DELIVERABLE 3.2

List of state of the art of technology in space

COST Action:	**CA15220**
Project acronym:	**QTSpace**
Project title:	**Quantum Technologies in Space**
Funding scheme:	**COST Association**
Start date of project:	**20 October 2016**
End date of project:	**19 April 2021**
Due date of the Deliverable:	**October 2018**
Deliverable issued:	**October 2018**
Dissemination Level:	**Public**
Version:	**2.0**

TABLE OF CONTENT

INTRODUCTION

In report on Deliverable 3.1, we highlighted that quantum technologies in space offer a vast panorama of uses ranging from fundamental-physics tests to technological applications. Thereby, quantum technologies in space can advance our knowledge in fundamental physics, by bridging the gap between relativistic physics and quantum physics. They can be enabling technologies, like deep space communication, allowing mankind to explore the solar system and beyond. In addition, they are attractive for commercial purposes, with satellite-based quantum key distribution and sensing with atom interferometry being a prominent example.

Here, we shine light on different examples of missions serving these purposes. These are proof-of-principle experiments in micro-gravity environments and implementations of the ideas reviewed in D3.1. We classify these experiments again corresponding to the physical platforms of cold atoms, photons, and optomechanical systems, which they are based on.

IMPLEMENTATION

1. Atomic Systems In Space

a. Atomic clocks in space

An implementation of quantum technologies in space is atom-based clocks. These are atomic and optical clocks, which provide increased accuracy and precision as frequency and time references and are nowadays the reference in modern time keeping systems. In conventional systems, primarily radio frequency-based references have been employed. As such, the current Galileo system is based on different such references. Optical systems, based on atomic transitions or fixed lengths, promise higher accuracy and precision [115,116].

Atomic clocks with hot atoms are widespread and offer compact and robust setups. As the system depends on the width of atomic lines, their accuracy and precision can be improved by reducing internal and external temperatures. Another improvement to atomic clocks is based on atom fountains, which increase the interrogation time for the atoms. Optical clocks, which are atom-based clocks with transition energies at optical frequencies, promise even higher precision. Hence, different concepts of generating a stable frequency reference exist [115,116]. Some optical systems exploit atomic, e.g. Ref. [117], or molecular transitions [118,119], while others rely on fixed distances [120]. Ground-based systems can make use of controlled environments, such as operating at cryogenic temperatures, or large volumes to generate the desired frequency stability. In space-based systems budgets are limited and the system needs to operate reliably without interference [121,122,123]. Consequently, several missions are deployed to test concepts. While atomic clocks might have more stringent demands in space, the microgravity environment can also improve performances. In addition to dedicated scientific missions, commercial systems have been used to measure fundamental principles.

The report on Deliverable 3.3 will be dedicated to outline a couple of those atomic clock missions in more detail to analyze the realistic time schedule for outstanding challenges.

Scientific Experiments: Scientific missions revolve around measuring the gravitational redshift caused by Earth and Sun, and probing special relativity. In addition, these systems aim at enabling next generation gravity missions and future global navigation satellite systems. Furthermore, clocks are necessary performing high precision experiments in space, such as the gravitational waves antenna LISA. These aims and goals are similar for all the scientific missions surrounding optical frequency references, either ongoing or planned, and that are reported in the following [122].

Sounding Rocket Missions: A first step towards optical clock operation in space is by sounding rocket missions. Here, three of the major developments in recent years are listed:

- **KALEXUS** (Kalium Laser-Experimente unter Schwerelosigkeit; English translation: Potassium Laser Experiment under Microgravity): Within the KALEXUS mission, two extended cavity diode lasers alongside an optical preparation stage were launched on a sounding rocket mission. With this mission the technological readiness of the Potassium laser system, automatic frequency stabilization of the lasers, and the switching between redundant systems during flight was demonstrated in 2016 [123].

- **FOKUS** (Faserlaserbasierter Optischer Kammgenerator unter Schwerelosigkeit; English translation: Optical Frequency Comb Metrology Under Microgravity): Within FOKUS, the technological readiness of optical frequency combs for deployment in space was demonstrated. For this purpose, a frequency comb alongside a diode laser and an optical preparation stage were mounted to a sounding rocked and launched into space in 2015 [124].

