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Einstein

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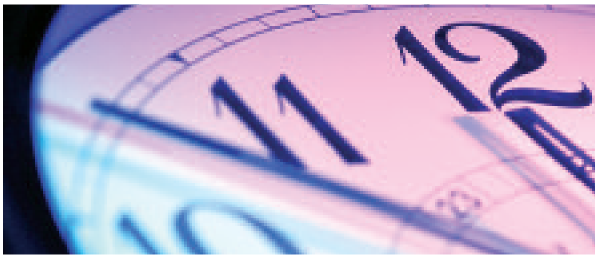
Albert Einstein was born in Ulm, Germany in 1879. When he died in 1955 he had transformed our understanding of the world in the most profound and fundamental ways. Some of his most important breakthroughs were published in 1905, and the National Physical Laboratory (NPL) is supporting the centenary of that year.



Einstein's discoveries included:

- time can stretch or shrink
- matter and energy can change into each other
- time flows at different rates in different places
- light behaves as streams of particles
- a way of mathematical modelling the universe
- the nature of gravity
- many ways of measuring atomic size

After an eventful upbringing in Germany, Italy and Switzerland, Einstein settled for a while in Switzerland, working in the patent office and producing some of his most important work in 1905. A number of university appointments followed as his prestige grew. During the First World War he campaigned for peace and developed his theory of gravity (general relativity).

A demonstration of the distortion of starlight during a solar eclipse in 1919 led to world-wide fame. When the Nazis came to power in 1933, Einstein campaigned against them - and they against him - and he left Germany, settling finally in the United States. After the war, though plagued by illness, he worked tirelessly for peace, campaigning against the hydrogen bomb, and McCarthyism. Scientifically, his major contributions ended in the 1920s but for the rest of his life he worked on a new theory that would unify all forces together with time, space and matter: a theory he never completed but which set the direction for today's embryonic 'Theories of Everything'.

To measure directly the effects at the velocities that vehicles can achieve on earth, or those caused by the Earth's gravity, extremely accurate clocks - atomic clocks - are required. The first operational atomic clock was developed at NPL, and NPL was involved in a recent verification of relativity using an atomic clock (*see page 2*).

In 1905, Einstein showed that light can be viewed as a stream of many tiny particle-like packets of energy called photons. Most light sources (such as lasers, light bulbs or stars) generate photons at enormous rates so that a continuous beam is all we can see, but NPL is making photons one by one (*see page 4*).

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Demonstrating Relativity by Flying Atomic Clocks

At speeds encountered in everyday life, relativistic effects are very small. When Einstein published his work on relativity the clocks then available were not sufficiently accurate to observe the predicted effects on time. Instead, indirect evidence obtained from astronomy and particle physics was used to support the relativity theories.

Highly accurate atomic clocks, the first of which was built and operated at NPL in 1955, opened up the possibility of directly measuring relativistic effects. Atomic clocks enable time to be measured far more accurately than any other physical quantity. The original NPL clock, like many that followed it, maintained time by counting cycles of an atomic frequency transition present within the caesium atom. Atomic clocks have been developed that are sufficiently portable to be flown in an aircraft, and possess sufficiently good timekeeping properties that the relativistic effects may be observed.

In 1971 Keating and Hafele operating from the United States Naval Observatory in Washington DC, performed the most famous flying clock experiment. Four commercial caesium atomic clocks were flown around the world on commercial aircraft, firstly travelling from east to west, and then travelling from west to east. The results of the experiment did indeed confirm the relativistic predictions.

To commemorate the 25th anniversary of the Keating and Hafele experiment, NPL featured in a BBC Horizon programme that involved flying a single caesium atomic clock from London to Washington and then back again. The timekeeping properties of atomic clocks had improved very significantly over the 25 years since the original experiment, and as a result relativistic effects would be observable following much shorter clock trips.

Several relativistic effects need to be considered when performing a flying clock trip, including:

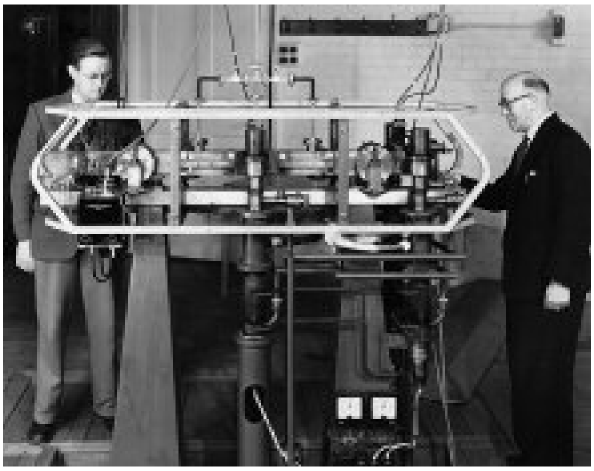
- The speed of the aircraft relative to an observer on the ground. This is a result of the special theory of relativity.
- The height and hence gravitational potential of the clock on the aircraft relative to an observer on the ground. This is a result of the general theory of relativity.

Before the start of the experiment, the travelling clock was compared directly against the UK's national timescale at NPL, to establish both its offset and rate. During the flights the height, speed and estimated position of the aircraft were regularly monitored. From these measurements the following predictions were made regarding the expected time gain of the travelling clock relative to NPL's reference timescale.

