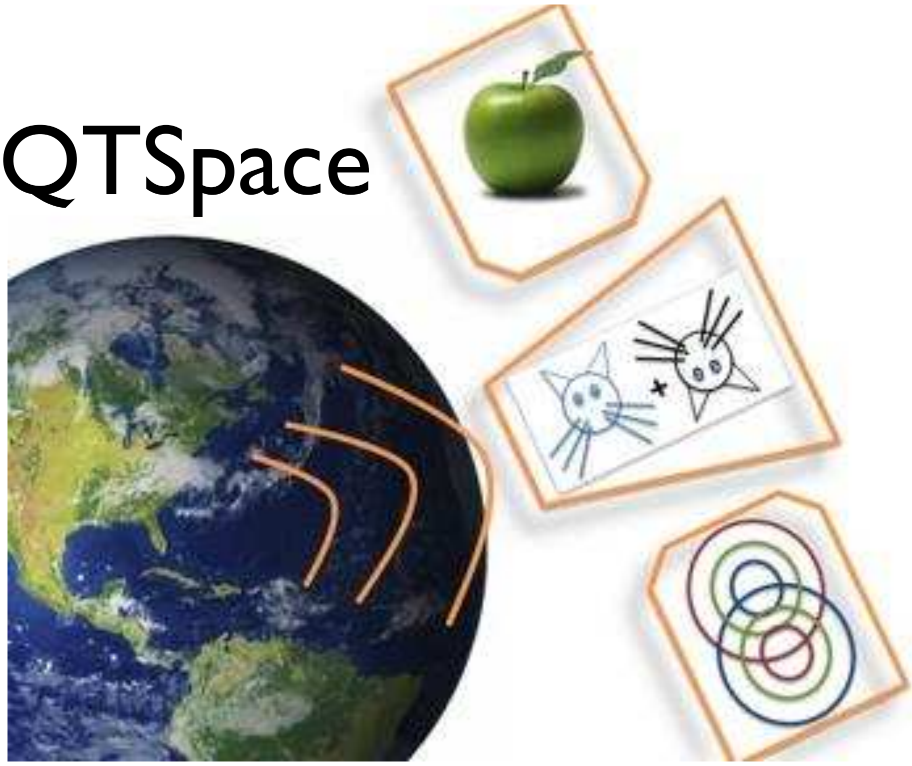

First Conference and Working Group Meeting

Valletta (Malta), 27-31 March 2017

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Quantum Communication with Satellites - complementing Quantum Optics with Space Weather considerations

Analyzing entanglement-based quantum key distribution on satellite-ground channel

Laszlo Bacsardi, Institute of Informatics and Economics, University of West Hungary (Hungary)

Using quantum key distribution (QKD), two communicating parties can exchange secret keys which can be used for symmetrical cryptographic protocols. Since the security of QKD is based on the fundamental properties of quantum mechanics, passive attack is not possible in these systems, the only types of attack is the active one. If an active eavesdropper approaches, a noise will appear in the communication channel which makes possible for the communication parties to learn about the presence of an eavesdropper.[1] There are two groups of the currently used QKD solutions. The first generation protocols use singe-photon sources, while coherent laser is used and the wave properties of light is exploited in the second generation protocols. This first approach is named as Discrete Variable QKD (DV-QKD), the second one is named as Continuous Variable QKD (CV-QKD).

Although commercial applications of QKD technology are already available, currently direct fiber-based QKD links cannot reach distances beyond a few hundred kilometers due to the optical losses on the fiber. With the help of quantum repeaters, long-distance QKD networks may be feasible, but such devices are not ready for operational integration.[2] Instead of wired-links, satellite links can be used as free-space quantum channels[3] to provide a global free-space QKD network.[4]

After examining the current state-of-the-art of free-space quantum key distribution protocols, we started to analyze the properties of the Earth-satellite quantum communication by simulating a global, satellite-based quantum key distribution network. We have proposed an entanglement-based QKD satellite network which consists of three satellites. One satellite serves as the source of entanglement, the two others work as mirrors to increase the coverage. For this constellations, we have calculated the maximum distance allowed between the satellites to minimize the atmospheric distortion of the transferred quantum states. Different simulations were made to determine the rotation of the basis states which has to be taken into account at the ground stations if we would like to use an entanglement-based QKD protocol.

The research was supported by the Hungarian Scientific Research Fund OTKA PD-112529.

Bibliography

1. L. Hanzo, H. Haas, S. Imre, D. O'Brien, M. Rupp and L. Gyongyosi. Wireless Myths, Realities, and Futures: From 3G/4G to Optical and Quantum WirelessÓ, Proceedings of the IEEE, Volume: 100 , Issue: Special Centennial Issue, pp. 1853-1888.
2. D.Stucki et al, High rate, long-distance quantum key distribution over 250km of ultra low loss fibersÓ, New J. Phys. 11 075003, 2009
3. P. Villoresi et al., ÓExperimental verification of the feasibility of a quantum channel between space and earthÓ, New Journal of Physics, Vol. 10, No. 3, p. 033038, 2008.
4. L. Bacsardi. On the Way to Quantum-Based Satellite CommunicationÓ, IEEE Comm. Mag.51:(08) pp. 50-55., 2013

Levitated optomechanics and optical fibre technology

James Bateman, University of Cardiff (UK)

A levitated nanoparticle in high vacuum offers a near ideal test-mass and a platform for ultra-sensitive force measurements. Approaching fundamental limits of this technique so that we might explore new physics, such as modifications to short-range gravity, or build technological devices, such as gravimeters or accelerometers, necessitates a stable and robust experimental base. By designing our optical system as far as practical around the mature technology of fibre optics, including waveguide modulators, fast low-noise detectors, and fibre optical amplifiers, we are constructing a platform with which to approach the standard quantum limit for position resolution, test techniques for suppressing sources of noise in this system, and explore connecting oscillators, via fibre optics, in geometries not be feasible with free-space systems.

Experimental Relativistic Quantum Information with a Geostationary Satellite

Oemer Bayraktar, Max Planck Institute for the Science of Light(Germany)

With quantum science in space we reach a regime of physics, where the interplay between general relativity and quantum theory is unclear. A contemporary experimental scenario is satellite-based quantum communication, where an investigation of the impact of gravitational effects is of both, fundamental and technological interest. Specifically, quantum field theory in curved space-time (or relativistic quantum information) is used to describe the aforementioned scenario, while experimental evidence for the predictions are not existing yet.[1] However, the rapid development of quantum technologies in space necessitates a thorough experimental investigation of the relevant physics.[2,3] Therefore, we investigate potential realization of relativistic quantum information experiments, based on a space-to-ground quantum communication link with a satellite in the geostationary Earth orbit.[4] Thereby, we aim to complement quantum field theory in curved space-time with experimental evidence and to explore possible limitations of satellite-based quantum communication.

Bibliography

1. R. Howl et al., arXiv:1607.06666 (2016).
2. D. Rideout et al., Class. Quantum Gravity 29, 224011 (2012).
3. G. Vallone et al., Phys. Rev. Lett. 116, 253601 (2016).
4. K. Gnthner et al., arXiv:1608.03511 (2016).

Space-EPS- a space suitable engineering model of an entangled photon source

Erik Beckert, Fraunhofer Institute for Applied Optics and Precision Engineering IOF (Germany)

The talk will report about the optical and opto-mechanical design of an entangled single photon source and its experimental evaluation. The optical design is based on a sagnac interferometer approach having a 405 nm pumped ppKTP down-conversion crystal for photon pair generation. A lab setup of this arrangement revealed that visibilities in HV and DA ¿98The opto-mechanical design is based on precision engineering techniques like usage of low CTE materials, high precision machining, adhesive-free bonding etc. to provide both an easy to align and ultra-stable setup so the entangled photon source can be placed on a satellite platform to create a LEO/ GEO to Ground link for QKD. The engineering process from design to manufacturing, setup and evaluation in a mechanical and thermal load environment as well as the roadmap for future flight models will be shown.

