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DELIVERABLE 3.4

Plan for strategic preparation of space missions based on experimental reality

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INTRODUCTION

The communion between quantum technologies and space science is bound to have drastic repercussions on our understanding of the physical world, both at the fundamental and applied level. We have shown that space offers novel avenues for applying and developing quantum technologies based, mainly, on three different physical platforms: cold atoms, photonics, and optomechanical systems. Some of these technologies have already shown readiness for operate in space while others are at earlier stages and in search for validation.

The widespread use of quantum technologies in space is becoming a reality nowadays. Quantum sensors have been employed in fundamental studies of Einstein theory of general relativity and in the first demonstration of the potential of satellite quantum communication. In the last couple of decades, proposals aimed at exploring fundamental questions at the boundary between quantum physics and relativity in space have sprout driven by the possibility to exploit the metrological advantages offered by quantum mechanics. At the same time, the applications of quantum technologies for communication - bearing with it the possibility of implementing quantum cryptographic protocols -, the possible advantages for navigation systems, and the promise of establishing a quantum internet in the future, have propelled the investigation into quantum technologies in space.

Crucial milestones have also been reached. In 2017 [166], the first demonstration of Bose-Einstein condensation and interferometry in a sounding rocket ushered the path that has led to have a cold atom interferometry laboratory on-board the international space station [287]. Atomic clocks are being employed in the Global Navigation Satellite System (GNSS), they have been used and envisaged for fundamental test of general relativity, and are expected to offer the possibility of independent spacecraft navigation in deep space without relying on communication to the ground. The Chinese-led mission QUESS, with the LEO satellite Micius, has been the first space-based quantum communication mission to be launched, allowing to demonstrate entanglement distribution, ground-to-satellite quantum teleportation, and the realization of a hybrid quantum communication network over hundreds of kilometer distances.

And the astounding results of the LISA Pathfinder mission have laid the ground for the more ambitious LISA, on the path to observing the gravitational waves sky in an uncharted range of parameters and opening an entirely new window on the early Universe.
There are calls out and road mapping exercises ongoing by the major space agencies for future missions involving quantum technologies, including the NASA Deep Space Gateway, BECCAL and the ESA Voyage 2050 and Lunar gateway.

The path ahead for quantum technologies in space is an exciting one but it is not devoid of challenges. Tackling them calls for a collaborative environment involving the academic as well as private sector and space agencies. This EU COST action QTSpace plays a vital role in community formation while also addressing technical issues. Here, in the Deliverable report on D3.4, we have summarized the extracted community response, which has been done as part of the operation of QTSpace between 2016 and 2021 on next steps and recommendations to drive forward quantum technologies for space.

IMPLEMENTATION

This report is again ordered according to the different experimental platforms. Beside an attempt to give timelines for milestones for technology development, and the related proof-of-principle tests, an exercise based on consultation with the different academic communities and also published elsewhere [ESA lunar & Martian gateway roadmap and Voyage 2050], we also highlight the relevance of exploitation and the impact on the national and international space ecosystem (academia-industry-agencies) on Earth, which in turn provides the main drivers for any future technology development. Different communities have more or less defined roadmaps for further progression of technology development, which we refer to in each relevant section. The strategic orientation of QT in space as described in this Working Group (WG) 3 (Proof-of-Principle Experiments) report is naturally linked to the defined objectives of QT in space for both, Fundamental Physics and Applications, and is therefore closely related to the outcomes of WG1 and WG2 of the COST action QTSpace.

1. Atomic Systems In Space

a. Atomic clocks in space

For next steps to develop further atomic clocks in space, as a briefing for the European Space Agency (ESA) as well as national space agencies, we list the following milestones for future technology developments:

- 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-ISOC era (10^{-19} performance).

Priorities for Atomic Clock technical developments – a timeline: is a list of milestones with an expected time horizon for their implementation and achievement.

- **Short-term goals (3-5 years):** Complete and fly ACES with utmost priority; prepare for the ACES follow-on mission, I-SOC Pathfinder; develop key optical clock technology for space in preparation for future missions with optical clocks; develop optical and microwave time transfer systems beyond those of ACES.