- **JOKARUS** (Jod-Kammresonator unter Schwerelosigkeit; English translation: Iodine, Comb, and Resonator Under Microgravity) Within the JOKARUS mission, a Iodine frequency reference, an optical frequency comb, and the optical and electrical preparation stages were launched to space on board of a sounding rocket at the end of 2017. This campaign served to demonstrate the miniaturization and deployment of key technologies in space [119,121]

Space-based Platforms: A prominent example of using frequency references in orbit for fundamental research is the experiment on the Galileo satellites executed in 2014:

- **Galileo Satellites:** In August 2014, two Galileo [125] satellites were launched, and - due to an error during launch - orbited Earth on eccentric orbits. Such an eccentricity allowed for measurements of the gravitational redshift similar to the measurements of Gravity Probe A [126].

Following the success of measuring the weak equivalence principle with the MICROSCOPE mission [127] and the need for more precise optical frequency references in space, different experiments and missions have been devised, which we describe briefly in the following.

Flown Missions:

- **CACES** (Cold Atomic Clock Experiment in Space): This is a mission started in 2011 under the Chinese manned space program. It sets out to test laser cooling and manipulation of atoms in orbit. It is based on laser-cooled Rubidium-87 atoms in an atomic fountain for stabilization of frequencies to a level of $2x10^{-16}$ on ground. The system was launched into space aboard the Chinese space laboratory Tiangong-2 in September 2016. It has proven long-term in-orbit operation of cold-atom clocks under various environmental effects such as varying gravity levels, magnetic fields and radiation [128].

- **DSAC** (Deep Space Atomic Clock): NASA founded DSAC is developed as a step towards independent spacecraft navigation in deep space as opposed to relying on communication to the ground. It houses a Mercury ion atomic clock and it has been launched in June 2019 [129,130].

Commercial Missions: Currently, the main commercial application of atomic clocks is in the Global Navigation Satellite Systems (GNSS). Starting with the initially military American

Global Positioning System (GPS) in 1978, four GNSS and several Regional Navigation Satellite Systems have been established. The latest GNSS is the European Galileo system. Each current generation Galileo Satellite contains two passive Hydrogen MASER atomic clocks and two secondary Rubidium atomic clocks. The use of other atomic clocks on future Galileo generations is currently under evaluation. Nowadays, the precise position and timing data provided by GNSS is indispensable for a modern economy and plays a key role for future developments such as autonomous vehicles. Several future commercial applications of quantum technologies in space are being studied. These include the use of atomic clocks as reference for deep space navigation and as sensors for the measurement of Earth's gravitational field.

b. Atom Interferometers

Cold atoms are one of the physical systems utilized to implement quantum technologies in space. They offer a well-controlled environment where employing interferometric effects leads to unprecedented precision in sensing applications. Low-gravity environments elevate the precision of these systems even further, mainly due to the increasing free fall times. In addition, ultra-cold atomic condensates can be considered as macroscopic systems showing quantum effects. Thus, in combination with environments where relativistic effects become relevant, they present an attractive playground for testing fundamental physics.
Cold atom experiments already have taken a long path from the laboratory environment today even into space. Therefore, in the following we list projects and missions, which are important milestones in enabling cold atom experiments in space. The ability to operate in harsh environments, like drop towers, ships, airplanes or sounding rockets, requires cold atom experiments to be robust and autonomous. Hence, it is an important indicator for the technological maturity of cold atom systems and paves the way for commercial utilization in e.g. Earth observation and in reaching unprecedented parameter regimes for fundamental physics tests.

Ground-based microgravity projects: Weightlessness on ground can be achieved for a payload by bringing it into free fall and, by this, compensating for the gravitational pull. For this purpose, drop towers have been erected from which prominently the_Drop-Tower Bremen at the Center of Applied Space Technology and Microgravity (ZARM) of the University of Bremen was chosen as microgravity platform for BEC experiments in weightlessness, as it provides good accessibility and superior quality of microgravity compared to other ground-based platforms. At ZARM, an experiment's capsule can either be dropped for 110 m inside the evacuated vacuum-tube of the drop tower to generate 4.72 s of microgravity time, or can be launched with a piston-catapult to almost double the microgravity time, ~9.3 s. In future, the GraviTower Bremen (GTB Pro) will become the third generation of drop towers at the ZARM, complementing the Bremen drop tower. The GTB Pro is designed to fit the same proven experiment designs and dimensions as used in the Bremen Drop Tower making both facilities fully compatible. The initial acceleration and the transition into microgravity are made very smooth by following a sine function limited to 5 g. With a repetition time of just three minutes each flight offers 2.5 s of microgravity - fully automated all day. Experiment preparation, automation, tests and flights are carried out in teamwork with the engineers of ZARM and in collaboration with the Bremen Drop Tower.

The interested reader is referred to [131,132].

