

Preface

From recent advances in research into the quantum nature of light and matter wave fields, the new area of quantum engineering has emerged. Quantum engineering has opened new horizons in quantum metrology for testing fundamental physical laws, reaching unprecedented levels of precision in measurements of space and time. The associated novel quantum technologies have led to atomic clocks and sensors that can be applied favourably in global geodesy, inertial sensing, navigation, and laser ranging.

The Physikalisch-Technische Bundesanstalt (PTB) has always been engaged in the development of precision measurement techniques beyond the state of the art. Over many years the PTB has had excellent cooperation partners at the Leibniz Universität Hannover (LUH), especially institutes in the faculties of mathematics and physics as well as geodesy, and at the Max-Planck-Institute for Gravitational Physics (Albert Einstein Institute, AEI), that perform top-level research in quantum engineering and closely related fields. Moreover, the close collaboration with the Laser Zentrum Hannover (LZH) and the Center of Applied Space Technology and Microgravity (ZARM) at the University of Bremen has proven to be extremely fruitful. This strong community was the prerequisite that eventually led to the establishment of QUEST – the Centre for Quantum Engineering and Space-Time Research – as a center of excellence at the Leibniz Universität Hannover.

Consequently, QUEST comprises the outstanding expertise of these partners to share knowledge within and improve the strengths of the Hannover-Braunschweig region. The central idea of the cluster is to link the four main research areas of quantum engineering, quantum sensors, space-time and enabling technologies, and to establish promising research activities, especially at the interface between the areas. Therefore, the future cooperation between PTB, LUH, AEI, LZH, and ZARM is systematically strengthened by a variety of QUEST-measures, for example by establishing a joint professorship and research groups on the campus of the PTB.

In this publication, the reader will be provided with an overview of the QUEST partners and of ongoing and planned QUEST-related research activities at the PTB.

We hope that the new QUEST institute at the PTB will live up to the highest expectations with leading contributions to the science and technology of quantum engineering and space-time research. We hope you enjoy reading this issue.



Professor Wolfgang Ertmer

Coordinator of the Centre
for Quantum Engineering and
Space-Time Research (QUEST)



Professor Ernst O. Göbel

President of the Physikalisch-
Technische Bundesanstalt
(PTB)

Fachorgan für Wirtschaft und Wissenschaft

**Amts- und Mitteilungsblatt der
Physikalisch-Technischen Bundesanstalt
Braunschweig und Berlin**

**Special Issue
Volume 119 (2009) No. 2**

Contents

QUEST (Centre for Quantum Engineering and Space-Time Research) at the PTB	
• <i>Stefan Pfalz</i> : Science in QUEST: The Quest of Science	5
• <i>Fritz Riehle</i> : QUEST at the PTB	11
• <i>Ekkehard Peik and Andreas Bauch</i> : More Accurate Clocks – What are They Needed for?	16
• <i>Ekkehard Peik and Uwe Sterr</i> : The Development of Accurate Optical Clocks	25
• <i>Dirk Piester and Harald Schnatz</i> : Novel Techniques for Remote Time and Frequency Comparisons	33
• <i>Christian Lisdat and Christian Tamm</i> : Super-Stable Lasers	45
• <i>Piet O. Schmidt, Borge Hemmerling, Birgit Brandstätter, Daniel Nigg</i> : Quantum Logic for Precision Spectroscopy	54
• <i>Uwe Sterr and Fritz Riehle</i> : Atom Interferometry	60

About this issue:

QUEST is a recently founded cluster of excellence funded by the German Science Foundation DFG. In the framework of QUEST, currently a new institute – the “QUEST institute at PTB” – is being implemented in order to conduct novel research into

quantum engineering, spectroscopy, atomic clocks, and time dissemination. The new institute closely interacts with and is supported by the PTB departments “Time and Frequency”, “Quantum Optics and Unit of Length”, and “Optical Technologies”.

Imprint

The **PTB-Mitteilungen** are the metrological specialist journal and official information bulletin of the Physikalisch-Technische Bundesanstalt, Braunschweig and Berlin. As a specialist journal, the *PTB-Mitteilungen* publishes scientific articles on metrological subjects from PTB's fields of activity. As an official information bulletin, the journal stands in a long tradition which goes back to the beginnings of the Physikalisch-Technische Reichsanstalt (founded in 1887). In the column "*Amtliche Bekanntmachungen*" (Official Notices), the *PTB-Mitteilungen* publish, apart from other things, the current tests and approvals of devices from the fields of verification, test centres, health care, radiation protection and safety engineering.

Publisher

Wirtschaftsverlag NW
Verlag für neue Wissenschaft GmbH
Bürgermeister-Smidt-Str. 74–76,
D–27568 Bremerhaven
Postfach 10 11 10, D–27511 Bremerhaven
Internet: www.nw-verlag.de
Email: info@nw-verlag.de

Editor

Physikalisch-Technische Bundesanstalt (PTB),
Braunschweig and Berlin
Postal address:
Postfach 33 45, D–38023 Braunschweig
Delivery address:
Bundesallee 100, D–38116 Braunschweig

Editorial staff/Layout

Press and Information Office, PTB
Dr. Dr. Jens Simon (editor in chief)
Dr. Christian Tamm (scientific co-editor of this issue)
Gisela Link
Tel.: +49 531 592-82 02
Fax: +49 531 592-30 08
Email: gisela.link@ptb.de

Reader and subscription service

Marina Kornahrens
Tel.: +49 471 9 45 44-61
Fax: +49 471 9 45 44-88
Email: vertrieb@nw-verlag.de

Advertising

Karin Drewes
Tel.: +49 471 9 45 44-21
Fax: +49 471 9 45 44-77
Email: info@nw-verlag.de

Frequency of publication and prices

The *PTB-Mitteilungen* are published four times each year in German language. An annual subscription costs Euro 55.00, one issue costs Euro 16.00, plus postage costs. The journal can be obtained from bookshops or from the publisher. Cancellations of orders must be made to the publisher in writing at least three months before the end of a calendar year.

© Wirtschaftsverlag NW, Verlag für neue Wissenschaft GmbH, Bremerhaven, 2009

All rights reserved. No part of this journal may be reproduced or distributed without the written permission of the publisher. Under this prohibition, in particular, comes the commercial reproduction by copying, the entering into electronic databases and the reproduction on CD-ROM and all other electronic media.

Science in QUEST: The Quest of Science

Stefan Pfalz¹

1 About QUEST

QUEST – the Centre for Quantum Engineering and Space-Time Research – is a recently founded cluster of excellence funded by the German Science Foundation DFG. QUEST comprises several institutes at the Leibniz Universität Hannover as well as the following partner institutions: The Albert Einstein Institute (Max Planck Institute for Gravitational Physics), the Laserzentrum Hannover e.V., the Physikalisch-Technische Bundesanstalt Braunschweig, and the Zentrum für Angewandte Raumfahrttechnologie und Mikrogravitation in Bremen.

Due to the outstanding expertise of all QUEST partners in the fields of quantum engineering and space-time research, the cluster aims for ambitious goals. In principle, QUEST will develop and exploit sophisticated methods and technologies to investigate fundamental issues arising from unsolved problems of modern physics. Today, questions like “How do quantum mechanics and gravity go together?” or “How did the Big Bang work?” are far from being understood in detail and show the limits of physical understanding. Nevertheless, the knowledge of the underlying physics would open new horizons and push forward the frontier of understanding fundamental physics. For example, temporal variations of fundamental constants or violations of Einstein’s equivalence principle are predicted by modern theories but up to now have not been found in experiments, mainly due to insufficient precision. If one could overcome these limitations and perform measurements with sufficient precision, the theories could be validated and even improved to model the underlying physics in more detail.

Therefore, the simultaneous development of techniques for high-precision measurements and implementation of modern theories beyond the state-of-the-art level is a promising way to efficiently explore exciting new physics. Thus, QUEST’s research plan is especially designed to perform top-level research following this

strategy: the synergetic combination of research and development in quantum engineering and space-time physics.

2 Quantum engineering: Engineering with light and matter at the quantum level

Lasers allow the manipulation of atomic or molecular inner degrees of freedom with ever increasing precision. Moreover, interference of laser light waves is one of the most powerful and precise tools for high-precision measurements, e. g. for measuring very small length changes. Due to the matter-wave duality in quantum mechanics, atoms and molecules also behave under certain circumstances like wave packets, so-called matter waves. Consequently, matter-wave interferometry has been successfully demonstrated and is a good candidate for next generation quantum sensors. Moreover, atom lasers have been proposed, leading to the new and promising field of atom optics.

In the recent past, stimulated by the development of laser cooling and trapped ion techniques, quantum engineering of matter waves has become the driving force of new inventions in atomic physics and quantum optics. Thus, today’s scientists are in the excellent situation of having control over the inner as well as the outer degrees of freedom of atoms (and probably soon of molecules) right down to the quantum limit. In parallel, the state-of-the-art of quantum engineering of light fields has propelled the measurement of space to entirely unforeseen horizons, finding its most spectacular realization in gravitational wave detectors. These devices demonstrate sensitivities for relative length changes at the 10^{-22} level, at which the direct measurements of gravitational waves is expected in the near future. Thus, the art of quantum engineering of matter and light as well as the capability of space-time measurements truly herald a new era for the exploration of fundamental

¹ Dr. Stefan Pfalz,
Chief Operating
Officer, Centre for
Quantum Engineering
and Space-
Time Research,
Leibniz Universität
Hannover
email: stefan.pfalz@
quest.uni-hannover.de

physical questions, for the onset of gravitational wave astronomy as well as for the invention of new quantum technologies.

3 Space-Time research: From the Big Bang to Einstein

One of the most challenging goals in fundamental physics is the unification of two well-established and confirmed theories: quantum theory and gravitation. During the last thirty years, theorists developed a plethora of sometimes rather radical concepts like string theory with extra space-dimensions, canonical or loop quantum gravity and non-commutative geometry. Although the ultimate theory of quantum gravity is not in our hands yet, the leading candidates all suggest specific novel space-time phenomena. Key examples are a violation of the equivalence principle, time variations of fundamental constants, space-time geometry fluctuations, anomalous dispersion relations, modified gravity, and a gravitational wave background. Research at the QUEST constellation will span topics from pure quantum gravity theory through phenomenology and up to experimental research and geodetic applications. The specific strength of QUEST lies in its unique mixture of space-time probes: novel quantum sensors and high-precision clocks may uncover a drift of the fine-structure constant and support millimetre-precision geodesy, which revolutionizes Earth system research and puts Einsteinian gravity to the test, while LISA and advanced ground-based gravitational wave detectors may test quantum cosmology with gravitational waves, thus complementing the research at high-energy colliders.

4 QUEST: Fostering synergies

QUEST merges quantum engineering and space-time research, which are of mutual benefit and stimulation: the expertise joined in QUEST enables us to address all key issues of relevance to success in both research fields. Research in QUEST is arranged in four global research areas that form the backbone of the structure of QUEST, namely "Quantum Engineering", "Quantum Sensors", "Space-Time", and "Enabling Technologies".

The research area "Quantum Sensors" is devoted to optical and matter-wave interferometry as used for gravitational wave detectors or high-precision measurements of long distances, to optical clocks, to inertial sensors of unprecedented precision and to novel fundamental tests based on atomic, molecular or mesoscopic quantum systems. This activity will translate the achievements of quantum engineering into new devices crucial for the exploration of space-time physics and the observation of the complex system Earth. These devices are expected to

outperform other state-of-the-art technologies in metrological applications displaying an excellent sensitivity for the absolute measurement of effects which bend and deform space and time. Quantum engineering of these devices will thus allow investigation of the nature of quantum physics and will challenge fundamental quantum theory with the best experimental tests available.

The research area "Enabling Technologies" comprises all efforts within QUEST to develop robust and reliable devices for the most sensitive experiments and tests in fundamental physics. The ambitious goals of QUEST's research challenge present technology in quantum optics and quantum engineering. These challenges include photonic devices such as novel laser sources, novel ultra-stable low-noise optical cavities, and novel comb generators. Robust and reliable devices are the key to explore the potential of quantum engineering and are mandatory for the most sensitive experiments and tests in fundamental physics. Doubtless, the development of enabling technologies, of new methods, materials, and of instruments aiming at sensors with unprecedented levels of sensitivity as well as at their conversion into reliable techniques for multidisciplinary applications on Earth and in space itself represents a pioneering field of applied sciences. This provides outstanding potential for the transfer of scientific and technological achievements to commercial applications. Thus, the development of enabling technologies for QUEST projects will presumably yield a significant advancement for high precision measurements and is one of the main tasks and goals of the cluster.

Apart from the research areas, QUEST makes use of task groups which are flexible units that respond to identified challenges emerging from the particular research areas. The task groups solve the specific tasks that require the co-operation of more than a single research area. Task groups are the work benches where specific visions are turned into reality.

5 QUEST: Providing top-class infrastructure for top-level research

To reach all their goals, the QUEST partners rely on a competitive scientific infrastructure in Hannover, Braunschweig, and Bremen. Consequently, QUEST supports all partners to improve and establish the infrastructure according to the needs of the cluster. Besides providing financial support for novel instrumentation, QUEST strongly aims to recruit top-level scientists at all stages of their career to strengthen both research and teaching. In the framework of QUEST, eight new W2/W3-professorships are installed at the QUEST institutes. Those professorships

are expected to work at the interfaces between well-established scientific fields within QUEST. Moreover, eight new junior research groups and also more than eight research groups are funded by QUEST providing the best conditions for young researchers. Finally, QUEST is committed to excellent quality in education especially for PhD students and thus has installed a PhD-Fellowship program to provide the best possible support for young talent.

6 The partners forming QUEST

Six different institutes of the Leibniz University Hannover and four external partner institutions with different competences that complement one another collaborate in QUEST.

Institute of Quantum Optics (IQ):

The Institute for Quantum Optics has a worldwide reputation in the fields of matter wave interferometry, Bose-Einstein-condensation, quantum optics, and ultrafast laser physics. Consequently, many scientists at the IQ are involved in QUEST research projects, especially in the fields of quantum engineering, quantum sensors, and enabling technologies. For example, ongoing experiments with Fermi-Bose mixtures will be extended to study system correlations and ultracold molecules in detail. Moreover, the expertise in atomic and molecular samples in periodic potentials is essential for the development of high-precision quantum sensors, one of the main tasks of QUEST. The ultrafast laser group at the IQ plays a leading role in all projects concerning quantum engineering of ultra-short light pulses, such as the realization of high power harmonic XUV sources. In addition, enabling technologies like novel light sources and novel optics are subjects of research and development carried out by the ultrafast laser group in close collaboration with the Laserzentrum Hannover and the Albert Einstein Institute.

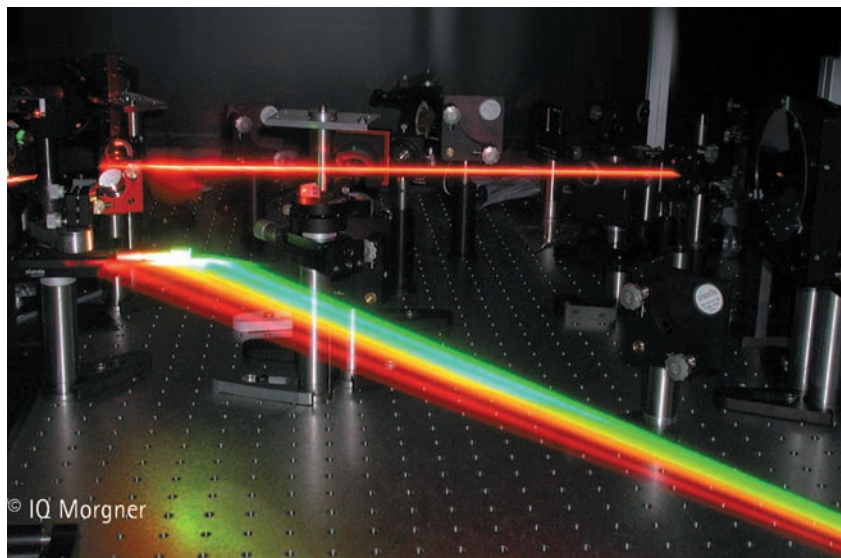


Figure 1:
The ability to control, manipulate, and shape laser pulses is one of the key technologies for research in QUEST. Here, ultrashort laser pulses are spectrally widened by guiding them through a photonic crystal fibre (courtesy of Uwe Morgner, IQ).

Institute for Gravitational Physics (IGP):

The IGP is collaborating with the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) in the Zentrum für Experimentelle Gravitationsphysik at the University of Hannover. The vision of the institute is directed towards gravitational wave astronomy both from the ground and in space. The institute plays a leading role in the LISA space mission for low-frequency observations and its precursor mission LISA Pathfinder. The institute also operates the German-British gravitational wave detector GEO600. This laser interferometer of the Michelson type, with an arm length of 600 meters, is located on university ground in Ruthe near Sarstedt. The institute's research work is concerned with problems of quantum physics (non-classical interferometry, squeezed light, negative dispersion without absorption, Heisenberg limit and quantum noise), control systems (high-stability laser systems, active damping of oscillations, adaptive optics), and gravitational physics (further development of the gravitational wave detector, analysis of the detector sensitivity, data analysis techniques and sources). All these research activities play an important role for QUEST, especially for the development of next-generation gravitational wave observatories.

Figure 2:
The two perpendicular arms of the gravitational-wave detector GEO600 (courtesy of IGP).



Institute for Theoretical Physics (ITP):

The ITP has long-standing experience in condensed-matter physics, quantum optics, and mathematical physics, in particular gravitation and quantum field theory. A part of the ITP is specialized in string theory and the quantization of gauge and gravitational theories. It brings in competence in the theory of General Relativity including mathematical tools and therefore contributes to many QUEST projects like the investigation of variation of fundamental constants, phenomenological signatures, and string cosmology. Another part of the ITP covers the fields of ultracold atomic gases, atom optics, and cold atoms in optical lattices, and contributes to nearly all QUEST research in the fields of quantum engineering and quantum sensors. For example the research on compound quantum systems or the development of new atom interferometers is based on sophisticated theoretical models and calculations developed by the ITP.

Institute for Applied Mathematics (IfAM):

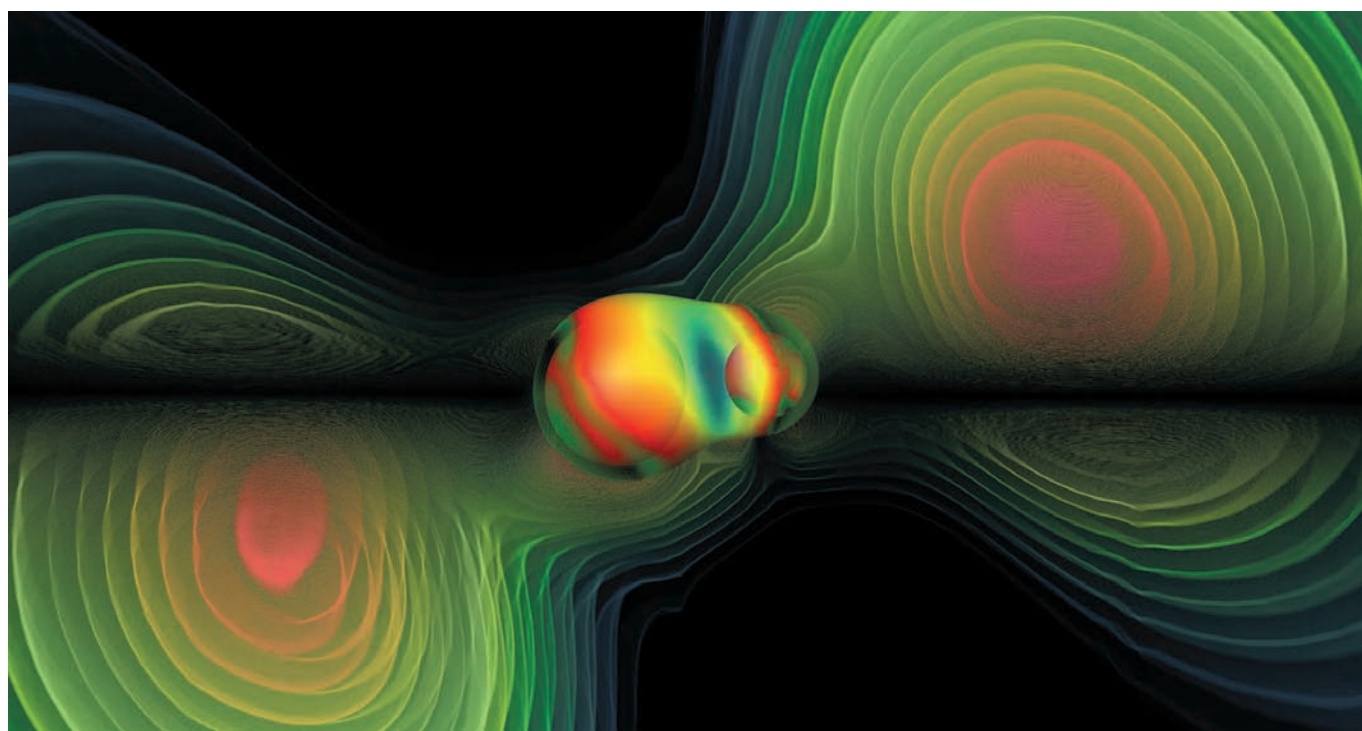
The research projects at the Institute for Applied Mathematics are directed towards problems of practical relevance from science and engineering. In particular, the mathematical modelling, numerical analysis, and simulation and optimization of natural and technical processes are covered by the research groups present at IfAM. In many cases these processes are described by nonlinear partial differential equations and boundary integral equations. Applications of the tools developed at IfAM (especially finite elements and boundary elements) are found, e.g.,

in the modelling and simulation of elastic and elastoplastic deformations of solids, flow in porous media, wave propagation, electromagnetic field computations, and optimization of water and gas networks. The Numerical Analysis Group at IfAM closely collaborates with ITP and the data analysis groups in QUEST to find efficient solutions of the partial differential equations that approximate huge systems and of integral equations for a variety of problems, especially in gravity field determination.

Institute of Geodesy (IfE, Institut für Erdmessung):

The IfE plays a leading role in terrestrial gravimetry and regional geoid determination and its combination with gravimetric satellite data, where the close interaction between theory and application is a key element. IfE acts as one of only four Lunar Analysis Centres of the International Laser Ranging Service (ILRS) worldwide, with strong concentration on relativistic effects in the Earth-Moon system. Here, a close cooperation with the German Fundamental Station Wettzell exists, which runs almost all space geodetic techniques to contribute to the determination of global reference frames and variations in Earth rotation. In addition, based on the data of the recent gravity field satellite missions related dynamic processes in the Earth system are investigated. In the framework of QUEST, IfE will investigate relativistic effects (e.g. temporal variations of Newton's constant G) using Lunar Laser Ranging data and exploit the potential of novel QUEST technology for high-precision geodesy on Earth and in space.

Figure 3:
Computation of the structure of gravitational waves emitted from black hole collisions. This work underpins the experimental research in QUEST that is dedicated to the development of high-precision tools for the measurement of gravitational waves (courtesy of Werner Benger).



Institute for Solid State Physics (IFKP, Institut für Festkörperphysik):

The nanostructures department at the Institute for Solid State Physics has a long heritage of expertise in the field of low-dimensional semiconductor systems like quantum wells and quantum dots. Research is carried out on transport phenomena and optical properties with a focus on coupled systems and spin phenomena. The excitation, manipulation, and detection of defined quantum states in low-dimensional systems using both transport and optical measurement systems are main research activities of the IFKP. Within QUEST, the IFKP will concentrate on condensed matter quantum systems on the one hand, but on the other hand also expand research activities towards compound quantum systems, i.e. condensed matter physics with atomic gases or integrated condensed matter and atomic quantum systems.

Max Planck Institute for Gravitational Physics (Albert Einstein Institute):

Research at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute; AEI) is aimed at investigating Einstein's relativity and beyond: mathematics, quantum gravity, astrophysical relativity, gravitational wave astronomy, data analysis, and cosmology. The institute is located in Potsdam (theoretical branch) and in Hannover (experimental branch). It is now the largest institute world-wide that is solely focused on researching the entire spectrum of gravitational physics. Besides the two experimental AEI departments in Hannover, the three theoretical departments in Potsdam-Golm – Geometric Analysis and Gravitation, Astrophysical Relativity and Quantum Gravity – also contribute to QUEST, especially in the fields of gravitation and space-time theory. One of the main tasks of the institute is the operation and further development of the German-British gravitational wave detector GEO600.

The Laser Zentrum Hannover (LZH):

Since it was founded in 1986, the Laser Zentrum Hannover has carried out research, development, and consultancy in the fields of laser technology, optics, and photonics. Through interdisciplinary cooperation, the LZH has been able to set high quality standards, belonging to the top league of regional, national, and international independent research institutes.

Over 270 scientists and employees from approximately 30 countries are active in research, from biophotonics to laser development, nanotechnology to material sciences, and industrial engineering to medical technology. National and international program funding allows the LZH to be engaged in both basic and application-ori-

ented research. Special mention should be made of the German Federation of Industrial Research Associations (AiF), the Federal Ministry of Education and Research (BMBF), and the German Science Foundation (DFG).

The LZH carries out industry-oriented projects for small, medium-sized and large enterprises from a wide spectrum of industrial branches.



The development of customer-specific solutions and technology transfer are vitally important at the LZH, allowing research results to be quickly turned into practical industrial uses and applications.

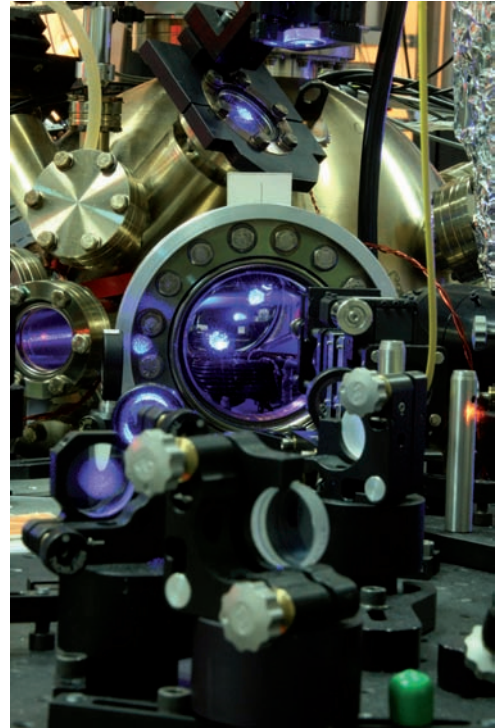
Center of Applied Space Technology and Microgravity (ZARM):

The Center of Applied Space Technology and Microgravity is a scientific institute of the Department of Engineering of the University of Bremen. The most outstanding facility is the Drop Tower Bremen, which provides a unique environment of about 5 seconds of zero gravity in an earthbound laboratory.

One of the main fields of interest and research of ZARM is fundamental physics, consisting of high-precision gravitational experiments, cryogenics, design and performance of space experiments, space technology, and relativistic gravity research. The research activities are embedded in many national as well

Figure 4: Precise control of light states requires the use of high-end technologies in experimental setups. Special optical components and coatings are designed and fabricated within the framework of QUEST as shown in this picture of the coating facility at LZH (courtesy of LZH).

Figure 6:
Heart of an optical atomic clock developed at the PTB. A cloud of laser-excited, laser-cooled strontium atoms is confined in a magneto-optical trap. The ability to precisely control and manipulate ultracold atoms and molecules gives rise to the new field of quantum engineering (courtesy of Christian Lisdat, PTB).



Physikalisch-Technische Bundesanstalt (PTB):

The Physikalisch-Technische Bundesanstalt is the national metrology institute of Germany. It provides scientific and technical services and belongs to the Federal Ministry of Economics and Technology (BMWi). Founded in 1887 as the Physikalisch-Technische Reichsanstalt, it has now 1350 staff members on its sites in Braunschweig and Berlin. The PTB performs fundamental research and development in the field of metrology as a basis for all the tasks entrusted to it directly by more than 60 laws and decrees. Among its tasks are the determination of fundamental and natural constants, the realization, maintenance, and dissemination of the legal units as defined by the international systems of units, safety engineering, services and metrology for the areas regulated by law and for industry, and technology transfer. The PTB is renowned in particular for its primary atomic clocks and its service to the worldwide time and frequency metrology community. The PTB offers numerous calibration services for measurement tasks which others cannot perform with the required precision.

The PTB is engaged continually in leading-edge metrological research and development. Prominent examples are the researches into the redefinition of several physical base units. What has already been accomplished for the meter, with its trace back to the speed of light in vacuum, is still pending for other base units: the tracing to fundamental constants. The PTB and QUEST will closely interact to incorporate and intensify new fields of research which up to now have not been pursued at the PTB or at the LUH with the necessary depth.



Figure 5:
Drop tower of the Center of Applied Space Technology and Microgravity (ZARM) with a height of 146 m (courtesy of ZARM).

as international collaborations. These activities cover the design of small satellites, high precision drag-free control for fundamental physics, geodesy, and astronomy satellite missions, the development of navigation systems as well as fundamental physics experiments like the test of the Equivalence Principle or the theoretical analysis of the Pioneer anomaly. ZARM is partner of the French mission MICROSCOPE (MICRO Satellite à traînée Compensée pour l'Observation du Principe d'Equivalence) for a space test of the Equivalence Principle as well as of the ESA/NASA LISA (Laser Interferometer Space Antenna) and LISA Pathfinder missions for the detection of gravitational waves in space. Recently, in collaboration with other German institutes ZARM opened up the new field of the development of new inertial sensors based on atomic interferometry and Bose-Einstein condensates.

QUEST at the PTB

Fritz Riehle¹

1 Introduction: Historical evolution and perspective

Over many decades the PTB has been among the world-leading National Metrology Institutes. Among other tasks, the generation and dissemination of legal time in Germany is an obligation based on the Time and Units Act [1]. The PTB can only live up to this goal to the best of its abilities if it conducts basic and applied research into future clocks, novel time and frequency dissemination schemes and related technologies. One example is the future satellite navigation system Galileo, which has to be supported scientifically and developed further for the far-reaching benefit of the German and European economy and industry.

In their treaty of 15 July 2005, the German federal and the state (Länder) ministries established an “Excellence Initiative” to strengthen science in Germany by sustainable support of the research forefront in universities and scientific institutions. Based on demonstrated outstanding scientific competence on an international scale, this program substantially supports the exploitation and preservation of excellence at universities and their cooperation with external research institutes like PTB.

The research conducted at the PTB belongs to the area of departmental research [2]. For many years, the PTB has been engaged in a fruitful strategic cooperation with the Leibniz Universität Hannover. The research results acquired, e.g., in the collaborative research centre SFB 407, “Quantum Limited Measurement Processes with Atoms, Molecules and Photons” of the German Science Foundation (DFG) have contributed to an engineer-like mastery of quantum physics. In the future, these novel techniques of “quantum engineering” will be used to answer urgent questions of modern basic physics by testing fundamental physical laws, to perform measurements of space and time quantities with unprecedented accuracy, and to develop quantum sensors for navigation, surveillance and monitoring of the Earth, and metrology.



The achieved excellent results together with forward-looking proposals for research and the structural development of the university [3] have led to the establishment of the Cluster of Excellence “Centre for Quantum Engineering and Space-Time Research” (QUEST) at Leibniz Universität Hannover, with partners described in the preceding contribution.

2 The QUEST Institute at PTB

In the framework of the Cluster of Excellence QUEST currently a new institute – the “QUEST Institute at PTB” – is being implemented in order to conduct novel forward-looking research into quantum engineering, spectroscopy, atomic clocks, and time dissemination. This new institute is jointly supported by Leibniz Universität in the framework of QUEST and by PTB under the auspices of the Federal Ministry of Economics and Technology (BMWi) and thus it can rely on the

Figure 1:
The QUEST Institute at PTB is located in the Max von Laue building on the campus of PTB in Braunschweig.

¹ Dr. Fritz Riehle,
Division “Optics”,
Physikalisch-Technische Bundesanstalt
Braunschweig
email: fritz.riehle@ptb.de

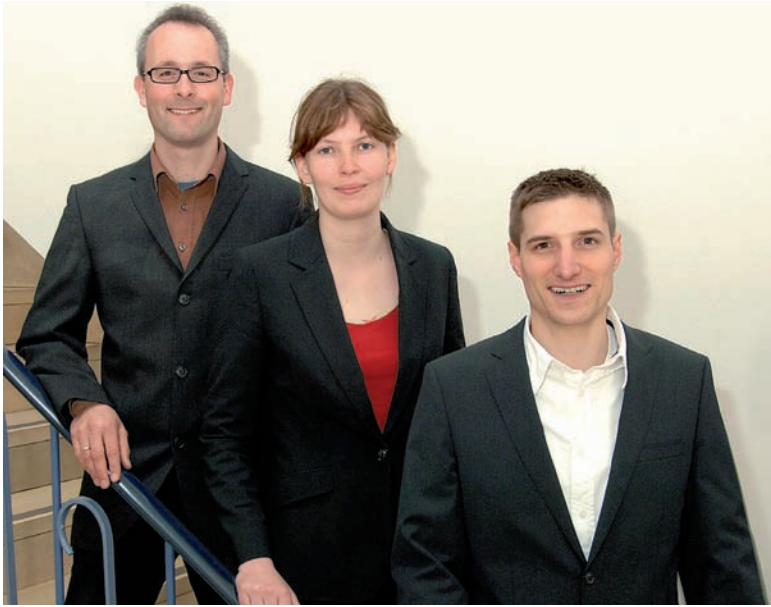


Figure 2:
The leaders of the newly founded QUEST research groups at PTB. From left: Prof. Piet O. Schmidt (Institute for Experimental Quantum Metrology), Dr. Tanja E. Mehlstäubler (Junior Research Group), and Dr. Thomas Kessler (Research project on Sub-Hertz Lasers and High-Performance Cavities).

resources of both institutions. The new institute closely interacts with and is supported by the PTB departments “Time and Frequency”, “Quantum Optics and Unit of Length”, and “Optical Technologies”. Researchers in these departments contribute to QUEST for example as principal investigators in the relevant fields. The new institute is situated on the PTB campus where it is located mainly in the Max von Laue building (Fig. 1).

In the framework of QUEST, new research groups have been created which are located at PTB and which are funded by the DFG for the duration of QUEST. The new research groups of the QUEST Institute at PTB comprise a professorship on “Experimental Quantum Metrology” which is the nucleus of the new institute, a Junior Research Group on “Quantum Sensors with Cold Atoms and Ions”, and the research project “Sub-Hertz Lasers and High-Performance Cavities”. After the funding period, the professorship will be made permanent by PTB and the BMWi. The planned main research threads of the three groups (Fig. 2) will be outlined in the following.

2.1 QUEST Institute “Experimental Quantum Metrology”

The work in this group will predominantly concentrate on novel techniques for precision spectroscopy that have already led to new applications during the past years and in particular to an enormous increase in the accuracy of microwave and optical clocks. Two of these techniques are the direct spectroscopy with frequency combs and the spectroscopy based on the methods of quantum logic. Direct frequency comb spectroscopy applies the equidistantly spaced spectral lines produced by an optical frequency comb generator directly to spectroscopic investigations of an atomic or molecular sample.

Methods of quantum logic that were originally developed for quantum computing on the basis of trapped ions will now be adapted to the spectroscopy of ions. Using these methods, a so-called logic ion with technically convenient properties can be used to manipulate, control and interrogate a different ionic species. A distinct advantage of this technique results from the fact that the investigated ions need not have optical transitions that are suitable for laser cooling and state detection. Hence, a large number of atomic and molecular species which previously could not be investigated are now accessible. The planned experiments include spectroscopic investigations on ions with unprecedented precision [4]. These investigations are relevant in particular to the question of whether fundamental physical constants such as the fine-structure constant exhibit variations on the cosmological time scale.

The quantum logic spectroscopy technique will also be used to develop an optical clock on the basis of an extremely narrow transition in a single aluminum ion. This system offers the prospect of becoming one of the world’s best atomic clocks. To this end it will be necessary to adapt the technologies for super-stable lasers that have been developed at PTB [5] and their advancement by the new QUEST research group that is described in more detail below.

2.2 Junior Research Group “Quantum Sensors with Cold Atoms and Ions”

This research group will concentrate on atomic interferometric sensors and the development of many-ion optical clocks.