- **Medium-term goals (5-10 years):** Fly a space mission in fundamental physics with an optical clock in space (SOC), on the ISS or on dedicated flyer.

- **Long-term goals (> 10 years):** Explore coherent optical link between the Lunar Gateway and Earth orbiting satellites or ISS for advanced Equivalence Principle tests. Extend this link technology to the red planet.

Exploration relevance: Accurate clocks in the ESA and NASA lunar and Mars program can be very profitably exploited in the context of precise spacecraft navigation. The need for innovative, largely autonomous, positioning systems requiring a minimal intervention from ground is highly desirable to effectively support exploration missions, both robotic and human.

Today the navigation of lunar probes is carried out with the traditional methods of orbit determination based upon radio-metric measurements (Doppler and range) generated at a ground station. More recently, attempts have been made to exploit the Earth orbiting GNSS satellites to provide real-time radio localization or, more precisely, the dynamical state of lunar orbiters, landers and rovers. This system has important limitations. In addition to the need of relatively large onboard antennas, it is anyway exploitable only for probes or spaceships not occulted by the Moon (i.e. in the near side of the moon). The geometrical dilution of precision is also quite unfavorable (the GNSS satellites are observed with an angular separation of about 4 degrees from the lunar orbit), leading to a strong degradation of the positional accuracy, especially in the plane orthogonal to the Earth-Moon line.

The use of radio signals provided by a stable and accurate clock on Artemis, or by a handful of pseudolites equipped with atomic clocks (all synchronized with the GNSS time) would drastically reduce this effect. Indeed, the radio-localization of a probe could rely on a variety of geometries, in addition to the use of the Earth GNSS signals. The combination of signals coming from a variety of directions would end up in substantial improvement in the positional accuracy. One could also conceive also pseudolites located in the far side of the Moon to provide navigational assistance that is otherwise impossible or difficult to obtain.

Synchronization with terrestrial time would require a relay satellite with precisely known ephemerides. One could obviously conceive a full GNSS constellation in lunar orbit. However, for the needs of the current exploration program, probably simpler solutions are sufficient. As mentioned above, if the timekeeping is maintained on an orbiter (e.g. Artemis), the determination of the ephemerides of the host has to be maintained with sufficient continuity with traditional methods. All these systems require accurate clocks onboard a constellation of satellites. The planetary environment and the large distance from the Earth pose significant problems, especially if the constellation is required to operate with an ample degree of autonomy and minimal intervention from ground. A concept that has been recently investigated is based on a network of small satellites capable of providing the relative and absolute positioning by means of intersatellite radio links (ISL) and the a priori knowledge of the rotation and the gravity field of the planet. (The Martian gravity field and rotational state is well known from previous missions and is continuously improved.)

The ISL configuration need not to be a GRACE or GRAIL-like (which requires frequent synchronization from Earth), but could be based on high accuracy two-way Doppler measurements driven by a standard ultra-stable oscillator [81]. The short round-trip light time strongly suppresses the clock noise, allowing range rate measurements with accuracies < $1x\ 10^{-6}$ m/s from 30 to 1000 s integration time. Once the ephemerides of the constellation have been precisely measured (e.g. by means of a Kalman filter running on a main node), user positioning can be obtained using a GNSS-like time and frequency distribution system, or using Doppler signal (an easier, although less precise architecture). This concept is likely to deliver positional accuracies that are inferior to those of a full-fledged Martian GNSS, but would certainly require a much less extensive (and expensive) infrastructure. It would be in any case the product of a fruitful joint effort from the fundamental physics community (providing the accurate clocks) and the navigation community.

Benefit for Earth and industrial relevance: Global time scales are relying on the comparison of distant clocks. The International Atomic Time (TAI) is generated by BIPM (Bureau International des Poids et Mesures) based on the comparison of primary frequency standards (Cs clocks) worldwide. TAI plays a major role in the definition of UTC (Universal Time Coordinated), which is today recognized as the official time scale. UTC is at the basis of several every day's life applications like precise navigation services via the GNSS network, synchronization of worldwide exchanges and markets, communication networks, national defense and security.

