Quantum science and sustainability project: Monitoring Earth's gravitational field variations using quantum technologies.

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1 Abstract

Earth's gravitational field variations are one of the direct consequences of global mass transport phenomena, such as ocean circulations, hydrological water redistribution and even core geodynamo activities (eg sismic activity) [1]. Gravitational field monitoring can play a key role in understanding climate change and its hazardous effects including melting of the glaciers and sea-level rise, as well as developing early warnings for droughts and flooding events [2]. Current missions, for example CHAMP [3], GRACE [4] and GOCE [5] are measuring the Earth's gravitational field from space.

The CHAMPS and GOCE mission were using the same gravitometer set up concept. It consisted of accelerometer coupled with GPS signal to be able to get the local gravitational field of the earth. However, the GOCE mission was a lot more recent, and thus the sensors were more than a hundred time more accurate than any captor send before. On the contrary, the GRACE mission was using two satellite evolving in parallel, with a known initial distance and angle, and then deduced the variation of gravity from the variation induced in the distance between the two satellites. All of these missions use classical captors, limited to a detection of one part in 10 million of the earth gravitational field. These captors suffer from bias, long term drift, and scale-factor errors, while gyroscope misalignment further reduces reliability [6].

Beyond these limitations, the broader geophysical processes driving gravity variations highlight the need for better precision. Mass redistribution arises from ocean and atmospheric circulation, ice-sheet melt, sea-level changes, and mantle convection. All these phenomena alter the gravitational potential in non-uniform ways [7]. With satellite gravimetry, it is possible to provides a global perspective on the water cycle, ice mass balance, and solid-Earth dynamics. This enables improved climate predictions and better understanding of long-term geophysical evolution. Classical missions have already revealed large-scale signals such as post-glacial rebound, aquifer depletion, and crustal deformation, but their spatial resolution (90–200 km) and temporal resolution (monthly for GRACE) remain insufficient for many climate phenomena.

Quantum technologies directly address these limitations. Emerging quantum sensors — cold-atom interferometers and optical clocks — exploit matter-wave interference and gravitational redshift to measure acceleration and gravity gradients with unprecedented long-term stability. Unlike classical accelerometers, which require continuous calibration and suffer from drift, quantum sensors provide a drift-free, self-calibrated observable derived from the phase shift of atomic wave packets [8]. Their sensitivity reaches the low-nano-g regime on Earth and is expected to improve further in space. This technological leap is at the core of the CARIOQA (Cold Atom Rubidium Interferometer in Orbit for Quantum Accelerometry) mission, which aims at sending quantum gravimeter and accelerometer to space within the next decade [9]. Reaching a sensitivity of 10^{-9} m/s^2 in space would already outperform the precedent missions mentioned by one to two orders of magnitude beyond the current GRACE accelerometer performance and enable significantly improved spatial and temporal resolution of the Earth's gravity field [10].

Building on these advances, quantum sensors are expected to improve gravity-field monitoring, which will refine estimates of ice mass balance — a key driver of global sea-level rise — and enhance our ability to model mantle dynamics, which influence sea-level trends, volcanic activity, and long-term climate feedbacks. Higher temporal resolution will also support early-warning capabilities for hydrological extremes such as droughts and floods, by tracking water redistribution in near-real time.

Finally, the deployment of quantum gravimetry in space raises geopolitical considerations. High-precision gravity maps can reveal underground structures, natural resources, and even military assets such as nuclear silo or submarines, contributing to a growing international "quantum race" between China, AUKUS and NATO. Ensuring open scientific collaboration while navigating security constraints will be essential for the success of future missions such as CARIOQA and its successors.

In summary, quantum technologies represent an important step for satellite gravimetry. By surpassing the sensitivity limits of classical sensors and enabling unprecedented monitoring of Earth's mass redistribution, they promise major advances in climate-change prediction, water-cycle understanding, and solid-Earth science.

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