The instability of the most advanced optical clocks with single ions is now limited by the quantum projection noise in the state detection of the ion and by the observed resonance linewidth which is typically in the range of 10 Hz. The linewidth limitation is set either by the natural linewidth of the reference transition or by the laser stability or by the length of the interaction time, which may be limited by heating of the ion. Improved stability is an important requirement in order to be able to verify and exploit the accuracy of these clocks. At the present level of instability, averaging times of up to 100 days would be necessary for a full evaluation to a relative uncertainty at the 10^{-18} level. This uncertainty level is the long-term goal in the development of optical clocks.

In this research project it is planned to investigate ways to improve the stability of the clocks by using many ions (ten to one hundred), which will reduce the relative amount of quantum projection noise in the atomic resonance signal. Besides the development of novel trapping structures, the research targets ions with $^1S_0 - ^1P_0$ reference transitions which are insensitive to the

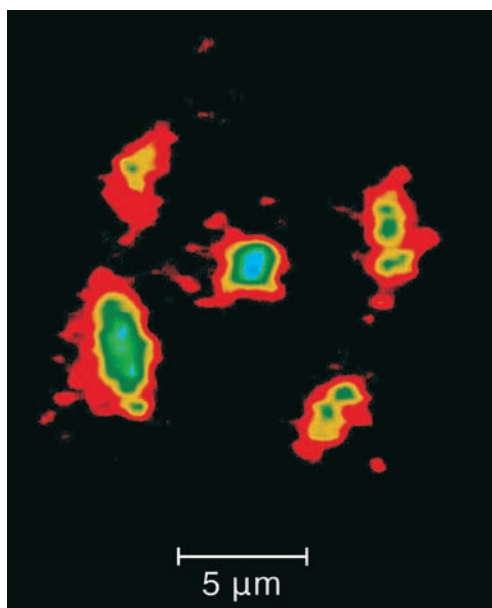


Figure 3:
Fluorescence of five laser-cooled Yb^+ ions in a radio-frequency trap (blue: high intensity; green, red: lower intensities). The use of more than a single ion in an optical clock requires novel technologies which allow to keep all ions in the field-free region of the trap where they are not affected by perturbations that shift the clock frequency.

electric field gradient produced by neighboring ions (Fig. 3).

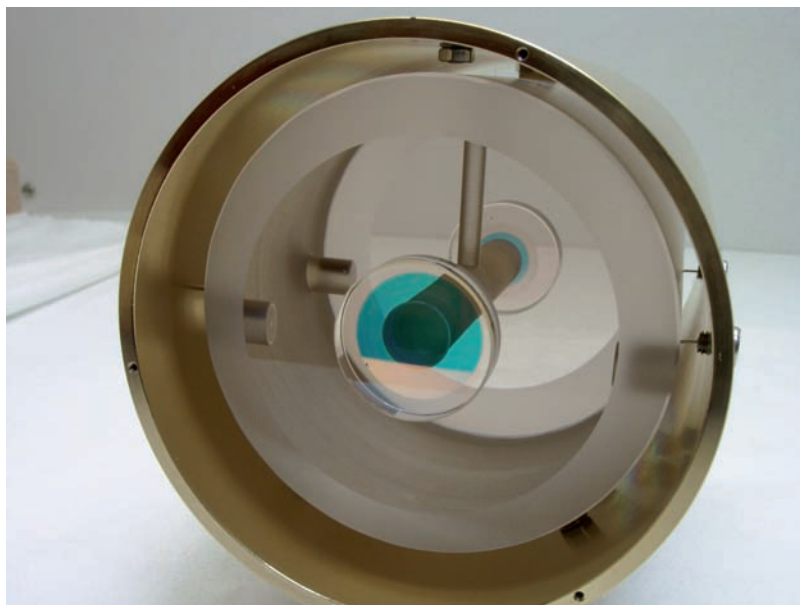
Measuring the frequency of a clock at the level of 10^{-18} will ultimately lead to sensitive devices that can determine the geopotential height with an accuracy of 1 cm. Currently the geoid of the Earth is known with an uncertainty of 30 ... 50 cm. In a further step, such clocks will enable the direct observation of tectonic plate drifts. Other quantum based sensors can provide complementary geodetic information: sensors based on cold atom interferometry can have various applications, for example as accelerometers, gravimeters, and gradiometers.

With the start of QUEST, interdisciplinary cooperations between navigation engineers, geodesists and cold-atom researchers are stimulated in order to develop novel sensors based on cold atoms for new applications in geoscience and gravity measurements. The Junior Research Group intends to contribute to this field with its expertise in manipulation of cold atoms and high-precision atom interferometry measurements.

2.3 Research project “Sub-Hertz Lasers and High-Performance Cavities”

Currently optical atomic clocks are about to outperform the best microwave clocks with respect to accuracy and stability. However, presently the short-term stability of optical clocks is limited by the frequency stability of the lasers that are employed to interrogate the atomic or ionic

Figure 4:
Optical reference cavity of an ultrastable laser in a noise-immune mounting developed at PTB.



transition that is used as the “pendulum” of the atomic clock. Highly stable narrow-linewidth lasers are furthermore indispensable for high-resolution spectroscopy, atom interferometers, fundamental physics tests, and for interferometric measurements in future space missions such as the gravitational-wave detector LISA.

To achieve the required stability, a laser is usually locked to a narrow resonance of an optical cavity. The cavity typically consists of two mirrors with very high reflectivity optically contacted to a spacer that keeps the mirrors at a well-defined distance (Fig. 4). The stability of the locked laser is determined by the stability of the optical length of the reference cavity [5]. Previously, in many experiments the most severe length fluctuations were caused by low-frequency seismic and acoustic vibrations, which couple through the mounting to the cavity and lead to quasi-static forces which deform the cavity and change its length. This problem has now been solved by the use of mounting techniques that are immune to vibrations, developed in a worldwide effort by several research groups including the PTB group [6]. Nowadays the frequency stability of the best lasers is ultimately limited by thermal length fluctuations of the reference cavities. These fluctuations are driven by the Brownian motion of the molecules of the cavity material. The stability degradation due to thermal noise poses a serious problem for the further development of ultra-stable lasers which will de-



Figure 5:
The new QUEST institute in the Max von Laue building (1) is in close vicinity to the Paschen (2), Giebe (3), and Kopfermann (4) buildings, where PTB groups work on neutral-atom clocks, single-ion clocks, and primary atomic clocks and time dissemination, respectively.

finitely hinder a number of promising fields discussed above from living up to their far-reaching expectations. Therefore the research project will concentrate with high priority on solving the thermal noise problem. Furthermore, cavities will be developed that can be used in transportable optical clocks on ground and in space for a multitude of leading-edge applications.

3 The PTB research groups and QUEST

The new QUEST Institute is located in close vicinity to the PTB groups that work on related fields, namely primary atomic clocks and time dissemination in the Kopfermann building, single-ion clocks and silicon technology in the Giebe building, and quantum optics and neutral-atom clocks in the Paschen building (Fig. 5). It can be expected that the strong interaction and close integration of working fields and researchers will lead to a joint research facility where the PTB and QUEST research groups and laboratories work together for the benefit of both partners.

The objectives of the PTB research on frequency standards, clocks, and time and frequency dissemination and the goals of QUEST have much in common. This inevitably results in the fact that a number of PTB researchers act as principal investigators in QUEST. PTB researchers for example lead the QUEST task groups “Transportable Ultra-Stable Clocks” and “Variations of Fundamental Constants”. The first task group responds to the situation that optical clocks are now at the point of outperforming the best primary microwave clocks. With the prospect of soon having clocks with orders-of-magnitude lower instability and higher accuracy, it is imperative to ensure that these new opportunities will not be restricted to a few specialized institutes like PTB. In order to accomplish the QUEST goals in quantum metrology, the support of space missions, and precision geodesy, clocks are needed with specifications that are

presently not available. The task group “Transportable Ultra-Stable Clocks” will develop a transportable optical frequency standard whose stability and accuracy exceeds that of the best present microwave standards. Transportable optical clocks will also be used to compare remote clocks and to test and improve novel techniques for remote time and frequency comparisons like long-haul optical fiber links [7].

The task group “Variations of Fundamental Constants” focuses on the investigation of a fundamental problem: most theoretical models that attempt to unify General Relativity and quantum mechanics propose temporal and spatial variations of fundamental constants. This issue is of high importance also for metrology as there is a program to base most if not all base units of the International System of Units (SI) on fundamental constants [8]. The task group will focus its activities on possible variations of three fundamental constants: the gravitational constant, the fine-structure constant, and the electron-to-proton mass ratio. Laboratory investigations into possible temporal variations of the two latter constants will benefit from the huge progress in the development of optical clocks [9, 10]. In order to obtain a robust system of frequency comparisons, the task group will coordinate and perform continuous comparisons between the frequency standards and clocks of QUEST and other highly accurate clocks operated worldwide. Apart from reducing the current limits on possible variations of the fundamental constants, these results will also be relevant to identifying the best candidate for a future redefinition of the SI second.

4 Outlook

With the joint QUEST Institute of PTB and the Leibniz Universität Hannover on the PTB campus in Braunschweig, a new era begins in several respects. First, in the new research network several fields of cutting-edge metrology can be pursued which due to the limited resources of PTB

so far could not be handled with the necessary persistence and clout. Such a field is the utilization of atom interferometry for high precision metrology [11]. Here the PTB group has made significant contributions since the early days of atom interferometry and now can join forces with other related activities in QUEST. Second, with the QUEST Institute the departmental research and university research are interlinked in a well-defined way that offers many opportunities of cross-fertilization. Third, with the presence in university and departmental research, there are new ways to contribute to and shape research programs within the national, European and international research bodies and space agencies. Fourth, the novel technologies resulting from the quantum-engineering research of QUEST are expected to lead to future-oriented cooperations with industrial partners in order to identify new applications and promote commercialization. Fifth, considering the unique working opportunities with full support from the university, the PTB, and from the other QUEST partners, it is expected that the best researchers in the pertinent fields can be attracted. The new positions temporally funded by the Cluster of Excellence constitute an additional support of the PTB which strengthens its position in particular in the fields of time and frequency metrology and quantum technology based precision measurements.

References

- [1] Gesetz über die Einheiten im Messwesen und die Zeitbestimmung (EinhZeitG). See, e.g.: http://www.gesetze-im-internet.de/me_einhg/BJNR007090969.html
- [2] Departmental research (Ressortforschung): this term denotes the research and development activities of the ministries of the German Federal Government and of the state (Länder) ministries. See, e.g.: http://www.bmbf.de/pub/konzept_ressortforschung.pdf
- [3] For more details see: <http://www.questhannover.de>
- [4] See the contribution "Quantum Logic for Precision Spectroscopy" in this issue, p. 54.
- [5] See the contribution "Super-Stable Lasers" in this issue, p. 45.
- [6] *T. Nazarova, F. Riehle, U. Sterr*: Vibration-insensitive reference cavity for an ultra-narrow laser. *Appl. Phys. B* 83, 531 (2006).
- [7] See the contribution "Novel Techniques for Remote Time and Frequency Comparisons" in this issue, p. 33.
- [8] Resolution 12 of the 23rd General Conference on Weights and Measures (2007): On the possible redefinition of certain base units of the International System of Units (SI). See: <http://www.bipm.org/utls/en/pdf/Resol23CGPM-EN.pdf>
- [9] See the contribution "More Accurate Clocks – What are They Needed for?" in this issue, p. 16.
- [10] See the contribution "The Development of Accurate Optical Clocks" in this issue, p. 25.
- [11] See the contribution "Atom Interferometry" in this issue, p. 60.

More Accurate Clocks – What are They Needed for?

Ekkehard Peik¹ and Andreas Bauch²

Figure 1:

The authors carry a commercial transportable caesium clock. The caesium fountain CSF2 of PTB is visible in the background.

1 The question

The measurement of time has an enormously wide range of applications. In fact, a clock is the only measurement device that most people carry around continuously during the day. A research group that happens to announce progress in the performance of clocks can be certain to attract a great deal of attention by the media. Many people are impressed by the achievable precision in atomic timekeeping but then they ask: what is this actually needed for? This is exactly the question we want to address in this paper. We will look at technical problems and scientific questions that provide motivation for the further development of atomic clocks. We give a cursory overview of applications of “better” clocks in a couple of fields, and try to make clear each time what property is actually needed to make the clock be called “better”.

2 Measures for the quality of clocks

Accurate and stable frequency references are critical for a lot of commercial, scientific, and military applications. For each type of application, a set of requirements has typically been developed. These cover on the one hand the performance of the clock output signal, such as frequency accuracy, frequency stability and phase noise. On the other hand, size, weight, power consumption, reliability, maintainability, and of course the cost can become equally important, depending on the application. It seems inadequate to use everyday terminology such as good, better, best without clearly defining the criteria of judgement. Figure 1 shows a commercial caesium clock, which costs 70 000 €, weighs 30 kg, has a power consumption of below 100 W, and provides standard frequency with a specified relative accuracy of $5 \cdot 10^{-13}$ and a long-term relative frequency instability below $1 \cdot 10^{-14}$. Figure 1 also displays CSF2, the second caesium fountain built at PTB, which is clearly stationary. Its construction needed 350 000 € capital investment, and a team of physicists and engineers has been engaged to design, build and operate it. It shall provide a realization of the SI second with



an uncertainty below $1 \cdot 10^{-15}$ and a long-term stability at the 10^{-16} level. Which clock is better?

The frequency of oscillators and clocks is subject to systematic and random variations with respect to the intended nominal output value. The variety of measures for quantitative characterization has been extensively covered in the literature [1], and we provide a somewhat formal introduction to the matter before we deal with the various applications of atomic clocks.

2.1 Frequency instability

We start with the expression for the (nearly) sinusoidal signal voltage generated by a frequency standard, given by

$$V(t) = [V_0 + e(t)] \sin\{2\pi\nu_0 t + \varphi(t)\} \quad , \quad (1)$$

where ν_0 , $\varphi(t)$, V_0 , and $e(t)$ are the nominal frequency, the instantaneous phase fluctuations, the signal amplitude, and its variations, respectively. We introduce the instantaneous phase-

¹ Dr. Ekkehard Peik, Department “Time and Frequency”, PTB Braunschweig, email: ekkehard.peik@ptb.de

² Dr. Andreas Bauch, Working Group “Dissemination of Time”, PTB Braunschweig, email: andreas.bauch@ptb.de

time variations, $x(t) = \varphi(t)/(2\pi\nu_0)$, and the instantaneous normalized frequency departure $y(t) = (d\varphi/dt)/(2\pi\nu_0)$. Both can be analyzed in the time domain and in the frequency domain. Here we restrict ourselves to time-domain quantities, based on mean frequency values measured during an averaging time τ , such as the Allan variance,

$$\sigma_y^2(\tau) = \left\langle \left(\bar{y}_{k+1}(\tau) - \bar{y}_k(\tau) \right)^2 \right\rangle. \quad (2)$$

Here the $\bar{y}_k(\tau)$ -values represent a contiguous (no dead time) series of data, and the brackets $\langle \rangle$ denote an infinite time average. In practice, a finite sum of terms is considered, and according to an empirical rule the number of samples should be ten or larger. In a double-logarithmic plot of $\sigma_y(\tau)$ versus τ , one can discriminate among some causes of instability in the clock signal because they lead to different slopes. If shot noise of the detected atoms is the dominating noise source, the frequency noise is white and $\sigma_y(\tau)$ decreases like $\tau^{-1/2}$. In this case, $\sigma_y(\tau)$ agrees with the classical standard deviation of the sample. Typically, however, one observes long-term effects due to coloured noise processes which indicate that parameters defining ν_0 are not sufficiently well controlled. In such a case, the classical standard deviation would diverge with increasing τ and increasing observation time whereas in a plot of $\log(\sigma_y(\tau))$ versus $\log(\tau)$, the slope approaches zero or just becomes positive. In Figure 2 we show examples of the frequency instability expected or observed for a variety of atomic frequency standards.

2.2 Frequency accuracy

The term *accuracy* is generally used to express the agreement between the clock's average output frequency and its nominal value conforming to the SI second definition. The manufacturers of commercial devices state the accuracy as a range of clock frequencies to be expected for a given model, usually without giving details about the causes of potential frequency deviations. A detailed uncertainty estimate has to be provided for primary clocks and for frequency standards that shall obtain a status akin to that of primary clocks. This estimate deals with the quantitative knowledge of all effects which may imply that the output frequency does not reflect the transition frequency of unperturbed atoms at rest. Taking into account the incomplete knowledge of the involved experimental parameters and of the underlying mechanisms, one first estimates the components of the uncertainty due to individual effects and finally states a combined uncertainty. An example for such an uncertainty estimate is given in Ref. [2].

There is a relation between the quantities instability and accuracy for the following reason: some systematic effects can be evaluated only by measuring the clock frequency relative to a reference clock. In this case, the clock frequency instability may mask the observation of systematic effects, and any gain in accuracy may be hampered by the long measurement times needed to evaluate the systematic effects. An example for this situation is the measurement of the collisional shift in fountain clocks [3].

In order to avoid measurements relative to a reference, as many effects as possible are determined theoretically or by the measurement of underlying quantities which provide a higher sensitivity than the clock transition itself. The most obvious example is the Zeeman shift. Here the shift is measured for a first-order sensitive transition in order to calculate the second-order shift of the clock transition.

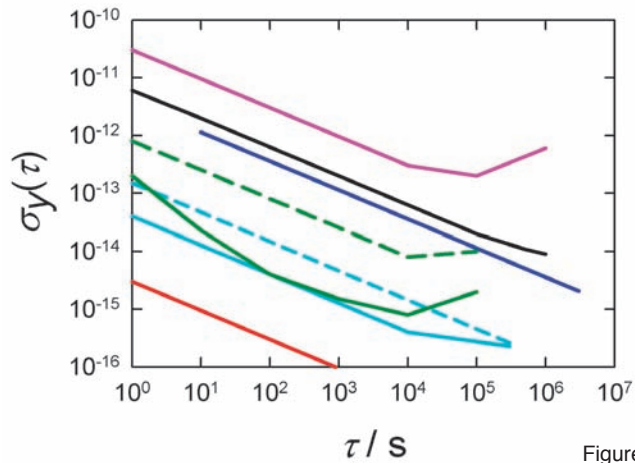


Figure 2: Relative frequency instability $\sigma_y(\tau)$ of different atomic frequency standards. Magenta: rubidium standard (typical); black: widely used commercial caesium standard Symmetricom 5071A (high-performance option); dashed green: typical performance of passive hydrogen masers; solid green: typical performance of active hydrogen masers; dashed and solid cyan: measured frequency instability of PTB CSF1 and LNE-SYRTE FO-2, respectively; blue: measured combined instability of CS1 and CS2 of PTB during 8 years of continuous operation; red: expected intrinsic stability limit of a Strontium optical lattice clock (see Ref. [9]).

3 International Time Scales

International Atomic Time (TAI) and Coordinated Universal Time (UTC) are maintained and disseminated by the Time, Frequency and Gravimetry Section of the Bureau International des Poids et Mesures (BIPM) [4]. They are the result of worldwide cooperation of about 65 national metrology laboratories and astronomical observatories that operate atomic clocks of different kinds. Each participating laboratory k realizes an approximation to UTC, denoted UTC(k), which is used as the reference for local clock comparisons and frequency distribution. Time transfer between the laboratories as described in Ref. [5] establishes the differences between the UTC(k) time scales. The dissemination of UTC by the BIPM takes the form of a time series of $[UTC - UTC(k)]$ for selected dates in the past month.

To which extent are accurate clocks instrumental in this activity? Combining the clock and time transfer data using the algorithm ALGOS leads to an averaged time scale called *Free Atomic Time Scale*. The algorithm is designed

to provide a reliable scale with optimized frequency stability for a selected averaging time, assigning statistical weights to individual clocks based on their performance during the last 12 months. In a second step, measurements of primary frequency standards realizing the SI second made over the previous one-year period are introduced to calculate the relative departure of the second of the free atomic time scale from the SI second. By application of a very gentle “frequency steering” which should not compromise the intrinsic stability, the free scale is transformed into an accurate atomic time scale named TAI. The SI second is currently best realized at national time laboratories maintaining

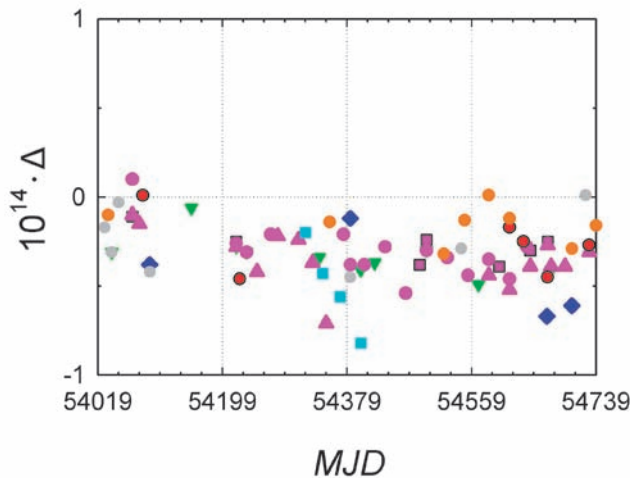


Figure 3: Comparison of fountains operated in National Metrology Institutes with TAI. Δ is the relative departure of the realized time unit from the TAI scale unit during individual operation periods of typically 20 to 30 days. The total time span is two years ending in September 2008. Blue: CSF1 of PTB; cyan: CsF1 of NPL (Teddington, UK); orange: F1 of NMIJ (Tsukuba, Japan); green: F1 of NIST (Boulder, USA); grey: CsF1 of NICT (Tokyo, Japan); red: CSF1 of INRIM (Torino, Italy); magenta squares: FO1, magenta triangles: FO2, magenta dots: FOM, of LNE-SYRTE (Paris, France).

caesium fountains. Figure 3 depicts the results of comparisons of all fountains operated worldwide with TAI over 2 years. The time scale UTC, which differs from TAI by just an integer number of seconds and which is the basis for all standard times throughout the world, is then the final product of the process.

In recent years there has been a rapid improvement in the development of optical frequency standards, and the clearest demonstration that the accuracies of some systems now surpass that of caesium standards was reported in Ref. [6]. This calls in the long term for a redefinition of the second. But how to approach this change, how to find the best suited atomic reference transition? The category “secondary representations of the second” has been defined [7], and a formal procedure has been established of taking note of measurements of transition frequencies in atoms and ions relative to the caesium frequency standard and of the pertinent uncertainty evaluations. Only frequency standards with accuracies of around one part in 10^{14} or better are currently considered. Presently, the list includes a Rb microwave standard, optical transitions in the ions $^{88}\text{Sr}^+$, $^{199}\text{Hg}^+$, and $^{171}\text{Yb}^+$, and a transition in ^{87}Sr . Further details are given in Ref. [7] and in documentation of the CCTF [8].

The direct comparison of two optical frequency standards can today be performed with lower uncertainty than the SI second is realized [9]. From such comparisons one can assess whether the reproducibilities of these new standards between successive periods of operation are in agreement with their stated uncertainties. If this is verified, they could constitute very valuable sources for the monitoring and steering of TAI, even if their full intrinsic uncertainty cannot be immediately used since they realize only secondary representations.

4 Clocks in Global Navigation Satellite Systems

Global Navigation Satellite Systems (GNSS) have become more and more widely used in our daily life, and this will continue with navigation functions becoming common in mobile phones and in cars. The functioning of GNSS depends on the measurement of signal propagation times between the satellites and receivers on ground. To be more specific, the signals transmitted from the satellites contain a prediction of the satellites’ actual clock offset from the GNSS system time and a prediction of the satellites’ actual orbit. These data are collected, processed and periodically uploaded to the satellites by the GNSS ground control infrastructure. The received information combined with the raw measurements of the signal arrival times are used for positioning and of course also for timing applications, depending on the type of receiver used [10].

The performance of a GNSS depends on the system architecture. The design parameters are: density of signal monitoring stations, frequency of data upload to the satellites, and – relevant in our context – the performance of clocks in space and in the ground segment, and thus the predictability of the individual clocks with respect to the GNSS system time.

4.1 GPS: current status

GPS time is constructed by combining all clocks in the ground and space segment. On ground, the major monitoring stations are equipped with commercial caesium atomic clocks. In the long term, GPS time is steered to follow the UTC realization of the United States Naval Observatory.

The GPS satellites launched nowadays carry three rubidium clocks. Operation of these clocks in sequence ensures that the present satellite lifetime specification of >7.5 years is met. The rubidium clocks are subject to substantial frequency drift and aging (change of the drift rate with time). As indicated in Fig. 2, the relative frequency instability is specified as $\sigma_y(1\text{ s}) \approx 3 \cdot 10^{-12}$, decreasing with time to a level of $\sigma_y(1\text{ h}) \approx 2 \cdot 10^{-13}$. Removing the drift from the data in retrospect reduces the relative frequency instability for the

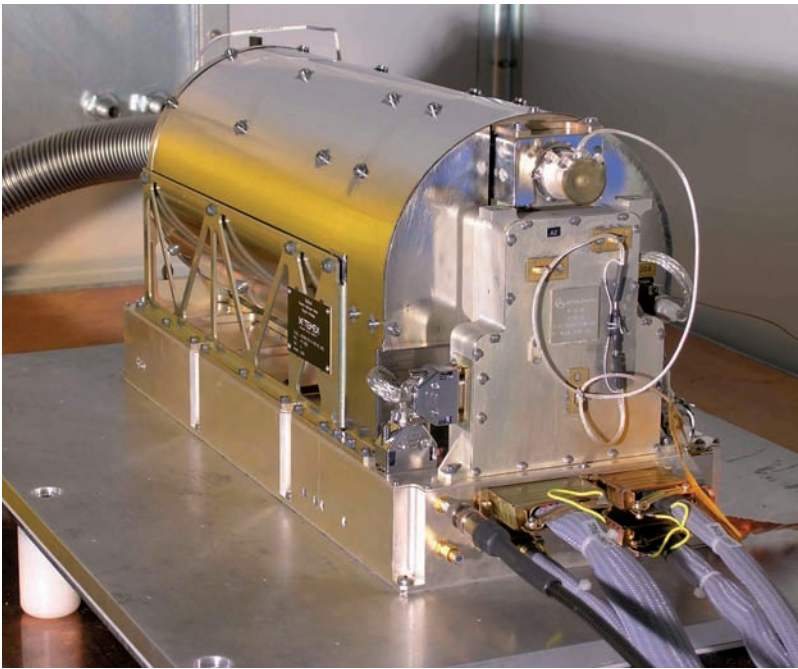


Figure 4:
Physics package of the
Galileo Space Passive
Hydrogen Maser. It will
be integrated with the
Electronics Package
built by Selex Galileo,
Milano, Italy. (Courtesy of
SpectraTime, Neuchâtel,
Switzerland)

best clocks to $\sigma_y(1 \text{ day}) \approx 3 \cdot 10^{-14}$. It appears that the performance of nominally identical clock devices shows a rather broad variability which makes system planning and maintenance a challenge [11].

4.2 Clocks for Galileo

The European Satellite Navigation System Galileo [12] has been designed under pressing funding restrictions. Its performance guarantees can be given with just two rubidium clocks in each satellite whose operating time shall be 20 years. The clocks' frequency instability is specified almost equal to that of the GPS clocks mentioned above. This is sufficient to ensure that the clock-prediction uncertainty (2σ) at the end of a 100-min interval – the processing period in Galileo – is below 4 ns. Operation of two clocks of this kind on board the first Galileo test-bed satellite GIOVE-A has confirmed that they meet the specifications most of the time [13]. In addition, Galileo satellites will most likely carry a space clock of unprecedented performance, a so-called passive hydrogen maser. This device, shown in Figure 4, was selected because of its predicted lower frequency instability at the averaging time of interest ($\sigma_y(\tau) < 1 \cdot 10^{-12} (\tau/s)^{-1/2}$ up to $\tau = 10000 \text{ s}$) which would improve the accuracy of the clock offset and orbit prediction [14]. One of these devices is currently flown on the second-generation Galileo test satellite, GIOVE-B, and results from the months June and July 2008 demonstrate the excellent performance of the maser [14].

The Galileo Ground Segment design is based on a rather conservative approach, including the best available commercial products to realize the Galileo System Time GST: caesium atomic clocks of type 5071A (manufacturer: Symmetri-

com, based on design and development dating from the years around 1990) and active hydrogen masers. Physically, GST will be realized in a redundant way in two Precise Timing Facilities (PTF) [15]. For one of them PTB has done the engineering and assembly of subsystems (see Figure 5).

During the Galileo Full Operations Capability phase, GST can be generated as a composite clock based on the 30 operational passive masers onboard the Galileo constellation, physically realized and backed up by a group of clocks in the PTFs. ESA has already initiated studies regarding the next generation Galileo, and one of the questions raised is whether "better" ground and space clocks could improve the performance of the navigation system. In a recent study by Moudrak et al. it was assumed that continuously operating optical clocks that provide a relative frequency instability of $\sigma_y(\tau) \approx 10^{-16}$ for $10^4 \text{ s} \leq \tau \leq 10^6 \text{ s}$ would be used as ground clocks – replacing the commercial caesium clocks in the PTFs – or as space clocks [16]. The authors conclude that a substantial reduction of clock-prediction uncertainty compared to the present Galileo system design could be expected only if the optical clocks were used as space clocks. In this case, values below 0.1 ns could be reached. The positioning errors could be reduced only slightly, at best by 50%. The study is currently being refined to include realistic scenarios of measurement noise and of signal processing techniques for the determination of clock offsets and orbits in the receiver.

5 The changing Earth

The Geodesy community recently agreed on the establishment of a Global Geodetic Observation

Figure 5:
The contribution of PTB to the Galileo Ground Segment instrumentation: Michael Rost making final adjustments to the ground caesium clocks. The rack to the right contains the Galileo System Time realization subsystem. Work performed under contract with Kayser-Threde GmbH, Munich, Germany.



System (GGOS) [17]. The reasons are manifold: only a clear understanding of the properties of the Earth as a whole and the measurement of a multitude of quantities with reference to SI units provides a basis for a meaningful judgment of the relevance and consequences of the “global warming”, of the threads of natural disasters (earthquakes, tsunamis), and also of the physics underlying the Sun-Planets-Earth-Moon system. The establishment of the GGOS will require a number of “fundamental stations” to be established world-wide, one example of which is the Wettzell station of the German Bundesamt für Kartographie und Geodäsie (BKG), depicted in Figure 6. In this station, BKG has established an almost complete set of geodetic observation systems including Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging, a magnetometer, and a local gravity measurement system.

Practically all these systems require a connection to a local timing system as time reference

or as frequency reference. In VLBI the phase difference between the plane wave emitted by a quasar and the local frequency reference is recorded on two sites separated by a typically inter-continental distance. Geodetic VLBI is used not as a technique to study stellar objects, but to determine the baseline between observatories with reference to the set of quasars defined as stellar reference objects by correlating the two sets of observation. The observations give direct access to the Earth rotation parameters Universal Time UT1 and polar motion. During each observation of one stellar object by two observatories, two time-related quantities have to be determined, the time offset and the rate difference between the two local clocks involved. In order that the rate difference is as stable as possible during the observation periods of several minutes, active hydrogen masers are used in each VLBI station. A lower instability and an *a priori* knowledge of the rate difference between the two clocks would largely facilitate these measurements. A connection to optical clocks on both sites would make the difference zero at the required level of uncertainty.

Another use of accurate and stable clocks has been proposed in a somewhat unexpected context. Geodesy still strives to combine the excellent positioning in the geometrically defined reference systems realized with GPS coordinates with terrestrial geophysically defined levelling systems. It is well known that the national height systems even in continental Europe, depicted in Figure 7, differ by some ten centimetres, and the situation is much worse for example in continental South America. The comparison of portable optical clocks with a stable fixed reference would allow an unambiguous determination of these height differences: A clock with an accuracy and stability of 10^{-17} could provide 10 cm accuracy in height measurement with respect to a clock at a well-defined reference height.

Figure 6:
View of the Fundamentalstation Wettzell of the Bundesamt für Kartographie und Geodäsie in Wettzell, with a variety of instrumentation for observation of Earth parameters and Earth rotation (Courtesy of BKG, Frankfurt, Germany)



6 Tests of fundamental principles

Time is one of the basic physical dimensions and also the physical quantity that can be measured to the highest precision. It is therefore not surprising that clocks and frequency standards have played an important role in quantitative tests of the fundamental principles of physics. The development of quantum mechanics relied largely on the success of the theory in explaining subtle features of atomic spectra, and the relevant experimental data are mainly the result of frequency (or wavelength) measurements. The fundamental constant that is known with the lowest relative uncertainty ($6.6 \cdot 10^{-12}$) is the Rydberg constant and its value is based on the measurement of transition frequencies in atomic hydrogen. Measurements of calculable quantum

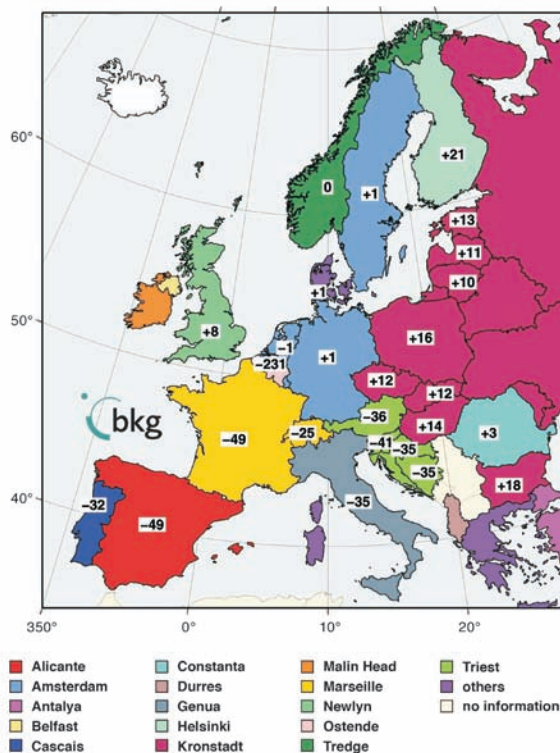


Figure 7: Transformation parameters between the European national height systems and the Universal European Leveling System (Courtesy of BKG, Frankfurt, Germany)

Other important tests of General Relativity are based on measuring the arrival times of radio pulses emitted from millisecond pulsars in binary systems [21]. These provide a unique opportunity to study relativity in the case of strong fields and have led to an indirect verification of the emission of gravitational waves. Data are recorded at the big radio observatories, typically relative to a hydrogen maser reference that is compared to UTC via GPS. For some time, it was speculated that millisecond pulsars may be more stable than atomic clocks at long observation times [22]. With further improvements in the stability of atomic timescales, this view is no longer substantiated. The small signal strength received from the pulsars limits the short term stability. Due to the precession of its emission cone, the pulsar

may disappear out of sight altogether over a period of a few decades. Nonetheless, pulsar timing is one of the most rewarding scientific applications for precise clocks and has yielded precise confirmation of General Relativity.

6.1 The search for “New Physics”

A strong motivation to continue testing the fundamental theories comes from the fact that although these theories are so successful in making quantitative predictions, they are not regarded as the final stage in a description of Nature. The most disturbing inadequacy in the view of many physicists is that there is no unified framework for gravity and the other fundamental interactions and that a link between quantum theory and the theory of relativity is missing. It is therefore a hope that one day a precision experiment may reveal a significant deviation from the predictions of the established theories and that such a result may guide the search for new theoretical models - like the failure of the Michelson-Morley experiment to detect the ether helped the development of the theory of Relativity.

Many of those searches for “new physics” look for violations of Einstein’s equivalence principle [23]. This basic postulate of Relativity separates gravitation from the other forces. While the former is intertwined with the metric, the equivalence principle states that the results of non-gravitational experiments are independent from when and where they are performed.

In consequence, relativistic effects should have the same effect on all clocks in one inertial system, no matter what kind of interaction determines the physical reference oscillator. A test of

systems like simple atoms or trapped electrons make Quantum Electrodynamics (QED) the most precisely tested theory. Continuous improvements over the last decades have been made in the precision of measurements and in the extensive computer calculations needed to evaluate higher-order QED terms. Most of the measurements were performed in university laboratories without direct access to primary clocks, but the required frequency reference was either obtained via radio or satellite link or with the help of a transportable frequency standard like the caesium fountain FOM of LNE-SYRTE [18]. This standard provides an uncertainty close to those of the best stationary fountain clocks and can be transported and set up in suitable laboratories within a few days. Figure 8 shows the FOM during its installation at a clean-room facility in preparation of the ACES mission (see below).

