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From apples to atoms: measuring gravity with ultra cold atomic test masses


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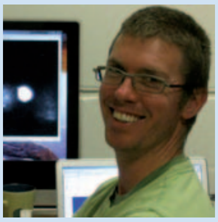
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Over 250 years ago Sir Isaac Newton, inspired by an apple falling from a tree in his orchard (Stuckeley 1752), made the mental leap to conjecture that the same force that caused this apple to fall also held the Moon to the Earth. This stimulated him to develop his Law of Gravitation, and led to the principle that all objects fall with the same acceleration irrespective of their mass, as observed by Galileo Galilei. Over 250 years ago, these scientists understood gravity as well as many people do today. In reality, we still measure gravity by dropping a proverbial apple – a falling test mass whose trajectory we measure through space–time. However, developments over the past two centuries have led to a vast improvement in our measurement precision. With the advent of the optical laser and atom interferometers over the past 50 years, we have far superior rulers, and far superior clocks with which to make such a measurement.

Mankind's most precise instruments are those that measure space and time. At the heart of these measurement devices is the phenomenon of wave interference. For example, the most precise rulers to date are optical interferometers, built for the detection of gravitational waves using very long baseline interferometers such as the Laser Interferometer Gravitational Wave Observatory (LIGO). This device measures distance with a sensitivity up to 1 part in 10^{24} (The LIGO Scientific Collaboration and The Virgo Collaboration 2012). On the other hand, the most precise keeper of time is an atomic clock. With its ceaseless ringing, a caesium atom is an oscillator that defines the International System of Units (SI) second at the level of 1 part in 10^{16} (Heavner *et al*. 2005). Precise measurement of the absorption of radiation at 9 192 631 770 Hz by caesium again relies on interference, in this case the interference of matter-waves in an *atom interferometer*.

More recently, atom interferometers have been used to measure inertial forces, such as the acceleration due to gravity. Indeed, state-of-the-art absolute gravimeters now include those that use free falling atomic ensembles (Altin *et al*. 2013, Peters *et al*. 2001). The measurement of gravity and its gradients has wide spread applications in the Earth sciences and the geophysics community. Such measurements give valuable information about density structure and changes to the geoid due to tectonic plate movement, magma flows, volcanic activity, and tidal forces. One notable recent example of gravity measurement is the data taken from the GRACE (Gravity Recovery and Climate Experiment) satellite mission (Leblanc *et al*. 2009), which has allowed monitoring of groundwater variation in the Murray-Darling tidal basin. Such measurements have a direct impact on Australian government policy.

In geophysical exploration, gravity and its gradients are a key metric for performing broad surveys of potential resource sites. For example, gravity gradients have become commercial ventures for Fugro, using its Falcon device, and Bell Aerospace with the Lockheed-Martin Full Tensor Gravity Gradiometer (FTG). These devices operate on mature, mechanical technology dating as far back as the 1970s. The University of Western Australia, in collaboration with Rio Tinto, has also been developing a competing aircraft-based gradient system (Anstie *et al*. 2010). More recently, time-resolved gravity data have been used to monitor oil and gas reservoirs, including the movement of fluid fronts (Zumberge *et al*. 2008).

Atomic gravimeters

As we move into the 21st century, atomic devices are not only becoming viable technology for the next generation devices, they also offer generous potential increases in precision. With increased precision, comes increased vision into the Earth's surface. In part, this is the result of developments in technology, which has seen our ability to control the motion of atoms using lasers reach exquisite levels. Combined with their universal properties (all atoms of a given element are equivalent), and their non-mechanical nature, atoms offer potentially fewer systematics, and more robust, reproducible, and configurable systems.