Demonstrating miniaturised, entangled photon pair sources on board nanosatellites to enable future QKD missions

Robert Bedington, Centre for Quantum Technologies, National University of Singapore

Proof-of-principle experiments need not be restricted to the ground; CubeSat nanosatellites allow for cost-effective demonstrations of smaller experiments and technologies in-orbit. We present our work at CQT establishing the space worthiness of highly-miniaturised, polarisation-entangled, photon-pair sources using CubeSats. We have a correlated photon source in orbit right now in the NUS Galassia 2U CubeSat. We also have an entangled photon-pair source in production and a high brightness (1Mcps) entangled photon-pair source in development for our upcoming CQT SpooQySat 3U CubeSats. All our sources are proof-of-principle demonstrations that the hardware necessary for entanglement-based QKD can be miniaturised and made sufficiently robust for operation in space. The photon pairs they produce are measured with liquid crystal based Bell state analysers and geiger-mode avalanche photo-diodes onboard of the source. These space missions allow our on-the-ground radiation, thermal and vibration tests to be validated and the real-world operation and ageing of the source in space to be studied. A BBM92 QKD-capable design of the source has been used in a phase-A study of a satellite-to-satellite QKD demonstration mission by UNSW Canberra (the University of New South Wales; Canberra). This mission study uses two 6U CubeSats in LEO and aims to demonstrate QKD over longer separations than any previous experiment.

The twins get computers: on the computational power of time-dilation

Jacob Biamonte, The University of Malta (Malta)

What if we could race off into space and return home to find solutions to problems that took computers epochs to solve? The associated runtime difference of identical algorithms executed by observers using identical computers but travelling different paths through Minkowski spacetime is due to time-dilation: an experimentally validated phenomenon whereby an observer finds that another's physically identical ideal clock has ticked at a rate different than their own clock. Even a type II civilization on the Kardashev-Zubrin range should be able to trade energy for solutions to computational problems, but this brings with it several predicaments and also touches on the meaning of time in the late-universe models. Here we quantify the energy-runtime relationship using ideas appearing in the framework of computational complexity theory. We report several findings including a general relationship quantifying time-dilation as an algorithmic resource relative to a decision oracle. A relativistic theory of computational complexity is essentially totally lacking in the literature, whereas closed time-like curves not only imply the collapse of the polynomial hierarchy, there existence would even imply that a single algorithm could solve undecidable problems efficiently. Then, assuming the chronology protection conjecture, what is the computational power afforded by manipulating space-time?

Heterodyne photodetection measurements on cavity optomechanical systems: Interpretation of sideband asymmetry and limits to a classical explanation

Kjetil Borkje, University College of Southeast Norway (Norway)

We consider a system where an optical cavity mode is parametrically coupled to a mechanical oscillator. A laser beam driving the cavity at its resonance frequency will acquire red- and blue-shifted sidebands due to noise in the position of the mechanical oscillator. In a classical theory without noise in the electromagnetic field, the powers of these sidebands are of equal magnitude. In a quantum theory, however, an asymmetry between the sidebands can be resolved when the oscillator's average number of vibrational excitations (phonons) becomes small, i.e., comparable to 1. We discuss the interpretation of this sideband asymmetry in a heterodyne photodetection measurement scheme and show that it depends on the choice of detector model. In the optical regime, standard photodetection theory leads to a photocurrent noise spectrum given by normal and time ordered expectation values. The sideband asymmetry is in that case a direct reflection of the quantum asymmetry of the position noise spectrum of the mechanical oscillator. Conversely, for a detector that measures symmetric, non-ordered expectation values, we show that the sideband asymmetry can be traced back to quantum optomechanical interference terms. This ambiguity in interpretation applies not only to mechanical oscillators, but to any degree of freedom that couples linearly to noise in the electromagnetic field. Finally, we also compare the quantum theory to a fully classical model, where sideband asymmetry can arise from classical optomechanical interference terms. We show that, due to the oscillator's lack of zero point motion in a classical theory, the sidebands in the photocurrent spectrum differ qualitatively from those of a quantum theory at sufficiently low temperatures. We discuss the observable consequences of this deviaton between classical and quantum theories.

Towards Relativistic and Quantum Technologies

David E Bruschi, University of York (UK)

The past decades have witnessed the birth of the first generation of quantum technologies, with applications that range from Quantum Key Distribution (QKD), Quantum Computing (QC) and ultra-precise measurements of important physical quantities (Quantum Parameter Estimation). Quantum mechanics, the theory of the very small, has been employed successfully as the main building block to model those systems that are at the core of these technologies. So far relativity, the theory of the very large, has been laregly ignored, most likely due to overwhelming experimental evidence that relativistic effects seem not to play a role. However, cutting edge experiments have reached regimes where relativistic effects cannot be ignored. It is an open question if and how relativity will be an important player in the development of the next generation of quantum technologies.

The novel field of Relativistic Quantum Information is an exciting and growing area of research focused on understanding physics at the overlap of relativity and quantum science. Among the most important goals of this field is to understand what are the effects of relativity on paramount resources, such as entanglement, for quantum information processing tasks. Research in this direction has spawned different, yet complementary, lines of research, which largely borrow from many diverse areas of physics.

We will introduce the basic core ingredients of this areas of research and present recent advances in the field of Relativistic Quantum Information. We will provide a wide overview of the most prominent achievements, the foreseen technological applications and the most challenging open questions.

Experimental bounds on collapse models from gravitational wave detectors

Matteo Carlesso, Universita' degli Studi di Trieste (Italy)

Wave function collapse models postulate a fundamental breakdown of the quantum superposition principle at the macroscale. We compute the upper bounds on the collapse parameters, which can be inferred by the gravitational wave detectors LIGO, LISA Pathfinder and AURIGA. We consider the most widely used collapse model, the Continuous Spontaneous Localization (CSL) model. We show that these experiments exclude a huge portion of the CSL parameter space, the strongest bound being set by the recently launched space mission LISA Pathfinder.

Cold Atom Interferometers Used In Space (CAIUS) for measuring the Earth's gravity field

Olivier Carraz, RHEA for ESA

In the past decades, it has been shown that atomic quantum sensors are a newly emerging technology that can be used for measuring the Earth's gravity field. Whereas classical accelerometers typically suffer from high noise at low frequencies, Cold Atom Interferometers are highly accurate over the entire frequency range.

There are two ways of making use of that technology: one is a gravity gradiometer concept, which relies on a high common mode rejection that relaxes the drag free control compare to GOCE mission; and the other one is in a low-low satellite-to-satellite ranging concept to correct the spectrally colored noise of the electrostatic accelerometers in the lower frequencies. We will present for both concepts the expected improvement in measurement accuracy and for the gravity gradiometer concept the expected improvement of Earth gravity field models, taking into account the different type of measurements (e.g. single vs. 3 axis, integration time, etc.) and different mission parameters such as attitude control, altitude of the satellite, time duration of the mission, etc.

ASI Hub for quantum communication in space

Daniele Dequal, ASI

The recent launch of the Chinese satellite Micius dedicated to quantum communication, and the interest expressed by the European Union on quantum technologies in space, indicates how the space segment will soon be at the center of a rapid expansion toward the realization of quantum experiments in space. With the envision, realization and launch of new payloads, it emerges the necessity of novel ground stations, dedicated to space quantum experiments. Within this context, the Matera laser ranging observatory (MLRO) has shown a great potential since the first single photon transmission from a low Earth orbit satellite (LEO), demonstrated in 2008. More recent results, obtained in collaboration with Padua University, include the realization of the first transmission of quantum states from several LEO satellites, the demonstration of single photon exchange from medium Earth orbit satellite, and the observation of the preservation of photon coherence beyond the Earth atmosphere. The peculiarities of MLRO have been crucial for these achievements, highlighting the potential of laser ranging stations in this field. For the expansion of these activities, the station is now planning a series of upgrades that will allow the reception of a broader range of quantum states in view of the realization of a general-purpose receiver of quantum states from satellites.

