Quantum Technologies in Space

Policy White Paper

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Executive summary

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 caliber 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. However, the successful development of a research line in quantum science of Space requires a separate approach, synergetic with the on-going activities of the QT Flagship, as time frames and budget requirements of the former are very specific.

This White Paper defines a roadmap for QTs applications for Space, addressing the major actors in this area: the Commission, ESA, National Space Agencies, and industries. The goal is the drawing of a full framework for the design, development, implementation, and exploitation of QTs in Space.

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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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 Communication - SC

Quantum SC provides a secure key exchange, alternative to common methods. SC in Space is complementary to ground networks; it is necessary in the case of large distance intercontinental links, for checking the ground network integrity, and substituting it in case of major disruptions on ground. Relevant scenarios for SC are ground-to-ground links via satellite, space-to-ground links, space-to space links on constellation (same orbit) or LEO to GEO/MEO.

Where we are

Both decoy-state and entangled photon QKD were demonstrated by Chinese satellite MICIUS. Feasibility studies under the ESA ARTES program, open calls for the development of a demonstrator for In-Orbit-Test (Scylight). In April 2019, EC and ESA signed an agreement on SC "to collaborate in designing a Quantum Communication Infrastructure (QCI). The QCI would represent the next generation of ultra-secure communications in Europe." Space and cybersecurity are key strategic elements in the definition of the current and future EC policies.

Short-term goals (5 years)

- Demonstrate the decoy-Discrete-Variable-BB84 from LEO.
- Better pointing and key rate increase with advanced payload schemes.
- Develop ground stations network and demonstrate the interoperability with the ground QKD network.

Medium-term goals (10 years)

- Advanced sources for high key rate and better pointing from LEO.
- Demonstrate the inter-satellite links; Extend protocols beyond QKD.

Long-term goals (> 10 years)

- Develop constellation for global QKD commercial service on LEO.
- Enable QKD-secure feeder links and MEO constellation.
- Entangled distribution and space quantum internet.

Proposed Actions

- Roadmap to develop an EU industry / scientific community, along the EC requirements and needs for a future SC infrastructure.
- Technology development of advanced sources and protocols for space QKD, via specific calls implementing goals at 5 and 10 years.
- Create and operate the ground segment technology and ground network interconnection.
- Stimulate technology development for space-borne complete QKD.

Time and Frequency Transfer - TFT

Time and Frequency Transfer (TFT) via space is an established technique, allowing for example the maintenance of the international atomic time. Clocks can be compared at the 10^{-16} level. The development of optical atomic clocks in many laboratories world-wide has improved accuracy and stability hundredfold compared to the clocks that define the unit of time, to the low 10^{-18} level, currently. The improvements are expected to continue. Such novel quantum sensors are opening up new domains of research and allowing substantive progress in ongoing investigations.

Where we are

ACES mission by ESA and CNES contains a cold-atom space clock, an optimized two-way microwave link and a single-photon laser link. A similar clock has been flown by China (with no metrology link to the ground). ESA is also developing a sequel mission, I-SOC, with a strongly improved performance, and a possible launch date in the early 2020s.

Short-term goals (5 years)

- An infrastructure capable of frequency comparisons at 10^{-18} level accuracy and time-scale comparisons at ps-level accuracy. TRL for this technology is currently at level 4 - 5.

Medium-term goals (10 years)

- A further improvement by a factor of 10 would be desirable. TRL for this technology is currently at level 2.

Long-term goals (> 10 years)

- Fly a state-of-the art optical clock with a high performance time transfer link. It has also a strong interest with respect to future evolution of space GW detectors.

Proposed Actions

- Support planned ESA missions (ACES and I-SOC) to achieve a rich science harvest, know-how generation and technology validation.
- Technology development for improved & new space TFT techniques, capable of satisfying the needs of the post-ACES/I-SOC era (10^{-19} performance), e.g. the next generation GALILEO technology.
- Development of a space TFT infrastructure having highest performance, for example based on a few geostationary satellites equipped with dedicated TFT equipment and laser terminals.
- A complementary approach consists of an ensemble of low-orbit mini-satellites with appropriate links.

Earth Sensing and Observation – EO

Gravity field mapping is a key for scientific, industrial and security-related tasks. Several sensors are available to such goal. The recent advent of laser cooling and the manipulation of atoms have led to a whole new class of quantum sensors based on atomic interferometry. Unlike all known inertial sensors, quantum gravi-gradiometers (QGG) use atoms as test masses. This potentially allows for greater measurement sensitivity, finer spatial resolution, and improved time tracking, thus providing new measurement capabilities.

Where we are

Pioneering ESA missions: PHARAO/ACES. ESA studies at different stages: SAI, SOC/I-SOC, HYPER, STE-QUEST.
Quantum Sensor development for space (not dedicated to geodesy): ICE (France), QUANTUS/MAIUS (Germany), CAL (USA), CCAL (China).

Short-term goals (5 years)

- Push TRL level of all subcomponents to >6 and test performance of interferometry in relevant environment (ground-based μg facilities).
- Study and choose to most efficient mission concept.

Medium-term goals (10 years)

- Develop a payload QGG EM and plan a mission of type Earth venture.

Long-term goals (> 10 years)

- Have a geodesy mission using one or multiple satellites quantum sensors.

Proposed Actions

- A concerted European effort to increase the TRL for key components.
- Prototyping and performance tests using European ground based microgravity facilities.
- Starting the process of transfer of know-how to industry, and developing space-qualified hardware.
- Development of an elegant breadboard for prototyping and performance tests in microgravity.
- Furthering the process of know-how transfer and the development of space-qualified hardware.
- Implement a pathfinder for atom interferometry in space.

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.

Where we are

The Chinese MICIUS satellite, US-lead CAL program on the ISS and German cold atom MAIUS rocket showed impressive QT-based results. Prominent FP mission proposals such as STE-QUEST, QUEST and MAQRO were investigated by ESA with no clear elected candidate. ESA opened a call on ideas for future science mission; QPPF was selected for a CDF study.

The ESA mission LISA could be used as a role-model for design and technology to host QT in Space. Available QT platforms include: photons, atomic clocks and atom interferometers, massive optomechanical systems.

There will likely be only one dedicated QT-based FP mission in the close future – budgetary constraints for M/L-class missions require collaboration across the scientific communities, industry, agencies, etc.

Short-term goals (5 years)

- Define a roadmap for each platform with concrete scientific FP target.
- Select the FP experiment for the mission.

Medium-term goals (10 years)

- Develop QTs to the required TRLs in micro-g environments.

Long-term goals (> 10 years)

- Fly the FP experiment.
- Develop a multi-spacecraft experiment.

Proposed actions.

- Implement a dedicated EU programme, together with ESA, to develop QT for FP in Space in the next years, funding collaborative projects, to increase required TRLs and for proof-of-principle tests.
- After the experiment is selected, the standard procedures and funding with ESA should take over.
- Installation of *incubator laboratories*, in collaboration between scientists, industry and national/international space agencies to develop and test each QT for Space towards the required TRLs.

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
ELIPS: European Programme for Life and Physical Sciences (ESA Programme).
GEO: Geostationary orbit (= 35786 Km).
GW: Gravitational waves.
HYPER: hyper-precision cold-atom interferometry in space (ESA mission).
I-SOC: Space Optic Clock on ISS, (candidate ESA mission).
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).
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.
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).