In an atomic based gravimeter, atoms are allowed to fall freely in vacuum, and their position is tracked precisely with an optical laser beam, while an atomic clock is used to time their motion. The laser, aligned vertically, effectively forms a ruler, encoding the number of wavelengths the atoms have fallen through onto the quantum state of the atoms. Interference of the atomic matter waves then allows precise counting of the number of traversed wavelengths, just as interference in an optical interferometer allows precise measurement of, for example, a

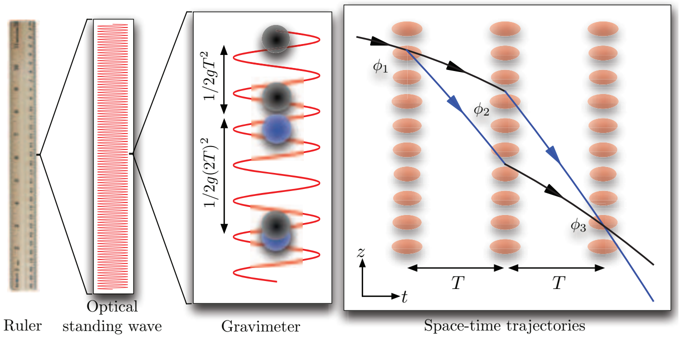

Fig. 1. *Basic operation of an atomic gravimeter. An atomic cloud falls freely under gravity through an optical standing wave, which forms an 'optical ruler' with a precision proportional to its wavelength. Three pulses of the standing wave are applied, separated equally in time and with appropriate durations to beam split, reflect, and recombine the atomic wave packets as shown in the space-time diagram on the right. The phase of the laser at each pulse is written onto the atomic state, encoding distance and time information onto the atomic state.*

mirror displacement. We extract this information by detecting and counting the number of atoms in each of two quantum states – equivalent to measuring an interference pattern in an optical interferometer. This idea is illustrated in Figure 1.

A gravimeter at the Australian National University

At the Australian National University, we have developed a state-of-the-art gravimeter, based on ultra-cold atoms and atom interferometry (Altin *et al*. 2013). A photograph of our laboratory and the device can be seen in Figure 2. Rubidium-87 atoms are laser cooled in a glass vacuum cell, and are dropped over a distance of ~20 cm. The cell can be seen in Figure 3, as well as an example of an example of a laser cooled atomic cloud. Laser cooling is important not only to localise the cloud, but to reduce its expansion during the drop due to thermal motion. This is equivalent to using collimated light in an optical interferometer. During the drop, the vertical reference laser – our ruler – is pulsed on in order to measure the position of the cloud. We use three pulses separated equally by a time T to build the atomic equivalent of a Mach-Zehnder interferometer.

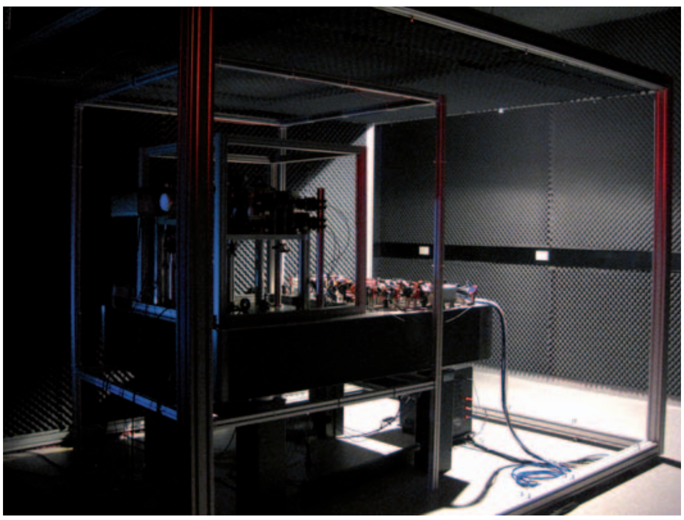

Fig. 2. *A photograph of our laboratory and the high precision atomic gravimeter.*

Typically, T is on the order of 100 ms. The resulting signal from the atom interferometer (or more precisely, the interferometer phase shift) is given by $\frac{4n\pi}{\lambda} gT^2$, where g is the acceleration due to gravity, λ is the wavelength of the vertical laser beam (~780 nm in our case), and n is an integer, which we choose experimentally, and determines how strongly the laser interacts with the atoms at each pulse. The colder the atoms, the more readily n can be increased (Debs 2012, Szigeti *et al*. 2012). For typical parameters, the signal is on the order of 10^7 radians, whereas noise in a quiet environment is typically on the order of 10^{-2} radians.

