8th Symposium on Frequency
Standards and Metrology 2015

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Program and book of abstracts

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8th Symposium on Frequency Standards and Metrology 2015

Symposium Chair

Fritz Riehle

at
Physikalisch-Technische Bundesanstalt
Bundesallee 100
38116 Braunschweig, Germany

phone: +49 531 592-4010
e-mail: fritz.riehle@ptb.de
web: www.ptb.de

Secretary

Ingrid Herrmann

at
Physikalisch-Technische Bundesanstalt
Bundesallee 100
38116 Braunschweig, Germany

phone: +49 531 592-4011
e-mail: 8fsm@ptb.de
web: www.ptb.de

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Welcome

Welcome to Potsdam for the 8th Symposium on Frequency Standards and Metrology (8FSM). The Symposium is an event held approximately every seven years as the forum for bringing together international scientists and technologists engaged in the development of precise frequency standards and their applications in metrology, to exchange information on the latest developments in the field, and to point out future directions. The first symposium was organized by Jaques Vanier in 1971 in Forêt Montmorency in Quebec, Canada. The next ones took place in 1976 in Copper Mountain, USA organized by Helmut Hellwig, 1981 in Aussois, France (Claude Audoin), 1988 in Ancona, Italy (Andrea de Marchi), 1995 in Woods Hole, USA (James Bergquist), 2001 in St Andrews, UK (Patrick Gill), and 2008 in Pacific Grove, USA (Lute Maleki).

The Symposium will be held in the Seminaris SeeHotel at the shore of the Lake Templin at Potsdam (Germany) not far from Berlin. This location provides a secluded environment that promotes a scientific exchange, with a single session approach which includes oral presentations by invitation and poster sessions. Proceedings of the contributions will be published.

We would like to thank our many sponsors listed on the previous page. Without their support the organization would not have been possible. We also would like to take this opportunity to thank the Governing Board of the Symposium and the International Steering Committee for their invaluable support and encouragement.

We hope you will enjoy the Symposium with new insights, novel ideas and new friends.

Fritz Riehle and the Local Organizing Committee

Physikalisch-Technische Bundesanstalt, Germany
October 2015

Symposium information

The Symposium starts with a welcome reception and registration on Sunday, October 11 at the Seminaris SeeHotel. The sessions will start in the morning of Monday, October 12 and will end on Friday, October 16 after lunch. There will be one keynote talk and 47 invited talks. Invitation for 110 poster presentations have been issued. All talks will be held in the conference room (Plenar- & Bankett Areal, PBA) next to the reception of the hotel. Except for the keynote speaker (1 h) all oral presentations have a slot of 30 minutes including 5 minutes of question time.

Laptop computers (MS PowerPoint & Adobe Acrobat Reader) will be provided. All presentations must be pre-loaded in the provided laptop at the latest during the break before the session. To avoid software compatibility problems (MS PowerPoint), speakers are advised to save their PowerPoint presentation in „pack-n-go" format and bring a backup PDF version of their presentation. PowerPoint files should be saved preferably as „Package for CD".

Poster sessions are on Monday and Tuesday afternoon and evening. The poster boards will be arranged in the foyer and rooms in the Executive Conference Center (ECC) by the numbers in this book. Material for putting up the posters will be provided near the poster board. Posters can be on display from Monday till Thursday.

Lunch and dinner is included in the conference fee and is served close to the conference room. The pre-booked excursions on Wednesday afternoon will start with buses from the Seminaris SeeHotel and come back to the starting point. The Symposium banquet will take place at the Seminaris SeeHotel on Wednesday after the excursions.

Registration and information desk hours

Sunday	11 October	4:00 pm – 8:00 pm
Monday	12 October	7:30 am – 6:30 pm
Tuesday	13 October	8:00 am – 5:00 pm
Wednesday	14 October	8:00 am – 1:30 pm
Thursday	15 October	8:00 am – 5:00 pm
Friday	16 October	8:00 am – 2:30 pm

During these hours the registration desk can be reached by phone (+49) 331/9090-510 or by mail 8fsm@ptb.de.

WLAN-key

For entering the free WLAN at Seminaris SeeHotel (Seminaris Hotspot), please use the following key:

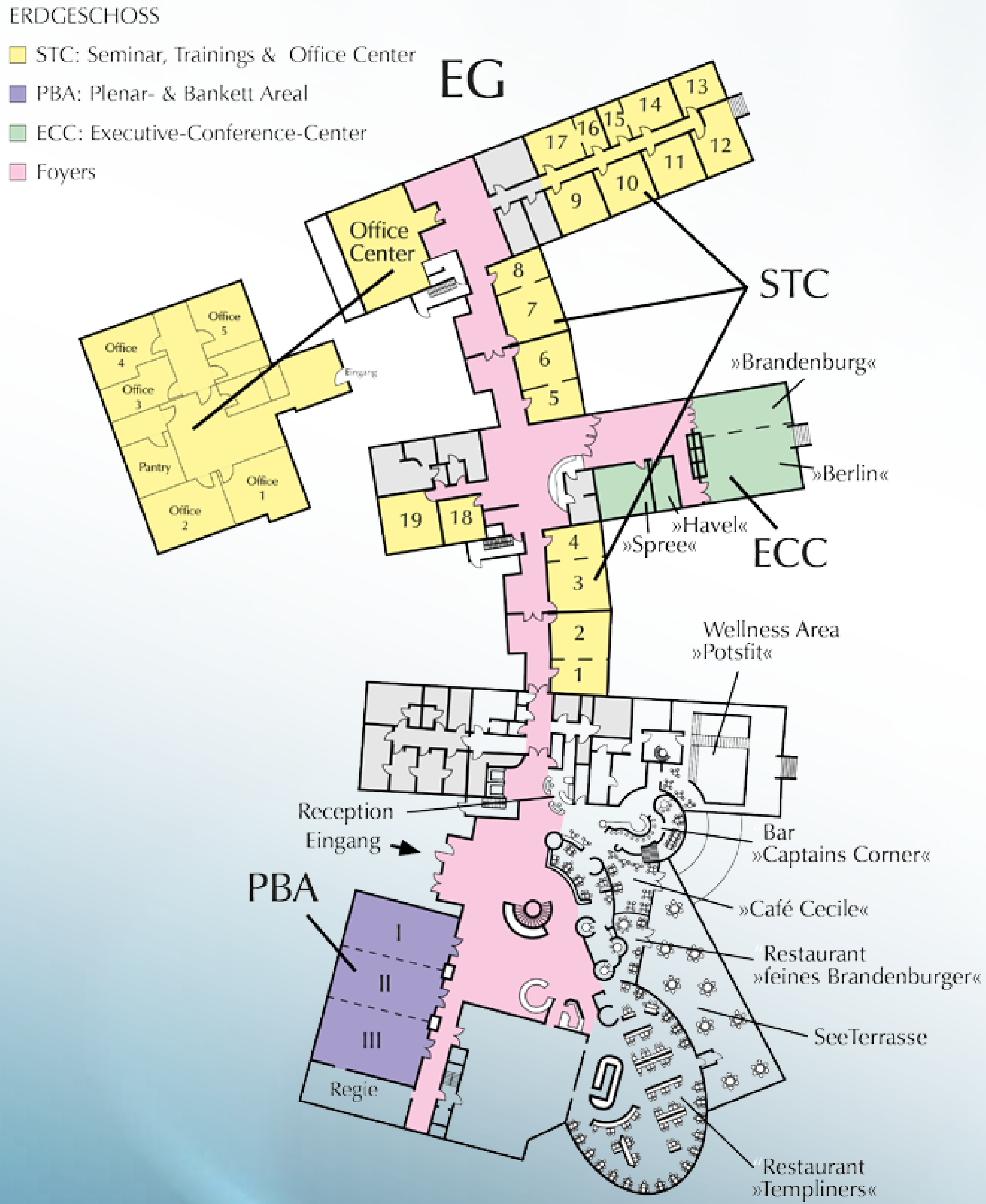
username: **FSM**
password: **53052**

Symposium proceedings

Participants of the symposium are requested to publish a contribution to the proceedings. Manuscripts are due preferably at the symposium but at the latest on November, 15.

The printed book of proceedings will be available in April 2016. A copy will be mailed to all participants. Please note that only papers presented at the Symposium will be included in the proceedings. For more information see "Conference Proceedings" on page 188.

Seminaris SeeHotel (Symposium floor)



Time Table

	Monday, 12 Oct	Tuesday, 13 Oct	Wednesday, 14 Oct	Thursday, 15 Oct	Friday, 16 Oct	
7:30 am	Breakfast	Breakfast	Breakfast	Breakfast	Breakfast	7:30 am
8:30 am to 10:30 am	Welcome & Opening **Chair:** Fritz Riehle	Optical Clocks I: Lattice Clocks **Chair:** Tetsuya Ido	Optical Frequency Comb **Chair:** Thomas Südmeyer	New Concepts and Novel Applications I **Chair:** Eric Burt	Ultrastable Oscillators: Microwave and Optical **Chair:** Jeremy Everard	8:30 am to 10:30 am
8:30 am	Welcome: Fritz Riehle	Hidetoshi Katori	Scott Diddams	Hao Zhang	John Hartnett	8:30 am
9:00 am	Keynote David Wineland	Andrew Ludlow	Kjeld Eikema	Ekkehard Peik	Vincent Giordano	9:00 am
9:30 am		Sébastien Bize	Long-Shen Ma	Svenja Knappe	Uwe Sterr	9:30 am
10:00 am	Andrei Derevianko	Jun Ye	Lute Maleki	John Kitching	Garrett Cole	10:00 am
10:30 am	Break	Break	Break	Break	Break	10:30 am
11:00 am to 12:30 pm	Tests of Fundamental Physics with Clocks **Chair:** Kurt Gibble	Atom Interferometry **Chair:** Peter Wolf	Towards the Future **Chair:** Salvatore Micalizio	New Concepts and Novel Applications II **Chair:** Lute Maleki	Ground and Space Links **Chair:** Piet Oliver Schmidt	11:00 am to 12:30 pm
11:00 am	Michael Tobar	Mark Kasevich	Jakob Flury	Nan Yu	Christophe Salomon	11:00 am
11:30 am	Magdalena Zych	Arnaud Landragin	José Crespo López-Urrutia	Ernst Rasel	Wolfgang Schäfer	11:30 am
12:00 pm	Isaac Fan	Achim Peters	Patrick Gill	Thomas Zanon-Willette	Nathan Newbury	12:00 pm
12:30 pm	Lunch	Lunch	Lunch	Lunch	Farewell / Lunch	12:30 pm
2:00 pm to 4:00 pm	Microwave Clocks I: Fountains **Chair:** Christophe Salomon	Optical Clocks II: Ion Clocks **Chair:** Rachel Godun	Free Time	Time and Frequency Transfer **Chair:** Anne Amy-Klein	End of Symposium	2:00 pm to 4:00 pm
2:00 pm	Kurt Gibble	David Leibrandt		Miho Fujieda		2:00 pm
2:30 pm	Krzysztof Szymaniec	Pierre Dubé		Jonathan Hirschauer		2:30 pm
3:00 pm	Steve Peil	Hua Guan		Paul-Eric Pottie		3:00 pm
3:30 pm	Steven Jefferts	Nils Huntemann		Daniele Rovera		3:30 pm
4:00 pm	Break	Break		Break		4:00 pm
4:30 pm to 6:30 pm	Posters **Chair:** Ekkehard Peik	Posters **Chair:** Christian Lisdat	Optional Excursions, Sanssouci, Einstein tower, Caputh	Microwave Clocks II: Miniature Clocks **Chair:** Elizabeth Donley		4:30 pm to 6:30 pm
4:30 pm				Peter Rosenbusch		4:30 pm
5:00 pm				Gaetano Mileti		5:00 pm
5:30 pm				Peng Liu		5:30 pm
6:00 pm				John Prestage		6:00 pm
6:30 pm	Dinner	Dinner		Dinner		6:30 pm
7:00 pm						7:00 pm
7:30 pm						7:30 pm
8:00 pm	Posters continued	Posters continued	Banquet			8:00 pm
8:30 pm						8:30 pm
9:00 pm						9:00 pm

Oral sessions – Overview

Sunday, October 11, 2015

4:00 pm – 8:00 pm	Registration
6:00 pm – 8:00 pm	Welcome Reception

Monday, October 12, 2015

8:30 am – 10:30 am	Welcome & Opening	Session Chair: Fritz Riehle

11:00 am – 12:30 pm	Tests of Fundamental Physics with Clocks	Session Chair: Kurt Gibble

2:00 pm – 4:00 pm	Microwave Clocks I: Fountains	Session Chair: Christophe Salomon

Tuesday, October 13, 2015

8:30 am – 10:30 am | Optical Clocks I: Lattice Clocks | Session Chair: Tetsuya Ido

11:00 am – 12:30 pm | Atom Interferometry | Session Chair: Peter Wolf

2:00 pm – 4:00 pm | Optical Clocks II: Ion Clocks | Session Chair: Rachel Godun

Wednesday, October 14, 2015

8:30 am – 10:30 am | Optical Frequency Comb | Session Chair: Thomas Südmeyer

11:00 am – 12:30 pm | Towards the Future | Session Chair: Salvatore Micalizio

Thursday, October 15, 2015

8:30 am – 10:30 am | New Concepts and Novel Applications I | Session Chair: Eric Burt

11:00 am – 12:30 pm | New Concepts and Novel Applications II | Session Chair: Lute Maleki

2:00 pm – 4:00 pm | Time and Frequency Transfer | Session Chair: Anne Amy-Klein

4:30 pm – 6:30 pm | Microwave Clocks II: Miniature Clocks | Session Chair: Elizabeth Donley

Friday, October 16, 2015

8:30 am – 10:30 am | Ultrastable Oscillators: microwave & optical | Session Chair: Jeremy Everard

11:00 am – 12:30 pm | Ground and Space Links | Session Chair: Piet Oliver Schmidt

The evolution of the Symposium and its physics

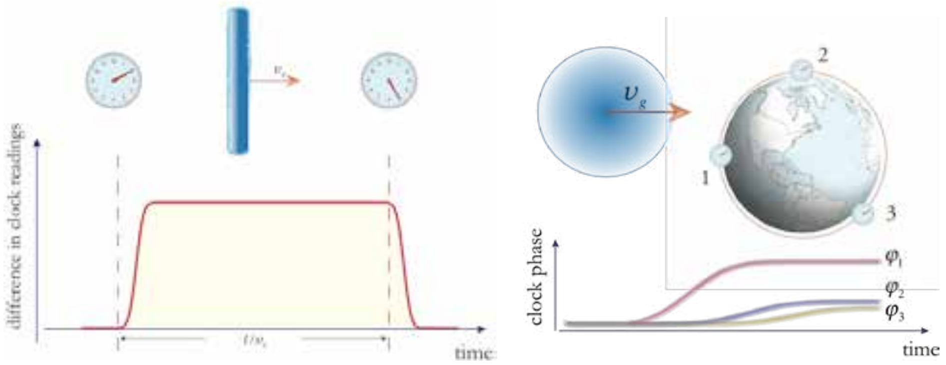
D. Wineland
Time and Frequency Division, NIST Boulder, Colorado
E-mail: david.wineland@nist.gov

Although I didn't attend the first Symposium on Frequency Standards and Metrology, I have been fortunate to attend all subsequent symposia, starting in 1976. I very much like this meeting, in part because it is held relatively infrequently and each new installment brings significant advances and renewed excitement in the field. In this talk, I will try to highlight some of these developments, particularly the advances in the physics of the frequency standards.

