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DELIVERABLE 3.3

Delivery of realistic time schedule for outstanding proof-of-principle tests

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INTRODUCTION

This report highlights the technical hurdles one must face to mature technology for space use. Due to a wealth of commercialization and prototyping activities led by the cold-atom and photonics community, many of these challenges are not insurmountable. The first part of this report describes how to build upon an already interconnected scientific and industrial community and what steps are needed to enable further cross-disciplinary networking and collaboration. Expanding the diversity of quantum experiments being performed in the optimal conditions of space and micro-gravity has clear benefits for the progression of our understanding of the universe and tangible economic and innovative outputs. We highlight these benefits and the need for a global effort to realize them. We show a technical wish list detailing the technological advancements needed to enable space-based experiments with quantum systems. In general, the following list of steps which have to be passed to demonstrate Technology Readiness Levels (TRL) to be ready for flight:

- **Miniaturization:** i.e. reduction of mass, power dissipation, volume (at least partly).
- **Ruggedisation/Qualification:** in respect to typical environmental condition e.g. vibrations, acoustic forces, thermo-vacuum, radiation and EMC.
- **Reliability and Stability:** Satellite instruments need to operate for several years in challenging environments without the possibility of adjustment.
- **Persistent Quality:** Each quantum technological system manufactured should have the same behaviour and at best be interchangeable.
- **Cost to performance ratio:** The additional investment in a QT device should be clearly compensated.

Typically, most of those demonstrations are performed by space industry, based on innovations from within academia. Some experimental platforms, such as the cold atom one have however shown great initiative to perform technology demonstrations from within the academic community and with support by national space agencies. We reported on those TRL achievements in Deliverable3.2 report.

IMPLEMENTATION

1. Technical Challenges To Be Mastered By Qts Towards Space

This is an attempt to summarie challenges faced by each intended space mission, coping which has to be demonstrated in proof-of-principle experiments at different levels of sophistication, aka TRL. Needless to mention that Space industry and Space Agencies have a well-defined catalogue of what each TRL means and has to deliver, details of which can be found elsewhere. Here, we rather intent to inform the motivated QTSpace enthusiast on the general flavor of challenges ahead. Of course, each of those challenges will be different for each anticipated mission depending on the needed conditions. We match our list of challenges with space heritage form earlier (non-QT) missions, which may help to identify solutions for future QTSpace missions.

Environmental Control: The environment of space is not homogeneous, with variations in temperature, vacuum pressure and radiation. Although working in space allows one to exploitation of the vacuum and coldness of space, maneuvering experiments from the inside to the outside of the space platform is complex. Instead, the route for a ground-based experiment to become space ready is to translate all the subcomponents to space-hardened components, developing a new equipment where necessarily.

- **Maintaining vacuum and environmental temperature:** Cryostats, to keep low temperature, cause vibration, examples are the Planck, Athena, and Gravity Probe B missions for space heritage on low temperature capabilities. Those missions use(d) dilution refrigerators in space. Also, to consider is the fact, that gases remaining can cause issues with gravitational field, which have been controlled by uses a sponge mechanism in baffles to prevent liquid helium sloshing, porous plugs are used to control the pressure in dewar and open versus closed loop cryogen provision at limited supply of liquid Helium limits the mission lifetime. Unaccounted for heating sources can cause depletion even faster. Power consumption limits the ability to do closed loop. [228-231, 235]. Examples of control of thermal conditions are laid out here [210,213]. One common solution for temperature control is passive shielding which helps with solar radiation; this is better than active cooling which require cryostats [214].

  Given that measuring extreme vacuum is a challenge in itself [232,233], also the generation of vacuum has to be done in a space-compatible way, e.g. by sealed devices that use getter [234,235]. Spacecraft out gassing [231] can ruin pressure but can also be improved by the radiation shields [214]. The best vacuum achievable *on ground* is 10^{-16} mbar in a facility at CERN, $7x10^{-17}$ mbar has been achieved at 4K [239]. There are plans that the new PUMA project (antiProton Unstable Matter Annihilation) will demonstrate storage and transporation of antimatter at pressures of 10^{-17} mbar. The vacuum level achievable in space is on the 10^{-10}-10^{-11} mbar for a small volume, as explore in the recent QPPF study by ESA [216].

- **Mechanical Stability/Vibration Isolation/Alignment**: Mechanical instability arises from

two sources; the environment or from movement inside the spacecraft. For environmental sources of vibration, atmospheric drag and solar wind can cause unwanted instabilities, which is why missions with demand on high mechanical stability are typically is planned for a Lagrange point (L2) orbit where there are reduced contributions from these noise sources, as for instance used by the LISA Pathfinder mission [237,238]. Vibrations within the experiment itself, for example, from cryostats require attention [239]. However, there are existing solutions used for Gravity Probe B and the Planck mission where closed loop cryostats show improved stabilization. It should be noted that closed loop cryostats also over a longer lifetime compared with open loop ones. Although the helium leakage is unavoidable and amplified when there are sources of heat within the chamber, closed loop recycles the helium in a more conservative manner [240].
Lack of access to experiments once launched requires detailed understanding of how component and mounts change dimension between initial alignment, usually conducted at atmospheric pressure and at room temperature, to the final environmental conditions e.g. cryostat temperatures or high vacuum. Out-gassing, flexure stresses and warping can all cause misalignment that is not easy to correct once the experiment is sealed.

- **Vibrations from micro-propulsion system** [210] where the force noise produced by LISA is not good enough for original proposal, but with longer free fall, larger fringes can be achieved when working with state-of-the-art micro-thrusters. Acceleration sensitivity of each mission has to be defined. Tilt noise has to be controlled for some missions. The length of time for measurements adds further requirements for stability/drift of instruments, depending on the mission details. For example, the MAQRO mission requires around 100 s measurement time per data point [216]. For this reason, an accelerometer is a central pre-requisite for MAQRO to prevent random relative motion between test particle and the spacecraft - two accelerometers are needed (one at the center of mass of the spacecraft). A similar solution has been have put forward by the ONERA sensor in a cryogenic environment.

- **Charge effects** from high energetic cosmic radiations and micro-asteroids are a well-known effect to be controlled for a broad range of space mission. The control of charging has been an issue for the LISA Pathfinder mission which could be controlled by frequent neutralization by UV radiation [223].

- **Depletion of nitrogen** from cold gas micro-propulsion system produces a deterministic gravitational drift typically several hundreds of fms^{-2}/day [226], which has to be considered.

Component Development & Access to space:

- **Miniaturization** is becoming less of a barrier for getting things into space - balance between cost of launch versus cost of development to miniaturize something (aka someone else has to miniaturize it so extra overheads too). For instance, SpaceX lowering cost of launch by x10, and cubesats opening up a lot of opportunity that isn't so restrictive on size (going from 6U-12U-24U). LISA limit is half a ton, because it needs to reach the geostationary orbit. So orbit choice is also related. SWaP budget is still a driver for the further away orbits. Often things are folded for launch, which then expand out in space, which adds risk for failure. This has to be considered, but space industry has a rich heritage on mechanical solutions for compactification.

- **Companies have started to provide commercial solutions** to some platforms, such as Cold quanta (US) create cold atom parts and chambers [241]; Miniaturization of vapour cells, where progress has been rapid due to GNSS use of rubidium cell frequency standards [242]. Additive manufacturing for space mission has seen examples for complete vacuum chambers of compact size and advanced geometry [243].

- **CAL:** Huge strides have been made on the sub-components required for atomic interferometry through a recent upgrade of the Cold Atom Lab (CAL) on board the ISS - it is the first atom interferometer to operate in space. The Cold Atom Lab is approximately the size of a dishwasher [169]. ALBERT is an online cold atom experiment.

- **Rockets:** Space is expensive (size and mass have a `cost'). Geostationary transfer orbit is the furthest orbit - so you want high initial velocity therefore low mass. BECCAL is 350kg/320kg - but it is not from the vacuum chamber (5kg) but from the sub-components - for example, the 16-17 lasers, and rack-sized electronics. The more functionality the more number of parts, or requirement for upgrades.

  Tsiolkovsky rocket equation, classical rocket equation, or ideal rocket equation are used to calculate the needs on the space vehicle. Space agencies know all about it. In a nutshell: In the rocket equation there is Delta-v, which is a scalar quantity dependent only on the desired trajectory and not on the mass of the space vehicle. For example, although more fuel is needed to transfer a heavier communication satellite from low Earth orbit to geosynchronous orbit than for a lighter one, the delta-v required is the same. Also, delta-v is additive, as contrasted to rocket burn time, the latter having greater effect later in the mission when more fuel has been used up. Small size/mass allows **for** piggybacking on missions. But it's a balance of money/political appetite.

- **Optics & Photonics components:** Single mode fibers in space are feasible but if they break, replacement is impossible. InP PICs miniaturization and radiation tolerant has been investigated by CERN [244,245]. Acuosto-Optical Modulators (AOMs) and Electro-Optical Modulators (EOMs) and optical amplifiers are developed for LISA. The DARWIN proposal [246] laid out a roadmap that included space-qualified delay lines to balance optical paths to nanometer accuracy and the use of single mode tested at ultra-high vacuum (UHV), temperatures as low as 10 K, an resistance to photon radiation and gamma radiation [210].

- **Lasers:** Laser pointing stability [210] and IR cavity finesse (high reflectivity mirror coatings) of above 3x10^4 possible, see QPPF study. Laser source at 1064 nm wavelength from non-planar ring oscillator laser was used by LISA PF and will be used for LISA. Laser sources in general are not at mature TRL at ultra-violet. If laser noise causes the same issues requiring either active feedback methods, or referenced to stable frequency source, or single photon sources that are space qualified [247,248]. Ferdinand Braun Institute (FBH) in Berlin build lasers for BECCAL and MAIUS [249]. TESAT create TRL 9 lasers at 1550nm [250] already used for satellite-to-satellite communications. DLR are building compact laser communication terminals for CubeSats (LCRT), also for UK OSCAR module. Look at clock [251].

Automation:

- **Power consumption**: has to be considered and typically optimized. For instance, MAQRO would require a solar array of 680 W, similar to that used by LISA Pathfinder [216], with the largest power consumption from data and diagnostics, and operating lasers. If a bake out of a heat-shield structure is required, this almost doubles the power consumption. Active cooling requires more power consumption.

- **Electronics & Control:** Although some electronics can be sourced of-the-shelf as space-approved items, calm current operation may not be guaranteed, with bespoke requirements such as fast switching times not commercially available. Sometimes the use of *large chips,* e.g. electronics, because of radiation issues like cosmic rays are advisable. A single cosmic ray could take out a transistor if its made on small node size but on the other hand, redundancy when working with small chips. Electronics requirements can be quite different to drawing based, plug and play components such as vacuum chambers, with added cost in miniaturization due to the high cost of developing and fabricating ASICs for low power and rigorized operation. STI work with space-related projects but its within their remit. Electronics, PCBs, and software typically needs specialist companies to work on. Data processing such as Power spectrums/FFT/big data storage e.g. random number generation needs Gb of storage Flash drives, SD cards are being used in space. Space industry and Space agencies have a lot of experience & knowledge on electronics for space.

Quality Assurance/Environmental Testing: Typically, all space payloads need to be tested for radiation hardening and quality assurance specifications and tested for temperature, shock, and vibration etc. Testing is done of TRL development by space industry for each approved mission or alternatively by the academic community before missions get approval. Dedicated facilities for space readiness testing exist at industry or space agencies. Environmental testing, access to facilities and expertise to perform tests exist in abundance: facilities for shake + bake, many engineering departments have their own facilities, and those are not too expensive for rental otherwise. Parameters, e.g. amplitude and frequency of mechanical vibrations to be reach in tests are known or provided by launch provider.

- **Qualification:** of technology is the expensive part of each mission development. Man hours are required, trace subcomponents to batches (documentation gets complex - even for screws (see LISA PF), have to retest if buy more etc. item cost can go up by x10). Traceability of components is important. The European Cooperation for Space Standardization (ECSS) is an initiative established to develop a coherent, single set of user-friendly standards for use in all European space activities.

