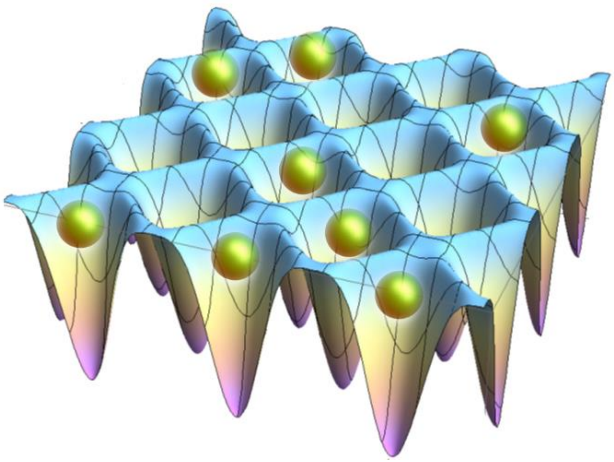
<Research on the optical lattice clock by Dr. Katori>

The importance of precision time measurement is growing ever greater in modern society each year. It forms an infrastructure vital to all social activities, including the Global Navigation Satellite System (GNSS) with atomic clocks on board, timestamps used in e-commerce, and precision measurements employed in cutting-edge science and technology.

At present, the definition of "one second" in the International System of Units (SI) is based on the unperturbed ground-state hyperfine transition frequency of the cesium 133 atom. International Atomic Time based on the cesium atomic clocks (with a microwave frequency of approx. 9.2 GHz) has an accuracy of about 15 digits. However, the optical atomic clock that uses optical transitions with a higher than microwave frequency holds the potential to create atomic clocks with higher precision. The most promising candidate for an optical atomic clock has been considered to be a clock based on a singly trapped ion in which the transition frequency of a single ion, cooled to ultracold temperature and trapped between electrodes, is repeatedly measured over a million times to achieve 18-digit precision. As each measurement takes one second, a million seconds (10 days) of averaging time is required.

Instead of averaging one million seconds, Dr. Katori conceived of an optical lattice clock to dramatically reduce the averaging time by measuring many atoms at a time. Atoms are trapped in an optical lattice created by the standing wave of light[*1] to reduce the Doppler effect caused by the atomic motion. At the same time, the quantum noise is reduced by averaging the signal from many trapped atoms. He proposed and demonstrated that the optical lattice does not affect the eigenfrequency of the atoms by tuning the laser to the magic wavelength[*2] to create the lattice.



Schematic representation of an optical lattice
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Such high-precision atomic clocks have been mainly studied in the laboratory, as they are consisted of many components and are sensitive to environmental conditions. The research team led by Dr. Katori conducted an experiment to compare two downsized optical lattice clocks—one installed on the observation deck and the other on the ground floor of Tokyo SkyTree, which is a broadcasting tower in Tokyo. In April 2020, the team published a paper reporting that the clock on the deck ticked faster by 4/1,000,000,000 of a second per day than the clock on the ground. This triggered a huge response from around the world, as the experiment verified Einstein's general theory of relativity with a precision comparable to that of spaceborne experiments using rockets and satellites, despite a height difference of only 450 meters. This demonstration was the first step toward relativistic geodesy employing high-precision atomic clocks.

Dr. Katori is presently working on the further downsizing of the optical lattice clock. While the SkyTree clock has a volume of approximately 1,000 liters, a smaller machine with a volume of 1/5 is underdevelopment. When continuous and stable operation of such downsized clocks becomes possible, a network of optical lattice clocks can be realized by installing them in various locations. The clock network will not only provide time reference with a precision far higher than GNSS but also will be able to detect spacetime curved by gravity, thus allowing precision monitoring and investigation of the environment on the earth's surface, as well as the oceans, climate, and crustal movements. For example, real-time monitoring of crustal movements may be used to study precursors of earthquakes.

*1 Standing waves: frequency waves with a fixed amplitude distribution in space.

*2 Magic wavelength: the wavelength where the polarizabilities of two electronic states used for the clock transition become equal. Because the polarizability of the atomic state depends on the electronic state, the light shift likewise differs with the electronic state. This results in a change in the resonant frequency of atoms trapped in the optical lattice. However, the optical lattice created with a laser tuned to the magic wavelength equalizes the polarizability for the two states and does not affect the resonant frequency of trapped atoms.