We have achieved state-of-the-art sensitivity to gravity of up to 2.7×10^{-8} ms^{-2} (equivalent to 2.7 μGal). To confirm operation and stability of the gravimeter, Figure 4 shows data monitoring the deviation of gravitational acceleration from its mean over a 36 hour period during 19–21 May 2012. Data points show a clear signature of the solid-Earth tide, with the solid line a tidal model calculated using the Tsoft software package of Van Camp and Vauterin (2005). No modification of the raw data logged from the gravimeter is performed in comparing the data to the model.

Measuring gravitational gradients

One of the fundamental principles of Einstein's theory of relativity is that it is not possible to distinguish between acceleration and a gravitational field. Thus, any vibrations of the reference laser used to measure the atomic trajectories, introduces parasitic noise into the gravitational signal. Every effort has therefore been taken to reduce environmental noise in out laboratory. In particular, no electronics are kept near the device, and the room has been acoustically damped (see Figure 2). Furthermore, the device sits on a vibration isolation system. This is indeed required of any absolute gravimeter, in order to reach state-of-the-art precision. Such a device is potentially suited to a ground station, where long-term data is required, and it can be setup in a purpose-engineered environment.

An alternative for noisy environments, such as a mobile device mounted in a vehicle or aircraft, is the measurements of gravity gradients. By using two spatially separated gravimeters, referenced to a common laser, vibrations become common to both sensors and can be subtracted, leaving only the gradient signal – the difference in gravity between the two gravimeters. Although devices such as Falcon and the Lockheed-Martin FTG system operate as excellent gradiometers, these devices are mechanical and specifically built for only this purpose. The ability to exquisitely control atoms using light allows us to split the atomic ensemble into two spatially separated ensembles, before releasing them into free fall. We may then perform the same measurement of their trajectories, and subtract the two signals giving the gravitational gradient. This whole process requires no hardware modification, only a minor variation to the control software of the system. In Figure 5(a), we show interference fringes from such a configuration. It is reasonably clear that the fringes are correlated (one is the negative of the other), and a correlation plot in (b) confirms this. Each data point in (b) is the signal of one sensor plotted against the other sensor for a given measurement. The correlation is evident as they both lie on a 45° line. Residual spread in the data is the result of atom-detection noise. Laboratory-based gravity gradiometers have already demonstrated sensitivities on the order of 10^{-9} s^{-2} (equivalent to 1 Eö) (McGuirk *et al*. 2002).