Towards diode laser systems for optical metrology on nanosatellites

Aline Dinkelaker, Humboldt-Universität zu Berlin (Germany)

Frequency stabilized laser systems are one of the key elements in modern precision experiments based on cold atom interferometry and optical (atomic) clocks. Future space missions such as quantum interferometry based gravity mapping, tests of the equivalence principle or the detection of gravitational waves require complex but robust and compact laser systems. Semiconductor lasers are a promising candidate for deployment in space - they are small, cost-effective and currently subject to a rapid performance increase.

In this talk, we present developments toward nanosatellite-borne diode laser systems and, more generally, optical quantum technologies for precision applications in space. Our laser systems are based on a micro-integrated laser technology platform developed at the Ferdinand-Braun Institute in a joint lab activity with Humboldt-UniversitŁt zu Berlin, providing compact, robust and energy-efficient semiconductor laser modules. They are operated in experiments at the Bremen drop tower to study ultracold clouds of rubidium and potassium atoms with the long-term goal of differential interferometry in microgravity.[1] Moreover, we have developed laser payloads for operation on sounding rockets and reached TRL 9 on such sub-orbital vehicles through flight qualification and successful mission operation.[2–4]

We will discuss potential nanosatellite mission scenarios in which laser systems and related optical quantum technologies can be studied in orbit, specifically regarding long term performance, radiation effects, and autonomous operation. Such missions would not only complement our existing drop tower and sounding rocket heritage but directly contribute towards the necessary technological maturity of laser systems for future long-term operation in satellite missions.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry for Economic Affairs and Energy under grant numbers DLR 50 WM 1237-1240, 1553, 1345, 1646 and 50 WP 1432.

Bibliography

1. M. Schiemangk et al., High-power, micro-integrated diode laser modules at 767 and 780 nm for portable quantum gas experiments,Ó Applied Optics 54, 53325338 (2015).
2. M. Lezius et al., "Space-borne frequency comb metrology," Optica 3, 1381-1387 (2016).
3. V. Schkolnik et al., A compact and robust diode laser system for atom interferometry on a sounding rocket,Ó Applied Physics B 122, 18 (2016).
4. A. N. Dinkelaker et al. "Autonomous frequency stabilization of two extended cavity diode lasers at the potassium wavelength on a sounding rocket." arXiv preprint arXiv:1610.09341 (2016).

When free-falling screen records interference and standing screen does not

Lajos Diosi, Wigner Research Center for Physics (Hungary)

Relativistic time-dilation couples internal and centre-of-mass motions, leading to decoherence of spatial motion. A closer look shows that the effect is frame dependent, even disappears in the free-falling frames. Calculating interference patterns on different screens confirms that fringes smashed on a standing screen become completely restored on a free-falling one.

An introduction to spontaneous wave function collapse models and their experimental tests

Sandro Donadi, Universita' degli Studi di Trieste (Italy)

Collapse models are phenomenological models, proposed to solve the measurement problem. In these models, the Schrödinger equation is modified and the state vectors evolve according to a non-linear and stochastic dynamics. The effect of these non-linear terms is to induce the wave function collapse in space. The dynamics is built in such a way that the deviations from the linear Schrödinger dynamics are very small for microscopic systems (e.g. particles and atoms) while they become more and more relevant when the systems size increases, explaining the quantum to classical transition. The models make predictions different from that of Quantum Mechanics and hence, they can be tested through experiments. These tests are also important as general tests of Quantum Mechanics and in particular the superposition principle. In this talk, I will give a general introduction to the most relevant collapse models and their properties. Then, I will present a summary of the current bounds set by different kind of experiments (macromolecule interference, radiation emission, cantilevers, cold atoms etc.) on the parameters of these models. To conclude, I will discuss about some recent proposals for testing these models with experiments done in space, where the absence of gravity makes it possible to keep systems in spatial superposition states longer than that on earth.

Free space quantum communication with quantum memory

Eden Figueroa, Stony Brook University (US)

The realization of an elementary quantum network that is intrinsically secure and operates over long distances requires the interconnection of several quantum modules performing different tasks. In this work we report the interconnection of four different quantum modules: (i) a random polarization qubit generator, (ii) a free-space quantum communication channel, (iii) a quantum memory and (iv) a qubit decoder, in a functional elementary quantum network capable of storing a sequence of random polarization qubits in a manner needed for quantum information distribution protocols. We create weak coherent pulses at the single photon level encoding polarization states H; V; D; A in a randomized sequence. The random qubits are sent over a 20m free space link and coupled into a dual rail room temperature quantum memory and after storage and retrieval are analyzed in a four detector polarization analysis akin to the requirements of the BB84 protocol. We have obtained quantum bit error rates of 11.0Our results pave the way towards memory assisted free space quantum cryptographic networks.

A fundamental limit in the capability of Gaussian systems in quantum metrology

Christos Gagatsos, University of Warwick (UK)

For a fixed average energy, the simultaneous estimation of multiple phases provides a better total precision than estimating them individually. We show that for a multimode passive interferometer with a phase in each mode and Gaussian inputs, this improvement is no more than a factor of 2. This suggests a fundamental limitation in the performance of Gaussian states. While such limitations are well known in quantum computation and communication, ours is the first such instance in the field of quantum metrology. While our proof of this limitation assumes equal squeezing magnitudes and an orthogonal transformation, that this factor-of-two is indeed a fundamental property of Gaussian states is supported by numerics on completely general systems.

Since this limitation does not exist for a single-phase estimation problem, our work shows the richness of quantum-limited multi-parameter estimation.

The strength of our work lies in its generality. It considers an arbitrary number of parameters, and applies to quantum-limited imaging and possibly future gravitational wave detection. It also makes no assumption of stationarity in time, a common feature in waveform estimation. It can thus be applied to emerging areas such as pulsed optomechanics, and combined with dephasing estimation schemes employed to study gravitational decoherence and possibly even dark matter.

RF dressed atoms: matter-wave bubbles

Barry Garraway, University of Sussex (UK)

RF-dressed cold atom traps[1] confine ultracold atoms using spin dependent adiabatic potentials, formed by the atomic interaction with a static and spatially dependent magnetic field and a radio frequency (RF) magnetic field. These traps offer an easy way to manipulate atoms coherently, making them favourable for atom interferometry, and have a range of potential applications such as rotation sensors and quantum simulators. The possibility of miniaturisation using atom chip technology leads to applications in quantum technology.

This presentation will discuss the potential for matter-wave bubbles to be explored using RF dressed atoms in space.

Bibliography

1. Topical Review: Recent developments in trapping and manipulation of atoms with adiabatic potentials, B.M. Garraway and H. Perrin, J. Phys. B 49, 172001 (2016).

Interstellar probes: are they feasible with present technology?

Giancarlo Genta, Politecnico di Torino (Italy)

Humankind started timidly its first steps outside its planet, by exploring directly with a few human missions the Moon and by sending probes toward all the major bodies of the solar system. The result of these studies deeply changed the knowledge we had of the solar system, to the point that planetary astronomy is now completely different from what it used to be only half a century ago.

The larger amount of scientific knowledge was gained on Mars, also because an in-depth study of that planet is required to prepare the human missions which will be the first step toward the colonization of that planet: the first step toward the creation of a spacefaring civilization. This process is however still a promise for the distant future.

In this situation, does it make sense to think about interstellar exploration? And is it worth while investing in this direction? Stars are so far away that current technology seems to be absolutely inadequate to reach them: at the speed reached by the probes used for studying the solar system it would take tens of thousands of years to reach the closest star.

Up to now some space agencies proposed just what is commonly defined 'interstellar precursor missions', which are not true interstellar missions, but much simpler missions to study the interstellar space just outside the heliopause, at the boundaries of the solar system and even these missions are terribly difficult.