One of the most precise tests of General Relativity is still the 1976 Gravity Probe-A mission [19], during which a hydrogen maser was launched on a rocket to an altitude of 10 000 km while comparing its frequency to that of a hydrogen maser on ground. The experiment verified the predicted gravitational redshift to an uncertainty of $1.4 \cdot 10^{-4}$ and the combined redshift and relativistic Doppler effect at the level of $7 \cdot 10^{-5}$. The use of modern clocks with laser-cooled atoms and longer observation times afforded by putting the clock into Earth orbit will allow to improve this test significantly. These plans will be described in the following section. Relativistic time dilation has been verified to an uncertainty below 10^{-7} [20] by measuring optical transition frequencies of fast ions in a storage ring.

Figure 8:
The transportable
caesium fountain FOM
of LNE-SYRTE at the
Toulouse laboratory of
CNES (Centre National
d'Etudes Spatiales,
France) in preparation
of the ACES mission.
(Courtesy of LNE-
SYRTE, Paris)



this principle is to compare the gravitational red shift of different clocks. The strongest variation of the gravitational potential available in a laboratory is caused by the varying distance to the Sun during the annual elliptic trajectory of the Earth. The supposed differential effect of the red-shift of two different clocks is parametrized as $\Delta f/f = (\beta_1 - \beta_2) \Delta\Phi/c^2$, where β_1 and β_2 are two clock-dependent parameters. In General Relativity, β is equal to 1 for all clocks. The annual variation of the term $\Delta\Phi/c^2$ is $\pm 3.3 \cdot 10^{-10}$. Several comparisons have been performed, using caesium fountains, ensembles of hydrogen masers and, more recently, also optical clocks. No significant annual variation of $\Delta f/f$ has been detected and the most stringent limit on $|\beta_1 - \beta_2|$ is now $5.8 \cdot 10^{-6}$. [24].

Much attention has recently been directed to the search for temporal variations of the fundamental constants, another effect that would violate the equivalence principle, and one that is predicted – at least qualitatively – by candidate theories of Quantum Gravity. This subject is of great relevance to metrology, because the postulate of the universality and unalterability of the fundamental constants establishes the foundation for the use of quantum standards [25]. In 2001, a group of astrophysicists presented evidence for a change of the fine structure constant α by about 6 parts in 10^6 over the last $5 \cdot 10^9$ to 10^{10} years [26]. The analysis relies on small spectral shifts in absorption lines of metal ions in interstellar clouds that are observed in the light from distant quasars. Since then, more data has been taken by different collaborations and the present situation is that of an unresolved controversy: some observations seem to suggest even larger relative variations in another fundamental constant, the mass ratio of electron and proton, and other studies arrive at the conclusion that there are no detectable changes. Atomic clocks lend themselves to a laboratory investigation of this question. The fine structure constant enters into transition frequencies via relativistic

contributions that become important in heavy atoms. Frequency comparisons between different atomic transitions over a period of time can therefore be used to look for changes of α during that interval. High precision data from optical clocks have been available now for only a few years, but with a relative accuracy in the range 10^{-15} and below, the sensitivity of those experiments to a supposed linear drift of α now actually exceeds those reached by the astrophysical observations on a cosmological timescale. All reported clock comparison experiments are in agreement with constancy of the constants and the lowest limit on $d\alpha/dt$ is now in the range of a few 10^{-17} per year [6].

These searches for violations of the equivalence principle directly exploit the highest precision available with atomic clocks and they benefit from the fact that there are precise clocks of different types, using different atomic transitions. So far, the equivalence principle has been confirmed with an uncertainty limited by that of the clocks. In these cases, progress in clock development directly leads to more sensitive experiments.

7 Clocks in Space

There are at least three good reasons for putting clocks into space:

- (i) clocks are needed as tools for navigation, either for providing navigational signals for users on the ground (see above) or for the navigation of the spacecraft itself.
- (ii) clocks as probes for gravitational physics on a large scale may be placed in Earth orbit or on interplanetary missions.
- (iii) a “master clock” in Earth orbit may ease the task of distributing time information in order to realize a highly precise terrestrial time scale.

For purpose (i), space-qualified versions of portable atomic clocks (Rb, Cs and H masers) exist. Reason (ii) has motivated a number of ongoing and proposed space projects and will be the subject of this section. The aim (iii) to put the primary clocks in space is the most ambitious one in this list because such a clock will only find widespread acceptance if its accuracy and reliability is as good as those of the best laboratory clocks. The trajectory of this clock has to be monitored precisely in order to apply the required relativistic corrections. An advantage to be gained may be that it will be easier to model the gravitational potential in Earth orbit than close to solid Earth, where it is influenced by tidal, geological, and atmospheric changes. The most advanced project towards putting an atomic clock of the highest precision (10^{-16}) into Earth orbit is ACES (Atomic Clock Ensemble in Space) [27], a joint ESA (European Space Agen-

cy) and CNES mission with a planned launch date in 2013. Operating onboard the International Space Station, ACES comprises the primary caesium frequency standard PHARAO and an active hydrogen maser. PHARAO (Figure 9) uses laser-cooled caesium atoms like in a terrestrial caesium fountain, but it makes use of longer interaction times (several seconds) made possible by the operation in a microgravity environment. The scientific objectives cover both fundamental physics and applications. Tests of Special and General Relativity with improved precision will be performed. In the application domain, comparisons between distant clocks will be performed with unprecedented resolution [5]. Connecting two clocks of sufficient quality, ACES may demonstrate a new type of “relativistic geodesy” which, based on a precision measurement of the gravitational red-shift, will resolve differences in the Earth gravitational potential at the 10 cm level (see Section 5).

In 2007, ESA issued a call for proposals under the title “Cosmic Vision 2015–2025”. In response, 50 mission concepts have been submitted, among them 12 proposals in fundamental physics with more or less direct relation to clocks. One of the most ambitious of these is SAGAS (Search for Anomalous Gravitation

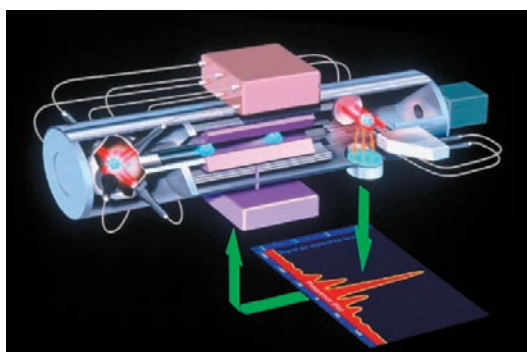
improved accuracy, and a search for scale-dependent gravity with a sensitivity that will allow to detect any effect of the size of the Pioneer anomaly to 1% uncertainty within 1 year. The Pioneer anomaly is a yet unmodeled acceleration of $9 \cdot 10^{-10} \text{ m/s}^2$ that has been observed on the Pioneer 10 and 11 spacecraft at heliocentric distances of 20–50 AU.

In the first selection of candidate missions for ESA, none of the fundamental physics proposals was successful, partly due to doubts about the “technology readiness” of the key components. Hopefully, the scientific potential that has been outlined in the studies will motivate combined efforts by space agencies, research groups and industry in order to improve this situation.

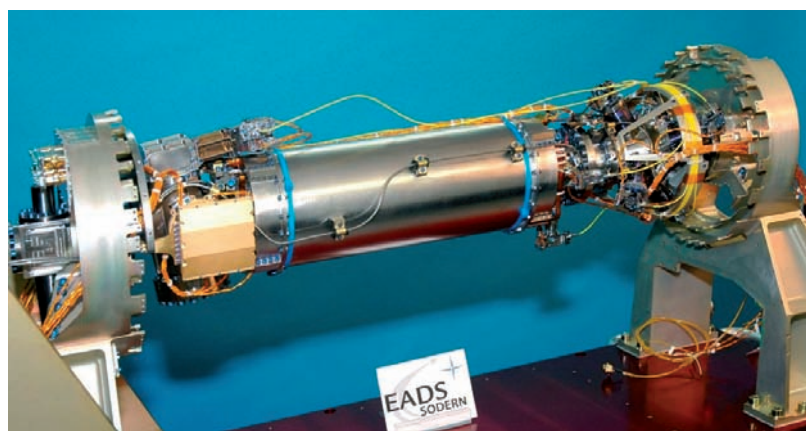
8 Summary

The accuracy of caesium atomic clocks has improved by about a factor of 10 per decade since 1955, when the first device started working. During the recent years, optical frequency standards have taken over the lead in terms of being able to reproduce the unperturbed transition frequency of atoms – now using spectral lines in the visible rather than in the microwave domain. In this contribution, we have shown that scientists are awaiting the availability of superior clock

Figure 9:
The caesium frequency standard PHARAO. The drawing on the left illustrates the loading (left hand side) and launching of cold caesium atoms along the vacuum tube. During their ballistic flight, the atoms cross two Ramsey interrogation regions where the clock transition is probed by a microwave field. Two resonant laser beams (right hand side) detect the population of the two hyperfine levels. The photo on the right shows the PHARAO caesium tube without magnetic shields. Fully assembled, the tube has a volume of 148 l and a mass of 44 kg. (Courtesy of ESA, Noordwijk)



with Atomic Sensors), proposed by P. Wolf from LNE-SYRTE together with more than 70 participants [28]. The concept combines a cold-atom absolute accelerometer (accuracy $5 \cdot 10^{-12} \text{ m/s}^2$) with a trapped-ion optical clock (accuracy $1 \cdot 10^{-17}$) and a laser link for frequency comparison and navigation on board of a spacecraft that should reach the outer solar system (about 50 AU) after 20 years. The complementary instruments will allow highly sensitive measurements of all aspects of gravitation via the different effects of gravity on clocks, light, and the free fall of test bodies. In particular, the scientific objectives of SAGAS include tests of gravitational redshift and time dilation with 4 to 5 orders of magnitude improvement, a measurement of light deflection during solar conjunction with 100 times



performance in order to test General Relativity, the constancy of fundamental constants and the properties of millisecond pulsars. The total number of clocks needed in such applications will remain few. A larger number is needed in more everyday applications such as navigation systems, network synchronization and secure provision of time and date information. The requirements in the latter cases are different to those mentioned previously: reliability, size, power consumption are the driving parameters and important development projects have been undertaken in that direction. Eventually a “clock on the chip” may become available. Like in many areas of innovative technology, the development of better clocks is partly driven by applications that demand new solutions and

partly by basic research emerging from curiosity. The most innovative atmosphere is often found where a mixture of both motivations can be maintained.

References

- [1] Standard definitions of Physical Quantities for Fundamental Frequency and Time Metrology. IEEE-Std 1189-1988 (1988).
- [2] A. Bauch, B. Fischer, T. Heindorff, R. Schröder: Performance of the PTB reconstructed primary clock CS1 and an estimate of its current uncertainty. *Metrologia* 35, 829 (1998).
- [3] R. Wynands, S. Weyers: Atomic fountain clocks. *Metrologia* 42, S64 (2005).
- [4] B. Guinot, F. Arias: Atomic time-keeping from 1955 to the present. *Metrologia* 42, S20 (2005).
- [5] See "Novel Techniques for Remote Time and Frequency Comparisons" in this issue, p. 33.
- [6] T. Rosenband et al.: Frequency ratio of Al^+ and Hg^+ single-ion optical clocks: metrology at the 17th decimal place. *Science* 319, 1808 (2008).
- [7] P. Gill, F. Riehle: On Secondary Representations of the Second. Proc. 20th European Frequency and Time Forum (Braunschweig 2006), p. 282.
- [8] <http://www.bipm.org/utls/common/pdf/CCTF17.pdf>
- [9] See "The Development of Accurate Optical Clocks" in this issue, p. 25.
- [10] Global Positioning System: Theory and Applications, vol. 1 and 2. Eds: B.W. Parkinson and J.J. Spilker jr., in: Progress in Astronautics and Aeronautics vol. 163, Am. Inst. of Aeronautics and Astronautics (1996).
- [11] J. Oaks, J.A. Buisson, M.M. Largay: A summary of the GPS constellation clock performance. Proc. 29th Ann. PTTL, p. 119 (2007).
- [12] A positioning system Galileo; strategic, scientific and technical stakes. Académie de Marine, Bureau des Longitudes, Académie nationale de l'Air et de l'Espace (Paris 2003).
- [13] J. Hahn et al.: GIOVE-A apparent clock assessment and results. Proc. 39th Ann. PTTL, p. 95 (2007).
- [14] Q. Wang, P. Mosset, F. Droz, P. Rochat, G. Busca: Verification and optimization of the physics parameters of the onboard Galileo passive hydrogen maser. Proc. 38th Ann. PTTL, p. 81 (2006); P. Waller et al.: In-orbit performance assessment of GIOVE clocks. Proc. 40th Ann. PTTL (2008), to be published.
- [15] S. Bedrich et al.: Design and performance of the precise timing facility for Galileo. Proc. 22th European Frequency and Time Forum (Toulouse 2008).
- [16] A. Moudrak, H. Klein, B. Eissfeller: Future Time, Opportunities for using optical clocks in GNSS systems. Inside GNSS (Sept./Oct. 2008), 45.
- [17] H. Drewes: Science rationale of the Global Geodetic Observing System (GGOS). In: Dynamic Planet, Internat. Ass. Of Geodesy Symposia vol. 130, Eds: P. Tregoning, C. Rizos, Springer (Berlin 2007) p. 703.
- [18] M. Fischer et al.: New limits on the drift of fundamental constants from laboratory measurements. *Phys. Rev. Lett.* 92, 230802 (2004).
- [19] R. F. C. Vessot, M. W. Levine: A test of the equivalence principle using a spaceborne clock. *J. Gen. Rel. and Grav.* 10, 181 (1979).
- [20] S. Reinhardt et al.: Test of relativistic time dilation with fast optical atomic clocks at different velocities. *Nature Physics* 3, 861 (2007).
- [21] I. H. Stairs: Testing General Relativity with Pulsar Timing. *Living Rev. Relativity* 6, (2003); <http://www.livingreviews.org/lrr-2003-5>
- [22] J. H. Taylor: Millisecond Pulsars: Nature's most stable clocks. *Proc. IEEE* 79, 1054 (1991).
- [23] C. M. Will: Theory and experimentation in gravitational physics (rev. ed.). Cambridge University Press (Cambridge 1993).
- [24] T. M. Fortier et al.: Precision atomic spectroscopy for improved limits on variation of the fine structure constant and local position invariance. *Phys. Rev. Lett.* 98, 070801 (2007).
- [25] See "Quantum Logic for Precision Spectroscopy" in this issue, p. 54.
- [26] J. K. Webb et al.: Further evidence for cosmological evolution of the fine structure constant. *Phys. Rev. Lett.* 87, 091301 (2001).
- [27] Ch. Salomon et al.: Cold atoms in space and atomic clocks: ACES. *C. R. Acad. Sci. Paris, t. 2, Série IV*, 1313 (2001).
- [28] P. Wolf et al.: Quantum physics exploring gravity in the outer solar system: The SAGAS Project. arXiv:0711.0304

The Development of Accurate Optical Clocks

Ekkehard Peik¹ and Uwe Sterr²

1 Introduction

Highly precise measurements of time and frequency play an important role in experimental tests of the foundations of physics as well as in technologies we use in our everyday life like navigation or telecommunication. Historically, the big advances in the accuracy of timekeeping were always connected with the introduction

of a new type of clock (see Fig. 1) that operated at higher frequencies than the previous generation: mechanical clocks tick at a rate of about 1 Hz, quartz clocks use mechanical vibrations of a few 10 kHz and the first atomic clocks relied on microwave transition frequencies in the range 1–10 GHz. The next change of generation is now ahead of us: the introduction of “optical clocks” that operate at the frequency of visible or ultraviolet light of about 10^{15} Hz. This opens the possibility of increasing the relative accuracy of atomic clocks by a factor 100 to 1000. The higher operating frequency allows to test the stability of the clock more quickly, i.e. to determine to what

degree it produces the same number of “ticks” in a given time interval. If the clock turns out to be stable, one can also make a statement on its uncertainty, which for an atomic clock always answers the question of up to what precision it realizes the transition frequency of an atom that is observed under idealized conditions, unperturbed and at rest.

The high operating frequency led to two major obstacles that had to be overcome in the development of optical clocks: firstly, the atoms that determine the pace of the clock must not move by more than a fraction of the wavelength that is used to interrogate them. Otherwise a significant frequency shift would be observed due to the Doppler effect. Secondly, the periods of the radiation at the atomic transition frequency must be countable in order to measure precisely and to realize a time scale. Both criteria are obviously much more easily fulfilled for microwaves than for optical radiation. Caesium clocks (at 9.19 GHz [1]) that realize the base unit second in the international system of units (SI) and hydrogen masers (at 1.42 GHz) therefore dominated precise time and frequency measurements since the 1950s. Only in recent years has it become possible to demonstrate the higher stability and accuracy of optical clocks. This was made possible by application of the methods of laser cooling and trapping of atoms [2,3], by the development of lasers with long coherence time up to 1 s and by the invention of the optical frequency comb generator [4] that has allowed the exact counting of periods of laser light.

2 Setup of an optical clock

The general setup of an optical clock is shown in Fig. 2. A narrow and ideally unperturbed absorption line of trapped atoms or ions defines the reference frequency f_0 . This line is detected by narrow-band laser radiation of frequency f . The probability to excite an atom depends on the detuning between the atomic transition frequency and the laser frequency. In modern atomic clocks the atoms are laser cooled before they are interrogated. Thus the absorption signal

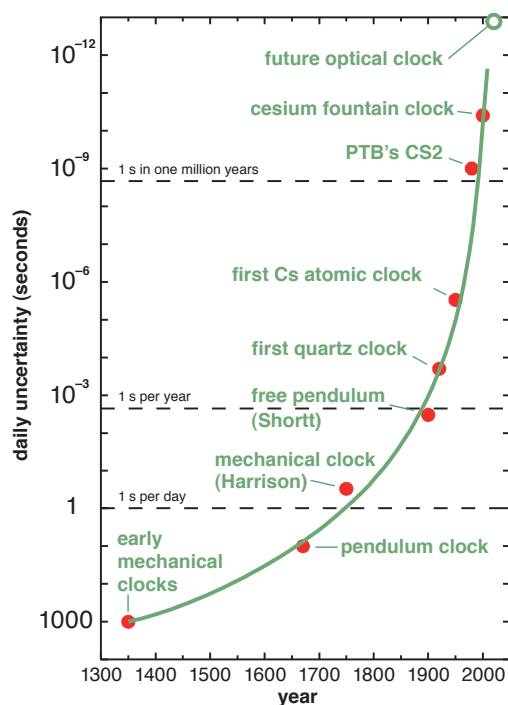


Figure 1:
Historical development in
the accuracy of clocks.

of a new type of clock (see Fig. 1) that operated at higher frequencies than the previous generation: mechanical clocks tick at a rate of about 1 Hz, quartz clocks use mechanical vibrations of a few 10 kHz and the first atomic clocks relied on microwave transition frequencies in the range 1–10 GHz. The next change of generation is now ahead of us: the introduction of “optical clocks” that operate at the frequency of visible or ultraviolet light of about 10^{15} Hz. This opens the possibility of increasing the relative accuracy of atomic clocks by a factor 100 to 1000. The higher operating frequency allows to test the stability of the clock more quickly, i.e. to determine to what

¹ Dr. Ekkehard Peik,
Department
“Time and Frequency”,
PTB Braunschweig,
email: ekkehard.peik
@ptb.de

² Dr. Uwe Sterr, Working
Group “Quantum
Optics with Cold Atoms”,
PTB Braunschweig,
email: uwe.sterr
@ptb.de

is not observed continuously, but periodically up to several times per second. This absorption signal is used to keep the laser frequency exactly at the center of the absorption line. The laser frequency is periodically tuned above and below the atomic resonance when the atoms are interrogated. If the absorption at both detunings is different this implies a deviation of the average laser frequency from the center of the atomic reference line and the laser frequency is corrected accordingly.

The optical frequency comb generator is used as a “clockwork” which divides the laser frequency of about 10^{15} Hz down to countable radiofrequencies. Optical frequencies cannot be processed electronically and until a few years ago extremely elaborate, cascaded frequency multipliers were used to compare optical frequencies to electronically countable ones [5]. This comparison is now greatly simplified by the invention of optical frequency comb generators, awarded by the Nobel prize 2005 for T. Hänsch and J. Hall [4].

Optical frequency comb generators rely on the fact that the spectrum of certain pulsed lasers consists of a broad comb of frequencies, where the distance is exactly equal to the laser’s repetition rate f_{rep} (Fig. 3). In these lasers a light pulse travels around the resonator and during each round trip a certain fraction is coupled out. The loss is compensated by the gain in the active medium. Dispersion in the resonator leads to different group and phase velocities. As a result, the pulse envelope is emitted strictly periodically with the repetition rate f_{rep} but the optical phase within the envelope varies from pulse to pulse. The Fourier decomposition of the pulse sequence leads to an overall shift of the comb spectrum by a carrier-phase-offset frequency f_{CEO} . If the radio-range frequencies f_{rep} and f_{CEO} are known, the frequency f_m of each comb line can be calculated from:

$$f_m = m \cdot f_{\text{rep}} + f_{\text{CEO}}.$$

The frequency of the reference laser is then obtained from the frequency difference from the nearest comb line; the frequency difference is

again in the radiofrequency range. Optical frequency comb generators, especially those based on fiber lasers, have now become very reliable. Their accuracy has reached a level that does not limit the overall accuracy of the optical clock when they are employed as an optical clockwork [6].

An important property of any clock is its stability, i.e. fluctuations of its clock rate. In each interrogation of the atomic absorption line noise is added, on the one hand because the laser frequency statistically fluctuates due to environmental disturbances, but on the other hand also due to fundamental quantum mechanical fluctuations of the atomic response. Because of this additional noise, the laser frequency never perfectly agrees with the absorption frequency. By averaging more and more interrogations, both frequencies will agree better, and the time required to reach a certain stability level depends on the signal-to-noise ratio and on the resolved linewidth.

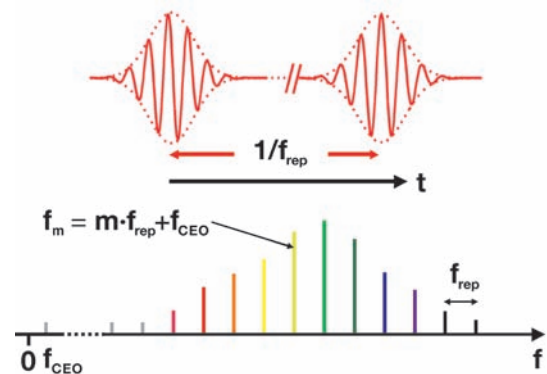
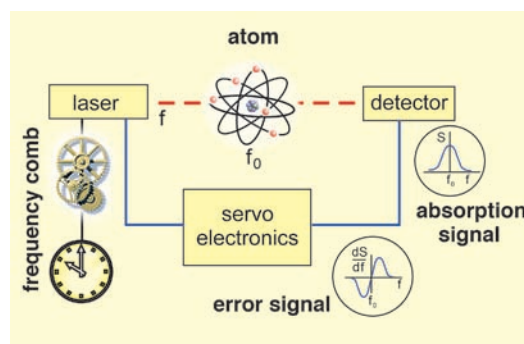


Figure 3:
Pulse sequence of a femtosecond laser (top) and corresponding frequency spectrum (bottom).

The currently best cesium microwave clocks [1] achieve a relative frequency stability $\delta f/f \approx 1.6 \cdot 10^{-14}$ for one second averaging time. If the fluctuations are independent from interrogation to interrogation, the stability will improve with the square root of the number of measurements. To reach a relative stability of 10^{-17} , an averaging time of 12 days would be required.

Even then, it is not guaranteed that the frequency agrees with the undisturbed absorption frequency of the atoms. The line might get shifted by, e.g., the Doppler effect caused by atomic motion. Also electric and magnetic fields and collisions can lead to a frequency shift. Improving clocks thus requires one to further reduce all these influences or at least to know and correct them as precisely as possible. In this respect the high frequency of optical clocks also helps, as in many effects the frequency shift is independent of the operational frequency and therefore

Figure 2:
Schematic of an optical clock.



the relative influence is more and more reduced as we operate clocks at higher frequencies. The absolute linewidth, given by the inverse interrogation time, is also independent of the operational frequency, which improves the stability of optical clocks accordingly. Therefore much less time is required to study systematic shifts by changing the environmental conditions. The best present optical clocks offer a stability of 10^{-15} in one second averaging time, thus measuring to 17 digits requires merely 3 hours of averaging time.

2.1 The linewidth of atomic absorption lines

The properties of atomic absorption lines play a crucial role for the performance of an optical clock. Atoms possess energy levels that are characterized, among other things, by the angular momentum of the electron shell and the spin of electrons and nucleus. Transitions between different energy levels are connected with the absorption and emission of light quanta. The so-called natural linewidth Δf of the radiation is obtained from the Fourier transform of an oscillation that is damped by the lifetime Δt according to

$$2\pi \cdot \Delta f \cdot \Delta t = 1.$$

The typical lifetime of an excited level of an “allowed” optical transition amounts to approximately 10 nanoseconds which corresponds to a natural linewidth of 16 MHz.

One distinguishes between “allowed” and “forbidden” transitions. As the photon has an intrinsic spin of $1 \cdot \hbar$, it follows from angular momentum conservation that only transitions that change the angular momentum of the atomic electron shell by not more than \hbar are “allowed”. All other transitions are called “forbidden”. In radiation of higher multipole orders the radiation field of the photon can carry additional angular momentum. Because of the small size of the atom in comparison with the wavelength, this process becomes more and more forbidden with increasing angular momentum. In the optical spectral region, an electric quadrupole transition has a typical lifetime in the order of 100 ms which corresponds to a linewidth of 1 Hz.

If the angular momentum in both levels is equal to zero, then because of angular momentum conservation no photon can be emitted. Only through interaction with additional fields, e.g. the magnetic field of the nucleus or an external magnetic field, can the angular momentum be supplied.

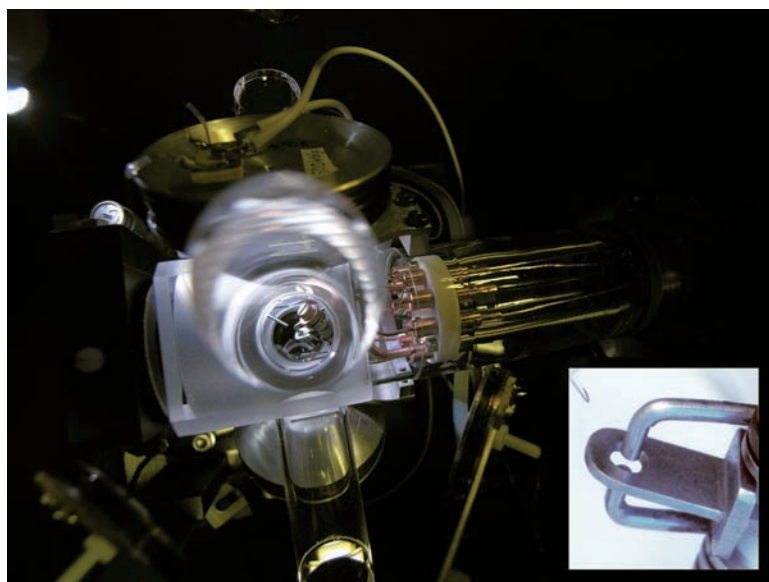
Ideally the observed linewidth is limited by the interaction time. In the Cs fountain clock, atoms travel under the influence of earth’s gravity on parabolic trajectories of height ~ 1 m, which

limits the interaction time to approximately 1 s. Because of the much shorter wavelengths, this method is not applicable to optical clocks. Consequently, to reach long interaction times and corresponding small resolved linewidths, in novel optical clocks neutral atoms or ions are trapped in electromagnetic fields.

3 Optical clocks with single stored ions

The requirement on localization can be met very satisfactorily with ions because here a holding force can be exerted on the ionic charge without significantly affecting the internal level structure. This applies particularly to the lower energy levels of positive ions that we consider here. In the Paul trap [2] a single ion is kept at the field-free saddle point of an oscillating quadrupole potential. For optical clocks a trap with a potential well depth of several electron volts is typically used. This corresponds to roughly one hundred times the thermal energy at room temperature and allows the ion to remain trapped for long times. At PTB we have once experimented with one and the same Yb^+ ion for 16 months. A simple method of laser cooling can be used to lower the temperature of the ion into the millikelvin range: the ion is excited by a single laser beam that is detuned somewhat below the resonance frequency. The Doppler

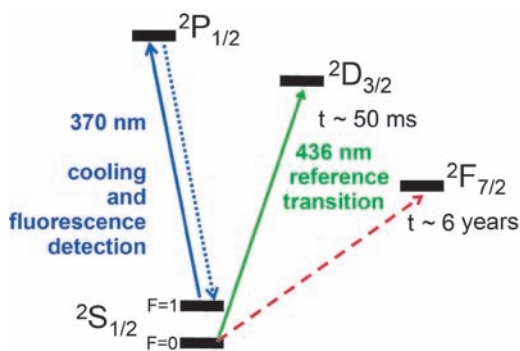
Figure 4: Photograph of the Paul trap used at PTB for the Yb^+ single-ion clock. The trap electrodes can be seen in the center of the glass vacuum vessel (cf. enlarged inset). The inner diameter of the ring is 1.4 mm. (Photo: PTB/Okerland-Archiv)



effect makes the ion absorb preferentially during the half period of its oscillation when it is moving towards the laser. The ensuing radiation pressure damps the motion of the ion. This so-called Doppler cooling reduces the oscillation amplitude to a few tens of nanometers, ensuring a close localization on the scale of the optical wavelength. More elaborate methods of laser cooling may bring the ion to the quantum mechanical ground state of motion in the trap so that localization and energy are controlled at the quantum limits.

In the operation of the optical clock one uses a double-resonance method in which two lasers excite two transitions originating from the common ground state. A fast transition serves for laser cooling and fluorescence detection of the ion. An electric dipole transition with a few nanoseconds lifetime of the upper level may provide enough signal for the detection of the ion within a few milliseconds. The second, “forbidden” transition connects the ground state with a metastable level, so that it possesses a small natural linewidth (a few Hertz or below) and can serve as the reference of the clock. An excitation to the metastable state prevents the further scattering of photons on the cooling transition. This will only resume after the ion has returned to the ground state. The preceding dark interval therefore gives a clear indication of an excitation of the ion on the reference transition. In order to avoid a frequency shift of the latter through the light of the cooling laser, reference and cooling laser radiation are applied alternately.

Figure 5: Simplified level scheme of $^{171}\text{Yb}^+$, showing the cooling transition at 370 nm and the reference transition of the clock at 436 nm (left). Excitation spectrum of the reference transition. The red curve shows the excitation probability calculated for idealized conditions (right).



A single measurement cycle of this kind will only yield a single binary unit of information: whether the excitation attempt was successful or not. If the interrogation is performed at the half maximum of the spectral line at an excitation probability of 50%, the averaged signal-to-noise ratio will be only unity. Nevertheless, it is possible to use such a sequence of measurements for the realization of a clock whose short-term stability is about 10 times superior to the best caesium clocks: if the interrogation is performed within 1 s with a resolution of 1 Hz at a frequency of 10^{15} Hz, the resulting relative instability is as low as 10^{-15} already.

The most striking advantage of the single-ion clock is its conceptual simplicity: a single atom at rest in ultrahigh vacuum allows for the precise control of all interactions with the environment, may these be wanted or a nuisance. Even a collision with a particle from the residual gas can be registered and the corresponding time interval excluded from the generation of the clock signal. The seminal ideas of the single-ion clock were published by Hans Dehmelt already in the 1970s: storage of ions in a Paul trap, laser cooling, and

double-resonance spectroscopy [2]. The first experimental demonstration of trapping and cooling of a single ion was reported in 1978. Today, about a dozen of groups around the world are active in this field. A remarkable multitude of elements is being studied, comprising Ca^+ , Sr^+ , Al^+ , In^+ , Hg^+ , and Yb^+ . All these candidates possess individual advantages and disadvantages and there is no consensus yet on the possibly optimum choice. The goal that is aspired to has also already been formulated by Dehmelt: a relative uncertainty in the range of 10^{-18} .

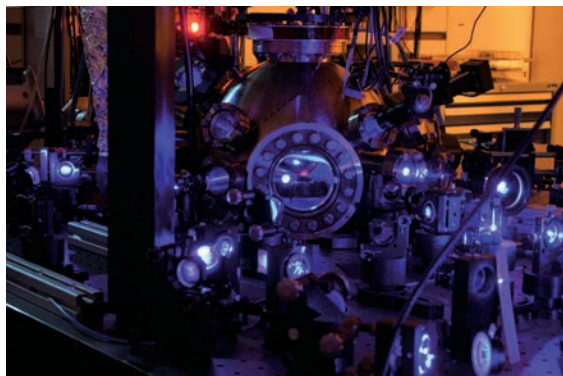
The $^{171}\text{Yb}^+$ ion is studied at PTB [7] as well as at the British National Physical Laboratory. A simplified level scheme of this ion is shown in Fig. 5, where the cooling transition $2S_{1/2} - 2P_{1/2}$ and the reference transition $2S_{1/2} - 2D_{3/2}$ are indicated. The required laser radiations in the ultraviolet and in the blue spectral range, respectively, can be produced by frequency doubling the output of semiconductor diode lasers. The $2D_{3/2}$ state differs from the ground state in its

orbital angular momentum by $2\hbar$ and consequently can not decay via the emission of electric dipole radiation. Only a quadrupole emission is possible and the resulting lifetime is 51 ms, corresponding to a natural linewidth of 3.1 Hz. The isotope $^{171}\text{Yb}^+$ possesses a nuclear spin of $\frac{1}{2}\hbar$ and a ground-state hyperfine level with vanishing total angular momentum. This provides a reference transition that is immune against frequency shift from magnetic fields via the linear Zeeman effect.

An excitation spectrum of the reference transition $2S_{1/2} - 2D_{3/2}$ of $^{171}\text{Yb}^+$ is shown in Fig. 5. The 436 nm laser was applied for pulses of 90 ms duration and the resulting linewidth is 10 Hz, corresponding to a line quality factor $f/\Delta f$ of $7 \cdot 10^{13}$. For each data point, 20 excitation cycles were performed and the noise that is visible in the spectrum is mainly determined by the counting statistics. The maximal excitation rate of 50% is already limited by the decay of the $2D_{3/2}$ level during the excitation, so that it would not be beneficial to use longer laser pulses in order to obtain a narrower linewidth. For further development in this direction, Yb^+ provides another

option: below the $^2D_{3/2}$ level lies the $^2F_{7/2}$ level that can only decay via the emission of octupole radiation and therefore possesses an extremely long lifetime of 6 years. This transition will allow a further reduction of the linewidth, up to the limits imposed by the achievable laser linewidth.

A different kind of forbidden transition is used in Al^+ , In^+ , and in the optical lattice clocks (see below). In those cases, the ground state 1S_0



as well as the first excited state 3P_0 have vanishing electronic angular momentum. Because angular momentum is conserved, a transition between these states with emission of a single photon is forbidden for all multipole orders of the radiation field. The interaction with the nuclear spin can make the transition weakly allowed and a narrow resonance line is obtained. Its frequency couples only weakly to external fields and is therefore well suited as the reference of a frequency standard. The Al^+ ion is investigated at NIST, the metrology institute of the USA [8]. This ion does not possess a cooling transition that is accessible with present laser technology and therefore the double-resonance method described above is not directly applicable. A more elaborate and quite flexible technique from research in quantum information processing with trapped ions is applied here: The Al^+ ion is stored together with a “logic ion” from a different element (Be^+ in this case). Laser cooling and state detection proceed via excitation of the Be^+ ion and via the coupling of both ions through their common oscillatory motion in the trap [9, 10].