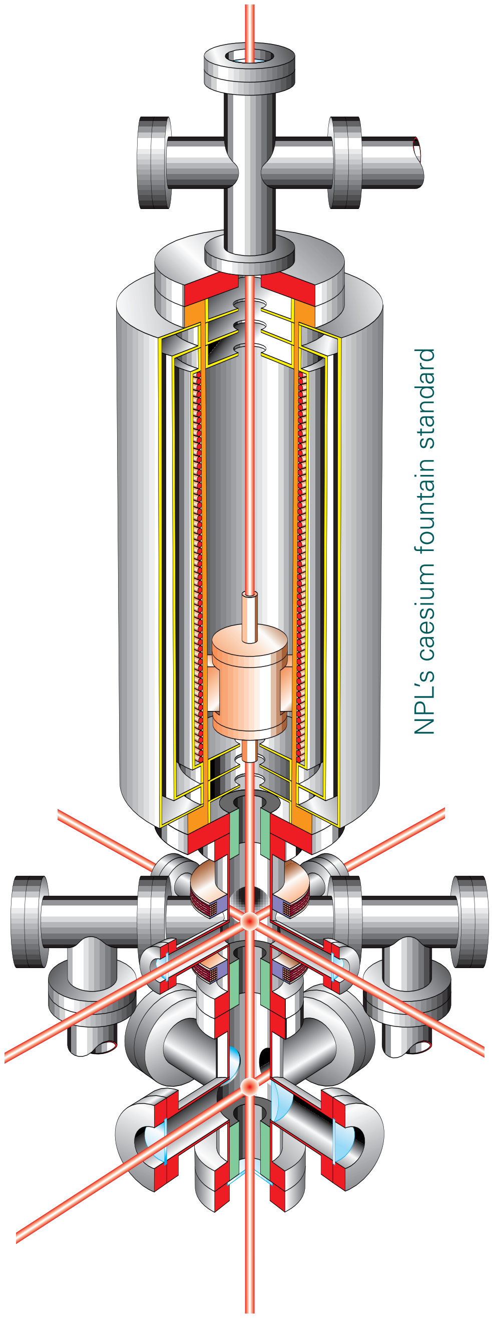
Results included:

- The combined flight times of 14 hours and mean height in excess of 10 km resulted in a predicted clock gain of 53 ns. This followed the principle that a clock in a weaker gravitational field (higher altitude) will run faster.
- The effect of the aircraft's speed relative to the Earth's surface resulted in a predicted clock loss of 16.1 ns. This followed the principle that a moving clock runs slow.

On return to NPL the travelling clock was predicted to have gained 39.8 ns, including an additional geometric factor. This compared remarkably well with a measured gain of 39.0 ns. We estimated the uncertainty due to clock instabilities and noise to be around ±2 ns. This short flying clock experiment therefore provided a clear demonstration of relativistic effects.



Essen (right) and Parry with the original NPL atomic clock



NPL's caesium fountain standard

Research is continuing to develop new atomic clocks that are either more stable, such as NPL's caesium fountain standard, or are very significantly smaller than those used in these flying clock experiments. There is considerable potential for future improvements. Atomic clocks now operate continuously in space on the US Global Positioning System satellites. The observation of relativistic effects and their correction has become an important part of both the operation of satellite navigation systems and of international timekeeping.

Einstein and Single Photons

NPL scientists are developing single-photon sources and the diagnostic instrumentation required to quantify their relevant parameters.

Einstein's proposal concerning photons was the key to a satisfactory explanation of experiments on the photoelectric effect. Each photon of visible or infra-red radiation has an extremely small energy. Moreover, it is possible to generate and detect individual photons. Technologies making use of the special properties of single photons include quantum cryptography, for the secure distribution of cryptographic keys. In the future, it may be possible to process quantum information using single photons and linear optics. For either of these quantum technologies, a source capable of generating single photons is a desirable resource.

Examples of physical systems that may be used to generate single photons include a single atom, and a single quantum dot in a semiconductor. In both instances, the energy levels of the system are discrete, or quantised, and the system may be determined to be in one state only at any given time. A solitary atom or dot in an excited energy level, decaying radiatively to a lower energy level, will emit one *and only one* photon at a time; it will *never* emit two photons simultaneously. It is this property of an individual quantum emitter that is fundamental to the generation of "single photons".

A single-photon source possesses fundamentally different properties when compared to a laser, a light bulb, or a star. Precise knowledge of these properties is required to quantify the performance of these light sources for scientific applications. In quantum cryptography for example, a less than perfect source opens the door to an undetectable eavesdropper, rendering the communication channel insecure. Futuristic technologies such as quantum computation will require similar characterisation of sources.

einstein year

The National Physical Laboratory (NPL) is proud to be supporting Einstein Year 2005 the UK & Ireland's contribution to World Year of Physics (WYP) and marks the centenary of the publication in 1905 of Einstein's three ground-breaking papers on special relativity, the photoelectric effect and Brownian motion. These papers provided the foundation of modern physics, and activities throughout Einstein Year will explore ideas in contemporary physics as well as showing how our everyday lives are influenced by Einstein's legacy.

Einstein Year is a whole year of activities that will get you fired up about physics, more information can be found at **www.einsteinyear.org**

NPL's The Learning Room **www.npl.co.uk/thelearningroom**
World Year of Physics **www.wyp2005.org**
Institute of Physics **www.iop.org**

NPL produces a range of free colourful, fun and educational posters aimed at GCSE/A-level students and are a very useful teaching resource. For a free set please fill in the on-line form at **www.npl.co.uk/thelearningroom/posters.html** or contact the NPL Helpline.

FURTHER INFORMATION

For additional copies of this newsletter, or for more information on any aspect of NPL's work and the range of services available from the Laboratory, call the NPL Helpline:
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