

Quantum Technologies in Space

**Intermediate Strategic Report for ESA
and national space agencies
November 2017**

Quantum technologies hold the potential to revolutionize the design and management of protocols for communication, observation, metrology and sensing by developing strategies enhanced by the exploitation of features of a genuine quantum mechanical nature, such as particles in the quantum ground state of motion, the wave nature of particles, coherent superpositions and non-classical correlations.

Owing to impressive recent developments, spurred by nearly thirty years of steady progresses at both the theoretical and experimental level, quantum technologies are now on the brink of a landmark breakthrough towards commercialization. Major industrial/communication/information-technology actors have stated or demonstrated their interest in the development of fully fledged quantum technology paradigms covering the areas mentioned above, and extending all the way to computing and simulation of complex problems. The very recent substantive investment from national funding agencies across the World in the field of quantum technologies and the major European initiative for the launch of a dedicated Flagship Programme are very significant tokens of the perceived importance that quantum technologies are enjoying from the broadest research & development community, policy makers, and industrial dimension.

The breath of applications of quantum technologies is ample and covers the tantalizing possibility to address space science and technology. The recent launch of a Chinese satellite with the scope of demonstrating the viability of primitives for quantum communication through satellite-to-ground channels is perceived as a technical stepping-stone. ESA and CNES have developed a QT mission, which will be launched to the ISS within the next few years, consisting of a complete cold atom clock with high-performance bidirectional space-ground microwave link. In the meantime, China has successfully operated a cold-atom clock apparatus in space for a full year.

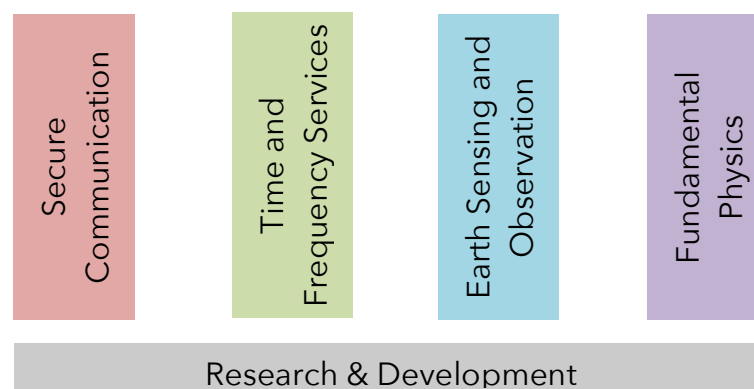
However, plenty is yet to be achieved towards the definition of a full-fledged paradigm for quantum technologies in and for space, including much needed research & technology developments in communication, metrology, and sensing, preparatory on-ground technical progress for the enabling of space-based missions and experiments, and the identification of foundational questions whose development would benefit uniquely and unambiguously from a space-based approach.

Such ambitious goals cannot be reached by the means of isolated and individual initiatives of specific countries, and requires a concerted, coordinated effort of a genuine European caliber and dimension. Examples

of such coordinated European efforts are the ACES mission and the I-SOC mission. Furthermore, new opportunities arise in the framework of the Quantum Technology Flagship and other initiatives (of a continental size), such as the COST Action CA15220 “Quantum Technology in Space”. The fierce competition from extra-European countries (US, China and Canada above all) calls loud for a significant European effort towards the development of quantum technologies for space applications.

The goal of this report is thus twofold. On one hand, it aims at putting together, in a concise manner, the state of the art in the development of technologies (with clear potential) for space applications. On the other hand, it delineates a clear roadmap, for the consideration of major actors in this area (including ESA, national space agencies, industries), towards the accomplishment of a full framework for the design, development, implementation, and exploitation of such new technologies of an exquisite quantum nature. The report is thus a strong and pressing invitation to such actors to engage with the Quantum Technology Flagship, COST Action CA15220, and the whole (academic and industrial) European community interested in quantum technologies for space to identify and implement the necessary steps towards the definition of a realistic avenue for the achievement of such a paradigm shift.

In light of the specific world-class competences present in its territory, Europe should lead the way towards such ambitious goals. This strategic report has the ambition to identify the necessary developments to reach them. The Scientific Committee in charge of the development of the report has identified five topical areas that will have to be addressed by any realistic attempt at producing working prototypes of quantum technologies for space applications, as reported in the figure below.