The most reliable way of obtaining information on the stability and accuracy of new and improved clocks is a comparison of at least two independent devices. For this purpose, our group at PTB has built two Yb^+ traps. Both realizations of the transition frequency at 688 THz were in agreement to within a difference of 0.26 Hz. This difference is not significantly different from zero, but within the relative uncertainty of the measurement of $6 \cdot 10^{-16}$ [7]. With this experiment it is possible to identify small frequency shifts in the range 10^{-15} within a few

minutes and to study the external influences that may cause these. Using a caesium clock as a reference, such a measurement would require half a day. The group at NIST has recently compared two clocks based on different ions, one with Al^+ as described above and the other with Hg^+ whose reference transition characteristics are similar to Yb^+ . Since both clocks operate at different frequencies and are both more precise than

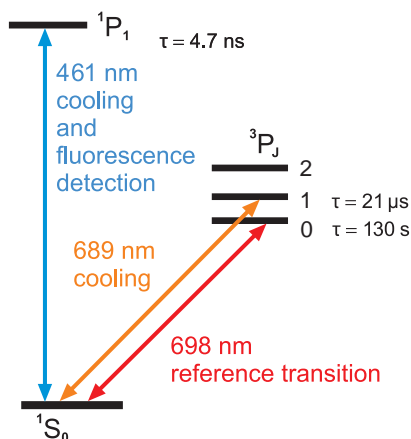


Figure 6: Vacuum chamber of the strontium lattice clock of PTB (left). The trapped atoms can be seen as a blue spot in the center of the chamber. Simplified level scheme of strontium, showing the cooling transitions at 461 nm and 689 nm and the reference transition of the clock at 698 nm (right).

a caesium clock, here a measurement of the difference frequency in SI hertz is not useful. Instead, the result of the comparison can be expressed as a frequency ratio, i.e. a dimensionless number. The ratio was determined experimentally with an uncertainty of $5 \cdot 10^{-17}$ [9] and is now the most precisely measured (non-integer and non-zero) number in Nature.

4 Optical lattice clocks

With single ions the signal-to-noise ratio is limited, as only one particle is interrogated. If many ion are stored at the same time in a Paul trap, the electrostatic interaction degrades the localization. With neutral atoms the mutual interaction is much smaller.

Neutral atoms experience no force in a homogeneous electric field. However, the fields can displace the positive charge center (atomic nucleus) and the negative charge center (electron shell) in the atom. The electric field E induces an electric dipole moment d , which is proportional to the applied field: $d = \alpha \cdot E$. The induced electric moment interacts with the field with an energy

$$U = -\frac{1}{2} \cdot d \cdot E = -\frac{1}{2} \cdot \alpha \cdot E^2 \quad ,$$

which in an inhomogeneous field leads to a potential gradient, i.e. to a force. Not only static fields can induce a dipole moment, but also the oscillating field of an intense laser. In this case the sign of the interaction energy depends on the position of the laser frequency relative to the atomic resonance. In analogy to a classical driven oscillator, below the resonance the atomic dipole oscillates in phase with the applied field, and

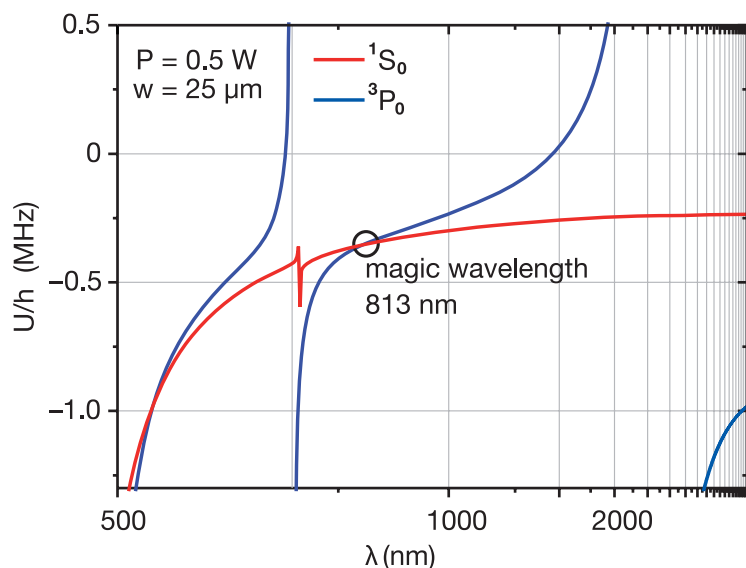


Figure 7:
Shift of the two energy
levels of a strontium
optical clock as a func-
tion of the wavelength of
the optical lattice.

above in anti-phase. In the first case the atom is pulled towards regions of high field strength, in the second one towards low fields. Unlike the storage of an ion in a Paul trap, the potential is generally different for both transitions of the reference transition and the reference transition is shifted by the trapping fields.

Depending on the atomic energy state, different transitions contribute to the dipole moment. This is shown in Fig. 7 for both states of the strontium clock transition. The behavior of the ground state potential (red) is determined by the strong absorption line at 461 nm, and the potential of the excited state is mostly determined by absorption lines to higher excited levels at wavelengths of 690 nm and 2300 nm. Both curves intersect at approximately 813 nm – the so-called “magic wavelength”. At this wavelength atoms can be stored in inhomogeneous fields in regions of high field strength without disturbing the reference transition.

The Doppler shift can be suppressed – similar to ion traps – when the atomic motion in the direction of the interrogation laser is restricted to much less than one wavelength. The necessary steep potential can be created by the interference of several laser beams. In the most simple setup a single retro-reflected laser beam is sufficient. In this standing wave, dark ranges and ranges with maximum intensity interchange with a period of half a wavelength – a so called one-dimensional optical lattice (Fig. 8). In 2001 the use of these special magic wavelength optical lattices was proposed by H. Katori [11]. Atoms are trapped in the potential minima, which are in regions of the highest intensity. Perpendicular to the propagation direction of the lattice beams, the potential is extended to approximately 100 μm due to the focusing of the beams. As the potentials rely on induced electric dipoles, the corresponding potential depths are much lower than in ion traps. Typical potential depths correspond to a

temperature of 100 μK, which requires that the atoms are laser cooled to a few microkelvin before they can be trapped. In addition, already a single collision with a hot background gas molecule is sufficient to expel an atom from the trap. Trapping times in ultrahigh vacuum (10^{-8} Pa) amount to few seconds, and thus for each interrogation cycle new atoms must be loaded.

For this type of optical clock, atoms with two valence electrons are especially suited. Similar to the case of Al^+ (see above), here the reference transition is between the ground state (spins oriented antiparallel) and the lowest triplet state (spins oriented parallel). Both states have a total angular momentum of $J = 0$. Clocks of this kind are currently investigated with magnesium, strontium, ytterbium, and mercury.

The currently best clocks of this type operate with ^{87}Sr [11,12] and are investigated in NIST (Boulder, USA), SYRTE (Paris), Tokyo University, and at PTB. The reference transition $^1\text{S}_0 - ^3\text{P}_0$ is at 698 nm and the lifetime of the excited state amounts to 130 s, corresponding to a natural linewidth of 1.2 mHz (Fig. 6). Strontium atoms are evaporated in an oven under ultrahigh vacuum, decelerated using laser light resonant on the allowed $^1\text{S}_0 - ^1\text{P}_1$ transition at 461 nm, and further cooled to a temperature of a few microkelvin in a magneto-optical trap. The optical lattice operates at the magic wavelength of 813 nm and stores about $10^3 - 10^4$ atoms. This corresponds to 10–100 atoms per potential well.

By laser cooling on the narrow $^1\text{S}_0 - ^3\text{P}_1$ transition the atoms can be cooled to the quantum motional ground state along the strongly bound direction. In the transverse, less tightly bound direction the atoms still populate higher vibrational states. As this motion is perpendicular to the direction of the interrogation laser beam, it does not influence the excitation of the reference transition. Despite different experimental setups, the frequencies of strontium lattice clocks in Boulder, Tokyo and Paris all agree to better than 2 Hz [13].

For the operation of a lattice clock a precise determination of the magic wavelength is crucial. This can be achieved by changing the power of the lattice laser and by monitoring the resulting shift of the clock transition in comparison to a reference laser. The power dependence of the shift changes sign exactly at the magic wavelength, which allows for a precise setting of the lattice wavelength. The sensitivity of the reference frequency amounts to only 1 Hz per gigahertz detuning of the lattice laser. By comparison of the lattice clock with a calcium optical atomic clock, various frequency shifting effects could be investigated in detail and the fractional uncertainty of the clock could be estimated to be $1.5 \cdot 10^{-16}$ [12]. A stability of $2 \cdot 10^{-15}$ was reached

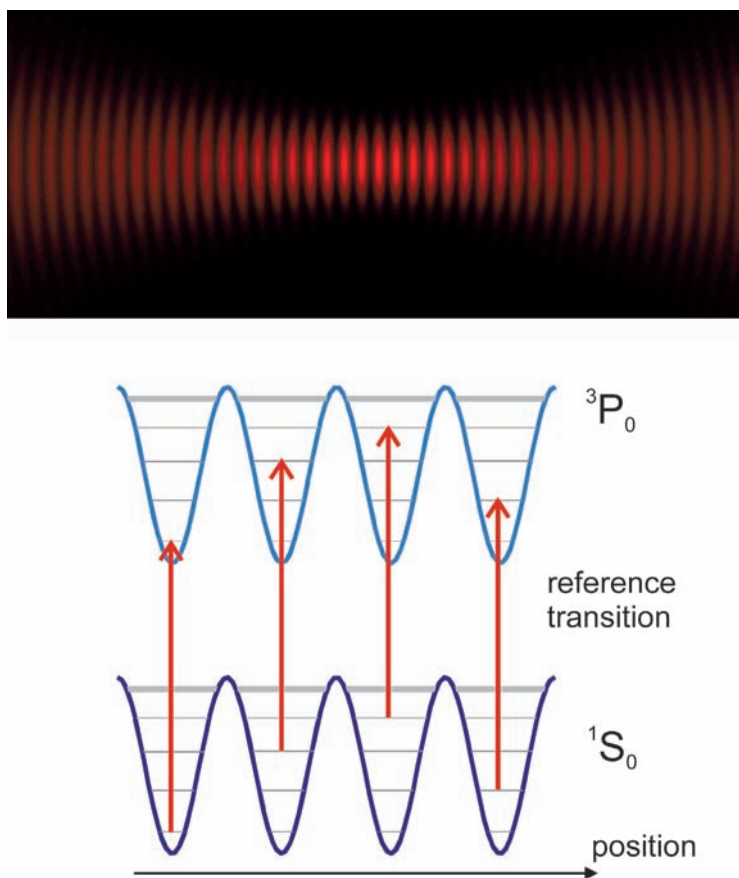
at one second averaging time, limited by the linewidth of the interrogation laser.

The biggest contribution to the uncertainty stems from a level shift by the black-body radiation of the environment. At room temperature the spectral maximum of this radiation lies at a wavelength of 10 μm . As can be seen from Fig. 7, in this range the ac Stark shift of both levels is quite different. From theory, a fractional shift of the transition frequency of $2 \cdot 10^{-15}$ at $T = 300 \text{ K}$ is calculated. Because of uncertainties of the atomic parameters and of the temperature distribution of the atomic environment, this shift can be corrected only approximately.

these clocks have gained enormous importance in many applications. Recently, the international committee for weight and measures BIPM has recommended the Hg^+ , Yb^+ , and Sr^+ single-ion clocks and the Sr lattice clock as so-called “secondary representations of the second” [14]. This can be seen as a first step towards a future redefinition of the second via an optical frequency.

We have started from the reasoning “higher frequency leads to higher accuracy”. Will it be possible to extrapolate this still further and will there be a clock operating with X-rays and precise to 10^{-21} ? Indeed it can be shown that nuclear transitions may offer some advantages for the

Figure 8:
The most simple optical lattice is made from the standing wave of a retroreflected laser beam. Intensity distribution (top) and potential for both levels of the atomic reference transition (bottom).



However, as the shift depends on the fourth power of the ambient temperature, it can be drastically reduced in future clocks by cooling the atomic environment to cryogenic temperatures.

5 Outlook

In several experiments described here it was possible to show that optical clocks outperform microwave atomic clocks in terms of stability and accuracy. It should be noted, however, that the maximal continuous operating time of these prototype optical clocks has not exceeded a few days and that therefore a practical definition of a clock as a device “that shows time” is not yet fulfilled. Over the last 40 years, caesium clocks have made the SI second the base unit that is realized by far with the lowest uncertainty and

realization of a precise clock, like the extremely high resolution that is possible in Mössbauer spectroscopy. The required coherent source of radiation is, however, still lacking.

Application of Einstein’s theory of relativity shows that the comparison or synchronization of two spatially separated clocks poses a great challenge already at the accuracy level of 10^{-18} . A frequency shift of this order of magnitude is produced by the Doppler effect if the relative motion amounts to just a few micrometers per day or by the gravitational red shift if the altitude of the clocks on Earth differs by 1 cm. Clocks of this precision will therefore become sensitive probes of their relativistic environment and may explore completely new applications for example in geodesy.

References

- [1] See, e.g., R. Wynands, S. Weyers: Atomic fountain clocks. *Metrologia* 42, 64 (2005).
- [2] W. Paul: Electromagnetic traps for charged and neutral particles. *Rev. Mod. Phys.* 62, 531 (1990); H. Dehmelt, Experiments with an isolated subatomic particle at rest. *Rev. Mod. Phys.* 62, 525 (1990).
- [3] S. Chu: The manipulation of neutral particles. *Rev. Mod. Phys.* 70, 685 (1998); C. Cohen-Tannoudji: Manipulating atoms with photons. *Rev. Mod. Phys.* 70, 707 (1998); W. D. Phillips: Laser cooling and trapping of neutral atoms. *Rev. Mod. Phys.* 70, 721 (1998).
- [4] J. L. Hall: Defining and measuring optical frequencies. *Rev. Mod. Phys.* 78, 1279 (2006); T. W. Hänsch: Passion for precision. *Rev. Mod. Phys.* 78, 1297 (2006).
- [5] H. Schnatz, B. Lipphardt, J. Helmcke, F. Riehle, G. Zinner: First phase-coherent frequency measurement of visible radiation. *Phys. Rev. Lett.* 76, 18 (1996).
- [6] P. Kubina, P. Adel, F. Adler, G. Grosche, T. W. Hänsch, R. Holzwarth, A. Leitenstorfer, B. Lipphardt, H. Schnatz: Long term comparison of two fiber based frequency comb systems. *Opt. Express* 13, 904 (2005); G. Grosche, B. Lipphardt, H. Schnatz: Optical frequency synthesis and measurement using fibre-based femtosecond lasers. *Eur. Phys. J. D* 48, 27 (2008).
- [7] T. Schneider, E. Peik, Chr. Tamm: Sub-Hertz optical frequency comparisons between two trapped ^{171}Yb ions. *Phys. Rev. Lett.* 94, 230801 (2005).
- [8] T. Rosenband et al.: Frequency ratio of Al^+ and Hg^+ single-ion optical clocks; metrology at the 17th decimal place. *Science* 319, 1808 (2008).
- [9] P. O. Schmidt, T. Rosenband, C. Langer, W. M. Itano, J. C. Bergquist, D. J. Wineland: Spectroscopy using quantum logic. *Science* 309, 749 (2005).
- [10] See "Quantum Logic for Precision Spectroscopy" in this issue, p. 54.
- [11] M. Takamoto, F.-L. Hong, R. Higashi, H. Katori: An optical lattice clock. *Nature* 435, 321 (2005).
- [12] A. D. Ludlow et al.: Sr lattice clock at $1 \cdot 10^{-16}$ fractional uncertainty by remote optical evaluation with a Ca clock. *Science* 319, 1805 (2008).
- [13] S. Blatt et al.: New limits on coupling of fundamental constants to gravity using ^{87}Sr optical lattice clocks. *Phys. Rev. Lett.* 100, 140801 (2008).
- [14] See "More accurate clocks – What are They Needed for?" in this issue, p. 16.

Novel Techniques for Remote Time and Frequency Comparisons

Dirk Piester¹ and Harald Schnatz²

1 Introduction

Time and frequency are the most precisely measurable physical quantities. Almost all technological processes require precise timing or reference frequencies, and improvements in the realization and dissemination of time and frequency are expected to have widespread impact on innovation, science, and daily life, in particular in the areas of communication and navigation. Hundreds of atomic frequency standards are in operation in telecom networks, military and science centers, and metrological institutes. To fully exploit this potential, novel techniques for time and frequency transfer are required.

National metrology institutes have significant capabilities in atomic clocks, time scale generation, time dissemination, space technology, and network synchronization. In a worldwide network, time laboratories contribute with presently approximately 250 atomic clocks to the international atomic time scale TAI. Caesium fountain clocks have demonstrated a relative accuracy of better than 10^{-15} with the potential to reach the low 10^{-16} range in the next five years [1]. In contrast to conventional atomic clocks which use atomic reference transitions in the microwave range, an emerging new generation of atomic clocks is based on laser excitation of reference transitions in the optical frequency range. These “optical” clocks have the potential to reach a relative accuracy of better than 10^{-17} together with a short-term stability (Allan deviation) in the range of $\sigma_y = 10^{-15} (\tau/s)^{-1/2}$ [2].

The wide range of different atomic clocks with diverse operational characteristics requires dedicated techniques for their comparison. On the one hand, routinely operational equipment is needed to compare continuously operating atomic clocks that are distributed worldwide. On the other hand, transfer links with extremely high stability are required to perform meaningful comparisons between optical clocks. According to these very different requirements, two different technical approaches are being pursued: while the worldwide network of atomic clock comparisons is based on microwave links

to satellites, optical clock comparisons use optical fiber connections between the sites involved.

Currently for satellite based comparisons there are two time and frequency comparison networks in operation, one employing the United States Global Positioning System (GPS) and one using two-way satellite time and frequency transfer (TWSTFT) via geostationary telecommunication satellites. In the following we briefly discuss GPS-based time and frequency transfer techniques and then take a closer look at the current performance of TWSTFT techniques. We also discuss new projects which are presently under development in order to significantly increase the stability of two-way transfer schemes: Atomic Clock Ensemble in Space (ACES) and Time Transfer by Laser Link (T2L2). These projects are not intended to remain operational for a long time but rather serve as demonstrator systems for future satellite-based time and frequency transfer.

For the further development and characterization of optical clocks, the ability to compare optical frequencies across the optical spectrum is of supreme importance. With the advent of frequency comb generators this problem is essentially solved for local comparisons [3]. Such clocks can now be compared with uncertainties approaching 1 part in 10^{19} [4]. The development of a new method for frequency comparisons between clocks separated by up to 1500 km with a resolution of 10^{-16} or better within one day could dramatically spur the development of high-performance optical clocks leading to a wide variety of applications. This point of view is also supported by recent recommendations of the Consultative Committee for Time and Frequency (CCTF) of the international standards organization BIPM [5]. We give an overview on the present development status of fiber-based transfer techniques and describe a recent experiment that investigates the transmission of a stable optical carrier frequency at 194 THz between PTB and the Institute of Quantum Optics at Leibniz Universität Hannover. We consider possibilities

¹ Dr. Dirk Piester, Working Group “Dissemination of Time”, PTB Braunschweig, email: dirk.piester@ptb.de

² Dr. Harald Schnatz, Working Group “Length Unit”, PTB Braunschweig, email: harald.schnatz@ptb.de

for a future European fiber network for remote optical clock comparisons and conclude with an outlook on future applications of the various time and frequency transfer techniques.

2 Satellite based clock comparisons

Facilities for satellite based time and frequency comparisons are standard equipment in every time laboratory. They are operated in a continuous mode to allow the computation of phase and frequency differences of atomic clocks and time scales. Both the GPS and TWSTFT techniques are used for frequency comparisons as well as for time transfer to realize the TAI time scale. Frequencies can be compared with an uncertainty in the 10^{-15} range with 1 day averaging [6], and time scale differences can be compared at the one nanosecond level [7].

2.1 Global Positioning System (GPS)

GPS has become a standard tool for time and frequency transfer between time laboratories [8]. The system maintains a minimum of 24 satellites in three orbits with a radius of 26600 km, such that at nearly each location on earth more than 4 satellites are simultaneously above the horizon. On each satellite a caesium or rubidium atomic clock serves as the onboard frequency and time reference. From this reference two carrier frequencies near 1600 MHz and near 1200 MHz are generated and transmitted. The transmitted signals are phase modulated by two characteristic and unique pseudorandom noise codes. The so-called coarse acquisition code is transmitted at 1600 MHz with a chip rate of ~ 1 Mch/s (corresponding to a modulation bandwidth of approximately 2 MHz), the precise code has a chip rate of ~ 10 Mch/s and is transmitted on both carrier frequencies. The coarse acquisition code includes the navigation message which contains a prediction of the satellite orbit, an almanac of the complete satellite constellation, a prediction of the onboard clock deviation relative to GPS system time scale, and an ionospheric model [9]. In time and frequency transfer applications, the received GPS signals are decoded in a way that permits a

time-of-arrival measurement with respect to the local reference clock and a reconstruction of the GPS carrier phase.

If the positions of the satellites and the receiver locations are precisely known, ground-based clocks can be compared with a typical precision of 10 ns (1 ns) using the coarse (precise) acquisition code. If the carrier frequency itself is used, the precision is in the range of 10 ps for suitable averaging times [10]. The accuracy actually achieved depends of course on the performance of the receiver and on the quality of the estimation of measurement errors: the signals from the satellites pass the ionosphere and the troposphere before reaching the receiver's antenna, and the effective propagation time can be altered by reflections from the neighbourhood of the antenna. All delay times in the signal path depend on the carrier frequency.

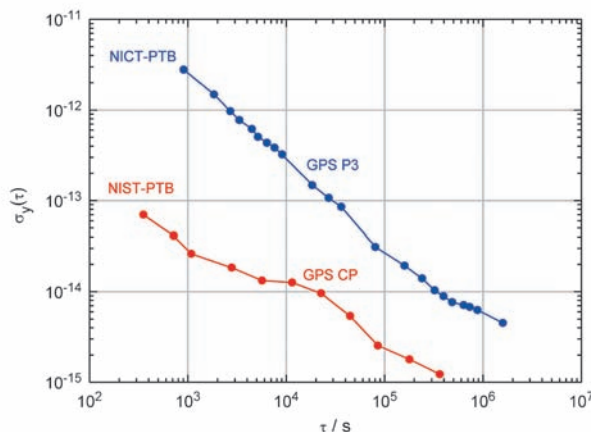
For time and frequency comparisons between two remote sites, two configurations can be employed: in the classical common-view configuration, two receivers record data from the same satellite at the same instant. It is obvious that the common-view technique has limitations if the two receivers are located far away from each other. In practice, the maximum baseline which can be bridged in this way is approximately 10000 km. By design the common-view configuration effectively reduces errors which are common to both receiver sites: the satellite clock errors and for small baselines also the errors caused by the ionosphere and troposphere.

There is no common-view requirement if the internal clocks of the GPS receivers are related to a common time scale. A very stable time scale (presently 10^{-15} relative stability at 1 day averaging) is provided via the Internet by the International GNSS Service IGS. Using the IGS time scale and multi-channel GPS receivers, ground clocks can be compared in such a way that the signals of all visible satellites are averaged. With this so-called all-in-view method, the main reasons for common-view comparisons vanish. Typically multipath effects and environmental influences on the receiver are the dominant error sources.

Most dual-frequency GPS receivers can decode the precise acquisition code, which allows to effectively reduce the ionospheric error by evaluating a suitable linear combination of the signals received on both transmission frequencies. The blue graph in Fig. 1 shows the stability of an intercontinental frequency comparison using this technique [10].

The best GPS-based frequency comparisons make use of the information contained in the carrier phase of the GPS signals. As indicated by the red graph in Fig. 1, about one order of magnitude in frequency transfer stability is gained

Figure 1:
Instability (Allan deviation as a function of averaging time) observed in long-baseline GPS frequency transfer. Blue: transfer to NICT (Japan) using a GPS common-view scheme with ionospheric error correction. Red: transfer to NIST (USA) using the GPS carrier-phase technique.



through the carrier phase (CP) technique [11]. The main problem with this technique is that conventional GPS signal evaluation software leads to jumps of the computed carrier phase at day boundaries. If clocks are compared over an extended period of time using the CP technique, these jumps have to be removed or to be taken into account as an additional uncertainty contribution. Concepts of combining code and carrier information and precise IGS clock and orbit data are currently under investigation to enable frequency and true time transfer with the stability of the CP measurements. Here a promising approach is the so-called Precise Point Positioning (PPP) technique, which is being investigated in particular in the context of the realization of the international atomic time scale TAI [12]. Presently 5 ns is the commonly assumed systematic uncertainty in time scale comparisons based on the long-term operation of GPS receivers.

2.2 Two-Way Satellite Time and Frequency Transfer

Two-Way Satellite Time and Frequency Transfer (TWSTFT) is the second leading technique for comparisons of remote atomic frequency standards [13]. The main advantage of the two-way technique is that undetermined delays along the signal path cancel out to first order because of the path reciprocity of the transmitted signals.

At present TWSTFT makes use of established satellite services in the Ku-band (11 GHz–14 GHz) and X-band (7 GHz–8 GHz). Time signals are transmitted by relating the phase of

taching the time interval measurement results to the transmitted timing signals.

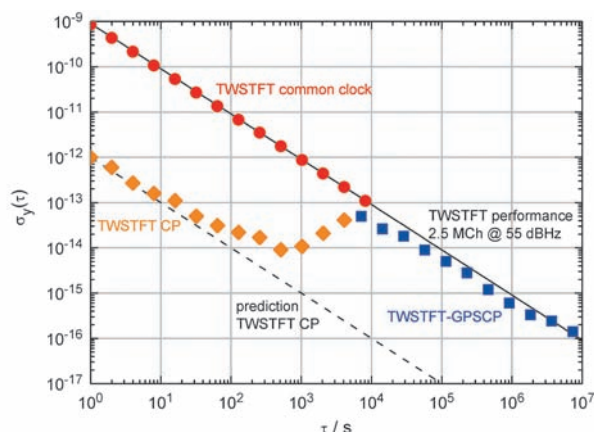
Fig. 2 shows stability test results and theoretical predictions for the current standard operational parameters of TWSTFT. An assessment of the performance of any comparison technique requires to suppress the contributions of the clocks compared. This is possible by operating two stations side-by-side connected to a common clock or for remote stations by forming double differences between results obtained with different techniques. Related data are shown in Fig. 2 for a comparison between the GPS carrier-phase and TWSTFT techniques. Surprisingly these data demonstrate a stability that is even slightly better than the prediction based on the expected measurement noise. The stability of TWSTFT can be enhanced if the transmission bandwidth (i.e., the employed chip rate) is increased. Currently available modems can handle chip rates up to 20 MCh/s, but their use is not common because this would significantly increase the cost of the transponder lease from commercial providers.

Fig. 2 also shows results of the first TWSTFT experiments where the carrier phase information of the satellite signal is used for frequency comparisons. This scheme has the potential to provide a frequency stability of $\sigma_y(\tau) = 10^{-12} (\tau/s)^{-1}$. As shown in Fig. 2, a good agreement with the predicted performance is observed for averaging times up to 100 s for both common-clock and transatlantic TWSTFT between USNO (United States Naval Observatory, Washington DC, USA) and PTB [14]. For longer averaging times the stability decreases significantly and appears to be limited by other noise sources than measurement noise. Nevertheless these initial results indicate that carrier-phase based TWSTFT frequency comparison has a strong development potential and might ultimately become attractive also for optical frequency standard comparisons.

It is well known that the path delay reciprocity is not completely fulfilled in TWSTFT. Nonreciprocal variations of the delay times are caused by residual satellite motion, by drifts of the signal delay times in the electronic components in the ground stations and in the satellite, and to a smaller degree by the difference between the uplink and downlink frequencies in combination with the propagation delay introduced by troposphere and ionosphere [15, 16].

Unfortunately most of the relevant variations occur with a daily pattern which complicates a quantitative analysis. Satellite motion impairs the transmission stability through both the path length variation and the variation of the propagation times due to the Sagnac effect. The ground station delays as well as the satellite

Figure 2: Instability (Allan deviation as a function of averaging time) of standard and carrier-phase based TWSTFT. Calculations and measurements were carried out for a TWSTFT signal modulated with a chip rate of 2.5 MCh/s and received with a carrier-to-noise ratio (link budget) of 55 dBHz. Full black line: calculated instability of standard TWSTFT. Red dots: instability measured in the common-clock mode which eliminates clock noise. Blue squares: instability of the difference between standard TWSTFT and GPS carrier-phase data in a clock comparison between NIST (Boulder, USA) and PTB. Dashed black line: calculated carrier-phase based TWSTFT instability. Orange diamonds: instability of carrier-phase based TWSTFT in a clock comparison between USNO (Washington DC, USA) and PTB.



a pseudorandom noise modulation to the one-pulse-per-second output of a local clock. Each station uses a dedicated code, and the receive equipment allows the reconstruction of the transmitted signal and its comparison with the local clock by means of a time interval counter. Following a prearranged schedule, both stations of a pair lock on the code of the remote station for a specified period, measure the signal arrival times, and record the results. The clock difference is obtained either in post-processing after exchanging the data files or in real time by at-



Figure 3:
Geographical distribution of the laboratories that contribute to TAI and employed clock comparison methods [17]. Adapted with kind permission of BIPM.

the atomic time scale TAI is shown. TWSTFT links are backed up by GPS time comparisons and the largest number of links relies entirely on GPS time comparisons. Since introduction of the all-in-view method, all laboratories equipped with GPS receivers are compared to a common pivot. Presently PTB is this reference point.

The BIPM estimates a 5 ns systematic uncertainty for a GPS link. TWSTFT comparisons can be per-

formed with a considerably lower uncertainty. The TWSTFT links between European stations and PTB were repeatedly calibrated by means of a portable station operated by the Technical University Graz (Austria) (see Fig. 4). In each campaign an uncertainty in the range of 1 ns was achieved. The most recent campaign in September 2008 included links to Graz, NPL (UK), OP (France), INRIM (Italy), METAS (Switzerland), and VSL (The Netherlands).

2.3 Time transfer for the realization of international atomic time

The *Bureau International des Poids et Mesures* (BIPM) organizes comparisons between time scales and atomic clocks in an international network. TWSTFT is the preferred method and gains importance as new ground stations at timing laboratories join the operational network [17]. In Fig. 3 the current geographical distribution of the laboratories contributing to

transponder delays are affected by environmental conditions like heating of the satellite by solar radiation and weather-related temperature and humidity changes on the ground. For a robust ground-station system it is recommended to place as much of the equipment as possible indoors in a suitable stable environment. Carefully controlled environmental conditions are also mandatory for next-generation TWSTFT schemes.

A remarkable series of calibrations of two independent TWSTFT links (Ku-band and X-band) between USNO and PTB permits an assessment of the long-term stability of the TWSTFT technique. The measured differential corrections to the previous calibration values are shown in Fig. 5. For the Ku-band (X-band) link, the 5-year mean of the corrections amounts to -0.46 ns (-0.50 ns) with a standard deviation of 1.43 ns (1.26 ns).

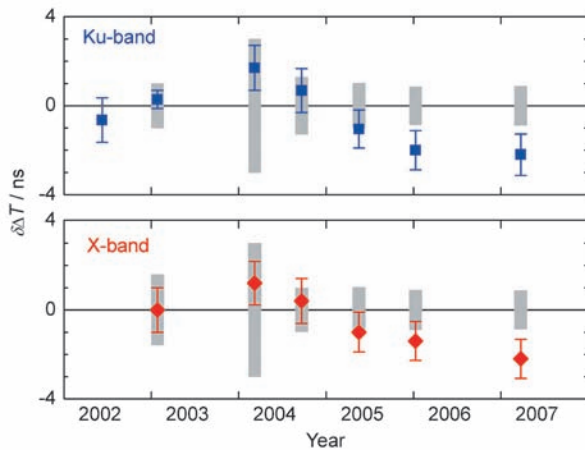
The calibration campaigns performed so far permit the conclusion that an uncertainty level of 1 ns can be reliably reached by the established measurement procedures and that the reproducibility is at the same level as the estimated uncertainty. Because of the high time transfer accuracy, TWSTFT was chosen as the primary means to synchronize the two Precise Timing Facilities of the future European satellite navigation system Galileo and to support the measurement of the difference between the GPS and the Galileo system time scales.



Figure 4:
Bernd Blanzano (Technical University Graz, on the left) and Jürgen Becker (PTB) adjust the antenna of the portable TWSTFT ground station of TU Graz during the latest link calibration campaign in September 2008. The other antennae belong to PTB reference stations.

Figure 5:

Time offsets measured during calibrations of the Ku-band and X-band TWSTFT links that connect the time scales UTC(USNO) and UTC(PTB). The error bars denote the associated measurement uncertainty. The offsets are measured relative to the offsets determined in the preceding calibration. The gray bars reflect the estimated link uncertainty immediately prior to the new calibration, taking into account known perturbations which might affect transmission delay times.



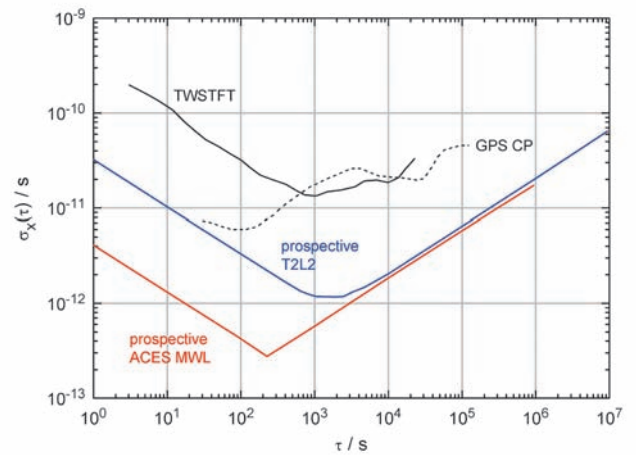
2.4 The T2L2 and ACES projects

Time Transfer by Laser Link (T2L2) is an experiment onboard the satellite Jason 2 which was launched in June 2008. First test measurements are scheduled for Spring 2009 [18]. The T2L2 concept employs the technique of satellite laser telemetry in order to compare two or more ground-based clocks: laser pulses that are synchronized with the ground clocks are transmitted to the satellite and retroreflected to the ground stations where the return times are recorded. The pulse arrival times at the satellite are registered relative to an onboard clock of high short-term stability. As shown in Fig. 6, the expected clock comparison uncertainty corresponds to a minimum time deviation of about 1 ps at an averaging time of 1000 s. This performance surpasses the precision of TWSTFT and GPS carrier-phase comparisons by approximately a factor of ten. As a result of the low satellite orbit radius of 1300 km, intercontinental comparisons must be carried out in a non-common-view mode where the achievable comparison stability is limited by the instability of the onboard clock.

Atomic Clock Ensemble in Space (ACES) is an ESA mission based upon the operation of atomic clocks in the microgravity environment of the international space station ISS. The time scale generated by the onboard atomic clocks is transferred to the ground through a high-performance microwave link. The microwave link uses two Ku-band frequencies for up- and downlink with chip rates of 100 MCh/s and an additional downlink in the S-band to accurately determine the ionospheric delay [19]. The expected link stability corresponds to a time deviation of less than 300 fs at an averaging time of

Figure 6:

Expected stability (time deviation σ_x as a function of averaging time) of time transmission using the T2L2 laser telemetry scheme and using the microwave links of the planned atomic clock ensemble ACES onboard the International Space Station. For comparison, exemplary data for time transmission based on TWSTFT and carrier-phase GPS are also shown [18].



300 s (see Fig. 6). This microwave link will allow to perform both space-to-ground and ground-to-ground comparisons of atomic frequency standards. The high stability of the onboard atomic clock ensemble will also enable non-common-view comparisons between ground atomic frequency standards with an uncertainty of less than 5 ps at an averaging time of 10^4 s.

3 Clock comparison by fiber link

Optical clocks based on cold atoms or a single ion presently achieve a short-term frequency stability in the range of $\sigma_y(\tau) \approx 10^{-15} (\tau/s)^{-1/2}$ [2]. These clocks are not transportable and require a frequency comparison technique that allows to reach the stability level of the clocks for measurement times between several minutes and several hours. As an alternative approach to satellite-based frequency transfer techniques, the use of optical fiber networks has been discussed extensively [20]. In order to bridge large distances, fiber transmission in the wavelength range of the telecommunications window around $1.5 \mu\text{m}$ is advantageous because signal loss is minimized.

