Getting the measure of atom interferometry

Interferometers that exploit the wave nature of atoms, rather than light, are being turned into precise inertial sensors for vehicle guidance systems. As **Franck Pereira Dos Santos** and **Arnaud Landragin** explain, such matter-wave interferometers also allow precise tests of fundamental physics

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Since the beginning of the 20th century, physicists have known that light must be considered as both a wave and a particle. Some properties of light – such as diffraction – can only be explained by treating it as waves, while others – like the photoelectric effect – can only be explained by treating it as particles. In the 1920s Louis de Broglie suggested that this wave–particle duality, which lies at the heart of the counterintuitive laws of quantum mechanics, could be extended to massive particles. In other words, electrons, atoms and molecules should diffract and interfere just like light does.

The wave nature of particles was first demonstrated in 1927, when George Paget Thomson – the son of J J Thomson, who discovered the electron in 1897 – found that a narrow beam of electrons produced an interference pattern after passing through a diffraction grating made from a thin metal film. Three years later, Immanuel Estermann and Otto Stern found that helium atoms generated a similar pattern when they were reflected from the surface of a crystal, which has a periodic structure like a grating does. Since then, a variety of tools have been developed to split these so-called matter waves into different parts as prisms and mirrors do for light. Unlike these optical elements, however, devices capable of manipulating matter waves need exotic structures such as mechanical and laser gratings. Armed with such devices, we can build a matter-wave interferometer.

Interferometers are a vital tool in physics. By analysing the interference pattern produced when two or more waves that have travelled along different paths interfere, an interferometer can reveal information about the physical environments of those paths or "arms" (figure 1). In an optical interferometer, for example, the separation of fringes in such an interference pattern depends on the relative phases of – and thus the distances travelled by – the waves in each arm of the device. Most interferometers use electromagnetic waves, but the principle is the same for sound and matter waves too. The latter, for instance, experience a phase shift that depends on the refractive index of the medium they are travelling through.

The crucial difference between a matter-wave and an optical interferometer, however, is that matter waves have mass while photons are massless. As a result, the phase of a matter wave is affected by gravity to a much greater extent, thereby offering a highly accurate way to test Newtonian gravity on very small scales and to measure certain fundamental constants (see box on page 37).

But atom interferometers also have much more practical applications. In particular, they can provide an absolute measure of rotation and acceleration, and have recently been used to build inertial sensors with an accuracy that rivals traditional devices. Indeed, it may not be long before such atom interferometers are used to guide aircraft, submarines and even spacecraft.