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Secure Communication

Scientific and strategic relevance

Space represents a framework suitable for the development of several applications. Quantum communication from Space is now crucial for providing the large-scale network of European Secure Communications (SC) that has been long sought after.

Indeed, the range of quantum secure key exchange is limited to 200km in standard fiber communications. Hence the main objective of SC is to develop new technologies and to demonstrate innovative techniques for satellite quantum communication, in order to overcome fiber loss limitations.

More in detail, the encoding of information in quantum states of light enables various disruptive applications in secure communications and computing. The most technologically mature is Quantum Key Distribution (QKD), which is the secure sharing of private encryption keys. QKD has two key features that make it unique with respect to classical (computational) security schemes: its security is robust against crypto-analytical progress (future proof) and secondly its operation reveals eavesdropping.

Commercial QKD systems for fiber communications are already on the market but fiber losses and the lack of a viable quantum-memory technology limits the range over which realistic key exchanges can be achieved to less than a few hundred km. The complementary technology to deliver transcontinental and global security is that of satellite-mediated QKD, which will eventually deliver longer-haul quantum communication protocols.

Background – ESA and national space agencies

- Feasibility studies under ARTES program, open calls for the development of a demonstrator for In-Orbit-Test (Scylight)
- Project QIPS: phase 1 of long-range quantum communication programme, demonstration of quantum links in the Canary Islands with a 143 km test bed.
- Call for Phase A study on ELIPS: Space QUEST
- European experiments already performed using Space-based channels:
 - Matera experiments - first ever qubit exchange from Space
 - Quantum-limited measurement of coherent states emitted from satellite

Background - World

Satellite-based QKD has recently received much attention due to the realisation of a working system developed by China: the MICIUS satellite has already been used to demonstrate a QKD protocol and entanglement-based extensions thereof. Japan also operates a 50kg satellite that demonstrated significant payload development for SC. This naturally makes it a pressing need for Europe to capitalise on the extensive work already done by European universities and research institutions.

Goals and enabling tools

The target is to map future progress towards: global-scale QKD, future applications and use of quantum technologies, transition from laboratory science to commercial exploitation in real-world settings.

The available platforms are: GEO, LEO 50-100kg, LEO CubeSat each with different application spaces. There are also various possibilities for high-altitude platforms (HAPS). Skimsats could also operate above HAPS but below conventional LEO (160 km).

The study of links with pointing in the few-microrads or below, with corresponding reduced footprint of the beam, will be instrumental to low-loss links from space and higher throughput QKD.

The Table summarises a proposed roadmap for development of satellite-based quantum technologies

Platforms	Short term <3 yr	Medium Term 3-10yr	Long Term >10yr
Large-scale GEO schemes	Tests on existing GEO optical platforms. Design of QKD-capable GEO systems. Choice of coding protocols (CV/discrete variable, hybrid)	Launch of QKD-enabled GEO satellites. Piggyback on optical communications terminals. Creation of commercial consortia	Fully-functional QKD Time distribution Quantum 2.0 applications
Medium-scale LEO 50-100kg	Off-the-shelf development using existing terminal designs. Develop EU-wide plans in light of MICIUS example. TRL level improvement for QKD-specific components. Development of novel coding schemes (CV, discrete, time bin)	-Reduction of the cost of commercial applications -Launch of LEO satellite within 5 years	-Worldwide coverage -Teleportation, relays, memories, distributed quantum information processing nodes

Low-cost CubeSat	-Developing key technologies: sources, pointing/tracking, detectors, data and communication systems, compact terminals -Launch of first CubeSat technology demonstrator	-Design and launch of complete system (within 5 years, hopefully)	-Constellations of CubeSat providing 24hr global coverage -Development of entangled sources
Ground station	-Develop ground-station technology demonstrators. -Demonstrate key download from existing MICIUS to EU locations	-EU-wide ground-station network -Low-cost ground-station development.	Small-scale ground-station for quantum to the home?
High-altitude platforms	-Preliminary low-level ground to drone experiments -Initial high-level platform designs and application models	Build and demonstration	Further extending applications beyond communications

Recommendations

From the table above, the technological and scientific recommendations for the European development of secure communications in space may be expressed as follows:

Near term:

- Achieve discrete point-to-point QKD with global reach
- Demonstrate satellite-to-satellite quantum communication and securing control & command channels
- Design and demonstration of digital signatures and examples of new cryptographic protocols
- Tests of fundamental principles (Bell tests, gravitational decoherence,..)
- Improve pointing and tracking capability, to develop low-loss channels - as the actual losses are more critical for quantum communications than for classical ones

Far term:

- Demonstration of quantum networks, teleportation, distributed quantum information processing
- Time and frequency distribution (using satellite generated frequency combs) - see next section
- Entanglement distribution to space-based constellations or formations for quantum-enhanced sensing (e.g. gravitational waves, Earth Observation).