Optical clocks, which already outperform Cs clocks by two orders of magnitude, are already being considered as central elements of new schemes and architectures for generating more precise global time scales. The continuous improvement of optical clocks and the ongoing efforts to compare them worldwide will soon lead to the re-redefinition of the second in the International System of Units (SI).

Global networks of atomic clocks can be used for the in-situ measurement of geopotential differences. Einstein's formula of the gravitational redshift can be used to convert the result of a frequency comparison between two remote clocks into a measurement of the gravitational potential difference at the location of the two clocks. A frequency uncertainty of $1x10^{-18}$ corresponds to a 1 cm resolution on the geoid height. This technique, usually referred to as relativistic or chronometric geodesy, has already been demonstrated in an experiment comparing two clock separated by a 15 km distance achieving an uncertainty of 5 cm on the height difference. Local measurements of geopotential differences are important to connect national height systems and resolve the discrepancies currently observed over intercontinental distances as well as at regional scales, e.g. in Europe. Phenomena such as sea level changes, ocean circulation, ice melting, glacial isostatic adjustment, and land subsidence as well as their mutual interaction can only be understood through high precision and long-term monitoring of gravity potential changes complemented by information on purely geometric height changes (from the GNSS network) and associated mass changes.

b. Atom Interferometers

For next steps to develop Atom interferometers in space we list the following timeline. Regarding the quests in fundamental science, the proposals submitted in response to ESA's call for ideas within the Voyage 2050 program and the associated white paper reflect the crucial importance of interferometry based on ultra-cold atoms and quantum degenerate gases. Obviously, the underlying concepts have also technological relevance and therefore define the road ahead to define proof-of-principle experiments.

Priorities for Atom Interferometer technology developments: Long free-evolution times are especially important for experimenting with interferometers involving quantum states of ultra-cold atoms or even quantum degenerate gases. The main drivers for exploring ultra-cold atoms in space are testing the fundamental laws with better stringency and explaining new phenomena such as dark matter and dark energy as well as Earth observation, space navigation, and planetary science and exploration.

- **Short-term goals (3-5 years):** Experiments in elevators performing quantum tests of the universality free-fall for narrowing the gap to sensitivities of 10^{-17} targeted by space missions.

- **Mid-term goals(5-10 years):** Exploring dual atom interferometry on the ISS or free flyers; pathfinder experiment on the ISS or a free flyer involving atom interferometry based on an optical clock transition.

- **Long-term goals (> 10 years):** Space-borne quantum test of the equivalence principle; space-borne detectors of ultra-light dark matter.

Exploration relevance: After the commercialization of the first atomic gravimeters surpassing classical techniques in various important aspects, such as quasi continuous absolute measurements, prospects for further improvements exploiting ultra-cold atoms and mobile operation, atom interferometers have become an established method for exploration. Indeed, since the first proposals for bias-free accelerometers in the SAGE mission to investigate the Pioneer anomaly, the underlying concepts have experienced substantial development and first atom interferometry experiments in space have already been performed. With a demonstrated
long-term stability of $0.5 nm/s^2$, these sensors are a promising technology for bias-free space navigation.

Benefit for Earth and industrial relevance:
Missions such as GOCE, GRACE and the current GRACE-FO have been successfully completed or are still delivering important observations. Without doubt, their results have been boosting and transforming satellite geodesy and gravimetry. New mission concepts are in the focus of current research. They are based on new, laser-interferometric distance measurements combined with atom interferometers featuring a sensitivity of $6x10^{-10}$ ms^{-2} $Hz^{-1/2}$, atomic gradiometers with a sensitivity of $5x10^{-12}$ s^{-2} $Hz^{-1/2}$, new proof-mass concepts

and associated tracking methods.

