DELIVERABLE 3.1

List of experimental parameters to be reached for each envisaged test

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INTRODUCTION

Quantum Technologies (QT) have to be developed in order to be applicable for space missions. Significant technological progress has been already made in the past decade for the different experimental platforms: cold atomic, photonic and large-mass quantum systems; in the defined topical pillars: Secure Communication, Time and Frequency Services, Earth Sensing and Observation and Fundamental Physics. A long-term process involving partners from academia, various industries and governmental institutions, funding bodies as well as multi-national agencies is required to push forward the technology level of QT by *proof-of-principle experiments* to fulfil *space qualifications* towards *mission design*.

Proof-of-principle experiments

Possible experiments highlighted in the different topical 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 endeavors:

- 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 two-fold approach to foster a healthy ecosystem for QTSpace:

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, QTs 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 has 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).

IMPLEMENTATION

1. Atomic Systems In Space

a. Atomic clocks in space

Atomic systems form a mature experimental platform for applications in space such as for time and frequency standards in form of atomic clocks [1], show promise for Earth observation and satellite-based sensing, but also for fundamental physics tests. 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 gravigradiometers (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.

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 [2–4], GOCE [5–7] and GRACE [8–10].

Atomic clocks for 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). Studies for concrete missions and tests in micro-g environments are here: [11–13]. 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 [14].

ESA and CNES were the first agencies world-wide that recognized the potential of next-generation TFT, by developing the ACES [15] mission. It contains a cold-atom space clock, an optimized two-way microwave link and a single-photon laser link. ACES was expected to be launched to the ISS in 2018. ESA is also developing a sequel mission, I-SOC (Space Optical

Clock on the ISS), with a strongly improved performance, and a possible launch date in the early 2020s [16, 17]. I-SOC, is in phase A.

Atomic clocks for fundamental physics include the experimental tests of relativity [18] such as SAGAS [19] and ACES [15] as well as the test of Lorentz invariance within BOOST [20, 21]. In the field of fundamental physics, TFT will allow a network of communicating clocks to be established for the search for dark matter effects.

Atomic clocks for sensing applications. 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. Development of QC and QGG geodesy missions benefits from pioneering missions such as PHARAO/ACES [22–25] which paves the way to future relativistic geodesy missions.

b. Atom interferometers

A plethora of studies on atom interferometers and their underlying cold atom technology for space have been performed and are underway, some which have been supported by ESA, NASA and national space agencies, providing a strong push to the development of quantum sensors. Atomic quantum sensor development for space with different fundamental scientific purposes to test relativity (UGR), the universality of free fall (UFF). Efforts are organized in different consortia, including:

- SAI (Space Atom Interferometer) [26, 27] and a space atom laser [28], and related cold atom technology [29]
- QUANTUS [30–38],
- MAIUS [39–44],
- CAL [45–47],
- BECCAL [48, 49].

Atom interferometers and atomic clocks for testing fundamental science. Many proposed missions in the realm of fundamental physics are based on cold atoms, for some of them atom interferometers and atomic clocks are combined in one experimental platform [12, 50–54]. Cold atoms and atom interferometry were pioneered by CNES on parabolic flights (ICE) [33, 55, 56], which emerged into the mission ACES [51, 57], which will operate a cold atom clock on the ISS in 2018+ [16, 17, 58]. Bose-Einstein condensation and interferometry was established by DLR in microgravity and space and became part of Q-WEP [59, 60] and STE-QUEST [61–63], 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. HYPER, the flexi-mission using atom interferometer gyroscopes proposal saw a ESA CDF study [64, 65]. Q-WEP, the atom interferometry test of UFF on ISS, is in the study phase. And STE-QUEST, the mission proposal to test UFF with and atom interferometer and the tests of UGR with microwave/laser links together with an atomic clock reached phase 0/A study phase at ESA.

Atom interferometers for sensing applications*.* 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) [33, 55, 56], QUANTUS (drop tower) [30–38] and most recently in space by the MAIUS mission (sounding rockets) [39–44]. 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 [48, 49]. Moreover, the FOKUS mission [13] brought the first frequency comb, an important enabling technology for clocks, to space, and served as demonstrator for test of GR effects. Finally, ESA has recently put strong emphasis on future gradiometry missions with multiple contracts for technical development related to cold atom technology:

- QGG vacuum payload design (RAL, UK),
- QGG laser development (Muquans, FR) [66],
- SOC optical cavity (HHUD, Ger - NPL, UK),
- Cold Atom space payload (E2V, UK),
- Gradiometry mission concepts (2 consortia).

2. Photonics Systems In Space

Photonics quantum systems are explored for use for quantum communications and to test fundamental physics, based on early experimental tests [67–75].

Fundamental physics with photons in space. Photonic quantum system are explored to test quantum mechanics [76–79] and gravity in space. Most of European experimental projects aim mainly at establishing quantum communication links (ARTES ScyLight- Secure and Laser Communication Technology) [80–85]. More fundamental projects include the mission proposal Space QUEST [77, 86]. It was first designed 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) [87–89].

Several activities are taking place around the world QESS mission (China) and the SOCRATES mission (Japan) [90– 92] and also a cubesat mission in Singapore. Currently several other missions are being planned on small platforms in Canada, UK and Austria [73, 86, 93].

Quantum Communication in space. Commercial Quantum Key Distribution (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 [84, 94, 95] based on already earlier demonstrated distribution of QK [96], which will eventually deliver longer-haul quantum communication protocols [97]. All tbis is based on the ability to free-space optically link [69, 98–101].

3. Large-Mass Systems In Space

Scientific research and technology development of both cavity optomechanics [110] and molecule interferometry [111, 112] are rapidly growing into the fundamental physics platform to investigate massive systems in the quan- tum domain [113, 114]. Technology needs to be developed to the right TRLs. Large-mass matterwave interferometry (LMMI) 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. Preparatory technology demonstrator experiments in micro-g environments such as drop tower and Einstein elevator are in the planning phase. Rapid progress is currently been made in levitated optomechanical systems research.

It will be 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 LMMI and technology heritage at ESA. Investigate options for optomechanical technology as spacecraft components, such as frequency conversion, and in other ESA directorates, such as for Earth observation and planetary exploration, to foster optomechanical technology development.

CONCLUSIONS

Different possible cases for QTs in space have been defined. Some are focused on testing fundamental physics is space while others make use of QT for applications in space. At this point, there is already interest, demand and investment for Quantum Communication Satellites on large scales, but also with newer nano-satellite technology underway. QKD in space is without question the most prominent new technology for space. Having said that, of course atomic clocks have undoubtedly their prominent place in space and already a long heritage in for instance GPS satellite navigation systems. Now new development with more precise clocks are underway for applications, but also to address fundamental physics questions. Atom interferometers have recently demonstrated an impressive technology readiness level by generating Bose Einstein Condensate (BEC) interferometers in the ZARM dropping tower and the MICIUS sounding rocket, both providing a micro-gravity environment on different timescales. Now, many projects are underway to apply atom interferometry sensors for instance for Earth Observation (EO) and for testing fundamental physics. Large-mass optomechanical systems are progressing well as a new Quantum Technology and a first proposal for a space-based test of the quantum superposition principle (MAQRO/ESA) has been proposed and evaluated by ESA, which resulted in a clear list of technology to be developed.

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