Quantum Technologies in Space

Policy White Paper

Executive summary

In an increasingly connected and digitalised society the reliance of satellites, and more broadly in space, are crucial for the well-functioning of our daily lives. The limitations and the challenges which the current generation of technologies face have called authorities to invest more in promising emerging technologies, such as quantum technologies (QT).

In very recent years, the European Commission (EC) and other European countries have announced large investments towards the commercialization of QT to address/mitigate some of the biggest challenges facing today's digital era – e.g. secure communication and computing power.

For more than two decades the QT community has worked on the development of QTs, which promise landmark breakthroughs towards commercialization in various areas. In recent years, the substantive increase in investment from national initiatives and the EU QT Flagship are significant tokens of the interest that QTs are raising in the broadest research & development community, policy makers, and industries.

In the words of the European Commission (EC): "Quantum technologies use the properties of quantum effects – the interactions of molecules, atoms, and even smaller particles, known as quantum objects – to create practical applications in many different fields […]. Now scientists can manipulate and sense individual particles, measuring and exploiting their properties." The EC prompts the factual development of solid industrial production line of quantum technologies that exploits the long-standing tradition and world-class leadership of the European research community working in quantum research. Only such a transformative step will enable the translation of high calibre academic research into potentially disruptive quantum devices.

Through the Quantum Technology Flagship (QT Flagship), the Commission has identified four application areas:

- quantum communication
- quantum simulation
- quantum computing
- quantum metrology and sensing.

Such research pillars should be underpinned by research in the basic science enabling quantum technologies. All such areas have immediate applications also to Space science and industry.

The ambitious goals of the QT community and expectations of EU authorities cannot be met by mere individual initiatives of single countries, and therefore, require a combined European effort with large and unprecedented dimensions. The strong competition from international countries – such as USA, China and Canada – calls for a coordinated European effort towards the development of QT in and for space, including research & development of technology in the areas of communication, metrology and sensing, useful for facing the current and upcoming challenges in security and defence in Europe.

This white paper aims at summarising the state of the art in the development of quantum technologies which have impact the field of space applications, and to also delineate a roadmap for the consideration of major actors in this area, i.e. from the European Commission – as responsible in the definition of the EU space strategy – to ESA, national space agencies and industries. The goal is to outline a complete framework for the design, development, implementation, and exploitation of such space QT. Moreover, the paper embodies an opportunity to identify and to implement the necessary steps towards the definition of a realistic avenue for achieving the goals of the European Commission in the development of a mid- and long-term strategic vision of QT in space more prosperous and reliable for Europe.

Following the QT Flagship, the long-term vision that should be pursued is to integrate the terrestrial quantum web with a space one, where quantum computers, simulators and sensors are interconnected via quantum communication networks.

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Chair and Deputy Chair

COST Action QTSpace: Quantum Technologies in Space

Supporting documents:
Quantum Manifesto (May 2016)
QTSpace – Intermediate Strategic Report (November 2017)
Supporting QT beyond H2020 (May 2018)

Secure Quantum Communication – QC

Quantum Communications (QC) use the transfer of quantum information between distant terminals. One of its possible uses is quantum key distribution (QKD), which counters threats by a quantum computer on widely used asymmetric encryption, leading to long-term secure communication. The quantum secure systems developed so far provide secure communication on ground. The extension to space and air will be the necessary complement to reach different networks of distant nodes. Essential quantum secure solutions have already been envisaged and partially developed but much more is needed in Europe for more advanced, widespread applications, and research programs.

Quantum adds to security

QC changes the paradigm with respect to current secure communication standards, making the transfer of information secure for long-term requirements and protecting against potential attacks, including those expected from quantum computers.

QKD consists of the distribution of secret keys in a way that is information theoretically secure. There are two types of protocols for this, namely "prepare & measure" (PM-QKD) and "entanglement-based" (ENT-QKD) ones.

QKD systems reached commercial-maturity level on ground fibre links, and are based on PM-QKD, among which BB84 is the most common. Key exchange exceeding a million secure bits per second was demonstrated on fibre links. QKD is currently under development for space channels. Such links, whose nodes – dubbed trusted – will allow the storage of keys for some time, will enable the realization of networks for key exchange of any size.