Hunting for dark matter with GPS and atomic clock networks

A. Derevianko
University of Nevada, Reno, USA
E-mail: andrei@unr.edu

Atomic clocks are arguably the most accurate scientific instruments ever built. Modern clocks are astonishing timepieces guaranteed to keep time within a second over the age of the Universe. Attaining this accuracy requires that the quantum oscillator be well protected from environmental noise and perturbations well controlled and characterized. This opens intriguing prospects of using clocks to study subtle effects, and it is natural to ask if such accuracy can be harnessed for dark matter searches.



By monitoring correlated time discrepancy between two spatially separated clocks one could search for passage of topological defects (TD), such as the domain wall pictured here (left panel). Domain wall moves at galactic speeds ~ 300 km/s. Before the TD arrival, the two clocks are synchronized. As the TD sweeps through the first clock, it runs faster (or slower), with the clock time difference reaching the maximum value. Time difference stays at that level while the defect travels between the two clocks. Finally, as the defect sweeps through the second clock, clocks resynchronize. For intercontinental scale network, l~ 10,000 km, the characteristic time 30 seconds. The right panel shows correlated response to a monopole TD.

The cosmological applications of atomic clocks so far have been limited to searches of the uniform-in-time drift of fundamental constants. We point out that a transient in time change of fundamental constants can be induced by dark matter objects that have large spatial extent, and are built from light non-Standard Model fields. The stability of this type of dark matter can be dictated by the topological reasons. We argue that correlated networks of atomic clocks (see figures), such as atomic clocks onboard satellites of the GPS constellation, can be used as a powerful tool to search for the topological defect dark matter. We envision using GPS as a 50,000 km-aperture dark-matter detector. Similar arguments apply to terrestrial networks.

References: A. Derevianko and M. Pospelov, Nature Phys. 10, 933 (2014)

Novel Microwave Oscillators and Resonant Structures for Precision Test of Fundamental Physics and Quantum Measurement

Michael Edmund Tobar[1]
1. ARC Centre of Engineered Quantum Systems, The University of Western Australia, Crawley, WA, Australia
E-mail: michael.tobar@uwa.edu.au

In this presentation I give an overview of the latest experiments at the University of Western Australia (UWA) and in cooperation with other institutes, which utilize precision microwave techniques to test fundamental physics and take on novel quantum measurements.

First we will present results in collaboration with Humboldt University of Berlin that shows extremely new sensitive tests of GR capable of probing suppressed effects emanating from the Planck scale [1]. In this work we use two ultra-stable oscillator frequency sources to perform a modern Michelson-Morley experiment and make the most precise measurement to date of the spatial isotropy of the speed of light, constraining $\Delta c/c$ to $9.2\pm10.7\times10^{-19}$. This allows us to undertake the first terrestrial test of Lorentz invariance at the Planck-suppressed electroweak unification scale, finding no significant violation of Lorentz symmetry.

Second, we show our progress in utilizing new microwave experiments to search for the Dark Sector Particles. Dark matter is a fundamental component of the universe yet the nature of its composition is still unknown. Through the development of remarkable precision electromagnetic measurement tools and techniques, we aim to perform a comprehensive laboratory search for dark matter axions at UWA in a mass range that is currently untested. We will also present results and new proposals that test for the Dark sector photon [2].

Third, we present the latest results from our spins in solids program, which aims to couple microwave photons strongly with spins at mK temperatures in the single photon regime using novel microwave cavities [3-6]. Some of this work has been done in collaboration with Saarland University, Macquarie University and the Royal Melbourne Institute of Technology.

Finally, I present progress on the precision measurement of optomechanical systems of order a kg using sapphire parametric technology. The goal is to cool the system to the ground state and read it out with quantum-limited precision. Such massive systems can be used to search for gravitational effects on the uncertainty relations [7].

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General relativistic effects in quantum interference of "clocks"

M. Zych[1], F. Costa[1], I. Pikovski[2], and Č. Brukner[3]

1. Centre for Engineered Quantum Systems, School of Mathematics and Physics, The University of Queensland, St Lucia, QLD 4072, Australia
2. ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
3. Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences, Boltzmanngasse 3, A-1090 Vienna, Austria

E-mail: m.zych@uq.edu.au

Quantum mechanics and general relativity have been successfully tested in many experiments. However, all experiments that measured the influence of gravity on a quantum system are still fully consistent with the non-relativistic, Newtonian gravity. Also in all to date performed tests of general relativity, the degrees of freedom relevant for the general relativistic effects can be described by classical physics.

Here we discuss new quantum effects arising from gravitational time dilation for composed quantum systems. In quantum mechanics time dilation in general entangles internal degrees of freedom and the center of mass: Consider a system with a time-evolving internal state – a "clock" – which is placed in a superposition of two different gravitational potentials, Fig.1. Each amplitude of the superposition will experience different proper time, due to the gravitational time dilation. According to quantum complementarity the visibility of quantum interference will thus drop to the extent to which the information about the path becomes available from the internal state of the "clock". The "clock" can be implemented in an internal energy level of an atom or a molecule [1], or in the position of a photon [2].

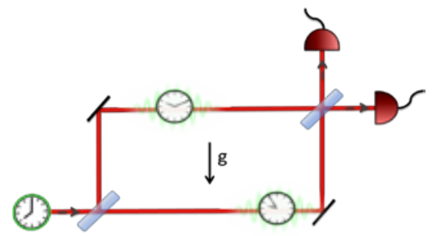

Fig.1 A "clock", particle with internal dynamics, following in superposition two paths at different gravitational potentials. Gravitational time dilation entangles internal states of the "clock" to the path, which results in a drop (and revivals, for a periodic "clock") of the interferometric visibility.

Time dilation limits center of mass coherence for any state with non vanishing internal energy spread, not only for specific "clock" states. For sufficiently large systems time dilation thus provides an effective decoherence mechanism [3]. New quantum effects arising from time dilation also call for conceptually new tests of the foundations of general relativity [4].

The regime of low-energy, composite quantum systems subject to weak gravity is particularly promising for laboratory-scale experimental exploration and might finally allow testing the interplay between quantum mechanics and general relativity.

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Direct Measurement of f_{He}/f_{Xe} Spin Precession Frequency Ratio with 10^{-7} Uncertainty

I. Fan, S. Knappe-Grüneberg, J. Voigt, W. Kilian, M. Burghoff, D. Stollfuss, A. Schnabel, G. Wübbeler, O. Bodner, C. Elster, F. Seifert and L. Trahms

Physikalisch-Technische Bundesanstalt, Abbestraße 2-12, 10587 Berlin, Germany

E-mail: isaac.fan@ptb.de

Theoretical background: The current baryon-to-photon ratio (η) measured by the Wilkinson microwave anisotropy probe (WMAP) mission is ≈ 6.19×10^{-10} [1]. This small, yet non-zero, η is a quantitative indicator for the matter-antimatter asymmetry in our universe. According to Sakharov's baryongenesis model, one of the three conditions that must hold during the first picosecond of the universe expansion to create such a baryon number asymmetry is a significant amount of CP symmetry violation. Evidences for CP violation have been observed experimentally in the decay of the kaon [2] and more recently in a number of B-meson systems [3]. Although the CP-violation phenomenon observed so far can be described via the CKM mechanism in the standard model, the corresponding CP-violating source is still too small to account for the baryon asymmetry. One possible new CP-violating (or T-violating) source is the electric dipole moment (EDM) of fundamental particles [4]. Under a change of the sign of T, the spin angular momentum of the particle is no longer invariant with respect to the original electric polarization dictated by the dipole moment.

The interaction of a nuclear electric dipole moment (**d**) with an external electric field (**E**) in the relativistic regime would create a measurable energy **d·E** for an atom despite Schiff's screening effect. Experimentally, this energy term corresponds to an additional shift to the Larmour frequency. To cancel out the common magnetic systematics and noise sources while detecting this shift, often the precession of two nuclear species are used. A crucial parameter for this comagnetometer scheme is the quotient of the gyromagnetic ratios. This quotient has been determined at high fields , e.g. 11.7 T, in separated frequency measurements of the two underlying nuclei [5]. To prove that this number is valid for our EDM search in the μT regime, a more reliable approach is to measure the two frequencies simultaneously to eliminate possible unknown systematics. Here, we report our *direct* measurement of the frequency ratio for ^{3}He/^{129}Xe nuclei. Without any systematic correction, the frequency ratio reaches a 10^{-7} Allan deviation at an integration time of 100 s.

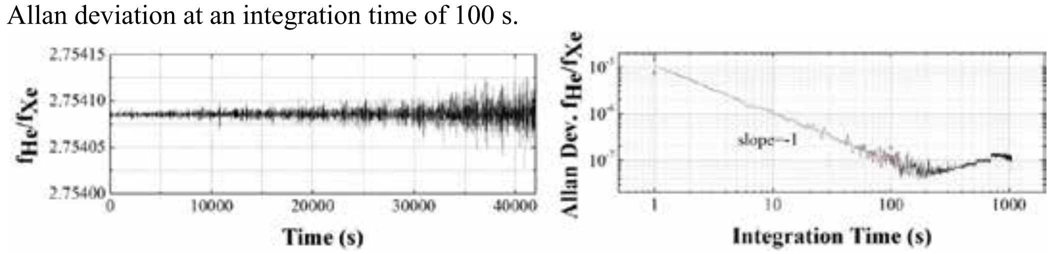

Fig. 1: (Left) Magnetic resonance frequency ratio of ^{3}He/^{129}Xe nuclei as a function of time. The fluctuation increases due to relaxation of the spin precession amplitudes. (Right) Allan deviation of the ratio at various integration times.

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Systematic effects in fountain clocks

K. Gibble
Department of Physics, The Pennsylvania State University, University Park, Pennsylvania, USA
E-mail: kgibble@psu.edu

We give an overview of laser-cooled atomic fountain clocks and the evaluation of their systematic uncertainties. Significant recent advancements are characterized by rigorous treatments of previously significant systematic errors, especially frequency shifts from distributed cavity phase [1-3], microwave lensing [4,5], and background gas collisions [6].

Distributed cavity phase shifts are a first-order Doppler shift due to small travelling waves in the microwave clock cavity and the motion of the cold atoms. Known for 40 years, measurements and calculations only recently agreed [3]. Stringent verification of our complete and rigorous model led to significantly smaller systematic errors and gave confidence to construct improved cavity designs with much smaller longitudinal phase gradients [2]. The most important feature to add is feeding clock cavities with 4 or more independent cables so that the atom trajectories can be precisely aligned with vertical. Several of the newest fountains have implemented the new designs, realizing more precise vertical alignments and now observing much smaller microwave amplitude-dependent frequency shifts.

The microwave photon recoil shift of $\delta\nu/\nu=1.56\times10^{-16}$ is now comparable to fountain clock inaccuracies. Because atoms in a fountain are localized to less than a microwave wavelength, the resonant microwave dipole forces do not yield resolved photon recoils but instead act as weak focusing and defocusing lenses on the atomic wave packets. The resulting frequency shift depends on the clock geometry and is typically 6×10^{-17} to 9×10^{-17} for fountains, and larger for the microgravity clock PHARAO, 12×10^{-17}. Although a number of clocks have been correcting for this bias, there are recent objections, which might be helpful to discuss.

Many cold atoms clocks, including fountains, lattice clocks, and quantum-logic ion clocks, have a different sensitivity to background gas collisions than room-temperature clocks because nearly all background gas collisions prevent the cold clock atoms from being detected. Therefore, room-temperature background gas shifts do not apply to cold-atom clocks. We have shown that there is a highly useful proportionality between background gas shifts and atom loss rates, which is essentially independent of the background gas, except for potentially helium. Thus, lifetime measurements can place accurate limits on background gas shifts.

We close with a summary of some options for the design of fountains that relatively easily realize these advances.

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NPL Cs fountain frequency standards – reaching the ultimate accuracy

K. Szymaniec[1], S. N. Lea[1], K. Gibble[2], S. E. Park[3], K. Liu[4], P. Głowacki[5]
1. National Physical Laboratory, Teddington, UK
2. Pennsylvania State University, City, USA
3. Korea Research Institute of Standards and Science, Daejeon, Korea
4. National Institute of Metrology, Beijing, China
5. Poznan University of Technology, Poznan, Poland
E-mail: krzysztof.szymaniec@npl.co.uk

The definition of the SI second is now realized with inaccuracies in the low 10^{-16} range by a number of caesium fountain frequency standards operated worldwide. Many of these standards contribute regularly to the evaluation of the TAI timescale and are used to discipline local timescales, significantly improving their accuracy. Cs fountains are also used in time and frequency labs for absolute measurements of the frequencies of narrow ‘clock’ transitions of new types of standards under development (e.g. optical clocks) and to place tighter constraints on time variation of fundamental constants.

NPL operates a system of two primary caesium fountain clocks consisting of a fully characterised standard NPL-CsF2 together with a new standard NPL-CsF3 that has been made operational during the preceding year. The two fountains have major design features in common, including: a single-stage vapour-loaded magneto-optical trap as the source of cold atoms, an easy to align (0, 0, 1) optical configuration, and accumulation of the $m_F = 0$ sublevel population by optical pumping. The potentially high cold collision frequency shift is approximately cancelled by manipulation of the atomic cloud size before launch and of the clock state population probabilities [1]. As a result, the related type-B fractional frequency uncertainty has been reduced below 10^{-16}. Subsequently, more subtle systematic effects, including the distributed cavity phase frequency shift, microwave lensing, and the frequency shifts due to microwave leakage and collisions with background gas have also been evaluated at the level of 10^{-16} or below [2, 3].

Under normal operating conditions, the short-term stability in NPL-CsF2/3 is limited at about 1.5×10^{-13} at 1 s by the phase noise of the room temperature quartz-based local oscillator. Recently an interrogation signal synthesized from an ultra-stable laser by means of a femtosecond optical frequency comb has been used, demonstrating four times lower instability. Based on the highest atom number observed in detection, an even lower value of 2.5×10^{-14} is expected. It is stressed that this state-of-the-art performance, both in terms of short-term stability and accuracy, is achieved in a relatively simple physics package.

As several systematic effects contribute to the fountains’ uncertainty budgets at similar level further significant improvement of their accuracy may be difficult to achieve. The short-term stability of these devices is also a significant factor limiting the overall precision as many days or even weeks of averaging is required for the type-A uncertainty to match that of the declared type-B part. Future efforts to advance this rather mature technology are now more likely to be devoted to improve reliability and robustness of operation.

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The USNO Rubidium Fountains

C. Ekstrom[1], J. Hanssen[1], T. Swanson[1], J. Taylor[1], S. Peil[1]
1. U. S. Naval Observatory, Washington DC/USA
E-mail: christopher.ekstrom@usno.navy.mil

Four rubidium fountains have been in continuous operation at USNO for over 4 years. They contribute to the local timescale and are reported to the BIPM as continuously running clocks – as opposed to secondary standards – the first cold-atom clocks so reported. Measurements among individual fountains demonstrate fractional-frequency stability that routinely reaches the low 10^{-16}s. The highest performing pair has shown relative stability characterized by a total deviation of $8 \cdot 10^{-17}$ at 10^{7} seconds, consistent with each fountain integrating as white-frequency noise below $6 \cdot 10^{-17}$, and with no drift between the fountains at the level of $7.5 \cdot 10^{-19}$/day. As an ensemble, the four fountains generate a timescale with short-term stability below $1 \cdot 10^{-13}$ at 1 second, an order of magnitude better than the ensemble of ~70 commercial cesium standards in the USNO timescale.

There are two additional rubidium fountains at USNO's Alternate Master Clock at Schriever AFB in Colorado. These fountains have been installed for a year and are being evaluated for inclusion into the operational time scale.