The maturity of Quantum Communications also makes realistic to envisage the near-term development of commercial drivers. The potential economic

value of quantum cryptography is considerable. Several industries are investigating such technology: manufacturers of telecom equipment and optoelectronic devices, communications providers, information technology enterprises, suppliers of internet services, and firms in the security & defense sectors. Various business models are being proposed and need to be researched in detail.

We believe it is appropriate to make the following recommendations on exploitation and policy:

Near term:

- Development of business cases, engaging Service providers (BT, Deutsche Telecom...), banking and finance, timing distribution, national Infrastructure
- Embed QKD into existing security infrastructure, addressing end-to-end security requirements
- Engage with national governments and EU policy-makers in light of the fact that future-proof communications security is an issue of national security

Long term

- Usage models where end users/customers buy security at home, access to distributed quantum computation resources.

Time and Frequency Services

Time and frequency transfer (TFT) via space is an established technique. The simplest approach for comparing ground clocks within the same continent is based on recording GNSS signals in common-view and post-processing of data. A more sophisticated approach is two-way satellite TFT (TWSTFT), which is used by national metrology laboratories to compare their atomic clocks and thus also the local atomic time scales. During a TWSTFT connection, two laboratories exchange time and frequency information. The results of such connection are input data for the realization of the international atomic time scale (TAI).

TWSTFT uses commercial telecommunication satellites, and connection time is rented in order to perform a connection. The accuracy of the comparison of the time scales of two laboratories is on the order of 1 ns. Clocks can be compared at the 10^{-16} level, appropriate for the performance of the cold-atom microwave Cs clocks that until today define the unit of time.

Scientific and strategic relevance

The development of optical atomic clocks in many laboratories world-wide has been spectacular in the last 15 years. Their accuracy and stability have improved hundredfold compared to Cs clocks, to the $(1-2) \times 10^{-18}$ level, currently. The performance improvements are expected to continue. These instruments are opening up new domains of research, or extending the performance of on-going ones, if TFT systems of appropriate performance are established.

For example, TFT at the 10^{-18} level will permit, for the first time, the implementation of relativistic geodesy with competitive performance levels for geophysics. In the field of fundamental physics, TFT will allow a network of communicating clocks to be established for the search for dark matter effects.

Background - ESA and national space agencies

ESA and CNES were the first agencies world-wide that recognized the potential of next-generation TFT, by developing the ACES mission. It contains a cold-atom space clock, an optimized two-way microwave link and a single-photon laser link. ACES is expected to be launched to the ISS in ca. 2018.

ESA is also developing a sequel mission, I-SOC, with a strongly improved performance, and a possible launch date in the early 2020s.

Goals and enabling tools

It has become essential to develop a new space-based infrastructure, for the comparison of present-day high-performance optical clocks and next-generation clocks, world-wide. The space-based system shall operate in synergy with the terrestrial fiber-optic networks already implemented and those to come.

Such a system should satisfy the following requirements:

- Be widely available, for metrology laboratories, universities and research institutes.
- Be available for mobile users.
- Provide a performance appropriate to the performance of the best clocks in 2020.
- Permanent availability to end-users.
- Reasonable cost of service for end-users.

Short-term goals (5 years)

- A space infrastructure capable of frequency comparisons at 1×10^{-18} instability and time-scale comparisons at 0.1 ps accuracy at 1 day integration time and 1 ps at 10 days.

Long-term vision (10+ years)

- Further enhancement of frequency comparison instability to 1×10^{-19} and time-scale comparisons to 0.3 ps at 10 days.

Enabling tools for the achievement of such goals include:

- Advanced two-way microwave link (currently under development under ESA contracts).
- Advanced single-photon laser link ELT+, under development by CTU Prague.
- I-SOC optical clock for space (currently under development by European teams and ESA).
- Femtosecond or coherent optical links.
- Laser Communication Terminals (LCTs)

Recommendations

We call on ESA and national space agencies:

- To support the ACES mission to the fullest, ensuring a rapid launch, an extended mission duration, and to provide additional microwave terminals to the community so as to enable several transportable ground clocks to participate in the measurement campaign.
- After ACES reaches its natural end, a continuation of time and frequency services to the community is needed, with enhanced

performance. Therefore, a continued rapid development of the I-SOC mission shall be enabled, with engineering and flight models to be completed within 5 years.