However, recently a combination of new scientific discoveries and of new technological opportunities changed the picture. In the last 10 years the interest in interstellar exploration is greatly increased due to the discovery of a large number of extrasolar planets and of the realization that many stars may have Earth-like planets. Even the closest star Proxima Centauri has a planet, although little is yet known about its characteristics.

At the same time the possibilities of miniaturizing the probes and that of building lightweight laser sails and powerful lasers allow to predict that in a reasonable time (two or three decades) it will be possible to build ultra-fast microprobes at a reasonable cost. The idea is not new, it was suggested by Bob Forward in the 1980s, but now it may became feasible.

Since such small microprobes can be built at a low cost (that is, while the development cost are very high, that of each individual probe can be strongly reduced), it is possible to send a whole swarm of spacecraft which can travel at about 20% of the speed of light, taking 20 years to reach the closest star. In 2016 a number of scientists, among which there is Stephen Hawking, included this project in the Breakthrough Initiative together with the Listen and the Message Projects devoted to SETI with the sponsorship of Yuri Millner and Marc Zuckerberg.

Many problems still need to be solved, from the miniaturization of the probe to the construction of a very light sail, from the stability and the control of the spacecraft to the possibility of broadcasting back to Earth the data gathered at such enormous distance.

Since the project is based on private funding, it will not negatively affect other space exploration endeavors, like the human exploration of Mars, which are more near-term oriented. On the contrary, the capability of sending very high speed microprobes can positively affect all other space activities, generally motivating aerospace research.

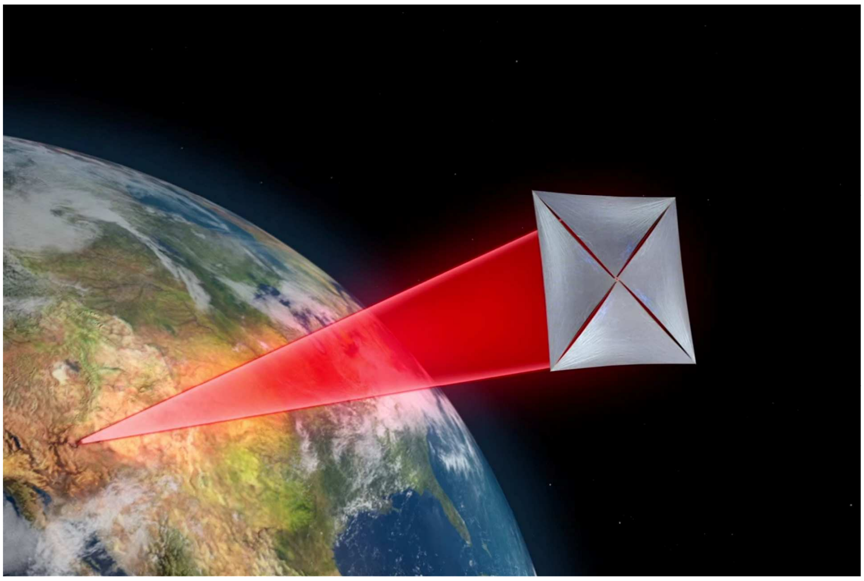

Figure 1. Breakthrough Starshot program: a microprobe pushed by a laser beam operating from the Earth surface.

Compact and rapid schemes for creation of ultracold and quantum degenerate gases

Aidan Arnold, University of Strathclyde (UK)

Laser cooled atoms form the basis of an entire field of quantum systems. Compared with terrestrial labs, SWAP (size, "weight" and power) is a very limited and expensive commodity in space-based experiments, which is being explored in a drive towards miniaturisation of the core technology required for laser cooling. At Strathclyde we have begun a sequence of experiments to create compact and robust systems for atom-optics based quantum technologies, with the aim of simplifying the core vacuum and optical systems for creation of laser-cooled and quantum-degenerate gases. In this talk I will report on how these are being developed as a ubiquitous tool, but will also discuss specific application to atomic clocks and atom interferometers.

This work is support by the UK National Quantum Technologies Programme, and by the European Space Agency.

When free-falling screen records interference and standing screen does not

Kevin Günthner, Max Planck Institute for the science of light (Germany)

Quantum key distribution (QKD) allows for information-theoretical secure key exchange between two remote parties and is one of the most developed applications of quantum mechanics.[1] QKD protocols have already been implemented in metropolitan networks all around the world. However, these networks are still missing long-haul links connecting them among each other. Optical satellite communication is a promising method to provide such links and thus QKD over larger distances. In order to establish this quantum technology in space, existent Laser Communication Terminals (LCTs) can be adapted to be suitable for quantum communication. To validate the feasibility of our approach, one needs to precisely characterize the quantum noise behaviour of the system including the channel. To this end we have performed quantum-limited homodyne measurements of optical signals from the LCT situated on the Alphasat satellite in geostationary Earth orbit.[2] We show that the coherence of the quantum states is preserved after they propagated over 38600 km and the turbulent atmosphere and we give an upper bound for any excess noise that the states might have acquired.[3]

Bibliography

1. V. Scarani et al., RevModPhys. 81, 1301 (2009)
2. F. Heine et al., Proc. SPIE 93540G (2015)
3. K. Guenthner, I. Khan et al., arXiv:1608.03511 (2016)

Miniature Magneto-Optical Traps for Quantum Technology

Matt Himsworth, University of Southampton (UK)

Space, power and weight are the major engineering challenges for any space mission. Typical cold-atom systems involve bulky and heavy ultra-high vacuum (UHV) systems which require constant pumping from power hungry ion pumps. Whilst in deep space or high earth orbits the environment precludes the need for a vacuum chamber, whereas at low earth orbit pressures skirt the boundary were neutral atoms can be cooled efficiently. Moreover, the systems require large UHV chamber for ground testing and the harsh conditions at launch will be a significant risk to alignment of precision optics. Our research aims to address the issue of compact UHV by adapting materials and methods from the semiconductor microfabrication industry to create matchbox-sized Magneto-optical traps. These incorporate passive (zero power) hermetic UHV cells, atoms sources, very low power magnetic field coils (mW) and integrated optics. The cells are fabricated from silicon and (radiation-tested) glass and are therefore very low weight and robust. This presentation will discuss our current state of development and explore the possibility of cold atoms in cube-sats for timing and sensing applications.

QUCODE: a robust encoder for alignment-free satellite QKD

Radu Ionicioiu, Horia Hulubei National Institute of Physics and Nuclear Engineering (Romania)

Satellite-based QKD is a key element of a future quantum internet. The recently launched Chinese quantum satellite (August 2016) is the first step towards this goal. A problem of the standard polarization-based QKD is basis alignment, i.e., the requirement to maintain a shared reference frame between the parties. This is especially critical in space-based scenarios (ground-to-satellite, satellite-to-satellite) in which the parties are moving at high relative speed. Active alignment involves extra resources (lasers, detectors, control electronics, actuators) which increase weight and complexity. A better solution is to encode the qubits into rotationally-invariant states which are immune to arbitrary rotations around the beam direction. In this case we encode one qubit into two degrees of freedom of a single photon, polarization and orbital angular momentum (OAM). This is usually done with a q-plate, an anisotropic, birefringent, liquid-crystal wave-plate which entangles the polarization and OAM. Since a q-plate requires electric tuning, this adds complexity and weight to the system (source, controller, voltage and temperature stabilisation etc). Thus a q-plate is not suited for a space-based platform.

Here we propose a robust, passive, bulk-optics encoder/decoder which has the same functionality as a q-plate but without its drawbacks. Our QUCODE uses only passive optical elements in a stable Sagnac configuration.

QUCODE has several advantages: (i) symmetry: QUCODE works as both an encoder and a decoder. This reduces the footprint in a satellite-based scenario; (ii) stability: compared to other setups, the Sagnac configuration is intrinsically stable; (iii) absence of active control: since we use only passive optics, no active control is required (in contrast to the q-plate). QUCODE is simpler and more robust, hence better suited for the harsh operating environment of a satellite.

