provides an absolute determination of the local gravitational field, the falling proof mass is replaced in these devices by a cloud of falling atoms.

Prototypes of such instruments have been already evaluated and compared to the reference free-fall absolute gravity meter (FG5) developed by Micro-g LaCoste (Niebauer et al., 1995) during specific campaigns including the International Comparisons of Absolute Gravimeters (ICAG). Despite the present-day relative low portability of the prototypes involved in these previous comparisons, they provided significant high-quality results and confirmed the ability of cold-atom gravimetry to perform gravity measurements at the best standard levels provided by the current instrumentation (Van Camp et al., 2005). Current instrumental developments in cold-atom gravimetry or gradiometry (Guirk et al., 2002) are aimed at building miniaturized and automated portable instruments. These new generations of absolute gravity instruments that will provide discrete or continuous measurements in laboratory or field conditions concern a wide panel of scientific or industrial applications (geodesy, geophysics, hydrology, civil engineering, oil and mineral prospecting, reservoir monitoring, physics, metrology, etc.). Main aspects and performances of cold-atom gravimetry are summarized hereafter.

Principle of Cold-Atom Gravimeters

A cold-atom gravimeter is an inertial sensor in which a cloud of cold atoms periodically falls under the action of gravity. The wave properties of matter are exploited to create an atom interferometer, sensitive to acceleration. In such devices, alkali atoms (Cs or Rb) are manipulated thanks to lasers that allow trapping, cooling, driving the interferometer, and detecting the atoms.

A cold-atom gravimeter performs cyclic measurements of the gravity field. A measurement cycle comprises a preparation phase, where cold atoms are prepared thanks to laser cooling and trapping techniques, an interferometer phase, and a detection phase. The cycle time is typically of order of a few hundred ms. First, a sample of hundreds of millions of atoms at temperatures of a few μK is collected within a fraction of a second in a three-dimensional magneto-optical

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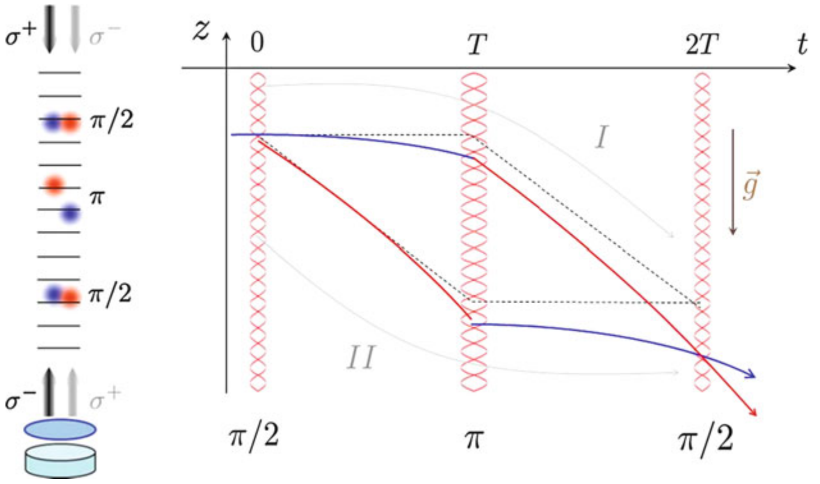


Cold-Atom Absolute Gravimetry, Figure 1 Schematic principal of cold-atom interferometry. A sequence of three Raman laser pulses allow splitting, redirecting, and recombining the matter waves, thus creating an atom interferometer, analogous to the Mach Zehnder in optics.

trap. Then, the sample of cold atoms is either dropped from the trap or launched upward. During its free fall, an atom interferometer is created in which atomic waves are split, redirected, and recombined using three laser pulses equally separated in time (see Figure 1). Finally, the atomic populations in the two output ports of the interferometer are measured. As in any two-wave interferometer, these populations depend on the interferometer phase, which is the difference of the phases accumulated by the atomic partial wave packets along the two arms. This phase difference is related to the laser phases at each pulse. It is given by a linear combination of the latter:

$$\Phi = \varphi_1 - 2\varphi_2 + \varphi_3 \tag{1}$$

where φ_i is the phase of the laser at the atoms position at the i-th pulse.

This writes

$$\mathit{\Phi} = k\left(z_1 - 2z_2 + z_3\right) = kgT^2 \tag{2}$$

where k is the wavevector of the laser, z_i the position of the atoms at the i-th pulse, g the gravity acceleration, and T the time between two consecutive pulses of the interferometer lasers. This is equivalent to a three-point measurement of the atomic trajectory, measured with a very fine ruler whose accuracy is linked to the precise knowledge of the laser wavelength. The scale factor of the sensor depends quadratically with the interferometer duration, so does the size of the trajectory of the atoms. Large-size instruments thus allow reaching higher intrinsic sensitivities (Dickerson et al., 2013).