- To initiate technology development for new space TFT techniques, in particular, optical ones, capable of satisfying the needs of the post-I-SOC era (10^{-19} performance).
- To initiate the development of a semi-permanent space TFT infrastructure having highest performance (reduced Doppler effects, long common-view observation durations), for example based on geostationary satellites equipped with dedicated TFT equipment and enhanced laser communication terminals (LCTs).
- To strengthen the international relationships with the Institutions of the Convention of the Meter in charge of these topics, in particular the Consultative Committee on Time and Frequency and its dedicated Working Groups.

Earth sensing and observation

Scientific and strategic relevance

Gravity field mapping is one of the key measures needed to understand solid earth, ice and oceans, and dynamic processes to compose a global model of our planet. For these reasons, several space missions aim for the measurement of the gravity, such as CHAMP, GOCE and GRACE. More generally, the measurement of the form and dimensions of the Earth, the location of objects on its surface and the figure of the Earth's gravity field are relevant problematics for space geodesy which can arbitrarily be classified in 3 categories:

- Geometric geodesy consisting in precise positioning and navigation
- Dynamical geodesy for the determination of the geoid, the spatial and temporal variations of the gravity field
- Measurement of geodynamical phenomena, such as crustal dynamics and polar motion

Space geodesy can take advantage of many available tools, missions and satellites: GPS/GNSS, laser ranging, Doppler/optical tracking, altimetry, gradiometry. For example, GNSS can be used as an economical tool for surveying and time transfer thanks to their atomic clocks and earth-space link. It is also used for monitoring Earth's rotation, polar motion, and crustal dynamics. The presence of the GPS signal in space also makes it suitable for orbit determination and satellite-to-satellite tracking. With the improvement of atomic clocks on ground and in space, similar techniques can potentially greatly improve the knowledge of the geopotential and its evolution.

Dedicated space geodesy missions can use the satellites themselves as test mass and the measurement of gravity is obtained by accurately recording the motion of the satellites. This is for instance the case of the GRACE mission and its follow-on. The GRACE mission uses microwave-ranging link between the satellites, while the follow-on mission will rely on laser ranging, in a configuration approaching the concepts developed in space laser interferometry for gravitational wave detection.

Other gravity mapping missions using mechanical gradiometers have also been launched or under study, such as GOCE or SGG.

The recent advent of laser cooling and the manipulation of atoms, has led to a whole new class of sensors: quantum clocks (QC) and quantum gradiometers (QGG) based on atomic interferometry. Unlike all known

inertial sensors, the QGG uses atoms as test masses. It is the wave nature of atoms that is used to perform an interferometric measurement of the effect of gravity on atoms. The potentially achievable sensitivity with these interferometers is very promising for improved performance in future spatial geodesy missions - greater measurement sensitivity, finer spatial resolution, and improved time tracking, thus providing new measurement capabilities. The improvement of QC, on the other hand, leads to the ability to read out, given an appropriate Time and Frequency Comparison infrastructure, frequency shifts resulting from geopotential heights differences of a cm today, and below a millimeter in the future (see previous section).

Background - ESA and national space agencies

Development of QC and QGG geodesy missions benefits from pioneering missions such as PHARAO/ACES which paves the way to future relativistic geodesy missions. A sequel QC mission by ESA, I-SOC (Space Optical Clock on the ISS), is in phase A.

Many other studies have been supported by ESA, providing a strong push to the development of Quantum Sensors. Among them:

- SAI (Space Atom Interferometer) and SOC/I-SOC (Space Optical Clock)
- HYPER (flexi-mission using atom interferometer gyroscopes proposal, CDF study), QWEP (atom interferometry test of UFF on ISS, study) and STE-QUEST (test of UFF with AI + tests of UGR with microwave/laser links, and possibly atomic clock, phase 0/A study)

Finally, ESA has recently put strong emphasis on future gradiometry missions with multiple contracts for technical development:

- QGG vacuum payload design (RAL, UK)
- QGG laser development (Muquans, FR)
- SOC optical cavity (HHUD, Ger - NPL, UK)
- Cold Atom space payload (E2V, UK)
- Gradiometry mission concepts (2 consortia)

Background - World

NASA (Goddard) has launched a prototype QGG development with AOSENSE (US company based in California).