QUCODE can be used also as a plug-and-play device to upgrade existing free-space QKD systems, by inserting the module before/after the channel. This relatively simple operation converts a standard QKD system requiring active alignment into an alignment-free system.

The Space Quest mission: Testing Gravitational Decoherence with Entanglement

Siddarth Joshi, IQOQI Vienna, Austrian Academy of Sciences

General relativity and quantum mechanics predict phenomena on very different scales and their merger has been a well studied field for ¿ 100 years. Several models predict a decoherence like effect due to gravity.[1] A recent advance[2] based on the event formalism predicts a non- linear quantum effect that can only be observed using entangled systems. We present a detailed mission proposal to measure this gravitational decoherence using an Optical Ground Station (OGS) and the International Space Station (ISS). Using time-energy entangled photon pairs form a Spontaneous Parametric Down Conversion source, Ref.[2] shows that the gravitational decoherence effect will result in a loss of correlation in the arrival times of the photons from a pair. Our experimentally feasible scheme utilizes the NightPod and the 400mm telephoto lens already on board the ISS. Using proof of principle experiments on a 144 km free-space optical link as well as calculations, we study the effect of losses, background noise, pointing errors, orbital motion and atmospheric effects. Further, our experimental scheme is ideal for ground to space quantum communication and testing other aspects of fundamental quantum mechanics, like Bell tests,[3] over unprecedented length scales which are inaccessible on the ground. Ultimately leading to a global quantum network and unconditionally secure communication.

Bibliography

1. Anastopoulos C and Hu B L 2013 Class. Quantum Grav. 30 165007.
2. Ralph, T. C. and Pienaar, J. Entanglement decoherence in a gravitational well according to the event formalism. New J. Phys. 16, 085008 (2014).
3. Scheidl, T., Wille, E. and Ursin, R. Quantum optics experiments using the International Space Station: A proposal. New J. Phys. 15, 111 (2013).

Fluctuating quantum optical channel

Evgeni Karpov, Universite Libre de Bruxelles(Belgium)

We consider information capacity of Satellite Earth quantum optical communications. Although being transparent in the optical domain the atmosphere partially absorbs/scatters passing light thus effectively behaving as a lossy channel, which is well represented by a Gaussian quantum map. The same effect arises due to beam wandering resulting in the partial loss of light. Moreover, the unstable atmospheric conditions lead to the variable losses. In order to take into account these variations we consider lossy bosonic quantum channels with fluctuating parameters. We investigate the influence of these fluctuations on the classical capacity and homodyne/heterodyne rates of the channel. Our model leads to a new averageÓ channel map. We analyze the capacity and the rates of the new channel and observe that the influence of the fluctuations on the average values is mainly defined by convexity properties of transmission rates. The influence of the fluctuations of the average map is not straightforward, because generally the map becomes non-Gaussian, however our results show that the behavior of its information transmission rates is qualitatively similar to the ones of the Gaussian channel determined by the corresponding average parameters. In particular, we show that the noise in the environment can even provide higher transmission rates.

Quantum Technologies at the European Space Agency

Bruno Leone, European Space Agency (ESA)

An brief overview of quantum technology activities at ESA will be presented, including: technology development activities, envisaged application areas and missions under study. A brief summary of the "Quantum Technology - Implementations for Space" workshop that took place at ESA/ESTEC last November will also be presented. The workshop brought together ESA, European space industry and research institutes, and, for the first time, a selection of national and EU QT commercialisation programmes. One of the workshop's finding is that space can, not only benefit from quantum technologies, but also play a key role in facilitating the emerging European quantum technology industry.

Quantum Optics Experiments on the Hard Road to Space

Matthias Lettner, OHB System AG

The field of Experimental Quantum optics is currently on the edge of evolving from demonstrations of fundamental physics in the laboratory towards real world applications. Especially the prospect to bring quantum technologies to space promises to open a wide field of interesting applications starting form extended tests of fundamental Physics over metrology of gravitational phenomena up to the concrete need for secure communication using quantum encrypted channels. However despite space being a quiet and favorable environment for precision experiments, mechanical stress during launch as well as thermal and radiation conditions in orbit pose strong requirements on technologies used on board of a satellite. In my talk I will try to lay out the main steps to be taken in order to "spacify" technology that is already successfully established in the Lab. OHB is one of the major Large System Integrators for space systems in Europe with considerable heritage in manned and unmanned space missions. By understanding the scientific use case and providing a profound knowledge of the current space flight market we want to bridge the gap between science and industry, thereby guiding quantum technologies towards their application in space.

Performance and security of single-photon receiver for a quantum satellite

Vadim Makarov, University of Waterloo (Canada)

I will summarize activities in Waterloo on development of compact single-photon polarization analyser module for the Canadian quantum satellite project. We have performed ground-based radiation testing and damage mitigation for Si APDs, with goal to achieve 2 years or longer operation lifetime in low-earth orbit. After thermal and high-power laser annealing, the damaged APDs recover their performance to well below 200 dark counts per second. Interestingly, laser annealing achieves much higher reduction of the dark count rate than thermal annealing at the same temperature. We have also studied potential security loopholes in free-space polarization analyser against a well-equipped attacker residing in the optical beam. Spatial mode efficiency mismatch in the receiver, and countermeasures to it, have been tested. We have demonstrated that the countermeasure can be destroyed by high-power laser damage. Backflash emission from the APDs has been quantified. We have demonstrated that an attacker can distinguish between photon polarization emitted back into the channel from the receiver. We have quantified the amount of leaked information, and eliminated it via additional privacy amplification. Our compact receiver is thus now ready at TRL4-5 for space applications, and provides a quantifiable level of security for QKD. The receiver has been part of a ground-to-airplane QKD experiment performed in Canada in September 2016.

Quantum engineering developments at ESA for future space missions

Eamonn Murphy, European Space Agency, ESA-ESTEC

The successful development of high resolution, ultra-sensitive (implicitly quantum) systems for future space missions requires the harmonious integration of payload and platform technical activities, guided by detailed system level design and implementation studies. This presentation will describe the ongoing and completed technical activities at ESA principally in the domains of Matter Wave Interferometry (MWI) and Optical Atomic Clocks (OAC) in support of future applications in Fundamental Physics and Earth Science. Key enabling generic elements have been selected by ESA in order to best support these applications. These developments include laser cooling and trapping systems, ultra-narrow linewidth laser systems and optical frequency combs which play key roles in these applications. The goals of these developments are to achieve the desired performance requirements and enhance the sub-system reliability and lifetime, while continually supporting an ongoing system level evolution.System evolution to flight is a complex process and ways and means to reduce the timeframe between Engineering Model (EM) and Flight Systems (FS) shall be explored invoking past successful experience with flight hardware development.[1] The presentation focusses on applications (WG3) but implicitly also combines elements of implementation (WG4).