A summary of different methods for frequency comparisons using optical fibers is given in [21]. Besides the transmission of solitons or of optical pulses from femtosecond lasers, two other methods have recently been established: the transfer of an ultrastable radiofrequency reference signal by amplitude modulation of an optical carrier [22], or the direct transfer of a highly stable optical carrier frequency [23]. Using the former technique, a relative frequency stability level of 10^{-18} at an averaging time of 1 day was achieved for an optical link of 86 km

length [24]. However, for longer links the dispersion in the fiber and signal attenuation become critical issues.

3.1 Comparison using a stable optical carrier frequency

The direct transfer of a highly stable optical carrier offers the advantage that stability degradations caused by down-conversion of optical frequencies to the microwave domain and by distortions of the modulation can be avoided. Optical clocks operating in remote laboratories can be compared by transmitting the radiation of a continuous single-frequency laser over an existing 1.5 μm -fiber network and comparing its frequency with that of the optical clocks located at both sites. Using femtosecond fiber laser based frequency comb generators, the frequency ratio between the laser and the optical clocks can be easily measured [25, 26]. Such optical frequency ratio measurements can reach an uncertainty level below 10^{-17} within a few hours of measurement time [27].

A prerequisite for long-haul frequency transmission is that the coherence length of the transmitted laser light exceeds the distance to be bridged. Otherwise the laser frequency noise limits the accuracy with which optical path length fluctuations can be controlled. In order to actively stabilize the frequency of the transmitted light, a local optical clock can serve as a reference.

Presently the established technique for direct frequency stabilization of a laser of arbitrary wavelength to an optical clock consists of transferring the stability of the clock to the output spectrum of a frequency comb generator [2]. The beat signal between a comb mode and the laser to be stabilized can then be used to lock its frequency to the comb spectrum and thereby to the optical clock.

Comb generators based on femtosecond fiber lasers bridge the frequency gap between optical clocks in the visible wavelength range and cw fiber lasers operating in the telecommunications window around 1.5 μm . Unfortunately, unstabilized fiber-based comb generators exhibit significant optical phase noise while their frequency control bandwidth is typically limited to less than 100 kHz. As a result, the phase noise of a fiber-based comb generator usually exceeds that of the optical standard to which it is stabilized by several orders of magnitude, and it is difficult to achieve a frequency stability of better than $\sigma_y \approx 10^{-14} (\tau/\text{s})^{-1/2}$ [28].

In order to overcome this problem, H. Telle et al. developed a technique in which the frequency comb generator is used as a transfer oscillator [29]. This scheme allows to compare laser frequencies in different spectral regions without stability degradation by the frequency

noise of the comb generator. Using this approach, a frequency comparison between distant optical clocks is performed in three steps:

- (1) A single-frequency fiber laser is phase-locked to one of the optical clocks using a fiber-based comb generator. This stabilized laser synthesizes a precisely known optical carrier frequency whose stability is equivalent to that of the optical clock.
- (2) The optical carrier is transmitted to the remote site using single-mode telecommunication fiber.
- (3) At the remote site, the frequency ratio between transmitted carrier and the local optical clock is measured by means of another frequency comb generator.

Step (1) of this concept was demonstrated by locking a continuous fiber laser oscillating at 1545 nm to a 871 nm diode laser which serves as the clock laser of a Yb^+ single-ion optical frequency standard and has a linewidth of less than 10 Hz [2, 30]. The fractional uncertainty of the synthesized frequency relative to the 871 nm reference approached 10^{-18} in a long-term frequency ratio measurement [31].

Step (2) was demonstrated in a collaboration with LNE-SYRTE (Paris). Here we distributed a precisely stabilized optical frequency over an urban telecom fiber network [23] (see below).

For a demonstration of Step (3), a good candidate is an optical frequency standard based on Mg atoms that is currently developed at the Institute of Quantum Optics (IQO) at Leibniz Universität Hannover. A frequency measurement of the $^1\text{S}_0$ - $^3\text{P}_1$ intercombination transition of Mg using a thermal atomic beam has been reported previously [32]. So far, a portable Caesium atomic clock and a GPS-controlled quartz oscillator have been used as local references. A considerable enhancement of measurement accuracy is expected from the further development of the Mg standard and from comparisons with one of the established optical frequency standards of PTB by means of a fiber link.

3.2 Optical path length stabilization

Common to all fiber based transfer techniques is that the frequency stability of any signal transmitted through an optical fiber is degraded by phase noise induced by mechanical stress and temperature variation in the fiber. In long-haul systems, fluctuations induced by temperature variations in the optical fiber dominate on long time scales. Other sources of low-frequency noise, such as polarization mode dispersion in optical fibers and temperature variations in peripheral equipment can also affect the long term stability. Noise sources that can play a role at

shorter time scales include thermal and electronic flicker ($1/f$) noise, photodetection shot noise, and amplitude-to-phase conversion processes.

Typically, in order to achieve ultra-stable frequency dissemination via optical fibers over distances exceeding 100 m, the phase noise of the fiber link must be suppressed by active optical path length stabilization.

Fig. 7 shows a schematic of an active fiber noise cancellation system that was first described by Ma et al. [33]. At the local site, a part of the laser output passes through an acoustooptic frequency shifter (AOM) that is driven by a voltage-controlled oscillator and is fed into the fiber link. At the remote end, a part of the signal is frequency shifted and retraced. The retraced light is frequency shifted again at the local site and is made to interfere with a part of the original laser output. The resulting beat signal is phase locked to a stable rf reference by controlling the frequency of a voltage-controlled oscillator. This interferometric arrangement cancels the fiber-induced phase noise at the remote end of the fiber link. The frequency shift of the retraced light at the remote site allows to discriminate it from other sources of backscattering. The analysis of the local photodetector signal provides an in-loop measurement of the residual phase noise. In test setups where the local and remote sites are located next to each other, direct out-of-loop measurements of the link stability can be performed by analyzing the beat signal between the laser output and the light received at the remote end.

3.3 Experiments

In our collaboration with LNE-SYRTE, we used a ^{87}Sr optical lattice clock [34] as the reference and an existing standard telecom fiber link. To simulate a user at a distant laboratory, the transmitted signal was looped back from the far end to the local laboratory resulting in a total transmission distance of 86 km. In some measurements the distance was further extended to 211 km using fiber spools. In the latter case, the resulting total single-path attenuation of 50 dB was compensated by an erbium-doped fiber amplifier. The optical clock, the frequency comb generator, and the laser and path length stabilization were continuously operational over periods of approximately 12 h. The 86 km fiber link achieved a relative frequency stability of $\sigma_y(1\text{ s}) = 2.2 \cdot 10^{-15}$ and reached an instability below $5 \cdot 10^{-18}$ within several hours. The mean of the transmitted frequency differed from the optical frequency at the local end by 3 mHz with an uncertainty of the mean of 4 mHz [23].

In the following we describe a fiber link connecting PTB with a laboratory of the IQO at Leibniz Universität Hannover. This recently es-

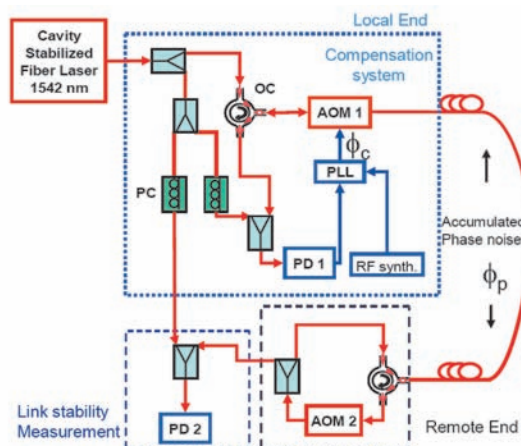


Figure 7:
Setup for active compensation of fiber noise (Courtesy of G. Santarelli).
AOM: acousto-optic modulator; PD: photo-diode; PLL: phase locked loop; PC: polarization controller; OC: optical circulator; RF synth: Radio-frequency synthesizer. For details see text.

established link (see Fig. 8) is part of a larger fiber network which will eventually connect optical clocks at PTB and at IQO with those operated at the Max Planck Institutes in Erlangen (Institute of Optics, Information and Photonics, IOIP) and Garching (Max-Planck-Institute for Quantum Optics, MPQ).

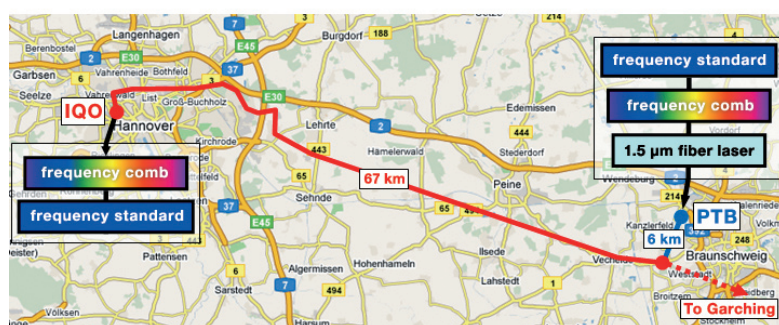


Figure 8:
Schematic of a comparison of remote frequency standards by means of a link based on dark telecommunication fibers (blue and red lines). The dashed line indicates a planned extension (see text). At PTB a $1.5\text{ }\mu\text{m}$ fiber laser is locked to an optical frequency standard. Its output is transmitted to Leibniz Universität Hannover where its frequency is compared with that of an optical frequency standard based on Magnesium atoms. (Map source: Google Maps)

The pipeline networks of gas distribution companies and local telecommunication providers offer significant potential for developing an area-wide fiberoptic infrastructure. The fiber routes from Braunschweig to Hannover and Garching are established in a collaboration with the German science communication network DFN, GasLINE (a fiberoptic cable provider established by German gas distribution companies), and EnBs (a local energy and telecommunications provider). Two dedicated pairs of dark fiber in a strand of commercially used fibers have been made available. As both fibers are located in the same strand, they are affected by the same environmental conditions and have the same characteristics.

The total fiber path distance from PTB to the IQO is 73 km. Via the local network of EnBs we connect our laboratory to the wide-area network of GasLINE. The use of this infrastructure permits a direct connection to the university's computing center, located about 400 m away from the IQO. An in-house fiber link provides access to the Mg frequency standard.

We used commercial SMF-28 fiber according to the ITU-T G.652 standard with a refractive

index of $n = 1.4681$ at 1550 nm, an attenuation of ≈ 0.23 dB/km, and a chromatic dispersion of ≈ 18 ps/(nm·km). An optical time domain reflectometer was used to obtain a detailed description of splice and connector positions along the link. The full link comprises 16 splices and approximately 10 connectors.

In order to characterize the stability of the link, a fiber loop of 146 km length whose ends are located in a PTB laboratory was established by connecting the ends of a fiber pair in Hannover. The measured overall attenuation of this loop is approximately 46 dB.

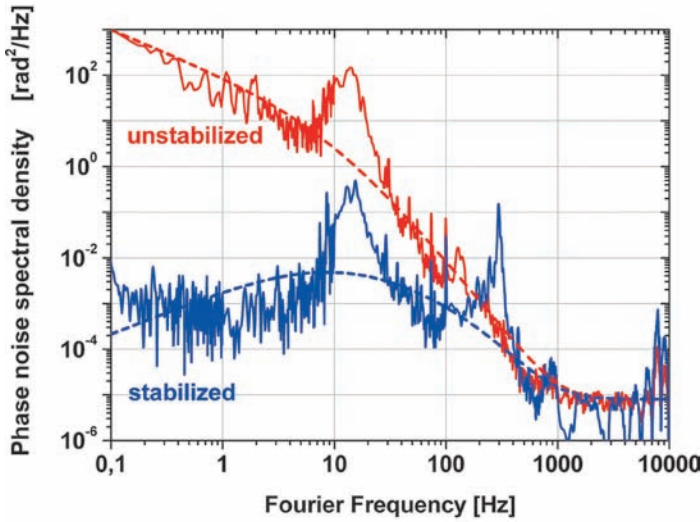


Figure 9: Observed phase noise spectral density [35] of a PTB-Hannover-PTB fiber link of 146 km length without optical path length stabilization (red) and with active stabilization (blue). The red dashed line indicates the asymptotic phase noise characteristic in the limit of high and low Fourier frequencies. The blue dashed line indicates the calculated suppression effect of the employed phase noise cancellation system for the asymptotic characteristic (see text).

The phase noise spectrum of the link is shown in Fig. 9 [35]. Without active path length stabilization, the observed phase noise spectrum can be approximated by

$$S_{\phi}(f) \approx \left[\frac{100 \text{ Hz}}{f} \cdot \left(1 + \frac{f}{10 \text{ Hz}} \right)^{-2} + c \right] \text{ rad}^2 \text{ Hz}^{-1}$$

if the distinct environmental noise maximum at $f \approx 15$ Hz is neglected. For Fourier frequencies $f \geq 100$ Hz, the phase noise decreases as $1/f^3$, while for $f \leq 10$ Hz the frequency dependence is that of flicker ($1/f$) phase noise. The constant noise floor at high frequencies is determined by the intrinsic noise of the detection system.

3.4 Stability limit

For any fiber link, a fundamental limit on the achievable degree of phase noise suppression arises from the propagation delay introduced by the fiber. The delay directly affects the maximum control bandwidth of the path length stabilization loop. As a result, the stability at high Fourier frequencies f is limited by unsuppressed noise of the fiber link. The spectral dependence of the achievable phase noise suppression can be estimated as

$$S_{\phi}^{\text{out}}(f) = \frac{4\pi^2}{3} \cdot \left(\frac{nL}{c} \right)^2 \cdot f^2 \cdot S_{\phi}^{\text{in}}(f) \quad \text{for } f < c/(nL)$$

where L is the one-way physical path length, n the index of refraction, c the speed of light, and S_{ϕ}^{in} denotes the phase noise of the unstabilized link [39].

The return signal used for path length stabilization of the PTB-Hannover-PTB link has a delay of 1.4 ms which limits the bandwidth of the stabilization loop to 350 Hz. As shown in Fig. 9, the measured phase noise of the stabilized link is in good agreement with the predicted frequency dependence of the phase noise suppression. The estimated frequency transmission stability of this link is $\sigma_y(\tau) \approx 3 \cdot 10^{-15} (\tau/s)^{-1}$ if the environmental noise peak at $f \approx 15$ Hz is neglected. Using a 871 nm clock laser reference (see above), we measured the fractional stability of the transmitted frequency at the remote end and found a value of $\sigma_y(\tau) = 2.5 \cdot 10^{-15} (\tau/s)^{-1}$ (see Fig. 10) [35].

This measurement demonstrates that a fiber link with low intrinsic phase noise permits the comparison of state-of-the-art optical clocks [2] which are separated by more than 100 km without degrading the stability afforded by the clocks.

Similar experiments have been performed by other groups and phase noise data of three other fiberoptic links have been published recently. These links have lengths of 40 km [36], 86 km [37], and 120 km [38]. In some cases the total link length was increased up to 251 km by adding additional fiber spools. While the phase noise characteristics of the 40 km and 80 km links are very similar to that of the PTB link, the 120 km link exhibits a noise level that is approximately 25 dB higher at $f = 1$ Hz and decreases proportional to $1/f^2$.

As $S_{\phi}^{\text{out}}(f)$ is proportional to $L^2 S_{\phi}^{\text{in}}(f)$, the attainable link stability in frequency comparisons decreases proportional to $L (S_{\phi}^{\text{in}})^{1/2}$. Since L is determined by the distance between the clocks that are compared, the only way to improve the link stability is to split the total length into subsections (to increase the control bandwidth) and/or to select a fiber link with low intrinsic phase noise.

With respect to phase noise suppression, fibers installed along gas-pipeline networks offer some advantages: the underground location of pipelines strongly suppresses diurnal temperature variations and other environmental perturbations. A long-haul optical link can be split into appropriate subsections as the typical distance between housings for installations like repeaters and amplifiers along a link is about 80 km.

3.5 Towards a European fiber network

With the availability of a national test facility between PTB and the MPQ in Garching, we now have the unique possibility to explore the first

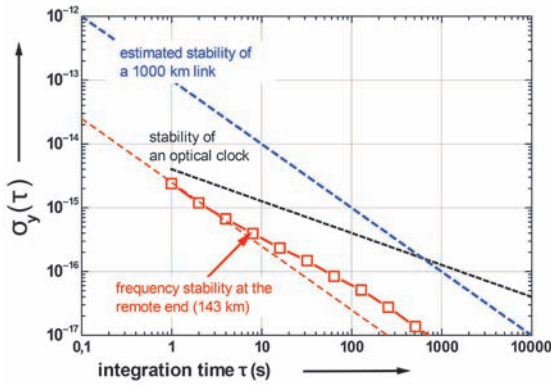


Figure 10:

The observed fractional stability of laser frequency transmission using the 146 km PTB-Hannover-PTB link [35] is compared with that of a state-of-the-art single-ion optical clock [2] and with the estimated stability of a link of 1000 km length (see text).

long-haul, all-optical carrier phase frequency transmission over a long-distance optical link of 900 km. This extends the transfer capability to the continental scale and will eventually allow to compare the very stable and accurate clocks that are located in many European laboratories. The 900 km fiber link which presently is being set up is a unique opportunity to study an advanced optical frequency dissemination system at real scale with representative environmental perturbations. We expect that this will boost new applications as well as significant advances in current research.

However, for the envisioned link lengths the cumulative loss of the link must be compensated by the insertion of amplifier stages. The amplifiers must operate bidirectionally and preserve the coherence of the input signal. Erbium-doped fiber amplifiers satisfy these demands and are commonly used in telecom fiber networks. Assuming a typical link loss of 0.2 dB/km and a gain of 20 dB–30 dB per amplifier, an amplifier spacing of 100 km is sufficient to establish a quasi-transparent optical link where the noise penalty due to the cascaded amplification is smaller than 10 dB [39].

In order to estimate the stability of the transmitted signal for a 1000 km link, we assume that the phase noise of the free-running link has a frequency dependence similar to that of the present PTB-Hannover link (see Fig. 9), but that the phase noise spectral density $S_{\phi}^{\text{in}}(f)$ is increased proportional to the link length. In this case, the phase noise level would still be smaller than that of the 120 km link investigated in Ref. 38. Thus, assuming a noise level of $S_{\phi}^{\text{in}}(f) = 5 \cdot 10^4 \text{ Hz}^2/f^2 \text{ rad}^2 \text{ Hz}^{-1}$ as a worst-case estimate, the calculated residual phase noise of the stabilized link is in the range of $S_{\phi}^{\text{out}}(f) \leq 50 \text{ rad}^2 \text{ Hz}^{-1}$, corresponding to an estimated fractional frequency stability of $\sigma_y(\tau) \approx 1 \cdot 10^{-13} (\tau/\text{s})^{-1}$.

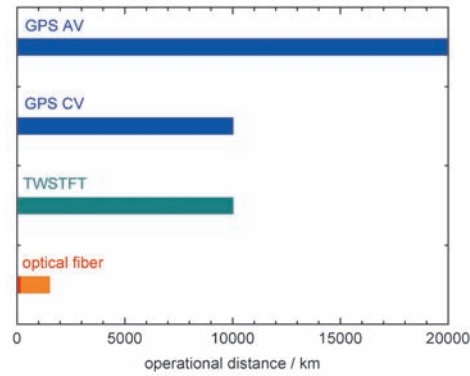


Figure 11:

Operational baseline lengths of time and frequency transfer links for different techniques. Currently, optical fiber links are realized over distances of about 250 km and extensions up to about 1500 km are planned.

As shown in Fig. 10, the estimated instability of a 1000 km link becomes smaller than that of the presently best optical clocks for an averaging time $\tau > 1000$ s. After an averaging time of 3 hours, the contribution of the optical link to the total instability would be negligible. Even with the assumed fairly high noise level of the link, a clock comparison by optical fiber could exceed the predicted capability of satellite-based comparisons using the carrier-phase TWSTFT technique (cf. Fig. 2) by one order of magnitude.

Thus, for optical-clock comparisons within Europe the use of optical fibers can be a powerful alternative to comparisons via satellite provided that suitable dark fiber will be accessible.

From the present point of view, the availability of dark fiber is not a problem, but the cost of rent over a period of 5 to 10 years is a critical issue. The search for dark fiber providers that will grant the national metrology institutes access to a European fiber network and support them in establishing national link capabilities will be one of the most important tasks of the near future.

4 Outlook

The operational distance of time and frequency transfer techniques is an important criterion if one considers the comparison of atomic frequency standards at remote sites. Fig. 11 compares the current and prospective baselines provided by the various techniques. The GPS all-in-view technique is unique: it allows comparisons between clocks wherever they are located on earth. For the classical common-view technique and for TWSTFT, the baseline limitation is approximately 10000 km because both sites must simultaneously point to one satellite. In the BIPM network for the computation of TAI, the TWSTFT link with the presently longest baseline is that between NICT (National Institute of Information and Communications Technology, Tokyo) and PTB. For significantly longer distances two-hop configurations appear feasible, but additional measurement noise must be taken into account. Such a link is currently in preparation between USNO and NICT using a relay station

in Hawaii. If this link is established, TWSTFT in a closed loop around earth will provide two independent links between each pair of participating sites. Presently a number of new laboratories particularly in Asia are about to join the worldwide TWSTFT network and also the number of laboratories that use GPS time transfer is increasing.

Despite the fast advances of clock comparisons via optical fiber links, we expect that also in the near future the baselines of such links will be restricted to less than approximately 1500 km. Nevertheless it appears that the advantages provided by optical fiber links and the availability of frequency-stabilized optical reference signals will stimulate new developments in science and technology. Using femtosecond frequency comb technology, the dissemination of frequency-stabilized 1.5 μm light enables the generation of radiofrequency and microwave signals with unprecedented stability without need for a local reference clock. Optical fiber links have the potential to provide an optical frequency reference for fundamental research and applied science with an accuracy and stability that today is available only at national metrology institutes and a small number of other dedicated laboratories. Applications range from low-level laser frequency calibration, length interferometry, and remote wavelength standard calibration to the synchronization and timing of accelerator facilities.

In the near future, the synchronization systems of next-generation linear colliders [40] and of large astronomical antenna arrays such as the Atacama Large Millimeter Array [41], both demanding low-noise frequency dissemination systems with minimal phase drifts and errors, will particularly strongly benefit from optical fiber links. The stable synchronization afforded by the transmission of an optical carrier frequency will also foster new developments in very long baseline interferometry (VLBI) astronomy, such as large-aperture VLBI in the near-infrared and optical wavelength range. The combination of high frequencies and long interferometric baselines requires the distribution of a local oscillator with low phase noise and low phase drift through the array [42]. For the Deep Space Network of NASA, a system of optical fiber links has been developed in order to distribute reference signals from a hydrogen maser for antenna synchronization [43].

The implementation of a European fiber network for highly stable optical frequency transmission will boost the field of time and frequency metrology. The network in particular will enable stability tests of satellite-based time transfer techniques (see above) and of the timing facilities of the global navigation satellite systems GPS and Galileo [44].

A number of fundamental physics research programs will benefit from the ability to compare distant optical frequency standards through optical fiber links without any significant loss in accuracy or stability. Prominent examples are tests on possible violations of the equivalence principle of General Relativity and on the possible drift of the fine structure constant [44]. Clearly, the ability to perform comparisons between distant optical clocks at the highest possible accuracy level is also a prerequisite for a possible redefinition of the SI second on the basis of an optical clock.

Acknowledgements

The authors would like to thank the staff members of PTB who have contributed to the results presented in this report: A. Bauch, J. Becker, T. Feldmann, G. Grosche, T. Legero, B. Lipphardt, C. Lisdat, M. Misera, T. Polewka, M. Rost, E. Staliuniene, U. Sterr, and O. Terra. We also express our gratitude to the colleagues from all the laboratories working in the field of time and frequency dissemination for their contributions. This work was partly supported by DFG through SFB 407.

References

- [1] See, e.g., R. Wynands, S. Weyers: Atomic fountain clocks. *Metrologia* 42, S64 (2005).
- [2] See the contribution "The Development of Accurate Optical Clocks" in this issue, p. 25.
- [3] T. Udem, J. Reichert, R. Holzwarth, T.W. Hänsch: Accurate measurement of large optical frequency differences with a mode-locked laser. *Opt. Lett.* 24, 881 (1999).
- [4] L. S. Ma et al.: Optical frequency synthesis and comparison with uncertainty at the 10^{-19} level; *Science* 303, 1843 (2004).
- [5] CCTF recommendation CCTF-3 to the CIPM (2006 meeting).
- [6] A. Bauch et al.: Comparison between frequency standards in Europe and the US at the 10^{-15} uncertainty level. *Metrologia* 43, 109 (2006).
- [7] D. Piester, A. Bauch, L. Breakiron, D. Matsakis, B. Blanzano, O. Koudelka: Time transfer with nanosecond accuracy for the realization of International Atomic Time. *Metrologia* 45, 185 (2008).
- [8] J. Levine: Time and frequency distribution using satellites. *Rep. Prog. Phys.* 65, 1119 (2002).
- [9] Understanding GPS: Principles and Applications. Eds.: E. Kaplan, C. J. Hegarty, Artech House (Norwood 2006).
- [10] T. Gotoh, A. Kaneko, Y. Shibuya, M. Imae: GPS Common View. *Journal of the NICT* 50, 113 (2003).

- [11] C. Hackman, J. Levine, T. Parker, D. Piester, J. Becker: A Straightforward frequency-estimation technique for GPS carrier-phase time transfer. *IEEE Trans. UFFC* 53, 1570 (2006).
- [12] G. Petit, Z. Jiang: Precise Point Positioning for TAI computation. *Int. J. Nav. Obs.*, article ID 562878 (2008).
- [13] D. Kirchner: Two-way satellite time and frequency transfer (TWSTFT): Principle, implementation, and current performance. In: *Review of Radio Sciences 1996-1999*, Oxford University Press (1999), p. 27.
- [14] B. Fonville, D. Matsakis, A. Pawlitzki, W. Schäfer: Development of carrier-phase-based two-way satellite time and frequency transfer (TWSTFT). *Proc. 36th PTTI Systems and Applications Meeting* (Washington DC, USA 2005), p. 149.
- [15] T. E. Parker and V. Zhang: Sources of instabilities in two-way satellite time transfer. *Proc. 2005 Joint IEEE International Frequency Control Symposium and PTTI Systems and Applications Meeting* (Vancouver, Canada 2005), p. 745.
- [16] D. Piester et al.: Studies on instabilities in long-baseline two-way satellite time and frequency transfer (TWSTFT) including a troposphere delay model. *Proc. 39th PTTI Systems and Applications Meeting* (Long Beach, USA 2008), p. 211.
- [17] E. F. Arias: Time scales and relativity. *Proc. International School of Physics "Enrico Fermi" Course CLXVI in Metrology and Fundamental Constants*, eds.: T. W. Hänsch et al., IOS Press (Amsterdam 2007), p. 367.
- [18] J. Weick, E. Samain, P. Vrancken, P. Guillemot: Prospective performance budget of the T2L2 experiment. *Proc. IEEE International Frequency Control Symposium jointly with the 21st European Frequency and Time Forum* (Geneva 2007), p. 312.
- [19] A. Seidel et al.: The ACES microwave link: instrument design and test results. *Proc. IEEE International Frequency Control Symposium jointly with the 21st European Frequency and Time Forum* (Geneva 2007), p. 312.
- [20] M. Amemiya et al.: Time and frequency transfer and dissemination methods using optical fiber network. *IEEE Trans. FM* 126, 458 (2006).
- [21] S. M. Foreman, K. W. Holman, D. D. Hudson, D. J. Jones, J. Ye: Remote transfer of ultrastable frequency references via fiber networks. *Rev. Sci. Instrum.* 78, 021101 (2007).
- [22] F. Narbonne et al.: High resolution frequency standard dissemination via optical fiber metropolitan network. *Rev. Sci. Instrum.* 78, 064701 (2007).
- [23] G. Grosche, B. Lipphardt, H. Schnatz, G. Santarelli, P. Lemonde, S. Bize, M. Lours, F. Narbonne, A. Clairon, O. Lopez, A. Amy-Klein, C. Chardonnet: Transmission of an optical carrier frequency over a telecommunication fiber link. *CLEO 2007 Technical Digest* (Baltimore, USA 2007). DOI: 10.1109/CLEO.2007.4452577
- [24] O. Lopez et al.: 86-km optical link with a resolution of 2×10^{-18} for RF frequency transfer. *Eur. Phys. J. D* 48, 35 (2008).
- [25] P. Kubina et al.: Long term comparison of two fiber based frequency comb systems. *Opt. Express* 13, 904 (2005), and references therein.
- [26] H. Inaba et al.: Long-term measurement of optical frequencies using a simple, robust and low-noise fiber based frequency comb. *Opt. Express* 14, 5223 (2006).
- [27] J. Stenger, H. Schnatz, Chr. Tamm, H. R. Telle: Ultraprecise measurement of optical frequency ratios. *Phys. Rev. Lett.* 88, 073601 (2002).
- [28] E. Benkler, H. R. Telle, A. Zach, F. Tauser: Circumvention of noise contributions in fiber laser based frequency combs. *Opt. Express* 13, 5662 (2005).
- [29] H. R. Telle, B. Lipphardt, J. Stenger: Kerr-lens mode-locked lasers as transfer oscillators for optical frequency measurements. *Appl. Phys. B* 74, 1 (2002).
- [30] See the contribution "Super-Stable Lasers" in this issue, p. 45.
- [31] G. Grosche, B. Lipphardt, H. Schnatz: Optical frequency synthesis and measurement using fibre-based femtosecond lasers. *Eur. Phys. J. D* 48, 27 (2008).
- [32] J. Friebe et al.: Absolute frequency measurement of the magnesium intercombination transition $^1S_0 \rightarrow ^3P_1$. *Phys. Rev. A* 78, 033830 (2008).
- [33] L.-S. Ma, P. Jungner, J. Ye, J. L. Hall: Delivering the same optical frequency at two places: accurate cancellation of phase noise introduced by an optical fiber or other time-varying path. *Opt. Lett.* 19, 1777 (1994).
- [34] R. Le Targat et al.: Accurate optical lattice clock with ^{87}Sr atoms. *Phys. Rev. Lett.* 97, 130801 (2006).
- [35] O. Terra, G. Grosche, T. W. Hänsch, R. Holzwarth, B. Lipphardt, K. Predehl, H. Schnatz: Comparing optical frequency standards over a 146 km using a commercial Telecom fiber. (manuscript in preparation)
- [36] P. A. Williams, W. C. Swann, and N. R. Newbury: High-stability transfer of an optical frequency over long fiber-optic links. *J. Opt. Soc. Am. B* 25, 1284 (2008).

- [37] *H. Jiang et al.*: Long-distance frequency transfer over an urban fiber link using optical phase stabilization. *J. Opt. Soc. Am. B* 25, 2029 (2008).
- [38] *M. Musha, F.-L. Hong, K. Nakagawa, K. Ueda*: Coherent optical frequency transfer over 50 km physical distance using a 120 km long installed telecom fiber network. *Opt. Express* 16, 16459 (2008).
- [39] *T. Schneider*: *Nonlinear Optics in Telecommunications*. Springer Verlag (Berlin 2004).
- [40] *J. Frisch, D. Bernstein, D. Brown, E. Cisneros*: A high stability, low noise rf distribution system. *Proc. IEEE Particle Accelerator Conference 2002*, 2, p. 816.
- [41] *W. Shillue*: Fiber distribution of local oscillator for Atacama Large Millimeter Array. *Proc. OFC/NFOEC 2008* (San Diego, USA 2008), p. 1; *B. Shillue*: ALMA Memo 443 (2002); <http://www.alma.nrao.edu/memos/>
- [42] *K. H. Sato et al.*: Application of phase-stabilized optical fiber in transmission of reference and IF signals in VLBI observation. *IEEE Trans. IM* 41, 385 (1992).
- [43] *M. Calhoun, S. Huang, R.L. Tjoelker*: Stable photonic links for frequency and time transfer in the Deep Space Network and antenna arrays. *Proc. IEEE* 95, 1931 (2007).
- [44] See the contribution "More Accurate Clocks – What are They Needed for?" in this issue, p. 16.

Super-Stable Lasers

Christian Lisdat¹ and Christian Tamm²

1 The goal: perfect coherence

In most conventional light sources, photons are emitted spontaneously by a hot surface, a discharge-excited plasma, or by recombination of charge carriers in a semiconductor. In classical physics, the resulting light is described as an electromagnetic field that consists of a stochastic superposition of wavelets. This type of light is usually termed incoherent. In incoherent light, phase and amplitude of the electric field exhibit strong uncorrelated temporal fluctuations. The characteristic time scale of these fluctuations, the coherence time τ_c , is given by $\tau_c \approx 1/\pi\Delta\nu$ where $\Delta\nu$ is the spectral width of the analyzed light. Spectral filtering with a bandwidth $\Delta\nu' < \Delta\nu$ increases the coherence time, but the power is reduced proportional to $\Delta\nu'/\Delta\nu$. Coherence times larger than a few nanoseconds are very difficult to achieve with incoherent light sources.

The light emitted by lasers has very different properties both at the quantum level and in the classical limit. The output of a continuously operating single-mode laser is a coherent electromagnetic wave with only small amplitude and phase fluctuations. An elementary perturbation is the diffusion-like phase variation of the optical field within the laser resonator that is caused by spontaneous emission in the laser gain medium [1]. In semiconductor lasers, this effect typically limits the achievable coherence time. Another source of laser frequency instability is the variation of the optical path length of the laser resonator due to acoustic perturbations and changes of the refractive index of the gain medium. For many types of lasers, simple passive stabilization measures are sufficient to achieve coherence times in the range $\tau_c \geq 1 \mu\text{s}$, corresponding to linewidths $\Delta\nu = 1/\pi\tau_c \leq 300 \text{ kHz}$. In this case, the remaining frequency fluctuations are sufficiently slow to be reduced further to a very low level by active stabilization.

1.1 Active frequency stabilization

Active laser frequency stabilization relies on detecting the frequency or phase deviations of the laser output by means of an optical fre-

quency discriminator or by comparison with a stable reference laser. The detected error signal is processed electronically in order to generate a feedback control signal which corrects the laser frequency. A substantial linewidth reduction is possible only if the response time of the feedback loop is smaller than the coherence time of the unstabilized laser light.

It is not surprising that the technically most convenient reference for active laser frequency stabilization is a stable reference laser whose frequency is close to that of the laser to be stabilized: the interference of the two laser fields on a photodetector gives rise to a beat signal at the difference of the optical frequencies. The beat signal and an auxiliary radiofrequency oscillator can be used to stabilize the laser frequency at the sum or difference frequency of the optical and radiofrequency references. Optical frequency comb generators make it possible to extend this technique to lasers whose frequencies lie arbitrarily far away from each other in the optical spectrum [2, 3].

In this article we will focus on laser frequency stabilization by optical resonators. Here the error signal is generated by an optical frequency discriminator whose central element is a Fabry-Pérot resonator of high intrinsic stability, the "reference cavity". In contrast to stabilization schemes that employ atomic or molecular absorption lines in order to enhance the long-term stability of the average laser frequency, the reference cavity technique aims predominantly at increasing the coherence time and at reducing the short-term frequency fluctuations.

In a cavity-based optical frequency discriminator, the frequency of a cavity mode is close to resonance with the laser frequency to be stabilized, and the error signal is derived from the power variations of the light transmitted through or reflected by the reference cavity. Any kind of detection noise is indistinguishable from real frequency fluctuations and therefore limits the achievable frequency stability. A categorical limit is set by the photodetection shot noise.

1 PD Dr. Christian Lisdat, Working Group "Quantum optics with cold atoms", PTB Braunschweig, email: christian.lisdat@ptb.de

2 Dr. Christian Tamm, Senior Scientist in Working Group "Optical clocks with trapped ions", PTB Braunschweig, email: christian.tamm@ptb.de

The magnitude of the photodetector signal δU caused by a laser frequency excursion $\delta \nu$ is determined by the response of the reference cavity, the incident optical power, and the photodetector sensitivity. A small resonance width Δ of the reference cavity obviously leads to a large discriminator slope $\delta U/\delta \nu$, which is advantageous because it reduces the relative contribution of shot noise and other spurious signals to the error signal.