On a smaller scale, a zero-g simulator, was designed and built by the French company Symétrie and is operated at LP2N, Bordeaux. This simulator works by moving a platform, on which the experimental apparatus rests, in a way that mimics the trajectory of an object in free fall, launched vertically, i.e. a parabola. The platform moves vertically between two granite columns thanks to two carriages with air bearings for a frictionless motion. Linear motors mounted on the sides of the columns are responsible for the accelerations of the moving parts necessary to perform parabolic trajectories. The 0-g simulator can provide up to half a second of weightlessness on every trajectory and, thanks to its very high repetition rate (1 parabola every 12s), gives access to a very long accumulated duration of 0-g.

Another very important large-scale facility renders the Einstein Elevator at HITec (Hannover Institute of Technology). This large-scale research device is a next-generation drop tower facility with a total height of 40m and therefore allows for four seconds of microgravity with residual acceleration of 10^{-6} g. Payloads with up to 1000 kg and a size of diameter of 1.7 m and height of 2 m can be operated with a repetition rate of 300 flights per day, thanks to the innovative electromagnetic linear motor drive unit. This is a great improvement in comparison to 3-4 drops possible with the ZARM drop tower. This motor drive additionally allows for hyper- or hypogravity to generate conditions as they prevail on other celestial bodies, like Moon or Mars. The first test operation started in 2019 [133] and the interested reader is referred to [134-136].

- **QUANTUS** (QUANTengase Unter Schwerelosigkeit , English translation: Quantum Gases under Microgravity): The DLR (Deutsches Zentrum für Luft- und Raumfahrt) funded QUANTUS-Project started in 2004 and aims at developing the necessary methods for space-borne microgravity platforms like sounding rockets, experiments on the ISS and on dedicated satellites. Within QUANTUS, the technology and the physical understanding of these complex experimental apparatuses are developed and preliminary studies for space-borne missions are performed. Using the first-generation payload QUANTUS-1, this capability has been used for the demonstration of the first BEC in microgravity in 2007 [137] and the first interferometry experiments with freely falling BECs [138]. Sine 2014, the second-generation apparatus 1350 QUANTUS-2 is operational at ZARM, featuring a novel compact high-flux BEC source [44]. This apparatus is more compact, so it allows for using the catapult mode of the Bremen Drop-Tower at ZARM [139] to double the time in microgravity and to increase the overall data rate. Additionally, it is designed to be able to use a second species, potassium. In recent years, using both apparatuses, novel interferometric schemes [140,141], large-momentum beam splitters [142] and 3D magnetic delta-kick collimation techniques in microgravity were developed to reduce the kinetic energy of the atomic ensemble down to 38 pK. These developments have enabled the MAIUS and BECCAL missions. More details are in [143,144-150].

- **PRIMUS** (PRäzisionsInterferometrie mit Materiewellen Unter Schwerelosigkeit, English translation: Precision Interferometry with Matter Waves in Zero Gravity): In addition to the magnetic trap based efforts of the QUANTUS project to utilize ultra-cold atom technologies in microgravity, since 2009 the potential of optical traps is investigated in the PRIMUS project. This project initially focused on a test of the weak equivalence principle, leading to outstanding ground-based results [151,152]. Lately, PRIMUS widened its spectrum of interests to more general questions concerning cooling and phase transitions. Within PRIMUS, a compact experimental setup was realized [153] to apply optical trapping in the drop tower of Bremen. Further milestones where the implementation of a single beam optical dipole trap in microgravity, successful evaporative cooling in weightlessness, and the advancement to a crossed beam configuration by actively stabilizing the trapping beam's pointing. In principle the absence of gravity should increase the dimension of evaporation, because the trap is not tilted anymore [154]. Previous studies did not observe this effect for magnetically tilted traps [155]. The nonexistence was confirmed in PRIMUS for evaporative cooling in microgravity and could be explained by the anharmonicity of the traps [156]. The interested reader is referred to [151,152,153,156].

- **I.C.E.** (Interferometrie atomique a sources Coherentes pour l'Espace, English translation: Coherent Source Atomic Interferometry for Space): Since 2018, the I.C.E. experiment is able to perform experiments in the laboratory thanks to the unique, purpose made Einstein elevator on which the experimental apparatus is installed. This device allows to produce Bose-Einstein condensates with forty thousand rubidium-87 atoms at a temperature of 35 nK in weightlessness [157].

<u>Air/Marine-borne cold atoms projects:</u> One way to achieve weightlessness is by parabolic flights in an aircraft by alternating upward and downward arcs interspersed with level flight. In April 2015, Novespace began operating its third aircraft, the Airbus A310 Zero-G to provide a microgravity environment for scientists to conduct research without going into space. Not directly benefiting from weightlessness, but still relevant for research on cold atoms in space, is one project, where cold atom interferometers are operated during flight or on a ship. Therefore, it is included in this list.