Bibliography

1. Kallenbach, R., et al, Space-qualified laser system for the BepiColombo Laser Altimeter, Applied Optics, Volume 52, Issue 36, December 20, 2013

Quantum Fuels for Quantum Machines

Ozgur Mustecaplioglu, Koç University (Turkey)

Quantum machines powered by non-thermal (quantum coherent) baths can be classified into two kinds:[1] (i) Machines of the first kind, where the working substance of the machine receives both heat and work from the non-thermal bath. (ii) Machines of the second kind, where the working substance of the machine can receive only heat from the non-thermal bath. Second kind machines act as genuine heat engines, subject to Carnot bound, and while the machines of the first kind are hybrid thermo-mechanical machines devoid of Carnot bound. We consider a generic micromaser setting used to introduce photo-Carnot engine[2] in which atomic clusters, as small finite size non-thermal baths, are used to periodically pump the micromaser cavity field acting as the working substance. We investigate how the quantum coherences in the non-thermal atomic clusters determine the kind of the quantum machine and the performance limits. We make a disjoint classification of quantum coherences (in non-thermal small finite baths) similar to the classification of the quantum machines.[3] We name the quantum coherences that lead to machines of second kind as "heat exchange coherences" while the others associated with the machines of the first kinds are named as "displacing" and "squeezing" coherences. We identify typical multiatom W-type states as quantum fuels with high octane and purely flammable coherences for genuine quantum heat engines. Our identification allows us to utilize five orders of magnitude larger coherences than the early photo-Carnot engines. An alternative scheme to energise a photo-Carnot engine as a quantum machine of second kind is proposed by using an ancillary single atom "bath" to harvest quantum coherences out of a "spin star network".[4] These results fundamentally distinguish the work and heat value of specific quantum coherences and practically suggest to engineer task dependent quantum fuels for specific quantum machines.

Bibliography

1. W. Niedenzu et al., New J. Phys. 18, 083012 (2016).
2. M. O. Scully et al., Science 299, 862 (2003).
3. C. B. Da? et al., 18, 244 (2016).
4. D. Turkpence et al., arXiv e-print: 1611.01475 (2016

Nanosatellites for Space Quantum Science & Technology

Daniel Oi, University of Strathclyde (UK)

Bringing quantum science and technology to space o?ers exciting prospects for both fundamental physics and applications such as long-range secure communication and quantum probes for inertial sensing with enhanced accuracy and sensitivity. But despite important terrestrial pathnding precursors and promising proposals, few large-scale quantum test beds in space have been realised due to the high costs and lead times of traditional Big Space' satellite development. But the small space' revolution, spearheaded by the rise of nanosatellites such as CubeSats, is an opportunity to greatly accelerate the progress of quantum space missions by providing easy and a?ordable space access and encouraging agile development. We review CubeSats, their rapidly developing capabilities, and how they are being used to advance quantum satellite systems.

Quantum technologies in Ireland: entangled photon emission from scalable arrays of site-controlled quantum dots

Emanuele Pelucchi, Tyndall National Institute (Ireland)

The Tyndall National Institute hosts a number of prominent experimental activities in the field of quantum information technologies. One of these is led by E. Pelucchi and his Epitaxy and Physics of Nanostructure group. His is the only experimental team in Ireland (at the moment) routinely performing cryogenic quantum optics experiments with quantumÓ sources. The group has developed a full technology thread in house, starting from the epitaxy of single site-controlled quantum dots, their quantumÓ characterization as, e.g., entangled photon emitters, to the development of single electrically pumped devices, which, as recently reported, allow Bell's inequalities violation. His research has been recently featured in Nature Photonics (http://www.nature.com/nphoton/journal/vaop/ncurrent/full/nphoton.2016.203.html)

Cold Atom Gravity Sensors for Geodesy

Franck Pereira dos Santos, Systmes de Rfrence Temps Espace (SYRTE) (France)

Today, atom interferometers perform measurements of inertial forces with sensitivities and accuracies that compete with state of the art classical sensors, and in particular of the Earth gravity acceleration with ground-based atom gravimeters. The space environment offers the possibility to drastically extend the interrogation time, up to several seconds, which increases the scale factor of the sensors by orders of magnitude, leading to new applications in fundamental physics and geodesy. I will discuss the potential applications of this technology to gravity field mapping onboard satellites and describe different instrument architectures and mission scenarii, optimized for the determination of the static gravity field with high spatial resolution or the time varying field over the long term. In particular, I will report on an ongoing ESA study of a "Cold atom interferometry gravity gradiometer and mission concepts" which lies on the instrument architecture proposed in.[1] Ongoing work focuses on a detailed model of the interferometer sensor and its different subsytems, on the determination of the impact of external perturbations and of the required control of the satellite attitude, and on the impact of the sensor performances on the determination of the Earth gravity field. I will also discuss related ongoing breadboarding activities.

Bibliography

1. Carraz, O., Siemes, C., Massotti, L. et al. Microgravity Sci. Technol. (2014) 26: 139.

Towards precise measurements in space with cold atoms

Simon Plant, University of Birmingham (UK)

Atom interferometry can provide extremely precise measurements of gravity. The technique is therefore promising for the exploration of fundamental physics, including tests of the equivalence principle, the detection of gravitational waves and for probing quantum phenomena. The deployment of atom interferometers in the microgravity and low-vibration environment of space may enable further enhancement of their performance, whilst permitting the investigation of physical phenomena over much larger spatial and temporal scales than is possible with a ground-based instrument. In space, atom interferometers could be utilised for Earth observation as part of a next generation gravity mission.

In this talk, I will present an overview of our efforts in developing and maturing atom interferometry technologies for space-based applications. I will report on progress of the development of a portable gravity gradiometer for ground-based measurements in the field, as well as our efforts towards a spaceborne gravity gradiometer aiming at next generation gravity missions. I will also introduce details of the CASPA project, an initiative to develop a cold atoms-based space payload.

Airborne Demonstration of a Quantum Key Distribution Receiver Payload

Christopher Pugh, University of Waterloo (Canada)

Demonstrations of quantum key distribution (QKD) with moving platforms are important to prove the viability of future satellite implementations. Thus far, however, demonstrations of QKD to aircraft have operated exclusively in the downlink configuration, where the quantum source and transmitter are placed on the airborne platform. While this approach has the potential for higher key rates, it is more complex and is not as flexible as an uplink configuration, which places the quantum receiver on the airborne platform while keeping the quantum source at the ground station. Here we present the first successful demonstration of QKD to a receiver on a moving aircraft.

The apparatuses for our demonstration consist of a QKD source and transmitter located at a ground station at Smiths Falls-Montague Airport, and a custom QKD receiver (built with future space flight in mind) located on a Twin Otter research aircraft from the National Research Council of Canada. The airplane flew two path types: circular arcs around the ground station, and lines past the ground station. The distances for each type of pass varied from 3 to 10 km.

In total, we were able to generate finite-size secure key in 5 passes of the airplane, with one showing over 800 kb. The loss in the various passes ranged from 34.4 to 51.1 dB. The circular passes allowed the demonstration of longer link times, whereas the line passes were more representative of a satellite pass over a ground station. Angular speeds (at the transmitter) between 0.4 degree/s and 1.28 degree/s were achieved.

We have demonstrated the viability of components of a quantum receiver satellite payload by successfully performing quantum key distribution in an uplink configuration to an airplane. The major components in the receiver payload (fine pointing unit, integrated optics assembly, detector modules, control and data processing unit) have a clear path to flight for future satellite integration.

Discrete-Variable Time-Frequency Quantum Key Distribution for Satellite Communication

Jasper Rödiger, Fraunhofer Heinrich Hertz Institute (Germany)

Quantum key distribution (QKD), the first applicable quantum technology, is used to distribute a secret key to two parties, which can then be used for absolutely secure communication. Establishing a QKD network over satellites is a promising way of making quantum-secure communication ready to use in a large area. For such a network a suitable QKD protocol is needed.

We investigate a discrete variable (DV) QKD protocol based on the time-frequency uncertainty relation and referred to as DV time-frequency (TF?) QKD. It is a BB84-like QKD protocol with the two bases being realized by discrete modulations in time and frequency, namely the pulse position modulation (PPM) and frequency shift keying (FSK). With one photon per pulse, measuring in one of the bases increases the uncertainty in the other basis and thus deletes the information possibly encoded therein.

DV-TF-QKD can be implemented mostly with standard telecom-technology in the 1550 nm band. The PPM basis can be implemented with modulators and the FSK basis with help of frequency-duplexing technology. In DV-TF-QKD, polarization is not used (contrary to polarization-based BB84) and thus can be used for duplexing. With PPM and FSK, it is possible to use an arbitrarily large alphabet and thus to transmit more than 1 bit/photon. Moreover PPM and FSK are robust in free-space channels.