In most of the first investigations into the use of optical resonators for laser frequency stabilization, the error signal was derived from the light transmitted through the reference cavity. This led to the dilemma that the response time of the frequency stabilization feedback loop was limited by the time constant $1/\pi\Delta$ of the reference cavity, and thus the stabilization could not be optimized with respect to both response

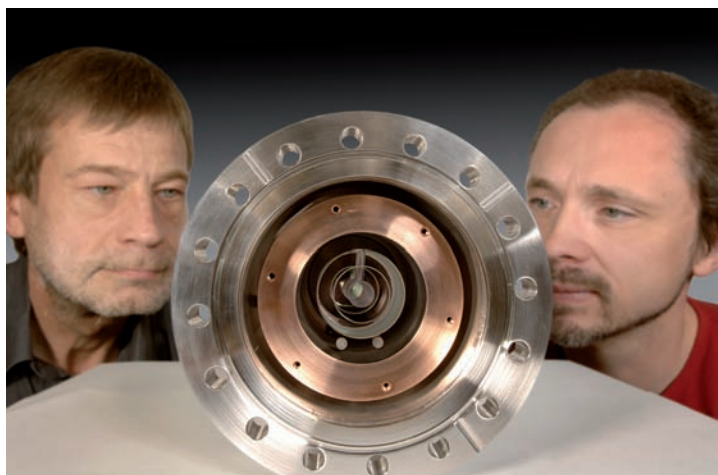


Figure 1:
Conventional mounting arrangement for a reference cavity (an innovative mounting scheme is described in Sec. 3.1). The reference cavity (center) is held by elastomer elements in a temperature-stabilized polished copper cylinder. The copper cylinder is fixed with minimum thermal coupling in a standard ultra-high vacuum vessel. The residual pressure during operation is in the range of 10^{-5} Pa.

speed and noise immunity [4]. This problem is overcome by the so-called Pound-Drever-Hall scheme which relies on the detection of the light reflected from the reference cavity [5]. Here a radiofrequency phase modulation technique is used in order to detect the phase shift of the intracavity field relative to the input field. For frequencies $f < \Delta$ of the error signal, the signal is proportional to $\delta \nu$ as in the transmission detection scheme. For frequencies $f > \Delta$, the error signal is proportional to the instantaneous phase difference between the incident field and the stored intracavity field. This permits the use of reference cavities with arbitrarily high resonance quality without bandwidth penalty.

1.2 Measures of frequency stability

The frequency stability of lasers can be characterized by several measures. Which measure is most adequate usually depends on the characteristics of the frequency fluctuation spectrum that is observed.

- In the case of white frequency noise, the laser output spectrum has a Lorentzian line-shape, and the corresponding *linewidth* $\Delta \nu$ is related to *coherence time* τ_c and *coherence length* l_c according to $\Delta \nu = 1/\pi\tau_c = c/\pi l_c$.
- Spectrally structured frequency noise is characterized by the frequency noise *spectral power density* $S_\nu(f)$ (dimension: Hz^2 per Hz analysis bandwidth). For white frequency noise, $S_\nu(f)$ is independent of the Fourier frequency f , and linewidth and $S_\nu(f)$ are related according to $\Delta \nu = \pi S_\nu(f)$.
- The *Allan deviation* $\sigma_y(\tau)$ is a measure of the relative frequency variation as a function of averaging time τ . For white frequency noise, $\sigma_y(\tau) = (\Delta \nu / 2\pi \nu_0^2 \tau)^{1/2}$; in the case of $1/f$ -noise ($S_\nu(f) \sim 1/f$), σ_y is independent of τ .

1.3 The state of the art

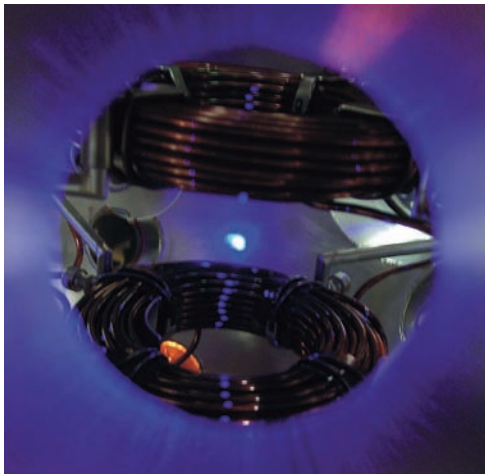
The frequency stability of a cavity-stabilized laser is generally determined by three factors: the stability of the frequency lock to the cavity resonance, the stability of the optical path length between laser and reference cavity, and the stability of the cavity itself.

The stability of the frequency lock to the reference cavity resonance is maximized by using a cavity with small resonance width Δ . The width is often expressed through the *fineness* $F = c/2L\Delta$ (c : speed of light; L : cavity length). It is now possible to fabricate dielectric mirror coatings that provide a finesse approaching $F = 10^6$ in the near-infrared wavelength range. Using reference cavities with $F \approx 10^5$ and $L \approx 100$ mm, the lock instability can be reduced to the range of $\sigma_y(\tau) < 10^{-15}$ for $0.1 \text{ s} \leq \tau \leq 100 \text{ s}$ if spurious error signal components are meticulously minimized [6, 7, 8].

Larger instability contributions typically arise from variations of the cavity resonance frequency. Significant variations can be caused in particular by thermal expansion, cavity distortions due to inertial forces, and by length fluctuations driven by thermal $1/f$ noise (Brownian motion) of the cavity material [9]. In order to reduce the sensitivity to ambient temperature variations, the cavity spacer and the mirror substrates are made from a glass material whose thermal expansion coefficient has a zero crossing near room temperature (ULE glass [10]). The cavity is surrounded by a temperature-stabilized heat shield and is operated in high vacuum (see

Fig. 1). Environmental mechanical perturbations are conventionally reduced by mounting the cavity vacuum chamber on a vibration isolation platform that has a resonance frequency of less than 1 Hz.

These stabilization measures are in many cases sufficient to reduce the linewidth of a laser oscillating in the visible or near-infrared range ($\nu_0 \approx 3 \cdot 10^{14}$ Hz) to the Hertz range. The drift of the stabilized laser frequency is typically in the range of $|d\nu_0/dt| \leq 0.5 \text{ Hz} \cdot \text{s}^{-1}$ and is determined by residual temperature variations and aging of the cavity spacer material. For time intervals in the range of 1 s to 100 s, the frequency stability is usually limited either by residual external mechanical perturbations or by thermal noise. So far the best frequency stability of a cavity-stabilized laser has been demonstrated in work conducted at the National Institute of Standards



and Technology (NIST, USA): a dye laser oscillating at 533 THz (wavelength $\lambda = 563 \text{ nm}$) is locked by two cascaded servo systems to an elaborately passively stabilized reference cavity. By comparison with a second similar system, an upper linewidth limit of $\Delta\nu = 0.6 \text{ Hz}$ and a thermal-noise limited Allan deviation $\sigma_y(\tau) \approx 4 \cdot 10^{-16}$ for $1 \text{ s} \leq \tau \leq 300 \text{ s}$ was inferred [11].

1.3 Where ultrastable lasers are needed

Laser light with a linewidth in the Hertz range permits uniquely precise measurements: if used in an interferometer, it is possible to monitor length variations at the scale of the proton diameter (1.6 fm) between reference points separated by one meter. If the high short-time frequency stability is utilized in a time interval measurement, intervals in the 1 s range can be measured with a resolution of less than one optical cycle (3.3 fs at $\nu_0 = 300 \text{ THz}$).

Interferometric gravitational-wave detectors like VIRGO and GEO 600 and the future space-based detector LISA use a complex optical setup and an elaborate laser frequency control system

in order to monitor gravitational-wave induced displacements of distant test masses [12]. Optical tests of Lorentz invariance constitute another active fundamental research field that relies on interferometry with highly stable lasers [13, 14].

Much of the present development work in the field of laser frequency stabilization is driven by the need for highly stable interrogation oscillators for optical clocks and frequency-sensitive atomic interferometers (see Fig. 2). The stability achievable by optical clocks essentially depends on the coherence time of the light that excites the atomic reference transition and thereby reads out the clock frequency [15]. The present state of the art of laser frequency stabilization makes it possible to surpass the stability of the best conventional microwave clocks by more than one order of magnitude.

2 Super-stable lasers at PTB

At PTB, a number of highly frequency-stable laser systems serve as interrogation oscillators of optical frequency standards and as reference oscillators in tests of long-distance optical frequency dissemination [3]. In the following we describe the design and performance characteristics of three technically similar systems. The frequency-doubled output of one of these lasers (fundamental wavelength $\lambda = 871 \text{ nm}$) excites the atomic reference transition in a single-ion optical clock [15]. The other two lasers [8, 16] were developed as interrogation oscillators for an atom interferometer based on laser-cooled calcium atoms ($\lambda = 658 \text{ nm}$) [17].

Figure 2: Calcium atoms confined in a magneto-optical trap. The laser cooling prepares an ensemble of slowly moving atoms. Subsequent pulsed excitation by laser light with high frequency stability allows to realize an atomic matter wave interferometer which can serve as an optical frequency standard (see also [17]).

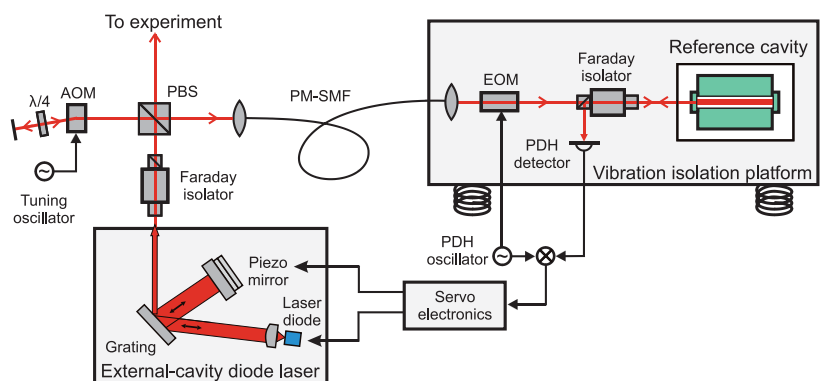


Figure 3: Schematic of the active laser frequency stabilization setup used at PTB to reduce the linewidth of diode lasers to the Hertz range. Light from the laser is frequency shifted by an acousto-optical modulator (AOM) and guided through a polarization maintaining single mode fibre (PM-SMF) to the reference cavity mounted on a vibration isolation platform. PDH: components of the Pound-Drever-Hall frequency discriminator; EOM: electro-optic phase modulator; PBS: polarizing beamsplitter; $\lambda/4$: quarter-wave retardation plate (for further details see text).

All three laser systems use semiconductor laser diodes in a wavelength-tunable external-cavity configuration that provides unstabilized laser linewidths in the range of $\Delta\nu \approx 100$ kHz. A schematic of the active frequency stabilization setup is shown in Fig. 3. A fraction of approximately $100 \mu\text{W}$ of the diode laser output is directed to an acousto-optic modulator which introduces a variable offset between the laser output frequency and a TEM_{00} resonance of the reference cavity. The frequency-shifted light passes through a polarization-maintaining single-mode optical fiber to a passive vibration isolation platform which holds the reference cavity (see Fig. 4). The light is coupled into the cavity through a Faraday isolator that separates the optical paths of incident and reflected light. The Pound-Drever-Hall frequency discriminator scheme is implemented by phase modulation of the incident light at a frequency of approximately 15 MHz and synchronous detection of the amplitude modulation of the reflected light. The laser frequency is corrected by changing the drive current of the laser diode and the optical path length of the external laser cavity. The unity-gain frequency of the laser frequency control loop is in the range of $f = 3$ MHz. For $f \leq 100$ Hz, the loop gain exceeds 160 dB. The employed reference cavities have lengths of $L \approx 100$ mm and finesse values in the range of $F = 5 \cdot 10^4$ to $F = 2 \cdot 10^5$. The temperature of the cavity enclosures is stabilized within 1 mK. The thermal isolation time constants are in the range of 30 h. The vibration isolation reduces horizontal and vertical accelerations to approximately $0.3 \mu\text{g}$ for frequencies in the range of $0.3 \text{ Hz} \leq f \leq 100 \text{ Hz}$ [18].

Figure 4:
Vibration isolation (digitally edited photo). The reference cavity is mounted on a passive vibration isolation platform (lower right). The vacuum vessel containing the reference cavity is held in a massive temperature-stabilized aluminium box. Thermal isolation material (light blue) has been partly removed. The optical setup on the platform comprises the Pound-Drever-Hall frequency discriminator and optics for fiber coupling and mode matching.

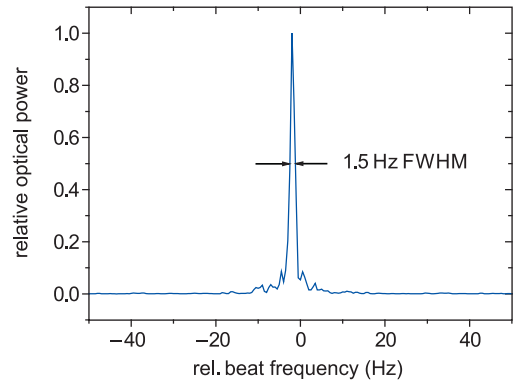


Figure 5:
Spectrum of the beat signal between two independent laser systems at $\lambda = 657$ nm [16]. Data acquisition time: 4 s; resolution bandwidth: 1 Hz.

Information on the linewidths of the two 658 nm lasers was obtained by superimposing their attenuated output beams on a photodetector and analyzing the spectrum of the beat signal. The spectrum shown in Fig. 5 was recorded with a resolution bandwidth of 1 Hz. The observed linewidth of 1.5 Hz (full width at half maximum) indicates a linewidth contribution of the beat signal of approximately 1.2 Hz. Neglecting line broadening due to the uncompensated linear drift of the beat frequency ($0.5 \text{ Hz} \cdot \text{s}^{-1}$), and assuming that the frequency fluctuations of both lasers are uncorrelated and contribute equally to the beat signal linewidth, a laser linewidth $\Delta\nu \approx 0.9$ Hz can be inferred from the measurement shown in Fig. 5.

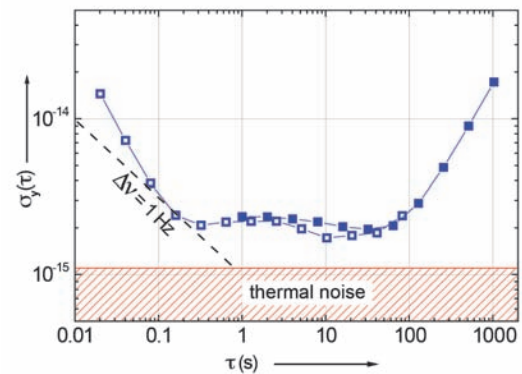
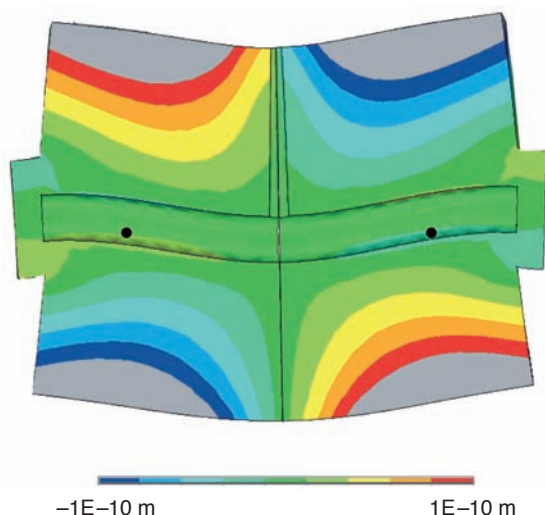


Figure 6:
Allan deviation $\sigma_y(\tau)$ of the frequency ratio of two lasers emitting at $\lambda = 658$ nm and at $\lambda = 871$ nm as a function of averaging time τ , showing the combined relative frequency instability of the two lasers. Also shown is the calculated $1/f$ -noise floor due to the thermal noise of the employed reference cavities and the instability characteristic of a single 658 nm laser with 1 Hz linewidth.

The combined frequency instability of one 658 nm laser and of the 871 nm laser was determined with the use of an optical frequency comb generator and the transfer oscillator technique [3]. The optical frequency ratio $\nu_0(658 \text{ nm})/\nu_0(871 \text{ nm})$ was registered in a continuous se-



quence of 20 ms averaging intervals. Before calculating the Allan deviation (see Fig. 6), a linear drift of approximately $5 \cdot 10^{-15} \text{ s}^{-1}$ caused by unbalanced drifts of the laser frequencies was removed from the recorded frequency ratio data. Figure 6 also indicates the level of thermal $1/f$ noise that is calculated according to the model of Numata et al. [9] for the employed combination of reference cavities. It appears that the observed frequency instability is not much larger than the expected thermal noise limit for averaging times in the range of $0.1 \text{ s} \leq \tau \leq 100 \text{ s}$. For $\tau \approx 0.1 \text{ s}$, the observed instability is comparable to that of a single 658 nm laser with $\Delta\nu = 1 \text{ Hz}$. For $\tau < 0.1 \text{ s}$, $\sigma_y(\tau)$ increases approximately proportional to τ^{-1} because the loop gain of the frequency stabilization control circuits decreases towards higher frequencies. For $\tau > 100 \text{ s}$, nonlinear frequency drifts lead to the observed increase $\sigma_y(\tau) \sim \tau$.

3 Advanced laser design at PTB

Ultrastable lasers are extremely powerful tools for fundamental research and precision measurements – yet their design can be further improved to increase their performance for special applications and to simplify their design and increase their reliability. However, a major breakthrough towards higher frequency stability can only be envisaged if several aspects are addressed simultaneously. Among these, thermal noise reduction is very important because presently this noise source limits the stability of the most stable lasers. But improvements on the thermal noise limit must be accompanied by enhanced short-time stability and better vibration isolation of the reference cavity if the laser performance is to be improved significantly.

3.1 Vibration-insensitive cavity

Conventionally, the reference cavity is held in the surrounding heat shield by elastomer elements which support the cavity spacer close to the lowest part of its cylindrical surface (Fig. 1).

This mounting configuration unavoidably leads to variations of the distance between the cavity mirrors if the spacer is elastically deformed by vertical acceleration. There are however alternative mounting schemes where the mirror distance and thus the cavity resonance frequency is independent of acceleration-induced deformations [19].

A novel vibration-insensitive cavity mounting scheme was demonstrated and investigated at PTB [18, 20]. Our design relies on supporting a cavity of cylindrical shape near its horizontal symmetry plane. Vertical accelerations mainly stretch and compress the cavity spacer above and below the symmetry plane while the mirror distance remains unaffected. By finite-element simulations we identified the position of the support points which decouples the optical resonance frequency of the cavity from vertical acceleration (see Fig. 7). This mounting scheme preserves the horizontal symmetry so that also the sensitivity to horizontal acceleration is ideally zero.

In our original implementation the cavity is held by cantilevers covered by Viton cylinders (see Fig. 8). Recent constructions use more rugged version of this support principle to avoid

Figure 7: Finite-element simulation of the deformation of a ULE-glass cavity, assuming a vertical acceleration of 10 m/s^2 and support points (black circles) that minimize acceleration-induced changes of the mirror distance [20]. The sag of the cavity spacer is magnified by a factor of 10^7 .

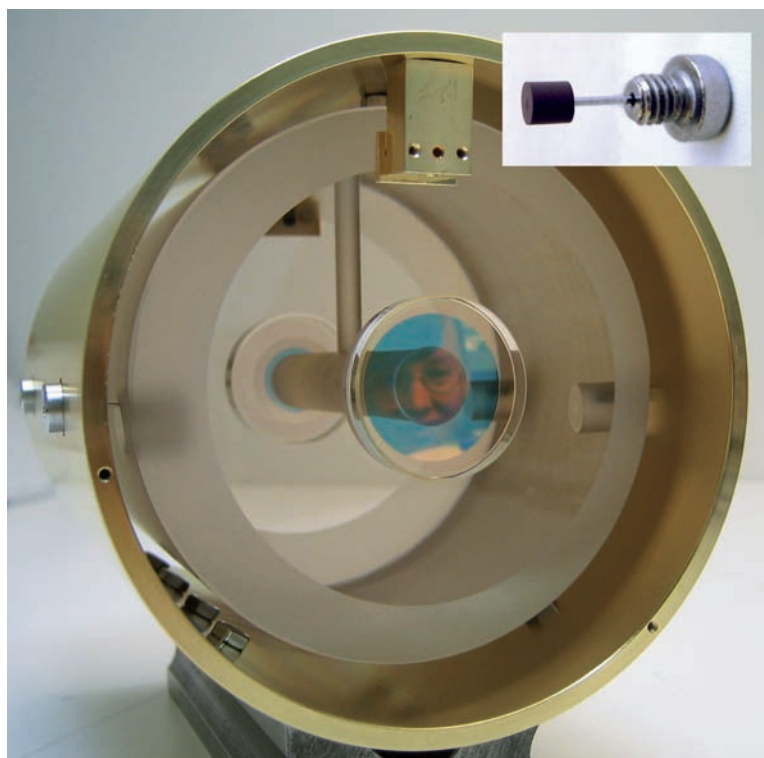


Figure 8: Technical realization of a cavity mount with support points as assumed in the the FEM simulation shown in Fig. 7. The inset shows one of the support cantilevers with Viton cylinder which protrude into the lateral blind holes of the ULE-glass cylinder.

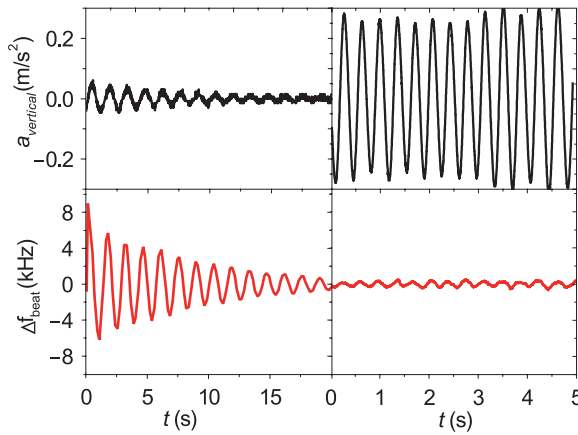


Figure 9: Laser frequency variations Δf_{beat} induced by periodic vertical acceleration a_{vertical} in the case of conventional cavity mounting (left) and for the investigated vibration-insensitive mounting scheme (right) [20].

damage during transport of the cavity. The sensitivity of the cavity-stabilized laser frequency to acceleration can be inferred from the experimental data shown in Fig. 9. The laser frequency was measured relative to a stable reference laser while the cavity was subject to periodic vertical acceleration. The experimental data show the dramatically enhanced stability of the new cavity mounting scheme.

Vibration-insensitive reference cavities are now increasingly applied in experiments with highly stabilized lasers and they will also play an important role in applications where environmental vibrations can not be strongly suppressed. The demonstrated high degree of vibration isolation is also a prerequisite for utilizing the stability advantages of reference cavities with reduced thermal noise (see Sec. 3.3).

3.2 Cavity filtering

Light pulses from frequency-stabilized lasers are used in Ramsey-Bordé atom interferometers [21] to split and redirect matter waves. The laser frequency sensitive variant of this interferometer has applications as optical frequency standard and was implemented with Ca atoms for this purpose at PTB and NIST [17]. Typically, the interrogation time in these interferometers is short compared to the whole measurement cycle time including the preparation and detection of the atoms. As a result of the low interrogation duty cycle, components of the laser frequency noise with high Fourier frequencies are efficiently down-converted in frequency and degrade the signal-to-noise ratio of the measurement. This aliasing effect is known as the Dick effect [22]. Unfortunately, the finite bandwidth of the laser frequency stabilization control circuit implies that the loop gain and thus the achievable laser frequency stability decrease towards higher Fourier frequencies (see Fig. 6). In combination with the Dick effect the insufficient short-time laser frequency stability can seriously limit the short-time stability of atom interferometers.

At PTB a novel approach was demonstrated to enhance the short-time frequency stability of cavity-stabilized lasers: in order to remove high-frequency components from the laser output spectrum, we use the light transmitted through the reference cavity. Here the reference cavity serves as an optimally tuned optical bandpass

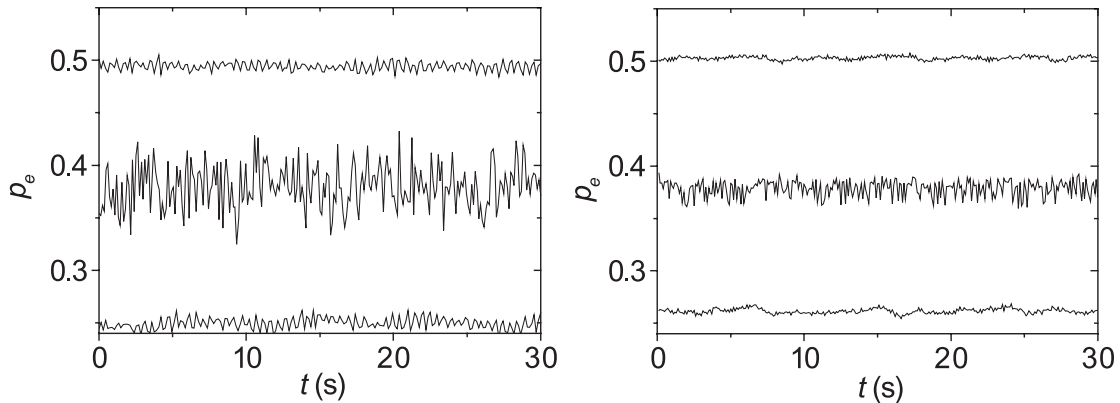


Figure 10: Temporal variation of the atomic excitation probability p_e in the PTB Ca atom interferometer at the maximum, minimum, and at the point of maximum slope of an interference fringe [23]. The graph on the left shows data recorded without cavity filtering. The data on the right were recorded with cavity filtering. The signal-to-noise ratio of the maximum-slope data reflects the short-time laser frequency stability enhancement achieved by cavity filtering (see text). Elimination of other noise sources in the interferometer setup leads to the larger signal-to-noise-ratio of the maximum and minimum signals in the graph on the right.

filter with very narrow bandwidth [18, 23]. In order to satisfy the optical power requirements of the experiment, the light transmitted through the reference cavity is used in an injection-locking scheme to control the emission spectrum of an additional “slave” laser diode.

Signals of the Ca atom interferometer were compared for operation with and without cavity-filtered light. In order to distinguish between laser frequency dependent noise contributions and other noise sources such as atom number fluctuations, interferometer signals were recorded at the maximum, the minimum, and at the

maximum slope of an interference fringe. To first order, only the latter measurement is sensitive to laser frequency noise. Figure 10 shows the strong improvement of the signal-to-noise ratio by cavity filtering. A quantitative analysis of the data shown in Fig. 10 permits the conclusion that for operation with cavity-filtered light, under typical operating conditions the signal quality of the Ca atom interferometer is not significantly reduced by short-time laser frequency instability but rather by the instability on the scale of the cycle time.

the mirror coatings become the limiting factor. However, the different thermal expansion coefficients of ULE and fused silica lead to mechanical stress when the temperature is varied. This significantly changes the temperature where the expansion coefficient of the compound system is zero.

We have modeled the cavity deformation (Fig. 11) with finite-element calculations and have measured the thermal expansion of a modified ULE cavity where one ULE mirror substrate is replaced by a fused silica substrate. In good

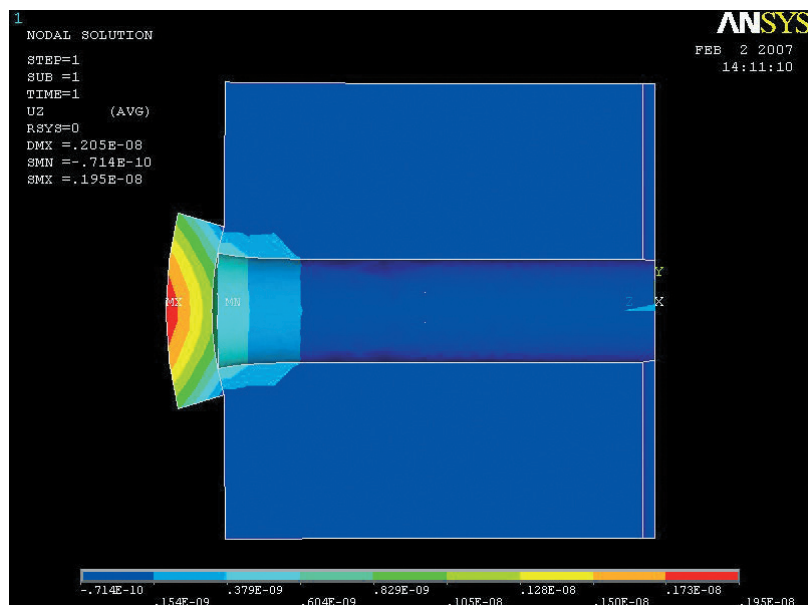


Figure 11:
Finite-element simulation of the deformation of a fused-silica mirror substrate in rigid contact with a ULE cavity spacer (one half shown), assuming a temperature change of 0.25°C after assembly. The colors indicate the axial displacement, ranging from -0.07 nm (blue) to 1.7 nm (red).

3.3 Overcoming the thermal noise limit

Thermal noise, i.e. the Brownian motion of the cavity material, leads to fluctuations of the cavity length. This effect limits the performance of present state-of-the-art lasers (see Sec. 2). According to the fluctuation-dissipation theorem, the use of materials with higher mechanical resonance quality factor Q reduces the magnitude of thermal-noise induced length fluctuations. For a typical ULE cavity with $L = 100$ mm and standard high-finesse dielectric mirror coatings, the thermal noise is dominated by the ULE mirror substrates ($Q = 6 \cdot 10^4$, relative contribution 84%), followed by the mirror coatings ($Q = 2.5 \cdot 10^3$, relative contribution 13%) [9].

Several approaches can be pursued to reduce the thermal noise limit. The high relative contribution of the mirror substrates to the thermal noise suggests to replace the ULE mirrors or to increase the overall length of the cavity. However, any significant upscaling of the cavity dimensions poses difficult design problems with respect to stable mechanical mounting.

Replacing the ULE mirror substrates with a substrate material with higher quality factor like fused silica ($Q > 10^6$) reduces the overall thermal noise by a factor of five for a 100 mm cavity, and

agreement with calculations, the measured zero-crossing temperature of the thermal expansion coefficient is in an inconvenient range below room temperature (Fig. 12). In order to avoid excessive thermal sensitivity of the optical resonance frequency, such a compound cavity would have to be operated either with elaborate thermal isolation or in a cooled enclosure.

Another idea pursued at PTB is to increase the effective size of the mirror area that is illuminated by the laser light whose frequency is to be stabilized. This method decreases the two

Figure 12:
Measurement of the length changes of an all-ULE cavity and of a cavity where one ULE mirror substrate is replaced with a fused-silica substrate. The zero crossing of the CTE is shifted from 21°C to 11°C.

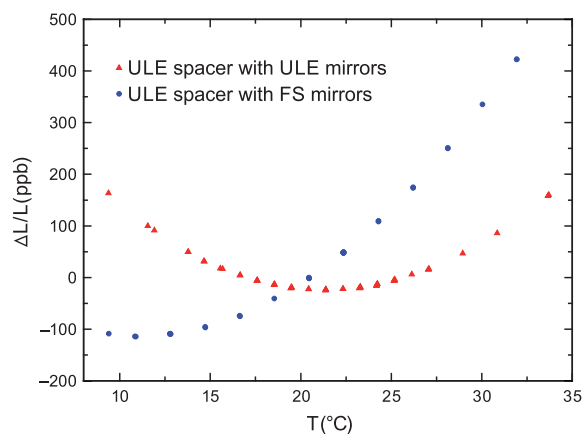
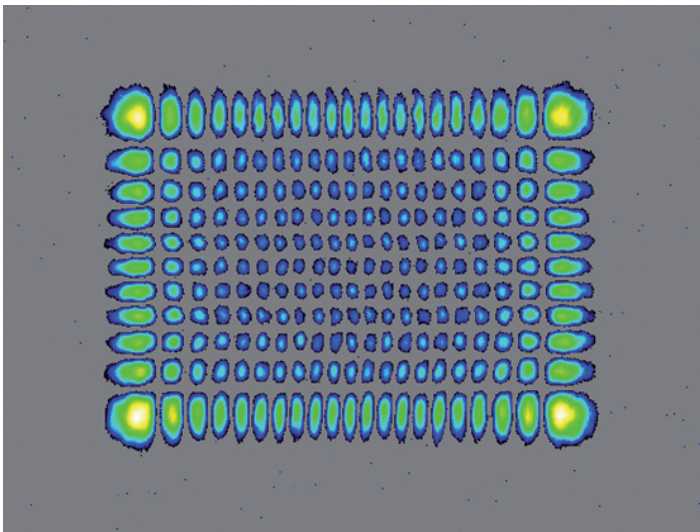


Figure 13:
Image of a $\text{TEM}_{20,10}$ light beam generated by a spatial optical phase modulator. The excitation of such high-order modes in a reference cavity reduces the effect of thermal noise in comparison with TEM_{00} excitation because thermal fluctuations are averaged over a larger area.



dominant noise contributions from mirror substrate and dielectric coating because the thermal fluctuations of the mirror surface are averaged over a larger area. For a given cavity length, significantly increasing the diameter of the fundamental TEM_{00} mode would lead to extreme tolerancing requirements with respect to separation and curvature of the cavity mirrors. An alternative approach which can be implemented in standard cavities is the excitation of Gauß-Hermite modes TEM_{mn} of high order ($m, n \gg 1$). We are investigating the possibility of using a liquid-crystal spatial optical phase modulator to holographically generate light beams that propagate as a single high-order mode (see Fig. 13) and to selectively excite such modes in high-finesse cavities.

The most obvious approach to overcome the thermal noise limit is to lower the temperature. Optical cavities operated at 4 K have shown very high long-term stability [13]. As a result of the mounting in a cryostat, it however appears difficult to achieve a short-time stability that is comparable with conventional mounting schemes. In combination with a vibration insensitive cavity mounting (Sec. 3.1), cryogenic cavities could lead to a breakthrough in the development of super-stable lasers. The choice of the cavity material is crucial since the gain due to the temperature reduction can be easily offset by a reduced mechanical Q -factor at low temperatures. In addition, a low thermal expansion coefficient is desirable to reduce the sensitivity to temperature variations. At PTB we are presently investigating the possibility to use silicon (Si) as cavity spacer and mirror substrate material in a cooled environment. The spectral transmission characteristic of Si suggests that a laser whose frequency is stabilized by a Si cavity would operate in the $1.5 \mu\text{m}$ telecom wavelength range where reliable laser sources with high passive stability are available. The stability of the Si cavity-stabilized laser

can be transferred to other wavelength ranges through the frequency comb technique [3].

4 Outlook

“Super-stable lasers” are an indispensable tool for experimental tests of fundamental physical laws and for measurements at unprecedented levels of precision. The systems constructed at PTB are of vital importance in particular for the research that aims at realizing the enormous accuracy and stability potential of optical clocks. In fact, presently the performance of some of the best optical clocks is limited by the frequency instability of the state-of-the-art lasers that are used as interrogation oscillators. The most urgent need for a breakthrough towards higher stability exists for the time range between 0.1 s and 100 s where presently the stability is limited by the thermal noise of the reference cavity. Probably the next generation of super-stable lasers will have to be optimized in several aspects because a number of instability sources must be eliminated in order to achieve significant improvements.

We also observe that the interest in lasers with linewidths in the Hertz range is no longer limited to fundamental research in well-protected laboratories but field applications come more and more into mind. Such applications require elaborately designed reference cavities with strongly reduced sensitivity to environmental perturbations like temperature changes and vibrations. We expect that the work presently conducted at PTB will spur the development of robust and portable super-stable lasers and optical clocks.

Acknowledgements

The authors would like to thank present and former staff of PTB who have contributed to the results discussed in this report: D. Griebisch, J. Helmcke, A. Hoppmann, Th. Leder, T. Legero, B. Lipphardt, F. Mensing, M. Misera, T. Nazarova, F. Riehle, T. Schneider, I. Sherstov, B. Stein, U. Sterr, and H. Stoehr. The work was supported by DFG through SFB 407 and by QUEST.