- **I.C.E.** (Interf_erometrie atomique _a sources Coh_erentes pour l'Espace, English translation: Coherent Source Atomic Interferometry for Space): The CNES-funded I.C.E. operated an atom interferometer for inertial sensing in reduced gravity on board the NOVESPACE Zero-G plane. During a 20 seconds-lasting ballistic parabolic flight residual acceleration on the order of 10^{-2} g are achieved. Within I.C.E., Ramsey fringes have been obtained in 2008 operating an atom interferometer using a series of two Raman transitions within cold Rubidium-87 atoms [159]. In 2011, the first airborne operation of a horizontally measuring high-resolution cold-atom inertial sensor, both at 1 g and in reduced gravity has been reported [160]. This measurement technique has been then advanced to a vertical mode and measurements of the acceleration along the vertical and horizontal axis with one-shot sensitivities of 2.3×10^{-4} g have been achieved [161]. The measured loss of contrast was attributed to the high level of vibrations on-board the aircraft and the large rotation rates during a parabolic flight. A first on-board operation of simultaneous Rubidium-87 and Potassium-39 interferometers in the weightless environment was demonstrated in 2016. In this parabola campaign, I.C.E. demonstrated its capability of operating a dual-quantum sensor and with this measured the Eötvös parameter with systematic-limited uncertainty of 3.0x10^{-4} in reduced gravity [162]. This constituted the _rst test of the equivalence principle in a free-falling vehicle with quantum sensors. During the last years, I.C.E. got upgraded and is now operated at a 3 m high 0 g-simulator built by the French company Symétrie, which gives access to microgravity in the laboratory. More details elsewhere [159,160,161,163].

- **GIRAFE** (Gravimètre Intérferométrique de Recherche à Atomes Froids, Embarquable ; English translation: Shipborne cold atom research interferometric gravimeter): In the scope of a funding program of the French DGA and CNES, since 2006 the company ONERA designed and built an absolute marine gravimeter based on atom interferometry called GIRAFE. GIRAFE was tested multiple times (in October 2015 and January 2016) at sea on an oceanographic survey vessel and demonstrated a superior performance compared to classical technology [164]. Subsequently, the GIRAFE instrument was adapted for airborne measurements for surveying areas where gravity is poorly resolved by ground or satellite measurements, as for example in coastal and mountainous areas. In April 2017, in an airborne campaign above Iceland, GIRAFE was compared with other conventional airborne gravimeter and inertial sensors and show differences with a standard deviation ranging from 3.3 to 6.2 mGal and a mean value ranging from 0.7 mGal to 1.9 mGal [165].

Space-based cold atoms projects: Since 2017, cold atom research reached space. Here, the microgravity platforms in use are parabolic sounding rocket missions and the International Space Station (ISS). A next interesting platform under investigation for cold atoms research can be CubeSats.

- **MAIUS** (MAteriewellen-Interferometer Unter Schwerelosigkeit, English translation: Matterwave Interferometry under Microgravity): The DLR funded MAIUS missions are the continuation of the aforementioned QUANTUS project. Their aim is to bridge the gap between laboratory or drop tower systems and future orbital missions by implementing cold atoms, BECs and atom interferometry on sounding rockets. In total, three sounding rocket missions are planned with the first, MAIUS-1, successfully launched in 2017 [166]. This constitutes a major advancement over the aforementioned projects, as it is not only the first setup to undergo environmental qualification but also operated autonomously in the harsh environment of an unmanned sub-orbital spacecraft. During the maiden flight in 2017 the first Bose-Einstein-condensate in space has been demonstrated and its collective dynamics were analyzed [166]. Additionally, important manipulation techniques, like internal state preparation, have been performed and autonomously optimized during the parabolic flight. Finally, first atom interferometry experiments in space have been conducted [158].

- **CAL** (Cold Atom Laboratory): The NASA-funded Cold Atom Laboratory (CAL) was developed by NASA's Jet Propulsion Laboratory and utilizes a compact atom chip-based system to create ultracold mixtures and degenerate samples of Rubidium-87, Potassium-39, and Potassium-41. It was launched to the ISS in 2018 and operates as a multi-user facility to provide the first persistent quantum gas platform in space for an international group of investigators with broad applications in fundamental physics and inertial sensing. Up to date, experiments transferring Rubidium-87 Bose-Einstein Condensates in ultra-shallow traps are realized based on adiabatic decompression ramps. Fast and perturbation-free transport with a micrometer-level control of the atomic positions is realized based on shortcut-to-adiabaticity protocols [167]. Moreover, a space atom laser [168] and a radio frequency bubble experiment are conducted. Finally, delta-kick collimation drastically reducing the free expansion rate of the atomic clouds has been performed on the ISS. At the beginning of 2020, the new science module SM3 has been installed on the ISS, adding the possibility to perform atom interferometry experiments with CAL. The interested reader is referred to [169,170].

