Lisbon Training Workshop on Quantum Technologies in Space

Instituto Superior Técnico
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11-14 September 2017

Book of Abstracts

We gratefully thank the support from:

PROGRAMME

MONDAY, 11.09.2017

08h30 – 09h00: REGISTRATION
09h00 – 10h00: *Tutorial on Quantum Communication*, Christoph Marquardt
10h00 – 11h00: *Tutorial on Quantum-enhanced measurements*, Antoine Heidmann
11h00 – 11h30: COFFEE BREAK
11h30 – 12h30: Hands-on *Mission Analysis Aspects*, Florian Renk
12h30 – 14h00: LUNCH
14h00 – 14h30: *The Quest for Quantum Projects in Space,* Diego Pozo-Morillas
14h30 – 15h00: *BEC interferometry in µg*, Naceur Gaaloul
15h00 – 15h30: *Testing gravity with atomic sensors on ground and in space*, Guglielmo Tino
15h30 – 16h00: COFFEE BREAK
16h00 – 16h30: *Optical Communications at ESA*, Zoran Sodnik
16h30 – 17h30: PANEL DISCUSSION, *Quantum Technologies in Space – Institutional and Commercial Interests*
17h30 – 18h00: BREAK
18h00 – 20h00: POSTER SESSION & EXHIBITION

TUESDAY, 12.09.2017

09h00 – 10h00: *A Fundamental Science Space Mission – LISA Pathfinder and the LTP Experiment*, Rüdiger Gerndt
10h00 – 11h00: *Tutorial on Quantum-enhanced measurements*, Antoine Heidmann
11h00 – 11h30: COFFEE BREAK
11h30 – 12h30: *Hands-on Bose-Einstein Condensates for Space*, Stephan Seidel (Leibniz University Hannover)
12h30 – 14h00: LUNCH
14h00 – 14h30: *Design considerations of a satellite quantum communication payload*, Matthias Fink
14h30 – 15h00: *Satellite-based quantum communication*, Jean-Philippe Bourgoin
15h00 – 16h00: PANEL DISCUSSION, *Quantum Communication*
19h00 – 22h00: CONFERENCE DINNER

WEDNESDAY, 13.09.2017

09h00 – 10h00: ***Implementation and Results of a Large Science Space Mission – Rosetta Mission*****, Rüdiger Gerndt**
10h00 – 11h00: ***Tutorial on Quantum Communication*****, Christoph Marquardt**
11h00 – 11h30: COFFEE BREAK
11h30 – 12h30: ***Hands-on Optical Trapping*****, James Millen (University of Vienna)**
12h30 – 14h00: LUNCH
14h00 – 14h30: ***Testing quantum technology on a cube satellite*****, Harald Weinfurter**
14h30 – 15h00: ***MAQRO & New Science Ideas*****, James Bateman**
15h00 – 15h30: ***Space test of Newtonian self-gravitation*****, André Großardt**
15h30 – 16h00: COFFEE BREAK
16h00 – 16h30: ***Searches for dark matter using cold atoms on ground and in space*****, Peter Wolf**
16h30 – 17h30: PANEL DISCUSSION, ESA's ***New Science Ideas***
17h30 – 18h00: BREAK
18h00 – 19h00: EVENING TALK ***Tests of quantum mechanics and gravitation with atom interferometry*****, Mark Kasevich**

THURSDAY, 14.09.2017

09h00 – 09h30: ***Platforms for Quantum Technologies in Space*****, Mike Cruise**
09h30 – 10h00: ***Controlling nanoparticles in vacuum*****, James Millen**
10h00 – 10h30: ***QuSpace: Quantum opto-mechanics in Space*****, Bob Dirks**
10h30 – 11h00: ***Technology developments in ground based astronomy with potential interest to space science mission*****, Gerald Hechenblaikner**
11h00 – 11h30: COFFEE BREAK
11h30 – 12h30: Talks by the winners of the poster prizes
12h30 – 14h00: LUNCH
14h00 – 14h30: ***The Case for QT in Space*****, Paolo Bianco**
14h30 – 15h00: ***Laser Communication Terminals as crucial building blocks for QKD from Satellite to Ground*****, Herwig Zech**
15h00 – 15h30: ***Satellite-based QKD activities at TNO/QuTech*****, Clara Osorio Tamayo**
15h30 – 16h00: COFFEE BREAK
16h00 – 17h00: PANEL DISCUSSION, ***Working Goup 2, Applications of Quantum Technologies in Space***
17h00 – 19h00: MANAGEMENT COMMITTEE MEETING (only for MC members)

Invited Talks

MONDAY 11.09.2017

8h30 – 09h00: REGISTRATION

9h00 – 10h00: ***Tutorial on Quantum Communication*****, Christoph Marquardt (Max Planck Institute for the Science of Light)**

10h00 – 11h00: ***Tutorial on Quantum-enhanced measurements*****, Antoine Heidmann, Laboratoire Kastler Brossel (UPMC-Sorbonne Universitès)**

11h00 – 11h30: COFFEE BREAK

11h30 – 12h30: ***Mission Analysis Aspects*****, Florian Renk (ESOC)**

12h30 – 14h00: LUNCH

14h00 – 14h30: ***The Quest for Quantum Projects in Space,*** **Diego Pozo-Morillas (Airbus D & S Toulouse)**
This presentation will summarize the different collaborations and attempts to test different quantum physics and communications concepts in Space over the last few years, and how big and settled space companies are now tackling the subject.