- **European Centre for Space Law** (ECSL). The ECSL was founded in 1989 on the initiative of the European Space Agency. Its objectives are the improvement in space law research, education and practice in Europe. The Consultative Committee for Space Data Systems (CCSDS) is an international voluntary consensus organization of space agencies and industrial associates interested in mutually developing standard data handling techniques to support space research, including space science and applications. [252]

- **The European Space Components Information Exchange System** (ESCIES) is a repository for EEE parts information hosted by ESA, on behalf of the Space Components Steering Board, as part of the European Space Components Coordination.

- **The European Preferred Parts List** (EPPL) is a list of preferred and suitable components to be used by European manufacturers of spacecraft hardware and associated equipment. It is part of the ECSS system with an updated parts list released every year, for example, EPPL Issue 41 corresponds to 2020. [253]

- **The International Standards Organization Standards** (ISO) catalogue.

- **Safety.** Product assurance encompasses quality and safety, risk (dependability) academia less familiar with process nor documentation.

2. Atomic Systems In Space

a. Atomic clocks in space

Currently Prepared Missions: In order to execute optical clocks in space, the following missions are currently prepared. They are targeting both, fundamental questions and technology development:

- **ACES** (Atomic Clock Ensemble in Space): This is an ESA-coordinated mission that will prepare a system of two atomic clocks in the Columbus module of the ISS. The two clocks are the laser-cooled Caesium atomic clock PHARAO (Projet d'Horloge Atomique par Refroidissement d'Atomes en Orbite), developed by CNES, an active hydrogen MASER, the SHM (Space Hydrogen maser), developed by Spectratime and a precise time and frequency transfer system [254]. The clock ensemble is expected to have a stability of $2x10^{-16}$ in the short term. Currently, launch for the ensemble is scheduled for 2021. The technical goal of this mission is testing the performance of a new generation of atomic clocks in space and the scientific goals are to perform fundamental physics tests, as for example an improved measurement of the gravitational redshift, the search for anisotropies of the speed of light, and for space-time variations of physical constants. In addition, the two atomic clocks will allow mapping the Earth's gravitational potential by measuring the differential gravitational redshift [255]. The ACES mission will also allow comparing the time reference with ground-based ones and the ultra-precise time-reference distribution [256].

- **COMPASSO** [257] is a DLR mission that aims at demonstrating necessary optical frequency and link technologies for future missions, such as BOOST, LISA, Next Generation Gravity Mission, and GNSS. In particular, the mission will be the first in-orbit verification of optical clocks. The payload consists of optical and radio frequency references, and a bidirectional optical link to compare the in-orbit measurements to frequency references on ground. This shall demonstrate the possibility to operate optical links to other space-based platforms and, in addition, will allow investigating atmospheric effects in space-to-ground clock distribution. The latter especially includes the comparison to a GNSS signal to demonstrate the readiness of optical technologies for GNSS applications. Currently, it is planned that COMPASSO will be operated starting with end of 2024 on the ISS aboard the Bartolomeo platform.

Proposed Missions: Based on the current technology additional missions have been proposed, some of which are listed below:

- **BOOST** (BOOst Symmetry Test): This is a DLR mission to conduct a Kennedy Thorndike experiment in space [258], which aims at improving the current boundaries set by ground based experiments [259]. Two optical references based on two different operational principles are compared. Here, an optical cavity is compared to an Iodine frequency reference. The targeted stability is better than 10^{-15} at orbit time, which takes around 90 minutes.

- **IVORY** (In-orbit Verification of stabilized Optical and microwave Reference sYstems): The DLR and Airbus Defense and Space joint project IVORY aims at verification of optical technologies, as optical clocks, frequency combs and space-to-ground laser communication, on the ISS aboard the Bartolomeo platform. It includes a Rubidium clock and a microwave reference system.

- **SOC** (Space Optical Clocks): The DLR and ESA funded project SOC aims at operating optical lattice clock systems on the ISS. The systems include Ytterbium and Strontium optical clocks. With these atoms cooled and trapped in a magneto-optical trap, a frequency stability of 10^{-16} is targeted [260].

b. Atom Interferometers

Beside the very many successfully operated proof-of-principle experiments for cold atoms in space, there ais here a list of concrete project for near-future completion:

Ground-based tests:

- **DESIRE** (Dark Energy search by Interferometry in the Einstein Elevator) Based on pre-studies [261,262], recently in 2021, a new NASA/JPL-DLR project started, which aims for a significant rise in sensitivity for the search of dark matter, which can be reached with atom interferometers using freefalling, compact low-energy wave packages in interaction with a specific test mass on macroscopic time scales of several seconds. To reach these time scales the apparatus will be operated in the Einstein-Elevator in Hannover. The DESIRE project utilizes the BEC interferometer of the MAIUS-1 mission, which will be modified for its use in the Einstein-Elevator. More details can be found elsewhere [166,261,262,263].

Space-based tests:

- After MAIUS-1, the second generation rocket payload MAIUS-B is in its setup phase. It reached its critical design review at the end of 2018 [264]. This apparatus features, additionally to Rubidium-87, also Potassium-41 atoms and aims at performing sequential atom interferometry experiments and mixture studies with both species during the second rocket mission MAIUS-2 currently scheduled for 2021. The launch of a third and final mission, MAIUS-3, is currently planned for 2022 and aims at demonstrating simultaneous atom interferometry in space, paving the path for tests of the universality of free fall using atoms. The interested reader is referred to [166, 256-270].

- **BECCAL** (Bose-Einstein Condensate and Cold Atom Laboratory): Built upon the heritage not only of the projects QUANTUS, MAIUS and CAL, but also of JOKARUS and KALEXUS, the NASA- and DLR-funded BECCAL will serve as the next generation multi-user and -purpose facility aboard the ISS [271]. The apparatus is designed to operate with cold and condensed ensembles of different isotopes of Rubidium and Potassium. Hence, BECCAL will enable the study of scalar and spinor degenerate gasses as well as mixtures thereof. BECCAL supports atom interferometry for fundamental physics and studies for future quantum sensors. Additionally, arbitrary shaped red- and blue-detuned potentials will be possible to implement, allowing for versatile trapping and anti-trapping configurations. Throughout its lifetime, BECCAL will perform a variety of experiments and serve as a pathfinder for future missions. The interested reader is referred to [271].

- **CASPA** (Cold Atom Space PAyload): In the Innovate UK and Engineering and Physical Sciences Research Council (EPSRC) funded project CASPA, a British consortium led by the company Teledyne e2v is designing a system for autonomous cold atom experiments in space. The project's aim is the elevation of Technology Readiness Level (TRL) of required subsystems and the tackling of challenges in building compact cold atom interferometers for space use. After a careful analysis of the environment's impact on the cold atom system, a prototype 6U CubeSat that is capable of trapping Rubidium atoms was built, qualified, and tested. CASPA has a weight of 4 kg, fits into four units of a CubeSat and consumes 12 W of electrical power. It can cool down atoms to the order of 100 μK. An actual cold atom sensor based on the heritage of CASPA is planned to be built [272].

3. Photonics Systems In Space

Applications of photons - QKD: A timeline of missions that have demonstrated key milestones or feasibility studies towards global satellite-based QKD is provided in [273]. This includes recently proposed mission that aim to integrate space and terrestrial segments to step closer to a globally quantum networking. Further dedicated reviews on space quantum communication missions can be found in Refs. [274,274] and Ref. [186] for a general overview of the field. The technical challenges to be address for quantum communication in the coming years include the following:

- **Deep space communication:** Among the planned projects for the future Lunar Orbital Platform-Gateway (LOP-G) station on lunar orbit, is the Deep Space Quantum Link [276]. The goals of the Deep Space Quantum Link are to test the effects of gravity and different inertial reference frames on quantum teleportation, and to establish a space-to-space QKD link between stations on lunar and low Earth orbits, i.e. the LOP-G and the International Space Station respectively.

- **Quantum Internet:** A road-map to the realization of a quantum internet requires the development of quantum networks with increased functionality [186,277]. Trusted repeater networks have already been demonstrated in metropolitan areas and between cities [278-281] and with satellite links [183]. An extension of this requires entanglement distribution through the network with and without quantum memories. This will enable implementation of clock synchronization tasks and blind quantum computing. The final development will require error correction capabilities throughout the network. This will permit the operation of high fidelity quantum entanglement distribution and error correction for globally distributed tasks. The step increase in functionality of the network comes at the expense of increased technological difficulty.

- **Quantum Number generators:** Despite these improvements to QRNGs, there are important challenges that need to be overcome for their use in space networks. First, the cost of QRNG technologies remain high and this makes alternative, less secure approaches attractive. Second, their miniaturization and space readiness is essential for small quantum satellite missions. Finally, the quality assurance, certification, and standardization of QRNGs is required. Current security evaluations of cryptographic and security products use the Federal Information Processing Standards Publication 140 standard, which defines the minimum-security level [282]. Such a standard may inhibit immediate adoption of QRNGs given their current technological readiness.

Fundamental Physics test with photons: Several other projects allowing to test BIV and quantum mechanical entanglement at large scales are been planned at the national and international level, driven mostly by the alluring possibility of a global quantum internet and long distance quantum communication and cryptography. Examples are the Canadian QEYSSat micro-satellite mission expected for 2022 [283] and the NASA's Deep Space Quantum Link (DSQL), which will employ the Lunar Orbital Platform-Gateway - a space station orbiting the moon - to establish a quantum link with ground stations which will allow testing BIV [276] in conditions in which the spacetime curvature is expected to play a role. The SAGE mission proposal includes among its main scientific objectives the test of BIV with two satellites at a distance between 5000 and 30000 km playing the role of Alice and Bob. At these distances, special and general relativistic effects are expected to be relevant.

4. Large-Mass Systems In Space

Om concrete space project under active development for large-mass optomechanical systems in space is the MAQRO/QPPF project. There are certain demands on technology, some of it new, as identified by ESA. Not all components or methods are interchangeable across the photonics, cold-atom and optomechanics platforms.

Unique for optomechanics is the need to trap, control, and cool macro-sized objects, which are substantially larger than single atoms and more prone to environmental decoherence than photons. The technical challenges unique to a levitated optomechanics platform to operate in space relate to the levitated test particles, their confinement, and enhancing the coherence time [209]. The test particles must be dielectric and highly transparent and also uncharged with uniform shape. Challenges to be addressed in the future include:

- **Particle:** The levitated optomechanics community uses the Stöber process to prepare silica nanoparticles which is an example of a liquid phase sol-gel process [284]. A molecular precursor (typically tetraethylorthosilicate) is first reacted with water in an alcoholic solution causing resulting molecules to join together to build larger structures. The reaction produces silica particles with diameters ranging from 50 to 2000 nm, depending on the preparation conditions [285]. Recently, efforts have been made to fabricate nanostructures using clean room processes on silicon wafers [286]. Since levitated nanospheres are bulk objects, they are prone to light absorption and internal heating that is harder to control than for atoms and photons. Decoherence associated to blackbody radiation should be smaller than $10^{-10}ms^{-2}/Hz^{1/2}$, requiring thermal stability at the milli-Kelvin level [209].

- **Particle source:** Ideally, the same nanoparticle would be used repeatability over several thousand runs. Since each run may take up to 1 s, the duration of time in which such measurements are taken will inadvertently introduce some error spread as the attitude motion of the spacecraft due to solar radiation may cause a shift in location. Levitated particles must remain limited to a confined region with limitations on the photon occupation numbers of <10 along the cavity and $<10^4$ perpendicular to it, to ensure suitably coherent and quantum measurements [209].

- **Cavity & Measurement:** The length of a typical cavity for MAQRO would be 97 mm, requiring a minimum finesse of $3x10^4$ to achieve cooling close to the quantum ground state. To ensure the nanosphere remains in the ground state, less than two collisions should occur with 80% probability during the measurement period, which can be sustained by the use of a reactive material, namely a getter material, placed inside the vacuum that maintains the pressure. Indeed, when gas molecules stroke the material, they combine with it chemically or by absorption.