2. Photonics Systems In Space

Transmission of quantum signals over long distances has been demonstrated through a series of satellite-based experiments and feasibility studies. The first proposals to implement satellites for this application emerged in the 1990s [171]. Since this initial proposal, numerous feasibility studies and demonstrations of satellites QKD have been made. They include free space QKD over high altitude ranges [171], feasibility of quantum communications in space [171,173], and a record-breaking inter-island key exchange over 144 km [174,175]. The feasibility of space links was realized through experiments that exchanged single photons from a low Earth orbit (LEO) satellite to ground by exploiting retro-reflectors aboard the spacecraft [176,177]. These experiments recorded small quantum bit error rate, which provided a concrete proof for satellite-based quantum communications. The transmission of quantum photonic signals has also been increased through use of Medium Earth orbit (MEO) satellites or higher orbits, up to the current single-photon exchange limit of 20,000 km [178,179].

Recently, the **QUESS** experiment involving the Chinese LEO satellite **MICIUS** became the first space-based quantum communication mission to be launched and has made further developments [180,181]. It has demonstrated entanglement distribution to two ground stations separated by 1200km [181], ground-to-satellite quantum teleportation over distances of up to 1400 km [182], and the realization of a hybrid quantum communication network with a total quantum communication distance of 4600km [183].

Despite these demonstrations, establishing long-term reliable ground and satellite links remains the principle challenge in satellite QKD. A notable development in space systems is the rise of in-orbit demonstrations with small satellites and CubeSats for rapid and less-costly space systems developments. This increase is partly driven by miniaturization and increasing robustness of quantum components. In addition, constellations of small satellites offer the possibility of a cost-effective approach to improving coverage and ground-satellite link reliability compared to traditional satellites. CubeSat missions in 2015 [184] and 2019 [185] have performed in-orbit demonstrations of miniaturized quantum photon pair sources.

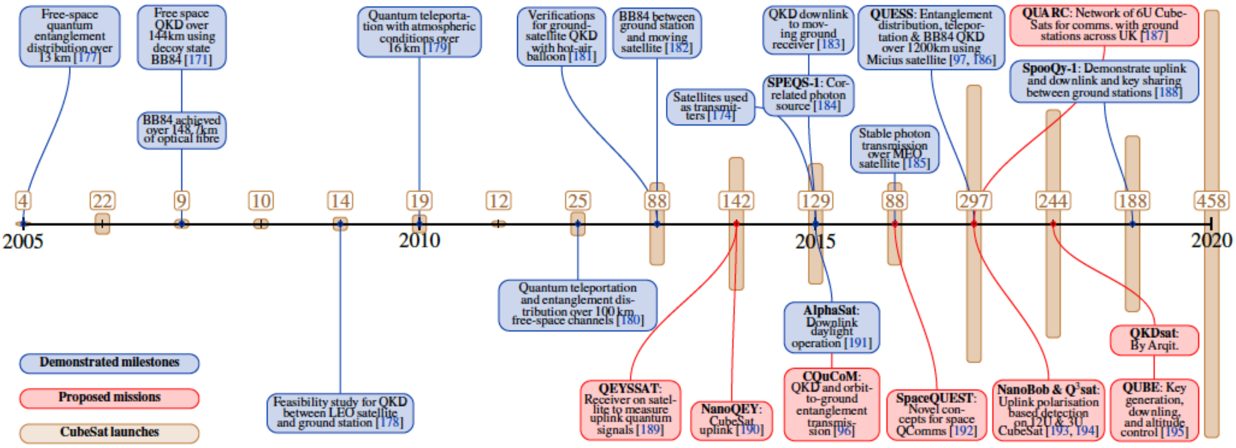

Figure 1: Timeline of key milestones in proof-of-principle field demonstration and feasibility studies towards the developments of satellite-based QKD. Notice that, the increase in the number of missions involving CubeSats reflects their growing importance in satellite-based global quantum communications. Image taken from [186] and references therein.

A timeline of missions that have demonstrated key milestones or feasibility studies towards global satellite-based QKD is provided in **Fig.1** [186]. 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. [187,188] and Ref. [186] for a general overview of the field.