ENT-QKD is also possible with the use of a photon-pair source mid-way between the two terminals where the key is generated. This kind of protocols is based on quantum entanglement distribution. It allows communication of arbitrary quantum states, and thus is a more generic communication mean (sometimes called 'quantum internet'), that can offer security applications beyond quantum cryptography. In particular, it allows establishing secret keys with the E91 protocol, with the satellite just distributing the entangled pairs to ground terminals. Yet the implementation of entanglement-based protocols is much more challenging for situations of high loss, such as those making use of long fibres or high-altitude space-based optical links. Such entanglement-based protocols might thus be a solution for the longer term.

Space-based QKD will be a crucial element of the quantum internet at the planetary scale and beyond. Both types of QKD protocols shall be used, based on the needs of specific applications being considered, with a natural progression from PM-QKD – which is already well developed on the ground – to ENT-QKD. Space QC are expected also to unlock the implementation of other relevant quantum communications applications beyond quantum cryptography, for instance in distribution of time, metrology and distributed quantum computation, besides fundamental investigations.

Security needs certification/accreditation

Although security can be quantified on the basis of QKD measurements, this is not sufficient for an operational system with mission-critical uses. In order to evaluate the security of a system, its use-case, boundary conditions and requirements need to be defined. The design and development of such a system shall then comply with rules derived from these requirements, and its compliance with them continuously assessed along the process.

In case of quantum cryptography, an interdisciplinary approach is required between quantum physicists, cryptography/security experts, and engineers. Standards need to be defined and certification procedures developed by the relevant agencies on both national and international levels. Moreover, quantum and classical security concepts need to be combined and assessed in a single framework.

Secure communication needs a system

The design of a secure communication requires a complete system including space and terrestrial components. The system design has to be adapted to different use-cases. On ground, fibre-based solutions will offer short-range secure communication. Satellite-based quantum communication will provide a means for reaching global distances and secure space assets. The technology of terrestrial components (ground stations and management centres) and space components (satellite or satellite networks) need to be adapted to different use-cases.

The deployment on ground of receiver of keys to be used in pan-European as well as national secure communications will be the most immediate results of such Space QKD system. The development of compact receivers, suitable for the roof of a normal building, would allow the demonstration of QKD to all Member States regardless of their geographical location, much before the development of a continental repeater network based on fibers.

A roadmap for space-based secure quantum communication

Quantum communication should be implemented on a practical and reliable platform to provide world-wide secure communication for European assets. This is needed as soon as possible, as is the European-scale demonstration and the involvement of all Member States in the QKD network. As time for implementation and service of usual satellite-based systems goes well beyond a decade, and the threat of a future quantum computer has to be taken into account in the same time-frame (even sooner in case of retroactive decryption), the urgency of action is striking.

Again, space-based QKD may provide access to such networks sooner and easier in the case of Member States that are geographically separated to others by longer stretches or by the sea.

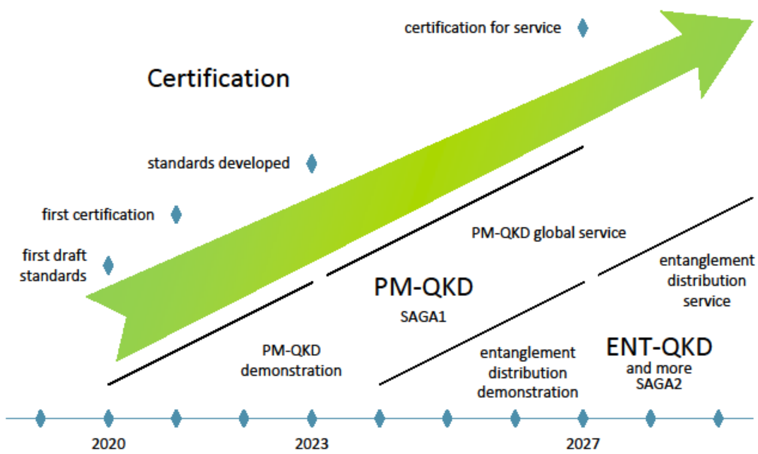
The pursuit of such goals defines a clear roadmap that includes the following key pillars, to be developed in parallel:

Operational systems. *SAGA (Security And cryptoGrAphic mission) was originally an ESA internal study for ENT-QKD. In this context, we use SAGA as* *refence to the space segment of the future QCI, comprising different types of implementation:*

- SAGA1: "Security & cryptography": The aim is to develop satellite-based quantum cryptography for world-wide secure key-distribution using PM-QKD protocols and networks with trusted nodes. The system should include key management, secure symmetric encryption on classical channels and options depending on user needs. Terrestrial terminals (ground receivers for the keys and interfaces to the fibre links) have to be developed as economically affordable, easily deployable and that can connect to ground-based fibre networks. (Demonstrations: 2020-23, Service: 2024-28.)
- SAGA2: "Further applications": entanglement-based & more. The aim is to develop entanglement-based quantum communication using satellites. Depending on use-cases the satellite may use different types of orbits. In addition, the quantum repeaters may be concretely realised in Space to enable further applications on a larger scale. As a vision a full quantum repeater service can be implemented world-wide. (Demonstrations: 2024-27, Entanglement distribution Service: 2027-33.)

<u>Standards/certification development</u>
Standardisation and certification efforts have to start in parallel to the development of the operational systems. The development of the operational systems serve both as an input to this process as well as later standards and certification requirements will steer the development. (First draft standards: 2021, first certification: 2020, advanced certification and standards developed: 2023, certification for service: 2027.)

This vision is encompassed the following graph.



R&D on security, quantum concepts, system concepts

In addition to the concrete operational developments, research and development is needed in interdisciplinary topics. These include the development of high-rate QKD payloads, advanced pointing systems, low-loss space-to-ground links, also based on adaptive optical systems, and inter-satellite links.

Moreover, we aim at the exploitations of quantum functionalities where a provable advantage can be shown and that require current or near-term quantum technology. The most notable ones are:

- The quantum random number generation.
- Quantum communication complexity protocols (with most prominent ones being quantum fingerprinting and hidden matching/sampling matching).
- quantum crypto primitives like position verification, oblivious transfer, coin flipping, anonymous message transmission, leader election, secret sharing.
- Distributed computing tasks like delegated quantum computing.

The EU effort in this regard is essential to complement that by the Space Agencies.
The exploration of QKD protocols using different photonic degrees-of-freedom (frequency, time bins, polarization, orbital angular momentum, ...) will require advanced security analysis and the development of frameworks enabling new, affordable and practical services and highest security applications and a variety of new applications involving time, position, navigation and much more.

A vision for financial support

To develop the program described here, we envisage a joint effort of the European Space Agency and the European Commission. For setting up of the space part of the European institutional QKD infrastructure, we recommend that ESA shall act as project management for the Commission for technological and programme implementation, as is the case for Galileo. In addition, development of protocols and R&D shall continue being supported by DG Grow and DG Connect directly.

Time and Frequency Transfer – TFT

Time standards and frequency transfer are fundamental for many modern day applications with high societal value. Fundamental TFT techniques are well established today enabling services in the fields of communication, metrology and GNSS. With the availability of optical atomic clocks and optical frequency transfer, QT allows to boost the TFT performance by several orders of magnitude. This new performance permits to keep pace with the development of needs in communications (timekeeping) and GNSS (geolocation), and enables new applications (geodesy, gravitational wave observation, synthetic aperture optical astronomy). A space component is relevant to the enhanced applications by enabling long range transfer, enhanced security and global availability.

Time standards and frequency transfer based applications

Time standards and Frequency Transfer have a rich set of applications relevant to engineering, science and society. In high-speed communications, timekeeping makes use of atomic clocks synchronized by GNSS based time dissemination services to perform time stamping and information routing. These capabilities are fundamental to the high performance and availability of the internet and all its associated services. GNSS based services rely on high performance TFT capabilities. They have spawned many services and applications leading to multi-billion Eur turnover per year, and are key to defence and security today as well as enabling for future applications such as autonomous driving.

Precision time standards are at the root of the aforementioned applications and modern day metrology. Precision time metrology is at the heart of the international standard definition and an enabling factor in a trade-based economy. In radio astronomy recently real time imaging of a black hole has been demonstrated using synthetic aperture imaging for radio frequency signals. This was enabled by TFT technologies.