In practice, as shown in Figure 2, the use of a hollow pyramid allows to perform all the required laser operations (cooling the atoms, driving the interferometer, and detecting the atoms) with a single laser beam arriving from the bottom, where a retroreflection mirror is used. The three-dimensional magneto-optical trap (MOT) includes magnetic coils in order to produce the null magnetic field required for atom trapping. The total height from the top of the pyramid to the detection is only 15 cm.

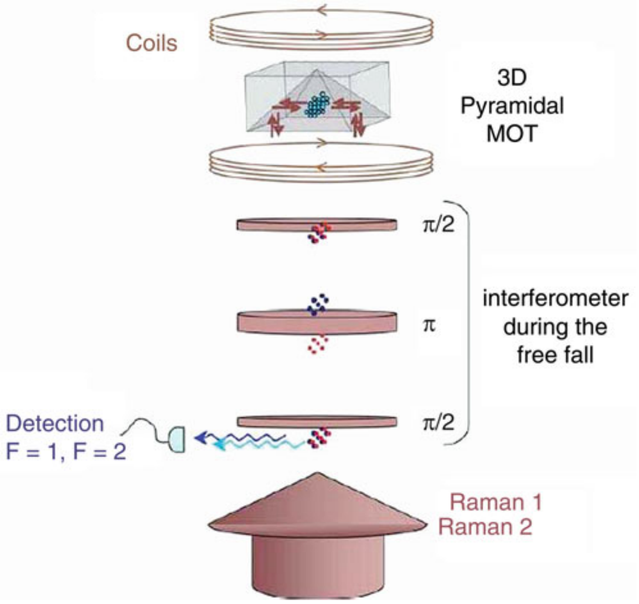
Examples and Results

Practical Realizations and Performances

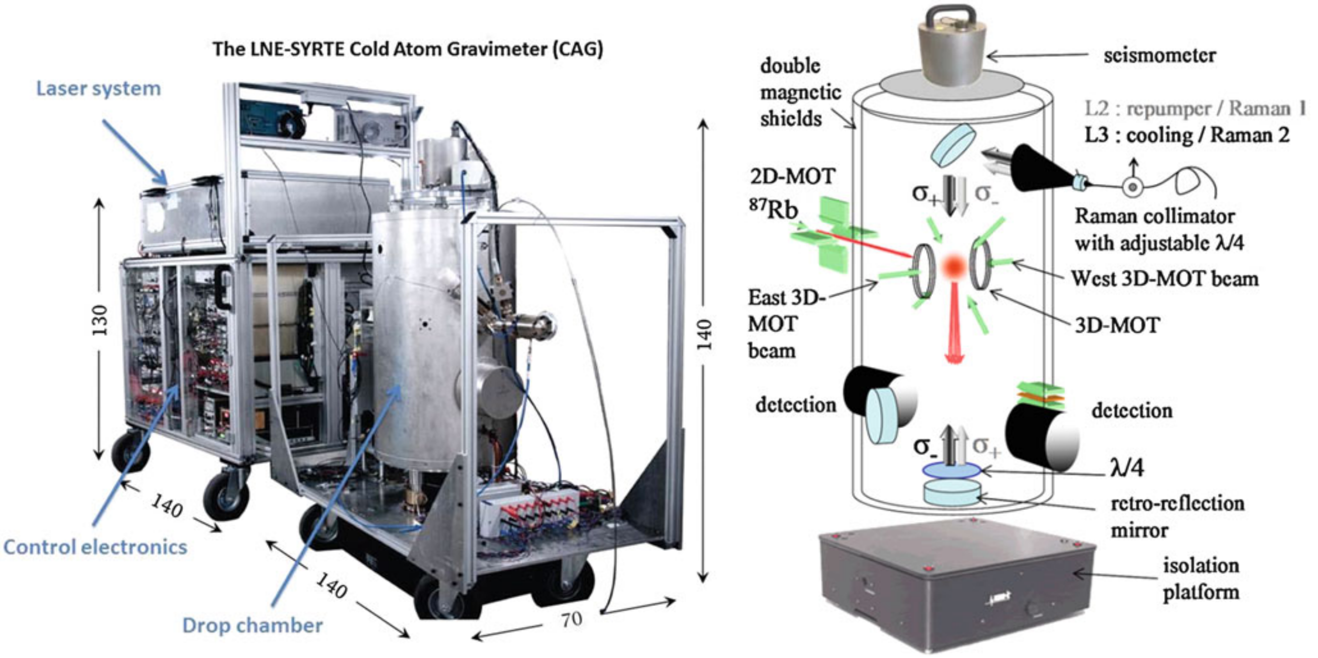
The first cold-atom gravimeter was developed in the 1990s in the group of Steve Chu at Stanford University (Peters et al., 2001). Since then, other instruments have been developed that reach performances that compete favorably with state-of-the-art classical corner cube gravimeters. With respect to the latter, cold-atom instruments allow for high cycling rate measurements (several Hz) and do not suffer from mechanical wear. They can thus perform continuous measurements for long times.

