Measuring height by connecting clocks

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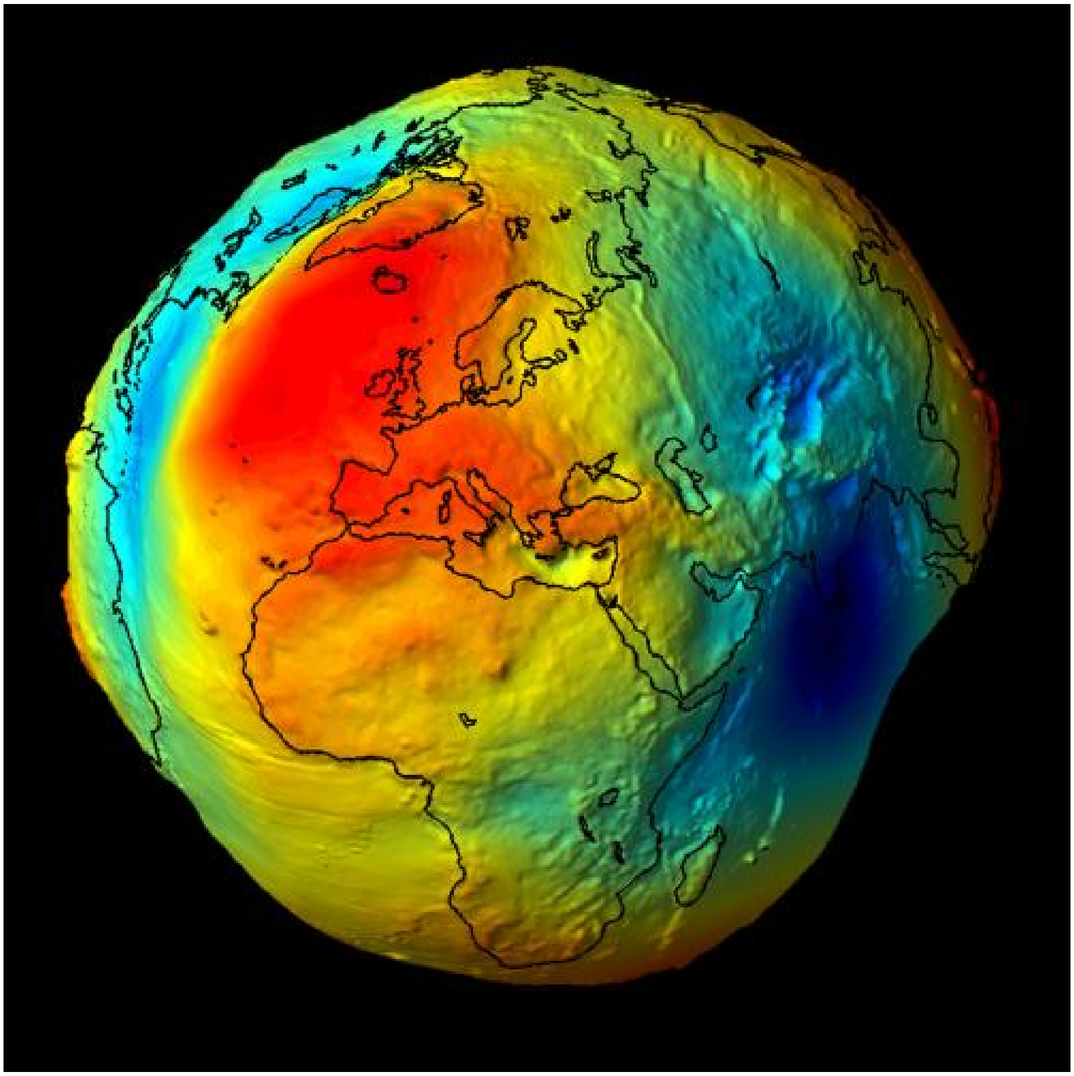

It resembles a baggy football: This is the Earth when it is represented as a geoid, i.e. when the actual distribution of the gravitational force is shown. Here, the height of the "bumps", which are related to the gravitational field of the Earth, has been determined by the Goce satellite. Although the data are precise as far as the respective height of the "humps" is concerned, the lateral resolution amounts to a few kilometers. In future, frequency comparisons between optical atomic clocks can be used if one wants to know the height of the smaller structures and places on Earth. Now it will be possible to transport the frequency over a distance of approx. 2000 km with a resolution which corresponds to a height difference of only 4 mm if the remote clocks support such accuracy. Credit: ESA

How far above sea level is a place located? And where exactly is "sea level"? It is one objective of the geodesists to answer these questions with 1 cm accuracy. Conventional measurement procedures or GPS technologies via satellites, however, reach their limits here. Now optical atomic clocks offer a new approach, because the tick rate of a clock is influenced by gravity. This well-known, but tiny effect was measured with unprecedented precision in 2010 using two optical clocks – however, they were located at the same institute. Now, up to 2000 km may lie between them. Using commercial optical fibers and a sophisticated amplifier technique, the frequency of one of the atomic clocks can be transported to the other where the frequencies may then be compared.