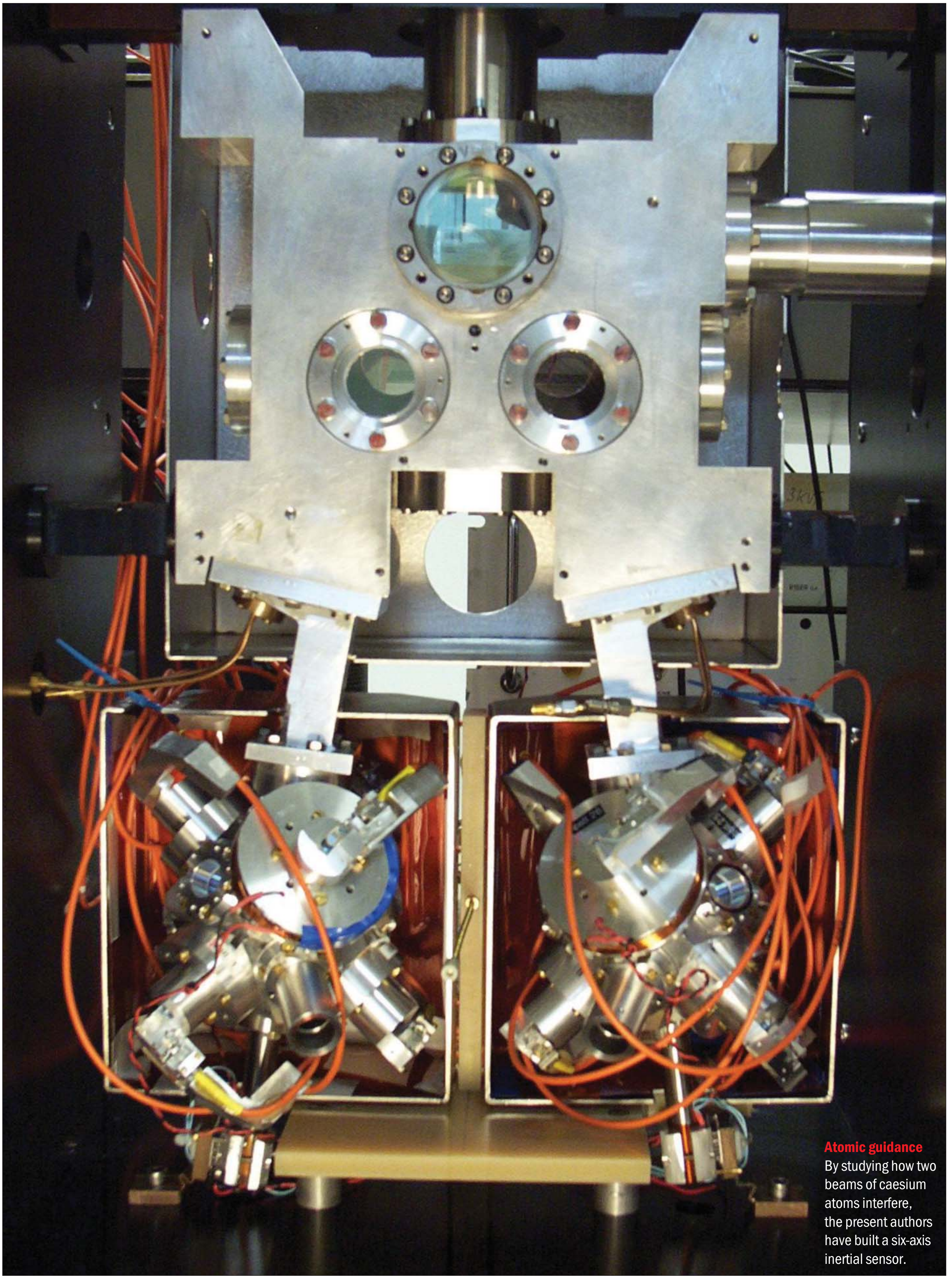
At a Glance: Atom interferometry

- According to quantum mechanics, atoms and molecules can also be treated as waves, which means that they can be made to reflect, diffract and interfere
- Matter-wave interferometers are similar to optical interferometers but instead of using a solid beam splitter, such as a prism, to control light, the atomic wave packets are split, redirected and recombined using lasers
- The phase of a matter wave is significantly affected by rotations and accelerations, which means that atomic interferometers can be used as highly sensitive inertial sensors
- Inertial sensors are primarily used in guidance systems for planes, submarines and spacecraft, but conventional technologies quickly lose accuracy
- Atomic inertial sensors can also be used to determine certain fundamental constants and test gravity at both very small and very large scales