Rare frequency changes (on order of 1 per year, possibly correlated with operator intervention) have been observed. These produce a signature of random-walk frequency noise in the Allan deviation of clock comparisons, at a level on order of $2 \cdot 10^{-20} \tau^{1/2}$ for each of the best fountains. Multiple fountains allow the effect of this type of behavior on timing applications to be mitigated. Performance of a simple paper fountain timescale versus the primary frequency standards contributing to TAI over four years will be presented.

The long continuous operation of these clocks has allowed us to identify necessary service tasks and estimates of component failure intervals. This has resulted in preventive maintenance schedules for a few optical and optomechanical elements. These will be presented as well.

The first 1.5 years of fountain data were used to put stricter limits on violations of Local Position Invariance and on the coupling of certain fundamental constants to gravitational potential [1]. Some of these latter constraints require microwave clocks – they are not accessible with only optical clocks – and we expect to present improved measurements using additional fountain data.

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Measurements of the Microwave Lensing shift in NIST-F1 and NIST-F2.

S.R. Jefferts, T.P. Heavner, S.E. Barlow, N. Ashby
NIST – Time and Frequency Division
Boulder, CO USA 80305
E-mail: steven.jefferts@nist.gov

With several Primary Frequency Standards (PFS) across the world demonstrating systematic fractional frequency uncertainties on order of 1×10^{-16}, it is crucial to accurately measure or model even small frequency shifts that could affect the ultimate PFS uncertainty, and thus ultimately impact the rate of Coordinated Universal Time (UTC). Recently there has been controversy about the physical causes and size of PFS frequency shifts due to microwave lensing effects. We present here the first measurements of microwave lensing frequency shifts in the PFS NIST-F1 and NIST-F2. The measured frequency shifts agree well with the recent theory of Ashby et al [1]. The method used here to measure and correct the frequency bias: measuring frequency shifts at elevated odd-integer multiples of the optimum microwave levels and using a regression to estimate the shift at optimum microwave amplitude is a correct and robust method of dealing with this systematic frequency shift. Given the current state of the art of the theory of the lensing shift, we believe it is crucial to measure, rather than calculate, this shift.

The preliminary measurement of the lensing shift in NIST-F1 and NIST-F2 gives $\delta\nu/\nu_o = 0.028 \pm 0.09 \times 10^{-15}$. This is to be compared to the estimate given by Ashby of $\delta\nu/\nu_o = 0.027$ [1] and Gibble of $\delta\nu/\nu_o = 0.09$ [2]. The data is presently not able to robustly distinguish between the two theories, but, as we discuss below, neither theory is sufficiently complete as to allow a precise calculation of this effect.

Existing theories of the microwave lensing bias share a common defect; they predict a frequency shift due to lensing which results from purely mechanical "clipping" of a portion of the atomic wavepacket for a particular atom. Essentially, most atoms have their wavefunctions clipped and both superposition components of the wavefunctions are clipped almost (but not quite) equally. Such purely mechanical clipping is, of course, only a mathematical artifice; physically, any such clipping is presumably the product of an interaction between the atom and the aperture doing the clipping and the resulting interaction Hamiltonian must be evaluated. Because one of the two microwave superposition states is clipped a small amount more than the other, a small differential phase shift between the two superposition states could easily be imposed by the clipping process. As a result of this imposed phase shift, both the scale and sign of the lensing shift could be vastly different from those predicted in [1,2]. It would seem therefore that the lensing shift cannot be calculated with sufficient robustness to be confidently used in a PFS at the present state of the theories.

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Frequency comparisons of Sr, Yb and Hg based optical lattice clocks in the lab and between the labs

H. Katori[1,2,3,4], **I. Ushijima**[1,2,4], **M. Das**[1,2,4], **N. Nemitz**[1], **T. Ohkubo**[1,2,3], **K. Yamanaka**[1,2,3], **N. Ohmae**[1,2,3], **T. Pruttivarasin**[1], **T. Takano**[2,3], **S. Okaba**[2,3], **T. Akatsuka**[1,2,4], **A. Yamaguchi**[1,2,4] **and M. Takamoto**[1,2,4]

1. Quantum Metrology Laboratory, RIKEN, Wako, Saitama 351-0198, Japan.
2. Innovative Space-Time Project, ERATO, Japan Science and Technology Agency, Bunkyo-ku, Tokyo 113-8656, Japan.
3. Department of Applied Physics, Graduate School of Engineering, The University of Tokyo, Bunkyo-ku, Tokyo 113-8656, Japan.
4. RIKEN Center for Advanced Photonics, Wako, Saitama 351-0198, Japan.

E-mail: katori@amo.t.u-tokyo.ac.jp

We report recent progress of optical lattice clocks [1] with neutral strontium (^{87}Sr), ytterbium (^{171}Yb) and mercury (^{199}Hg) atoms. In particular, we present frequency comparison between the clocks locally via an optical frequency comb and between two Sr clocks at Riken and the University of Tokyo using a phase-stabilized fibre link [2]. We first describe cryogenic Sr optical lattice clocks [3] that reduce the room-temperature blackbody radiation shift by two orders of magnitude and serve as a reference in the following clock comparisons. Similar physical properties of Sr and Yb atoms, such as transition wavelengths and vapour pressure, have allowed our development of a compatible clock for both species [1]. A cryogenic Yb clock is evaluated by referencing a Sr clock. We also report on an Hg clock [4], which shows one order of magnitude less sensitivity to blackbody radiation, while its large nuclear charge makes the clock sensitive to the variation of fine-structure constant. Connecting all three types of clocks by an optical frequency comb, the ratios of the clock frequencies are determined with uncertainties smaller than possible through absolute frequency measurements. Finally, we address a synchronous frequency comparison [2] between two Sr-based remote clocks over a distance of 15 km between RIKEN and the University of Tokyo, as a step towards relativistic geodesy.

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High-stability Yb optical lattice clock with 10^{-18}-level uncertainty

A. D. Ludlow[1], **K. Beloy**[1], **N. Hinkley**[1,2], **M. Schioppo**[1], **T. H. Yoon**[1,3], **R. Brown**[1], **W. F. McGrew**[1], **N. B. Phillips**[1,4], **J. A. Sherman**[1], **and C. W. Oates**[1]

1. Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado USA
2. Department of Physics, University of Colorado, Boulder, Colorado USA
3. Department of Physics, Korea University, Seoul, Korea
4. Stable Laser Systems, Boulder, Colorado USA

E-mail: ludlow@boulder.nist.gov

In recent years, optical lattice clocks have demonstrated the ability to reach fractional instability at the 10^{-18} level [1,2,3]. Such measurement instability plays a vital role in the detailed characterization of systematic effects influencing the lattice clock. We report on a systematic evaluation of the NIST Yb optical lattice clock with a total uncertainty at the 10^{-18} level, and detail the experimental measurements which support this uncertainty. Utilizing an enhancement cavity, we have quantified lattice Stark shifts over a wide range of trap depths, yielding a precise measure of both hyperpolarizability and scalar polarizability effects. The cold atom sample is enclosed in a room-temperature blackbody shield, thereby enabling determination of the BBR Stark shift with an environmental uncertainty of 5×10^{-19}[4]. This enclosure also functions as a Faraday shield against stray electric fields. With the ability to apply high voltage potentials directly to the shield windows, we have experimentally confirmed that stray DC Stark shifts are consistent with zero at a level of $\leq 4\times10^{-19}$. Weak transversal confinement in the optical lattice and ultracold atomic temperatures (2-3 μK) which suppress p-wave atomic interactions [5] limit density-dependent shifts to the 10^{-18} level. Residual first-order Doppler effects due to lattice phase variations are measured and then nulled with active compensation. Furthermore, we have performed improved measurements of the probe AC Stark shift and second-order Zeeman shift. Comparative measurements between two Yb optical lattice clocks will also be reported at the 10^{-18} level. Finally, the implementation of an improved optical local oscillator for the clock transition at 578 nm will be described, towards achieving a clock frequency instability of $\leq 1\times10^{-16}/\tau^{½}$, for averaging time *t*.

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Hg optical lattice clock

S. Bize, M. Favier, L. De Sarlo, R. Tyumenev
1. LNE-SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, 61 avenue de l'Observatoire, 75014 Paris, France
Email: sebastien.bize@obspm.fr

(Note: this is the abstract for an already invited presentation)

Among the different atomic species considered for optical clocks, neutral mercury has several favorable atomic properties that reduce the impact of systematic effects currently limiting the accuracy of optical lattice clocks. The $^1S_0 - {}^3P_0$ clock transition in Hg is weakly coupled to thermal radiation and to static electric fields. For instance blackbody radiation sensitivity in Hg is a factor of ~30 less than in Sr. Mercury has a high vapor pressure at room temperature, which allows eliminating large temperature gradients in the experimental setup due to heating systems. Furthermore the isotope 199 has a spin ½ which suppresses several systematic effects related to the lattice trap. Finally Hg atoms can be laser-cooled to rather low temperature of 30 μK with a single stage magneto optical trap (MOT), performed directly on $^1S_0 - {}^3P_1$ intercombination transition, and then straightforwardly loaded in the optical lattice. Mercury has 7 naturally occurring isotopes which are potentially interesting for a clock and more generally, for atomic physics. For applications in fundamental physics tests, mercury has a fairly high sensitivity to a variation of the fine-structure constant α.

The biggest challenges in the Hg-based optical lattice clock operation lie in the requirement of the three UV lasers (253.7 nm, 265.6 nm and 362.5 nm for cooling, probing, and trapping at the magic wavelength, respectively) and in the reduced polarizability that makes obtaining deep lattice trap comparatively harder. In spite of these challenges, we have completed many of the steps towards the realization of a high accurate Hg optical lattice clock. We will report on this work and on the recent experiments with our Hg optical lattice clock. This includes magneto-optic trapping and laser cooling, development of a highly stable interrogation laser linked to primary references, lattice trapping of mercury. We have demonstrated Lamb-Dicke spectroscopy of the clock transition and the experimental determination of the magic wavelength. We made the first absolute frequency measurement of the Hg lattice clock against atomic fountains at this level to an uncertainty of 5.7 parts in 10^{15}. We will report on our latest work toward higher uncertainties and optical-to-optical frequency comparisons with Sr lattice clocks.

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High accuracy atomic clock and its probe of quantum many-body physics

J. Ye, M. Bishof, B. J. Bloom, S. L. Bromley, S. L. Campbell, R. B. Hutson, G. E. Marti, R. L. McNally, T. L. Nicholson, J. R. Williams, W. Zhang, and X. Zhang
JILA, National Institute of Standards and Technology and University of Colorado,
440 UCB, Boulder, CO 80309-0440, USA
E-mail: Ye@jila.colorado.edu

Using a highly stable laser (1×10^{-16} stability from 1 to 1000 s) [1] to probe 2000 Sr atoms confined in a zero-differential ac Stark shift optical lattice, we achieve optical atomic clock stability of $2.2 \times 10^{-16}\ \tau^{-1/2}$ versus averaging time τ. With this stability, we have performed a new round of systematic evaluation of the JILA Sr clock, improving many uncertainties that limited our previous measurements [2]. For the lattice laser ac Stark uncertainty, we identify the operating optical frequency where the scalar and tensor components of the shift cancel, allowing for state-independent trapping with clock shifts at the 1×10^{-18} level. For the blackbody radiation-induced frequency shift uncertainty, we control and monitor the atoms' thermal environment using accurate radiation thermometry, which is traceable to the NIST ITS-90 absolute temperature scale [3]. We also directly measure the component of the strontium atomic structure that is responsible for the spectral response to room-temperature BBR. We have thus reduced the total uncertainty of the JILA Sr clock to 2.1×10^{-18} [4]. The clock precision has opened a new platform to explore a strongly interacting spin system. Our collective spin measurements reveal signatures of the development of many-body correlations during the dynamical evolution [5], including non-equilibrium two-orbital SU(N) magnetism when we open the system to as many as 10 nuclear spin sublevels [6].

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Atom interferometry, optical atomic clocks and gravitational wave detection

P. Assenbaum, C. Donelly, N. Engelsen, O. Hosten, T. Kovachy, R. Krishnakumar, C. Overstreet, J. Hogan and M. Kasevich

Department of Physics, Stanford University, Stanford, CA

Advances in atomic physics and optical physics have provided tools which enable new classes of precision measurements. These tools include atom interferometry, where quantum mechanical interference of atomic de Broglie waves enables precise force measurements, and ultra-stable lasers, which have led to a generational advance in the performance of clocks. The marriage of these methods will result in a next generation of ultra-precise inertial sensors superbly suited to gravitational wave detection and geodesy [1,2]. A space-based implementation can operate with two, rather than three, satellite stations, substantially simplifying the system architecture over conventional optical approaches (see Fig. 1). In this talk, we will describe the basic approach and indicate the atomic physics technology status. In particular, we will describe recent experiments which have demonstrated de Broglie wave interference for atomic wavepackets separated by 54 cm, and squeezed state metrology which has realized a 20 dB improvement beyond the quantum projection noise limit.

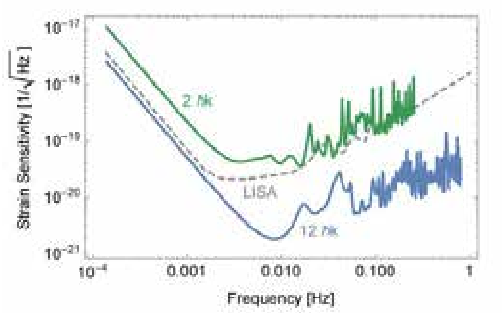

Fig. 1. Strain sensitivity for the proposed gravitational wave detectors, as described in Ref. 1. Green: 2 photon recoil atomic Sr, $2x10^9$ m baseline. Blue: 12 photon recoil atomic Sr, $6x10^8$ m baseline. The strain responses have been averaged over gravitational wave propagation direction and polarization, and several interferometer interrogation times.

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Metrology with atom interferometers: inertial sensors from the laboratory to the field

A. Landragin, I. Dutta, P. Gillot, D. Savoie, B. Cheng, B. Fang, C. Garrido Alzar, R. Geiger, S. Merlet and F. Pereira Dos Santos

LNE-SYRTE, Observatoire de Paris, CNRS et UPMC, 75014 Paris, France
E-mail: arnaud.landragin@obspm.fr

Since more than twenty years, atom interferometry has been developed as a remarkable tool for fundamental physics in laboratories. Their constant sensitivity improvement foresees new applications with very large experiments on ground or space. Nevertheless, most of these experiments realize differential measurements between two accelerometers and escape, at least in a partial way, to the problem of the aliasing of the high frequency vibration noise, which in practice limits their sensitivity. Furthermore, they do not take advantage of the intrinsic control and knowledge of the scaling factors of atom interferometers, which gives them unmatched properties for metrology of inertial forces.

The gravimeter is now obviously the best example of metrology with a atom interferometer. As an example, the SYRTE gravimeter has been developed in the frame of the French watt balance to be used as an accurate gravimeter (called "absolute" gravimeter in geophysics) [1]. Based on the manipulation of Rb cold atoms by two photon Raman transitions, it can be considered as a standard in gravity measurement. We have realized a very careful analysis of systematics errors taking into account the atom-laser interactions and their imperfections in a practical experiment. The device has been made transportable in order to participate to comparisons with classical devices, including 3 key comparisons, which have validated the accuracy budget. It can be consider as the state of the art in gravimetry with record sensitivities at short and long terms [2]. Concurrently, development of architectures and concepts for compact gravimeters [3] opens the way for field and onboard applications for geophysics or inertial guidance.

