Monitoring vertical deformation with optical lattice clock –an application of relativistic geodesy

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Crustal deformations due to earthquake and volcano activities have been detected by geodetic observation methods. The obtained deformations have been analyzed together with horizontal components and physical mechanisms (e.g., fault slip) to cause such deformations have been investigated. Representative methods to observe vertical deformation are leveling survey as a terrestrial method and the Global Navigation Satellite System (GNSS) as a space geodetic technique. The latter includes the Global Positioning System (GPS). Leveling has a long history (>100 years) and is still the most precise method to measure the height difference between relatively near two sites (e.g., <5 mm for 4 km). However, measurement errors increase with longer survey routes and it needs considerable time to complete the survey when the network is larger (about 2 km/day). GNSS, having a shorter history (<30 years), can measure the height difference over a long distance more precisely than levelling (plus-minus 1 cm for 24-hour average for \sim 100 km baseline). The spatial resolution is also better than levelling, thanks to the dense observation network such as GEONET in Japan. However, GNSS suffers from serious atmospheric noises. The precisions to detect vertical deformations in time scales shorter than 24 hours degrade (e.g., plus-minus 3 cm for 3-hour average) due to insufficient measurement time for canceling out the atmospheric noises. Seasonal time-scale crustal deformations are also hard to discriminate from the effects of atmospheric water vapor.Recently, precisions of atomic clocks have become better and better. In particular, optical lattice clock proposed in Japan (Katori 2002; 2017) achieved a relative precision of 5 x 10^-19 in three hours, which is approximately 3 orders of magnitude better than Cesium atomic clocks used to determine 1 second of International System of Units (SI). By the general relativity, the length of 1 second measured by an atomic clock changes according to the variation in the local gravitty potential (gravitational red shift). In general, the length of 1 second becomes shorter at higher altitude with smaller gravity potential energies. Fiber linked two optical lattice clocks can measure the relative potential difference between the two sites. The precision of 5 x 10^-19 corresponds to the height difference of 5 mm. Tectonic gravity potential changes in geodetic time scales are negligible in most cases since even an M-9 earthquake causes a geoid height change by only a few cm at maximum. This means that most part of the temporal variation in the measured gravity potential difference reflects the temporal change in height. The above-mentioned measurement precision and time by optical lattice clock is superior to GNSS, implying that optical lattice clock can replace GNSS as for monitoring of vertical deformation. Since November 2018, Japan Science and Technology (JST) has begun a new project regarding optical lattice clock, consisting of developers of optical lattice clock and geodesists. In this presentation, we will introduce this new project and the goal of the "relativistic geodesy" group. We discuss possible applications of optical lattice clock to crustal deformation monitoring.

Keywords: optical lattice clock, relativity theory, crustal deformation, gravity potential, atomic clock, relativistic geodesy