Separating states

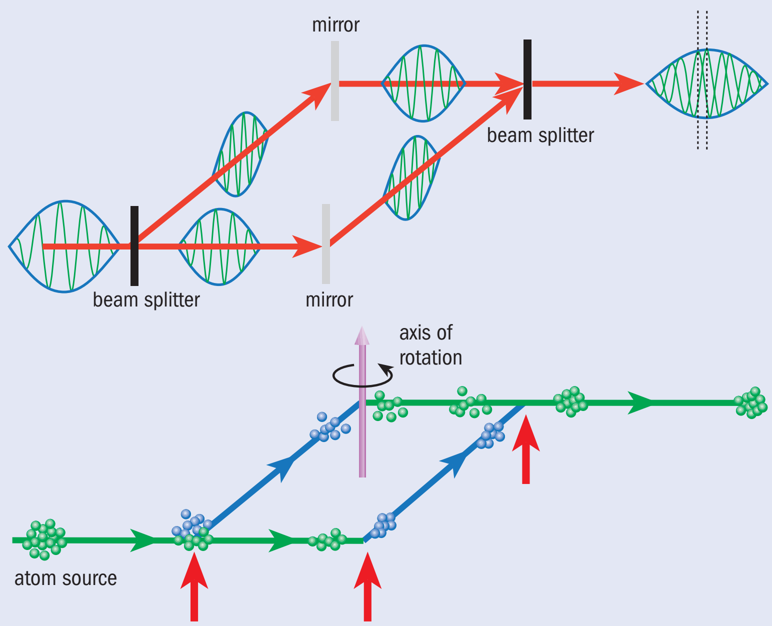
The first matter-wave interferometer was built in the 1950s by Norman Ramsey, who shared the 1989 Nobel Prize for Physics for the work. Ramsey and his colleagues set out to measure the resonance frequency of an electronic transition in hydrogen molecules – the principle on which atomic clocks are based. To do so, they constructed an interferometer using two separated microwave cavities.

In the first cavity a cloud of hydrogen molecules was put into a quantum superposition of different energy states by firing a microwave pulse at it. When a molecule or atom in its ground state absorbs a photon with the right energy, it moves to an excited state, where it



Atomic guidance
By studying how two beams of caesium atoms interfere, the present authors have built a six-axis inertial sensor.

1 Interferometry matters



In an optical "Mach–Zehnder" interferometer (top) a partially reflecting mirror splits a beam of light so that it travels along two different paths. Any difference in the physical properties of these paths – for instance if one is slightly longer than the other – causes the two beams to acquire different phase shifts, so that when they are recombined, they produce an interference pattern that contains information about those properties. Since particles can also be considered as waves, the same principle can be used to build a "matter-wave" interferometer (bottom) in which clouds of cold atoms are manipulated using lasers rather than mirrors. First a laser pulse (red arrow) places the atomic wave packets into a superposition of two partial wave packets with different momenta (green and blue) so that they follow two separate paths. A second laser forces the wave packets to converge, while a third recombines them to generates the interference pattern. Because atoms are massive particles, matter-wave interferometers with this geometry are sensitive to acceleration along the direction of diffraction and to rotations about an axis perpendicular to the atomic paths. The larger the separation of the two paths, the better the sensitivity to inertial forces.

may remain or return to its ground state by re-emitting a photon. By adjusting the duration and/or the amplitude of the microwave pulse, Ramsey was able to split the "wave packet" of individual hydrogen molecules into two partial wave packets that together made up a coherent superposition of the ground and excited states.

These partial wave packets were then made to travel to the second microwave cavity, each incurring a phase shift the size of which depends on its energy. In the second cavity another microwave pulse recombined the two partial wave packets, which generated an interference pattern. Because the difference between the phase shifts accumulated by the matter waves along each path is proportional to the difference between the energies of the two states, and since the energy of a photon is directly proportional to its frequency, Ramsey's interferometer allowed him to determine the resonance frequency of electronic transitions in molecular hydrogen.

Since atoms are massive particles, their energy is affected by inertial forces, so that a matter-wave interferometer of a similar type also provides a natural inertial or motion sensor. Inertial sensors measure the displacement of an object with respect to an inertial (i.e. non-accelerating) reference frame. Gyroscopes, for example, measure the angle or rotation rate of a rotating body either mechanically or optically, while accelerometers – which are usually microelectromechanical devices that measure the deflection of a cantilever – are sensitive to accelerations.

DHD Multimedia Gallery

In a spin Conventional mechanical gyroscopes use the forces on a spinning flywheel to measure rotations.

Spacecraft, missiles, submarines and modern aircraft are all equipped with inertial-measurement units that detect acceleration as well as changes in rotation in 3D (i.e. its "pitch", "roll" and "yaw"). With the help of a computer, the geographic position can then be tracked using a process known as dead reckoning. The Global Positioning System (GPS) is designed specifically for navigation purposes, but it relies on communicating with external satellites. Inertial-measurement units, on the other hand, are closed systems with much faster response times and are not affected by storms or other disturbances that can interrupt the GPS signal.