Gyroscopes are the other type of inertial sensors having already demonstrated performances close to the state of the art. Nevertheless, improvement of the long term stability is still needed to be competitive. We will present first results of our very large atom gyroscope based on Sagnac effect for matter-wave in a four pulse configuration and which benefits from an total area of 11 cm^2 (about 30 time larger than ever demonstrated). It has already demonstrated record performances at short and long term for a cold atom gyroscope [4]. Large sensitivity enhancement is under study and is based on method of joint interrogation in a single atom interferometer, which overcomes the dead time between consecutive measurements [5].

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Mobile atom interferometer for absolute gravity measurements

A. Peters[1], C. Freier[1], M. Hauth[1], V. Schkolnik[1], B. Leykauf[1], M. Schilling[2], H. Wziontek[3], H.G. Scherneck[4]

1. Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
2. Institut für Erdmessung, Leibniz Universität Hannover, Hannover, Germany
3. Bundesamt für Karthographie und Geodäsie (BKG), Leipzig, Germany
4. Onsala Space Observatory, Chalmers University of Technology, Gothenburg, Sweden

E-mail: achim.peters@physik.hu-berlin.de

Since their first realization in the 1990s, one of the main applications for atom interferometers (AI) have been precision gravity measurements [1]. The Gravimetric Atom Interferometer (GAIN) is a transportable experiment designed to perform gravity measurements with high sensitivity and accuracy. It is based on interfering ensembles of laser-cooled ^{87}Rb atoms in an atomic fountain configuration and stimulated Raman transitions. The Mach-Zehnder type interferometer sequence with a relatively large pulse separation time up to 0.3s was chosen to maximize the sensitivity to accelerations while at the same time simplifying the treatment of systematic effects in order to optimize accuracy.

After discussing our setup, we show gravity data from two measurement campaigns carried out in Wettzell, Germany and in Onsala, Sweden. Up to 10 days of gravity recordings were compared to superconducting relative gravimeters (SG) on site. The data show excellent agreement between both instruments and indicate a relative stability of 7×10^{-11} g. The absolute gravity value obtained from the 2nd campaign deviates by $7\pm7\times10^{-9}$ g from a simultaneous measurement by a state-of-the-art commercial absolute gravimeter, which is comparable to the results achieved by other mobile AI [2]. These results show that AI are now suitable for applications previously limited to superconducting gravimeters.

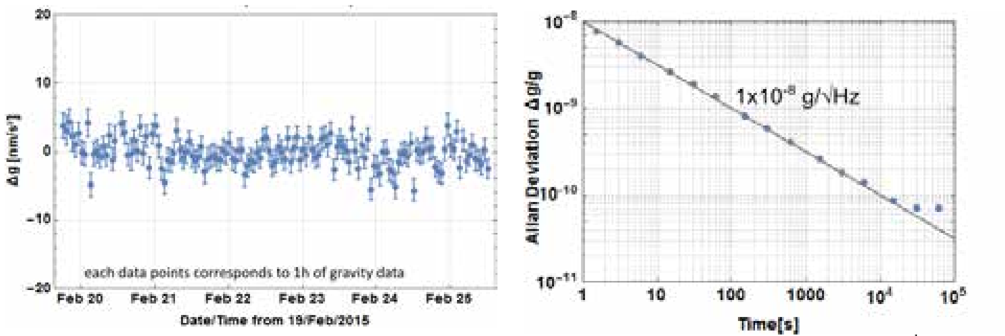

Fig. 1: Preliminary version of the residual gravity signal after subtraction of SG data, taken during the 2nd campaign in Sweden. We suspect that the noise floor in the Allan deviation will disappear after a more thorough analysis.

Both long-term stability and accuracy indicate effective control of systematics present in the system. The largest remaining effect is caused by wavefront distortions caused by optical elements in the Raman beam path. We also show a novel approach to reduce its impact by probing the Raman wavefront using a Shack-Hartmann sensor and calculating the resulting interferometer phase shift.

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The NIST Al^+ quantum-logic clock*

S. M. Brewer[1,2], J. S. Chen[1], D. B. Hume[1], C. W. Chou[1], A. M. Hankin[1], J. C. Bergquist[1], D. J. Wineland[1], T. Rosenband[1,3], and D. R. Leibrandt[1]

1. National Institute of Standards and Technology, Boulder, CO 80305, USA
2. Massachusetts Institute of Technology, Cambridge, MA 02139, USA
3. Harvard University, Cambridge, MA 02138, USA

E-mail: david.leibrandt@nist.gov

Optical atomic clocks based on quantum-logic spectroscopy of the $^1S_0 \leftrightarrow {}^3P_0$ transition in $^{27}Al^+$ have reached a systematic fractional frequency uncertainty of 8.6×10^{-18} [1], enabling table-top tests of fundamental physics [2] as well as measurements of gravitational potential differences and relativistic time dilation [3]. The clock transition in $^{27}Al^+$ has the lowest known sensitivity to blackbody radiation of any atom currently considered for optical clocks. A recent measurement of this sensitivity has further reduced our overall systematic uncertainty to 8.0×10^{-18}. Currently, the largest limitations to the accuracy are second order time dilation shifts due to the driven motion (i.e., micromotion) and thermal motion of the trapped ions.

We are developing a third-generation $^{27}Al^+$ quantum-logic clock with the goals of portability and reduced systematic uncertainty. In order to suppress the time dilation shifts, we have designed and built a new ion trap based on a gold-plated, laser-machined diamond wafer with differential RF drive (see Fig. 1). Furthermore, we have performed and optimized low-duty-cycle sympathetic Raman sideband cooling suitable for maintaining the $^{27}Al^+$ / $^{25}Mg^+$ crystal in its six-mode motional ground state during clock operation.

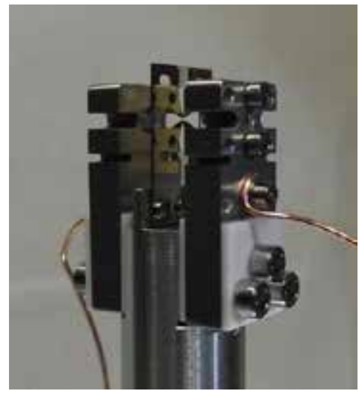

Fig. 1: New ion trap based on a gold-plated, laser-machined diamond wafer (center) with two machined endcaps electrodes (left and right sides).

Applications in geodesy will require that such clocks be robust and packaged so that they can be deployed to, and operated at, sites of interest outside the laboratory. To this end, we have built and operated an $^{27}Al^+$ clock using a robust, portable clock laser based on a spherical Fabry-Pérot cavity with a thermal noise limited instability of 1.2×10^{-15} and an acceleration sensitivity below 10^{-12} g^{-1} [4]. In this talk, we present details of the trap design and operation as well as a preliminary characterization of the clock performance.

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Sr^+ single ion clock

P. Dubé[1], A.A. Madej[1,2], and B. Jian[1,2]

1. Measurement Science and Standards, National Research Council, Ottawa, ON, Canada
2. Department of Physics and Astronomy, York University, Toronto, ON, Canada

E-mail: pierre.dube@nrc-cnrc.gc.ca

For the last number of years, our group at the National Research Council of Canada has developed an optical frequency standard based on the $5s\,^2S_{1/2}-4d\,^2D_{5/2}$ transition of a single trapped ion of $^{88}Sr^+$. The fractional frequency uncertainty of the *S–D* transition has been reduced by four orders of magnitude since 2004, from 1×10^{-13} to 1×10^{-17} [1].

No matter the system chosen, there are a number of important systematic shifts that must be understood and controlled in order to achieve the extremely low uncertainty levels currently reported in the literature. For the $^{88}Sr^+$ ion, the main ones are the time dilation shift, the scalar Stark shift, the electric quadrupole shift, the tensor Stark shift, and the blackbody radiation (BBR) shift. Several measures were implemented to control them, some of the most effective rely on intrinsic properties of the clock transition. The micromotion-induced time dilation and Stark shifts are reduced to about 10^{-17} in our system by carefully positioning the ion in the trapping field, achieved by measuring and minimizing micromotion in three dimensions. Further reduction of those shifts is obtained by observing that the scalar Stark shift and the time dilation shift caused by micromotion are perfectly correlated and of opposite sign. By tuning the trap frequency to adjust the time dilation shift to match in magnitude the scalar Stark shift, a reduction by a factor of >200, to the 10^{-19} level, is obtained. The cancellation effect is illustrated in Fig. 1. The data of Fig. 1 was also used to determine to high-accuracy the differential scalar polarizability coefficient, $\Delta\alpha_0$, of the clock transition. This coefficient determines the response of the clock transition to the BBR field. The contribution of $\Delta\alpha_0$ to the uncertainty of the BBR shift has been reduced from 2×10^{-17} to 8.3×10^{-19} with the data shown in Fig. 1 [1]. The electric quadrupole and tensor Stark shifts are canceled very effectively by measuring continuously several pairs of Zeeman components. The most important remaining source of uncertainty is currently the evaluation of the BBR field at the ion, at a level of $\approx 1\times10^{-17}$. Its improved evaluation is expected to reduce the total fractional frequency uncertainty of the $^{88}Sr^+$ ion system to $\lesssim 3\times10^{-18}$.

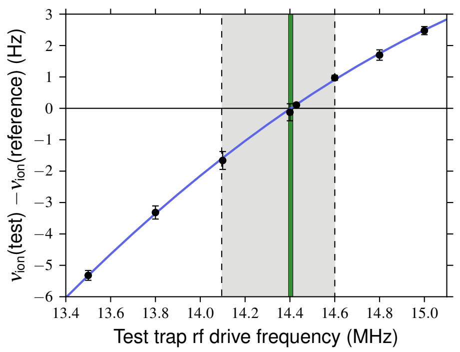

Fig. 1: Comparison of the clock transition frequency of two single $^{88}Sr^+$ ion traps, as a function of the rf drive frequency of the test trap [1]. The test trap has high micromotion shifts that are revealed by a frequency shift between the two ions and a variation with drive frequency. The narrow vertical band shows the experimental determination of the drive frequency where the shifts cancel each other. The gray area is the predicted zone for the cancellation based on state-of-the-art theoretical calculations [2].

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Agreement of two $^{40}Ca^+$ optical clocks at 10^{-17} level

Yao Huang, Wu Bian, Pei-Liang Liu, Hua Guan and Ke-Lin Gao*

Wuhan Institute of Physics and Mathematics (WIPM), Chinese Academy of Sciences, Wuhan 430071, China

*E-mail: klgao@wipm.ac.cn

Frequency comparison is one of the most efficient ways to evaluate the performance of a frequency standard, both for testing the stability and the reproducibility. Besides, from the comparison, we can test the systematic evaluation of the clocks. Based on the pre-existing $^{40}Ca^+$ optical frequency standard (ion trap-I) [1, 2], we set up the second $^{40}Ca^+$ optical frequency standard (ion trap-II), which has been improved in the materials and structure of ion trap for better control of the magnetic field. For the ion trap-II is driven by a rf source with an amplitude Vp-p of ~1200 V and a frequency of ~2π × 24.7 MHz at which the rf-induced Stark shifts and second-order Doppler shifts cancel each other [3]. We compensated precisely the ion's micromotion in both ion traps by the rf-photon correlation technique [4] and monitoring the image of the ion with an electron-multiplying coupled-charge device camera (EMCCD).

The systematic uncertainties of both traps have been evaluated at 10^{-17} level. The results for the frequency comparison between two clocks are shown in Fig. 1(a). Corrected with the systematic shifts, the weighted average frequency difference between the two clocks is -3(8) mHz. Considering this statistical uncertainty (type A) of 8 mHz (1.9×10^{-17}) together with the systematic uncertainty (type B) of 21 mHz (5.1×10^{-17}), the total uncertainty for the comparison is 23 mHz (5.5×10^{-17}). For the longest continuous data sets (>2 days) the Allan deviation of the frequency difference between two traps is shown in Fig. 1(b). Considering the common mode contribution for both clocks are small relative to the total uncertainty, the Allan deviation for the frequency difference between the two clocks is simply divided by $\sqrt{2}$ to represent the stability for the single clock. The new result is about 37 times better than the comparison result of ion trap-I and the Hydrogen maser published in our previous work [1]. The absolute frequency of the clock transition is revised to be 411 042 129 776 401.7(1.1) Hz.

(a) (b)

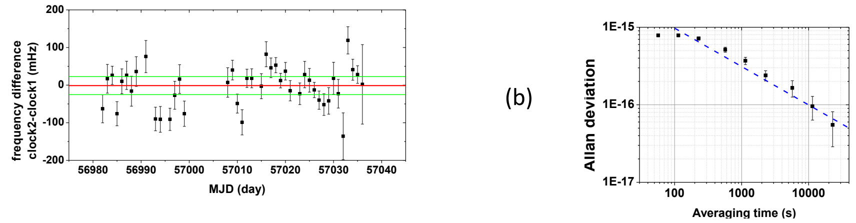

Fig. 1(a) Two-trap frequency comparison data from Nov. 2014 to Jan. 2015. The mean frequency difference between the traps of -3(8) mHz (straight lines) is within the measurement uncertainties. The mean frequency is indicated by the red line and the uncertainties by green lines; (b) Standard Allan deviation of the frequency difference between the two $^{40}Ca^+$ clocks divided by $\sqrt{2}$ to reflect the performance of a single clock. The dash blue line represents an instability of $\sigma = 1\times10^{-14}\tau^{-1/2}$.

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The $^{171}Yb^+$ single-ion optical clocks

N. Huntemann, C. Sanner, B. Lipphardt, Chr. Tamm, V. Gerginov, S. Weyers, E. Peik
Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
E-mail: nils.huntemann@ptb.de

$^{171}Yb^+$ provides two reference transitions that are adequate for the realization of an optical frequency standard: the $^2S_{1/2}(F=0)\rightarrow{}^2D_{3/2}(F=2)$ electric quadrupole (E2) transition at 436 nm and the $^2S_{1/2}(F=0)\rightarrow{}^2F_{7/2}(F=3)$ electric octupole (E3) transition at 467 nm.

The E2 transition allows us to precisely determine magnetic and electric fields as well as to characterize residual motion of the single laser-cooled $^{171}Yb^+$ ion in our trap. However, its natural linewidth of 3 Hz limits the achievable frequency stability of the optical frequency standard. We have evaluated all relevant frequency shift effects and found the fractional systematic uncertainty of the frequency standard to be 1×10^{-16}, dominated by the uncertainty of the blackbody radiation shift [1].

For the realization of a frequency standard with very small systematic uncertainty the E3 transition is advantageous due to its significantly lower sensitivity to electric and magnetic fields [2]. Furthermore it has a natural linewidth in the nHz-range that provides the potential for very high stability. Because of its extremely small oscillator strength the excitation requires very high intensity which in turn introduces a significant light shift. To avoid this frequency shift, we have implemented the Hyper-Ramsey excitation scheme with a pulse sequence that is tailored to produce a resonance signal that is immune to such frequency shifts during the interrogation pulses [3]. Our experiments demonstrate a suppression of the light shift by four orders of magnitude and immunity against its fluctuations [4]. For the operation as a frequency standard, a servo system corrects for variations of the light shift to ensure its suppression and the related uncertainty becomes negligible. A measurement of the static differential polarizability of the E3 transition with an uncertainty of less than 2% based on light shift measurements with near-infrared lasers and an improved knowledge of the thermal radiation affecting the ion allow us to correct the blackbody radiation shift with an fractional uncertainty of less than 2×10^{-18} that reduces the total systematic uncertainty to 3×10^{-18}.