14h30 – 15h00: ***BEC interferometry in µg*****, Naceur Gaaloul (Leibniz University Hannover)**
Atom interferometry in microgravity promises a major leap in improving precision and accuracy of matter-wave sensors [1]. When taking advantage of the unique micro-gravity environment, fundamental tests challenging the state-of-the-art can be performed using quantum gases systems. In this talk, we report about our recent progress in devising atom interferometry experiments to test Einstein's equivalence principle at the 10^{-15} level or better [2] and detecting gravitational waves with high accuracy. The use of cold atoms as a source for such sensors poses however intrinsic challenges mainly linked to the samples size and mixture dynamics in case of a dual-atomic test. Proposals to mitigate leading systematics in projects involving extensive interferometry times are discussed in this talk as well. Innovative methods of quantum engineering at lowest energy scales inspired from our droptower experiments and sounding rocket missions are therefore considered in this context [3-5].

[1] N. Gaaloul, et al. Proc. Int. School of Physics "Enrico Fermi" Volume 188 (2014).
[2] D. N. Aguilera et al., Class. Quantum Grav. 31, 115010 (2014).
[3] T. van Zoest et al., Science 328, 1540 (2010).
[4] H. Müntinga et al., Phys. Rev. Lett. 110, 093602 (2013).
[5] J. Rudolph et al. New J. Phys. 17, 079601 (2015).

15h00 – 15h30: ***Testing gravity with atomic sensors on ground and in space*****, Guglielmo Tino (University of Florence)**
Quantum sensors based on ultra-cold atoms, namely, atom interferometers and optical atomic clocks are new tools enabling precision measurements in gravitational physics. I will discuss recent results and future prospects of experiments to test gravity in laboratory and in space.

15h30 – 16h00: COFFEE BREAK

16h00 – 16h30: ***Optical Communications at ESA*****, Zoran Sodnik (ESA)**
The presentation will start with an explanation why ESA is pursuing optical communications technologies, followed by a summary of the main space activities performed. It will then introduce the latest development trends and give an outlook for future developments.

16h30 – 17h30: PANEL DISCUSSION, *Quantum Technologies in Space – Institutional and Commercial Interests*

17h30 – 18h00: Break

18h00 – 20h00: POSTER SESSION & EXHIBITION

9h00 – 10h00: ***A Fundamental Science Space Mission – LISA Pathfinder and the LTP Experiment*****, Rüdiger Gerndt (Airbus D & S, Germany)**

10h00 – 11h00: ***Tutorial on Quantum-enhanced measurements*****, Antoine Heidmann (Laboratoire Kastler Brossel, UPMC-Sorbonne Universitès)**

11h00 – 11h30: COFFEE BREAK

11h30 – 12h30: ***Hands-on Bose-Einstein Condensates for Space*****, Stephan Seidel (Leibniz University Hannover)**

12h30 – 14h00: LUNCH

14h00 – 14h30: ***Design considerations of a satellite quantum communication payload*****, Matthias Fink (Institute for Quantum Optics and Quantum Information – Vienna)**

Quantum communication using optical satellites links will be one solution to overcome distance limitations imposed by loss in the optical fiber and noise in the detectors. In this talk, we investigated the feasibility of bringing quantum technology science payload into space, on-board a small CubeSat platform. We will focus on the link budget of a quantum key distribution mission and discuss the impact of pointing, tracking and acquisition precision on the quantum bit error rate (QBER).

14h30 – 15h00: ***Satellite-based quantum communication*****, Jean-Philippe Bourgoin (Institute for Quantum Computing, University of Waterloo)**

Quantum key distribution (QKD) utilizes fundamental principles of quantum mechanics to establish provably secure communications between two parties. However, technological realities limit terrestrial implementations to distances of only a few hundred kilometers. One promising solution is the use of low-Earth-orbit satellites as nodes in a global-scale quantum communications network. Recently, China has demonstrated this solution a satellite QKD transmitter. Independently, Canada has been advancing it's own satellite QKD project towards a satellite QKD receiver. In this talk I will be giving an overview of the Canadian project, with a focus on the detailed link analysis to predict the performance of the systems, and on the hardware development and tests conducted to prepare for this satellite QKD mission.

15h00 – 16h00: PANEL DISCUSSION, ***Quantum Communication***

19h00 – 22h00: CONFERENCE DINNER

WEDNESDAY 13.09.2017

9h00 – 10h00: ***Implementation and Results of a Large Science Space Mission – Rosetta Mission*****, Rüdiger Gerndt (Airbus D & S, Germany)**

10h00 – 11h00: ***Tutorial on Quantum Communication*****, Christoph Marquardt (Max Planck Institute for the Science of Light)**

11h00 – 11h30: COFFEE BREAK

11h30 – 12h30: ***Hands-on Optical Trapping*****, James Millen (University of Vienna)**

12h30 – 14h00: LUNCH

14h00 – 14h30: ***Testing quantum technology on a cube satellite*****, Harald Weinfurter (Ludwig Maximilian University of Munich)**
How small a satellite can be used for QKD? We describe plans to test components suitable for cube-sats.

14h30 – 15h00: ***MAQRO & New Science Ideas*****, James Bateman (University of Swansea)**
MAQRO is a proposal to use levitated optomechanics, in a space environment, to test the quantum superposition principle with large masses. This talk will outline the science goals of MAQRO, describe the experimental approach, and discuss some of the recent progress and outstanding technical challenges.

15h00 – 15h30: ***Space test of Newtonian self-gravitation*****, André Großardt (Queen's University Belfast)**
We discuss the hypothetical possibility of a theory in which only matter is quantised, but gravity is described by the classical theory of General Relativity, even at the fundamental level. From the most naive approach for such a theory, a gravity-matter coupling according to the semi-classical Einstein equations, one obtains the Schrödinger-Newton equation as a non-relativistic limit. We present possibilities of experimental tests of such an alternative to Quantum Gravity both on Earth and in space.