3. Large-Mass Systems In Space

Following the first motional ground state cooling of a clamped optomechanical resonator in 2010 [189], the technological advances in laser cooling and trapping have allowed larger objects to enter the quantum regime. Many clamped systems have reached close to, or have entered, the quantum regime [190], c.f. **Fig.2**. Examples include a nano-drum [191], a silicon nanobeam [192], a membrane [193], a whispering gallery mode microresonators [194,195], a membrane where both coherent light and squeezed microwave fields are used for cooling [196], and a millimeter sized membrane that also acts as a photonic crystal [197].

Operating in the quantum regime with free or levitated particles allows the generation of macroscopic quantum states that are less coupled to their environment than clamped systems, which greatly enhances the coherence time of the quantum states [198]. A macroscopic quantum state is created by cooling the center of mass (c.o.m.) motion of the nanosphere at trapping frequency provided by an optical tweezer, optomechanical cavity, ion trap or magnetic field [199], where the ground state condition requires the average phonon occupancy to be less than 1 at this trapping frequency. Typical c.o.m. oscillation frequencies of levitated nanoparticles range from 10-200 kHz while the mass varies from 10^{-19} kg to 10^{-16} kg [200,198]. To understand the feasibility of performing measurements with a quantum nanoparticle, we consider its positional spread. This grows approximately linearly in time when the particle is released from the levitating potential. Considering typical parameters for a levitated nanoparticle of mass m = 10^{-18} kg and Ω_m= 2π$\times 10^5$ rad/s, this yields zero-point displacement fluctuations on the order of σ_{zpf} =10^{-11} m, requiring hundreds of seconds of expansion until the quantum position spread is as large as the particle with a radius of r = 35 nm, a reasonable definition of a macroscopic quantum state. In order to ascertain when the ground state condition has been reached, a narrow cavity resonance linewidth κ is preferred as it enables one to reach the resolved-sideband regime, assuming that the mechanical frequency Ω_m is larger than κ. This allows read-out of energy transfer between the optical and mechanical modes in an anti-Stokes/Stokes process [190]. The sideband asymmetry allows for measurement of the number of phonons and is considered a more accurate method of thermometry than read-out of the mechanical mode's power spectral density. Although a cavity is not necessarily required to reach the ground state, it provides resonant enhancement in read-out and interaction strength, thereby reducing the number of photons needed to interact with the mechanical oscillator and improving the signal to noise ratio [201].

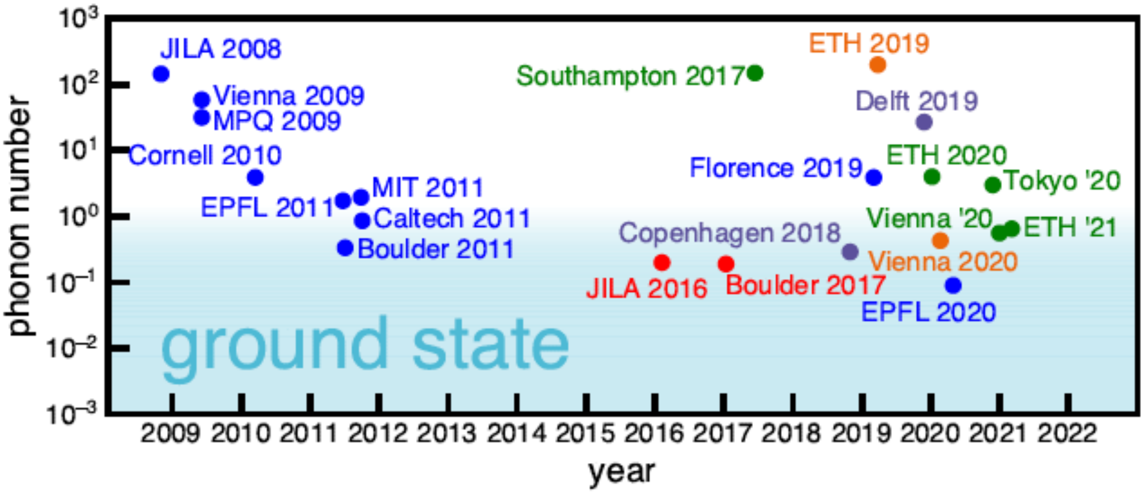

Figure 2: *Experimental results for cooling of macroscopic systems over the years. Minimum phonon occupation number is plotted against the date of publication. Blue data points represent experiments relying only on passive cavity cooling: JILA 2008, Vienna 2009, MPQ 2009, Cornell 2010, MIT 2011, EPFL 2011, Caltech 2011, Boulder 2011, Florence 2019 and EPFL 2020. Red data points are results using squeezed light to surpass the standard quantum limit imposed on cavity cooling: JILA 2016 and Boulder 2017. Purple data points present results using a feedback cooling scheme: Copenhagen 2018 and Delft 2019. Orange data points show recent results of cooling levitated nanoparticles using coherent scattering in a cavity: ETH 2019 and Vienna 2020. Green data points show recent data of a nanoparticle feedback cooled in an optical tweezer using no cavity for cooling or read-out purposes: Southampton 2017, ETH 2020, Tokyo '20, Vienna '20 and ETH '21.*