Repeated frequency measurements over the recent years of the two transitions of $^{171}Yb^+$ against caesium fountain clocks with uncertainties as small as 4×10^{-16} provide a stringent constraint on a temporal variation of the proton-to-electron mass ratio [5].

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Optical Frequency Combs: From Lab Scale to Chip Scale

Scott A. Diddams[1]
1. Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO USA
E-mail: scott.diddams@nist.gov

In the past fifteen years we have witnessed significant advances associated with the frequency stabilization of the comb present in the output of a mode-locked femtosecond laser. While proving itself to be fantastically successful in its role as the "gears" of optical atomic clocks, the optical frequency comb has further evolved into a valuable tool for a wide range of applications, including ultraviolet and infrared spectroscopy, frequency synthesis, optical and microwave waveform generation, astronomical spectrograph calibration, and attosecond pulse generation, to name a few [1,2]. In this talk, I will trace our progress on a few of these applications, and highlight the frequency comb advances that have made them possible. In addition, I will attempt to offer a perspective on the challenges and opportunities for frequency combs that might lie ahead. Along these lines, I will describe research into a new class of parametric frequency combs that are based on monolithic microresonators [3,4]. Such microcomb devices are compatible with semiconductor processing and could be further integrated with other photonic and electronic components on a silicon chip. In the future, such technology may bring the precision, flexibility, and measurement power of frequency combs to a wide range of new and emerging applications beyond the confines of the metrology laboratory.

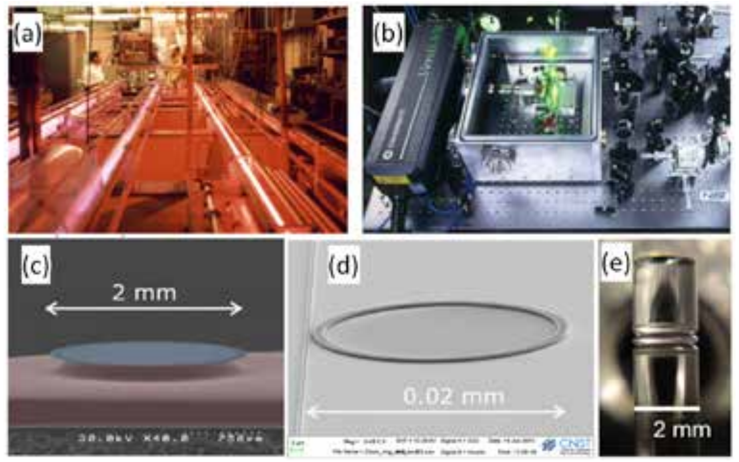

Fig. 1: Optical frequency metrology tools over the past 40 years. (a) Harmonic frequency chain of the 1980s that filled an entire lab; (b) Ti:sapphire laser frequency comb in 2000 that easily fit on a 1 m^2 breadboard; (c)-(e) examples of microresonators from circa 2010 that are the basis of millimeter and sub-millimeter chip-scale frequency combs.

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Ramsey-comb spectroscopy in the deep ultraviolet

R.K. Altmann[1], S.A. Galtier[1], L.S. Dreissen[1], K.S.E. Eikema[1]
1. LaserLaB Amsterdam, VU University, Amsterdam, Netherlands
E-mail: k.s.e.eikema@vu.nl

Quantum-Electrodynamics theory (QED) is one of the best-tested theories based on e.g. precision spectroscopy in atomic hydrogen on the 1S-2S transition. However, spectroscopy of muonic-hydrogen (2S-2P) has lead to sizeable discrepancies between theory and experiment, resulting in the so called 'proton-size puzzle' [1]. One possibly way to investigate this conundrum is to perform 1S-2S spectroscopy on the helium-ion and compare this with measurements on muonic helium-ions. Experimentally, however, helium+ spectroscopy poses a great challenge as it requires wavelengths in the extreme-ultraviolet to excite the 1S-2S transition.

We developed a new method aimed to overcome these challenges, based on pairs of amplified frequency-comb laser pulses (see Fig. 1). Amplified (~ mJ) frequency comb pulses can easily be upconverted using frequency-doubling or high-harmonic generation. Excitation with the two of those pulses then resembles a Ramsey-type experiment. By combining Ramsey signals at different macroscopic delays (multiples of the repetition time, see bottom half of Fig. 1), a Ramsey-comb signal is produced from which we can recover the full frequency comb accuracy and resolution. We demonstrated this for near-infrared wavelengths with 5 kHz accuracy [2,3] on Rb and are currently extending it to shorter wavelengths by two sequential stages of frequency doubling in BBO. First results are presented of Ramsey-comb excitation on a two-photon transition ($4p^6$ - $4p^5 5p[1/2]_0$) in Krypton at 212 nm in a counter-propagating configuration. Assessment of the systematic effects is in progress, but we expect a final accuracy of about 50-100 kHz. This would be an improvement of nearly two orders of magnitude on this transition, limited mainly by the excited state lifetime of 26 ns.

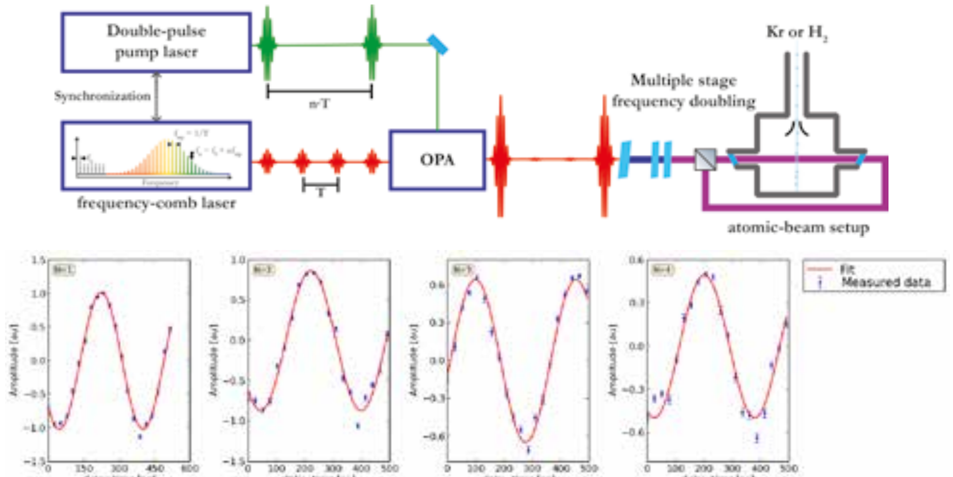

Fig. 1 Top half: Schematic of the Ramsey-comb setup in the deep-UV. Bottom half: Ramsey-comb Kr signal on a two-photon transition at 2x212 nm; x-axis relative to a course delay of T=8, 16, 24, and 32 ns.

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Frequency transfer in the optical domain with uncertainty of 1.5×10^{-20}

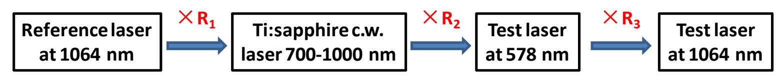
Yuan Yao[1], Yanyi Jiang[1], Hongfu Yu[1] , Zhiyi Bi[1], Longsheng Ma[1]*

1. State Key Laboratory of Precision Spectroscopy, East China Normal University, Shanghai, China
E-mail: lsma@phy.ecnu.edu.cn

In the past years, optical atomic clocks have made significant progress with fractional uncertainties at the 10^{-18} level. Using optical clocks, scientists can search for possible variations of fundamental constants in laboratories, re-define the unit of time and test fundamental physics. All these applications need precise transfer of a clock frequency to another without degrading its stability, accuracy and coherence. Two methods of frequency transfer were demonstrated by using optical frequency combs. One way, an optical frequency comb is phase-locked to a reference laser precisely. Then a slave laser is phase-locked to a selected comb tooth. Frequency transfer instability is demonstrated to be 8×10^{-18} at 1 s [1]. For another, an optical frequency comb is used as a transfer oscillator [2]. Frequency transfer instability is reduced to 4×10^{-18} at 1 s and 1×10^{-19} at 1000 s [3].

Here we combine the above two methods. Using an optical frequency comb as a transfer oscillator, the performance of a cavity-stabilized reference laser at 1064 nm is transferred to a Ti:sapphire c.w. laser with tuning range of 700-1000 nm. In the transfer oscillator scheme, the error signal for phase locking is immune to the frequency noise of the comb. However, due to the time delay of the DDSs, the fast varying signals input to DDSs affects the performance of frequency transfer. Therefore, we also phase-locked the comb to the reference laser to make the input signals of the DDSs relatively stable. Meanwhile, using an optical down-converted RF signal from the reference laser with the comb and DDSs as the time base of all RF synthesizers, the frequency of the slave lasers depends only on the reference laser frequency with a frequency transfer ratio of R_1.

To characterize frequency transfer instability and accuracy, the performance of the Ti:sapphire laser is further transferred to two other test lasers in sequence, as shown in the figure. By comparing the last test laser with the reference laser at 1064 nm, frequency transfer instabilities of 7.6×10^{-19} at 1 s and 2.7×10^{-20} at 1000 s are demonstrated. An uncertainty of 1.5×10^{-20} for frequency transfer ratio is obtained.



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Spectrally Pure Kerr Comb RF Photonic Oscillators

L. Maleki, W. Liang, D. Eliyahu, A. Savchenkov, V. Ilchenko, A. Matsko
OEwaves Inc., 465 N. Halstead Str., Pasadena, CA 91107, U.S.A.
E-mail: andrey.matsko@oewaves.com

Seven years ago at the 7th Symposium on Frequency Standards and Metrology we presented the first experimental and theoretical study of RF photonic oscillators based on Kerr frequency comb generators. We showed that pumping a monolithic resonator with strong enough continuous wave coherent light results in appearance of optical sidebands around the optical carrier. The pumping threshold of the oscillation can be in a few microWatt range for resonators with ultra-high quality factors, greater than 10^9. Natural cascading of the nonlinear hyperparametric process leads to mode locking of the sidebands and emergence of an optical frequency comb. Demodulation of the comb by means of a fast photodiode produces a high frequency spectrally pure RF signal, the frequency of which is given by the resonator morphology. We also noted that damped driven nonlinear Schrodinger equation can be used to describe the frequency comb oscillator theoretically. In this presentation we will discuss recent advances in both theory and experiment resulting in development of higher performance RF photonic oscillators.

We have demonstrated a free running 10 GHz microresonator-based RF photonic oscillator characterized with phase noise better than -65 dBc/Hz at 10 Hz, -90 dBc/Hz at 100 Hz, and -155 dBc/Hz at 10 MHz (see Fig. 1). The device consumes less than 25 mW of optical power. We found a correlation between the frequency of the continuous wave laser pumping the nonlinear resonator and the generated RF frequency. The performance of the device is comparable with the performance of a standard optical fiber-based coupled opto-electronic oscillator developed at OEwaves. The measured performance is limited by our phase noise measurement system.

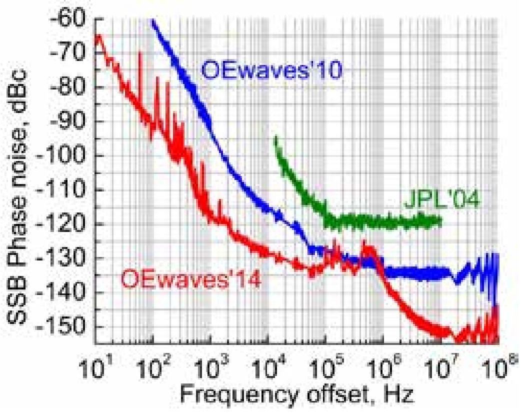

Fig. 1: A picture illustrating progress in development of low phase noise of 10 GHz RF photonic oscillator during last decade at JPL/OEwaves Inc.

The oscillator is based on locking a semiconductor pump laser to a microresonator mode using self-injection technique. We found that the optical frequency and the comb repetition rate frequencies drift together and the ratio of their drifts was constant and equal to the ratio of the free spectral range of the resonator and optical frequency. We demonstrated that the close-in phase noise of the laser and the oscillator are both limited by the thermal drift of the resonator mode. The degree of correlation has to be studied in more details. However, even at this point, we were able to conclude that the close-in phase noise of the RF photonic oscillator was strongly influenced by the thermal drifts of the WGM resonator, and that stabilization of the resonator temperature should reduce the noise. We stabilized the resonator temperature by locking the resonator mode to Rb transition via the pump laser and confirmed this prediction.

Relativistic Geodesy

J. Flury[1] and the geo-Q team
1. Institut für Erdmessung, Leibniz Universität Hannover
E-mail: flurry@ife.uni-hannover.de

Quantum techniques enable new applications in geodesy. The recent progress in optical atomic clocks and in long-distance frequency transfer by optical fiber together pave the way for using measurements of the gravitational frequency redshift for geodesy. The remote comparison of frequencies generated by calibrated clocks will allow for a relativistic determination of differences in gravitational potential and height between stations on Earth surface (chronometric leveling). On the long run, this technique could provide the basis for an atomic height reference and a relativistic geoid definition. Complementarily, gravity measurements with atom interferometric setups, and satellite gravimetry with space borne laser interferometers allow for new sensitivities in the measurement of quantities of the Earth's gravity field. We discuss the current status on this field in the Collaborative Research Centre "Relativistic Geodesy and Gravimetry with Quantum Sensors (geo-Q)" of Leibniz Universität, as well as the complementarity of these new techniques for gravitational geodesy.

Frequency metrology using highly charged ions

J. R. Crespo López-Urrutia
Max-Planck-Institut für Kernphysik, Heidelberg, Germany
E-mail: crespojr@mpi-hd.mpg.de

Recently, the sympathetic cooling of highly charged ions (HCI) [1] in a linear RF trap has been demonstrated in our group, thus opening this broad class of spectroscopic targets to high precision frequency metrology. HCI offer a very large number of forbidden optical transitions within their respective ground state configurations, which all show a very large relativistic fine structure splitting. In the case of a few hydrogen-like ions, even optical hyperfine transitions within the *1s* ground state are possible. Due the intrinsically low polarizability of HCI, such transitions are extremely impervious to external perturbations such as black-body radiation shifts. Their Zeeman splitting is, by comparison with the relativistically magnified spin-orbit coupling and corresponding transition frequency, small. Appropriate choices of states with suitable total angular momentum can cancel residual quadrupolar shifts. These properties are very advantageous for their use as frequency standards. Furthermore, the large relativistic, quantum electrodynamic, and nuclear size contributions to the binding energies of the optically active electrons in HCI are beneficial for fundamental investigations, and their application to the study of a possible time variation of the fine structure constant has been suggested by several authors. For these purposes, a cryogenic RF trap, CryPTEx [2] has been developed and operates at the Max-Planck Institute for Nuclear Physics, and upgraded devices are now under construction there for their future use at the Physikalisch-Technische Bundesanstalt.

The electronic structure of complex HCI, exception made of a few isoelectronic sequences, is not very accurately known, and in particular the multitude of forbidden transitions in their ground states has only began to be investigated in the detail needed as a prerequisite for our laser excitation studies [3]. HCI are mostly produced and studied using electron beam ion traps. Systematic studies of the emission spectra of the isoelectronic sequences of interest under electron-impact excitation are needed, since theoretical calculations are very complex and do no yield the needed accuracy. The data obtained on, e. g., M1 and very weak E1 lines at level crossings allows for the determination of the level structure and enables the search for transitions with extremely low decay rates. An example is our analysis of the Ir17+ ion [4], a prime candidate for the search of a time variation of the fine structure constant.

With the rapid development of frequency combs in the vacuum ultraviolet region and possibly beyond, further applications of highly charged ions as frequency standards at higher photon energies – the typical realm of HCI spectroscopy – are under consideration, and experiments are being prepared in our group for exploring those.