15h30 – 16h00: COFFEE BREAK

16h00 – 16h30: ***Searches for dark matter using cold atoms on ground and in space*****, Peter Wolf (SYRTE, Observatoire de Paris)**
We use 6 yrs of accurate hyperfine frequency comparison data of the dual rubidium and caesium cold atom fountain FO2 at LNE-SYRTE to search for a massive scalar dark matter candidate. Such a scalar field can induce harmonic variations of the fine structure constant, of the mass of fermions, and of the quantum chromodynamic mass scale, which will directly impact the rubidium/caesium hyperfine transition frequency ratio. We find no signal consistent with a scalar dark matter candidate but provide improved constraints on the coupling of the putative scalar field to standard matter. Our limits are complementary to previous results that were only sensitive to the fine structure constant and improve them by more than an order of magnitude when only a coupling to electromagnetism is assumed. We present our recent results published in [PRL 117, 061301 (2016)] and discuss some future directions of research that could be pursued in this field on ground and in space.

16h30 – 17h30: PANEL DISCUSSION, ESA's ***New Science Ideas***

17h30 – 18h00: BREAK

18h00 – 19h00: EVENING TALK *Tests of quantum mechanics and gravitation with atom interferometry*, Mark Kasevich (Stanford University)

Recent de Broglie wave interference experiments with atoms have achieved wavepacket separations as large as 54 cm over time intervals of 2 sec. These experiments, and their impact on gravitational and quantum physics, will be discussed.

THURSDAY 14.09.2017

9h00 – 09h30: ***Platforms for Quantum Technologies in Space*, Mike Cruise (University of Birmingham)**
This talk will trace the development of space platforms for fundamental physics experiments and the properties which they offer for Quantum Measurement. Following examples from previous space projects, the philosophy of instrument design will be explored in an attempt to bring forward useful principles for future missions.

9h30 – 10h00: ***Controlling nanoparticles in vacuum*, James Millen (University of Vienna)**
Levitated nanoparticles are seen as excellent devices for testing quantum physics, building quantum technologies and for sensing tiny forces. In this talk, I will discuss techniques for manipulating nanoparticles at low pressures, controlling their motion and rotation, and how we understand their interaction with the environment. Nanofabrication can be used to optimize the material and geometry of the nanoparticles under study, and also to produce new tools to bring the motion of such nano-objects into the quantum regime. Finally, I will discuss the challenges of, and solutions to, working with nanoparticles in ultra-high vacuum.

10h00 – 10h30: ***QuSpace: Quantum opto-mechanics in Space*, Bob Dirks (TNO)**
QuSpace aims to elucidate one of the longest-standing issues in physics: explaining how our classical world emerges from quantum mechanics. Quantum behavior, in the form of quantum superpositions, has been confirmed in small particles like electrons, atoms and small molecules (<10-20 g), while 'classical' behavior (characterized by the absence of superposition) is expected to hold for objects down to 10e-6 g. This leaves an unexplored gap of 14 orders of magnitude wherein it is unknown if objects behave classically or quantum mechanically, which is mainly due to the lack of experimental evidence available. In this presentation we will explain our proposal to examine the quantum behavior of macroscopic objects. We describe a series of unprecedented quantum optomechanical experiments using mechanical micro-oscillators in the mass range from 10e-12 g to 10e-6 g. A space environment would be ideal thanks to the strongly reduced seismic and technical noises but also to enable the unique possibility to investigate quantum evolution of massive superpositions in a different gravitational field than on Earth. We will discuss the recent progress of earth-bound experiments and explore a possible future space experiment and the challenges that come along with it.

10h30 – 11h00: ***Technology developments in ground based astronomy with potential interest to space science mission*, Gerald Hechenblaikner (European Southern Observatory)**
The past decades have seen extensive technology developments in the area of ground based astronomy, allowing the construction of increasingly larger telescopes for improved angular resolution and sensitivity. Active optics, adaptive optics and new developments in image sensors for the infrared and optical domains are among the core enabling technologies. In this presentation we will discuss recent developments on ground and their potential use for fundamental science space missions.

11h00 – 11h30: COFFEE BREAK

11h30 – 12h30: Talks by the winners of the poster prizes

12h30 – 14h00: LUNCH

14h00 – 14h30: ***The Case for QT in Space*, Paolo Bianco (Airbus UK)**
The presentation will cover the rationale on why space is an attractive application field for QTs (extending from Malta workshop) and what it requires to QTs to be attractive to space (both institutional and commercial). This will be presented and analysed from the perspective of the forthcoming EC QT Flagship, ESA programmes and competing effort from other players.

14h30 – 15h00: ***Laser Communication Terminals as crucial building blocks for QKD from Satellite to Ground*****, Herwig Zech (Tesat)**

In the last years, optical communication in space has evolved significantly. Opitcal communication between satellites and from LEO or GEO satellites to ground was demonstrated. The European Data Relay System (EDRS) is using optical intersatellite links in a data relay application. Since the beginning of 2017 the related commercial data relay service is operational, bringing data from the LEO satellites of the Copernicus fleet to ground on a daily basis. In parallel, several direct to ground laser terminal developments took place. The OSIRIS terminal, developed by DLR Institute of communication and navigation, was launched to orbit for direct communication from LEO satellites to ground. In summary, optical communication in space has reached a high level of maturity and numerous applications are under discussions for future space missions. Quantum key distribution is seen as a key application for optical communication in space. A QKD source can be combined with a Laser Communication Terminal and the QKD signal can be sent to an optical ground station. The advantage of QKD from space is to overcome the distance limit of terrestrial fiberbased QKD systems. The combination of QKD and LCT technology has therefore a high potential for future key distribution systems. In this talk, the status of Laser Communication Terminals for space applications will be given and the application of QKD in combination with LCTs will be described.