In fact, interferometry is already used in conventional inertial-measurement units in the form of optical gyroscopes. These devices contain a coil of optical fibre, along which two light beams propagate in opposite directions. If the coil rotates in the plane of the beams, then the beam travelling against the rotation experiences a slightly shorter path than the other, which induces a phase shift between the beams – known as the Sagnac effect. The interference that results when the beams are recombined therefore provides a direct measure of the rotation rate.

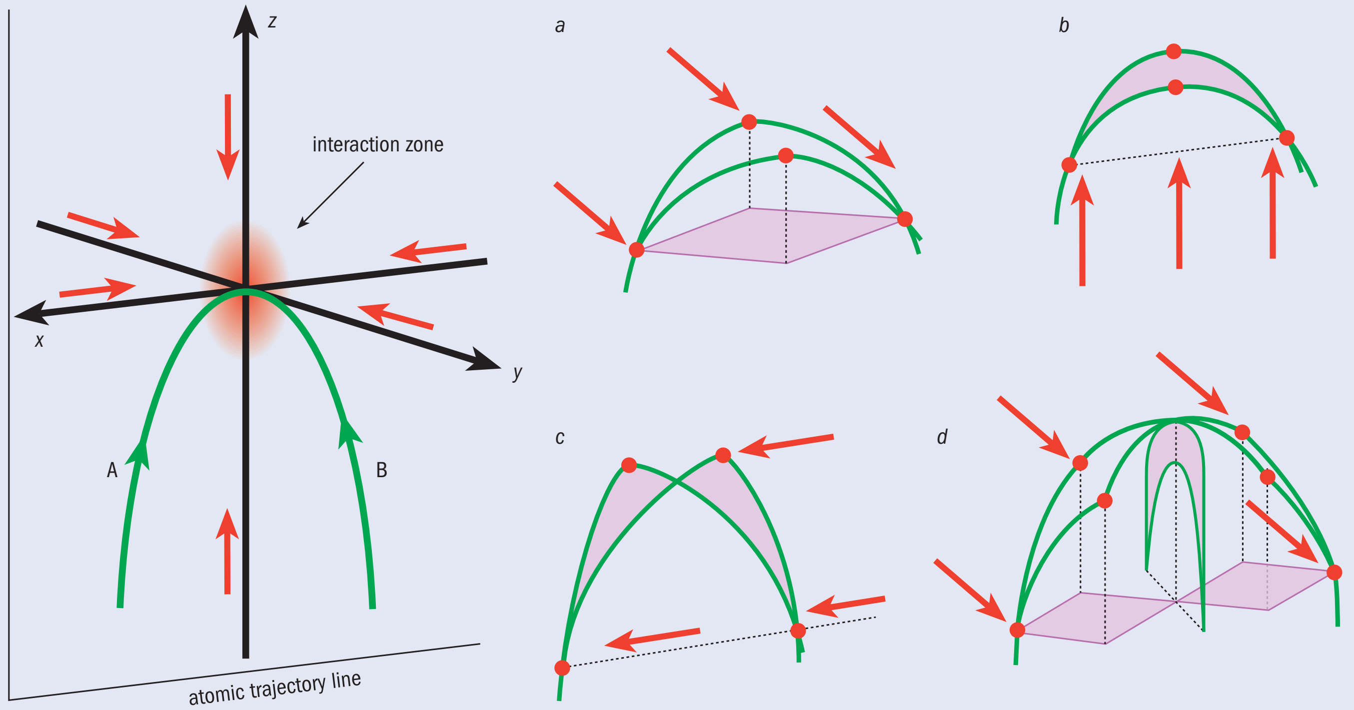
Because matter waves travel much slower than light waves, however, rotation sensors based on atom interferometry are potentially much more sensitive than optical gyroscopes because the matter waves spend more time in the interferometer and hence accumulate greater phase shifts. Furthermore, matter-wave interferometers provide absolute measurements of the displacement of the atoms and therefore eliminate the instrumental bias that limits the accuracy of conventional inertial sensors. This is because the lasers used to send the atoms along different paths define perpendicular planes in which the phase of the light waves is constant. Since these planes are fixed with respect to the rest of the instrument, and are separated by increments equal to the wavelength of the laser, they provide a precise reference ruler against which to measure the displacement of the atoms. This also means that matter-wave interferometers can only measure accelerations in the direction of propagation of the lasers.