CNES is conducting a Phase-0 study of potential space geodesy mission using QGG (FR). Potential mission scenario can be tested in the 0-g airbus (ICE program).

Quantum Sensor development for space (not dedicated to geodesy):
QUANTUS/MAIUS (Ger), CAL (USA), CCAL (China)

Goals and enabling tools

Short-term goals (3-5 years)

- Push TRL level of all subcomponents for QGG to >6
- Study and chose to most efficient missions concept for gradiometry

Mid-term vision (5-10 years)

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

Long-term vision (10+ years)

- Have a geodesy mission using multiple satellites quantum sensors

Among the enabling tools for such goals are space missions and payloads (ACES, ICE, MAIUS, CAL), currently developed payload (SAI, SOC, Space QGG components), prototype QGG currently developed in France (SYRTE) and the UK (Birmingham).

Recommendations

It is urgent to coordinate efforts (National and EU) towards a space QGG EM. Review potential mission opportunities and organize efforts towards such opportunities (Earth venture/pathfinder in US, earth explorer mission in EU).

Fundamental Physics

Space provides an unprecedented environment of unique conditions to test fundamental physics and to extend our understanding of the universe according to the laws of physics, especially because of the long free-fall times available, long observation times without levitation, quiet gravitational environment and the variability of gravity and laboratory speed.

In the last decade, the fast advance of quantum technologies based on cold atoms, photons and opto-mechanical systems opened up completely new perspectives for experiments in the realm of fundamental physics. They allow creating new experimental opportunities, the most familiar ones being clocks, inertial sensors, and interferometers.

Here, we give a short survey of science quests, which are in detail discussed in literature.

Quantum tests of relativity, redshift, dark energy and gravitational wave detection. Important questions remain open in fundamental physics both at microscopic and cosmological scales. In this context, high-precision measurements based on atom interferometry and atomic clocks, both relying on the use of (ultra) cold atoms and their manipulation with laser light, offer a very valuable complement. By testing the universality of free fall (UFF) and of gravitational redshift (UGR) as well as local Lorentz invariance, they can be sensitive to small violations of Einstein's equivalence principle. Furthermore, these atomic sensors could help to detect dark matter candidates corresponding to temporal oscillations or topological defects of ultra-light scalar fields weakly coupled to standard model particles and to test thoroughly the predictions of certain Dark Energy models such as Chameleon fields. Finally, they could also provide a longer-term alternative for gravitational-wave detection in low-frequency bands, test quantum superpositions and perform EPR tests.

Long-distance entanglement and non-locality tests. Another approach to test the interplay between QM and GR, in the search of a unified theory is to test entanglement and non-locality in extreme conditions with respect to special and general relativity. Space tests can be performed in various relative reference frames and over large distances, as well as in curved space-time. The experimental requirements for such tests are very similar to the ones for quantum communication. Thus, strong synergies are expected between those two aspects of QT in space.

Tests of quantum mechanics. Long free-evolution times are especially

important for experimenting with quantum states of very massive objects such as large molecules, nano- and micro-particles, as well as suspended membranes and cantilevers. Fundamental physics questions with such objects are concerned with tests of large-mass limits of quantum mechanics and the interplay between gravity and quantum mechanics. For example, the presently considered mass limit for quantum superpositions on Earth is 10^8 amu (atomic mass units). Space seems the only reliable option for a test of quantum mechanics beyond that mass limit within the foreseeable future. Direct tests of dark matter and dark energy will be considered.

At the theoretical level, there is a strong need for the development and use of interdisciplinary approaches based on current knowledge in the fields of General relativity, Quantum information, Quantum field theory in curved space-time, Quantum gravity theories in relation with the propagation of light and matter, Decoherence theories [including time dilation effects, gravity induced phase shifts for single photons] aimed at the design and characterization of experimental efforts in the three platforms addressed in this section.

Scientific and strategic relevance

The cooperation between the European flagship on quantum technologies (EU QT Flagship), ESA, National Space Agencies, and relevant industrial actors provides the opportunity to advance the scientific goals listed above. The strategic measures for achieving this have to include the advancement of the quantum technologies based on *cold atoms, photons and optomechanical systems*. It is paramount to incorporate European industry with their expertise in space related and enabling technology.