Ground-based quantum state preparation: A range of passive and active cooling methods to achieve quantum ground state preparation of macroscopic objects using the optomechanical coupling are described in multiple review papers [190, 198], with many techniques such as side-band resolved cooling derived from the cold atom community [202].

- **Cavity Cooling:** In 2020, the c.o.m. motion of a 143nm diameter silica nanosphere levitated by an optical tweezers within an optical cavity was cooled to its zero-point energy, which corresponds to an average phonon occupancy smaller than one, using the cavity optomechanical interaction together with a coherent scattering scheme [200]. This experimental set-up uses a technique called coherent scattering [203,204]. The tweezers reduce the chances of losing the particle when reaching ultra-high vacuum, as compared to direct trapping by the optical cavity field. The coupling strength is at its highest when the particle is held at the cavity node. The optical cavity is not pumped separately, rather the trapping optical tweezers' frequency is stabilized relative to the cavity resonance using a weak beam which minimally interacts with the nanoparticle.

Light scattered out of the tweezers field by the nanosphere then bounces off the cavity mirrors and interacts coherently with the oscillator again. Pumping of the cavity using only light scattered by the nanoparticle is a key feature. Consequently, each photon populating the cavity mode interacts with the particle, increasing the optomechanical coupling rate. As a result, the quantum cooperativity of the experiment, namely the ratio of the optomechanical coupling strength and the product of the optical and mechanical decay rates, is well above 1000. To put this into perspective, a system with a quantum cooperativity bigger than 1 has been a long-pursued goal in levitated optomechanics and is the benchmark for entering the quantum backaction regime [198]. A high cooperativity is also known in cold-atom physics to produce a constant cooling rate for cavity assisted molecule cooling in dynamical potentials [202]. Compared to the general cavity cooling scheme [205], the estimated improvement in cooperativity is 105-fold [206] due to the coherent scattering procedure, with the added benefit of a reduced cavity drive power.

- **Feedback Cooling:** At the end of 2020, the ground state cooling of the c.o.m. motion of a 143nm diameter levitated nanosphere using optimal control, was announced [207]. This type of cooling differs from the passive scheme employed in coherent scattering through the use of active feedback loops to generate the damping forces. A combination of an optical tweezers trap and a state-estimation feed-back algorithm is used, enabling cooling of the 105 kHz c.o.m. in one direction with a final average phonon occupancy of n = 0.56+/-0.02 quanta. Crucial for the success of this ground-state cooling scheme were the Heisenberg limited con-focal position detection and a combined implementation of a Kalman filter together with a linear-quadratic regulator [207,208] determining the optimal feedback output control. The optimized detection of the particle's motion in the back-scattering plane of the optical tweezers allows to follow the particle's position with an uncertainty that is 1.3 times the size of the zero-point motion fluctuation.

  Additionally, the identification of important external noise sources and photon/information loss mechanisms of the experimental setup enabled to provide a high confidence in the accurateness of the model parameters of the employed Kalman-Bucy filter. Interestingly, the authors point out that the ground-state of a levitated particle can be reached even with a simple derivative filter using the correct gain settings [207]. Many quantum sensing proposals that utilize spin-coupling do not require the mechanical oscillator to be in the ground state. Instead, low phonon occupancy (n < 10) is sufficient as, even at this regime, the zero-point motion emerges as a sizable contribution to the dynamics.

- **Velocity Damping:** In 2020, this was shown using a 136nm diameter nanoparticle trapped only by an optical tweezers, and cooled using active velocity damping [201]. Also notable is the absence of a cavity which reduces the configuration overheads and allows for less obstructed measurements. For measurement protocols, it removes timing constraints posed by the response time of the cavity, possibly enabling faster pulse sequences and sampling rates. The c.o.m. mode was cooled to an average occupation of $n = 4$ phonons at frequency 50 kHz. A major benefit of this scheme is the use of backscattering to detect the oscillation along the cooling axis, which allows for cooling to the ground state provided that the laser noise on the detector is sufficiently low.