15h00 – 15h30: ***Satellite-based QKD activities at TNO/QuTech*****, Clara Osorio Tamayo (TNO)**

For over 50 years, TNO has developed scientific instrumentation for space: from ultra-accurate spectrometers used to monitor climate change to optomechatronic systems for astronomic measurements. Based on this experience, and thanks to our collaboration with TU Delft in the QuTech consortium, we are expanding our research towards space-based quantum technologies. During this talk, I will describe our recent developments on quantum communications. In particular, I will discuss our new laser satellite communications system, which is the ideal platform for the implementation of satellite-based quantum key distribution protocols.

Posters

Experimental Relativistic Quantum Information with a Geostationary Satellite

Ömer Bayraktar[1,2], Kevin Günthner[1,2], Imran Khan[1,2], Dominique Elser[1,2], Christoph Marquardt[1,2], Gerd Leuchs[1,2]

[1] Max Planck Institute for the Science of Light (MPL), Erlangen
[2] Institute of Optics, Information and Photonics, Friedrich-Alexander University Erlangen-Nürnberg (FAU)

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-basedquantum communication.

[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. Günthner et al., arXiv:1608.03511 (2016).

Phase estimation with multi-mode Gaussian states

Dominic Branford[1], Haixing Miao[2], Animesh Datta[1]

[1] Department of Physics, University of Warwick
[2] School of Physics and Astronomy, University of Birmingham

Phase estimation is one of the most fundamental applications of quantum metrology, with relevance to tasks including magnetic field estimation and gravitational wave detection. Gravitational waves can be observed through measuring the displacements in test masses in an interferometer, such displacements are detected through reflecting light off these test masses and measuring the phase shift in the reflected light. In order to better resolve displacements it is beneficial to use higher intensity light, yet reflected photons cause random fluctuations in the mirror's motion which can obscure the gravitational wave signal amidst this radiation-pressure noise. We explore the extent to which multi-mode states of light-generated by driving the interferometer with a set of lasers each operating at a distinct frequency-can provide an advantage in overcoming radiation-pressure and how the fundamental limit to precision is affected. Real-world limitations of such experiments are considered in the form of optical loss, as well as how multi-mode interferometers benefit from methods such as inputting squeezed light and frequency-dependent measurements which are beneficial to single-mode interferometers.

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

Oliver Burrow[1], Aidan Arnold[1], Erling Riis[1], Paul Griffin[1]

[1] Department of Physics, University of Strathclyde

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 poster 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.

MoSi SNSPDs for space-to-ground quantum communication

Felix Bussières[1,2]

[1] Group of Applied Physics, Université de Genève (GAP)
[2] ID Quantique (IDQ)

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.

Experimental bounds on collapse models from gravitational wave detectors

Matteo Carlesso[1,2], Angelo Bassi[1,2], Paolo Falferi[3,4], Andrea Vinante[3]

[1] Department of Physics, University of Trieste
[2] Istituto Nazionale di Fisica Nucleare, Sezione di Trieste (INFN Trieste)
[3] Istituto di Fotonica e Nanotecnologie (CNR), Fondazione Bruno Kessler
[4] INFN - Trento Institute for Fundamental Physics and Applications

Wave function collapse models postulate a fundamental breakdown of the quantum superposition prin- ciple 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 and preparatory laboratory activities.

Olivier Carraz[1], Luca Massotti[1], Christian Siemes[1], Roger Haagmans[2], Linda Mondin[3], Eamonn Murphy[3], Pierluigi Silvestrin[3]

[1] RHEA for ESA, Netherlands
[2] ESA, France
[3] ESA, Netherlands

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 compared to the 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.

Additionally, a short outline of planned mission preparatory laboratory activities shall be presented.

QUANTUS-2 - Ultra-low expansion rates of an atomic ensemble for matter-wave interferometry in microgravity

Merle Cornelius[1], Tammo Sternke[1], Sven Herrmann[1], Claus Lämmerzahl[1], The Quantus-Team[2,3,4,5,6]

[1] ZARM, Universität Bremen
[2] Institut für Quantenoptik, Leibniz Universität Hannover
[3] Institut für Physik, Humboldt-Universität zu Berlin
[4] Institut für Physik, Johannes Gutenberg-Universität Mainz
[5] Institut für Quantenphysik, Universität Ulm
[6] Institut für angewandte Physik, TU Darmstadt

The goal of the QUANTUS-2 experiment is to perform dual-species matterwave interferometry in microgravity at the drop tower in Bremen, Germany. Aiming for precision measurements to test the equivalence principle, long interferometer times in the range of seconds are crucial to increase the sensitivity of the measurement. Therefore ultra-low residual expansion rates of the used atomic ensembles are required, which can be achieved by magnetic lensing - also known as delta-kick collimation.

Here we present our results of a magnetic lens to collimate a rubidium BEC in microgravity and demonstrate expansion rates of 100m/s in all directions, which is equivalent to the expansion of a thermal ensemble with a temperature of less than 100pK. This enables the observation of the ensemble after 2s of free evolution time with a high signal to noise ratio. Lens aberrations and possible optimization approaches to lower the expansion rate further will be discussed. Hence, in the future an ideal source for precision atom interferometry in microgravity can be provided.

Feasibility of Quantum Key Distribution from Space

Daniele Dequal[1], Luis Trigo Vidarte[2,3], Giuseppe Vallone[4,5], Paolo Villoresi[4,5], Eleni Diamanti[3]

[1] Agenzia Spaziale Italiana (ASI)
[2] Institut d'Optique Graduate School, Institut d'Optique Graduate School (IOGS), Palaiseau
[3] LIP6 UPMC, Université Pierre et Marie Curie, Paris
[4] Dipartimento di Ingegneria de l'Informazione (DEI), Department of Information Engineering Via Gradenigo, Padova
[5] Istituto di Fotonica e Nanotecnologie (IFN), Padova