References

- [1] A. L. Schawlow, C. H. Townes: Infrared and optical masers. *Phys. Rev.* 112, 1940 (1958).
- [2] T. Udem, J. Reichert, R. Holzwarth, T. W. Hänsch: Accurate measurement of large optical frequency differences with a mode-locked laser. *Opt. Lett.* 24, 881 (1999).
- [3] See “Novel Techniques for Remote Time and Frequency Comparisons” in this issue, p. 33.

- [4] J. Helmcke, S. A. Lee, J. L. Hall: Dye laser spectrometer for ultrahigh spectral resolution: design and performance. *Appl. Opt.* 21, 1686 (1982).
- [5] R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, H. Ward: Laser phase and frequency stabilization using an optical resonator. *Appl. Phys. B* 31, 93 (1983).
- [6] Ch. Salomon, D. Hils, J. L. Hall: Laser stabilization at the millihertz level. *J. Opt. Soc. Am. B* 5, 1576 (1988).
- [7] M. Eichenseer: Aufbau und Charakterisierung eines hochstabilen Nd:YAG-Lasers für ein Indium-Frequenznormal. Ph.D. thesis, Ludwig-Maximilians-Universität München (2003).
- [8] H. Stoehr: Diodenlaser mit Hertz-Linienbreite für ein optisches Calcium-Frequenznormal. Ph.D. thesis, Univ. Hannover (2004).
- [9] K. Numata, A. Kemery, J. Camp: Thermal-noise limit in the frequency stabilization of lasers with rigid cavities. *Phys. Rev. Lett.* 93, 250602 (2004).
- [10] Product information available at: http://www.corning.com/specialtymaterials/products_capabilities/ULE.aspx
- [11] B. C. Young, F. C. Cruz, W. M. Itano, J. C. Bergquist: Visible lasers with subhertz linewidths. *Phys. Rev. Lett.* 82, 3799 (1999).
- [12] H. Grote et al.: The status of GEO 600. *Class. Quantum Grav.* 22, S193 (2005), and references therein; J. Hough, D. Robertson, H. Ward, P. McNamara and LISA science team: LISA - the interferometer. *Adv. Space Res.* 32, 1247 (2003).
- [13] P. Antonini, M. Okhapkin, E. Göklü, S. Schiller: Test of constancy of speed of light with rotating cryogenic optical resonators. *Phys. Rev. A* 71, 050101(R) (2005).
- [14] H. Müller: Testing Lorentz invariance by the use of vacuum and matter filled cavity resonators. *Phys. Rev. D* 71, 045004 (2005).
- S. Herrmann, S. Senger, E. Kovalchuk, H. Müller, A. Peters: Test of the isotropy of the speed of light using a continuously rotating optical resonator. *Phys. Rev. Lett.* 95, 150401 (2005).
- [15] See "The Development of Accurate Optical Clocks" in this issue, p. 25.
- [16] H. Stoehr, F. Mensing, J. Helmcke, U. Sterr: Diode Laser with 1 Hz linewidth. *Opt. Lett.* 31, 736 (2006).
- [17] U. Sterr, C. Degenhardt, H. Stoehr, Ch. Lisdat, H. Schnatz, J. Helmcke, F. Riehle, G. Wilpers, Ch. Oates, L. Hollberg: The optical calcium frequency standards of PTB and NIST. *C. R. Physique* 5, 845 (2004).
- [18] T. Nazarova: Towards the quantum noise limit in Ramsey-Bordé atom interferometry. PhD thesis, Leibniz Universität Hannover (2007).
- [19] M. Notcutt, L. S. Ma, J. Ye, J. L. Hall: Simple and compact 1-Hz laser system via an improved mounting configuration of a reference cavity. *Opt. Lett.* 30, 1815 (2005); S. A. Webster, M. Oxborrow, P. Gill: Vibration insensitive optical cavity. *Phys. Rev. A* 75, 011801(R) (2007).
- [20] T. Nazarova, F. Riehle, U. Sterr: Vibration-insensitive reference cavity for an ultranarrow-linewidth laser. *Appl. Phys. B* 83, 531 (2006).
- [21] C. J. Bordé: Atomic interferometry with internal state labelling. *Phys. Lett. A* 140, 10 (1989).
- [22] G. Dick: Local oscillator induced instabilities in trapped ion frequency standards. In: *Proceedings of 19th Annual PTTI Application and Planning Meeting*, p. 133 (1987).
- [23] T. Nazarova, Ch. Lisdat, F. Riehle, U. Sterr: Low-frequency noise diode laser for atom interferometry. *J. Opt. Soc. Am. B* 25, 1632 (2008).

Quantum Logic for Precision Spectroscopy

Piet O. Schmidt¹, Borge Hemmerling², Birgit Brandstätter³,
Daniel Nigg⁴

1 Introduction

Our current understanding of physics is based on the standard model of particle physics. Although this model has proven to be valid in many aspects, it is widely believed that it will be replaced by a more complete theory. Such a theory would need to be a quantum theory unifying all four fundamental forces. Some of the candidates for such a “theory of everything” allow for a variation of fundamental constants. The idea of changing physical constants was first conceived by Dirac who related in his “Large Number Hypothesis” the ratio between the strength of electro-magnetic and gravitational interaction with the age of the universe. As the universe continues to age, one of the fundamental constants describing electromagnetism and gravitation must change as well, according to the hypothesis. In the meantime many extensions and variations of this hypothesis have been postulated. Observing such a temporal variation of fundamental constants would revolutionize our current understanding of physics. Even restricting the rate for a possible variation to smaller and smaller values could aid to test predictions of theories beyond the standard model. It is convenient to consider only dimensionless constants, since one would otherwise not be able to distinguish between a change in its value or its dimension. Possible experimentally accessible candidates for a time variation (among others) are the fine-structure constant α , describing the strength of electro-magnetic interactions, and the electron-to-proton mass ratio m_e/m_p [1].

In 2001 the discussion about a change in the fine-structure constant was spurred by a publication of Webb and coworkers [2] who claimed to have observed a change in α on cosmological timescales. For their analysis, they recorded spectra of light emitted by quasars. The spectra show absorption lines of atoms and molecules found in interstellar clouds that have been imprinted onto the light as it passed through these clouds on its way to earth. A comparison with present-day laboratory spectra indicated that around 10^{10} years ago, α may have had a value

$(5.4 \pm 1.2) \cdot 10^{-6}$ smaller than today. Similar investigations by other collaborations could not confirm this result [3, 4], leaving the outcome of the dispute open. Currently, one of the limitations of the analysis is the precision with which laboratory spectra are known [5]. An approach to study the possible variation of fundamental constants on laboratory time scales consists of a long-term highly accurate frequency comparison of atomic or molecular transitions that depend differently on a change in the constant. An example is the recently performed comparison of the single-ion mercury and aluminum optical clocks [6]. Over the course of almost a year, frequency ratio measurements between the clock transitions of these two ions have been performed that yielded an upper bound for a relative change in α of $(-1.6 \pm 2.3) \cdot 10^{-17}/\text{year}$.

In the following, we will describe two projects that are currently being set up at the QUEST Institute for Experimental Quantum Metrology with the goal of helping to solve the question of a possible time variation of fundamental constants.

2 Quantum logic and precision spectroscopy

Common to both projects is the use of quantum logic techniques developed for quantum information processing with trapped ions. The idea is to use a string of trapped ions in a linear Paul trap that are strongly coupled via their mutual Coulomb repulsion. The external motion of the ions is most conveniently described in a normal-mode picture, involving motion of all ions. Using laser pulses of appropriate frequency and duration, it is possible to change not only the internal electronic state of the ions, but also their motional state in the trap. Cirac and Zoller proposed to use such laser pulses to entangle ions and perform quantum logic gates using the normal modes in the trap as a “quantum bus” [7].

Shortly after this seminal idea, a controlled-NOT (C-NOT) gate between a trapped atomic ion and its motional mode in the trap was de-

¹ Prof. Dr. Piet O. Schmidt, QUEST Institute for Experimental Quantum Metrology, PTB Braunschweig and Leibniz Universität Hannover
email: piet.schmidt@ptb.de

² Dipl.-Phys. Borge Hemmerling, QUEST Institute for Experimental Quantum Metrology, PTB Braunschweig

³ Dipl.-Ing. Birgit Brandstätter, Institute for Experimental Physics, University of Innsbruck

⁴ Daniel Nigg, QUEST Institute for Experimental Quantum Metrology, PTB Braunschweig and Institute for Experimental Physics, University of Innsbruck

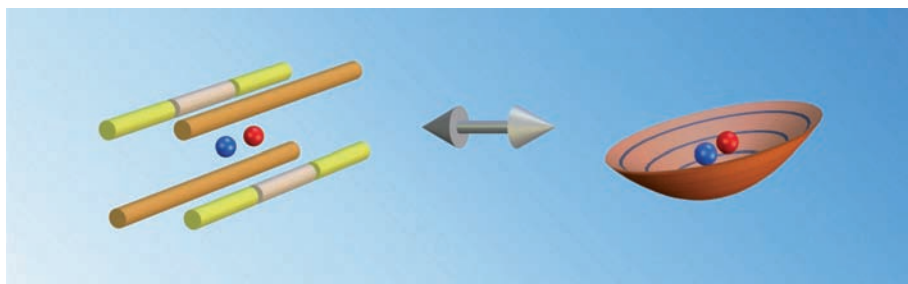


Figure 1:
Two ions trapped in a linear Paul trap. Left: Ions are trapped via radio-frequency (orange) and DC (yellow and grey) fields applied to electrodes. Right: The resulting potential is harmonic in three dimensions. The motion of the ions is strongly coupled via the Coulomb repulsion.

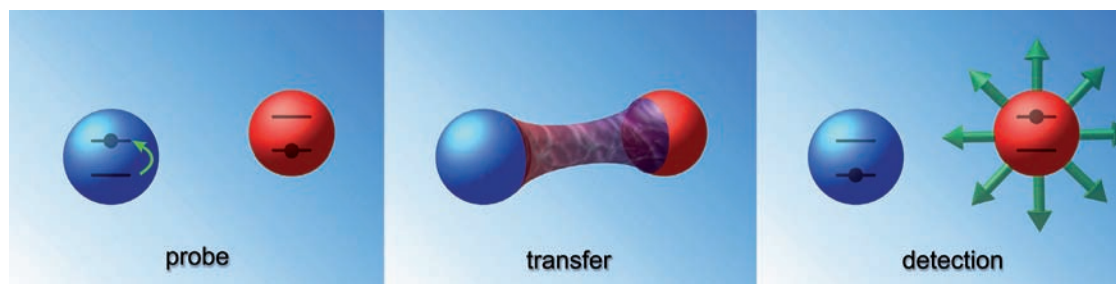
monstrated in a pioneering experiment [8]. After this demonstration of exquisite coherent control over the internal and external degrees of freedom in an atomic system, quantum information processing with trapped ions has flourished and impressive results, such as teleportation, error-correction and the implementation of the Deutsch-Jozsa and semi-classical Fourier transformation algorithms have been achieved. Current state of the art is the manipulation of up to eight qubits [9, 10] and two-ion gate fidelities exceeding 99.3% [11]. These accomplishments were only possible through efficient decoupling of the internal and external atomic degrees of freedom from the decoherence-inducing environment and manipulation of the internal states with highly coherent light fields. The same requirements hold true for precision spectroscopy,

proposal, a spectroscopy ion is trapped simultaneously with a logic ion in the same potential well of a linear Paul trap (see Figure 1).

Owing to the strong motional coupling between ions, laser cooling of the logic ion sympathetically cools the spectroscopy ion. Using quantum logic protocols, the internal state information of the spectroscopy ion after probing the transition can be faithfully transferred to the logic ion, where it is detected with near unit efficiency (Figure 2).

Furthermore, the internal state of a spectroscopy ion within the spectroscopy manifold of states can be deterministically prepared using this technique [14]. Therefore, quantum logic techniques allow us to fulfill all requirements to perform precision spectroscopy on ions that would otherwise be inaccessible due to the lack

Figure 2:
Schematic description of quantum logic spectroscopy. Left: The transition of the spectroscopy ion (blue) is probed with a laser. Middle: The state information is mapped to the logic ion (red). Right: Efficient state discrimination using electron shelving on the logic ion.



where a frequency measurement of an unspoiled atomic or molecular transition is performed. In fact, the two fields have a lot in common and already a number of quantum logic techniques beneficial for precision spectroscopy have been proposed [12, 13] and demonstrated [14, 15].

Precision spectroscopy is typically performed by laser cooling of an atomic sample to reduce Doppler shifts and increase interrogation times. Then, the transition of interest is probed with a frequency stabilized laser. The excitation probability is detected via either direct fluorescence or the electron shelving technique involving a third atomic level. In both cases a cycling transition is required to collect a sufficient number of photons for state discrimination. This severely restricts the number of accessible species for high precision spectroscopy. Dave Wineland suggested in 2001 the use of quantum logic techniques to overcome this limitation [12]. In his

proposal, a spectroscopy ion is trapped simultaneously with a logic ion in the same potential well of a linear Paul trap (see Figure 1). Owing to the strong motional coupling between ions, laser cooling of the logic ion sympathetically cools the spectroscopy ion. Using quantum logic protocols, the internal state information of the spectroscopy ion after probing the transition can be faithfully transferred to the logic ion, where it is detected with near unit efficiency (Figure 2). Furthermore, the internal state of a spectroscopy ion within the spectroscopy manifold of states can be deterministically prepared using this technique [14]. Therefore, quantum logic techniques allow us to fulfill all requirements to perform precision spectroscopy on ions that would otherwise be inaccessible due to the lack

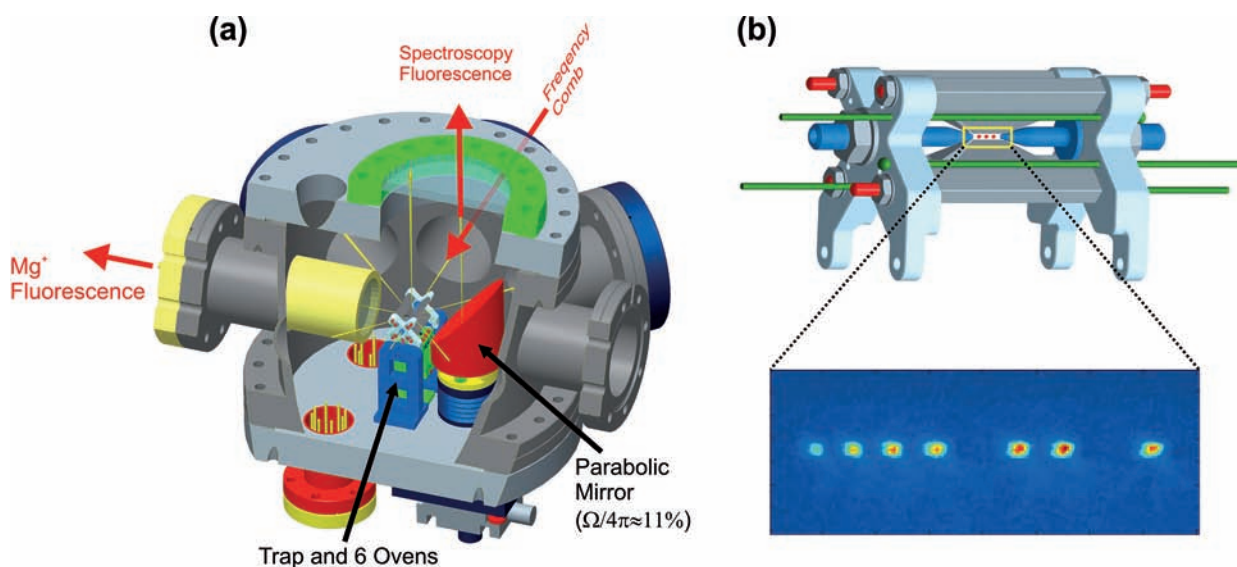
3 Direct frequency comb spectroscopy using quantum logic

Many atomic and molecular species with interesting spectroscopic features have a very complex level structure. As described above, quantum logic techniques can be employed to prepare and probe the ion within the spectroscopy manifold. Nevertheless, if too many levels are involved, initial state preparation can be challenging. Conventional spectroscopy typically circumvents this issue by probing very many atoms in a beam or gas cell, thus severely compromising the accuracy of the measurement due to level shifting and broadening effects. Another solution is the use of optical pumping to repump the atom from metastable states back into the

spectral output of the comb. Direct frequency comb spectroscopy has been implemented in a variety of flavors: (i) a single comb tooth interacts with a single transition [19]; (ii) the comb as a whole is used to drive two-photon transitions, possibly enhanced by near-resonant coupling to an intermediate level [20, 21]; and (iii) the comb is used as a broadband source that simultaneously interacts with many transitions in the atomic or molecular species [22].

We are currently setting up an experiment in which we plan to perform direct frequency comb spectroscopy on metal ions, such as Ca^+ , Ti^+ and Fe^+ , using quantum logic for state preparation and detection. Depending on the ion species, we will either use the comb to drive two-photon

Figure 3:
Experimental setup.
(a) Construction drawing of the vacuum chamber.
(b) Detail of the ion trap and a string of magnesium ions observed in the trap (false-color image).



spectroscopy manifold. For this, light at many different colors is needed to access all transitions. One such light source with a very large spectral bandwidth is an optical frequency comb [18]. Its invention by T.W. Hänsch and J.L. Hall has been awarded with the Nobel Prize in Physics in 2005. Today, two major frequency comb technologies have been established: Ti:Sa-based systems with repetition rates ranging from 80 MHz to up to 10 GHz and a spectral emission between 600 and 1200 nm, and fiber-laser based systems with repetition rates ranging from 100 to 200 MHz and a spectral emission between 900 nm and 2 μm . External frequency doubling and tripling in nonlinear crystals, and high-harmonic generation in gas jets allows to shift the output of the lasers to different spectral regions. The evenly spaced spectral comb emitted by these systems is phase and frequency stabilized to provide a fixed ruler in frequency space, acting as an array of thousands of phase-locked weak continuous-wave lasers. This makes frequency combs not only ideal instruments to count optical frequencies [18], but also to directly perform precision spectroscopy with the broad

transitions (Ca^+), or use it as a broadband source of light, interacting with many transitions simultaneously (Ti^+ , Fe^+). Optical transitions in these ions are used in the analysis of quasar absorption spectra and are currently known only to an accuracy ranging between a few 10 MHz to a few GHz [23]. To improve the analysis for a possible time variation of fundamental constants, accuracies on the order of 1 MHz are required [5].

In our experiment, we plan to trap a single spectroscopy ion together with the logic ion Mg^+ in a linear Paul trap inside a vacuum chamber. Light from the optical frequency comb is applied along the symmetry axis of the trap (see Figure 3).

Our first candidate is Ca^+ , for which accurate data on the $^2\text{S}_{1/2} \leftrightarrow ^2\text{P}_{3/2}$ transition is missing [24]. Spectroscopy is performed in several steps (see Figure 5): (i) the ion crystal is cooled to the ground state of axial motion via Raman side-band cooling on Mg^+ ; (ii) the optical frequency comb is adjusted in its frequency and applied for a few hundred milliseconds to the spectroscopy ion; and (iii) scattering of photons heats

the ion crystal to a higher vibrational quantum number, which can be detected with near unit efficiency on the Mg^+ ion. Performing these steps in a sequence and adjusting the frequency comb spacing or offset allows the determination of the global electronic level scheme of the atomic system [21] by comparison with a theoretical model [see Fig. 5(c)].

A similar method will be used to perform spectroscopy on Ti^+ and Fe^+ . In principle, it should be possible to use the same versatile apparatus to investigate a wide variety of spectroscopy ions, provided the spectral range of the frequency comb covers all involved atomic transitions. We will collaborate with other QUEST

4 A single-ion quantum logic optical clock

Another application of quantum logic spectroscopy is the development of next-generation optical clocks [26]. Up to now, atomic species considered for optical clocks had to fulfill several criteria: they needed to provide a proper transition for laser cooling and detection, and a narrow-linewidth clock transition with high resilience to external field perturbations. With quantum logic spectroscopy, the only requirement is a suitable clock transition, since all other steps will be performed via the logic ion. This has been successfully demonstrated with aluminum and beryllium as the clock and logic ion species [14].

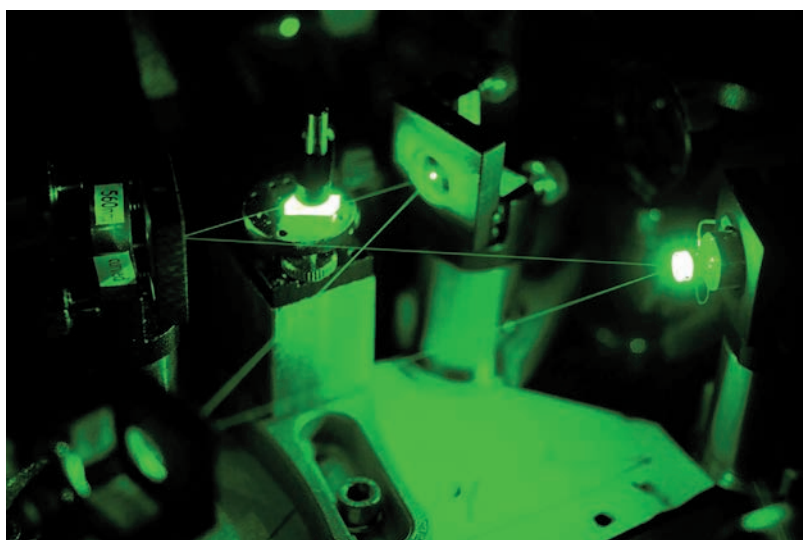


Figure 4:
Detail of the experimental setup. Photo of the last frequency-doubling stage to generate the ultraviolet light used for cooling and detecting magnesium ions. Four mirrors form a bow-tie resonator for the pump light at 560 nm which is converted to 280 nm in a non-linear crystal. Source: Universität Innsbruck.

partners (U. Morgner and LZH) to extend optical frequency combs into the near ultra-violet spectral regime, relevant to many atomic ion species.

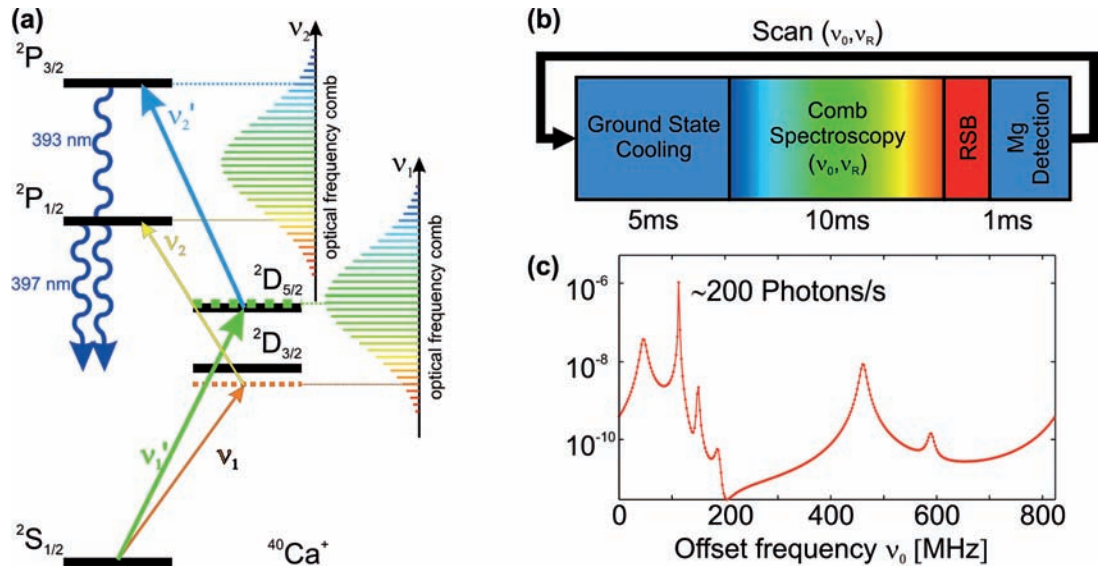
The quantum logic techniques described above can be employed not only for precision spectroscopy, but also to cool the rotational states of a molecule [25]. Having ground-state cooled molecules at our disposal allows us to perform a large variety of fascinating experiments. One possibility is to conduct precision measurements of various electronic and rovibrational transitions using the direct frequency comb spectroscopy techniques developed above.

This would be particularly interesting for the astrophysically important CaH^+ molecule, for which no experimental data is available. We will also explore the possibility of implementing our scheme with other small molecules including H_2^+ and HD^+ , which are relevant for m_e/m_p measurements.

In the meantime, the aluminum ion optical clock has advanced to being one of the most accurate clocks in the world [6]. The limitations in this experiment are frequency shifts due to micro- and secular motion of the ion in the trap. Micromotion is most likely introduced by charging of the electrodes by ultraviolet laser photons. Heating of the ion crystal during interrogation is responsible for a systematic uncertainty in the amplitude of the secular motion and therefore the second-order Doppler shift. Both effects can be significantly reduced in a new setup, featuring a trap with lower heating rates of the secular motion and different electrode material, less susceptible to the photo effect. We plan to set up such an experiment with aluminum as the clock ion species and a new trap design to overcome the limitations described above. Having a clock with such a high accuracy available at PTB will pave the way not only to establish the single-ion aluminum clock as a secondary frequency standard, but also to perform precision measurements with unprecedented resolution. One example for such an experiment would be to compare the aluminum ion frequency standard to other

Figure 5:
Direct Frequency Comb
Spectroscopy of Ca^+ .

(a) Partial level scheme of Ca^+ and excitation by optical frequency comb.
(b) Quantum logic spectroscopy sequence.
(c) Density matrix simulation of the number of scattered photons on the $P_{1/2} - S_{1/2}$ transition as a function of the frequency comb's offset frequency, scanned over one repetition rate (824 MHz).



frequency standards at PTB over the course of many years and derive an upper limit for a temporal change in the fine-structure constant on a laboratory time scale.

Acknowledgements

We acknowledge support from Manuel Kluibenschädl, Arthur Wander, Gerhard Händl (electronics workshop), Helmut Jordan, Anton Schönherr, Andreas Strasser, and Stefan Haslwanter (mechanical workshop), and Lukas An der Lan during construction of the apparatus. This project has been funded through the University of Innsbruck, the START award of the Austrian Ministry for Science and Research (BMWF), and the Centre for Quantum Engineering and Space-Time Research (QUEST). Furthermore, we are thankful to Rainer Blatt for generous equipment loan and support.

References

- [1] See "More Accurate Clocks – What are They Needed for?" in this issue, p. 16.
- [2] J. Webb et al.: Further evidence for cosmological evolution of the fine structure constant. *Phys. Rev. Lett.* 87, 091301 (2001).
- [3] R. Srianand, H. Chand, P. Petitjean, B. Aracil: Limits on the time variation of the electromagnetic fine-structure constant in the low energy limit from absorption lines in the spectra of distant Quasars. *Phys. Rev. Lett.* 92, 121302 (2004).
- [4] R. Quast, D. Reimers, S. A. Levshakov: Probing the variability of the fine-structure constant with the VLT/UVES. *Astron. Astrophys.* 415, L7 (2004).
- [5] J. C. Berengut et al.: Laboratory spectroscopy and the search for space-time variation of the fine structure constant using QSO spectra. *arXiv: physics/0408017* (2004).
- [6] T. Rosenband et al.: Frequency Ratio of Al^+ and Hg^+ single-ion optical clocks; metrology at the 17th decimal place. *Science* 319, 1808 (2008).
- [7] J. I. Cirac and P. Zoller: Quantum computations with cold trapped ions. *Phys. Rev. Lett.* 74, 4091 (1995).
- [8] C. Monroe, D. M. Meekhof, B. E. King, W. M. Itano, D. J. Wineland: Demonstration of a fundamental quantum logic gate. *Phys. Rev. Lett.* 75, 4714 (1995).
- [9] H. Häffner et al.: Scalable multiparticle entanglement of trapped ions. *Nature* 438, 643 (2005).
- [10] D. Leibfried et al.: Creation of a six-atom 'Schrödinger cat' state. *Nature* 438, 639 (2005).
- [11] J. Benhelm, G. Kirchmair, U. Rapol, T. Körber, C. F. Roos, R. Blatt: Measurement of the hyperfine structure of the $S_{1/2} - D_{5/2}$ transition in $^{43}\text{Ca}^+$. *Phys. Rev. A* 75, 032506 (2007).
- [12] D. Wineland, J. Bergquist, J. Bollinger, R. Drullinger, W. Itano: Quantum computers and atomic clocks. In: *Proc. 6th Symposium on Frequency Standards and Metrology* (St. Andrews, Scotland, 2001), ed. P. Gill (World Scientific, Singapore, 2001), p. 361.
- [13] C. F. Roos: Precision frequency measurements with entangled states. *arXiv:quant-ph/0508148* (2005).
- [14] P. O. Schmidt, T. Rosenband, C. Langer, W. M. Itano, J. C. Bergquist, D. J. Wineland: Spectroscopy using quantum logic. *Science* 309, 749 (2005).
- [15] C. F. Roos, M. Chwalla, K. Kim, M. Riebe, R. Blatt: 'Designer atoms' for quantum metrology. *Nature* 443, 316 (2006).
- [16] J.-P. Uzan: The fundamental constants and their variation: observational and theoretical status. *Rev. Mod. Phys.* 75, 403 (2003).

- [17] S. G. Karshenboim: Fundamental physical constants: looking from different angles. arXiv: physics/ 0506173 (2005).
- [18] T. Udem, R. Holzwarth, T. W. Hänsch: Optical frequency metrology. *Nature* 416, 233 (2002).
- [19] V. Gerginov, C. E. Tanner, S. A. Diddams, A. Bartels, L. Hollberg: High-resolution spectroscopy with a femtosecond laser frequency comb. *Opt. Lett.* 30, 1734 (2005).
- [20] A. Marian, M. C. Stowe, J. R. Lawall, D. Felinto, J. Ye: United time-frequency spectroscopy for dynamics and global structure, *Science* 306, 2063 (2004).
- [21] A. Marian, M. C. Stowe, D. Felinto, J. Ye: Direct frequency comb measurements of absolute optical frequencies and population transfer dynamics. *Phys. Rev. Lett.* 95, 023001 (2005).
- [22] M. Thorpe, J. Ye: Cavity-enhanced direct frequency comb spectroscopy. *Appl. Phys. B* 91, 397 (2008).
- [23] D. C. Morton: Atomic data for resonance absorption lines. III. Wavelengths longward of the Lyman limit for the elements Hydrogen to Gallium. *Astrophys. J. Suppl. Ser.* 149, 205 (2003).
- [24] A. L. Wolf, S. A. van den Berg, C. Gohle, E. J. Salumbides, W. Ubachs, K. S. E. Eikema: Frequency metrology on the $4s\ ^2S_{1/2}-4p\ ^2P_{1/2}$ transition in $^{40}\text{Ca}^+$ for a comparison with Quasar data, *Phys. Rev. A* 78, 032511 (2008).
- [25] P. O. Schmidt et al.: Spectroscopy of atomic and molecular ions using quantum logic. In: *Non-Neutral Plasma Physics VI: Workshop on Non-Neutral Plasmas 2006*, eds. M. Drewsen, U. Uggerhøj, H. Knudsen, vol. 862 (AIP, 2006), p. 305.
- [26] See "The Development of Accurate Optical Clocks" in this issue, p. 25.

Atom Interferometry

Uwe Sterr¹ and Fritz Riehle²

1 Introduction

The experiments of Fizeau and Young in the 19th century constituted the crucial proof of the wave nature of light. Interferometry with light then found widespread use for precision experiments at the end of the 19th century. The idea that matter also has to be described by waves was introduced in the early days of quantum mechanics by E. Schrödinger and L. de Broglie. They attributed to a particle of momentum p a wavelength $\lambda = h/p$, where h denotes Planck's constant. For a laser cooled particle at $T = 20 \mu\text{K}$, the corresponding de Broglie wavelength is in the range of 100 nanometers. For room-temperature thermal velocities, the wavelength is of the order of a few picometers which is 5 orders of magnitude less than the wavelength of visible light. Thus atom interferometers promise a much higher sensitivity than optical interferometers. However, for a long time the construction of practical atom interferometers met with technical difficulties, since coherent beam splitters and coherence-preserving mirrors for matter waves were not readily available. After the first atom diffraction experiments in the 1930s, it took until the end of the 1980s to set up the first atom interferometers, using techniques that belong to the foundation stones of quantum engineering.

Present atom interferometers use microstructured mechanical gratings, far detuned standing-wave light fields or the interaction with resonant light fields as beam splitters (see Ref. 1 for a recent review). Here we want to concentrate on the latter concept, in particular on the so-called Ramsey-Bordé atom interferometers. The term "Ramsey-Bordé interferometry" reflects the historical situation that a particular arrangement for excitation in separated fields was invented by N. Ramsey in the 1950s in the context of precision spectroscopy and atomic frequency standards [2]. In 1989, this arrangement was identified by Ch. Bordé as an atom interferometer [3]. In this contribution, we will briefly review the work conducted at PTB using calcium atoms in a Ramsey-Bordé interferometer, discuss related work in QUEST, and propose some future opportunities.

2 Principles of Ramsey-Bordé atom interferometry

Ramsey-Bordé atom interferometers use laser beams whose frequency is resonant with a suitable atomic transition as splitters and mirrors for the atomic waves. During the excitation of an atom by a resonant light field, both energy and photon momentum is transferred to the atom. The strength of this interaction can be tailored experimentally in such a way that after the interaction the atom is in a superposition of its ground state $|g\rangle$ and its excited state $|e\rangle$. The excited state acquires the additional momentum $\hbar k$ of the photon, where k is the wave vector $2\pi/\lambda_L$ of the light (Fig. 1). Analogously, stimulated emission can be used to transfer momentum to an atom that is initially in the excited state. In the simplest case, the interaction can be a single-photon transition to a long-lived atomic excited state, but also Raman transitions between different hyperfine levels of the atomic ground state are widely used.

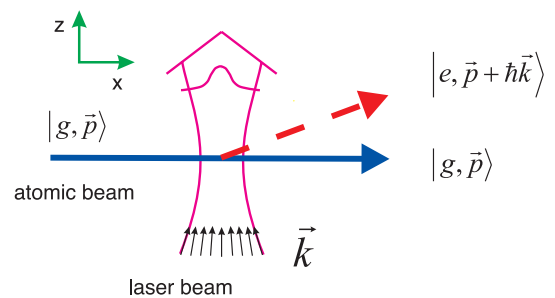


Figure 1: Atomic beam splitter based on the interaction of a single atom with a laser beam. Due to the interaction with a photon of the laser beam, an atom with momentum p is transferred from the ground state $|g\rangle$ to a superposition of the ground state and the excited state $|e\rangle$. In the excited state, the momentum p of the atom is increased by the momentum $\hbar k$ of the absorbed photon. Momentum transfer also occurs for an excited atom that is brought into the ground state by stimulated emission.