We have demonstrated an implementation of the DV-TF-QKD protocol using two symbols per basis over fiber and over a free-space testbed. Especially the free-space tests are an important step towards satellite based QKD networks. Furthermore an experiment using four symbols in each basis (4-PPM and 4-FSK) were successfully demonstrated as the first step toward large alphabets. In addition we performed numerical simulations to optimize the pulse forms used in the two modulations. Currently we are implementing a bidirectional beam-steering system satisfying the requirements of QKD which will compensate for vibrations and atmospheric turbulences.

The DV-TF-QKD protocol has significant advantages over the BB84 QKD protocol over free space. Thus the DV-TF-QKD protocol is a promising candidate to be used in future QKD networks, particularly with regard to satellite links.

Spacetime metric fluctuations and gravitational decoherence

Albert Roura, Universität Ulm (Germany)

It has been argued in a number of studies that a stochastic background of gravitational waves (GWs), or even the quantum fluctuations of the graviton vacuum, can lead to potentially observable decoherence in matter-wave interferometry experiments. By exploiting the similarities with the more familiar case of electromagnetism, I will introduce some of the key concepts and ideas in a non-technical manner. In particular, I will emphasize the importance of considering gauge-invariant operational observables and outline a simple derivation of the decoherence effects induced by a stochastic background of GWs for matter-wave interferometry experiments in space.

To conclude, I will show that although the effects of quantum vacuum fluctuations of the spacetime metric are extremely small at present, it is believed that they played a crucial role in the early universe. Indeed, in the current cosmological paradigm the primordial inhomogeneities that acted as seeds for the large-scale structure formation of the universe are the result of the amplification and stretching to cosmological scales of microscopic vacuum fluctuations during an early period of quasi-exponential accelerated expansion known as cosmological inflation.

Mission I-SOC: an optical clock on the ISS

Stephan Schiller, Heinrich-Heine-Universität Düsseldorf and the I-SOC science team

CThe ESA mission "Space Optical Clock on the ISS", I-SOC, aims at operating an optical lattice clock on the ISS in 2022$+$. The mission is the natural follow-on of the ACES mission. The scientific goals of the mission are to perform tests of fundamental physics (Einsteins gravitational time dilation), to enable space-assisted relativistic geodesy, and to intercompare optical clocks on the ground at the 1×10^{-18} level. The geodesy goal will allow the determination of the local gravity potential with accuracy at equivalent level of 1 cm within 1 day measurement time. Comparison of ground clocks via the ISS will be performed using enhanced MWL and ELT. The space clocks specification is 1×10^{-17} inaccuracy, mass approximately 100 kg, power consumption of 250 W. A modular, transportable breadboard demonstrator has been developed and has reached less than 2×10^{-17} instability. Critical technology development is under way, funded by ESA.

Quantum to Classical transition induced by time dilation

Boris Sokolov, University of Turku (Finland)

We study gravitational decoherence induced by time-dilation[1] for a Schroedinger cat state, considering also the effect of a non-asymptotic observer. We five a holistic view of the quantum to classical transition by comparing the dynamics of several non-classicality indicators, such as the Wigner function interference fringe, the negativity of the Wigner function, the non-classicality depth, the Vogel criterion and the Klyshko criterion. Our results, show that, only the first indicator depends critically on to the size of the cat, namely on how macroscopic the superposition is. Finally we compare the gravitational-induced decoherence times to the typical decoherence times due to classical noise originating from statistical fluctuations in the characteristic parameters of the system.[2] We show that the experimental observation of decoherence due to time-dilation imposes severe limitations on the allowed levels of classical noise.

Bibliography

1. I. Pikovski, M. Zych, F. Costa and C. Brukner, Nat. Phys. 11, 668 (2015).
2. J. Trapani, M. Bina, S. Maniscalco, and M. Paris, Phys.Rev. A 91, 022113 (2015).

Broadband energy entangled photons and their potential for space applications

Andre' Stefanov, Institute of Applied Physics, University of Bern (Switzerland)

We present recent experiments performed with broadband energy entangled photons. Their high entanglement content find applications for quantum information with entangled qudits. Together with their high production rate, they are good candidates for distributing entanglement over large distances. They strong temporal correlations can find also applications for clock comparison and for ranging.

Fundamental Physics Experiments in Space

Timothy Sumner, Imperial College London (UK)

A number of existing and proposed space experiments to test fundamental physics theories will be discussed. These will all be based around the concept of macroscopic proof-masses as the central scientific instrument payload. Experiments covered will include GP-B, STEP, GAUGE, Microscope, LISA Pathfinder and LISA. The talk will emphasise the requirement specification placed on the proof-masses and discuss technical challenges posed by each.

Detecting metrologically useful entanglement in Dicke states

Geza Toth, University of the Basque Country (Spain)

Dicke states have raised considerable attention, since they are highly entangled, yet much more robust to particle loss than the famous Greenberger-Horne-Zeilinger (GHZ) states. They have been realized in photonic systems. Recently, there have been successful experiments in creating symmetric Dicke states of thousands of atoms in Bose Einstein condensates. Such states, in principle, make quantum metrology possible with a Heisenberg scaling. Note that this is not true for spin-squeezed states which are used typically for metrology in cold gases.

We discuss, how to detect multi-particle entanglement in Dicke states prepared in an experiment with few measurements. We also show how to verify the metrological usefulness of quantum states based on few measurements, without the need to carry out the metrological procedure itself. According to the most accepted definition of macroscopicity, states with a high metrological usefulness possess macroscopic entanglement and in a sense, they are close to Schrodinger cats. Hence, our method also helps us to study macroscopic entanglement in experiments. All these help in characterizing the quantum state with the smallest experimental effort possible.

CubeSat Opportunities For In-Flight Testing Of Quantum Technologies

Marius Trușculescu, Institute of Space Science (Romania)

The poster presents an overview of the CubeSat centered activities at the Institute of Space Science in Romania. We first present an outline of GOLIAT a CubeSat type nanosatellite launched in 2012 for which most of the subsystems were fully developed in house. We continute with the evolution from GOLIAT to other similar missions (RoBiSAT as part of QB50), involvement in ESA projects related to nanosatellites, and to the development of specialized hardware for small satellite missions through national grants. These research activities create a basis for rapidly developing experiments centered on the CubeSat platform with the purpose of in-flight validation and testing of new technologies. The poster therefore ellaborates on the opportunities for proof-of-concept missions focused on several quantum related technologies by evaluating their requirements within the limitations of the nano class of satellites. We conclude with a general presentation of the expertise and infrastructure of the nanosatellite research group at the institute.

Towards Atom Interferometry in Space

Tristan Valenzuela, STFC - Ruterford Applerton Laboratory (UK)

Since the early 90's Matterwave interferometry has shown its potential as a new implementation of inertial sensors. During the last decade, many efforts have been put into the development of portable Gravity sensors based on Cold Atom Interferometers (CAI) and a few proposal for space instruments have been put forward but failed, mainly, due to the relatively low readiness level (TRL) of the involved technologies. At RAL Space we have recently set up a Cold Atom laboratory that will use the long experience in developing space instruments to raise the TRL of critical subsystems. In particular, as a first step, we are developing Space qualifiable control electronics for Cold Atoms experiments. Here we are presenting on one side the development of a CAI based Gravity Gradiometer being developed as a test bed for all the required technologies and the electronics developments on the other side.

Study of Relativistic effects observed in Space Quantum Channel

Paolo VIlloresi, Universita' degli Studi di Padova (Italy)

The exchange of qubits along Space channels was experimentally demonstrated with quantum bit error rate (QBER) low enough to envisage the realization of global secure communications based on QKD. However the opportunity provided by the different conditions of the space terminal with respect to the ground one, an in particular a constantly varying relative velocity of the order of several km/s and the different gravitational potentials are opening a new class of investigations on Quantum Physics in Space. Here we report on the experiments investigations on the relativistic transformation of the phase of a flying time-bin qubit along a 5000 km path, together with a general perspective of the research area.