Quantum Key Distribution (QKD) is commercially available using optical fiber links that allow the secure establishment of key between two parties at distances in the order of a few hundred km. For longer distances the attenuation of the fiber limits the range at which the security of these protocols is still valid. Satellite links allow the communication in free-space where the losses per km are much lower, extending the range of QKD to intercontinental distances in principle. There are nonetheless other effects that have to be taken into account in order to calculate the expected secure key rate for a certain link. The scenario assessed in this work examines a downlink setting where a LEO satellite (Alice) sends information to the ground (Bob). The information secretly shared between Alice and Bob that is not known by a possible attacker (Eve) will determine the secret key rate, which will depend on the protocol used and the evolution of the channel. The analysis covers both discrete variables (DV-QKD) and continuous variables (CV-QKD) protocols. The channel is considered non-static and the expected distribution of availability is parameterized modeling errors due to pointing, divergence and optic imperfections. This allows the segmentation of the received symbols into bins that can contribute to the key rate or be discarded. The security of this segmentation is discussed. Particular emphasis is taken in order to cover realistic implementations, including the coupling from free-space to single-mode fiber or the use of adaptive optics.

Numerical Modelling and prototyping of a Helical Resonator for Ion Traps

F. J. Diaz-Otero[1], D. A. Outerelo[1], F. I. De Vicente[1], L. Pedrosa-Rodriguez[2], R. Gómez-Alcalá[3]

[1] Signal Theory and Comms Dept, University of Vigo
[2] OHB System AG, Predevelopment and Studies, Oberpfaffenhofen
[3] University of Extremadura

Ion traps have proven themselves to be a powerful tool for mass spectrometry [1] and frequency standards [2], while being at the same time one of the most promising candidates for quantum optics [3] and quantum computation [4]. In recent years technological advances tried to miniaturize ion traps while minimizing perturbation from the trap's electromagnetic field and maximizing the number or ions confined. The latter is obtained through carefully designed surface-electrode ion traps while the former is done applying a high potential to the trap electrodes employing a high-quality (Q) factor resonator.

We design a stable, high voltage and low noise helical coil resonator to generate a trapping radio frequency (RF) potential for charged particles. We perform an analytical approach to determine an optimal relationship between the physical dimensions of the resonator and the corresponding quality factor following classical RF filter equations[4] and an empirical study of shielded helical coil resonators. Moreover, computational electromagnetics commercial software is used to confirm the validity of the analytical approach. This allows us to predict the Q-factor, resonant frequency, S-parameters and electrical properties of the lumped circuit. This systematic approach permits to fabricate a RF helical resonator devised for ion trapping particles for space applications with enhanced performance as compared with the original model.

[1] Paul, W., Rev. Mod. Phys., Vol. 62, No3, 531–540, 1990.
[2] Bollinger, J. J., et al., IEEE T. Instrum. Meas., Vol. 40, No, 2,126–128, 1991.
[3] Cirac, J. I. and Zoller, P., Phys. Rev. Lett., Vol. 74, No, 20,4091–4094, 1995.
[4] Häffner, H., Roos, C. F. and Blatt, R., Physics Reports. , Vol. 469, No, 4,155–203, 2008.

Optical distribution board for atom quantum experiments in space

Ioannis Drougkakis[1,2], Konstantinos Mavrakis[2,1], Konstantinos Poulios[1], Dimitrios Papazoglou[1,2], Wolf Von Klitzing[1]

[1] Institute of Electronic Structure and Laser, Foundation for Research and Technology Hellas
[2] Materials Science and Technology Department, University of Crete (MSD-UoC

A large number of optical systems used in space applications, such as interferometers, telescopes, telemetry and communications systems require optical benches that are extremely robust, stable, reliable and efficient. For quantum experiments in space [1-2] a major challenge is coupling light into single mode optical fibers after having traversed a number of active and passive optical elements (fiber-free space-fiber scheme) arising the need of accurate and stable optical breadboard technology. This leads to high level of complexity for the benches and for the sub-components used. As a consequence of trade-offs between robustness, complexity, reliability and constrains in manufacturing, coupling efficiencies lie typically below 50% while efficiencies at the order of 80% have been demonstrated [3] at the cost of an increased complexity of their sub-components and procedures. Here we report a novel scheme, which allows precise beam-steering for fiber-free space-fiber systems on a Zerodur breadboard using optical wedges and flats. This approach greatly reduces the complexity of the optical system. In particular it allows to use less precise sub-components, simplifies the fiber couplers used as well as the manufacturing process. We present an in-depth analytical theoretical treatment of the scheme, along with raytracing numerical simulations for a number of different optical systems. We corroborate our analysis with preliminary thermal performance tests performed on a Zerodur prototype breadboard, exhibiting 88% coupling efficiency with 2% fluctuations at a 10-40°C temperature range.

”Space-Time Explorer and QUantum Equivalence Space Test”, Yellow Book of STEQUEST, ESA/SRE 6 (2013)

[1] R. Kaltenbaek et al. EPJ Quantum Technology 3, 5 (2016)
[2] H. Duncker et al., Appl. Opt. Vol. 53, pp. 4468-4474 (2014)

Free-space Quantum Network of Room-Temperature Quantum Devices

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We are progressing towards building a free-space quantum network, containing several high duty-cycle room-temperature quantum memories interconnected using high-rate single photon sources. The realization of a quantum network that is intrinsically secure and operates over long-distances requires the interconnection of several quantum modules performing different tasks. Progressing quantum technologies towards room temperature operation is key to unlock the potential and economical viability of these novel architectures. Along these lines, warm vapor alleviates the need for laser trapping and cooling in vacuum or cooling to cryogenic temperatures.

We have shown for a first time a network of quantum devices in which breakthrough operational capabilities are possible and have achieved the first proof of principle combination of free-space propagation of random single-photon level polarization qubits and their storage and retrieval in a room temperature quantum memory. These results effectively constitute the quantum part of the *BB84* protocol with the addition of a quantum memory. Furthermore we have shown noise-suppression techniques that allow our network to operate in a regime useful for quantum cryptographic communication with low *QBER*'s. Lastly, we have developed ultra-low noise fully-portable room-temperature quantum memories. This allows their use in remote observatory locations and opens a pathway for experiments with photons travelling over ultra-long satellite communication channels, paving the way towards memory assisted all-environment free-space quantum cryptographic networks.