Basically, a cold-atom gravimeter is comprised of a dropping chamber, where the atoms are trapped and the interferometer takes place, a laser system, which delivers the required laser beams to the chamber, and a control electronics system, which supplies or acquires all necessary signals. As in other classical devices providing accurate absolute gravity measurements (i.e., free-fall absolute gravimeters), the dropping chamber needs to be isolated from ambient ground vibrations (related to seismic, environmental, or man-induced activities), which otherwise severely limit the sensitivity of the gravity measurement. Different types of compensation systems have been developed using either passive or active solutions.

Figure 3 represents the cold-atom gravimeter developed in LNE-SYRTE (Paris Observatory, France) that is a mobile laboratory instrument. The interferometer is realized in a titanium vacuum chamber, shielded from magnetic field fluctuations with two layers of mu metal (Le Gouët et al., 2008; Merlet et al., 2010; Figure 4).



Cold-Atom Absolute Gravimetry, Figure 2 Schematic experimental setup of a compact cold-atom gravimeter (From Bodart et al., 2010).

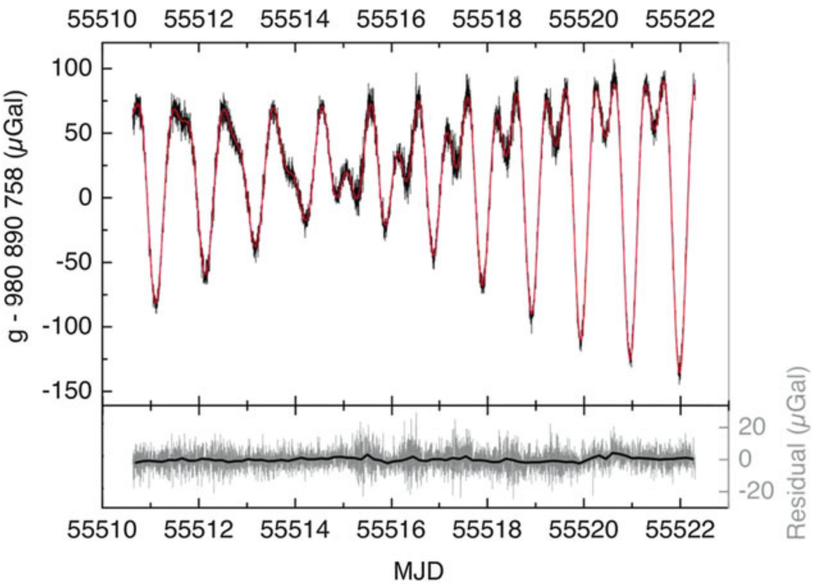


Cold-Atom Absolute Gravimetry, Figure 3 The LNE-SYRTE cold-atom gravimeter. The drop chamber is a titanium vacuum chamber, placed onto a passive isolation platform. The lasers are brought from the laser system to the chamber thanks to optical fiber. Dimensions are in cm (From Merlet et al., 2010; Louchet-Chauvet et al., 2011).

Results from Intercomparisons

Several comparisons between simultaneous measurements performed by cold-atom and corner cube gravimeters have been done in the frame of regional or international metrological campaigns (Arias et al., 2012; Francis et al., 2013). The measurement of the atom gravimeter was found to be, within its claimed inaccuracy, in agreement with the reference value obtained by averaging the measurements of all instruments. Up to now, only one atom gravimeter has participated to such international comparisons, and three times, but more such instruments are expected in the future.

In some cases, the superior sensitivity of the cold-atom technology with respect to corner cube technology has been shown (Gillot et al., 2014). A best short-term sensitivity of 4.2×10^{-9}g at 1 s was demonstrated in Hu et al. (2013), and



Cold-Atom Absolute Gravimetry, Figure 4 Comparison of continuous gravity recording performed with the cold-atom gravity meter from SYRTE (*black*) with a local model of Earth tides (*red*). Lower graph shows the residual when correcting the measurements from tides. Units are in μGal (From Louchet-Chauvet et al., 2011).

long-term stabilities in the low 10^{-10}g have been demonstrated.