Fundamentally TFT is based on two technological elements: precision time standards (clocks) and the ability to transfer frequency (more precisely the phase of the clock) over a large distance with high precision. State of the art commercial atomic clocks operate at radio frequencies (several GHz) and achieve accuracies down to 10^{-15}. Current time standards are defined on improved clocks of the same type with accuracies of 10^{-16}. The limitation of these clocks is given by the fundamental frequency of operation (GHz) and the ability to measure these. Phase (and frequency) transfers are standard methods in high frequency RF communications and have been demonstrated on satellite links with a performance of 10^{-15} – with the same fundamental limitations imposed by the frequency used for the transfer. These technologies are about to be demonstrated at increased accuracy in space in ESA's ISS based ACES project, which contains both frequency standards and transfer capabilities to ground.

Quantum enhanced performance, quantum enabled applications

The fundamental improvement enabled by QT is given by an increase in fundamental frequency from the radio frequency domain into the optical domain by a factor of 10^5. This step is possible based on the evolution of laser technology (stable optical oscillators and frequency combs) and optical clock development (quantum state control). Optical clocks have been demonstrated in laboratory environment to have a fractional uncertainty of less 10^{-18} with further improvements expected (optical lattice clock and single ion clock). Frequency transfers have been demonstrated on a ground-based optical fiber link with a length of 920km at an accuracy of better than 4×10^{-19}.
ESA has studied the implementation of a sequel mission to ACES based on an optical atomic clock and optical links concept (ISS Space Optical Clock – I-SOC) with a possible implementation until the early 2020s. These experiments clearly show the superior performance of the QT based optical TFT which have an improved the performance at this early stage of development already by three orders of magnitude.
Making use of the technological advancement will allow improving the quality of existing applications or allowing building more efficient system architectures. Time dissemination services and metrology will have a direct improvement of three orders of magnitude. High precision clocks in space will provide a secure (i.e. hard to jam) and independent time base for global time keeping. Combined with space-space and space-ground optical links they will allow global TFT. Such space-based time standard and time distribution system will provide an efficient globally available infrastructure (compared to fiber networks which are only available in densely populated areas) for all of the above applications. For GNS Systems, the system architecture is suggested to be improved with a more efficient implementation then possible and a higher accuracy for specific use cases.
With the accuracy of optical clocks and the capability to compare these at large distances, new applications now become feasible. As the relative gravitational red shift is 10^{-18} per cm of geopotential height, clocks and optical transfers can be used to measure the geopotential difference of two locations. If one location is e.g. in orbit the absolute geopotential on earth's surface can be characterized (geodesy application). Similar to this application gravitational waves can be detected by comparing two optical clocks on two distant satellites. This concept augments the ESA/NASA LISA system in the fact that it has very high sensitivity to gravitational waves at low frequency – complementary to LISA. Finally, in analogy the radio frequency synthetic aperture observation concept, an optical synthetic aperture telescope can be

envisaged by the fact that a set of fully synchronized optical clocks enables a phase measurement of the impinging light wave at several locations with large separation. This allows synthesizing by analysis a telescope with an aperture size comparable to the separation of the locations (potentially 1000s of kms) leading to the capability of direct observation of planets.

Roadmap for QT enhanced TFT

The following roadmap for the maturation of QT enhanced TFT technologies is suggested based on the maturity and complexity of the individual elements.

<u>Short-term goals (5 years)</u>

As the technology elements for frequency transfer are readily available for fiber and free-space links and several applications are possible using frequency transfer without space-based optical clocks (geo-potential comparison, clock comparison) it is suggested to establish an infrastructure capable of frequency comparisons at 10^{-18} level accuracy. The TRL for this technology is currently evaluated at level 4 – 5.

In preparation of an optical clock in space the selection of clock concepts and technology shall mature.

<u>Medium-term goals (10 years)</u>

Building on the results of optical link demonstration and improvement of one order of magnitude in frequency transfer shall be achieved (10^{-19}).

An in-orbit technology demonstration of the selected optical clock concept with a goal accuracy of 10^{-18} shall be realized.