ESA have launched a project in 2020 to address the particle source challenge for the MAQRO mission. The project was allocated to the Tyndall institute in Ireland and is ongoing. The approach is to build a technology based on a ultra-sound source to launch particles of various sizes from surfaces on demand and to load those into the optical cavity trap.

CONCLUSIONS

D3.3 reports on running and planned space missions using quantum technologies. We also report on concrete technical challenges which have to be overcome by specific projects and experimental platforms. We further report on general exercises to be done for progression of technology TRLs, eventually ending up in space. The different experimental platforms are developed to a different degree. Atomic Clocks (AC) and Cold Atoms (CA) communities work on a number of concrete mission projects and the roadmaps lay clear ahead. The impact of AC and CA is on both Fundamental Physics and Applications such as Earth Observations. Quantum Communication (QC) is much likely the hottest space QT at the moment and a vast amount of project is ongoing, planned and considered – many of which undisclosed to the authors of this report. QC is becoming of considered security relevance and the technology is already mature. Large-mass optomechanical system are much younger, but have seen the development of key technologies, space missions could heavily rely on space technology heritage, especially form LISA PF and LISA. A clearer trajectory seems to appear for the formation of a strong consortium to push for large-mass optomechanical quantum experiments in space. Applications of optomechanical devices on spacecrafts will be and should be a field of future investigation and innovation. The potential of the technology is immense.

Strategically, it could be of importance to anticipate joint missions between different QTs. There is technological scope for this, such as by combining QC photonics technology with quantum optomechanics as part of a ground-space-linked quantum internet. Atomic clock satellite networks could be linked by QC light sources, and Cold atoms could be linked with optomehanical sources. Various combinations are thinkable and indeed STE-QUEST, a hybrid between AC and CA, had been proposed already a decade ago.

In general, two aspects have to be considered for such cross combinations: (i) The targeted Fundamental Physics questions to be answered in space has to have the need to use more than one QT, equally the QT applications for timing, navigation, Earth Observation or Sensing must have a need for more than one QT, and (ii), the matching fit of different quantum technologies and to fit on one satellite. It is our opinion that (i) is the more demanding condition.

REFERENCES (FOR ALL WG3 DELIVERABLES)

[1] C. Salomon, N. Dimarcq, M. Abgrall, A. Clairon, P. Laurent, P. Lemonde, G. Santarelli, P. Uhrich, L. Bernier, G. Busca, *et al.*, Comptes Rendus de l'Acad´emie des Sciences-Series IV-Physics **2**, 1313 (2001).

[2] P. Touboul, E. Willemenot, B. Foulon, and V. Josselin, Boll. Geof. Teor. Appl **40**, 321 (1999). [3] C. Reigber, H. Lühr, and P. Schwintzer, Advances in Space Research **30**, 129 (2002).

[4] N. Jakowski, V. Wilken, and C. Mayer, Space Weather **5**, 1 (2007).

[5] F. Migliaccio, M. Reguzzoni, F. Sanso, C. Tscherning, M. Veicherts, *et al.*, in *Proceedings of the ESA living planet symposium*, Vol. 28 (Citeseer, 2010).

[6] M. Drinkwater, R. Floberghagen, R. Haagmans, D. Muzi, and A. Popescu, Space Science Reviews **108**, 419 (2003).

[7] A. Albertella, F. Migliaccio, and F. Sanso´, in *Modern Celestial Mechanics: From Theory to Applications* (Springer, 2002) pp. 1–15.

[8] A. Cazenave, K. Dominh, S. Guinehut, E. Berthier, W. Llovel, G. Ramillien, M. Ablain, and G. Larnicol, Global and Planetary Change **65**, 83 (2009).

[9] J. Chen, C. Wilson, D. Blankenship, and B. Tapley, Geophysical research letters **33** (2006).

[10] B. Tapley, J. Ries, S. Bettadpur, D. Chambers, M. Cheng, F. Condi, and S. Poole, in *AGU Fall Meeting Abstracts* (2007). [11] L. Liu, D.-S. Lu¨, W.-B. Chen, T. Li, Q.-Z. Qu, B. Wang, L. Li, W. Ren, Z.-R. Dong, J.-B. Zhao, *et al.*, Nature communications **9**, 2760 (2018).

[12] S. Schiller, G. Tino, P. Lemonde, U. Sterr, C. Lisdat, A. G¨orlitz, N. Poli, A. Nevsky, and C. Salomon, in *International Conference on Space Optics?ICSO 2010*, Vol. 10565 (International Society for Optics and Photonics, 2017) p. 1056531.

[13] V. Schkolnik, K. D¨oringshoff, F. B. Gutsch, M. Oswald, T. Schuldt, C. Braxmaier, M. Lezius, R. Holzwarth, C. Ku¨rbis, A. Bawamia, *et al.*, EPJ Quantum Technology **4**, 9 (2017).

[14] J. Grotti, S. Koller, S. Vogt, S. H¨afner, U. Sterr, C. Lisdat, H. Denker, C. Voigt, L. Timmen, A. Rolland, *et al.*, Nature Physics, 1 (2018).

[15] L. Cacciapuoti and C. Salomon, The European Physical Journal Special Topics **172**, 57 (2009).

[16] K. Bongs, Y. Singh, L. Smith, W. He, O. Kock, D. S´wierad, J. Hughes, S. Schiller, S. Alighanbari, S. Origlia, *et al.*, Comptes Rendus Physique **16**, 553 (2015).

[17] S. Origlia, S. Schiller, M. Pramod, L. Smith, Y. Singh, W. He, S. Viswam, D. S´wierad, J. Hughes, K. Bongs, *et al.*, in *Quantum Optics*, Vol. 9900 (International Society for Optics and Photonics, 2016) p. 990003.

[18] C. L¨ammerzahl, C. F. Everitt, and F. W. Hehl, *Gyros, Clocks, Interferometers...: Testing Relativistic Gravity in Space*, Vol. 562 (Springer Science & Business Media, 2001).

[19] P. Wolf, C. J. Bord´e, A. Clairon, L. Duchayne, A. Landragin, P. Lemonde, G. Santarelli, W. Ertmer, E. Rasel, F. Cataliotti, *et al.*, Experimental Astronomy **23**, 651 (2009).

[20] N. Guurlebeck, L. W¨orner, T. Schuldt, K. D¨oringshoff, K. Gaul, D. Gerardi, A. Grenzebach, N. Jha, E. Kovalchuk, A. Resch, *et al.*, Physical Review D **97**, 124051 (2018).

[21] L. Woerner, T. Schuldt, A. Resch, A. Peters, E. M. Rasel, N. Gu¨rlebeck, U. Johann, C. Braxmaier, M. Krutzik, S. Her- rmann, *et al.*, in *42nd COSPAR Scientific Assembly*, Vol. 42 (2018).

[22] P. Laurent, M. Abgrall, A. Clairon, P. Lemonde, G. Santarelli, C. Salomon, F. Picard, C. Sirmain, D. Massonnet, and L. Cacciapuoti, in *Time and Frequency Metrology*, Vol. 6673 (International Society for Optics and Photonics, 2007) p. 667308.

[23] V. Candelier, P. Canzian, J. Lamboley, M. Brunet, and G. Santarelli, in *Frequency Control Symposium and PDA Exhibition Jointly with the 17th European Frequency and Time Forum, 2003. Proceedings of the 2003 IEEE International* (IEEE, 2003) pp. 575–582.

[24] T. L´ev`eque, B. Faure, F. Esnault, O. Grosjean, C. Delaroche, D. Massonnet, C. Escande, P. Gasc, A. Ratsimandresy, S. B´eraud, *et al.*, in *International Conference on Space Optics?ICSO 2014*, Vol. 10563 (International Society for Optics and Photonics, 2017) p. 105632H.

[25] P. Peterman, K. Gibble, P. Laurent, and C. Salomon, Metrologia **53**, 899 (2016). [26] S.-w. Chiow, J. Williams, and N. Yu, Physical Review A **92**, 063613 (2015).

[27] S. Loriani, D. Schlippert, C. Schubert, S. Abend, H. Ahlers, W. Ertmer, J. Rudolph, J. Hogan, M. Kasevich, E. Rasel, *et al.*, arXiv preprint arXiv:1812.11348 (2018).

[28] M. Meister, A. Roura, E. M. Rasel, and W. P. Schleich, arXiv preprint arXiv:1807.09817 (2018).

[29] C. Spindeldreier, W. Bartosch, T. Wendrich, E. M. Rasel, W. Ertmer, and H. Blume, in *Laser Resonators, Microres- onators, and Beam Control XX*, Vol. 10518 (International Society for Optics and Photonics, 2018) p. 1051813.

[30] N. Gaaloul, H. Ahlers, T. Schulze, Y. Singh, S. Seidel, W. Herr, W. Ertmer, E. Rasel, *et al.*, Acta Astronautica **67**, 1059 (2010).

[31] J. Rudolph, N. Gaaloul, Y. Singh, H. Ahlers, W. Herr, T. A. Schulze, S. T. Seidel, C. Rode, V. Schkolnik, W. Ertmer, *et al.*, Microgravity Science and Technology **23**, 287 (2011).

[32] M. Cornelius, C. Laemmerzahl, T. Sternke, and S. Herrmann, in *42nd COSPAR Scientific Assembly*, Vol. 42 (2018). [33] V. M´enoret, R. Geiger, G. Stern, P. Cheinet, B. Battelier, N. Zahzam, F. P. Dos Santos, A. Bresson, A. Landragin, and P. Bouyer, in *International Conference on Space Optics?ICSO 2010*, Vol. 10565 (International Society for Optics and Photonics, 2017) p. 1056530.

[34] C. Spindeldreier, T. Wendrich, E. M. Rasel, W. Ertmer, and H. Blume, in *Application-specific Systems, Architectures and Processors (ASAP), 2016 IEEE 27th International Conference on* (IEEE, 2016) pp. 207–212.

[35] C. Schubert, S. Abend, M. Gebbe, M. Gersemann, H. Ahlers, H. Mu¨ntinga, J. Matthias, M. Sahelgozin, W. Herr, C. L¨ammerzahl, *et al.*, in *EGU General Assembly Conference Abstracts*, Vol. 18 (2016) p. 14817.

[36] N. Gaaloul, W. Ertmer, E. M. Rasel, Q. Collaboration, M. Collaboration, *et al.*, in *APS Meeting Abstracts* (2018).

[37] S. Abend, M. Gebbe, M. Gersemann, E. M. Rasel, Q. Collaboration, *et al.*, in *APS Division of Atomic, Molecular and Optical Physics Meeting Abstracts* (2017).

[38] M. Gebbe, S. Abend, M. Gersemann, H. Ahlers, H. Muentinga, S. Herrmann, C. Laemmerzahl, W. Ertmer, E. M. Rasel, Q. Collaboration, *et al.*, in *APS Division of Atomic, Molecular and Optical Physics Meeting Abstracts* (2017).

[39] S. Seidel, M. Lachmann, D. Becker, J. Grosse, M. Popp, J. Wang, T. Wendrich, E. Rasel, Q. Collaboration, *et al.*, in *22nd ESA Symposium on European Rocket and Balloon Programmes and Related Research*, Vol. 730 (2015) p. 309.

[40] J. Grosse, S. Seidel, M. Krutzik, T. Wendrich, A. Stamminger, M. Scharringhausen, Q. Consortium, *et al.*, in *22nd ESA Symposium on European Rocket and Balloon Programmes and Related Research*, Vol. 730 (2015) p. 301.

[41] M. Lachmann, H. Ahlers, D. Becker, S. Seidel, T. Wendrich, E. M. Rasel, and W. Ertmer, in *Complex Light and Optical Forces XII*, Vol. 10549 (International Society for Optics and Photonics, 2018) p. 1054909.

