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QTSPACE

# DELIVERABLE 2.1

# Identified concrete application(s) of quantum technologies in space

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## INTRODUCTION

The same advantages space offers for fundamental tests, also make it attractive for applied purposes. The long lines of sight and the low losses of free-space optical transmission in space compared with the losses in fibre or the free-space transmission through the atmosphere is the driving motivation for satellite quantum key distribution (SatQKD) as well as for longer term applications for quantum communications beyond quantum key distribution (QKD) like entanglement distribution and the quantum internet. The vantage point from low Earth orbits (LEOs) is valuable for remote sensing and remote observation, for example in applications of Earth observation. The development of quantum sensors may bring many benefits to existing markets, and these developments may open up new avenues of exploration. Space-based quantum clocks allow for the distribution and synchronisation of timing information and promise performance upgrades of existing global navigation satellite systems (GNSS). In this report, we will review concrete applications of quantum technology in space and the benefits and features these quantum technologies may bring. In particular, we will focus on two applications: Quantum Key Distribution and Quantum Sensing.

### Quantum Key Distribution

The goal of a QKD protocol is to privately share a secure random encryption key between two remote trusted parties [1–4]. Upon successful realization of the protocol, the security of the shared key is guaranteed by the fundamental principles of quantum physics. Access to a link granting such level of security and integrity is an important asset to critical infrastructure providers, governmental, military and corporate sectors [5,6]. A QKD link can be used for protection of data backup, continuity processes, transactions, as well as for securing network infrastructure, systems of supervision and control, etc.

### Quantum Sensing

We can define quantum sensing in two ways: quantum limited transduction, or sensing that exploits either superposition or entanglement, the features of the so-called "second quantum revolution" [7]. Quantum-limited transduction can be achieved by using shot-noise limited light, where fluctuations in the optical frequency and intensity are limited by the quantum-statistical nature of photons [8,9]. One can also use squeezed light, where either the phase-noise or the amplitude noise is reduced at the expense of increasing the uncertainty in the other quadrature, to further boost the sensitivity [10]. The harnessing of quantum superposition and/or entanglement is of particular interest as these methods have no classical counterpart.

## IMPLEMENTATION

We will provide a description of the two applications chosen and possible ways how they could be implemented.

### Quantum Key Distribution

While sharing a common goal, there's a variety of approaches to how exactly to implement QKD protocols, differing in preparation techniques, encoding, measurement types, assumptions made regarding used equipment, etc. The QKD protocols can be divided into two main families, namely discrete-, and continuous-variable (DV and CV respectively). The former makes use of quantum systems defined on finite-dimensional Hilbert spaces, encoding key bits onto discrete degrees of freedom of a carrier system (ideally a single photon) [2]. The best-known representative of DV family protocols is the seminal BB84 protocol that employs polarization qubits [11]. CV QKD protocols, on the other hand, use quantum systems described on infinite-dimensional Hilbert spaces, and encode the key bits onto continuous observables of the light field, such as quadrature of generally multiphoton Gaussian coherent or squeezed states [12,13].

Both families can be further divided with respect to the realization scheme, be it prepare-and-measure or entanglement-based. The former is designed for the sender to prepare an optical signal and actively alter its state according to the prescribed key mapping. In the entanglement-based scheme, the trusted parties share an entangled state and conduct independent measurements on a received subsystem, obtaining knowledge about the state of a remote subsystem. Regardless of the preparation, the secure key stems from the correlated data on both sides that is processed (typically one-way) using authenticated classical communication.

### Quantum Sensing

There have been considerable developments in quantum technologies for sensing applications, such as enhanced magnetometry [14,15], electric field sensors [16–18], bio sensing [19,20] and position measurements [10,21]. Taking advantage of this progress in quantum sensing for enhancing space-based sensors holds significant promise for the application of quantum technology in space. The focus of this section will be quantum-enhanced sensing where either the microgravity environment of space aids sensing protocols, as is the case for gravimetry, or the isolated landscape of space requires additional precision, for example, for the navigation of a satellite or a space probe. In the following, we will discuss the current state-of-the-art in quantum gravity sensors and inertial measurement units. We will focus on cold-atom laboratory devices and optomechanical quantum sensor proposals fit for a space mission.

The geoid, defined by Earth's gravitational field, is a surface of equal gravitational potential. In the absence of tides and currents it follows a hypothetical ocean surface at rest. A precise model is crucial for understanding the ocean circulation, sea-level change and terrestrial ice dynamics, all of which are affected by climate change. Through gravimetry, one can directly infer information about sub-surface mass distribution, including volcanic activity monitoring [22], ice mass changes [23], subsidence monitoring [24], and the detection of underground cavities [25]. The latter is of interest to the oil and gas industry as well as the construction industry.

Free-fall acceleration sensors are known as absolute gravimeters because they give a direct measure of gravity in units of $m/s^2$ traceable to metrological standards. Relative gravimeters are masses supported by a spring, for example, the stiffness of a cantilever, magnetic levitation, or the optical trapping of a nanosphere. One must calibrate relative gravimeters by measuring the stiffness of the spring and placing the instrument in a location with a known gravitational acceleration. Absolute gravimeters are therefore required to calibrate relative ones. Free-fall accelerometers are particularly suited for gravimetry applications aimed at resolving the temporal and spatial fluctuations of gravitational acceleration at the Earth's surface, which can vary roughly between 9.78 $m/s^2$ and 9.83 $m/s^2$ [26].

Gradiometers on the other hand, are devices which can resolve gravity gradients by evaluating the difference between two measurements. For a clamped device such as a cantilever, a gravity gradient can be measured through the pull of gravity acting on two spatially separated masses. For cold atom systems, gradiometers often employ two ensembles of atoms injected into two interferometer paths vertically spaced apart [27,28].

## CONCLUSIONS

We identified two (among many) promising applications for quantum technology in space: Quantum Key Distribution and Quantum Sensing. In both cases, one can classify the possible implementations into different architectures. For QKD, these are discrete-variable (DV) and continuous-variable (CV) schemes. In quantum sensing, there are multiple physical architectures that can be used. Examples are atom interferometers and optomechanical devices.

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