A highly sensitive interferometry method allows the long-distance transfer and comparison to be performed with an accuracy of 19 digits. The results of the successful cooperation between the Max Planck Institute of Quantum Optics (MPQ) in Garching and the Physikalisch-Technische Bundesanstalt (PTB) have been published in the current edition of the scientific journal *Physical Review Letters*. They also provide an important basis for a special research area of PTB and Hanover University with Bremen University which has now been applied for.

Quite a lot of things may go wrong in bridge building. The inhabitants of the German and the Swiss parts of Laufenburg were already looking forward to a new bridge over the Rhine, the High Rhine Bridge, when people were taken aback: The heights of the two bridge parts growing towards each other differed by 54 centimeters. An embarrassing error: Someone had, in the height networks of Switzerland and Germany, included the known height difference of 27 centimeters incorrectly into the calculation so that they were doubled instead of deleted. This height difference existed because the Germans refer, for such calculations, to the sea level of the North Sea, whereas the Swiss refer to the sea level of the Mediterranean Sea. This means that "sea level" is not the same everywhere. To rule such errors out in future, the geodesists would like to re-compute sea level on the basis of the gravitational force of the Earth. It is the objective of the geodesists to exactly determine the so-called geoid of the Earth to a few centimeters. For this purpose, the optical atomic clocks, which have for some years been developed by physicists of PTB and elsewhere, are exactly what they need. These clocks offer the perspective of realizing a frequency with such accuracy that even the small frequency deviations, which are caused by a height difference of a few centimeters, eventually become evident. What lies behind this is Einstein's general theory of relativity, the so-called gravitational red shift: If a clock is further way from the Earth, time actually runs a little faster for it. For a height difference of one meter, the rate (i.e. the frequency) of a clock changes by 10^{-16}.

A lot of things have already been investigated in this field: Atomic clocks have, for example, been transported halfway around the world in aircraft – and afterwards it was actually found that their time had passed slightly differently to that of an atomic clock on Earth. And three years ago, Chou et al. (Science 2010) installed two optical aluminium clocks in neighboring laboratories with a height difference of 33 cm – and they were able, in fact, to measure the influence this small height difference has on the frequencies of the two clocks. "But how can I measure the height difference, i.e. this frequency difference, if the two clocks are not standing side by side? That is to say: How can I establish the connection to a second clock which is standing where a height must be measured with such accuracy?" asks Gesine Grosche, physicist at PTB. To find an answer to this question, she and her colleagues from the Max Planck Institute of Quantum Optics in Garching have investigated in the past few years how such "precision frequencies", as they can be generated by an optical atomic clock, can be sent on a journey. After they reported last year in the journal *Science* that they had succeeded in realizing a frequency comparison over the section of 920 km between the MPQ and PTB, they have now doubled this section – and generated even better stabilities. "We can obtain the required correct values very quickly without having to perform long measurements," explains Stefan Droste from the MPQ. "The total measurement uncertainty lies at only 4×10^{-19}, allowing a height difference of 4 mm between clocks to be resolved within 100 seconds of measurement time only."

Such values make the new technology highly interesting for practical applications. "In principle, optical clocks in research institutes which are further away can now be quasi 'interconnected' and used for all purposes, for which such 'good' frequencies are required," explains Ronald Holzwarth from the MPQ.

A first application for basic research has also just been documented, i.e. in June 2013 in the journal *Physical Review Letters*: Researchers from the MPQ and PTB as well as French researchers have used this possibility to carry out spectroscopic investigations on hydrogen, which are important for the fundamental question of whether quantum mechanics really gives a good description of the world.

And now the geodesists are virtually just around the corner. "Together with the universities of Hanover and Bremen, we are preparing the application for a special research area," says Gesine Grosche. In addition, this research could also be used for radio-astronomic investigations. For that purpose, our colleagues in Australia do not want to compare frequencies over 2000 km, but over approximately 4000 km which is, of course, making things even more complicated. But Gesine Grosche is optimistic: "Now that we have laid the foundations for this, we will probably also achieve it!"

And, naturally, also the good cooperation over many years between PTB and the MPQ in this field will continue. Perhaps some day the height between Braunschweig and Garching will be measured over the large distance – of course also via the glass fiber link and with the aid of a clock comparison.

More information: S. Droste, F. Ozimek, Th. Udem, K. Predehl, T. W. Hänsch, H. Schnatz, G. Grosche, R. Holzwarth: Optical Frequency Transfer over a single-span 1840-km Fiber Link. Phys. Rev. Lett. 111, 110801 (2013) prl.aps.org/abstract/PRL/v111/i11/e110801

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