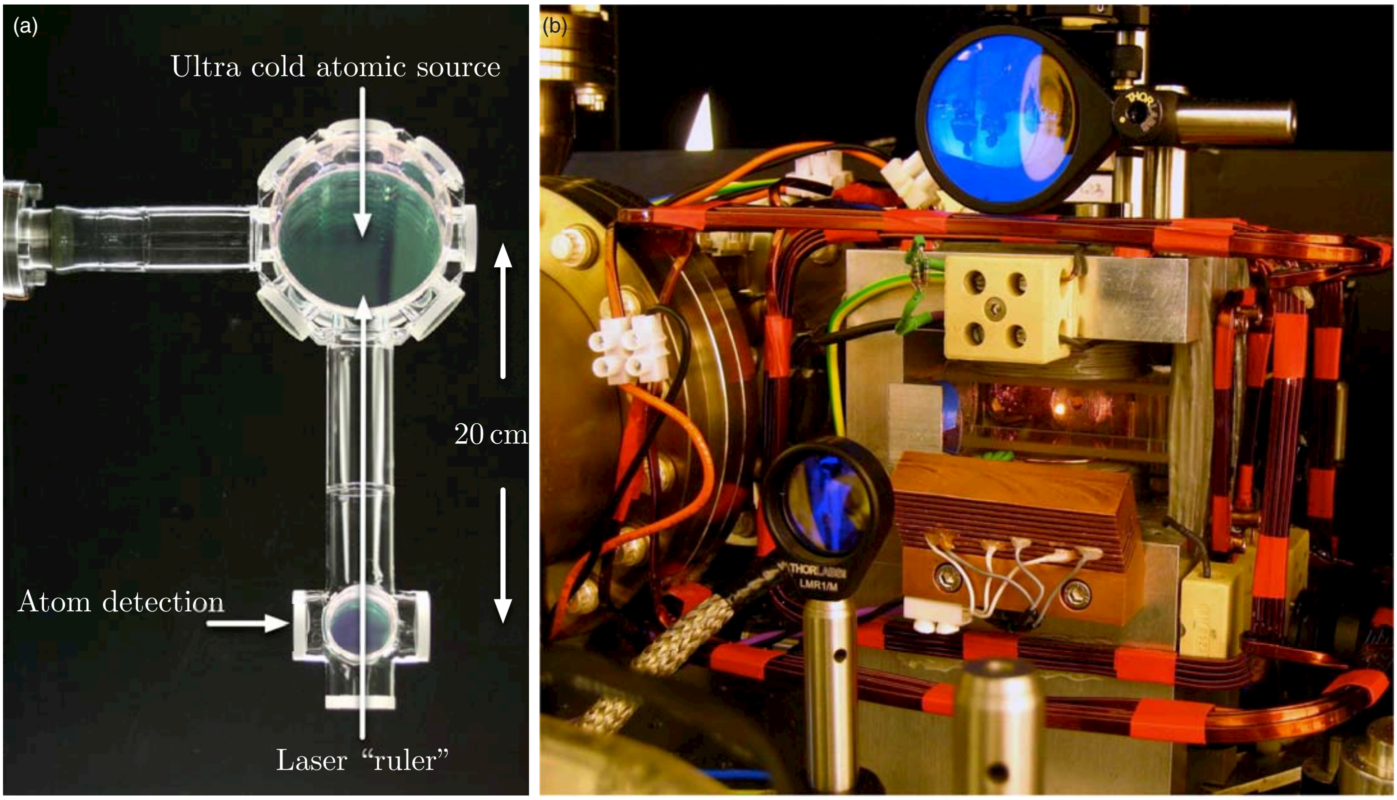

Fig. 3. *(a) Photograph of the glass vacuum cell in which atoms are dropped to measure gravity. (b) An example of a laser cooled cloud in one of our other experiments. The glowing ball in the centre of the glass cell can be seen as it scatters photons while being laser cooled.*

The future and miniaturisation

One key question for our team at ANU is whether such a device could ever be field deployable? The answer is a confident 'yes', provided there is a reasonable effort and investment in engineering. There is already work internationally, which has demonstrated the ability to miniaturise and cut power requirements of such atomic systems. For example, in Germany, the QUANTUS project has managed to reduce a system of similar complexity to that of Figure 1, to a volume on the order of 1 m^3 (Müntinga *et al*. 2013). The purpose of the project is to perform experiments under micro-gravity in a 110 m drop tower in Bremen. The entire device, including vacuum system, laser systems, electronics, and battery power, is placed inside a drop capsule. This is then loaded into the tower and dropped, experiencing 4.5 s of free-fall during which experiments are performed. The entire unit is not only compact, but robust enough to survive the 'catch' stage where it experiences 50*g* of deceleration, in order to be reloaded for the next experimental run. The long-term goal of such research aims to put these devices in satellite orbit, in order to make space-based measurement of, for example, gravity, as well as other tests of fundamental physics. There is also work in the USA, which has seen relatively high bandwidth (up to 330 Hz), high precision atomic inertial sensors reduced in size to approximately 0.2 m^3, operating under the same principles discussed above (McGuinness *et al*. 2012).