[42] D. Becker, M. D. Lachmann, S. T. Seidel, H. Ahlers, A. N. Dinkelaker, J. Grosse, O. Hellmig, H. Mu¨ntinga, V. Schkolnik, T. Wendrich, *et al.*, Nature **562**, 391 (2018).

[43] M. Christ, A. Peters, and M. Krutzik, in *The European Conference on Lasers and Electro-Optics* (Optical Society of America, 2017) p. CH P 30.

[44] J. Rudolph, W. Herr, C. Grzeschik, T. Sternke, A. Grote, M. Popp, D. Becker, H. Müntinga, H. Ahlers, A. Peters, *et al.*, New Journal of Physics **17**, 065001 (2015).

[45] E. R. Elliott, M. C. Krutzik, J. R. Williams, R. J. Thompson, and D. C. Aveline, npj Microgravity **4**, 16 (2018). [46] D. Aveline, E. Elliott, J. Williams, and R. Thompson, Bulletin of the American Physical Society (2018).

[47] J. Williams and J. D'Incao, in *APS Division of Atomic, Molecular and Optical Physics Meeting Abstracts* (2017). [48] W. Herr, in *42nd COSPAR Scientific Assembly*, Vol. 42 (2018).

[49] D. Becker, K. Frye, C. Schubert, E. M. Rasel, B. Collaboration, *et al.*, in *APS Meeting Abstracts* (2018).

[50] G. Tino, L. Cacciapuoti, K. Bongs, C. J. Bord´e, P. Bouyer, H. Dittus, W. Ertmer, A. G¨orlitz, M. Inguscio, A. Landragin, *et al.*, Nuclear Physics B-Proceedings Supplements **166**, 159 (2007).

[51] P. Laurent, D. Massonnet, L. Cacciapuoti, and C. Salomon, Comptes Rendus Physique **16**, 540 (2015). [52] J. Williams, S.-w. Chiow, N. Yu, and H. Mu¨ller, New Journal of Physics **18**, 025018 (2016).

[53] L. Liu, "Exploring the universe with matter waves" (2018).

[54] X. Wu, F. Zi, J. Dudley, Z. Pagel, B. Malek, P. Canoza, and H. Mu¨ller, in *Steep Dispersion Engineering and Opto-Atomic Precision Metrology XI*, Vol. 10548 (International Society for Optics and Photonics, 2018) p. 105481X.

[55] B. Barrett, L. Antoni-Micollier, L. Chichet, B. Battelier, T. L´ev`eque, A. Landragin, and P. Bouyer, Nature communica- tions **7**, 13786 (2016).

[56] B. Battelier, P. Bouyer, A. Landragin, G. Condon, M. Rabault, and B. Barrett, in *42nd COSPAR Scientific Assembly*, Vol. 42 (2018).

[57] F. Meynadier, P. Delva, C. le Poncin-Lafitte, C. Guerlin, and P. Wolf, Classical and Quantum Gravity **35**, 035018 (2018). [58] S. Origlia, M. Pramod, S. Schiller, Y. Singh, K. Bongs, R. Schwarz, A. Al-Masoudi, S. D¨orscher, S. Herbers, S. H¨afner, *et al.*, Physical Review A **98**, 053443 (2018).

[59] F. Sorrentino, K. Bongs, P. Bouyer, L. Cacciapuoti, M. de Angelis, H. Dittus, W. Ertmer, J. Hartwig, M. Hauth, S. Herrmann, *et al.*, in *Journal of Physics: Conference Series*, Vol. 327 (IOP Publishing, 2011) p. 012050

[60] B. Dubetsky, arXiv preprint arXiv:1810.04218 (2018).

[61] B. Altschul, Q. G. Bailey, L. Blanchet, K. Bongs, P. Bouyer, L. Cacciapuoti, S. Capozziello, N. Gaaloul, D. Giulini, J. Hartwig, *et al.*, Advances in Space Research **55**, 501 (2015).

[62] P. Wolf and L. Blanchet, Classical and Quantum Gravity **33**, 035012 (2016).

[63] N. Gaaloul, W. Ertmer, E. Rasel, C. Braxmaier, A. Landragin, P. Bouyer, K. Bongs, and G. Tino, in *International Conference on Space Optics?ICSO 2012*, Vol. 10564 (International Society for Optics and Photonics, 2018) p. 105641L.

[64] G. Bagnasco and S. Airey, in *IAF, International Astronautical Congress, 52 nd, Toulouse, France* (2001). [65] C. Jentsch, T. Mu¨ller, E. Rasel, and W. Ertmer, General Relativity and Gravitation **36**, 2197 (2004).

[66] V. M´enoret, P. Vermeulen, N. Le Moigne, S. Bonvalot, P. Bouyer, A. Landragin, and B. Desruelle, Scientific reports **8**, 12300 (2018).

[67] M. Aspelmeyer, H. R. B¨ohm, T. Gyatso, T. Jennewein, R. Kaltenbaek, M. Lindenthal, G. Molina-Terriza, A. Poppe, K. Resch, M. Taraba, *et al.*, science **301**, 621 (2003).

[68] P. Villoresi, F. Tamburini, M. Aspelmeyer, T. Jennewein, R. Ursin, C. Pernechele, G. Bianco, A. Zeilinger, and C. Barbieri, in *Quantum Communications and Quantum Imaging II*, Vol. 5551 (International Society for Optics and Photonics, 2004) pp. 113–121.

[69] P. Villoresi, T. Jennewein, F. Tamburini, M. Aspelmeyer, C. Bonato, R. Ursin, C. Pernechele, V. Luceri, G. Bianco, A. Zeilinger, *et al.*, New Journal of Physics **10**, 033038 (2008).

[70] J. M. P. Armengol, B. Furch, C. J. de Matos, O. Minster, L. Cacciapuoti, M. Pfennigbauer, M. Aspelmeyer, T. Jennewein, R. Ursin, T. Schmitt-Manderbach, *et al.*, Acta Astronautica **63**, 165 (2008).

[71] A. Fedrizzi, R. Ursin, T. Herbst, M. Nespoli, R. Prevedel, T. Scheidl, F. Tiefenbacher, T. Jennewein, and A. Zeilinger, Nature Physics **5**, 389 (2009).

[72] F. Steinlechner, P. Trojek, M. Jofre, H. Weier, D. Perez, T. Jennewein, R. Ursin, J. Rarity, M. W. Mitchell, J. P. Torres, *et al.*, Optics express **20**, 9640 (2012).

[73] T. Scheidl, E. Wille, and R. Ursin, New Journal of Physics **15**, 043008 (2013).

[74] M. Krenn, R. Fickler, M. Fink, J. Handsteiner, M. Malik, T. Scheidl, R. Ursin, and A. Zeilinger, New Journal of Physics **16**, 113028 (2014).

[75] M. Krenn, J. Handsteiner, M. Fink, R. Fickler, R. Ursin, M. Malik, and A. Zeilinger, Proceedings of the National Academy of Sciences **113**, 13648 (2016).

[76] R. Ursin, F. Tiefenbacher, T. Schmitt-Manderbach, H. Weier, T. Scheidl, M. Lindenthal, B. Blauensteiner, T. Jennewein, J. Perdigues, P. Trojek, *et al.*, Nature physics **3**, nphys629 (2007). [77] R. Ursin, T. Jennewein, J. Kofler, J. M. Perdigues, L. Cacciapuoti, C. J. de Matos, M. Aspelmeyer, A. Valencia, T. Scheidl, A. Acin, *et al.*, Europhysics News **40**, 26 (2009). [78] X.-S. Ma, T. Herbst, T. Scheidl, D. Wang, S. Kropatschek, W. Naylor, B. Wittmann, A. Mech, J. Kofler, E. Anisimova, *et al.*, Nature **489**, 269 (2012). [79] C. Agnesi, F. Vedovato, M. Schiavon, D. Dequal, L. Calderaro, M. Tomasin, D. G. Marangon, A. Stanco, V. Luceri, G. Bianco, *et al.*, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences **376**, 20170461 (2018).

[80] H. Hauschildt, C. Elia, H. L. Moeller, and D. Schmitt, in *2017 IEEE International Conference on Space Optical Systems and Applications (ICSOS)* (IEEE, 2017) pp. 250–254.

[81] C. Edwards, Communications of the ACM **61**, 12 (2018).

[82] H. Zech, F. Heine, and M. Motzigemba, in *Space Optical Systems and Applications (ICSOS), 2017 IEEE International Conference on* (IEEE, 2017) pp. 193–198.

[83] T. Araki, in *2017 IEEE International Conference on Space Optical Systems and Applications (ICSOS)* (IEEE, 2017) pp. 199–202.

[84] I. Khan, B. Heim, A. Neuzner, and C. Marquardt, Optics and Photonics News **29**, 26 (2018).

[85] B. L. Edwards, K.-J. Schulz, J. Hamkins, B. Robinson, R. Alliss, R. Daddato, C. Schmidt, D. Giggenbach, and L. Bratz, in *IEEE International Conference on Space Optical Systems and Applications (ICSOS)* (2017) pp. 1–9.

[86] S. K. Joshi, J. Pienaar, T. C. Ralph, L. Cacciapuoti, W. McCutcheon, J. Rarity, D. Giggenbach, J. G. Lim, V. Makarov, I. Fuentes, *et al.*, New Journal of Physics **20**, 063016 (2018).

[87] D. K. Oi, A. Ling, G. Vallone, P. Villoresi, S. Greenland, E. Kerr, M. Macdonald, H. Weinfurter, H. Kuiper, E. Charbon, *et al.*, EPJ Quantum Technology **4**, 6 (2017).

[88] R. Bedington, E. Truong-Cao, Y. Tan, C. Cheng, K. Durak, J. Grieve, J. Larsen, D. Oi, and A. Ling, in *Electro-Optical and Infrared Systems: Technology and Applications XII; and Quantum Information Science and Technology*, Vol. 9648 (International Society for Optics and Photonics, 2015) p. 964811.

[89] E. Gibney, Nature **535**, 478 (2016).

[90] M. Toyoshima, in *Frontiers in Optics* (Optical Society of America, 2015) pp. FTh2D–2.

[91] A. Carrasco-Casado, H. Takenaka, D. Kolev, Y. Munemasa, H. Kunimori, K. Suzuki, T. Fuse, T. Kubo-Oka, M. Akioka, Y. Koyama, *et al.*, Acta Astronautica **139**, 377 (2017).

[92] M. Toyoshima, T. Fuse, D. R. Kolev, H. Takenaka, Y. Munemasa, N. Iwakiri, K. Suzuki, Y. Koyama, T. Kubooka, M. Akioka, *et al.*, in *Space Optical Systems and Applications (ICSOS), 2015 IEEE International Conference on* (IEEE, 2015) pp. 1–5.

[93] C. Bonato, A. Tomaello, V. Da Deppo, G. Naletto, and P. Villoresi, New Journal of Physics **11**, 045017 (2009). [94] R. Bedington, J. M. Arrazola, and A. Ling, NPJ Quantum Information **3**, 30 (2017).

[95] T. Jennewein, in *2018 IEEE Photonics Society Summer Topical Meeting Series (SUM)* (IEEE, 2018) pp. 217–218.

[96] T. Schmitt-Manderbach, H. Weier, M. Fu¨rst, R. Ursin, F. Tiefenbacher, T. Scheidl, J. Perdigues, Z. Sodnik, C. Kurtsiefer, J. G. Rarity, *et al.*, Physical Review Letters **98**, 010504 (2007).

[97] R. Kaltenbaek, M. Aspelmeyer, T. Jennewein, C. Brukner, A. Zeilinger, M. Pfennigbauer, and W. R. Leeb, in *Quantum Communications and Quantum Imaging*, Vol. 5161 (International Society for Optics and Photonics, 2004) pp. 252–269.

[98] G. Vallone, V. D?Ambrosio, A. Sponselli, S. Slussarenko, L. Marrucci, F. Sciarrino, and P. Villoresi, Physical review letters **113**, 060503 (2014).

