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Probing geophysical processes through the successive derivatives of the gravitational field: towards a better source separation

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The knowledge of the gravitational field at the surface of the Earth is of great interest to understand various geophysical processes but interpreting gravimetric data is usually difficult because different geophysical sources can have similar signature on the gravitational field. However, such geophysical processes affect differently the gravitational potential, the acceleration of the Earth's gravity g, and the gravity gradients. It thus appears fruitful to probe the geophysical source of interest with these three different observables simultaneously. This means locally approximating the gravitational field using its successive derivatives measured locally, thus allowing to circumvent the problem of source separation.

Recent developments of Quantum Technologies have given birth to extremely sensitive instruments able to provide access to the first three derivatives of the gravitational potential. Optical Clocks connected by fiber links can now measure gravitational potential differences. Inertial atom interferometers using laser cooled atoms can measure the acceleration of the Earth gravity g and the vertical gradient of g. In the future, testing the above mentioned approach experimentally will require the availability of robust, performing and easy-to-use pieces of technology.
We report here on the industrial development of two specific instrumental advancements which go along this path: a quantum gravity gradiometer and optical fiber links dedicated to remote optical clock comparisons.

First, we present the development of gravity gradiometer relying on atom interferometry with cold 87Rb atoms. Although this instrument relies on the same principle of operation as other types of quantum gravimeters exploiting the free-fall of laser-cooled atoms, the gravity acceleration is in this case measured simultaneously at two heights in order to access the vertical component of the gradient. Thanks to common mode rejection of noise, performance are expected to be much better than measuring the acceleration with two instruments. Short term stability is expected to be around 100 E/$\sqrt{\text{Hz}}$ (1E = 1e-9 s-2 = 0.1 μGal/m), long term stability close to 1E. These performances shall allow to be sensitive to various interesting geophysical sources in the field of hydrology and volcanology among others. Furthermore, the instrument will be able to measure simultaneously the gravity acceleration and its gradient making it relevant for aforementioned applications.
Second, we describe our work to improve the reliability, the performances and the availability of optical fiber links that are used to compare optical clocks remotely, hence enabling to measure gravitational potential differences over long distances. As an example, we present the world's first optical frequency transfer link deployed and operated at an industrial level in the frame of the REFIMEVE+ project in France. This fiber link, between Paris and Lille, is operational since October 2017. We report on a stability of the frequency transfer at the 1e-20 level in a real field environment, well below the stability of the current best optical clocks operated in the world.
Such on-going developments pave the way to new measurements capabilities in Geodesy and other fields of Geophysics.