Atom interferometers merge new approaches of optical read-out and entirely new test masses based on floating ultra-cold atoms or quantum degenerate gases. Several proposals have been studied by ESA and national agencies like CNES, DLR and ESA. Commercialization of these sensors has already started and they represent the earliest commercial products of the latest quantum technologies. It is therefore foreseeable that this evolution will grow in view of the new concepts developed for space exploration.

2. Photonics Systems In Space

Satellite-based QKD has recently received much attention due to the realization 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 50 kg satellite that demonstrated significant payload development for SC. This naturally makes it a pressing need for Europe to capitalize on the extensive work already done by European universities and research institutions.

In Europe, feasibility studies under ARTES program, and open calls for the development of a demonstrator for In-Orbit-Test (Scylight) are underway:

- 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: a) Matera experiments - first ever qubit exchange from Space. b) Quantum-limited measurement of coherent states emitted from satellite.

The future 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). Skim-sats 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.

<u>Priorities for the QKD developments – a timeline:</u> All Fundamental Physics experiments based on photonic systems hinge on space based quantum technologies and satellite constellations for optical communication. The major driving force behind the development of these technologies is space based quantum communication. The commercial motivation behind this is rapidly driving improvement in space-suitable detectors, photonic chips, entangled photon sources, and quantum information processing nodes. Since many of these experiments require long base line measurements, constellations of CubeSats are potentially the most cost effective way forward.

In terms of mission timeline, we can in general group the proposed experiments as follows:

- **Short-term goals (3-5 years):** In the short term, space qualification and technology readiness will limit us to experiments testing theories that predict the largest effects (such as Space QUEST on the ISS).

- **Medium-term goals (5-10 years):** More sensitive experiments will benefit significantly from lower loss links (i.e., links without the Earth's atmosphere) and are thus medium-term goals because they rely on constellations of a few satellites. Bell inequality experiments from GEO may also become possible in this time frame.

- **Long-term goals (> 10 years):** Tests of dark matter, exotic light fields, etc., are based on large numbers of quantum sensors operating in tandem and are thus longer-term goals.

Clock distribution/synchronization and mapping of gravitational fields are vital for navigation/ space exploration. The proposed experiments promise significant technological development along these lines. In the long term, understanding the potential modifications to general relativity due to quantum physics could possibly help design better relativistic and possibly even faster than light propulsion methods.

Benefit for Earth and industrial relevance: An important driving factor for the development of quantum links comes from their relevance for achieving global-scale quantum-enabled secure communication that can be beneficial for the protection of both private (e.g. financial, medical) and public (e.g. governmental or critical infrastructure) sensitive data. The distribution of complex entangled states (required by some of the above experiments), would enable quantum networks to link quantum computing nodes ushering in a new information era. Additionally, better measurements of physical constants, relativistic effects, and the relationship between quantum physics and GR are all immediately applicable towards better navigation for spacecrafts, propulsion methods, etc. These applications are expected to stimulate an important industrial activity covering the entire supply chain of technologies required for establishing quantum links.

3. Large-Mass Systems In Space

Activities towards space-based large-mass matter-wave interferometry have been coordinated within the MAQRO consortium. ESAs 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 a CDF study in first half of 2018 with a debrief happened at ESTEC in November 2018.

Over the years a mission scenario has been developed to some detail and the relevant literature is here: [210–220]. Some aspects, especially the thermal shielding and how cold one can get in space was studied numerically in detail. A publication related to the debrief of the ESA CDF study on the MAQRO related Quantum Physics Payload Platform (QPPF) has been published in January 2019 [209]. Such objectives can be summarized as follows:

- 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 microgravity environment (drop-tower, parabola flights, etc.) for proof-of-principle experiments or prototyping.

- 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).

Priorities for technology development for large-mass optomechanical systems: 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 large-mass particle platforms addressed in this section, but also beyond in synergy with photonic and cold atom platforms.

Scientific research and technology development of cavity optomechanics, electro-mechanics, magneto-mechanics and large-mass interferometry are rapidly growing into the fundamental physics platform to investigate massive systems in the quantum domain.