[99] D. Elser, K. Gunthner, I. Khan, B. Stiller, C. Marquardt, G. Leuchs, K. Saucke, D. Trondle, F. Heine, S. Seel, *et al.*, in *Space Optical Systems and Applications (ICSOS), 2015 IEEE International Conference on* (IEEE, 2015) pp. 1–4.

[100] P. Chaiwongkhot, K. B. Kuntz, Y. Zhang, A. Huang, J.-P. Bourgoin, S. Sajeed, N. Lu¨tkenhaus, T. Jennewein, and V. Makarov, arXiv preprint arXiv:1902.01288 (2019).

[101] R. Tannous, *Polarization Entangled Photon Sources for Free-Space Quantum Key Distribution*, Master's thesis, University of Waterloo (2018).

[102] R. J. Hughes and J. E. Nordholt, Nature Photonics **11**, 456 (2017).

[103] H. V. Nguyen, P. V. Trinh, A. T. Pham, Z. Babar, D. Alanis, P. Botsinis, D. Chandra, S. X. Ng, and L. Hanzo, IEEE Access **5**, 12301 (2017).

[104] N. Hosseinidehaj, Z. Babar, R. Malaney, S. X. Ng, and L. Hanzo, IEEE Communications Surveys & Tutorials (2018). [105] T. Jennewein and B. Higgins, Physics World **26**, 52 (2013).

[106] S.-K. Liao, W.-Q. Cai, J. Handsteiner, B. Liu, J. Yin, L. Zhang, D. Rauch, M. Fink, J.-G. Ren, W.-Y. Liu, *et al.*, Physical review letters **120**, 030501 (2018).

[107] J.-G. Ren, P. Xu, H.-L. Yong, L. Zhang, S.-K. Liao, J. Yin, W.-Y. Liu, W.-Q. Cai, M. Yang, L. Li, *et al.*, Nature **549**, 70 (2017).

[108] H. Takenaka, A. Carrasco-Casado, M. Fujiwara, M. Kitamura, M. Sasaki, and M. Toyoshima, Nature photonics **11**, 502 (2017).

[109] T. Schmitt-Manderbach, T. Scheidl, R. Ursin, F. Tiefenbacher, H. Weier, M. Fu¨rst, T. Jennewein, J. Perdigues, Z. Sodnik, J. Rarity, *et al.*, in *International Conference on Space Optics?ICSO 2006*, Vol. 10567 (International Society for Optics and Photonics, 2017) p. 1056728.

[110] M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, Reviews of Modern Physics **86**, 1391 (2014).

[111] K. Hornberger, S. Gerlich, P. Haslinger, S. Nimmrichter, and M. Arndt, Reviews of Modern Physics **84**, 157 (2012). [112] T. Juffmann, H. Ulbricht, and M. Arndt, Reports on Progress in Physics **76**, 086402 (2013).

[113] M. Arndt and K. Hornberger, Nature Physics **10**, 271 (2014).

[114] A. Bassi, K. Lochan, S. Satin, T. P. Singh, and H. Ulbricht, Reviews of Modern Physics **85**, 471 (2013).

[115] L. Hollberg, C. W. Oates, G. Wilpers, C. W. Hoyt, Z. W. Barber, S. A. Diddams, W. H. Oskay, J. C. Bergquist, Optical frequency/wavelength references, J. Phys. B: At. Mol. Opt. Phys. 38 (2005) S469.

[116] E. Batori, N. Almat, C. Aölderbach, G. Mileti, GNSS-grade space atomic frequency standards: Current status and ongoing developments, Advances in Space Research (2020). doi:https://doi.org/10.1016/j.asr.2020.09.012.

[117] S. Falke, N. Lemke, C. Grebing, B. Lipphardt, S. Weyers, V. Gerginov, N. Huntemann, C. Hagemann, A. Al-Masoudi, S. Häfner, S. Vogt, U. Sterr, C. Lisdat, A strontium lattice clock with 3x10^{-17} inaccuracy and its frequency, New Journal of Physics 16 (2014) 073023.

[118] T. Schuldt, K. Döringshoff, A. Milke, J. Sanjuan, M. Gohlke, E. V. Kovalchuk, N. Gürlebeck, A. Peters, C. Braxmaier, High-performance optical frequency references for space, Journal of Physics: Conference Series 723 (2016) 012047.

[119] K. Döringshoff, F. B. Gutsch, V. Schkolnik, C. Kürbis, M. Oswald, B. Pröbster, E. V. Kovalchuk, A. Bawamia, R. Smol, T. Schuldt, M. Lezius, R. Holzwarth, A. Wicht, C. Braxmaier, M. Krutzik, A. Peters, Iodine frequency reference on a sounding rocket, Phys. Rev. Applied 11 (2019) 054068.

[120] J. Sanjuan, K. Abich, M. Gohlke, A. Resch, T. Schuldt, T. Wegehaupt, G. P. Barwood, P. Gill, C. Braxmaier, Long-term stable optical cavity for special relativity tests in space, Opt. Express 27 (2019) 36206-36220.

[121] V. Schkolnik, K. Döringshoff, F. B. Gutsch, M. Oswald, T. Schuldt, C. Braxmaier, M. Lezius, R. Holzwarth, C. Kürbis, A. Bawamia, et al., Jokarus-design of a compact optical iodine frequency reference for a sounding rocket mission, EPJ Quantum Technology 4 (2017) 9.

[122] C. Lämmerzahl, G. Ahlers, N. Ashby, M. Barmatz, P. Biermann, H. Dittus, V. Dohm, R. Duncan, K. Gibble, J. Lipa, et al., Experiments in fundamental physics scheduled and in development for the ISS, General Relativity and Gravitation 36 (2004) 615-649.

[123] A. N. Dinkelaker, M. Schiemangk, V. Schkolnik, A. Kenyon, K. Lampmann, A.Wenzlawski, P.Windpassinger, O. Hellmig, T.Wendrich, E. M. Rasel, et al., Autonomous frequency stabilization of two extended-cavity diode lasers at the potassium wavelength on a sounding rocket, Applied Optics 56 (2017) 1388-1396.

[124] M. Lezius, T. Wilken, C. Deutsch, M. Giunta, O. Mandel, A. Thaller, V. Schkolnik, M. Schiemangk, A. Dinkelaker, A. Kohfeldt, et al., Space-borne frequency comb metrology, Optica 3 (2016) 1381-1387.

[125] S. Herrmann, F. Finke, M. Lülf, O. Kichakova, D. Puetzfeld, D. Knickmann, M. List, B. Rievers, G. Giorgi, C. Günther, H. Dittus, R. Prieto-Cerdeira, F. Dilssner, F. Gonzalez, E. Schönemann, J. Ventura-Traveset, C. Lämmerzahl, Test of the gravitational redshift with galileo satellites in an eccentric orbit, Phys. Rev. Lett. 121 (2018) 231102.

[126] R. Vessot, M. Levine, A test of the equivalence principle using a space-borne clock, General relativity and gravitation 10 (1979) 181-204.

[127] P. Touboul, M. Rodrigues, G. Mffetris, R. Chhun, A. Robert, Q. Baghi, E. Hardy, J. Bergffe, D. Boulanger, B. Christophe, et al., Microscope mission analysis, requirements and expected performance, arXiv preprint arXiv:2012.06472 (2020).

[128] L. Liu, D.-S. Lu�, W.-B. Chen, T. Li, Q.-Z. Qu, B. Wang, L. Li, W. Ren, Z.-R. Dong, J.-B. Zhao, et al., In-orbit operation of an atomic clock based on laser-cooled 87 Rb atoms, Nature Communications 9 (2018) 2760.

[129] NASA activates deep space atomic clock. URL https://www.jpl.nasa.gov/news/nasa-activates-deep-space-atomic-clock.

[130] NASA extends deep space atomic clock mission. URL https://www.jpl.nasa.gov/news/nasa-extends-deep-space-atomic-clock-mission.

[131] A. Gierse, U. Kaczmarczik, A. Greif, H. Selig, P. von Kampen, T. Könemann, C. Lämmerzahl, A fast and self-acting release-caging-mechanism for actively driven drop tower systems, Microgravity Science and Technology 29 (2017) 403-414.

[132] T. Könemann, U. Kaczmarczik, A. Gierse, A. Greif, T. Lutz, S. Mawn, J. Siemer, C. Eigenbrod, P. von Kampen, C. Lämmerzahl, Concept for a next-generation drop tower system, Advances in Space Research 55 (2015) 1728-1733.

[133] HITec, First flight - successful debut launch of the Einstein-elevator, https://www.hitec.uni-hannover.de/en/large-scale-equipment/einstein-elevator/first-flight/.

[134] C. Lotz, Y. Wessarges, J. Hermsdorf, W. Ertmer, L. Overmeyer, Novel active driven drop tower facility for microgravity experiments investigating production technologies on the example of substrate-free additive manufacturing, Advances in Space Research 61 (2018) 1967-1974.

[135] C. Lotz, L. Overmeyer, Mechanische Ersatzmodelle zum Nachweis der Realisierbarkeit minimaler Restbeschleunigungen während der Freifallphase im Einstein-elevator, Logistics Journal 2013 (2013).

[136] C. Lotz, T. Froböse, A. Wanner, L. Overmeyer, W. Ertmer, Einstein-elevator: A new facility for research from 0-g to 5g, Gravitational and Space Research 5 (2017).

[137] T. van Zoest, N. Gaaloul, Y. Singh, H. Ahlers, W. Herr, S. Seidel, W. Ertmer, E. Rasel, M. Eckart, E. Kajari, et al., Bose-Einstein condensation in microgravity, Science 328 (2010) 1540-1543.

[138] H. Müntinga, H. Ahlers, M. Krutzik, A. Wenzlawski, S. Arnold, D. Becker, K. Bongs, H. Dittus, H. Duncker, N. Gaaloul, C. Gherasim, E. Giese, C. Grzeschik, T. W. Hänsch, O. Hellmig, W. Herr, S. Herrmann, E. Kajari, S. Kleinert, C. Lämmerzahl, W. Lewoczko-

Adamczyk, J. Malcolm, N. Meyer, R. Nolte, A. Peters, M. Popp, J. Reichel, A. Roura, J. Rudolph, M. Schiemangk, M. Schneider, S. T. Seidel, K. Sengstock, V. Tamma, T. Valenzuela, A. Vogel, R. Walser, T. Wendrich, P. Windpassinger, W. Zeller, T. van Zoest, W. Ertmer, W. P. Schleich, E. M. Rasel, Interferometry with Bose-Einstein condensates in microgravity, Phys. Rev. Lett. 110 (2013) 093602.

[139] Cover picture: Fortschritte der physik 1 / 2015, Fortschritte der Physik 63 (2015), doi:https://doi.org/10.1002/prop.201570001.

[140] H. Ahlers, H. Müntinga, A. Wenzlawski, M. Krutzik, G. Tackmann, S. Abend, N. Gaaloul, E. Giese, A. Roura, R. Kuhl, C. Lämmerzahl, A. Peters, P. Windpassinger, K. Sengstock, W. P. Schleich, W. Ertmer, E. M. Rasel, Double Bragg interferometry, Phys. Rev. Lett. 116 (2016) 173601.

[141] S. Abend, M. Gebbe, M. Gersemann, H. Ahlers, H. Mu□ntinga, E. Giese, N. Gaaloul, C. Schubert, C. Lämmerzahl, W. Ertmer, W. P. Schleich, E. M. Rasel, Atom-chip fountain gravimeter, Phys. Rev. Lett. 117 (2016) 203003.

[142] M. Gebbe, S. Abend, J.-N. Siem_, M. Gersemann, H. Ahlers, H. M□untinga, S. Herrmann, N. Gaaloul, C. Schubert, K. Hammerer, C. Lämmerzahl, W. Ertmer, E. M. Rasel, Twin-lattice atom interferometry (2019). arXiv:1907.08416.

[143] V. Mffenoret, R. Geiger, G. Stern, P. Cheinet, B. Battelier, N. Zahzam, F. P. Dos Santos, A. Bresson, A. Landragin, P. Bouyer, A transportable cold atom inertial sensor for space applications, in: International Conference on Space Optics: ICSO 2010, Vol. 10565, International Society for Optics and Photonics, 2017, p. 1056530.