A. Cold atoms

Background - ESA and national space agencies

Many proposed missions in the realm of fundamental physics are based on cold atoms. Cold atoms and atom interferometry were pioneered by CNES on parabolic flights, which emerged into the mission ACES, which will operate a cold atom clock on the ISS in 2018+. Bose-Einstein condensation and interferometry was established by DLR in microgravity and space and became part of Q-WEP and STE-QUEST, performing tests of the redshift test and the universality of free fall with matter waves. Novel atomic clocks in the optical domain triggered proposals such as I-SOC to bring them to the ISS. This mission is now under development. Missions are thought of to search for long-range forces and for gravitational wave and dark matter detection.

There have been several ESA projects to advance enabling technology

related to atomic clocks, frequency combs and ultra-stable lasers, frequency links as well as for atom interferometry.

Background - World

The mature technology of cold and ultra-cold atoms is one of the strongest contenders in QTs worldwide. Atom interferometry has been already experimentally performed on microgravity platforms: ICE (parabolic flights), QUANTUS (drop tower) and most recently in space by the MAIUS mission (sounding rockets). On the ISS, cold-atom physics will be soon studied within the project CAL and a new initiative strives to study quantum matter and interferometry with Bose-Einstein condensates with BECCAL. Moreover, the FOKUS mission brought the first frequency comb, an important enabling technology for clocks, to space, and served as demonstrator for test of UGR.

Goals and enabling tools

Short-term goals (3-5 years)

- Establish a call for European consortia for developing prototypes of space instruments addressing the above-mentioned science goals
- Establish programs for developing future methodologies
- Establish a program for developing the technologies making space implementation of these experiments feasible
- Establish flight opportunities for such experiments or prototyping.

Long term vision (10+ years)

- Solid program for fundamental physics space mission based on cold atom technology potentially combined with other quantum technology platforms.

The main enabling tools for such goals coincide with those mentioned for Earth sensing and time-and-frequency distribution. Enabling technologies include: ultra-stable lasers, frequency dissemination, UHV technologies, photonics and detection.

Recommendations

To set up in collaboration with the EU QT Flagship a programme for instrumentations comparable to the one in the space sector of Horizon 2020. This could ease the constraints in the existing ESA budget. The primary goal is to support European efforts to enhance TRL of QT. We recommend the set-up of a quantum technology readiness program.

B. Photons

Background - ESA and national space agencies

Most of European experimental projects aim mainly at establishing quantum communication links (ARTES ScyLight- Secure and Laser Communication Technology). More fundamental projects include the mission proposal Space QUEST. It was first design with an entangled source on the ISS and more recently with a single photon detector on the ISS. An industrial phase A/B study is currently performed under an ESA SciSpace contract. One can also mention the space interferometer project LISA. The other notable European activities are the experiments at the Matera Laser Ranging Observatory establishing a ground-space quantum link with many faint coherent pulses, the quantum-limited measurement of coherent states from satellite was shown and the CubeSat projects (Vienna/Nottingham, Munich, UK).

Background - World

Several activities are taking place around the world QESS mission (China) and the SOCRATES mission (Japan) and also a cubesat mission in Singapore. Currently several other missions are being planned on small platforms in Canada, UK and Austria.

Goals and enabling tools

Short-term goals (3-5 years)

- The first goal is to capitalize on the long-standing activities done in Europe and gather a large community by realizing a one-way ground-space link with true quantum light with either detectors or source in space, use it to violate Bell inequalities and perform first tests of entanglement in curved space-time (TRL: high, steps: launch).

Long term vision (10+ years)

- In order to test theories beyond standard QM and GR, a dedicated satellite with entangled source will be needed, as well as very large interferometers probed with quantum light. [TRL: middle or high (see Chinese satellite)].

Most of the experimental tools can be shared with a quantum link for quantum communications, namely: dedicated experimental ground-ground link, high efficient quantum light sources, detectors (homodyne, single photon detectors (SPD), SPD arrays with high count rates and high temporal resolution), adaptive optics, models of turbulence.

Recommendations

Identify the requirements needed to be able for double use of the quantum

links for QKD and for fundamental physics.

