DELIVERABLE 2.2

List of technical requirements for each application of quantum technologies in space

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INTRODUCTION

Based on the deliverable D2.1, where we identified two concrete applications of quantum technology in space, the present deliverable will provide an overview of the "technical requirements" for implementing these applications. By "technical requirements", we are not referring to the standard use of this phrase in the space industry, but we intend to provide an overview of the technology required for different forms of implementing Quantum Key Distribution and Quantum Sensing.

IMPLEMENTATION

We discuss “technical requirements” for the two applications chosen.

Quantum Key Distribution

The precise technical requirements will vary depending on the particular implementation of QKD chosen as well as on the orbit configuration for space-based QKD. All forms of space-based QKD will rely on optical links between ground stations and satellites, but the number of required links may vary, and whether the implementation requires up-links or down-links. The technology required for establishing and maintaining optical links will depend on the orbit and is essentially equivalent to the requirements for classical optical links. The main difference to classical optical links is the potential sensitivity of quantum protocols to scattered sunlight because the protocols work at the single-photon level. Narrow band-pass filters can, however, mitigate this challenge. Because this is a common challenge to all quantum communication protocols, we will not specifically address it in our table of technical requirements. We will describe different possible implementations of QKD as well as their advantages and/or disadvantages in more detail in deliverable D2.3. To keep the table simple, we specify the protocol as BB84 even if the protocol goes beyond the original BB84 protocol, e.g., by using decoy states for the DV architecture or squeezed states for the CV architecture.

In all cases, the possible link attenuation is limited by the fact that the signal-to-noise ratio has to be sufficiently high such that one can still distill a secure key. While it has been demonstrated that this is possible for prepare-and-measure (PM) protocols as well as for entangled-photon protocols (ENT), ENT protocols require two simultaneous links whereas PM protocols require only one link at a time. For this reason, PM protocols can typically tolerate more loss. At the same time, ENT protocols do not have to rely on trusted nodes and the required infrastructure for sharing entanglement is more versatile because it can, in principle, also be used for more complex quantum communication protocols. In addition, ENT protocols allow device-independent QKD in principle. The table listing the required technology does not take into account additional adaptations necessary to achieve device-independent QKD. These adaptations will be discussed when we describe these protocols in deliverable D2.3.

Architecture	Protocol	Links	Technology on ground	Technology in space
DV	PM	Up	Weak-pulse or single-photon source, amplitude modulation for the decoy-state protocol, time synchronization, time tagging	Detectors, standard optical elements, time synchronization, time tagging
DV	PM	Down	Detectors, standard optical elements, time	Weak-pulse or single-photon source, amplitude modulation

			synchronization, time tagging	for the decoy-state protocol, time synchronization, time tagging
DV	ENT	2xUp	Source of entanglement, standard optical elements	Detectors, time synchronization, time tagging, standard optical elements
DV	ENT	2xDown	Detectors, time synchronization, time tagging, standard optical elements	Source of entanglement, standard optical elements
CV	PM	Up	Narrow-band laser, amplitude modulation, standard optical elements	Narrow-band laser for phase-sensitive measurements, phase synchronization, photodiodes, standard optical elements
CV	PM	Up	Narrow-band laser for phase-sensitive measurements, phase synchronization, photodiodes, standard optical elements	Narrow-band laser for phase-sensitive measurements, phase synchronization, photodiodes, standard optical elements
Squeezed CV	PM	Down	Narrow-band laser for phase-sensitive measurements, phase synchronization, photodiodes, standard optical elements	Narrow-band laser, amplitude modulation, standard optical elements

Quantum Sensing

As described above, the main focus of this report will remain on applications based on

- Cold and Condensed Atoms
- Optomechanics

For the two technologies, the current state-of-the art, the requirements, and the solutions are very different but have one similarity: the desired size, mass, and power (SWaP) budgets. Especially in space applications, the SWaP budgets are essential to the realization of missions. In consequence, one major challenge is miniaturization of the complete system including supporting infrastructure, such as laser modules and electronics.

Cold and condensed atom systems are developed far, and first principles of sensors for fundamental tests, such as of the equivalence principle or measurements of the gravitational constant, in astro physics, such as for gravitational wave detection, for navigation, as cold optical clocks and inertial sensors, and for Earth observation, such as gradiometry or gravimetry, have been developed [1,2]. There are already companies developing sensors for geodesie or for setting up cold atom experiments (see, e.g. Ref.[30]). However, those experiments are still rather complex to handle and large to employ. Consequently, the area would benefit mainly from miniaturized vacuum and optical systems. Additionally, increasing the flux or the usage of the flux of atoms increases the sensitivity and thereby applicability of the system. While the systems can currently operate in laboratories, the necessary next step is the deployment in industrial or academic applications. Additional developments, adapting the systems and proofing their operation in orbit, are necessary.

The past years have demonstrated huge steps in the development of optomechanics. The center-of-mass motion of macroscopic particles can now be cooled to its quantum ground state [4,5]. While there have been proposals to use optomechanical systems for fundamental physics tests [6,7] and for gradimetry [8], optomechanical systems have not yet been deployed in any system with outside limitations on SWaP budgets. Consequently, the next steps are to develop hardened systems, capable of withstanding harsh environments, and investigate requirements by users for the adaptation into industrial or academic applications. Similarly to cold and condensed atoms this requires smaller systems with stringent vacuum requirements and complex infrastructures. Many of the technologies necessary to implement and to operate optomechanical systems are already available in space. Examples are narrow-band tunable lasers, similar to the laser systems or precise optical alignment and bonding as used in the LISA Technology Package [9,10]. In order to use optically trapped test particles for space-based experiments or applications, further technology development is required. For example, loading test particles into optical traps in ultra-high vacuum is a technique that remains to be elusive even in ground-based experiments [11]. Techniques like ground-state cooling that have recently been demonstrated on ground will need additional technology development before they are ready to be used in space-based setups.

CONCLUSIONS

We focused on two specific applications of quantum technology, namely quantum key distribution (QKD) and quantum sensing to provide an overview of the technology required to implement these technologies in the future. In the case of QKD, some of the required technology depends on the specific QKD protocol to be implemented like, e.g., the requirement of phase stabilization and narrow-band lasers for continuous-variable QKD or the need for single-photon detectors for discrete-variable QKD. Some enabling technologies will be required for all the protocols presented like, e.g., fast and reliable ways for amplitude modulation or high-quality, radiation-resistant nonlinear optical crystals. High-precision sensors based on cold-atom interferometry have experienced significant progress over the last decades, and there have been notable efforts to build miniaturized and rugged commercial devices. The realization of space-based atom interferometers like CAL and BECCAL on the ISS have led to an additional boost to the technological readiness of atom interferometers.

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