- **Short-term to medium-term goals (< 10 years):** The immediate goal is to develop and grow a community of academics, industry, space agencies and funding bodies, coordinated by the QPPF effort with an efficient management structure to work on large-mass matter- wave interferometry and optomechanics based test of fundamental physics in space based on the successful CDF study, which has clear recommendations for technology development. Such technology development is already underway, supported by ESA and national and European funding agencies as well as the preparation for first tests in micro-gravity environments. The community has to foster proof-of-principle experiments on ground and the development of technology into sufficient TRLs. A large ERC project has been funded recently to test nanoparticle interferometry to the maximum possible mass on Earth. Especially important is the early collaboration of the large-mass interferometry community with the space sector and relevant industry to establish flight opportunities such as in CubeSats and tests in micro-gravity environment (drop-tower, parabola flights, sounding rockets) for proof-of-principle experiments or prototyping, such as large-particle interferometry on platforms such as ISS.

- **Long term goal (> 10 years):** The community has to work towards a fundamental science space mission, using heritage of the LISA and LISA Pathfinder missions and technology, 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. Technology needs to be developed to the right TRLs. QPPF 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.

Exploration relevance: Beside the unparalleled ability to explore fundamental physics in a multitude of directions, large-mass systems are also superb sensing platforms for inertial forces, gravity, rotation and electro-magnetic interactions to a record low level as demonstrated in research labs, even outperforming for instance the best magnetic sensors realized by cold and warm atomic vapours and defect centres in diamond to record low level of 10^{-15} Tesla and indeed low-frequency classical mechanical silicon-based sensors are already used as gravimeters on Mars demonstrating the technical applicability of mechanical sensors in space environment and especially on ISS, Moon and Mars missions.

Benefit for Earth and industrial relevance:

This immense potential will soon find applications of mechanical systems, classical or quantum, in space, such as for the measurement of non-gravitational accelerations on the spacecraft like magnetic fields, e.g. the measurement of the World Magnetic Model (WMM), gravity gradient mapping. It will be straight-forward to extend the large-mass technology for planetary studies from space.

The unique physical performance of mechanical oscillators at record low force noise of 10^{-21}N/Hz$^{1/2}$, torque noise at 10^{-29} Nm/ Hz$^{1/2}$ and position resolution (10^{-15}m) allows for a broad variety of application, just appearing on the horizon and will soon find their well-deserved place amongst high-precision devices for sensing and metrology. Some examples beyond the aforementioned applications are frequency conversion and timing, also hybrid devices which can do sensing and timing at the same time. And indeed the use of quantum metrological tools for the application of mechanical systems for gravimetry and gradiometry have already been proposed.

Indeed, mechanical sensors have already found their way for exploration in gravity based geology and resource exploration, mining as well as navigation and the defense sector and various industry projects, spin-out activities are under way in many European countries and we will see the benefit of such developments for the fundamental science space sector very soon.

CONCLUSIONS

This is the concluding report on the work of Working Group 3 (WG3) on proof-of-principle experiments to develop Quantum Technologies in space for both, Fundamental Physics tests and applications such as Earth Observation or timing & navigation. We report on Deliverable 3.4. As such we give a future perspective of steps to be taken in the coming years and, for each experimental platform, we recommend concrete objectives to be achieved in terms of technology development, closing linked to the achievement of the scientific objectives in fundamental and applied science and engineering.

We have already seen very impressive progress of proof-of-principle demonstrations for QTs in and for space across all experimental platforms, and that has been reported on in reports for D3.1, D3.2 and D3.3.

It is clear that QT in space will only be successful in the future if communities collaborate and exchange knowledge and technical solutions across the different experimental platforms. Heritage of technology is central to allow large space missions to progress on reasonable timescales. The new avenue to test new technology on micro-satellites will be crucial, and already is, for the development and space testing of new Quantum Technologies and components.

Especially for large (L-class) scientific missions, it appears to us that both on the technological and scientific motivation level, it is feasible to define space missions which combine different quantum technologies to achieve one defined scientific or technological goal in space. Different attempts have been made already, most prominently by the STE-QUEST proposal. We encourage the QTSpace communities to develop such collaborative mission ideas further.

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