Quantum-Limited Measurements of Optical Signals from a Geostationary Satellite

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Quantum key distribution protocols have already been implemented in metropolitan networks all around the world. A promising method to provide the still missing long-haul link between such networks is optical satellite communication. To this end, existing Laser Communication Terminals (LCTs) can be upgraded to be suitable for quantum communication. An important step towards this objective is to precisely characterize the quantum noise behaviour of the system including the channel. We have performed quantum-limited measurements of optical signals from the Alphasat TDP1 LCT in geostationary Earth orbit. We show that quantum coherence is preserved after propagation of the quantum states over 38600 km. An upper bound for the excess noise that the states could have acquired after propagation is estimated [1].

[1] K. Günthner, I. Khan et al., Optica 4, 611-616 (2017).

JOKARUS-A spaceborne iodine frequency reference based on a diode laser at 1064nm

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Laser-based frequency references with high accuracy and stability are needed for future space missions dedicated to precision tests of fundamental physics, Earth observation or gravitational wave astronomy (e.g. LISA). Laser frequency stabilization to the narrow (sub-MHz) hyperfine transitions of the R(56)32-0 line in molecular iodine provides the means to reach the required performance of planned space missions.

The JOKARUS payload comprises a compact optical frequency reference based on Doppler-free modulation transfer spectroscopy (MTS) in molecular iodine at 532nm, using an externally frequency-doubled, micro-integrated, narrow-linewidth ECDL MOPA. It is optimized for autonomous operation onboard a TEXUS sounding rocket scheduled to start this year. In order to verify the lock stability, there will be an in-flight comparison to an RF-clock-referenced frequency comb. The JOKARUS mission provides the first spaceborne operation of an optical absolute frequency reference in space and therefore constitutes a pathfinder for future global navigation systems.

In this poster, we report on the system design and preliminary, ground-based performance. Further, we present the autonomy concept as well as an approach for reliable experiment control and monitoring. Both come in form of a modular open-source software which is adaptable to other spectroscopy-based active optical frequency references or similar setups.

Quantum Optics Experiments on the Hard Road to Space

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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 from 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 favourable 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. I will present the main steps to be taken in order to ”spacify” technology that is already established successfully 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 are a valuable partner to bridge the gap between science and industry in current and future missions. The poster will present some of OHB’s recent endeavours towards our particular aim: guiding quantum technologies to their application in space.

Optimal detection of precessing spin ensembles

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Precise knowledge of the spin orientation of atomic ensembles is demanded in a wide range of scenarios, from further progress in best-in-class atomic clocks and magnetometers to the preparation of non-classical states of matter and memories. Implementing quantum-limited detection schemes is challenging, however. Shot-noise in the detectors can mask the motion of the spins limiting the precision of estimations. Here I describe recent work and results aimed at overcoming this challenge in alkali-based sensors. Particularly, I will report our progress in the development and verification of optimal techniques for real-time spin state estimation such as required in magnetic field sensing and control applications. The prospects of integrating these techniques with recently developed miniaturized spin polarized sensors, which may be deployed in space, will be discussed as well.

An optical dipole trap for dual-species atom interferometry with K and Rb in space

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The MAIUS II/III missions will perform dual-species atom interferometry with ultracold mixtures of Rubidium and Potassium quantum gases onboard sounding rockets. This platform enables longer, uninterrupted timescales of microgravity (µg) than any other ground based µg-facility. Therefore, these flights constitute an important demonstrator and pathfinder for future spaceborn missions targeting at high-precision quantum tests of the Einstein's Equivalence principle on persistent µg platforms like satellites or the International Space Station.

An important challenge for such a mission is the careful preperation of the quantum probes entering the interferometer which, amongst others, requires precise control of the center-of-mass (COM) positions. In MAIUS II/III, the dual-species mixture is therefore initially trapped and cooled in an atom chip based trap and then transferred into an optical dipole trap (ODT) which allows for tuning of the collisional properties via Feshbach resonances and the application of optical lensing methods for both species.

In this poster, we present the optical dipole trap laser system at 1064 nm for the MAIUS II/III payload. It is based on a microintegrated extended cavity diode laser, master oscillator power amplifier (ECDL-MOPA) module. We report in detail on design and performance of our compact, all-fibered system including acusto-optical modulator and optical switch, as well as on the results of environmental testing.

crypteq – a planned quantum communication spin-off at the Max-Planck-Institute for the Science of Light

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crypteq is currently a project at the Max-Planck-Institute for the Science of Light in Erlangen, Germany focused on the applications of quantum communication. The project is hosted within the Quantum Information Processing group of Dr. Christoph Marquardt in the division of Prof. Dr. Gerd Leuchs.

For over 15 years, a major focus of the group has been on technology using the concept of continuous variables and coherent states. Continuous variables refer to a measurement result yielding a continuous value when performing homodyne detection, as opposed to a discrete photon click/no-click event. The light emitted by a laser can be described by coherent states, which makes them simple to produce and a versatile tool in continuous-variable quantum communication protocols.

Protocols such as quantum key distribution were investigated and experimentally demonstrated in our group. There, a shared secret key is established between two communication partners by distributing quantum states and estimating the statistics of the measurement results to make sure no eavesdropper was listening.