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Is the time right for a redefinition of the second by optical atomic clocks?

Patrick Gill
Quantum Metrology Institute, National Physical Laboratory, Teddington, UK
E-mail: Patrick.gill@npl.co.uk

The microwave caesium atomic clock has been the basis for the SI second for almost a half-century. There have been a number of caesium clock technology advances during that time, the most significant of which has been the advent of laser cooling and its role in the development of cold caesium fountain clocks, some of which now achieve systematic frequency uncertainties of ~ $1\text{-}2\times10^{-16}$ and report regularly to the BIPM. Fountain clocks continue to provide the primary means for validation of international timescales such as TAI and UTC, and local dissemination of time and frequency for high technology and industrial applications. However, since the turn of the century, the pace of optical atomic clock R&D has quickened considerably, with result that several optical clock systems based on different atomic species now achieve lower systematic uncertainties than the best fountain clocks. Already fundamental science is benefitting in a number of cases from the lower uncertainties available from optical clocks, and the question of whether the time is right for a redefinition of the second becomes increasingly relevant.

Optical clocks comprise frequency-stabilised lasers probing very weak absorptions either in a single cold ion confined in an electromagnetic trap, or in an ensemble of cold atoms trapped within an optical lattice. Those optical clock species now surpassing the Cs fountain capability include the $^{27}Al^+$, $^{199}Hg^+$, $^{171}Yb^+$ and $^{88}Sr^+$ trapped ion systems and ^{87}Sr, ^{171}Yb atoms in optical lattices, with reported uncertainties in the few $\times10^{-17}$ to few $\times10^{-18}$ range. Currently, benchmark frequency instabilities for single cold ion and multiple atom systems are $\sim3\times10^{-15}\tau^{-1/2}$ and $\sim3\times10^{-16}\tau^{-1/2}$ respectively. Recent ^{87}Sr lattice clock results report a relative frequency uncertainty of $\sim 2\times10^{-18}$ [1].

In preparation for a redefinition of the second, and given the range of high performance clocks of different species being researched in different labs internationally, it is beholden on the frequency standards community to directly intercompare individual systems against each other to provide independent validation, and even to determine whether there is a "best choice" candidate for a redefinition. Several NMIs are pursuing a number of clocks with different species and of course femtosecond combs now readily allow such local intercomparisons between different species clocks in the same institution. It has been demonstrated that such intercomparisons do not compromise uncertainty due to the comparison process, with comparison accuracies of 10^{-21} for optical frequency ratios being achievable, eg.[2]. Further, point-to-point direct intercomparison of remote clocks in different national laboratories using dark fibre or dark channels in fibre has recently become viable [3,4], and a number of direct remote optical clock comparisons are underway. This presentation aims to take stock of the current status of optical frequency standards and clocks, and progress in their direct international intercomparison, and the implications for a redefinition of the second.

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Entanglement with negative Wigner function of almost 3000 atoms heralded by one photon

H. Zhang[1], **R. McConnell**[1], **J. Hu**[1], **S. Ćuk** [1,2], **V. Vuletić**[1]
1. Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, USA
2. Institute of Physics, University of Belgrade, Belgrade, Serbia
E-mail: htzhang@mit.edu

State-of-the-art atomic clocks and many other interferometers based on atomic ensembles are limited no longer by the technical noise, but rather by the fundamental quantum fluctuations of uncorrelated atoms, known as the standard quantum limit (SQL). Entangled states of many atoms can improve measurement sensitivity beyond this limit. Spin-squeezed states [1] have been realized in many experiments, with the best demonstrated spin noise of 10 dB [2] less than the SQL. However, spin-squeezed states have Gaussian spin distributions therefore they can be viewed semi-classically, where the entanglement of atoms enters only to set the amount of Gaussian spin noise. A rich class of entangled states with non-Gaussian distributions, including Schrödinger cat states, can display spin distributions with shaper features for realizing better quantum sensors beyond the SQL. We have recently generated entangled non-Gaussian states of roughly 3000 atoms [3], by interacting atoms with very weak light, and detecting one photon emerging with a certain polarization. By measuring the non-Gaussian spin distributions, a negative Wigner function is reconstructed (Fig 1), manifestly demonstrating that the atoms are entangled. We also show that nearly all of 3000 atoms are involved in the entanglement following a recent work [4] using an entanglement measure known as the entanglement depth. The achieved purity of our entangled state is slightly below the threshold for improving metrology beyond the SQL, but further technical improvement should allow the generation of states that surpass this threshold. Our method can also produce more complex non-Gaussian states including Schrödinger cat states for quantum metrology and information processing.

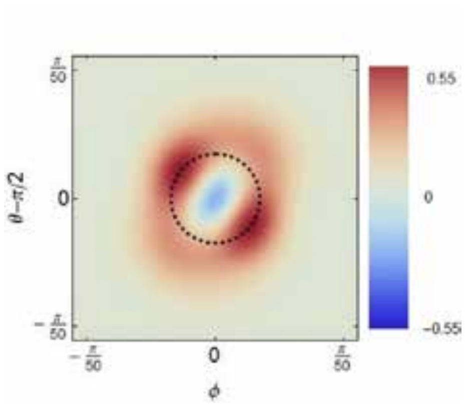

Fig. 1 Reconstructed Wigner function $W(\phi,\theta)$ for the entangled non-Gaussian state on the Bloch sphere, where θ is the polar angle of the Bloch sphere and ϕ is the azimuthal angle. The Wigner function value in the center is -0.27 ± 0.08, compared to $W\left(\frac{\pi}{2},0\right)=1$ for the unentangled coherent spin state. To provide a reference scale for the size of the negative region, the black dashed line shows the contour at which the coherent spin state has a Wigner function value equal to $1/e$.

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Search for the low-energy isomer in ^{229}Th and the nuclear optical clock

E. Peik
Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
E-mail: ekkehard.peik@ptb.de

The existence of a nuclear isomeric state in ^{229}Th at about 8 eV excitation energy has stimulated the development of novel ideas in an unexplored domain of atomic and nuclear physics where the nuclear excitation energy is in the same range as transition energies of valence electrons [1,2]. An optical nuclear clock, using a γ-transition as a reference - instead of a transition in the electron shell - offers advantages like an insensitivity against field-induced systematic frequency shifts and the opportunity to obtain high stability from interrogating many nuclei in the solid state (see [3] for a recent review).

A direct optical detection of the ^{229}Th isomer's excitation or decay is still missing. While the expected natural linewidth is 1 mHz or less, the transition wavelength in the vacuum-ultraviolet is presently known only with a large uncertainty as 160(10) nm. An additional difficulty arises from the fact that ^{229}Th is radioactive so that experiments are restricted to small particle numbers and fluorescence detection in solid samples is often plagued by a background of radio-luminescence.

Our approach to achieve laser excitation of the isomer is to use two-photon laser excitation via electronic bridge processes in trapped $^{229}Th^+$ ions [4]. In resonant two-step laser excitation of $^{232}Th^+$ [5], we have observed 43 previously unknown electronic energy levels within the search range from 7.3 to 8.3 eV [6]. This high density of states promises a strongly enhanced nuclear excitation rate because it makes it likely that an excited electronic level with suitable quantum numbers is close to the nuclear excited state. Using laser ablation loading of the ion trap we efficiently load and store ions of the ^{229}Th isotope. We have measured the hyperfine structure and isotope shifts of two resonance lines that are suitable as first stages of the electronic bridge excitation and can be used to infer nuclear moments of the isomer. Presently, the experimental search for laser excitation of the isomeric state is ongoing.

For a different search approach of the isomeric transition in solid samples [7], we have developed a novel adsorption technique which prepares ^{229}Th on a surface of CaF_2. The adsorbed ^{229}Th is exposed to highly intensive undulator radiation in the wavelength range between 130 nm and 320 nm, which includes the indirectly measured nuclear resonance wavelength. After the excitation, light emission from the sample is detected with a VUV sensitive photomultiplier tube. No clear signal relating to the nuclear transition has been observed. Possible explanations include non-radiative relaxation of the nuclear excitation or a transition strength that is weaker than presently expected.

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Microfabricated Optically-Pumped Magnetometers for Biomedical Applications

S. Knappe[1,2], **D. Sheng**[2], **O. Alem**[2], **J. Kitching**[1]
1. Time and Frequency Division, NIST, Boulder, CO, USA
2. University of Colorado, Boulder, CO, USA
E-mail: knappe@nist.gov

The combination of microfabrication and precision laser spectroscopy of atoms has enabled the development of a number of small, low-power high performance sensors and instruments [1]. Microfabricated versions of optically-pumped magnetometers (μOPMs) are attractive for surveillance and space applications, due to their scalar nature, potential for good long-term stability and accuracy, and demonstrated low-power operation. For biomedical applications, their high sensitivity without the need for cryogenics, in combination with small size and positioning flexibility are attractive [2].

Over the last decade, we have improved the sensitivity of μOPMs by over 4 orders of magnitude, now reaching sensitivities of 5 $fT/Hz^{1/2}$, and therefore approaching the sensitivity of commercial superconducting quantum interference devices (SQUIDs). We have developed a fiber-coupled 32-channel magnetic imaging system and demonstrated its use in biomagnetic applications as well as high-performance gradiometers. While many of the technical issues we encounter, such as the control of light shifts and atom number fluctuations, are very similar to those in chip-scale atomic clocks, others are specific to magnetometers. The presence of thermally-induced eddy currents in conductive materials near the sensor must be minimized, for example. We will present estimates for relevant noise sources of our μOPMs.

Magnetoencephalography (MEG), along with its electrical equivalent, electroencephalography (EEG), is an important non-invasive electrophysiological brain imaging method, which can measure and localize the tiny magnetic fields emitted by neural currents in the brain. While current MEG systems provide high temporal resolution, the spatial resolution has been limited in SQUID-based systems due to the large distance between the sensors and the source, as a result of the low-temperature SQUIDs requiring thick Dewar walls. SQUID systems are consequently static, bulky, and expensive. Tiny uncooled sensors, such as μOPMs, could change that. We will present recent results from our MEG measurements and cross-validation of our sensors with standard SQUID MEG.

Finally, we will discuss other possible biomedical applications for μOPMs, such as fetal magnetocardiography [3] and the detection of magnetic nanoparticles.

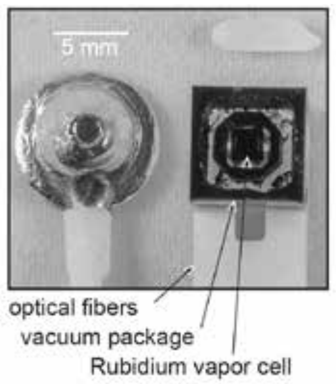

Fig. 1: Photography of a standard EEG electrode (left) and a μOPMs (right) with a grain of rice (top).

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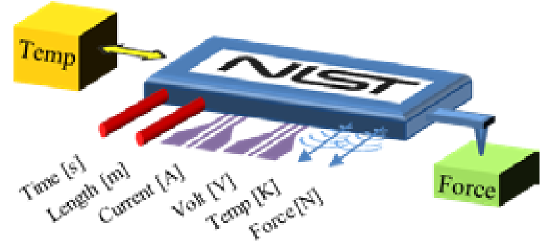
NIST on a Chip: Realizing SI Units with Microfabricated Alkali Vapor Cells

J. Kitching[1], **E. Donley**[1], **S. Knappe**[1], **K. Srinivasan**[2], **V. Aksyuk**[2], **A. Lal**[3]
1. Time and Frequency Division, NIST, Boulder, CO USA
2. Center for Nanoscale Science and Technology, NIST, Gaithersburg, MD USA
3. Department of Electrical and Computer Engineering, Cornell University, Ithaca, NY USA
E-mail: john.kitching@nist.gov

The National Institute of Standards and Technology has recently embarked on an ambitious research program to develop compact, low power instruments that realize one or more SI units and that can be mass-produced at low cost. These calibration "chips" are intended to provide the capability for certain stand-alone SI-traceable calibrations to be carried out inexpensively in commercial or industrial settings, perhaps even within larger, more complex instruments, without the need for participation from national metrology institutes or other certified calibration laboratories. Such a vision has also been articulated in the Vision for Metrology in the 2020s developed at the National Physical Laboratory [1].



We propose that the development of microfabricated alkali vapor cells over the last decade may enable a number of base SI units, specifically the second, the meter, the ampere and the kelvin, to be realized at useful levels of uncertainty in chip-scale format using simple atomic spectroscopy. This paper will outline the prospects for such instruments, present some possible designs and assess the performance possible.

The SI second might be realized with a microfabricated cold atom platform based on passive getter pumping and narrow-linewidth vertical-cavity surface emitting lasers. Key challenges are high-vacuum pumping, small atom number due to the small capture volume [2] and the compact optical system. Lasers locked to optical transitions in atoms confined in microfabricated vapor cells can be integrated with SiN single-mode photonic waveguides. The accurate measurement of magnetic fields can be implemented using nuclear magnetic resonance [3]. An accurate magnetometer, coupled with an interferometrically-measured coil system carrying currents and referenced to an accurate clock and wavelength standard could enable the realization of the SI ampere. Finally, Doppler thermometry of alkali atoms [4] in microfabricated vapor cell may enable accurate measurements of temperature in a compact, low-power platform.

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Quantum Test of the Equivalence Principle and Space-Time (QTEST)

N. Yu

QTEST concept study team
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA. USA
E-mail: nan.yu@jpl.nasa.gov

We report on a pre-phase A study for Quantum Test of Equivalence Principle and Space Time (QTEST), a concept of a dual atomic species interferometer experiment on ISS for precise tests of Einstein's equivalence principle. Its primary science objective is to test Einstein's equivalence principle with two rubidium isotope gases at a precision better than 10^{-15}, a 100-fold improvement over the current limit on equivalence principle violations, and over 1,000,000 fold improvement over the similar quantum experiments demonstrated in laboratories. Distinct from the classical tests is the use of quantum wave packets and their expected large spatial separation in the QTEST experiment. This dual species atom interferometer experiment will also be sensitive to time-dependent equivalence principle violations that would be signatures for ultralight dark-matter particles.

The predicted high measurement precision of QTEST comes mainly from the microgravity environment on ISS, offering extended free fall times in a well-controlled environment. QTEST plans to use high-flux, dual-species atom sources, and advanced cooling schemes, for $N > 10^6$ non-condensed atoms of each species at temperatures below 1nK. The highly symmetric interferometer configuration and its ability for common-mode error rejection drive the QTEST design. It uses Bragg interferometry with a single laser beam at the "magic" wavelength, where the two isotopes have the same polarizability, for mitigating sensitivities to vibrations and laser noise, imaging detection for correcting cloud initial conditions and maintaining contrast, modulation of the atomic hyperfine states for reduced sensitivity to magnetic field gradients, two source-regions for simultaneous time reversal measurements and redundancy, and modulation of the gravity vector using a rotating platform to reduce otherwise difficult systematics to below 10^{-16}.

In this paper, we will present the science feasibility study for the overall mission concept and detailed analysis of error budgets. We will also describe findings of the engineering feasibility study and instrument payload design, as well as discuss risks, challenges, mitigation plans and justifications.

This work was carried out at the Jet Propulsion Laboratory under contract with the National Aeronautics and Space Administration.