[144] N. Gaaloul, H. Ahlers, T. Schulze, Y. Singh, S. Seidel, W. Herr, W. Ertmer, E. Rasel, et al., Quantum tests of the Equivalence Principle with Atom Interferometry, Acta Astronautica 67 (9-10) (2010) 1059-1062.

[145] J. Rudolph, N. Gaaloul, Y. Singh, H. Ahlers, W. Herr, T. A. Schulze, S. T. Seidel, C. Rode, V. Schkolnik, W. Ertmer, et al., Degenerate quantum gases in microgravity, Microgravity Science and Technology 23 (2011) 287-292.

[146] M. Cornelius, C. Lämmerzahl, T. Sternke, S. Herrmann, Quantus-2-a mobile high-flux BEC source in microgravity, in: 42nd COSPAR Scientific Assembly, Vol. 42, 2018.

[147] C. Schubert, S. Abend, M. Gebbe, M. Gersemann, H. Ahlers, H. Müntinga, J. Matthias, M. Sahelgozin, W. Herr, C. Lämmerzahl, et al., Atom chip gravimeter, in: EGU General Assembly Conference Abstracts, Vol. 18, 2016, p. 14817.

[148] N. Gaaloul, W. Ertmer, E. M. Rasel, Q. Collaboration, M. Collaboration, et al., Degenerate gases at the frontiers of matter-wave interferometry, in: APS Meeting Abstracts, 2018.

[149] S. Abend, M. Gebbe, M. Gersemann, E. M. Rasel, Q. Collaboration, et al., Symmetric large momentum transfer for atom interferometry with becs, in: APS Division of Atomic, Molecular and Optical Physics Meeting Abstracts, 2017.

[150] M. Gebbe, S. Abend, M. Gersemann, H. Ahlers, H. Muentinga, S. Herrmann, C. Laemmerzahl, W. Ertmer, E. M. Rasel, Q. Collaboration, et al., Atom-chip-based

interferometry with bose-einstein condensates, in: APS Division of Atomic, Molecular and Optical Physics Meeting Abstracts, 2017.

[151] D. Schlippert, J. Hartwig, H. Albers, L. L. Richardson, C. Schubert, A. Roura, W. P. Schleich, W. Ertmer, E. M. Rasel, Quantum test of the universality of free fall, Physical Review Letters 112 (20) (2014) 203002.

[152] H. Albers, A. Herbst, L. Richardson, H. Heine, D. Nath, J. Hartwig, C. Schubert, C. Vogt, M.Woltmann, C. Lämmerzahl, et al., Quantum test of the universality of free fall using rubidium and potassium, arXiv preprint arXiv:2003.00939 (2020).

[153] S. Kulas, C. Vogt, A. Resch, J. Hartwig, S. Ganske, J. Matthias, D. Schlippert, T. Wendrich, W. Ertmer, E. Maria Rasel, et al., Miniaturized lab system for future cold atom experiments in microgravity, Microgravity Science and Technology 29 (1-2) (2016) 37-48.

[154] W. Ketterle, N. V. Druten, Evaporative cooling of trapped atoms, Vol. 37 of Advances In Atomic, Molecular, and Optical Physics, Academic Press, 1996, pp. 181-236.

[155] C.-L. Hung, X. Zhang, 3495 N. Gemelke, C. Chin, Accelerating evaporative cooling of atoms into bose-einstein condensation in optical traps, Phys. Rev. A 78 (2008) 011604.

[156] C. Vogt, M. Woltmann, S. Herrmann, C. Lämmerzahl, H. Albers, D. Schlippert, E. M. Rasel, et al., Evaporative cooling from an optical dipole trap in microgravity, Physical Review A 101 (2020) 013634.

[157] G. Condon, M. Rabault, B. Barrett, L. Chichet, R. Arguel, H. Eneriz-Imaz, D. Naik, A. Bertoldi, B. Battelier, P. Bouyer, A. Landragin, All-optical bose-einstein condensates in microgravity, Phys. Rev. Lett. 123 (2019) 240402.

[158] M. D. Lachmann, H. Ahlers, D. Becker, A. N. Dinkelaker, J. Grosse, O. Hellmig, H. Müntinga, V. Schkolnik, S. T. Seidel, T. Wendrich, et al., Ultracold atom interferometry in space, Nature Communications 12 (2021) 1-6.

[159] G. Stern, B. Battelier, R. Geiger, G. Varoquaux, A. Villing, F. Moron, O. Carraz, N. Zahzam, Y. Bidel, W. Chaibi, et al., Light-pulse atom interferometry in microgravity, The European Physical Journal D 53 (3) (2009) 353-357.

[160] R. Geiger, V. M_enoret, G. Stern, N. Zahzam, P. Cheinet, B. Battelier, A. Villing, F. Moron, M. Lours, Y. Bidel, et al., Detecting inertial effects with airborne matter-wave interferometry, Nature communications 2 (2011) 1-7.

[161] B. Battelier, B. Barrett, L. Fouch_e, L. Chichet, L. Antoni-Micollier, H. Porte, F. Napolitano, J. Lautier, A. Landragin, P. Bouyer, Development of compact cold-atom sensors for inertial navigation, Quantum Optics (2016).

[162] B. Barrett, L. Antoni-Micollier, L. Chichet, B. Battelier, T. Lfevfeque, A. Landragin, P. Bouyer, Dual matter-wave inertial sensors in weightlessness, Nature Communications 7 (2016).

[163] L. Antoni-Micollier, B. Barrett, L. Chichet, G. Condon, B. Battelier, A. Landragin, P. Bouyer, Generation of high-purity low-temperature samples of 39K for applications in metrology, Phys. Rev. A 96 (2017) 023608.

[164] Y. Bidel, N. Zahzam, C. Blanchard, A. Bonnin, M. Cadoret, A. Bresson, D. Rouxel, M. Lequentrec-Lalancette, Absolute marine gravimetry with matter-wave interferometry, Nature communications 9 (2018) 1-9.

[165] Y. Bidel, N. Zahzam, A. Bresson, C. Blanchard, M. Cadoret, A. V. Olesen, R. Forsberg, Absolute airborne gravimetry with a cold atom sensor, Journal of Geodesy 94 (2020) 20.

[166] D. Becker, M. D. Lachmann, S. T. Seidel, H. Ahlers, A. N. Dinkelaker, J. Grosse, O. Hellmig, H. Müntinga, V. Schkolnik, T. Wendrich, et al., Space-borne Bose-Einstein condensation for precision interferometry, Nature 562 (7727) (2018) 391.

[167] R. Corgier, S. Amri, W. Herr, H. Ahlers, J. Rudolph, D. Gu_ery-Odelin, E. M. Rasel, E. Charron, N. Gaaloul, Fast manipulation of bose-einstein condensates with an atom chip, New Journal of Physics 20 (2018) 055002.

[168] M. Meister, A. Roura, E. M. Rasel, W. P. Schleich, The space atom laser: An isotropic source for ultra-cold atoms in microgravity, arXiv preprint arXiv:1807.09817 (2018).

[169] D. C. Aveline, J. R. Williams, E. R. Elliott, C. Dutenhoffer, J. R. Kellogg, J. M. Kohel, N. E. Lay, K. Oudrhiri, R. F. Shotwell, N. Yu, et al., Observation of Bose-Einstein condensates in an earth-orbiting research lab, Nature 582 (2020) 193-197.

[170] J. Williams, J. D'Incao, Opportunities for maturing precision metrology with ultracold gas studies aboard the iss, in: APS Division of Atomic, Molecular and Optical Physics Meeting Abstracts, 2017.

[171] R. Hughes, W. Buttler, P. Kwiat, S. Lamoreaux, G. Luther, G. Morgan, J. Nordholt, C. Peterson, Quantum cryptography for secure free-space communications, Proc SPIE 3615 (1999) 98-103, and C. Kurtsiefer, P. Zarda, M. Halder, H. Weinfurter, P. Gorman, P. Tapster, J. Rarity, A step towards global key distribution, Nature 419 (2002) 450-450.

[172] M. Aspelmeyer, T. Jennewein, M. Pfennigbauer, W. R. Leeb, A. Zeilinger, Long-distance quantum communication with entangled photons using satellites, IEEE Journal of Selected Topics in Quantum Electronics 9 (2003) 1541-1551.

[173] J. Rarity, P. Tapster, P. Gorman, P. Knight, Ground to satellite secure key exchange using quantum cryptography, New Journal of Physics 4 (2002) 82.

[174] R. Ursin, F. Tiefenbacher, T. Schmitt-Manderbach, H. Weier, T. Scheidl, M. Lindenthal, B. Blauensteiner, T. Jennewein, J. Perdigues, P. Trojek, et al., Entanglement-based quantum communication over 144 km, Nature Physics 3 (2007) 481-486.

[175] T. Schmitt-Manderbach, H.Weier, M. F▯urst, R. Ursin, F. Tiefenbacher, T. Scheidl, J. Perdigues, Z. Sodnik, C. Kurtsiefer, J. G. Rarity, et al., Experimental demonstration of free-space decoy-state quantum key distribution over 144 km, Physical Review Letters 98 (2007) 010504.

[176] G. Vallone, D. Bacco, D. Dequal, S. Gaiarin, V. Luceri, G. Bianco, P. Villoresi, Experimental satellite quantum communications, Physical Review Letters 115 (2015) 040502.

[177] P. Villoresi, T. Jennewein, F. Tamburini, M. Aspelmeyer, C. Bonato, R. Ursin, C. Pernechele, V. Luceri, G. Bianco, A. Zeilinger, et al., Experimental veri_cation of the feasibility of a quantum channel between space and earth, New Journal of Physics 10 (2008) 033038.

[178] D. Dequal, G. Vallone, D. Bacco, S. Gaiarin, V. Luceri, G. Bianco, P. Villoresi, Experimental single photon exchange along a space link of 7000 km, Physical Review A 93 (2016) 1-5.

[179] L. Calderaro, C. Agnesi, D. Dequal, F. Vedovato, M. Schiavon, A. Santamato, V. Luceri, G. Bianco, G. Vallone, P. Villoresi, Towards quantum communication from global navigation satellite system, Quantum Science and Technology 4 (2018) 015012.

[180] J. Yin, Y. Cao, Y.-H. Li, S.-K. Liao, L. Zhang, J.-G. Ren, W.-Q. Cai, W.-Y. Liu, B. Li, H. Dai, et al., Satellite-based entanglement distribution over 1200 kilometers, Science 356 (2017) 1140-1144.

[181] S.-K. Liao, W.-Q. Cai, W.-Y. Liu, L. Zhang, Y. Li, J.-G. Ren, J. Yin, Q. Shen, Y. Cao, Z.-P. Li, et al., Satellite-to-ground quantum key distribution, Nature 549 (2017) 43.

[182] J.-G. Ren, P. Xu, H.-L. Yong, L. Zhang, S.-K. Liao, J. Yin, W.-Y. Liu, W.-Q. Cai, M. Yang, L. Li, et al., Ground-to-satellite quantum teleportation, Nature 549 (2017) 70.

[183] Y.-A. Chen, Q. Zhang, T.-Y. Chen, W.-Q. Cai, S.-K. Liao, J. Zhang, K. Chen, J. Yin, J.-G. Ren, Z. Chen, et al., An integrated space-to-ground quantum communication network over 4,600 kilometres, Nature 589 (2021) 214-219.

[184] Z. Tang, R. Chandrasekara, Y. C. Tan, C. Cheng, L. Sha, G. C. Hiang, D. K. Oi, A. Ling, Generation and analysis of correlated pairs of photons aboard a nanosatellite, Physical Review Applied 5 (2016) 054022.

[185] A. Villar, A. Lohrmann, X. Bai, T. Vergoossen, R. Bedington, C. Perumangatt, H. Y. Lim, T. Islam, A. Reezwana, Z. Tang, et al., Entanglement demonstration on board a nano-satellite, Optica 7 (2020) 734-737.