Our recent studies have shown that continuous-variable quantum key distribution systems can learn from the years of experience the telecom industry has put into the careful design of so-called coherent communication systems. The technological similarity of the two fields is rapidly increasing with state-of-the art experiments, however one has to be careful not to implement every trick of the trade of coherent communication systems, since these tricks may sometimes lead to unwanted side channels that compromise the security of a quantum key distribution system.

cypteq is an effort to commercialize the technology behind quantum key distribution so that it may be employed in many different scenarios, ranging from metropolitan fiber networks, inner-city free-space quantum communication, links to aerial vehicles or space scenarios involving satellite links.

Quantum communications and metrology in satellite-based experiments

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We investigate quantum communication schemes and estimation techniques with photons sent from a planet or a satellite to a satellite, taking into account relativistic effects. We first derive the expression of the frequency shift for the photon travelling radially between different observers through the Kerr spacetime. We quantify how the relativistic alterations affect a simple QKD protocol. Working within the framework of relativistic quantum metrology, we are able to give precision bounds for the quantum measurements of physical parameters encoded in the spacetime surrounding the rotating planet, for example the planet's Schwarzschild radius and equatorial angular velocity.

A Cost-Effective Approach for Satellite Based Quantum Key Distribution

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A key technology for quantum experiments is quantum cryptography, and in particular quantum key distribution (QKD), which bridges the gap between fundamental tests of the concepts of quantum mechanics and potential applications in communication technology. While ground-based QKD systems are now in place in several institutions across the globe, their range on earth is fundamentally limited (absorption losses, line-of-sight).

To overcome this limitation, space-based QKD satellites have been proposed and first proof-of-concept satellites have been developed and deployed in the recent years. Despite its advantages, space-based QKD suffers from high costs and system complexities. In order to minimize the costs for the demonstration of space-based QKD, we are working on an iterative approach in which entangled photon sources are operated in a low-earth orbit aboard low-cost nanosatellites. This provides a cost-effective alternative to a full-scale QKD satellite.

At the heart of our technology lies the Small Photon Entangling Quantum System (SPEQS), a specifically designed, small entangled photon source based on spontaneous parametric down conversion (SPDC). The first generation of SPEQS that produced correlated photon pairs was successfully launched and its in-orbit operation was demonstrated. The source design will be further improved to produce entangled photon pairs. We give a brief overview on the progress made on this source (SPEQS-1) which will be launched within a year.

Our final goal is the development of a source (SPEQS-2) that provides entangled photon pairs with higher pair rates to overcome atmospheric turbulence and absorption losses and enable space based QKD on a small and cost-effective platform. Here, we present the progress on our final source design. First experiments show that an in-orbit rate of 1 million entangled photon pairs per second is within reach.

Zerodur based optical modules for space and other adverse environments

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Numerous applications of quantum optics greatly benefit from a microgravity environment, e.g. atom interferometry. Such conditions can be realized by performing experiments in space aboard a sounding rocket, a dedicated satellite or a space station. Both the harsh conditions in space and during a rocket launch impose stringent requirements in terms of mechanical robustness and thermal stability.

To this end, we have developed a laser bench technology based on the glass ceramic Zerodur. This material has a vanishing first order coefficient of thermal expansion and exhibits great robustness against mechanical vibrations. Using sophisticated manufacturing techniques, we are able to fabricate miniaturized optical setups that can be accommodated in the limited space of a sounding rocket or space station. These include fibre couplers, mountings for the individual optical components as well as optical benches. The individual parts are joined using light-curing adhesives.

In combination with fibre-integrated components, we have implemented a variety of modules for laser frequency stabilization, intensity switching and beam distribution. These modules have been successfully used in the scope of three sounding rocket missions, namely MAIUS, KALEXUS and FOKUS, showing a technology readiness level of 9 (TRL for sounding rockets). We also plan to use the technology in the BECCAL experiment, a dual-species atom interferometry experiment aboard the International Space Station.

The role of quantum correlations in Cop and Robber game

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We introduce and study quantized versions of Cop and Robber game. We achieve this by using graph-preserving unitary operations, which are the quantum analogue of stochastic operations preserving the graph. We provide the tight bound for the number of operations required to reach the given state. By extending them to controlled operations, we define a quantum controlled Cop and Robber game, which expands the classical Cop and Robber game, as well as classically controlled quantum Cop and Robber game. In contrast to the typical scheme for introducing quantum games, we assume that both parties can utilise full information about the opponent's strategy. We show that the utilisation of the full knowledge about the opponent's state does not provide the advantage. Moreover, the chances of catching the Robber decreases for classically cop-win graphs. The result does not depend on the chosen model of evolution. On the other hand, the possibility to execute controlled quantum operations allows catching the Robber on almost all classically cop-win graphs. To provide interesting, non-trivial quantized Cop and Robber game, we need to enrich the structure of correlations between the players' systems. This result demonstrates that the ability to utilise quantum controlled operations is significantly stronger that the control restricted operating on classical selecting quantum operations only.

Drag-Free Sensors for fundamental physics and planet geodesy

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ONERA has been developing for 40 years space accelerometers with resolutions from the nano-g to the femto-g. The principle of operation of these accelerometers relies on the electrostatic levitation of a test-mass without any mechanical contact except a thin gold wire of less than 7µm. This gold wire maintains the stability of the test-mass charge in orbit when it is bombarded by cosmic particles. A capacitive sensor bridge measures very accurately the position of the test-mass along the 6 degrees of freedom at 10-11 m/Hz1/2. This measurement is used by a servo-loop controller that calculates the voltages to be applied on electrodes surrounding the test-mass. And thus, electrostatic forces and torques are exerted to maintain the test-mass motion-less with respect to the electrodes.

The low range and high resolution of servo controlled electrostatic accelerometers are well suited for geodesy and fundamental physics applications. For Geodesy, the CHAMP, GRACE, GOCE and GRACE-FO missions embark electrostatic accelerometers developed and tested in the laboratory. For the fundamental physics, MICROSCOPE aims to test the Equivalence Principle with 2 orders of magnitude better than current laboratory experiments. MICROSCOPE embarks a dedicated payload made of 4 electrostatic accelerometers derived from the GOCE/GRACE type accelerometers. Launched in 2016, the MICROSCOPE science is led by ONERA which developed the associated Science Mission Center in collaboration with the Observatoire de la Cote d'Azur.