The single-beam interaction illustrated in Fig. 1 can be used as a building block for different types of atom interferometers, as depicted

¹ Dr. Uwe Sterr, Working Group "Quantum Optics with Cold Atoms", Physikalisch-Technische Bundesanstalt Braunschweig email: uwe.sterr@ptb.de

² Dr. Fritz Riehle, Division "Optics", Physikalisch-Technische Bundesanstalt Braunschweig email: fritz.riehle@ptb.de

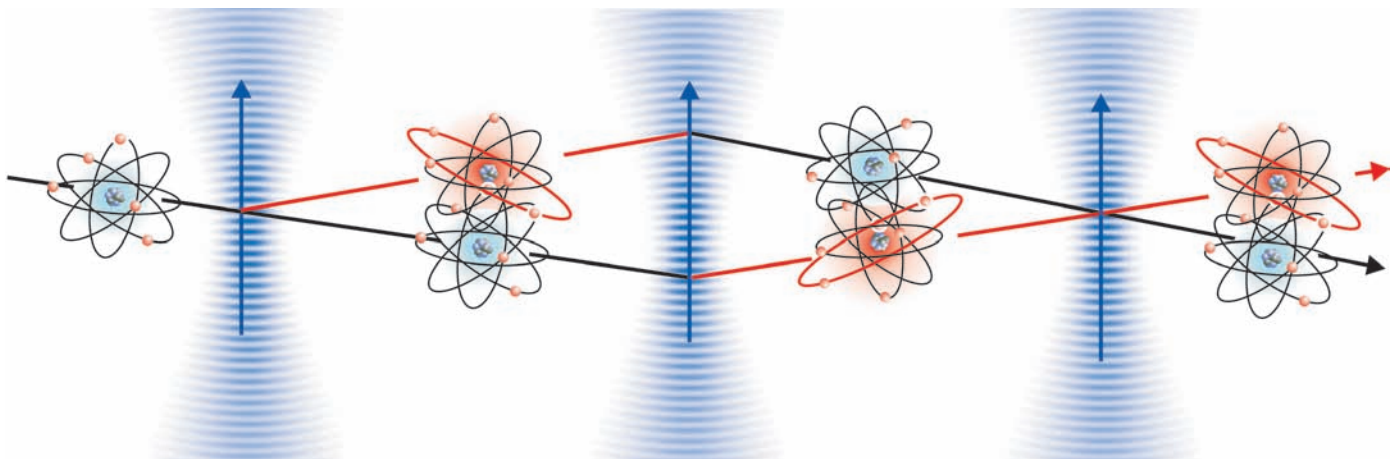
in Figs. 2 and 3. The first interaction coherently splits the atomic wave into two partial waves. (Here we consider only two partial waves even though in some interferometers more than two partial waves can interfere.) In the second interaction zone, these partial waves are deflected – again by momentum transfer from the laser field to the atomic waves – and in the third interaction zone the partial waves are recombined. Thus the two partial atomic waves interfere at the output of the interferometer. Depending on the phase difference $\Delta\varphi$ between the partial waves, the amplitudes of the combined atomic waves (and hence the atom numbers) in the two output ports of the interferometer vary sinusoidally. If the velocity of the atoms is large, the spatial separation between the exit ports can be very small because the transferred momentum is much smaller than the total atomic momentum. Nevertheless, since the atoms in both output ports are in different atomic states, the interference signal can be identified unambiguously by optical detection.

$$\Delta\Phi = \frac{1}{\hbar} \int \Delta U(t) dt \quad (1)$$

where $\Delta\Phi$ denotes the acquired phase difference. The energy U can be different for the two partial waves as a result of the interaction with external potentials or because of the difference in internal atomic energy. In interferometers where the beam splitters are realized by laser light, the optical phase at the point of interaction is also imprinted on the atomic wave.

In the interferometer shown in Fig. 2, the first and the last laser pulse act on the atoms as so-called $\pi/2$ pulses, i.e., atoms entering in the ground state leave the interaction in a superposition between the ground and excited states with equal amplitudes of the two partial waves. By increasing the time of the interaction or the power of the laser pulse, a π -pulse is generated which transfers a ground-state atom to the excited state and vice versa. In this way, the interaction acts like a mirror rather than a beam splitter.

Figure 2: Symmetric Ramsey-Bordé atom interferometer. Only paths that lead to an interference pattern are shown. The black (red) trajectory indicates an atomic partial wave where the atom is in the ground (excited) state.



The first atom interferometers used thermal atomic beams that interacted with spatially separated beam splitters. In analogy with optical white-light interferometers, here the broad range of velocities in the thermal atomic beam leads to a broad spectrum of de Broglie wavelengths. Subsequently laser cooling techniques were employed to narrow the velocity width of the atomic ensemble. Typically atoms are cooled and trapped in a magneto-optical trap. The cloud of cold atoms is released and the freely falling atoms interact with the beam splitters which are realized by pulsing the light fields. In this case, the horizontal scale associated with the atomic trajectories shown in Fig. 2 can be thought of as being a temporal rather than a spatial coordinate.

If the path of the atoms is described in the time domain, the phase evolution of the atomic wave function depends on the energy U of the particle according to the Schrödinger equation

This is assumed for the central interaction zone in Fig. 2. In both arms of the interferometer, the atoms spend the same time in the ground and in the excited state. Thus the phase shift expressed by Eq. (1) is equal for both partial waves and the phase difference between interferometer arms is exclusively determined by the phase difference $\Delta\varphi$ that is associated with the spatial phases φ_i of the laser beams in the three interaction zones $i = 1, 2, 3$:

$$\Delta\varphi = \varphi_1 - 2\varphi_2 + \varphi_3. \quad (2)$$

Depending on the experimental geometry, this phase difference can be sensitive to, e.g., acceleration or rotation of the interferometer.

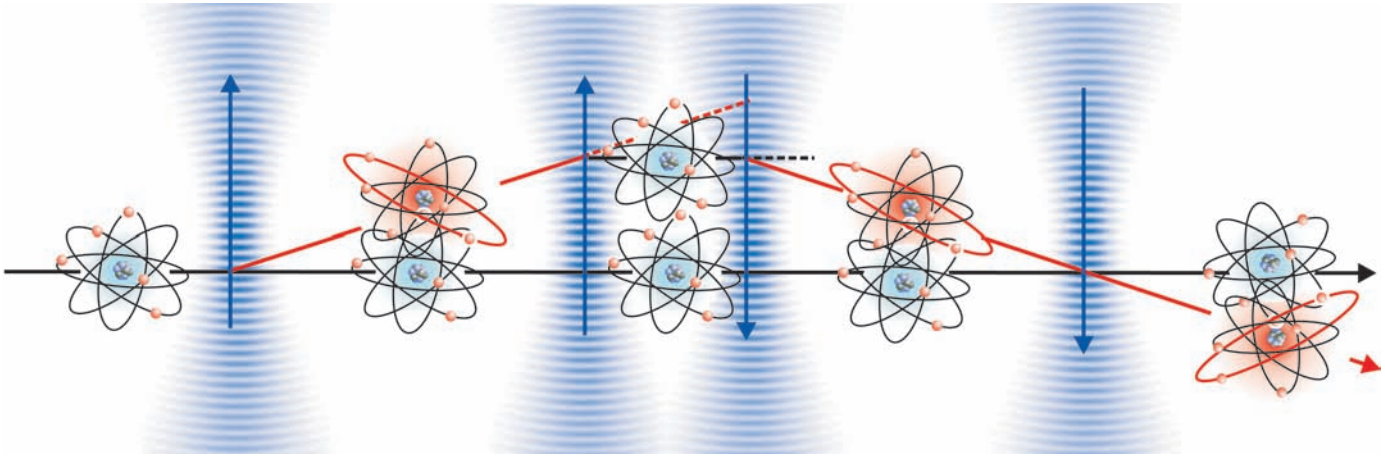
A second type of interferometer consisting of two counterpropagating pairs of laser beams or laser pulses is shown in Fig. 3. Besides non-interfering paths there are two closed combinations of paths which form interferometers. Only one of

these combinations is shown in Fig. 3. Here the time spent by the atoms in the ground and excited states is different for the two interferometer arms. In addition to the phase of the laser fields, the phase difference therefore also depends on the detuning $\Delta\nu$ between the laser and the atomic transition frequency:

$$\Delta\varphi = 2\pi \left[\Delta\nu \pm \frac{h\nu^2}{2Mc^2} \right] 2T + \varphi_1 - \varphi_2 + \varphi_3 - \varphi_4. \quad (3)$$

Here, M is the atomic mass and T is the time between the first and the second, or the third and the fourth interaction.

Figure 3:
Asymmetric Ramsey-Bordé atom interferometer. Only one of the two possible path combinations forming an interferometer are shown.



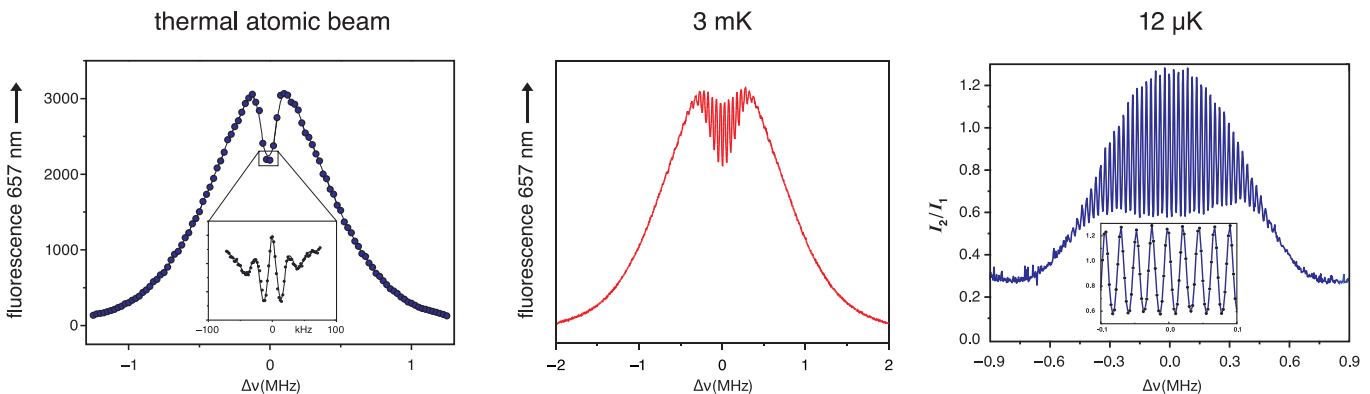
3 Precision measurements using atom interferometry: Early investigations at PTB

In this section we present applications of Ramsey-Bordé atom interferometers to precision measurements that were demonstrated at PTB. The interferometers used the $^1S_0 - ^3P_1$ intercombination transition of calcium at $\lambda_L = 657$ nm in order to split, modify and recombine the atomic waves. In the first experiments, thermal atomic beams with short coherence length were used. Laser-decelerated atomic beams and Ca atoms cooled to temperatures of 3 mK and 20 μ K in a magneto-optical trap were employed later. The reduction of the temperature leads to a dramatic improvement in the signals as shown in Fig. 4.

Figure 4:
Signals of laser frequency-sensitive calcium atom interferometers, showing measurements performed with a thermal atomic beam and with laser-cooled atoms.

3.1 Measurement of rotations: The Sagnac effect

Shortly after the interpretation of the Ramsey excitation scheme as an atom interferometer by Bordé, the Sagnac effect was observed and measured using a four-beam calcium atom interferometer [4]. The setup comprised a thermal atomic beam apparatus on a rotation stage that allowed to rotate the setup with an angular frequency of up to $\Omega = 0.12$ s $^{-1}$ (Fig. 5). The interferometer used four interaction zones. The corresponding laser beams were derived from the collimated output of a single-mode optical fibre that directed the laser output to the rotation stage. Two cat's eyes were used to obtain the four parallel laser beams defining the interaction zones (Fig. 6).



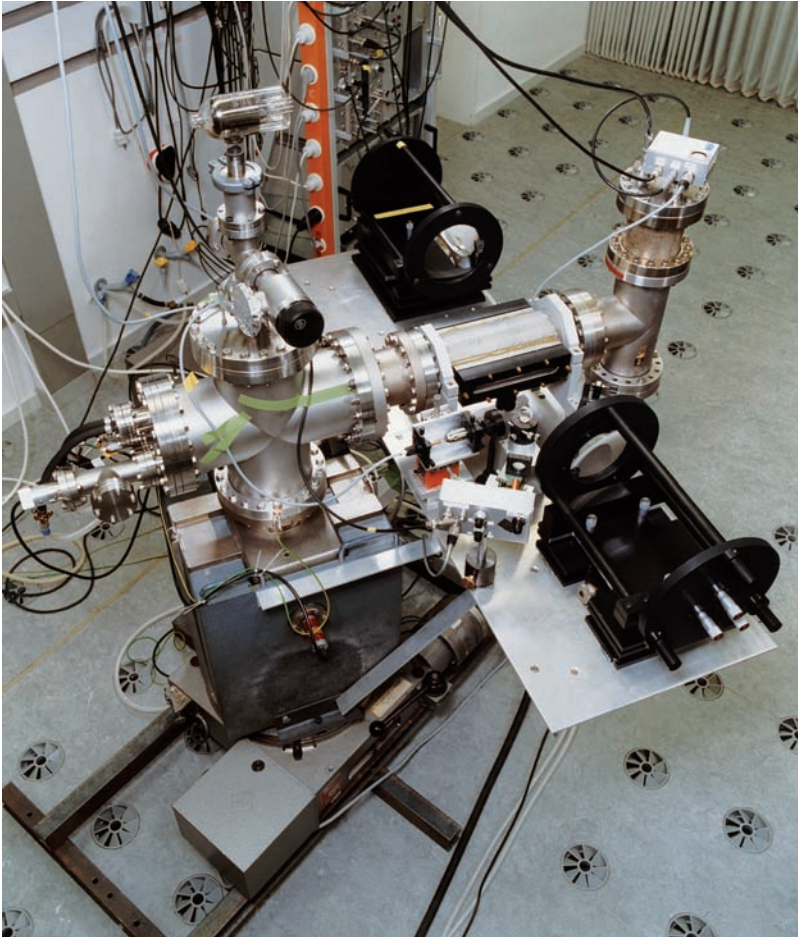


Figure 5:
Rotatable atom interferometer. A beam of calcium atoms is used for the first measurement of the Sagnac effect by atom interferometry.

In this setup the phase difference between the two partial waves in the exit ports of the interferometer is given by

$$\Delta\varphi = 2\pi \left[\Delta v \pm \frac{h\nu^2}{2Mc^2} + \Omega \frac{D+d}{\lambda_L} \right] \left[\frac{2D}{v} \right] \quad (4)$$

where v is the velocity of the atoms and D and d are given in Fig. 6. Thus the rotation with angular frequency Ω leads to a frequency shift

$$\Delta v_{\text{Sagnac}} = \Omega(d+D)/\lambda_L. \quad (5)$$

In the experiment a good agreement with this prediction could be demonstrated. Less than two decades after this landmark experiment, an improvement by twelve orders of magnitude has been reached using laser cooled caesium atoms and Raman transitions between their ground-state hyperfine levels [5]. This accuracy now rivals the best mechanical and laser gyroscopes [6].

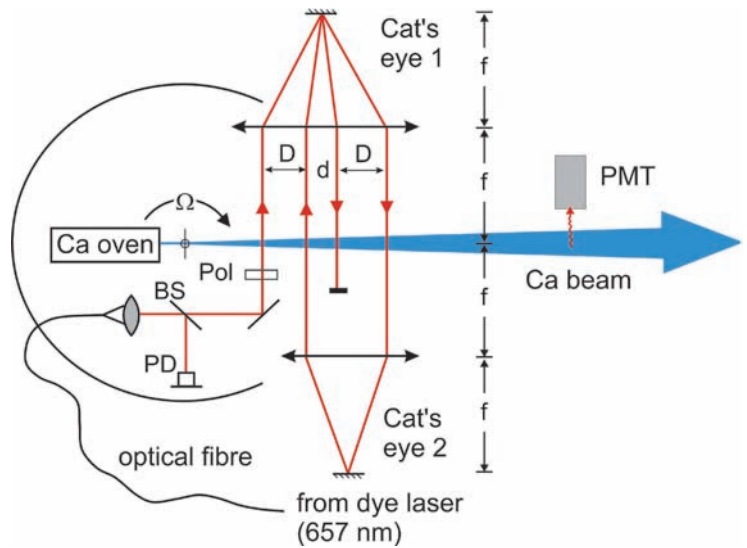
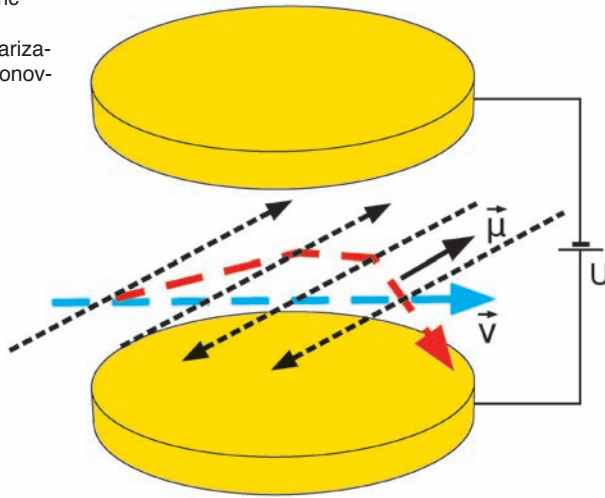


Figure 6:
Setup for the first measurement of the Sagnac effect with an atom interferometer. BS: beam splitter; PD: photodiode; Pol: polarizer; PMT: photomultiplier tube.

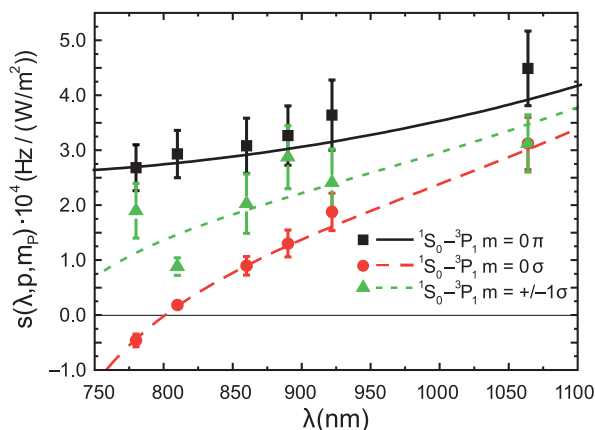
3.2 Measurement of atomic properties: Static and dynamic polarizability

If a Ramsey-Bordé interferometer is operated in an electric field, the polarizability of the atoms can be determined from the field-dependent shift of the interferometer phase. Since in this kind of interferometer the partial waves are labelled by the atomic state, it is not necessary to spatially restrict the field to one interferometer arm if the quantity of interest is the difference of the polarizabilities of the two atomic states. In our experiments, the whole interferometer [7] or a part of it [8] were placed in a capacitor-like arrangement of plane electrodes (Fig. 7).

Figure 7:
An atom interferometer exposed to an electric field can be used to measure atomic polarizabilities and the Aharonov-Casher phase [7].



Later, the dynamic polarizability of calcium was measured at PTB in a time-domain interferometer. An additional laser pulse of variable wavelength (between 780 nm and 1064 nm) was applied between the first and the second interferometer pulse [9]. Measurements using this setup improved the knowledge of the magnitudes of the Ca transition matrix elements and thus allowed to determine the so-called magic wavelength of calcium. In a calcium lattice clock operating with the optical lattice field at the magic wavelength, the clock frequency is unaffected by the lattice field (Fig. 8) [10].



3.3 Measurement of topological phase shifts

The arrangement developed by Karsten Zeiske [7] also permitted a measurement of the so-called Aharonov-Casher phase, a phase difference between two partial waves of an atom with nonzero magnetic dipole moment that arises if the trajectories of the partial waves enclose a uniform line charge. This topological phase shift appears even though there is no accelerating force acting on the atom. The magnitude of the shift is independent of both the detailed atomic path and the velocity. It was possible to experimentally confirm the predicted magnitude of the Aharonov-Casher phase with a relative uncertainty of 2.2 %.

3.4 Optical Frequency Standards

The sensitivity of asymmetric four-pulse and four-beam atom interferometers to the difference between the laser frequency and the frequency of the atomic transition can be employed to precisely measure the atomic transition frequency. The calcium atom interferometer, first in its thermal atomic beam version and later with laser cooled atoms in a magneto-optical trap, was used to measure the frequency of the $\lambda = 657$ nm $^1S_0-^3P_1$ intercombination line of calcium. This system served as one of the best optical frequency standards of its time and was seminal for the development of the optical clocks that now rival the best microwave clocks [11].

4 Precision measurements using atom interferometry: Ongoing work in QUEST

There is a variety of atom interferometer research going on in QUEST for both basic research and applications. This work is introduced in the following.

4.1 Cold Atom Sagnac Interferometer

In the framework of QUEST, a transportable matter wave interferometer named CASI (Cold Atom Sagnac Interferometer) is currently being set up at the Institute of Quantum Optics (IQO) at Leibniz Universität Hannover (Fig. 9). With CASI, it will be possible to test and compare different Sagnac gyroscopes, for example the huge stationary optical interferometers operated in Christchurch (New Zealand) and Wettzell (Germany) which are used to monitor the changing rotation rate of the Earth. CASI will also serve as a ground based test facility for future satellite missions.

Figure 8:
Normalized shift of the calcium interferometer signal for different Zeeman components of the $^1S_0-^3P_1$ transition as a function of wavelength λ of the additionally applied laser field [9].

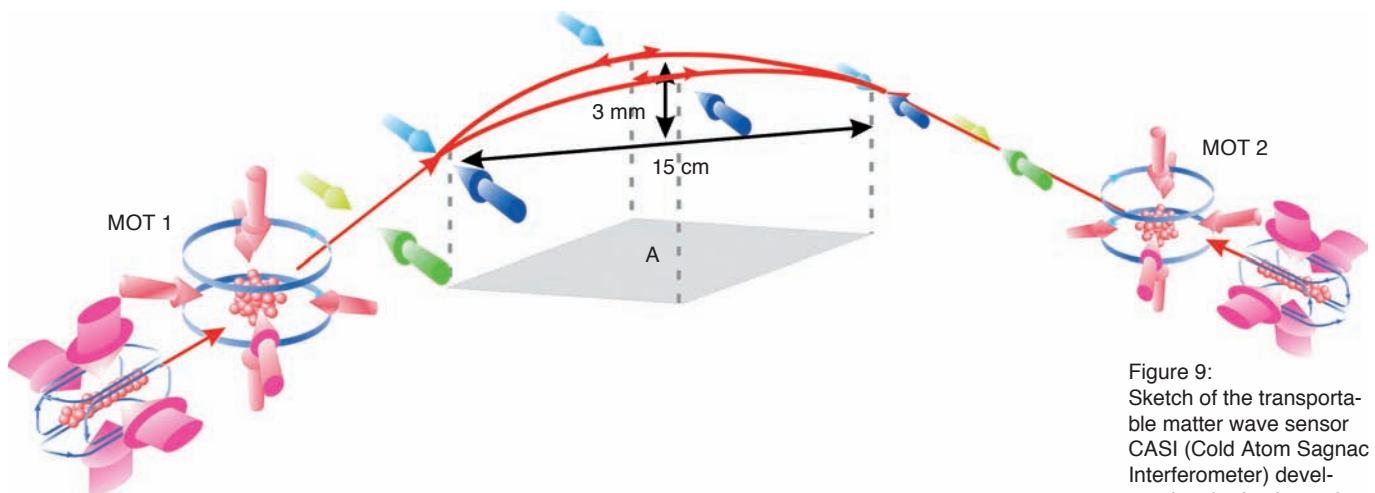


Figure 9: Sketch of the transportable matter wave sensor CASI (Cold Atom Sagnac Interferometer) developed at the Institute of Quantum Optics at Leibniz Universität Hannover.

CASI employs two sources of laser-cooled rubidium atoms. Each atomic source comprises a three-dimensional magneto-optical trap (MOT) which is loaded from a two-dimensional MOT optimized for high atomic flux. From the two MOT systems, two counterpropagating beams of cold atoms are launched onto ballistic trajectories using a so-called moving molasses technique. The atomic waves of these beams are split, redirected, and recombined by laser beams which intersect the atomic trajectories near their apex (blue arrows in Fig. 9). The phase shift between the atomic partial waves depends on the rotation rate and the area enclosed by the partial waves. The use of counterpropagating atomic beams significantly increases the accuracy of the interferometric measurement since most of the external perturbations that might cause phase shifts are independent of the direction of the atomic beam, whereas the sign of the Sagnac phase shift depends on the beam direction. Hence, by subtracting the signals delivered by the two counterpropagating atomic beams the pure rotation signal can be extracted while per-

turbations, for example those introduced by imperfections of the beam splitters, are eliminated to first order.

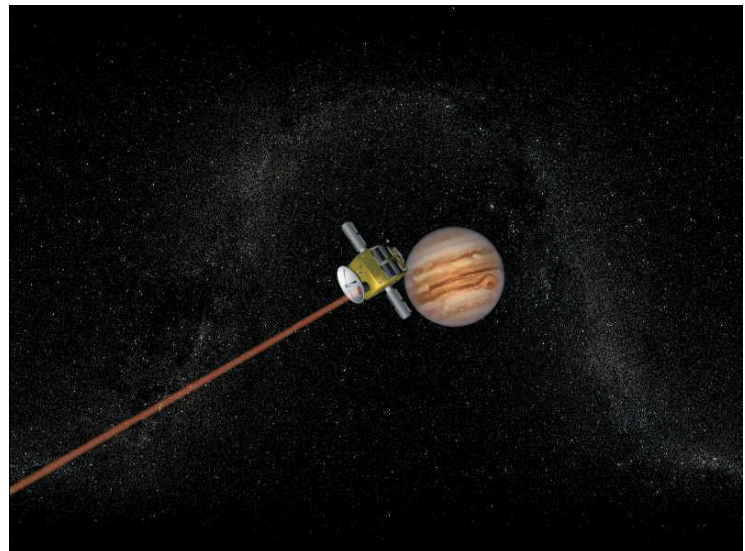
4.2 Atom interferometry for space-time sensors

In addition to the transportable CASI system, rubidium atom interferometers of the Ramsey-Bordé type are also investigated at the Institute for Quantum Optics as rotation and acceleration sensors [12]. Interferometers of this type might be used as sensors in space missions like HYPER (Fig. 10) to test predictions of General Relativity like the challengingly small Lense-Thirring effect. This effect is related to the prediction that the rotating Earth drags the surrounding space-time with it, which could be detected by the rotation of test bodies. With high sensitivity the frame-dragging effect could be detected by an atom interferometer located in a satellite that circles the Earth in a sun-synchronous polar orbit [13].

In another project study termed SAGAS (Search for Anomalous Gravitation with Atomic Sensors) [14], it is proposed to look for devia-



Figure 10: Proposed satellite missions like HYPER (left, courtesy of ESA) and SAGAS (right, courtesy of P. Wolf, LNE-SYRTE) rely on atom interferometers.



tions from the Newtonian law of gravitation in the outer region of the solar system using the combination of an atomic clock and of an acceleration sensor based on atom interferometry.

Currently the “technology readiness” of these sensors for space missions is being improved in several projects in QUEST.

5 The measurement of fundamental constants

The accurate determination of fundamental constants is of utmost importance for metrology and there is a program to base most if not all of the base units in the International System of Units (SI) on fundamental constants [15].

5.1 Fine structure constant

The fine structure constant α characterizes the strength of the electromagnetic interaction. The presently most precise value has been determined by a measurement of the anomalous g -factor of the electron. This parameter depends in a very complicated way on the fine structure constant, so that the evaluation of α requires extensive quantum-electrodynamic calculations. The current calculations extend to the eighth order of perturbation theory and yield α with a relative uncertainty of $3.7 \cdot 10^{-10}$ [16]. In order to confirm these calculations, an independent measurement of α is urgently needed. The fine structure constant can also be derived from the Rydberg constant and the ratio h/M between Planck’s constant and the mass M of a particle. Currently the best measurements of h/M rely on atom interferometric measurements where the recoil velocity $v = \hbar k/M$ or the recoil energy shift $\hbar^2 k^2/2M$ of isolated atoms is determined.

These measurements make use of asymmetric atom interferometers. Here, the two recoil components of the excited atomic transition are separated by a frequency difference $\Delta\nu = \hbar/(\lambda_L^2 M)$. However, in the case of calcium for example this shift amounts to only 23 kHz, and to reach a relative uncertainty of 10^{-10} , a resolution in the microhertz range would be required, much less than the atomic linewidth. Therefore in most atom interferometric recoil shift measurements many recoil momenta are transferred to increase the sensitivity. In the Stanford atom interferometer, a sequence of Rabi flopping pulses is applied between the first and the second beam splitter pulse in order to increase the transferred momentum to 24 photon momenta [17].

Another approach uses Bloch oscillations of atomic matter waves in an optical lattice under the influence of gravity or in an accelerated lattice. Here the atoms are trapped in a periodic potential. If a force is applied to the atoms, they are accelerated until they undergo a Bragg re-

flection which changes the atomic momentum by exactly $\hbar k$. In an experiment performed at the École Normale Supérieure (Paris), up to 1600 photon recoil momenta were transferred and the fine structure constant was determined with a relative uncertainty of $4.5 \cdot 10^{-9}$ [18].

5.2 The gravitational constants g and G

Atom interferometry is especially suited for the measurement of small forces acting on atoms. In a setup with three interaction zones as shown in Fig. 3, the phase shift due to an acceleration a parallel to the laser beams is given by

$$\Delta\varphi = \varphi_1 - 2\varphi_2 + \varphi_3 = -kaT^2. \quad (6)$$

Currently the acceleration $a = g$ in the gravitational potential of the Earth is measured by atom interferometers with a resolution of $0.8 \cdot 10^{-7} \text{ m/s}^2$ at 1 s averaging time [17, 19, 20, 21]. The precise value of the gravitational acceleration g is needed for example in a Watt balance which compares electrical and mechanical work. Here g is required to determine the weight force of a given mass. Using a measurement of the electric work based on the Josephson effect and the quantum Hall effect, a value for Planck’s constant was obtained with a relative uncertainty of $6.6 \cdot 10^{-9}$ [22].

If additional field masses are placed around an atom interferometer, the measured gravitational acceleration is modified by the gravitational action of the field masses. From the measured change of the acceleration for various positions of the test masses the Newtonian gravitational constant G was determined with a relative uncertainty of $2 \cdot 10^{-3}$ [23].

We note that the measurement of small forces by atom interferometry also allows the investigation of weak forces at small distances. This is of interest in particular for measurements of the Casimir-Polder force and of the gravitational force at small distances.

6 Outlook

Considering the successful application of atom interferometry to precision measurements in various fields of metrology, it appears that atom interferometry holds the potential for further dramatic improvements. One of the biggest challenges of atom interferometry on the way to fully using its potential is due to the fact that – in contrast to photons in optical interferometers – the atoms have a nonzero rest mass and consequently are accelerated in the gravitational field of the Earth. This limits the usable interaction time of the atoms in the interferometer and thus the size of the apparatus and the achievable accuracy. One solution to this problem is to operate atom interferometers in a microgravity environment.

Another possible solution is an interferometer where the atoms are guided in static magnetic or electric fields or in optical fields. However, such guiding fields easily lead to uncontrollable phase shifts. A possible way to avoid this problem is to store the atoms in an optical guiding structure that operates at the magic wavelength (see Sec. 3.2). This new approach will be investigated at PTB.

Another option to overcome the influence of the gravitational attraction is to construct an atom interferometer where the beam splitting pulses levitate the atoms in a suitable way. This proposal of Impens and Bordé [24] could be realized with the PTB calcium atom interferometer.

A promising research field whose full potential still has to be explored is the utilization of Bose-Einstein condensates (BEC) for high-precision atom interferometry. Although a large variety of atom interferometry experiments have been performed with BEC, in many cases only qualitative or semiquantitative results were obtained. On the one hand, the high atomic density of BEC is indispensable for experiments that investigate the behaviour of matter waves in nonlinear regimes. On the other hand, the interaction between atoms in a BEC easily leads to spatially varying phases that prohibit accurate interferometric measurements. Here, BEC consisting of alkaline-earth atoms offer an advantage because the intercombination transitions of these atoms have very narrow linewidths. These transitions have been used previously in optical frequency standards and their properties with respect to external perturbations are well known. Using this knowledge and the frequency measurement techniques developed for optical atomic clocks, phase shifts can be detected with high sensitivity and analyzed quantitatively. At PTB, experiments are in progress which aim at obtaining calcium and strontium Bose-Einstein condensates and applying them to atom interferometry.

References

- [1] A. D. Cronin, J. Schmiedmayer, D. E. Pritchard: Atom Interferometers. To appear in *Rev. Mod. Phys.* (2009).
- [2] N. F. Ramsey: Experiments with separated oscillatory fields and hydrogen masers. *Rev. Mod. Phys.* 62, 541 (1990).
- [3] Ch. J. Bordé: Atomic interferometry with internal state labelling. *Phys. Lett. A* 140, 10 (1989).
- [4] F. Riehle, Th. Kisters, A. Witte, J. Helmcke, Ch. J. Bordé: Optical Ramsey spectroscopy in a rotating frame: Sagnac effect in a matter-wave interferometer. *Phys. Rev. Lett.* 67, 177 (1991).
- [5] D. S. Durfee, Y. K. Shaham, M. A. Kasevich: Long-term stability of an area-reversible atom-interferometer Sagnac gyroscope. *Phys. Rev. Lett.* 97, 240801 (2006).
- [6] G. E. Stedman, R. B. Hurst, K. U. Schreiber: On the potential of large ring lasers. *Opt. Commun.* 279, 124 (2007).
- [7] K. Zeiske, G. Zinner, F. Riehle, J. Helmcke: Atom interferometry in a static electric field: Measurement of the Aharonov-Casher phase. *Appl. Phys. B* 60, 205 (1995).
- [8] V. Rieger, K. Sengstock, U. Sterr, J. H. Müller, W. Ertmer: Atom-interferometric determination of the dc-Stark shift of the Mg-intercombination line. *Opt. Commun.* 99, 172 (1993).
- [9] C. Degenhardt, H. Stoeck, U. Sterr, F. Riehle, Ch. Lisdat: Wavelength dependent ac-Stark shift of the $^1S_0 - ^3P_1$ transition at 657 nm in Ca. *Phys. Rev. A* 70, 023414 (2004).
- [10] See the contribution "The Development of Accurate Optical Clocks" in this issue, p. 25.
- [11] G. Wilpers, T. Binnewies, C. Degenhardt, U. Sterr, J. Helmcke, F. Riehle: Optical clock with ultracold neutral atoms. *Phys. Rev. Lett.* 89, 230801 (2002).
- [12] K. Eckert, P. Hyllus, D. Bruns, U. V. Poulsen, M. Lewenstein, C. Jentsch, T. Müller, E. M. Rasel, W. Ertmer: Differential atom interferometry beyond the standard quantum limit. *Phys. Rev. A* 73, 013814 (2006).
- [13] C. Jentsch, T. Müller, E. M. Rasel, W. Ertmer: HYPER: A satellite mission in fundamental physics based on high precision atom interferometry. *General Relativity and Gravitation* 36, 2197 (2004).
- [14] P. Wolf et al.: Quantum physics exploring gravity in the outer solar system: the SAGAS project. *Experimental Astronomy* 23, 651 (2009).
- [15] On the possible redefinition of certain base units of the International System of Units (SI). Resolution 12 of the 23rd General Conference on Weights and Measures (2007): <http://www.bipm.org/utis/en/pdf/Resol23-CGPM-EN.pdf>
- [16] D. Hanneke, S. Fogwell, G. Gabrielse: New measurement of the electron magnetic moment and the fine structure constant. *Phys. Rev. Lett.* 100, 120801 (2008).
- [17] H. Müller, S. Chiow, Q. Long, S. Herrmann, S. Chu: Atom interferometry with up to 24-photon-momentum-transfer beam splitters. *Phys. Rev. Lett.* 100, 180405 (2008).
- [18] M. Cadoret, E. de Mirandes, P. Cladé, S. Guellati-Khélifa, C. Schwob, F. Nez, L. Julien, F. Biraben: Combination of Bloch oscillations with a Ramsey-Bordé interferometer: New determination of the fine structure constant. *Phys. Rev. Lett.* 101, 230801 (2008).

- [19] *J. Le Gouët, T. E. Mehlstäubler, J. Kim, S. Merlet, A. Clairon, A. Landragin, F. Pereira Dos Santos*: Limits to the sensitivity of a low noise compact atomic gravimeter. arXiv:physics/0701023v1 (2008).
- [20] *A. Peters, K. Y. Chung and S. Chu*: High-precision gravity measurements using atom interferometry. *Metrologia* 38, 25 (2001).
- [21] *J. B. Fixler, G. T. Foster, J. M. McGuirk, M. Kasevich*: Atom interferometer measurement of the Newtonian constant of gravity. *Science* 315, 74 (2007).
- [22] *I. Robinson, B. P. Kibble*: An initial measurement of Planck's constant using the NPL Mark II watt balance. *Metrologia* 44, 427 (2007).
- [23] *G. Lamporesi, A. Bertoldi, L. Cacciapuoti, M. Prevedelli, G. M. Tino*: Determination of the Newtonian gravitational constant using atom interferometry. *Phys. Rev. Lett.* 100, 050801 (2008).
- [24] *F. Impens, Ch. J. Bordé*: Space-time sensors using multiple-wave atom interferometry. arXiv:physics/0808.3380v2 (2008).