[186] J. S. Sidhu, S. K. Joshi, M. Gundogan, T. Brougham, D. Lowndes, L. Mazzarella, M. Krutzik, S. Mohapatra, D. Dequal, G. Vallone, P. Villoresi, A. Ling, T. Jennewein, M. Mohageg, J. Rarity, I. Fuentes, S. Pirandola, D. K. L. Oi, Advances in space quantum communications (2021). arXiv:2103.12749.

[187] R. Bedington, J. M. Arrazola, A. Ling, Progress in satellite quantum key distribution, npj Quantum Information 3 (2017) 1-13.

[188] O. Lee, T. Vergoossen, A. Ling, An updated analysis of satellite quantum-key distribution missions, arXiv preprint arXiv:1909.13061 (2019).

[189] A. D. O'Connell, M. Hofheinz, M. Ansmann, R. C. Bialczak, M. Lenander, E. Lucero, M. Neeley, D. Sank, H. Wang, M. Weides, J. Wenner, J. M. Martinis, A. N. Cleland, Quantum ground state and single-phonon control of a mechanical resonator 464 (2010) 697-703.

[190] M. Aspelmeyer, T. J. Kippenberg, F. Marquardt, Cavity optomechanics, Reviews of Modern Physics 86 (4) (2014) 1391.

[191] J. D. Teufel, T. Donner, D. Li, J. W. Harlow, M. S. Allman, K. Cicak, A. J. Sirois, J. D. Whittaker, K. W. Lehnert, R. W. Simmonds, Sideband cooling of micromechanical motion to the quantum ground state, Nature 475 (2011) 3675 359-363.

[192] J. Chan, T. P. M. Alegre, A. H. Safavi-Naeini, J. T. Hill, A. Krause, S. Groblacher, M. Aspelmeyer, O. Painter, Laser cooling of a nanomechanical oscillator into its quantum ground state, Nature 478 (2011) 89-92.

[193] R. W. Peterson, T. P. Purdy, N. S. Kampel, R. W. Andrews, P.-L. Yu, K. W. Lehnert, C. A. Regal, Laser Cooling of a Micromechanical Membrane to the Quantum Backaction Limit, Phys. Rev. Lett. 116 (6) (2016) 063601.

[194] A. Schliesser, T. J. Kippenberg, Cavity Optomechanics with Whispering-Gallery-Mode Microresonators, Springer Berlin Heidelberg 2014, pp. 121-148.

[195] A. Schliesser, R. Riviere, G. Anetsberger, O. Arcizet, T. J. Kippenberg, Resolved-sideband cooling of a micromechanical oscillator, Nature Physics 4 (2008) 415-419.

[196] J. B. Clark, F. Lecocq, R. W. Simmonds, J. Aumentado, J. D. Teufel, Sideband cooling beyond the quantum backaction limit with squeezed light, Nature 541 (7636) (2017) 191-195.

[197] M. Rossi, D. Mason, J. Chen, Y. Tsaturyan, A. Schliesser, Measurement-based quantum control of mechanical motion, Nature 563 (2018) 53-58.

[198] J. Millen, T. S. Monteiro, R. Pettit, A. N. Vamivakas, Optomechanics with levitated particles 83 (2020) 026401.

[199] A. B. Matsko, S. P. Vyatchanin, L. Yi, On mechanical motion damping of a magnetically trapped diamagnetic particle, Physics Letters A 384 (26) (2020) 126643.

[200] U. Delic, M. Reisenbauer, K. Dare, D. Grass, V. Vuletic, N. Kiesel, M. Aspelmeyer, Cooling of a levitated nanoparticle to the motional quantum ground state, Science 367 (2020) 892-895.

[201] F. Tebbenjohanns, M. Frimmer, V. Jain, D. Windey, L. Novotny, Motional sideband asymmetry of a nanoparticle optically levitated in free space, Physical Review Letters 124 (1) (2020) 013603.

[202] H. Ritsch, P. Domokos, F. Brennecke, T. Esslinger, Cold atoms in cavity-generated dynamical optical potentials, Reviews of Modern Physics 85 (2013) 553.

[203] D. Windey, C. Gonzalez-Ballestero, P. Maurer, L. Novotny, O. Romero-Isart, R. Reimann, Cavity-based 3d cooling of a levitated nanoparticle via coherent scattering, Physical review letters 122 (2019) 123601.

[204] V. Vuletic, S. Chu, Laser cooling of atoms, ions, or molecules by coherent scattering, Physical Review Letters 84 (2000) 3787.

[205] U. Delic, D. Grass, M. Reisenbauer, T. Damm, M. Weitz, N. Kiesel, M. Aspelmeyer, Levitated cavity optomechanics in high vacuum, Quantum Science and Technology 5 (2020) 025006.

[206] U. Delic, Cavity cooling by coherent scattering of a levitated nanosphere in vacuum, Ph.D. thesis, Uni Wien (2019).

[207] L. Magrini, P. Rosenzweig, C. Bach, A. Deutschmann-Olek, S. G. Hofer, S. Hong, N. Kiesel, A. Kugi, M. Aspelmeyer, Optimal quantum control of mechanical motion at room temperature: ground-state cooling, arXiv preprint arXiv:2012.15188 (2020).

[207] H. Kwakernaak, R. Sivan, Linear optimal control systems, Wiley Interscience, New York, 1972.

[208] L. Bouten, R. V. Handel, ON THE SEPARATION PRINCIPLE IN QUANTUM CONTROL, in: Quantum Stochastics and Information, WORLD SCIENTIFIC, University of Nottingham, UK, 2008, pp. 206{238.

[209] T. Voirin, M. Bandecchi, P. Falkner, A. Pickering, CDF study report (QPPF), Assessment of a quantum physics payload platform, European Space Agency: http://sci.esa.int/future-missions-department/61074-cdf-study-report-qppf/ CDF-183(C) (2019).

[210] R. Kaltenbaek, G. Hechenblaikner, N. Kiesel, O. Romero-Isart, K. C. Schwab, U. Johann, M. Aspelmeyer, Macroscopic quantum resonators (MAQRO), Experimental Astronomy 34 (2) (2012) 123-164.

[211] R. Kaltenbaek, Testing quantum physics in space using high-mass matter-wave interferometry, arXiv preprintarXiv:1508.07796 (2015).

[212] R. Kaltenbaek, 2980 G. Hechenblaikner, N. Kiesel, U. Johann, M. Aspelmeyer, Maqro-testing the foundations of quantum physics in space, in: APS Division of Atomic, Molecular and Optical Physics Meeting Abstracts, 2013.

[213] G. Hechenblaikner, F. Hufgard, J. Burkhardt, N. Kiesel, U. Johann, M. Aspelmeyer, R. Kaltenbaek, How cold can you get in space? Quantum physics at cryogenic temperatures in space, New Journal of Physics 16 (1) (2014) 013058.

[214] A. P. Zanoni, J. Burkhardt, U. Johann, M. Aspelmeyer, R. Kaltenbaek, G. Hechenblaikner, Thermal performance of a radiatively cooled system for quantum optomechanical experiments in space, Applied Thermal Engineering 107 (2016) 689-699.

[215] R. Kaltenbaek, Maqro: Testing quantum physics in space, in: 40th COSPAR Scienti_c Assembly, Vol. 40, 2014.

[216] R. Kaltenbaek, M. Aspelmeyer, P. F. Barker, A. Bassi, J. Bateman, K. Bongs, S. Bose, C. Braxmaier, C. Brukner, B. Christophe, et al., Macroscopic quantum resonators (MAQRO): 2015 update, EPJ Quantum Technology 3 (1) (2016) 5.

[217] R. Kaltenbaek, Testing quantum physics in space using optically trapped nanospheres, in: Optical Trapping and Optical Micromanipulation X, Vol. 8810, International Society for Optics and Photonics, 2013, p. 88100B.

[218] R. Kaltenbaek, P. Schmid, U. Sezer, J. Horak, M. Aspelmeyer, M. Arndt, E. Wille, Final report the work described in this report was done under esa contract. responsibility for the contents resides in the author or organisation that prepared it. (2013).

[219] R. Kaltenbaek, M. Aspelmeyer, Optomechanical Schrnödinger cats - a case for space, arXiv preprint arXiv:1502.02876 (2015).

[220] R. Kaltenbaek, Towards testing quantum physics in deep space, in: 41st COSPAR Scienti_c Assembly, Vol. 41, 2016.

[221] R. Kaltenbaek, Concepts and technology development towards a platform for macroscopic quantum experiments in space, in: APS Meeting Abstracts, 2017.

[222] A. Resnick, Design and construction of a space-borne optical tweezer apparatus, Review of Scientific Instruments 72 (2001) 4059-4065.

[223] M. Armano, H. Audley, G. Auger, J. Baird, P. Binetruy, M. Born, D. Bortoluzzi, N. Brandt, A. Bursi, M. Caleno, et al., Charge-induced force noise on free-falling test masses: results from LISA pathfinder, Physical review letters 118 (2017) 171101.

[224] M. Armano, H. Audley, J. Baird, P. Binetruy, M. Born, D. Bortoluzzi, N. Brandt, E. Castelli, A. Cavalleri, A. Cesarini, et al., Sensor noise in lisa pathfinder: In-flight performance of the optical test mass readout, Physical Review Letters 126 (2021) 131103.

[225] B. Schläppi, K. Altwegg, H. Balsiger, M. Hässig, A. Jäckel, P. Wurz, B. Fiethe, M. Rubin, S. Fuselier, J.-J. Berthelier, et al., Influence of spacecraft outgassing on the exploration of tenuous atmospheres with in situ mass spectrometry, Journal of Geophysical Research: Space Physics 115 (A12) (2010).

[226] M. Armano, H. Audley, J. Baird, P. Binetruy, M. Born, D. Bortoluzzi, E. Castelli, A. Cavalleri, A. Cesarini, A. Cruise, et al., Beyond the required LISA free-fall performance: new LISA pathfinder results down to 20 mHz, Physical review letters 120 (2018) 061101.

[227] M. Armano, H. Audley, J. Baird, P. Binetruy, M. Born, D. Bortoluzzi, E. Castelli, A. Cavalleri, A. Cesarini, A. Cruise, et al., LISA pathfinder platform stability and drag-free performance, Physical review D 99 (2019) 082001.

[228] M. DiPirro, The superfluid helium on-orbit transfer (shoot) flight demonstration, in: Cryostat Design, Springer, 2016, pp. 95-116.

[229] L. Duband, Space cryocooler developments, Physics Procedia 67 (2015) 1-10.

[230] P. D. D. Schwindt, Y.-Y. Jau, H. Partner, A. Casias, A. R. Wagner, M. Moorman, R. P. Manginell, J. R. Kellogg, J. D. Prestage, A highly miniaturized vacuum package for a trapped ion atomic clock, Review of Scientific Instruments 87 (2016) 053112.

[231] G. Birkl, J. Fort_agh, Micro traps for quantum information processing and precision force sensing, Laser & Photonics Reviews 1 (2007) 12-23.

[232] P. Redhead, Extreme high vacuum, Tech. Rep., CERN (1999).

[233] N. Yoshimura, Vacuum technology: practice for scientific instruments, Springer Science & Business Media, 2007.

[234] R. Boudot, J. P. McGilligan, K. R. Moore, V. Maurice, G. D. Martinez, A. Hansen, E. de Clercq, J. Kitching, Enhanced observation time of magneto-optical traps using micro-machined non-evaporable getter pumps, Scientific Reports 10 (2020) 1-8.

[235] J. A. Rushton, M. Aldous, M. D. Himsworth, Contributed Review: The feasibility of a fully miniaturized magnetooptical trap for portable ultracold quantum technology, Review of Scientific Instruments 85 (2014) 121501.

[236] G. Gabrielse, X. Fei, L. Orozco, R. Tjoelker, J. Haas, H. Kalinowsky, T. Trainor, W. Kells, Thousandfold improvement in the measured antiproton mass, Physical review letters 65 (1990) 1317.