Magnetic field enabled Lamb-Dicke spectroscopy of the $^1S_0$-$^3P_0$ transition in ^{24}Mg

E.M. Rasel, D. Fim, N. Jha, A. Kulosa, S. Rühmann S. Sauer, K. Zipfel and W. Ertmer

Leibniz University Hanover, Institute of Quantum Optics, 30167 Hannover, Germany
E-mail: rasel@iqo.uni-hannover.de

We excite the electronic state $^3P_0$ in ^{24}Mg in presence of a magnetic field, which enhances the coupling to optical dipole radiation [1,2]. The atoms were laser cooled to few Mikrokelvins [3] and trapped in an one dimensional optical lattice [4]. In this way we determined the magic wavelength, where the ac Stark shift of the $^1S_0$-$^3P_0$ transition due to the lattice vanishes, the quadratic magnetic Zeeman shift and the transition frequency, to 468.463(207) nm, −206.6 (2.0) MHz/T2 and 655 058 646 691(101) kHz, respectively. We compare the observed values with results derived from theoretical predictions [5-8] as well as from complementary experiments [9,10] and discuss future prospects for a clock operated with bosonic magnesium.

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Composite pulses in Hyper-Ramsey spectroscopy for the next generation of atomic clocks

T. Zanon-Willette[1,2], M. Minissale[1,2], V.I. Yudin[3] and A.V. Taichenachev[3]

1. Sorbonne Universités, UPMC Univ. Paris 6, UMR 8112, LERMA, F-75005, Paris, France,
2. LERMA, Observatoire de Paris, PSL Research University, CNRS, UMR 8112, F-75014, Paris France,
3. Institute of Laser Physics, Siberian Branch of Russian Academy of Sciences, Novosibirsk 630090, Russia, Novosibirsk State University, Novosibirsk 630090, Russia, and Novosibirsk State Technical University, Novosibirsk 630092, Russia

E-mail: thomas.zanon@upmc.fr

We present a generalization of the Ramsey separated oscillating field method [1] with composite pulses to suppress field frequency shifts induced by the interrogation laser itself for the next generation of high precision atomic, molecular and nuclear clocks.

The sequence of pulses reported in Fig.1 is a generalized three-pulse Mach-Zehnder configuration with an intermediate composite "echo" pulse tailored in frequency detuning, field amplitude, phase and duration. We accurately describe various proposals starting from the Hyper-Ramsey scheme [2] to the more recent fault tolerant Hahn-Ramsey interferometer [3]. In order to investigate very precisely these modified versions of Ramsey spectroscopy, we have numerically studied the generalized transition probability with associated phase-shifts driving the resonance frequency position around the extremum of the central fringe.

Non-linear behaviors of the central fringe frequency-shift versus a small frequency perturbation in the clock detuning have been investigated and presented in Fig.1.

The generalized form of the spectral resonance has been extended to include potential biases, higher-order light-shift corrections on detuning and various modifications of laser parameters exploring non linear frequency responses of quantum particles for ultra precise frequency measurement.

We present an exact analytical expression of the Hyper-Ramsey transition probability and the associated frequency-shift [4] which are of considerable importance in the design, interpretation and very high accuracy of future laser pulses experiments in fundamental and applied physics.

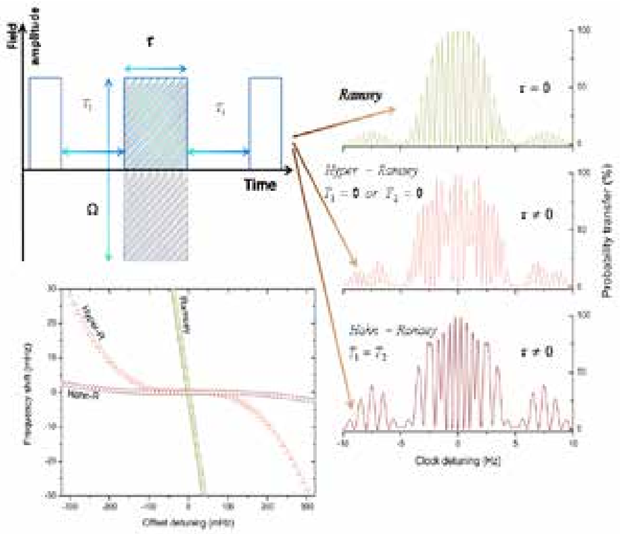

Fig. 1: Sequence of composite pulses with specified laser parameters including spectral lineshapes and frequency-shifts of the central fringe.

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Frequency comparison of optical clocks by carrier-phase two-way satellite frequency transfer

M. Fujieda[1], T. Gotoh[1], H. Takiguchi[1], H. Hachisu[1], T. Ido[1], and Y. Hanado[1]

1. Space-Time Standards Laboratory, National Institute of Information and Communications Technology, 4-2-1, Nukui-kitamachi, Koganei, Tokyo, 184-8795, Japan

E-mail: miho@nict.go.jp

Two-way satellite time and frequency transfer (TWSTFT) has been adopted for the determination of International Atomic Time (TAI). The measurement is normally performed by code phase of signal modulated by a pseudo-random sequence with a chip rate. Higher chip rate enables better measurement precision. However, due to a high rental cost of satellite transponder, a 2.5-Mcps signal is typically used where precision is about 0.5 ns with a C/N0 value of 55 dB/Hz. In order to improve the precision, on the other hand, we've developed two-way satellite technique using carrier phase (hereafter TWCP), where we utilize a slow chip-rate signal of 127 kHz and it also contributes to reduce the rental cost. After the demonstration of TWCP's measurement precision in 0.1 ps level in a short baseline [1], the uncertainty in a long baseline was evaluated by a frequency comparison of Sr lattice clocks in collaboration with PTB [2].

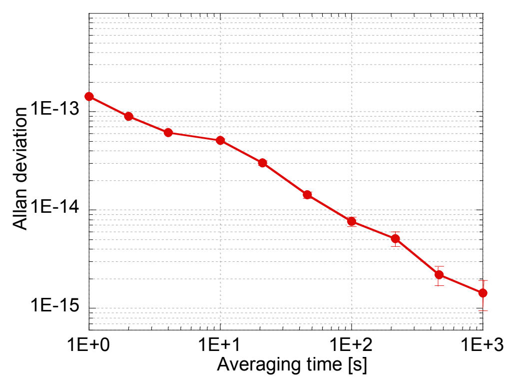

Fig. 1: Instability of TWCP satellite-based frequency comparison for optical clocks. Sr-based microwave signal is evaluated via TWCP system with respect to UTC(NICT).

Recently we've improved the system so that an H-maser is not required for the comparison as a frequency reference. The system enables the evaluation of an optical clock at a remote place where no frequency reference is available. In this system, an optical clock frequency is converted to microwave by an optical frequency comb, and the microwave signal is used as a reference signal of the TWCP system. The frequency of the remote optical clock is directly compared with respect to a local reference. We evaluated the instability of the comparison using a Sr lattice clock and two TWCP stations at NICT. The UTC(NICT) and Sr-based signals were used as references. Fig. 1 shows the system instability of $2x10^{-15}$ at 1000 seconds, which is compatible to in-house comparison using a local H-maser. Additionally we confirmed that the system did not induce a frequency bias within a combined uncertainty of the Sr lattice clock and UTC(NICT).

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The Future of Satellite Time and Frequency Transfer

J. Hirschauer[1]

[1]U.S. Naval Observatory, Washington, D.C., USA

Currently, time and frequency transfer via GNSS or Two Way Satellite Time and Frequency Transfer (TWSTFT) are nominally of subnanosecond precision, but robust only at the nanosecond level. While these techniques are complementary, neither is completely superior in terms of robustness or accuracy. Proper use of redundant systems, full environmental care, and improvements to the Precise Point Positioning algorithm can significantly improve the precision, accuracy, and robustness (PAR). Combined with advances such as carrier phase TWSTFT and DPN, one can imagine attaining very subnanosecond levels in PAR - 100's of picoseconds if not better. However, TWSTFT will always suffer from high costs and the sparse availability of geostationary satellites. This talk will develop these themes.

Linking Metrology Institutes in Europe by Optical Fibers

M. Abgrall[1], A. Al-Masoudi[2], A. Amy-Klein[3], S. Bilicki[1], E. Camisard[4], C. Chardonnet[3], N. Chiodo[3], S. Dörscher[2], C. Grebing[2], G. Grosche[2], S. Häfner[2], A. Koczwara[2], S. Koke[2], A. Kuhl[2], Y. Le Coq[1], T. Legero[2], R. Le Targat[1], C. Lisdat[2], J. Lodewyck[1], O. Lopez[3], F. Meynadier[1], D. Nicolodi[1], N. Quintin[3], S. Raupach[2], J.-L. Robyr[1], G. Santarelli[5], H. Schnatz[2], F. Stefani[1, 3], U. Sterr[2], S. Weyers[2], F. Wiotte[3], P.-E. Pottie[1]

1. Laboratoire National de Métrologie et d'Essais–Système de Références Temps-Espace, Observatoire de Paris, CNRS, UPMC, Paris, France
2. Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
3. Laboratoire de Physique des Lasers, Université Paris 13, Sorbonne Paris Cité, CNRS, Villetaneuse
4. RENATER, 23-27 rue Daviel, 75014 Paris, France
5. Laboratoire Photonique, Numérique et Nanosciences, Université de Bordeaux 1, Institut d'Optique and CNRS, Talence, France

E-mail: paul-eric.pottie@obspm.fr

The direct comparison of distant optical clocks with an uncertainty below 10^{-16} is out of reach to date for satellite techniques [1]. Optical clock comparison is a challenge that strongly motivates the development of optical fiber links. For a decade coherent optical fiber link were improved and extended to a larger range, and reach typically 10^{-15} relative stability at one second integration time in one Hz bandwidth over typical distance of 1000 km (see [2, 3] and references therein). Linking frequency metrology institutes in Europe with optical fibers becomes a reality that will accomplish a major step towards a possible redefinition of the SI second. Fiber links are also expected to play a key role for fundamental physics and high resolution atomic and molecular physics with the development of national fiber networks between research laboratories as for instance REFIMEVE+ in France and LIFT in Italy.

In this talk, we will report on the cascaded optical link of 720 km over the Internet fiber network from LNE-SYRTE, Paris to the IT center of the University of Strasbourg (UoS) at the French-German border, and the German counter part of 720 km that connects PTB, Braunschweig to UoS over a dedicated fiber. The focus will be given on cascaded optical links using repeater laser stations to regenerate coherently the metrological signal. We will present our collaborative work to realize the interconnection of these two long-haul cascaded links, that finally connect for the first time to our knowledge two National Metrology Institutes with a fiber link. We will report the relative frequency stability obtained in Strasbourg, and show that this combined optical frequency link is able to compare Sr lattice clock with an unprecedented level of accuracy for remote clocks, beyond the SI limit. The result of the first international optical clock comparison with fiber links will be presented.

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A direct comparison between two independently calibrated time transfer techniques: T2L2 and GPS Common-Views.

G. D. Rovera[1], **M. Abgrall**[1], **C. Courde**[2], **P. Exertier**[2], **P. Fridelance**[3], **Ph. Guillemot**[4], **M. Laas-Bourez**[2], **N. Martin**[2], **E. Samain**[2], **R. Sherwood**[5], **J.-M. Torre**[2], and **P. Uhrich**[1]

[1] LNE-SYRTE, Observatoire de Paris, PSL Res. Univ. CNRS, Sorbonne Univ. UPMC Univ. Paris 06
[2] Geoazur, CNRS, Observatoire de la Côte dAzur, UNS, 06560 Sophia-Antipolis
[5]NERC Space Geodesy Facility Herstmonceux, United Kingdom
[4]CNES French Space Agency, Paris, France
[3]Phusipus Intégration, Saint Vallier, France
Email: daniele.rovera@obspm.fr

We present a direct comparison between two time transfer techniques on independently calibrated links: Time Transfer by Laser Link (T2L2) and Global Positioning System (GPS) satellite common-views (CV). The T2L2 principle is derived from classical satellite laser telemetry techniques, with a dedicated on-board instrumentation able to time tag the laser pulses reaching the satellite. The uncertainty budget estimation shows that T2L2 is able to perform common-view time transfer between remote sites with an expanded uncertainty better than 140 ps (k = 2) [1]. For GPS CV, a GPS receiver collects measurements of the differences between the local time scale and GPS Time, the common satellite system time scale. Data processing consists in building the differences between such data collected at separate sites at the same epoch. It has been shown that a GPS link calibration can be achieved within an expanded uncertainty of 1.5 ns to 2.1 ns (k = 2) [2].

The direct comparison has been carried out between three European stations: Géoazur in Observatoire de la Côte d'Azur (OCA), Calern, France, LNE-SYRTE in Observatoire de Paris (OP), Paris, France and NERC Space Geodesy Facility (SGF), Herstmonceux, United Kingdom. In OCA and SGF, a fixed laser station is operated, where a mobile OCA laser station had been temporarily implemented in OP.

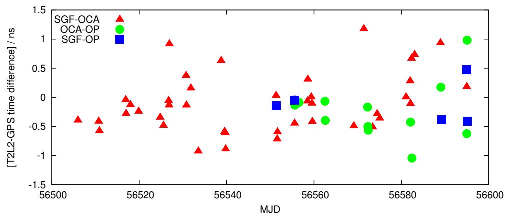

Figure 1: Differences between time comparison made by GPS-CV and T2L2. Red triangle SGF-OCA, green circle OCA-OP, blue square SGF-OP.

Despite the T2L2 limitations coming from either the meteorological conditions or the small number of Jason-2 passes in common-view of two stations, Fig. 1 shows the convergence of both techniques. The resulting average of the differences is below 240 ps for all the links.

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Trapped Atom Clock on a Chip (TACC)

C. Deutsch[1], **V. Dugrain**[1], **J.-N. Fuchs**[2], **K. Gibble**[3], **R. Kohlhaas**[4], **C. Lacroute**[4], **F. Laloe**[1], **W. Maineult**[4], **K. Ott**[1,4], **F. Piechon**[5], **F. Ramirez-Martinez**[4], **F. Reinhard**[1], **T. Schneider**[1], **R. Szmuk**[4], **J. Reichel**[1], and **P. Rosenbusch**[4]

1. LKB, Ecole Normale Supérieure, CNRS, UPMC, Paris, France
2. LPTMC, UPMC, CNRS, Paris, France
3. Department of Physics, The Pennsylvania State University, University Park, Pennsylvania, USA
4. LNE-SYRTE, Observatoire de Paris, CNRS, UPMC, Paris, France
5. LPS, CNRS, Université Paris-Sud, 91405 Orsay, France

E-mail: Peter.Rosenbusch@obspm.fr

Atomic clocks, nuclear magnetic resonance and other precision spectroscopy techniques are based on the coherent manipulation of an ensemble of spins ½. Highest sensitivity requires narrow linewidth and good signal-to-noise i.e. long coherence times and the interrogation of many spins. Usually these are contradictory as interactions destroy coherence and field gradients create dephasing. Known mechanisms to battle dephasing include experimental techniques like spin-echo or interaction-driven random fluctuations leading to motional narrowing and exchange narrowing.

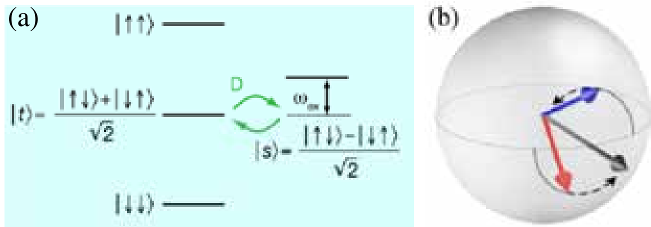

Fig. 1: (a) The exchange interaction shifts dephasing from the triplet to the singlet state out of resonance, here for s-wave interaction in fermions (from [1]). (b) The energy gap drives a rotation of the two individual Bloch vectors around their sum (from [3]).