C. Optomechanics and Large-mass Matterwave Interferometry

Background - ESA and national space agencies

Activities towards space-based large-mass matter-wave interferometry have been coordinated within the MAQRO consortium. ESA's fundamental science directorate has invited MAQRO for a maturation process towards a future M-class proposal, while M3 and M4 proposals had been submitted previous. MAQRO has been shortlisted for ESA's call for New Science Ideas in 2017 and has now been approved for a CDF study in first half of 2018.

Background - World

Scientific research and technology development of both cavity optomechanics and molecule interferometry are rapidly growing into *the* fundamental physics platform to investigate massive systems in the quantum domain.

Goals and enabling tools

Short-term goals (3-5 years)

- The immediate goal is to develop and grow a community of academics, industry, space agencies and funding bodies, coordinated by the MAQRO consortium with an efficient management structure to work on large-mass matter-wave interferometry and optomechanics based test of fundamental physics in space.
- Define precise scientific goals to be explored in space.
- Foster proof-of-principle experiments on ground and the development of technology into sufficient TRLs.
- Establish flight opportunities such as in CubeSats and tests in micro-gravity environment (drop-tower, parabola flights, etc.) for proof-of-principle experiments or prototyping.

Long term vision (10+ years)

- Work towards a single space mission, in collaboration with ESA. This will need a considerable push of TRL on component level. Then to fly a dedicated space mission to perform a fundamental physics experiment in space based on quantum states of a large-mass object with a timescale for launch in the mid or late 2030s (beyond LISA).

Technology needs to be developed to the right TRLs. MAQRO needs the development of a reproducible particle source and the selection of an appropriate particle type with tailor-made optical and electric properties, as well as the development of efficient particle detectors. Some of the components as well as technology for the spacecraft is considered to be

available as heritage of past and present ESA missions, such as LISA PF, Gaia, Plato and the James Webb Space Telescope. Collaboration with ESA is needed to define the key technologies within a CDF study and a way to achieve TRLs for components.

Recommendations

MAQRO - ESA collaboration: first to define a precise goal for a science mission and second to steer the development of technology to the right TRLs. Define overlap between technology needs of MAQRO and technology heritage at ESA. Investigate options for opto-mechanical technology as spacecraft components, such as frequency conversion, and in other ESA directorates, such as for Earth observation and planetary exploration, to foster opto-mechanical technology development.

Research and Development

Research and Development (R&D) activities underpin the development of the four pillars discussed previously by focusing on theory, experiments and organizational issues. Synergies between the technologies needed for the pillars can be identified and leveraged here. In what follows, the priorities for theory, proof-of-principle experiments, and organisation are addressed individually with explicit reference to the needs of each scientific pillar.

Theory modelling

Secure communication in space. The need here is the identification of weak points of a secure space channel. This would require the modelling of the possible attacks to a space link and the upgrade of existing classical communication systems to quantum approaches.

Time and frequency services. This pillar requires the critical assessment of the challenges in on-Earth implementations of a metrological link and the understanding of how these would be translated into specific challenges for the implementation of such a link in space. In particular, it would be crucial to determine if a quantum upgrade on existing typical GPS networks is necessary.

Earth sensing and observation. The challenge here is the provision of a realistic estimate for the advantages provided by the monitoring the planet's surface via its gravitational field through quantum strategies. Moreover, it will be crucial to determine what would be necessary to achieve in order to make such monitoring possible from a satellite. Analogous considerations on the need for the determination of clear quantum advantages hold when addressing atmosphere and weather sensing, cosmic and electromagnetic radiation.

Fundamental Physics. It will be necessary to provide extensive simulations of the different components of a space mission, from the experiment (if there is an experiment, not just a satellite orbiting in space) to the module and its launching, to the conditions in space, with varying parameters in order to define the best working conditions, to be subsequently tested in proof of principle experiments. Attempts at this have been made independently for different platforms, and it would be advisable to create the conditions for sharing knowledge, like a common library of numerical codes, which can be implemented in different platforms.

Proof-of-principle-experiments

Possible experiments highlighted in the different pillars have to be prepared with proof-of-principle experiments on ground and parameters have to be studied that are valid for space qualification. The road to space-readiness should be supported by different experimental endeavours:

- Upgrading known proof-of-principle experiments to parameters
- that are relevant for space (e.g. temperature requirements, power requirements, shock proof apparatus, losses in transmission)
- Testing known proof-of-principle experiments in shared testing facilities
- Testing components (part of full experiments) individually as additional payload on other missions or on small (Cubesat) missions.