[237] Y. Lu, Q. Shao, H. Yue, F. Yang, A review of the space environment effects on spacecraft in different orbits, IEEE Access 7 (2019) 93473-93488.

[238] D. McKnight, Examination of spacecraft anomalies provides insight into complex space environment, Acta Astronautica 158 (2019) 172-177.

[239] D. Schmoranzer, A. Luck, E. Collin, A. Fefferman, Cryogenic broadband vibration measurement on a cryogen-free dilution refrigerator, Cryogenics 98 (2019) 102-106.

[240] J. W. Vorreiter, Cryogenic systems for spacecraft, Contemporary Physics 21 (1980) 201-217.

[241] S. Kim, H. Yu, S. Gang, J. Kim, Matter-wave beam splitter on an atom chip for a portable atom interferometer, Applied Physics B 123 (2017) 154.

[242] E. Batori, N. Almat, C. A_olderbach, G. Mileti, GNSS-grade space atomic frequency standards: Current status and ongoing developments, Advances in Space Research (2020).

[243] M. Rinaldi, F. Cecchini, L. Pigliaru, T. Ghidini, F. Lumaca, F. Nanni, Additive manufacturing of polyether ether ketone (peek) for space applications: A nanosat polymeric structure, Polymers 13 (2021) 11.

[244] S. Alt, Photonic integrated circuit (pic) device structures: Background, fabrication ecosystem, relevance to space systems applications, and discussion of related radiation effects (2016).

[245] H. Zhao, S. Pinna, B. Song, L. Megalini, S. T. S. Brunelli, L. A. Coldren, J. Klamkin, Indium phosphide photonic integrated circuits for free space optical links, IEEE Journal of Selected Topics in Quantum Electronics 24 (2018) 1-6.

[246] A. Leger, T. Herbst, Darwin mission proposal to ESA, arXiv:0707.3385 [astro-ph] (08 2007).

[247] J. Millen, P. Fonseca, T. Mavrogordatos, T. Monteiro, P. Barker, Cavity cooling a single charged levitated nanosphere, Physical Review Letters 114 (2015) 123602.

[248] C. Cheng, R. Chandrasekara, Y. C. Tan, A. Ling, Space-qualified nanosatellite electronics platform for photon pair experiments, Journal of Lightwave Technology 33 (2015) 4799-4804.

[249] A. Bawamia, C. Kuerbis, R. Smol, A. Wicht, Semiconductor laser modules for precision spectroscopy applications in space, in: International Conference on Space Optics: ICSO 2018, Vol. 11180, International Society for Optics and Photonics, 2019, 111805C.

[250] M. Gregory, F. Heine, H. Kämpfner, R. Meyer, R. Fields, C. Lunde, TESAT laser communication terminal performance results on 5.6 GBit coherent inter satellite and satellite to ground links, in: International Conference on Space Optics: ICSO 2010, Vol. 10565, International Society for Optics and Photonics, 2017, p. 105651F.

[251] M. N. Ott, C. H. Parvini, H. L. Jakeman, W. J. Thomes, E. E. Onuma, Space-flight LIDARs, navigation, and science instrument implementations: lasers, optoelectronics, integrated photonics, fiber optic subsystems, and components, in:

Photonic Instrumentation Engineering VII, Vol. 11287, International Society for Optics and Photonics, 2020, p. 112870I.

[252] G. Laferranderie, S. Marchisio, E. C. for Space Law, The Astronauts and Rescue Agreement: Lessons Learned, European Centre for Space Law, 2011. URL https://books.google.co.uk/books?id=O4lcuAAACAAJ

[253] ESCC, European preferred parts list (2020). URL https://escies.org/webdocument/showArticle?id=166

[254] L. Cacciapuoti, C. Salomon, Space clocks and fundamental tests: The aces experiment, The European Physical Journal Special Topics 172 (2009) 57-68.

[255] M. Augelli, Aces operations: an ISS external scientific payload looking for experimental confirmations on the general relativity theory, in: 14th International Conference on Space Operations, 2016, p. 2407.

[256] F. Meynadier, P. Delva, C. le Poncin-La_tte, C. Guerlin, P. Wolf, Atomic clock ensemble in space (aces) data analysis, Classical and Quantum Gravity 35 (2018) 035018.

[257] DLR, Compasso, URL https://www.dlr.de/gk/en/desktopdefault.aspx/tabid-14174/24592_read-59743/

[258] N. Gürlebeck, L. Woerner, T. Schuldt, K. Doringsho, K. Gaul, D. Gerardi, A. Grenzebach, N. Jha, E. Kovalchuk, A. Resch, et al., Boost: A satellite mission to test Lorentz invariance using high-performance optical frequency references, Physical Review D 97 (12) (2018) 124051.

[259] M. E. Tobar, P. Wolf, S. Bize, G. Santarelli, V. Flambaum, Testing local Lorentz and position invariance and variation of fundamental constants by searching the derivative of the comparison frequency between a cryogenic sapphire oscillator and hydrogen MASER, Phys. Rev. D 81 (2010) 022003.

[260] S. Schiller, G. Tino, P. Lemonde, U. Sterr, C. Lisdat, A. Görlitz, N. Poli, A. Nevsky, C. Salomon, The space optical clocks project, in: International Conference on Space Optics: ICSO 2010, Vol. 10565, International Society for Optics and Photonics, 2017, p. 1056531.

[261] P. Hamilton, M. Jaffe, P. Haslinger, Q. Simmons, H. Müller, J. Khoury, Atom-interferometry constraints on dark energy, Science 349 (2015) 849-851.

[262] S.-W. Chiow, N. Yu, Multi-loop atom interferometer measurements of chameleon dark energy in microgravity, Physical Review D 97 (2018) 044043.

[263] M. D. Lachmann, H. Ahlers, D. Becker, A. N. Dinkelaker, J. Grosse, O. Hellmig, H. Müntinga, V. Schkolnik, S. T. Seidel, T. Wendrich, et al., Ultracold atom interferometry in space, Nature Communications 12 (2021) 1-6.

[264] M. Elsen, J. Grosse, E. Rasel, C. Braxmaier, T. MAIUS, The pathway to launch the maius-2/3 payload on a sounding rocket (2019).

[265] S. Seidel, M. Lachmann, D. Becker, J. Grosse, M. Popp, J. Wang, T. Wendrich, E. Rasel, Q. Collaboration, et al., Atom interferometry on sounding rockets, in: 22nd ESA Symposium on European Rocket and Balloon Programmes and Related Research, Vol. 730, 2015, p. 309.

[266] J. Grosse, S. Seidel, M. Krutzik, T. Wendrich, A. Stamminger, M. Scharringhausen, Q. Consortium, et al., Mechanical and thermal design and qualification of an atom interferometer sounding rocket payload, in: 22nd ESA Symposium on European Rocket and Balloon Programmes and Related Research, Vol. 730, 2015, p. 301.

[267] M. Lachmann, H. Ahlers, D. Becker, S. Seidel, T. Wendrich, E. M. Rasel, W. Ertmer, Creating the first Bose-Einstein condensate in space, in: Complex Light and Optical Forces XII, Vol. 10549, International Society for Optics and Photonics, 2018, p. 1054909.

[268] M. Christ, A. Peters, M. Krutzik, Towards compact optical quantum technology for space environments, in: The European Conference on Lasers and Electro-Optics, Optical Society of America, 2017, p. CH P 30.

[269] J. Rudolph, W. Herr, C. Grzeschik, T. Sternke, A. Grote, M. Popp, D. Becker, H. Müntinga, H. Ahlers, A. Peters, et al., A high-flux BEC source for mobile atom interferometers, New Journal of Physics 17 (6) (2015) 065001.

[270] C. Spindeldreier, T. Wendrich, E. M. Rasel, W. Ertmer, H. Blume, Fpga-based frequency estimation of a DFB laser using Rb spectroscopy for space missions, in: Application-speci_c Systems, Architectures and Processors (ASAP), 2016 IEEE 27th International Conference on, IEEE, (2016) 207-212.

[271] K. Frye, S. Abend, W. Bartosch, A. Bawamia, D. Becker, H. Blume, C. Braxmaier, S.-W. Chiow, M. A. Efremov, W. Ertmer, et al., The bose-einstein condensate and cold atom laboratory, EPJ Quantum Technology 8 (2021) 1-38.

[272] D. Devani, S. Maddox, R. Renshaw, N. Cox, H. Sweeney, T. Cross, M. Holynski, R. Nolli, J. Winch, K. Bongs, et al., Gravity sensing: cold atom trap onboard a 6u cubesat, CEAS Space Journal 12 (4) (2020) 539-549.

[273] J. S. Sidhu, S. K. Joshi, M. Gundogan, T. Brougham, D. Lowndes, L. Mazzarella, M. Krutzik, S. Mohapatra, D. Dequal, G. Vallone, P. Villoresi, A. Ling, T. Jennewein, M. Mohageg, J. Rarity, I. Fuentes, S. Pirandola, D. K. L. Oi, Advances in space quantum communications (2021). arXiv:2103.12749.

[274] R. Bedington, J. M. Arrazola, A. Ling, Progress in satellite quantum key distribution, npj Quantum Information 3 (2017) 1-13.

[275] O. Lee, T. Vergoossen, A. Ling, An updated analysis of satellite quantum-key distribution missions, arXiv preprint arXiv:1909.13061 (2019).

[276] M. Mohageg, D. Strekalov, S. Dolinar, M. Shaw, N. Yu, Deep space quantum link, LPICo 2063 (2018) 3039.

[277] S. Wehner, D. Elkouss, R. Hanson, Quantum internet: A vision for the road ahead, Science 362 (6412) (2018).

[278] D. Castelvecchi, The quantum internet has arrived (and it hasn't), Nature 554 (2018) 289-292.

[279] J. F. Dynes, A. Wonfor, W. W. S. Tam, A. W. Sharpe, R. Takahashi, M. Lucamarini, A. Plews, Z. L. Yuan, A. R. Dixon, J. Cho, et al., Cambridge quantum network, NPJ Quantum Inf. 5 (2019) 101.

[280] Q. Zhang, F. Xu, L. Li, N.-L. Liu, J.-W. Pan, Quantum information research in China, Quantum Science and Technology 4 (2019) 040503.

[281] S. K. Joshi, D. Aktas, S. Wengerowsky, M. Lonfcarifc, S. P. Neumann, B. Liu, T. Scheidl, G. C. Lorenzo, Z. Samec, L. Kling, et al., A trusted node-free eight-user metropolitan quantum communication network, Science Advances 6 (2020) 0959.

[282] NIST, Fips pub 140-3: Security requirements for cryptographic modules, https://doi.org/10.6028/NIST.FIPS.140-3

[283] T. Jennewein, J. Bourgoin, B. Higgins, C. Holloway, E. Meyer-Scott, C. Erven, B. Heim, Z. Yan, H. Hübel, G. Weihs, et al., QEYSSAT: a mission proposal for a quantum receiver in space, in: Advances in photonics of quantum computing, memory, and communication VII, Vol. 8997, International Society for Optics and Photonics, 2014, p. 89970A.

[284] W. Stöber, A. Fink, E. Bohn, Controlled growth of monodisperse silica spheres in the micron size range, Journal of Colloid and Interface Science 26 (1968) 62-69.

[285] D. Levy, M. Zayat (Eds.), The Sol-Gel handbook: synthesis, characterization, and applications, Wiley-VCH, Weinheim, 2015.

[286] S. Kuhn, P. Asenbaum, A. Koslo_, M. Sclafani, B. A. Stickler, S. Nimmrichter, K. Hornberger, O. Cheshnovsky, F. Patolsky, M. Arndt, Cavity-Assisted Manipulation of Freely Rotating Silicon Nanorods in High Vacuum, Nano Letters 15 (2015) 5604-5608.

[287] D. Aveline, E. Elliott, J. Williams, R. Thompson, NASA's Cold atom Laboratory (CAL): system integration and ground tests, Bulletin of the American Physical Society (2018).