<u>Long-term goals (> 10 years)</u>

With the QT enabled TFT technologies now at sufficient accuracy for many applications and with a TRL greater than 6 several mission can be realized:

- Universal time dissemination
- Geodesy service
- New GNSS architectures
- Gravitational wave detection at low frequency
- Fundamental physics experiments
- Optical synthetic aperture telescopes

Earth Sensing and Observation – EO

Gravity field mapping from space provides crucial information for the understanding climate change, hydro- and biosphere evolution, and tectonics and earthquake prediction. The recent advent of macroscopic quantum matter such as Bose-Einstein condensates and the associated Nobel-prize winning protocols, have led to inertial quantum sensors based on atom interferometry. Quantum gravity sensors use coherent quantum matter waves as test masses, which leads to far more sensitive and precise instruments. Space based quantum sensors will enable better monitoring of the earth's resources and improve the predictions of earth-quakes and the adverse effects of climate changes like the draughts and floods.

The need for Space-Based Quantum Sensing

Given the extreme effects of global warming that mankind is facing, earth observation is maybe the most important scientific endeavour of our times. Already today, the study of global mass transport phenomena via satellite gravimetry provides important insights for the evolution of our planet and climate change, by improving our understanding of the distribution of water and its changes. Recently, the NASA gravity mission, Grace, found that the temperature of the water in the deep ocean rifts has not changed in recent decades. It is now used as an early warning system for floods as well as draughts both in the agriculturally important Midwest of the US and in the rainforest in Congo. ESA's gravity mission (GOCE) produced detailed maps of deep-sea Ocean currents, which are very important drivers of earth's climate. It revealed the remnants of lost continents hidden deep under the ice sheet of Antarctica, where it also detected a post-glacial rebound. The changes of Earth's gravity scarred by earthquakes gives valuable data for predicting future earthquakes. Its data is also being used to improve models of Earth's geology, indicating the potential locations of subsurface energy sources. Just like gravitational waves herald a new age in astronomy, mapping the earth's gravitational field proves an immensely valuable tool in understanding earth.

ESA and NASA are working on future versions of their gravity missions, which will have much improved resolution and sensitivity. However, it has become clear that the classical measurements cannot be pushed much further. Classical accelerometers used so far in gravity missions exhibit increased noise at low frequency and have large long-term drifts. This severely limits the ability of faithfully reconstructing the earth gravity field at low degrees and precisely modelling its temporal fluctuations. The NASA future geodesy mission, Mass Change (MC) mission, is under preparation for launch by 2026.

Quantum mapping of the Earth' mass dynamics

Today, the study of global mass transport phenomena via satellite gravimetry provides important insights for the evolution of our planet and the climatic change. Atom interferometry will play an instrumental role to improve satellite-based measurements for space-geodesy. Classical electrostatic accelerometers used so far in gravity missions exhibit increased noise at low frequency and long-term drifts pose severe limits. This is particularly true for the ability to faithfully reconstruct the earth gravity field at low degrees and even more for precisely models of its temporal fluctuations.

Atom-interferometric quantum sensors offer far superior long-term stability and higher sensitivity. For this reason, quantum sensors are already officially considered by ESA as a potential instrument, or a demonstrator. ESA future geodesy mission classified as Mission of Opportunity, Next Generation Gravity Mission, will include laser ranging but consider quantum sensors as a candidate for the following mission if the technology is ready at that time.

Europe's pioneering of space quantum sensing

Since 2000, missions exploiting Inertial quantum sensors (IQS were proposed to ESA. In 2010, an ESA road map highlighted space-borne IQS for fundamental physics in space, such as gravitational wave detection. IQS were selected for studies by ESA for satellite gravimetry (CAI), the Lense-Thirring effect (HYPER), as transportable devices (SAI) and, most recently, was among the three selected candidate missions for a quantum test of the equivalence principle (STE-QUEST). Concerns of technological immaturity prevented selection and motivated support for some critical payload sub-components.

Since the first decade of this century, national agencies supported space-borne quantum-sensor development. Important milestone were achieved by ICE (France) on parabolic flight studies for dual-species interferometry, by QUANTUS/MAIUS (Germany) establishing interferometry with Bose-Einstein condensates in space based on drop-tower and sounding-rocket experiments, and by CAL (USA), where US teams including German scientists explore physics with Bose-Einstein condensates in orbit. Benefiting from the space activities, novel terrestrial sensors and commercial spin-offs were created and will continue to emerge as industry starts to engage in the development of cold atom payloads.