Bibliography

1. D. Rideout et al., Fundamental quantum optics experiments conceivable with satellites reaching relativistic distances and velocities, Classical and Quantum Gravity **29**, 224011 (2012).
2. H. Xin, Science **332**, 904 (2011)
3. P. Villoresi et al., Experimental verification of the feasibility of a quantum channel between space and Earth, New J. Phys. **10**, 033038 (2008).
4. G. Vallone et al, Experimental Satellite Quantum Communications, Phys. Rev. Lett. **115**, 040502 (2015). Editors Suggestion. Viewpoint http://physics.aps.org/articles/v8/68. Selected as Highlight of the Year 2015, American Physical Society, http://physics.aps.org/articles/v8/126.
5. D. Dequal et al. Experimental single photon exchange along a space link of 7000 km, Phys. Rev. A **93**, 010301(R) (2016).
6. G. Vallone et al. Interference at the Single Photon Level Along Satellite-Ground Channels, Phys. Rev. Lett. **116**, 253601 (2016).

Cavity optomechanics: a playground for fundamental tests of physics

David Vitali, Universita' degli Studi di Camerino (Italy)

Optomechanical and electromechanical systems play an important role within current information and communication technologies, enabling applications in disparate fields, from sensing to wireless communication . These systems have recently entered the quantum regime, and squeezed and entangled states of radiation and mechanical degrees of freedom have been generated and detected. These devices offer therefore a unique playground, either for new technological solution in the field of classical and quantum information processing, and for investigating fundamental aspects of quantum theory. Here we provide a brief review of how these systems can be prepared and monitored in order to test quantum mechanics and in particular the largely unexplored region where quantum mechanics meets gravity.

Zerodur based optical systems for precision measurements in space

Andre' Wenklawski, University of Strathclyde (UK)

Robust and stable optical systems are a key technology for experiments concerning quantum science or the application of quantum technology to e.g. precision measurements based on ultra-cold atoms.

Next to the experimental requirements, their utilization in space imposes a number of additional demands on the systems, like mechanical and thermal stability which have not been met by commercial providers.

To meet these requirements, we have developed optical systems based on Zerodur glass ceramics. This is a material which is characterized by a vanishing coefficient of thermal expansion (CTE) over a very large temperature range (0ąC - 50ąC) and is therefore very suitable for the high temperature fluctuations to be expected during a space mission.

The optical components are connected to a Zerodur optical bench by means of various adhesives. This permits direct adjustment during the curing process of the adhesive, and at the same time the combination of various light-curing adhesives allows for the manufacturing and adjustment of more complex components, like fiber couplers.

Within the DLR-funded projects FOKUS, KALEXUS, LASUS and MAIUS, various systems ranging from spectroscopy modules for the frequency stabilization of lasers to complete beam distribution and switching modules for precision experiments with atom interferometry using ultra-cold quantum gases have already been built and tested on sounding rockets.

The aforementioned projects are supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant numbers DLR 50 WM 1131 1137, DLR 50 WM 1237-1240, DLR 50 WM 1345, and DLR 50 WP 1431 1435.

Chip scale mesoscopic nanosphere optical trapping

George Winstone, University of Southampton (UK)

Efforts to create a centimeter scale chip based levitated mesocopic nanosphere optical trap are detailed. Microchip scale vacuum technologies are combined with high numerical aperture parabolic mirrors in order to reduce the system characteristic length for a high Q optomechnical system to that compatible with both a circuit board and a cube satellite.

Atoms in space

Wolf von Klitzing, FORTH IESL (Greece)

Despite their sometimes complicated internal structure, atoms are a workhorse of quantum optics. They serve as quantum memory in quantum communication or computation, as the basic constituent of matter-wave interferometers and of the macroscopic quantum states of a Bose Einstein condensate. They also act as the reference for time and frequency. We have acquired an almost incredible level of control over all properties of atoms. They can be trapped and cooled into the motional ground state. Their spin can be controlled with nearly infinite precision. Their electronic state can be manipulated on a time-scale of atto seconds and with a precision of milli Hertz.

In this talk, I will attempt to give an overview over the various ongoing activities to bring this extraordinary level of control to space. I will give examples of fundamental experiments as well as more applied sensors.

CETAL: a research infrastructure for photonic-based technologies

Marian Zamfirescu, National Institute for Laser, Plasma and Radiation Physics(Romania)

The Center for Advanced Laser Technologies (CETAL) is a new research infrastructure recently commissioned in Bucharest-Magurele (Romania). CETAL is dedicated to research and innovation in advanced photonic technologies and includes three main laboratories: 1. LaMP, Laboratory for Laser Material Processing 2. PhIL, Photonic Investigations Laboratory 3. CETAL-PW, Laboratory for High-Field Laser Physics.

The CETAL infrastructure can be used to fabricate, characterise and test integrated optics as promising devices for quantum technologies for space.

At LaMP we can fabricate photonic crystals, metamaterials and optical waveguides as components for future photonic quantum devices. For this we employ 3D laser lithography using two-photon polymerisation (TPP) or laser direct writing (LDW) with sub-micrometer resolution. The integrated optical components are then characterised using the photonic investigation equipment from PhIL.

We can do simulations of space-like environment using temperature, vibration and radiation testing. The vibrometry set-up can perform tests from 5 to 3000 Hz and shock tests with acceleration of up to 100G. Using the interaction of ultra-short and high-intensity laser pulses with matter, the petawatt (PW)-class laser at CETAL generates energetic particles and radiation with energies from few MeV to tens of MeV. This can be used to test the fabricated integrated optical devices in simulated space radiation conditions.

The CETAL infrastructure is available for research institutes as well as for industrial entities.

MoSi SNSPDs for space-to-ground quantum communication

Hugo Zbinden, University of Geneva (Switzerland)

Detection of single photons is a fundamental tool to implement quantum communication from space to ground. We will give an overview our effort to develop efficient, fast and low-noise superconducting nanowire single-photon detectors based on molybdenum silicide. We discuss their potential for realising large collection areas compatible telescope-based optical receivers.

Quantum Communication with Satellites - complementing Quantum Optics with Space Weather considerations

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Space weather, the branch of space physics concerned with the environmental conditions of Earth's magnetosphere, ionosphere and thermosphere, plays an essential role in studying and designing traditional free-space optical (FSO) communication systems with satellites. In particular, frequency ranges and transmission rates are often determined by space weather considerations (for the case of geostationary communications satellites, see e.g.[1]). When considering different FSO quantum communication schemes with satellites, space weather aspects will be even more relevant due to the fragile nature of entangled states. In this context, one has to deal with a complex physical situation: quantum optics has to be complemented with knowledge about the electromagnetic environment of Earth (and its disturbances). From the theoretical side one can hope to capture the relevant effects and build a dissipative open system model, however, due to the complicated physics involved, these models has to be later thoroughly tested against future experimental data. To tackle the emerging complex problems, we have followed the interdisciplinary approach of QTSpace; within Hungary, respective groups working on space and quantum physics has planned a joint effort on studying these questions. Here we report to the QTSpace COST Action about the first steps taken by the joint Hungarian effort. Specifically, we have considered our recent magnetosphere model obtained from measurement data,[2] and have tried to the isolate the main effects on quantum communications. We will discuss some crude estimates of these relevant effects, and how one can make more precise calculations and modeling. Finally, we discuss also practical aspects of a possible experiment.

Bibliography

1. W. Lohmeyer, "Data Management of Geostationary Communications Satellite Telemetry and Correlation to Space Weather" PhD Thesis, MIT Space Systems Laboratory (2013).
2. G. Facskó et al, One year in the Earth's magnetosphere: A global MHD simulation and spacecraft measurements, Space Weather 14 (5), 351-367 (2016).