Space Feasibility studies: The advantages of performing quantum optomechanics experiments in space is a reduction in ground-based noise sources such as seismic noise and changes to Earth's gravitational field. Vibrations, gravitational field-gradients, and decoherence through interaction with the environment fundamentally limit ground-based macroscopic quantum superpositions. This is particularly important for sensing, for example to eliminate the bulky and complex stabilization platforms required for gravitational wave detection. Furthermore, many fundamental tests of physics require a micro-gravity environment ($<10^{-9}$ g), long free-fall times (100 s), and large number of repetitions (10^4) per measurement, which are more easily fulfilled with a space-based setup [209].

- **MAQRO/QPPF:** Over the years, the mission scenario Macroscopic Quantum ResOnators (MAQRO) has been developed with this aims [210-221]. Some aspects, especially the thermal shielding and how cold one can get in space, were studied numerically in detail. A publication related to the debrief of the ESA CDF study on the MAQRO related Quantum Physics Payload Platform (QPPF) has been published in January 2019 [209]. The core levitated optomechanics experiment platform, along with all the mission design considerations, indicating the technology maturity and projects that have arisen to solve certain technological challenges.

Space heritage: It is important for any new platform technology to consider legacy components and methods that are already present in space. For example, optomechanical experiments share very similar components to those on-board the ISS and LISA Pathfinder.

- **Optical tweezers** already present on the ISS as part of the Light Microscopy Module [222], which was the first optical tweezers deployed in a microgravity environment with military specifications, are crucial building blocks for future space-based optomechanics missions.

- **The LISA Pathfinder** mission established to be capable of handling large test-masses (cube of 46 mm size and 1.928 kg mass) in free-fall tests. The mission found excess noise at lower frequencies from forces acting on the surface of the spacecraft such as spontaneous out-gassing, virtual leak pressure effects, electrostatic noise from fluctuating small-scale surface charges [223], or other short-range forces [224].

Additional effects characterized include mass depletion [225] and the generation of false acceleration due to electrostatic noise [223]. For optimum stability, LISA Pathfinder highlighted that noise from control voltages, electrostatic potentials, and laser intensity needs to be reduced such that it causes displacement changes no greater than fm s^{-2} /$Hz^{1/2}$ [227].

In 2021 the LISA Pathfinder achieved an in-flight measurement, with background stabilization of $32x10^{-15}$ $ms^{-2}/Hz^{1/2}$ [224]. In previous tests, the reduction of the different noise sources enabled a stability measured at close to 1mHz of the LISA Pathfinder mission along the three axes as X: $5x10^{-15}ms^{-2}/Hz^{1/2}$, Y and Z: $4x10^{-14}ms^{-2}/Hz^{1/2}$, while the angular acceleration noises are respectively $3x10^{-12}rads^{-2}/Hz^{1/2}$ and $3x10^{-13}rads^{-2}/Hz^{1/2}$ [227].

CONCLUSIONS

Deliverable 3.2 report is summarizing the state of play on testing the different experimental QT platforms on their technological readiness level for space missions. In general, two types of scenarios exist for space missions, those which traditionally involved long-term planning and testing and eventually ending in large-scale and expensive missions, but also those which are more recent and make use of micro-satellite capabilities to test QT on a faster tune-around, inevitably with a larger risk.

Impressive progress has been made to demonstrate the maturity for both of those approached, long-term and short-term. The different experimental platforms, cold atoms & atomic clocks, photonic systems and large-mass systems have reached different level of technical maturity and attention by society. Strong QTSpace communities have been formed and are pushing ahead to ever more challenging objectives, to the great benefit of national and international industry and society.

Naturally, the D3.2 is the longest report, as it summarizes in some detail all those efforts. Atomic clocks are well established and mature in space, pushing for implementing ever higher sensitivity and time resolution. One focus here is the test of predictions by the theory of General Relativity on the fundamental physics side, while of course the main application is in the timing and communication sector. Photonic systems, with successful QKD satellite missions and many more to come, have seen great attention by the security and communication sector, while also here there is great scope to test Quantum Mechanics at truly galactic scales. Cold atoms in the concrete case of atom interferometers have seen a multitude of demonstrators of space-readiness levels in micro-gravity environments on ground and in space, mostly supported by national space agencies. Clearly, this community is now preparing for large-scale missions for both the addressing of Fundamental Physics questions and applications such as Earth Observations. Last not least, large-mass optomechanical systems have made super-fast progress on ground, have become a true quantum technology, and especially levitated optomechanical systems are of high potential for space applications in the sensing area. One concentrated effort to use large-mass interferometry to test Quantum Mechanics in space is pushing ahead, and very well on ESA's radar.

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. D�oringsho_, 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).