Space qualifications

Space qualification is a lengthy and costly process. Quantum technology groups from academia and industry mostly do not have sufficient experience to readily cope with these high demands.

Centers both at a National Space Agency and ESA level, as well as with industry should be supported and funded to be able to combine the knowledge in quantum technology and space qualification. Strong collaborations among quantum groups from academia, space agencies and industry is key to success.

In addition to “classical” space qualification, novel standards have to be defined for quantum technology hardware in space (in collaboration with international standards organizations and national standards institutions). The sharing of resources and knowledge will enable also SME and small academic groups to pursue novel ideas in space.

The main goal is the creation of an ecosystem of *academia / industry / institutions where quantum technology can be developed (offering networking, schools and conferences)*.

On the academic and SME side, the creative power of “fablab”-like centers for quantum technologies in space will enable the input and education of a new generation of quantum space engineers.

Mission Design

Industry and space agencies can support academia and companies in quantum technologies in defining and working out concrete missions. This requires a twofold approach:

Involving Quantum Technologies Companies in Space Industry. Involvement in the space industry of companies operating in the field of QT (QT companies) can occur following the traditional path that is used by ESA and the existing space industry players to involve non-space companies in space programs.

Such path is carried on in a joint way by ESA, National Space Agency and an industrial System Integrator (e.g. a Large System Integrator, or LSI). The path consists in bringing the technology to space standard and to an adequate TRL by means of existing ESA programs (such as TRP, GSTP, ARTES), with a progressively increasing role of the System Integrator, aimed at coaching the non-space (QT) company and providing consultancy for the definition of the technology development plan and steering during the progress on such plan.

This way is well proven and threaded and a fully functional ecosystem of government organisation, agencies, funding, programs and industrial players is already in place.

The difference between a QT company and other non-space companies could be that for QT space application can be a valid kick-started of a process that could bring QT application to a far wider market.

This is thanks to the fact that space applications are usually required a very limited number of devices while allowing time and support for extensive tests and functionality verification in the most challenging conditions.

On the other hand, it is important for the QT company to consider space industry as the first step towards larger markets and have plans in place for this since the beginning. Space is a relatively niche market so that a big growth of the QT company is more likely to occur in another field.

Involving Space Industry Companies in Quantum Technologies. QTs are emerging technologies that are coming on the stage with big expectations in terms of new performance levels. This matches very well the typical operation of companies operating in the space industry (space companies), that are not afraid of technology development with its involved risk and are experienced on working together with ESA to turn novel technologies into devices that work.

However, QT are coming with challenges that risk to be underestimated by non-QT players. Such underestimation usually regards both the needed time and the needed funds.

It is therefore necessary for ESA and National Agencies to ensure a clear and open dialogue between space companies and QT companies in order to ensure a full understanding of the actual TRL level and of the effort needed to reach the target one.

A first tool to ensure such dialogue is already present and is the Quantum Technology workshop for space applications, organised and held by the Agency: ideally this should become a regular annual event in order to inform and raise awareness. Next to it, more specific technical events shall be held in order to go a step further into making space companies appreciating the challenges of QTs in progressing on the TRL ladder. Also this type of event have already been organised by ESA, either self-standing (SpaceQuest science requirements workshop) or as a part of a wider programme (the Quantum Secure Comms items in ScyLight workshop).

Shared Resources

Testing facilities are an important resource that should be used in a shared way as much as possible (thermal, radiation tests etc. / drop tower). Often the resources would be available but have to be identified. Networks should be established to find out synergies (the COST Action CA15220 QTSpace will be able to help in this respect).

At the platform level, proper quantum/space networks will identify possible missions with a joint effort of different quantum communities for tests in space on joint satellite platform.

The development of common enabling technologies will be crucial to render QT in space more economical and boost its applications. This especially means the development of versatile and economical space compatible key components for QT (e.g. lasers, vacuum systems, optical components, telescopes).

Recommendations

- Support of theoretical modelling and proof-of-principle-experiments that precede space missions and identify synergy.
- Establish infrastructure for space qualification and testing that is accessible also to SME and small academic groups from quantum

technologies (creation of ecosystem also leading to a new generation of quantum affine space engineers).

- Establish and support networking / conference / schools that connect QT and space fields.
- Support the development of affordable and reusable enabling technologies that are crucial for quantum technology experiments in space.

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