Worldwide Earth observation with European quantum technologies

GALILEO exemplifies Europe's ambition to establish its independence regarding key technologies for space. In the recent past, stepping-stones were placed in developing methods for space-borne high-precision gravity sensing. These sensors promise to improve Earth observation by their long-term stability and low drift. The grip of gravity is compromising the analysis of the performance of these sensors. Microgravity facilities provide only limited access to extend the free fall and space-like environment for raising the TRL of key components and method development; only a pathfinder can sound out the potential performance in relevant environment. The European competences have to be firmly bundled to master this challenge and to establish space-hardware for such a sensor. Mission design and exploitation plans need a close interdisciplinary cooperation between the quantum sensor community, high-tech industry and geodesists. At this point, firm commitments between partners and stakeholders are required to jointly prepare such a mission.

A roadmap for quantum sensors for Earth sensing and observation

1. Key-component TRL needs first to be advanced to 6 and beyond, via a coordinated European effort. This requires the prototyping and performance tests in a joint laboratory (C-COOL) using European ground-based microgravity facilities and exploiting European heritage and synergies. Parallel to this, the most efficient mission concept for satellite gravimetry with quantum sensors should be consolidated especially with respect to improving ultimate performances (enhanced sensitivity, AOCS, size, mass and power reduction) and a pathfinder on a small sat with science case shall be defined and ready for launch (5 years).
2. A model of an IQS for space needs to be developed and engineered. An Earth-Venture-like mission should be designed as pathfinder for in-orbit validation. This will start the crucial process of transfer of know-how to industry, the development of space-qualified hardware, and of an elegant breadboard for prototyping and performance tests in microgravity (10 years).
3. The final goal is to perform a geodesy mission using one or multiple space-borne quantum sensors; exploit quantum sensors for other applications such as navigation, exploration and planetology (moon, mars) (> 10 years).

Fundamental Physics – FP

Space is an exquisite environment for unique experimental tests of the fundamental laws of nature: general relativity (GR), quantum mechanics (QM), Cosmology (Dark Energy and Dark Matter). In space, cutting-edge technology can achieve extremely low-noise, low-gravity conditions, which are necessary to push the boundaries of our understanding of Nature, foremost testing the existence of macroscopic quantum states.

Advancement of QT in space

The Chinese MICIUS satellite, US-lead CAL on the ISS and German MAIUS rocket exploring Bose-Einstein condensates showed impressive QT-based results. In 2010, ESA published with community support a road map for fundamental physics highlighting the role of quantum technologies. Prominent FP mission proposals such as QUEST and MAQRO were investigated by ESA with no clear elected candidate. HYPER and, recently QPPF, were selected for a pilot study by the concurrent design facility (CDF). STE-QUEST was selected as candidate for medium-sized missions within Cosmic Vision. So far, no proposed or pre-selected mission exploiting QT was finally nominated due to major concerns about technology immaturity and feasibility.

FP benefits from QT in space

Nearly 30 years ago, LISA, a long-standing L-class ESA mission to detect gravitational waves, faced similar scepticisms for technological and even fundamental reasons. Starting with a low TRL of the employed sensing method, a dedicated pathfinder mission was created to demonstrate the appropriateness and performance of the proposed measurement concept, and was successfully completed only last year. In this sense, LISA could be seen as a successful role model for design of high-risk experiments to host QT in Space where Europe demonstrated leadership.

Clearly, space is the only environment to enable some of the ambitious scientific goals such as the generation of macroscopic quantum superposition and entangled states – the ultimate test of quantum mechanics.

QT developments - three platforms: photons, atoms, optomechanics

Available QTs for a fully fletched FP mission include: classical and non-classical optical interferometry, the generation of non-local superpositions and entangled states, and the demonstration of robust in the field quantum information protocols with photons. Atomic clocks and interferometers resembling the most precise meters and clock around building on quantum superposition states are getting ever more robust and compact.