The accelerometers used on the 2 last missions (GOCE for ESA and MICROSCOPE for CNES) were also used as drag-free sensors to reduce the range level of accelerations to be measured. The poster presented in Lisbon focuses on these two missions.

Fermionic Mode Entanglement Transformations

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In this study we aim to explore the possibility of entanglement transformations for a system with fermionic mode entanglement from a single particle source. Single particle entanglement as an idea is a relatively new concept which requires shifting the focus from entangled particles to mode entanglement. Hence in which extent can it be used for the purposes of quantum communication and information processing is an active area of research. In this study we focus on the entanglement transformations, such as distillability, of mode entangled single particle systems under LOCC. We try to explain the mode entanglement from a single fermionic source within the resource theory of entanglement and investigate compatibility of such systems for satellite and LEO communication.

Quantum dark solitons as qubits in Bose-Einstein condensates

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We study the possibility of using dark solitons in quasi-one-dimensional Bose-Einstein condensates to produce two-level systems (qubits) by exploiting the intrinsic nonlinear and coherent nature of the matter waves. We calculate the soliton spectrum and the conditions for a qubit to exist. We also compute the coupling between the phonons and the solitons and investigate the emission rate of the qubit in that case. Remarkably, the qubit lifetime is estimated to be of the order of a few seconds, being only limited by the dark-soliton ”death” due to quantum evaporation.

Tomography of Correlation Functions in Sodium Bose-Einstein Condensates

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We present a novel experimental scheme for reconstructing single-particle correlation functions of ultracold atoms from absorption images taken after various time of flights. The efficiency of this scheme is experimentally demonstrated in comparison of two different systems. Firstly, we created a quasi-one-dimensional Bose gas of ultracold sodium atoms, which is supposed to have a uniform phase distribution. Secondly, we used a digital mirror device to imprint phase pattern on the quasi-1D gas of the same condition. The result of the first system shows an approximate uniform correlation function, while that of the second shows an obvious different distribution. This scheme is independent of atomic species, and may thus be applicable to other ultracold atomic systems.

Quantum teleportation with misaligned reference frames

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Postselected quantum teleportation was recently performed from Earth to a satellite using an optical link [Ren et al 2017], a step towards building a 'quantum internet'. Reference frame uncertainty, due in this case to rotation of the satellite around the axis of the optical link, reduces the fidelity of the protocol, and is likely to be a recurrent problem in implementations of multi-party quantum protocols in space. We present a scheme for substantially reducing errors due to reference frame misalignment, applicable to a range of quantum protocols. Our scheme requires no additional protocol steps or communication bandwidth compared to the naive protocol, and is robust against dynamic reference frame errors, where the misalignment changes rapidly over time. We give worked examples for U(1) misalignment (rotation about an axis), and SU(2) misalignment (arbitrary spin rotation).

Autonomous control of ECDLs for dual-species atom interferometry on a sounding rocket

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We present the architecture of a robust and compact laser system for dual-species atom interferometry with Rubidium (Rb) and Potassium (K) quantum gases on a double-stage sounding rocket. As part of the MAIUS II/III payload, it is designed for laser cooling and optical trapping of both atomic species as well as simultaneous Raman double-diffraction interferometry to probe for differential accelerations.

The design of the laser system is based on the heritage of three sounding rocket flights, which demonstrated the first distributed feedback diode (DFB) laser based optical frequency reference, the first autonomously operating ECDL based laser payload for potassium spectroscopy and the first Bose-Einstein condensate (BEC) – each in space.

The laser sources for the MAIUS II/III laser system are micro-integrated diode laser modules that allow for compact size, small weight and superior mechanical stability while delivering sufficient optical power and spectral properties. One major challenge for reliable operation of the experiment in flight is the precise control of the laser frequencies throughout the interferometer sequence. In this poster, we report in detail on our concept for autonomous frequency control of extended cavity diode lasers (ECDL) in the challenging environment of a sounding rocket.

BOOST: A Test of Special Relativity

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BOOST is a mission that aims at testing the foundations of Special Relativity. The centre piece of BOOST are two frequency references mounted on a satellite. It is dedicated to test the validity of Lorentz invariance by comparing a length reference (i.e. a highly stable optical resonator) with a molecular frequency reference.

The current best Earth-bound test has been performed by Tobar et al. [1], being able to determine the Kennedy-Thorndike coefficient with an accuracy of 4 10-8 over the course of six years. By operating a state-of-the-art experimental setup in space for a duration of two years, that accuracy could be improved by two orders of magnitude.

In addition, BOOST could be employed to observe Lorentz violations and CPT violations. These violations are described by the standard model extension by introducing new terms to the according Lagrangian[2]. The accuracy of the associated coefficients could be improved by a two orders of magnitude in the electron sector by BOOST.

Finally, the molecular frequency reference is based on transitions in molecular iodine, which is sensitive to variations of the fine structure constant. Thus, BOOST allows an improvement in the constraints of the boost dependence of the fine structure constant up to two orders of magnitude compared with current best ground based experiments [3].

Furthermore, the expected scientific outcome, BOOST offers substantial technological progress. The operation of highly stable optical resonators and thereby optical clocks on board of a satellite is important for future scientific and technological missions, such as navigation and Earth observation.

While the BOOST payload is of low complexity, the experiment will allow substantial technological and scientific advancements.

[1] Tobar, et al., Physical Review D, 81 (2010) 022003.
[2] Colladay, et al., Physical Review D, 58 (1998) 116002.
[3] Tobar, et al., Phys. Rev. D, 87 (2013) 122004.