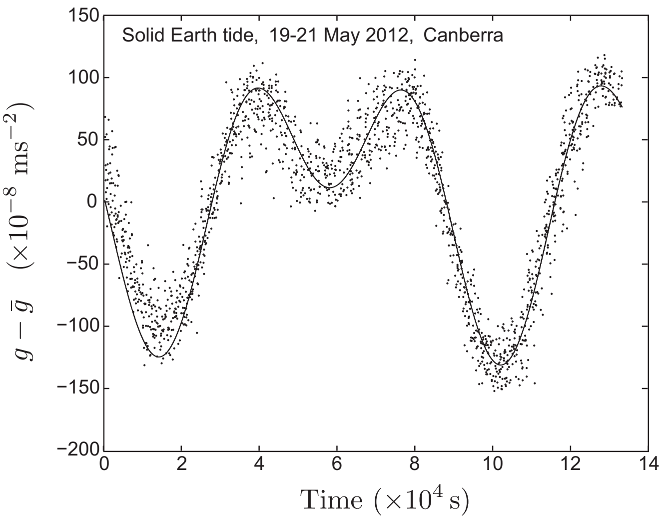

Fig. 4. *Gravity data taken over a 36 h period compared with a solid Earth tide model. Each data point represents the average of 38 individual measurements.*

Our current work is centred around improving the sensitivity and stability of our sensor. In particular, the Heisenberg uncertainty limit in quantum mechanics places a fundamental limit on the sensitivity of such a device. This limit depends on the number of atoms detected in the sensor (10^6 atoms in a typical device). Currently, our and other similar atomic devices are two orders of magnitude above this fundamental limit.

Our group has a history of working with atom-lasers. Compared with a thermal atomic gas, atom-lasers are the atomic analog of the optical laser, compared with light from an incandescent bulb. Given the immensely positive influence the optical laser had, and continues to have, on precision measurement, and particularly optical interferometers, it is reasonable to ask if the atom-laser can offer similar advantages for atom interferometers.

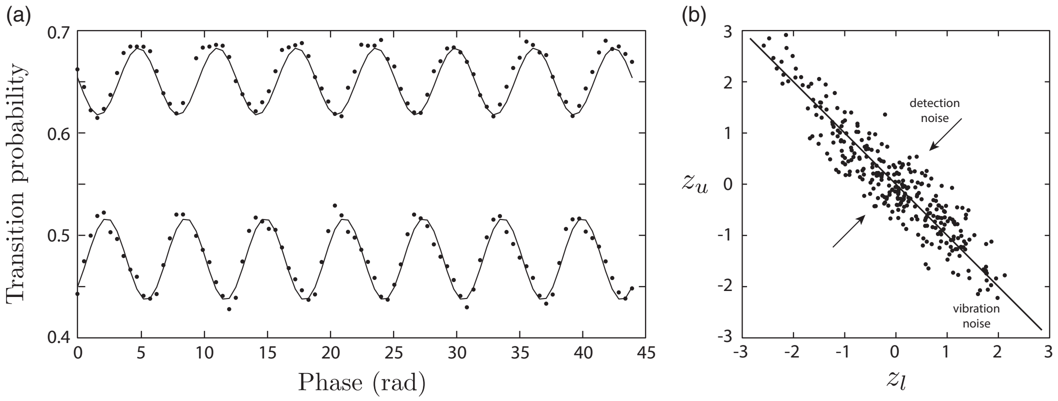

Fig. 5. *(a) Fringes from simultaneous gravimeters with T = 40 ms separated by a vertical distance of 2.4 cm and driven by the same Bragg laser beam. (b) Normalised (z-value) phase of the lower and upper interferometer plotted against each other, showing correlation. Vibration noise is common to both interferometers and does not affect the gradiometer signal. Residual uncorrelated fluctuations are caused by detection noise.*

We believe the answer to this question is yes, for similar reasons that the optical laser has been so successful, as outlined in the thesis of Debs (2012). We are currently implementing an atom laser into our existing gravimeter, and aim to soon answer this question. Such a device operating as a gradiometer has the potential to approach the fundamental limit sensitivity limit, opening access to a new regime of precision gravity measurements.

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