As for the accuracy, it is limited by wavefront distortions of the interferometer lasers, which are due to optical aberrations. Reducing this effect requires extremely high-quality optics, of flatness better than $\lambda/100$. Best accuracies of a few 10^{-9}g (Peters et al., 2001; Louchet-Chauvet et al., 2011) have been validated, in bilateral comparisons (Peters et al., 2001; Merlet et al., 2010) or large international comparisons campaigns (Arias et al., 2012; Francis et al., 2013).

Perspectives

The maturity of the cold-atom technology and its potential for applications in the fields of geophysics and defense have triggered the creation of companies that now manufacture cold-atom gravimeters (see, for instance, AOSense – http://aosense.com/solutions/gravimeter or the μQuans gravimeter displayed on figure 5, μQuans http://www.muquans.com/index.php/products/aqg). New generations of absolute gravity meters are thus expected in a very next future.

Providing that significant improvements with respect to the existing laboratory instrumentation will be done (i.e., portability, thermal control, autonomous power supply, etc.), such gravity meters are likely to offer new facilities to acquire accurate and absolute measurements of the Earth's gravity field in laboratory and field conditions. As such devices do not suffer from mechanical wear, they can perform continuous measurements, as diplayed on figure 4, at high acquisition rates (typically 1 Hz) for long times (over months or years). Such performances may be of special interest in many applications covered nowadays by free-fall absolute gravity meters and by relative superconducting gravity meters.

Concepts of using cold-atom interferometers for future space gravity missions for measuring the diagonal elements of the gravity gradient tensor and the spacecraft angular velocity have been also suggested (Carraz et al., 2014). They are believed to provide better performances than previous space gravity missions GRACE and GOCE for determining the fine structures of the gravity field and detecting time-variable signals in the gravity field respectively. Such technology might then open also new perspectives for measuring gravity anomalies from moving platforms from space (future satellite missions) as well as on Earth's surface (airborne, marine, or submarine surveys) (Geiger et al., 2011). Other applications of atom interferometers for gravimetry are the determination of the Newtonian gravitational constant (Fixler et al., 2007; Rosi et al., 2014), the test of the weak equivalence principle (Bonnin et al., 2013; Aguilera et al., 2014), and long baseline gradiometry for gravitational wave detection (Dimopoulos et al., 2008).

Conclusions

Cold-atom gravimetry uses the wave properties of matter to create an atom interferometer, sensitive to acceleration. In such technology, lasers are used to first prepare samples of cold atoms that are then let to freely fall. During their fall, a sequence of laser pulses creates an atom interferometer, in which gravity acceleration induces a difference in the phase

Cold-Atom Absolute Gravimetry, Figure 5 Example of compact cold-atom gravimeter: The first commercial absolute quantum gravimeter developed by μQuans, France http://www.muquans.com/index.php/products/aqg

accumulated by the atomic wave packets in the two arms of the interferometer. This phase difference is readout by detecting the atoms in the output ports of the interferometer.

Developed since the 1990s, the cold-atom gravimetry now reaches a level of maturity that enables practical realizations with compact and high sensitivity instruments. Their performances, evaluated from intercomparisons with classical free-fall absolute gravity meters, confirm that cold-atom gravity meters are able to perform absolute gravity measurements at the μGal level within the best standard measurements.

New generations of instruments, currently under development, are believed to perform absolute gravity measurements in laboratory or field conditions, thus providing a wider instrumentation for acquiring discrete or continuous determination of the gravity field. Such instrumentation may concern a wide panel of scientific or industrial applications (geodesy, geophysics, hydrology, oil and mineral prospecting, reservoir monitoring, civil engineering geodesy, physics, metrology, etc.). Along with existing classical relative and absolute gravimeters and other geodetic instruments, these new instruments should significantly contribute to improve, for instance, the determination of gravity field anomalies and gravity field time series (spatial and time-variable gravity), of gravity networks (earthquake, volcano, or hydrological geodesy), and the interrelation Geodesy-Geophysics (fundamental geodetic stations, reference frames, gravity, and geodetic datum).

Cross-References

- ▶ Absolute Gravity Measurements
- ▶ Earthquake Geodesy
- ▶ Engineering Geodesy
- ▶ Fundamental Geodetic Stations
- ▶ Geodetic Datum
- ▶ Gravity Anomalies
- ▶ Gravity Field Time Series
- ▶ Gravity Networks
- ▶ Interrelation Geodesy-Geophysics
- ▶ Reference Frames
- ▶ Regional Gravity Field Determination
- ▶ Superconducting Gravity Meters

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