Optomechanical systems and matter-wave interferometers are pushing the boundaries of macroscopic quantum states in laboratory environments.
The interplay of Relativity with quantum phenomena shall be studied in the framework of the observation of the strength of quantum correlations using photon states of different types, entangled or not. Space allows for experimental schemes that are impossible on the ground, in term of gravitational potential variations, length scales and relative velocities, that widens the domain in which we are testing our current understanding of Nature.

A collaborative effort

Budgetary constraints for M/L-class missions require collaboration across the scientific communities, industry, agencies, on an international level and the joint decision on only a few topical FP missions and on their execution on a single or multi-platform approach. Europe has to be at the forefront in QT in order to launch a mission with ESA only or in cooperation with strong worldwide partners.

Drawing a roadmap for FP with QT in space

For the first 5 years, we propose to define a roadmap for various selected scientific objectives and to develop key QT methods for the payload in a joint European effort. The advance of QTs to the required TRLs in micro-g environments remains the major technical challenge.
In the medium term (5-10 years), the FP community needs support to develop demonstrators for tests in microgravity environment and has to define pathfinders for validation of QT in orbit. An import objective is to explore platforms for multiple pathfinder activities.
Clearly, the long-term goal (> 10 years) is to exploit QT for the scientific objective to test quantum mechanical states in an ESA mission with/without worldwide partners.

Proposed actions

We recommend to implement a dedicated sustainable EU program (5-10 years) to develop QT for FP in Space in the next years for funding European collaborative projects, in order to perform proof-of-principle tests (5 years) and for increasing required TRLs (10 years) in order to be competitive in ESA's calls. It is clear, that we need to exploit ESA's mission heritage to define and develop together with ESA sustainable (5-10 year) programs for the transfer of technical innovations to space industries.
We further propose the establishment of joint, international laboratories for research teams to assemble core skills and knowledge to develop and test QTs for Space towards the required TRLs and prepare the FP space missions.

List of acronyms

ACES: Atomic Clock Ensemble in Space (ESA mission).
ARTES: Advanced Research in Telecommunications Systems (ESA Programme).
BB84: The most utilized protocol for QKD.
CAI: Col Atom Interferometry.
CAL: Cold Atom Laboratory (NASA mission on the ISS).
CDF: Concurrent Design Facility.
ENT-QKD: “entanglement”-based QKD.
EC: European Commission.
GALILEO: Europe’s global navigation system.
GEO: Geostationary orbit (= 35786 Km).
GW: Gravitational waves.
HYPER: hyper-precision cold-atom interferometry in space (ESA mission).
ICE: Interférométrie atomique à sources Cohérentes pour l'Espace (CNES mission)
I-SOC: Space Optic Clock on ISS, (candidate ESA mission).
IQS: Inertial Quantum Sensor.
ISS: International Space Station
LEO: Low Earth Orbit (< 2000 Km).
LISA: Laser Interferometer Space Antenna (ESA mission).
LISA Pathfinder: ESA mission.
MAIUS: Matter-Wave Interferometry in Weightlessness (QUANTUS space experiment)
MAQRO: Large-mass matterwave interferometry and optomechanics (candidate ESA mission).
MEO: Medium Earth Orbit (LEO < MEO < GEO).
MICIUS: Chinese satellite implementing the QUESS Mission.
PHARAO: Projet d'Horloge Atomique par Refroidissement d'Atomes en Orbit (CNES mission).
PM-QKD: “prepare & measure” QKD.
QC: Quantum Communication.
QCI: Quantum Communication Infrastructure.
QPPF: Quantum Physics Platform (ESA CDF study).
QUANTUS: Quantum Gases in Weightlessness (research project).
QUESS: Quantum Science Experiment Satellite (Chinese Mission).
QKD: Quantum Key Distribution, the most popular quantum cryptographic protocol.
QT: Quantum Technology, Quantum Technologies.
SAGA: Security And cryptoGrAphic mission (ESA ARTES precursor mission study).
ScyLight: Secure and Laser Communication Technology (ESA ARTES programme).
Space QUEST: QUantum Entanglement for Space ExperimenTs (candidate ESA mission).
STE-QUEST: Space-Time Explorer and QUantum Equivalence Principle Space Test (candidate ESA mission).

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[1] As of 5th August 2019.