Gathering inertia

Inertial sensors based on atom interferometers were first demonstrated in 1991 by Steven Chu's group at Stanford University in the US and by Jürgen Helmcke's group at the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany. These early devices were sensitive to acceleration due to gravity and to rotation rate. For example, in the PTB interferometer the wave packets of calcium atoms were put into a superposition of states with different momenta using a laser, similar to the way Ramsey used microwaves to manipulate the electronic states of hydrogen molecules. As in the case of an optical gyroscope, rotating the PTB apparatus introduced a phase shift between the two beams of partial wave packets that was proportional to the rotation rate.

Since this experiment was carried out, researchers have improved the sensitivity and accuracy of matter-

2 The six-axis inertial sensor



Since atoms (unlike photons) have mass, atomic or matter-wave interferometers make ideal inertial-motion sensors. For example, the present authors have recently built a six-axis inertial sensor based on a double interferometer in which two counter-propagating atomic clouds follow parabolic trajectories (A and B) and are split into partial wave packets at the apogee of these trajectories using lasers (red arrows). In order to measure all three components of rotation, Ω, and acceleration, $\boldsymbol{a}$, the set-up requires the successive use of four different laser configurations. Configurations *a*, *b*, and *c* use Mach–Zehnder three-pulse configurations with the lasers propagating along the *y*-, *z*- and *x*-axes, respectively; while in configuration *d*, four pulses cause the atomic wave packets to follow a figure-of-eight-shaped path. In each case the interferometer is sensitive to accelerations along the direction of propagation of the lasers and rotations around the axis perpendicular to the purple shaded area. This area is the projection of the atom paths onto the plane of interest.. As a result, configurations *a* and *b* each measure one component of acceleration and one of rotation (Ω_z and $\boldsymbol{a}_y$; and Ω_y and $\boldsymbol{a}_z$, respectively). Configuration *c* only measures acceleration along the *x*-axis ($\boldsymbol{a}_x$) and has no sensitivity to rotation (since the purple areas cancel out), while configuration *d* measures rotation around the *x*-axis (Ω_x) without being sensitive to acceleration.

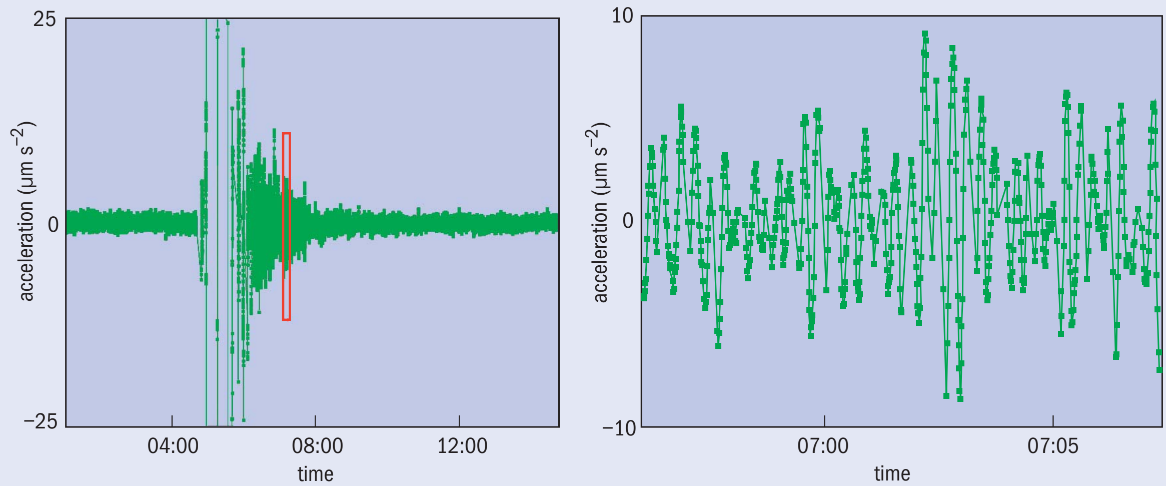
wave inertial sensors beyond what can be achieved by classical instruments. In our laboratory at the Observatoire de Paris, for instance, we are currently developing an inertial sensor that can measure all three rotation and all three acceleration components, and hence simultaneously function as a gyroscope and an accelerometer for navigation applications. In contrast, previous atomic gyroscopes – such as that built by Mark Kasevich, then at Yale University, and co-workers in the late 1990s – were designed to measure the vertical component of rotation and the horizontal component of acceleration only. Our six-axis sensor is thus a key step towards a practical navigation instrument, for which one needs to measure motion along all possible directions.

In fact, our device consists of a double interferometer in which two clouds of cooled caesium atoms follow parabolic trajectories in opposite directions (figure 2). We use infrared lasers to launch the atoms along the parabolic trajectories, split the atomic wave packets into partial wave packets with different energies, and to recombine them again in order to generate the interference patterns. As both atomic samples share the same lasers, this allows us to tell which contribution to the resulting interference patterns comes from the rotation and which comes from the acceleration. The rotation signal changes from positive to negative when the atoms change direction; but the acceleration signal does not, which means that we can extract the acceleration and rotation from the sum and difference of the signals from the two interferometers, respectively.

We chose caesium atoms because they can be cooled very efficiently, which means that since they are moving so slowly, they spend longer in the interferometer, thus making it more sensitive. The other key feature of our device is the highly curved parabolic trajectories of the atoms. These let us measure all the components of acceleration and rotation because it means we can arrange the apparatus in many different configurations without equipment getting in the way of the lasers or atoms. Three of these configurations use a "Mach–Zehnder" set-up with three laser pulses forming the interferometers, while a fourth configuration uses four laser pulses and makes the atomic wave packets follow a figure-of-eight-shaped path. So far we have measured the Earth's rotation rate and the tidal effect resulting

Matter-wave interferometers eliminate the instrumental bias that limits the accuracy of conventional inertial sensors

3 Detecting earthquakes



Matter-wave interferometers allow us to measure accelerations very accurately. For example, an "atomic gravimeter" can provide an accurate measure of the acceleration due to gravity, *g*, by allowing researchers to study clouds of cold atoms in free fall. This is particularly important for "watt balance" experiments that attempt to redefine the kilogram in terms of only fundamental constants (see box on page 37), but such a device is so sensitive that it can detect vibrations originating from the other side of the planet. For example, on 13 January the atomic gravimeter in our lab at the Observatoire de Paris detected an earthquake of magnitude 8.1 on the Richter scale in the Kuril Islands between Russia and Japan about 15 minutes after it occurred (left). Unlike standard absolute gravimeters, the high (4 Hz) repetition rate of the instrument clearly resolves the long-period ground oscillations (right).

from the gravitational interaction between the Earth, Sun and Moon with sensitivities of 2×10^{-7} rad s^{-1} for rotation and 4×10^{-7} m s^{-2} for acceleration, both for a 1 s measurement time. This is competitive with the best commercial optical gyroscopes, but we hope to improve the sensitivity in the near future.

One way to achieve better sensitivities is to use atom interferometers that measure rotation around just one axis. Ernst Rasel and Wolfgang Ertmer at the University of Hanover in Germany, for example, are currently developing an experiment that will push the sensitivity of atom interferometers to their limits (expected to be about 10^{-8} rad s^{-1}) on Earth and allow the technology to be tested for possible applications in the guidance systems in spacecraft. Their set-up is a Mach–Zehnder configuration in which the atoms travel 10 times faster than they do in our six-axis sensor, thus increasing the area of the interferometer and so making it more sensitive to rotation. Since the resulting trajectories are almost horizontal, the interferometer is sensitive to at most two components of rotation and two components of acceleration.

Atom interferometers could potentially distinguish between the predictions of general relativity and those of alternative gravity theories

The outer limits

A matter-wave inertial sensor in space would provide an important test of fundamental physics. For example, atom interferometers can be used to measure gravity both over microscopic distances and at the very large scale of the solar system, which means that they could potentially distinguish between the predictions of general relativity and those of alternative gravity theories such as modified Newtonian dynamics. In particular, matter-wave interferometers allow a test of the weak equivalence principle, which states that the trajectory of a falling test body depends only on its initial position and velocity, and is independent of its composition.

The absence of gravity and the low level of vibrations in space allows the measurement time to be increased 10-fold, which improves the sensitivity of an atomic inertial sensor by several orders of magnitude. Since 2000 the European Space Agency has been considering a project called HYPER (hyper-precision cold-atom interferometry in space), which would involve sending interferometers into space to test the gravitomagnetic "frame-dragging" effect of the Earth that is predicted by general relativity and to measure the fine-structure constant. Although HYPER is not scheduled for launched, it has shown that such sensors are feasible, and in the past couple of years more space missions have been proposed (see *Physics World* September 2006 p7).

For example, researchers in our laboratory (together with several other institutions) have proposed a project called SAGAS (Search for Anomalous Gravitation using Atomic Sensors). This would send an atom interferometer to the far reaches of the solar system in order to test whether the trajectories of the Pioneer probes – which were launched in the 1970s and appear to be experiencing an anomalous acceleration towards the Sun – are indeed due to a real gravitational effect. When this or a similar mission successfully gets off the ground – which could take up to 20 years – it will open the door for many more space-based applications of atom interferometry.

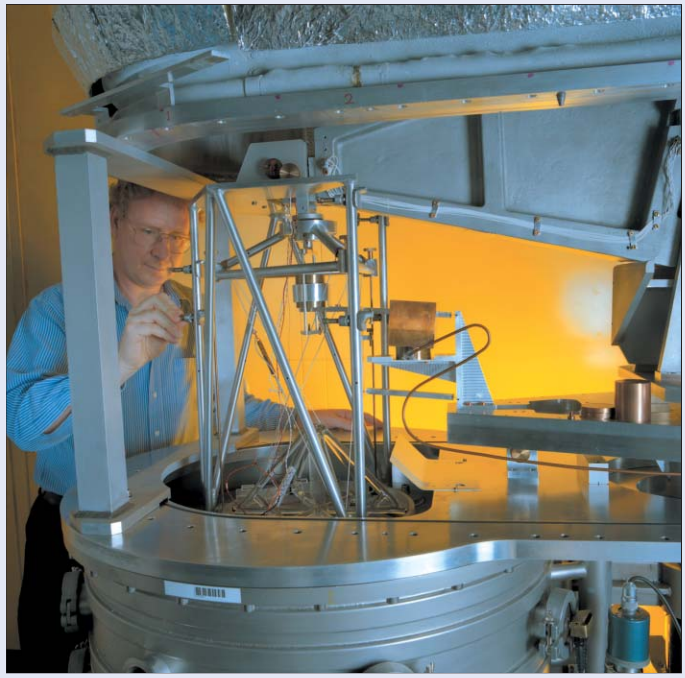
Back on Earth, many research teams have now developed reliable matter-wave interferometers for geophysics and geodesy (figure 3). These instruments can detect tiny changes in the Earth's gravitational field, which can reveal features such as underground structures or the presence of oil. As for navigation applications, vehicles equipped with atomic instruments should be able to evaluate their positions much more accurately than is possible with conventional inertial sensors. This is because atomic accelerometers have an intrinsically stable "scale factor", which relates the

Atom interferometry for fundamental physics

As well as providing accurate navigation systems, sensors based on atom interferometers can also be used to measure atomic quantities, to test Einstein's general theory of relativity and to determine fundamental constants. The gravitational constant, G, for example, can be determined by measuring the accelerations of two vertically separated clouds of atoms in free fall (each of which constitutes a separate interferometer). By adding and removing a control mass between the two interferometers, researchers can deduce the differential acceleration induced by this mass, which is proportional to G. Since each interferometer experiences the same platform vibrations, this approach is potentially much more sensitive than traditional methods used to determine G, for example those based on torsion balances, because the vibrations cancel out. The first experiment of this kind was performed at Stanford University by Mark Kasevich's team in the early 2000s, which led to a relative uncertainty of just 5×10^{-3}. Another team at Firenze University in Italy expects to achieve a relative uncertainty of 1×10^{-4} soon. (The smallest relative uncertainty achieved with a torsion balance experiment is about 1×10^{-5}.)

Atom interferometers also have an important role to play in redefining the kilogram – the last SI unit to be defined by an artefact. In an effort to redefine the kilogram in terms of only fundamental constants, thus bringing it in line with other SI units such as the metre and the second, researchers have turned to an instrument known as a watt balance (see *Physics World* May 2004 pp31–35). In such a device the gravitational force on an object (i.e. which has a nominal mass of 1 kg) is balanced with the electromagnetic force produced by a current-carrying coil in a magnetic field. Once the balancing condition is met, the weight of the object can be determined in terms of the Josephson effect and the quantum Hall effect, which relate it back to Planck's constant and the charge on the electron.

To then find out the object's mass, it is necessary to know the local value of g – the acceleration due to gravity – very accurately, and this is where atom interferometry comes in. As part of the a watt-balance project being undertaken at the Laboratoire National de Métrologie et d'Essais in France, for example, the present authors are developing an atom interferometer in which cold rubidium atoms are dropped from a magneto-optical trap and then made to interact with three laser pulses that cause the wave packets to split, converge and then recombine during their fall. Since the atomic trajectories and the direction of propagation of the beam splitters both lie along the vertical direction, the interferometer is only sensitive to accelerations, not rotations, and the set-up should yield a relative uncertainty of 1×10^{-9}.


NPL

Well balanced Using a watt balance, like this one at the National Physical Laboratory in the UK, requires a precise knowledge of the local acceleration due to gravity.

Such a high accuracy is possible because the main source of uncertainty in measurements of g is vibrations induced by human activity, and atomic interferometers perform considerably better in noisy environments than conventional absolute gravimeters based on optical interferometers. Firstly, they have a high repetition rate (4 Hz), which allows better averaging of the vibrational noise. Secondly, atom interferometers are more stable over time than conventional instruments, so they can provide the continuous measurements that are needed for the watt-balance project. These attributes also make gravimeters based on atomic interferometers useful for applications in geophysics, where changes in Earth's gravitational field in different regions over time can help determine the structure of the planet.

output signal of the interferometer (say phase or voltage) with the actual quantity of interest, e.g. acceleration. In conventional optical gyroscopes, thermal instabilities cause the scale factor to change over time, which means the devices have to be frequently recalibrated. Such recalibration is not a major problem for aircraft but it could be for submarines and spacecraft, which must spend long periods of time out of contact with the outside world.

However, several technical challenges still need to be overcome before inertial sensors based on atom interferometry can equip actual planes, spacecraft or submarines. Current atom interferometers are several cubic metres in volume, so the technology needs to be made significantly more compact and able to operate in noisy environments. We also need to develop robust optical components, such as lasers and optical fibres, so that devices are able to run for several years without major maintenance.

A few years ago Mark Kasevich, now at Stanford University, began development work aimed at achieving onboard instruments. Kasevich is working with the US military and has a large team of researchers and a budget of millions of dollars to develop a practical device that can be used in military planes and submarines. The French aerospace lab ONERA has also now started similar work.

Much of this research is secret, so it is difficult to say what progress has been made so far. But it is hoped that we will have operational matter-wave interferometer systems within the next decade. We will then have a system that turns one of the most intangible and bizarre concepts in physics – the wave-like behaviour of matter – into one of the most useful. ■

More about: Atom interferometry

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J B Fixler *et al.* 2007 Atom interferometer measurement of the Newtonian constant of gravity *Science* **315** 74–77
A Miffre *et al.* 2006 Atom interferometry *Phys. Scr.* **74** C15–C23
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