We present a new interaction-driven deterministic mechanism that may be seen as intrinsic spin-echo or intrinsic spin-locking. The exchange symmetry of identical particles opens an energy gap between the singlet and triplet states that shifts dephasing out of resonance [1]. In the Bloch sphere representation, the two spins rotate around their sum [2]. The mechanism sustains rephasing and 20-fold increased coherence times of 58 ± 12 s [3]. The energy gap and spin rotation are also observed as (deleterious) collisional shift if the local oscillator radiation is inhomogeneous and thus couples to the singlet state [4]. Such inhomogeneity inevitably excites spin waves. We show how this fundamental effect improves the stability [5] *and* accuracy of trapped atom clocks. We study the particular case of ^{87}Rb in a Trapped Atom Clock on a Chip destined for mobile applications; however our results apply to a broad range of spin ensembles [6], in particular optical lattice clocks for which this exchange interaction has been studied [7].

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High performance and miniature vapor cell frequency standards

C. Affolderbach, T. Bandi, M. Gharavipour, F. Gruet, S. Kang, S. Karlen, M. Pellaton and G. Mileti
Laboratoire Temps – Fréquence (LTF), Université de Neuchâtel, Switzerland
E-mail: gaetano.mileti@unine.ch

In the area of ultra-stable vapor-cell Rubidium clocks, our research has recently focused on the laser-pumped microwave-optical Double Resonance (DR) scheme and exploited low-Q magnetron-type microwave cavities [1] ensuring a sufficiently homogeneous RF field while enabling compact physics packages (1-2 L, including the frequency-stabilized laser head), with excellent short and medium term frequency stabilities ($\sim 2 \cdot 10^{-13}\ \tau^{-1/2}$) .

In Continuous Wave (CW) operation, the laser and microwave fields are applied continuously and simultaneously. The absence of "dead time" relaxes the requirements on the phase noise of the microwave Local Oscillator (Dick effect) but sets stringent constraints on the laser medium and long term intensity and frequency stability (light-shift effect) [2].

In the pulsed optical pumping (POP) scheme [3], a Ramsey-type sequence may be used, and the laser and microwave fields are not applied simultaneously, which suppresses the light-shift effect and allows a separate optimization of the laser pumping and detection parameters. However, to fully take advantage of these possibilities, superior phase noise performances of the LO are demanded, as well as a greater homogeneity of the microwave field inside the resonance cell [4]. Pulsed schemes also make possible in-situ measurements of relevant physical quantities such as the DC and microwave magnetic fields as well as the longitudinal and transverse relaxation times, with sub-mm scale spatial resolution [5].

The talk will first present our developments and latest results in terms of improved short and medium term frequency stability, including a quantitative comparison of the CW and POP schemes using the same physics package. We will then discuss into more details selected relevant physical effects such as the microwave power-shift and the light-shift versus laser intensity and frequency. Finally, we will address the possibility to exploit the POP DR method also in atomic clocks using micro-fabricated alkali-vapor cells [6], and present our preliminary investigations in this area.

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Compact cold atom clock based on diffuse laser cooling in a cylindrical cavity

Peng Liu, Yanling Meng, Jinyin Wan, Ling Xiao, Xiumei Wang, Yaning Wang, Huadong Cheng and Liang Liu

Key Laboratory of Quantum Optics and Center of Cold Atom Physics,
Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences,
Shanghai 201800, China
E-mail: liang.liu@siom.ac.cn, chenghd@siom.ac.cn

We present a compact Rubidium cold-atom clock with a cylindrical microwave cavity in which the diffuse light cooling [1], microwave interrogation and the detection of clock signal are completed. Typical width of the Ramsey fringe is about 24 Hz with a contrast of 96.3% and the signal-to-noise ratio is about 450 as shown in Fig.1.The frequency stability of $6.6\times10^{-13}\ \tau^{-1/2}$ has been achieved recently. This cold atom clock has a potential use in space due to its high stability and small size. As an example, the HORACE has been developed for onboard and space applications at SYRTE [2].

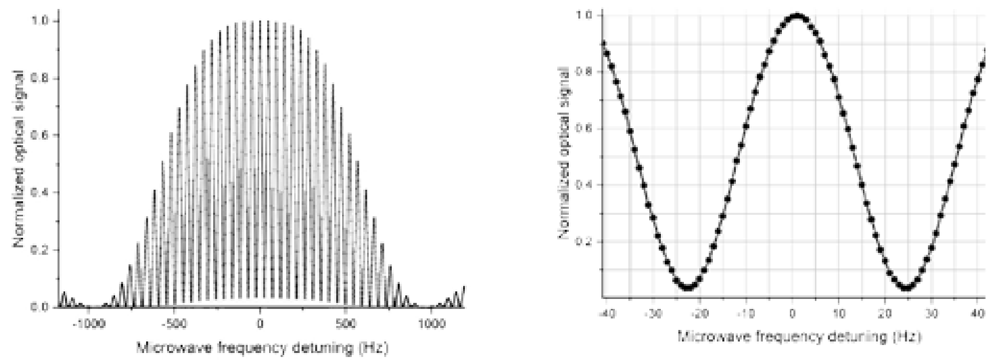

Fig. 1: Ramsey fringes of the compact Rubidium cold-atom clock. The central fringe is shown inset with FWHM~24Hz, contrast~96.6%.The interrogation time is 22ms.

The cooling and pumping lights are injected into the cylindrical microwave cavity by four multi-mode fibers fixed in the lower surface of the cavity. The diffuse light is generated by the reflection of the injected laser on the inner surface of the microwave cavity with the reflectivity of about 96.6%. The Rubidium atoms are cooled and manipulated in the center of the microwave cavity with such a structure of the optical field [3].
The scheme of the physical package provides a solution for a robust and compact atomic clock with an excellent stability. Now the main efforts are concentrated on the issues of the AM and FM noise of the probe light, the Dick effect and the cavity pulling effect for better long-term stability.

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Clocks Based on Multipole Ion Traps

John D. Prestage[1] and Robert L. Tjoelker[1]

1. California Institute of Technology, Jet Propulsion Lab, Pasadena, CA

Ion clock technologies are being developed for various applications ranging from laboratory ultra-stable primary standards to small transportable instruments. Ion clocks have advantages when long term autonomous operation in a small package is required. At JPL, mercury ion clock technology is currently being developed for space and ground applications, including deep space navigation of planetary missions where many years of continuous operation is required. The use of an rf discharge Hg isotopic lamp for state selection allows several years operation in the space radiation environment, but also forces the development of ion trapping techniques where large numbers of ions are held. Large ion clouds are necessary to achieve good signal-to-noise in the detected clock transition where only 1-2 photons per ion per second are scattered to provide 10^{-15} performance after a few hours averaging time.

The methods and traps for manipulating large ion clouds will be discussed, including use of multipole traps where space charge frequency pulling is reduced. Vacuum tube methods are employed to avoid the use of active (power consuming) vacuum pumps. Some of the earliest ion trap tubes built this way have demonstrated 10 year sealed life, with large cloud ion hold times close to a year after being sealed 10 years.

Other much smaller ion trap packages (~1 cm^3) have been fabricated using similar methods and have demonstrated clock operation into the 10^{-14} range.

Ultra-stable Cryocooled Sapphire Oscillators

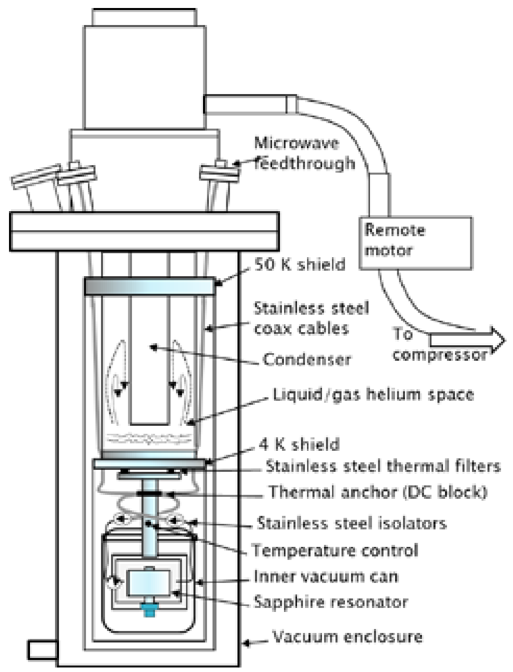
J.G. Hartnett[1], A.P. Hilton[1], A.N. Luiten[1]

1. Institute for Photonics & Advanced Sensing (IPAS), and, the School of Physical Sciences, the University of Adelaide, Adelaide, S.A., Australia
E-mail: john.hartnett@adelaide.edu.au

Cryogenically cooled sapphire oscillators (CSO) have achieved a performance that is state-of-the art for X-band signal generation, both in frequency stability and phase noise close to the carrier. We present an overview of our design that saw the transition of the CSO from a system with a cryostat using liquid helium as a coolant, and hence regular refills, to a system using a pulse-tube cryo-refrigerator and a specially designed low-vibration cryostat (see below) and practically no maintenance. That transition saw improvements both in the oscillator frequency stability as well as its long term continuous operation, making it field deployable.

The cryogenic sapphire crystal, at the heart of the oscillator, as the main frequency determining element, needs to remain relatively immune to vibrations induced by the cryocooler compressor. That necessarily required a specially designed low-vibration cryostat. This was developed in conjunction with CryoMech Ltd, who patented the design. They also invented the pulse-tube system.

We present an analysis of the main noise sources determining the oscillator phase noise and frequency stability. These include vibration, temperature, frequency, power and residual AM control, and they are described where they dominate. The limitations on the short term stability, and hence phase noise, will be discussed and how it can be improved. Several improvements to achieve better long term stability with very little frequency drift will be described.



Autonomous Cryocooled Sapphire Oscillator: A Reference for Frequency Stability and Phase Noise Measurements

V. Giordano[1], S. Grop[1], C. Fluhr[1], B. Dubois[2], Y. Kersalé[1], E. Rubiola[1]
1. Dpt TF, FEMTO-ST Institute, Besançon, FRANCE
2. FEMTO Engineering Besançon FRANCE
E-mail: giordano@femto-st.fr

The Oscillator-IMP project targets at being a facility dedicated to the measurement of noise and short-term stability of oscillators and devices in the whole radio spectrum (from MHz to THz), including microwave photonics, widely available to Agencies, to research institutions and to private companies in a frame of partnerships. The scope spans from routine measurements to the research on new oscillators, components, and measurement methods. The Oscillator-IMP platform consists of highly sophisticated instruments for the measurement of short-term stability and spectral purity, and of the most stable frequency references, i.e., atomic clocks and ultra-stable oscillators. Among them, a set of three nearly identical Cryogenic Sapphire Oscillators (CSO) constitutes a unique tool permitting to reach an unprecedented noise floor in the frequency stability measurement. These oscillators exhibit a stability of parts in 10^{-16} from 1 s to $5x10^3$ s, and a drift of $5x10^{-15}$ at 1 day. One of these CSOs, codenamed ULISS, can be transported with a small truck modified for this purpose. In the last two years it visited several European sites, traveling more than 10,000 km. The two others constitute our ultra-stable references for short-term frequency stability evaluation. Since the set of three is now operational, we are able to measure ULISS before and after traveling, which validates the stability and the spectral purity at the remote site. They have been used for example to check the performance of a laser stabilized on a ULE cavity. In the nominal functioning of the Oscillator-IMP platform, these three CSOs will be compared with the three-cornered-hat method, which permits to extract the individual frequency stabilities. An oscillator under test can be compared simultaneously to each CSO. Correlating the three results we will get the DUT noise, while the noise of the references is rejected proportionally the square root of the number of averages. As the CSO short-term stability is better than 1×10^{-15}, a noise floor of 10^{-16} can be easily reached by averaging few hundreds of samples. In this paper we present the design of the CSO set, a characterization of the phase noise and the first performance evaluation of the three CSOs using the three-cornered-hat method.

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Low Thermal Noise Optical Cavities

U. Sterr[1], T. Legero[1], D. G. Matei[1], Ch. Grebing[1], S. Häfner[1], Ch. Lisdat[1], R. Weyrich[1], F. Riehle[1], W. Zhang[2], L. Sonderhouse[2], J. Ye[2]
1. Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
2. JILA, National Institute of Standards and Technology and University of Colorado, 440 UCB, Boulder, CO 80309-0440, USA
E-mail: uwe.sterr@ptb.de

Thermal noise fundamentally limits the length stability of optical cavities and thus the frequency stability of ultrastable lasers. Even today's most stable lasers only achieve coherence times of a few seconds, which are still at least an order of magnitude away from the coherence times of the clock transitions in neutral atoms or ions that are employed in the best optical clocks. Thus at present the resolved linewidth of these clock transitions are mostly limited by the quality of the laser, and to further exploit the potential of these clocks, improved interrogation lasers are urgently needed.

While promising results have been obtained from alternative laser stabilization methods like spectral hole burning or active clocks, the longest coherence times are still provided by laser systems stabilized to optical cavities. To further reduce the influence of thermal noise, various techniques have been approached, like increasing the cavity length, lowering the temperature or using low mechanical loss spacer and coating materials.

Extending previous work based on the PTB-JILA collaboration [1,2], we have now set up two silicon cavities, operated at the crossover temperature of the thermal expansion coefficient near 124 K with expected thermal noise limited instability of 7×10^{-17}. The control of the resonator temperature is greatly enhanced using a combination of several temperature sensors and low-thermal conductivity materials. Owing to the anisotropic elasticity of the single-crystal silicon, the vertical acceleration sensitivity can be minimized by rotating the resonator around the optical axis (Fig. 1).

Fig. 1: Vibration insensitive mounting of the 21 cm long single-crystal silicon cavity.

We report on the current progress and on the comparison to the PTB 48 cm room-temperature cavity [3], its use in PTB's optical Sr lattice clock and discuss further improvements using crystalline coatings and operation at lower temperatures.

We gratefully acknowledge support from the Centre for Quantum Engineering and Space-Time Research (QUEST), NIST, and DARPA.

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Crystalline Coatings with Optical Losses Below 5 ppm

<u>G. D. Cole</u>[1,2], D. Follman[1], P. Heu[1], C. Deutsch[2], W. Zhang[3], L. Sonderhouse[3], M. Notcutt[4], J. Ye[3], M. Aspelmeyer[5]

1. Crystalline Mirror Solutions LLC, Santa Barbara, CA USA
2. Crystalline Mirror Solutions GmbH, Vienna, Austria
3. JILA, NIST, and University of Colorado, Boulder, CO USA
4. Stable Laser Systems, Boulder, CO USA
5. Faculty of Physics, University of Vienna, Vienna, Austria

E-mail: g.cole@crystallinemirrors.com

Coating Brownian noise, driven by excess mechanical dissipation in high-reflectivity ion-beam sputtered (IBS) films imposes a severe limit on the performance of state-of-the-art precision measurement systems, such as stabilized lasers for optical atomic clocks and interferometric gravitational wave detectors [1]. As a consequence, a concerted effort has been focused on the identification of optical coatings capable of simultaneously achieving high reflectivity and minimal mechanical dissipation. Building upon advances in semiconductor microfabrication, we have successfully integrated low-loss epitaxial multilayers with standard cavity end mirror designs. Our innovative coating technology entails the selective removal of crystalline films from the original growth wafer, followed by direct bonding to an arbitrary (curved or planar) optical component. Recently, these "crystalline coatings" have demonstrated an exceptionally low mechanical loss angle of $0(4)\times10^{-5}$, a tenfold reduction when compared with the best dielectric multilayers at room temperature [2].

Over the past two years, a significant effort has been undertaken to improve the optical performance of these novel coatings through optimization of the crystal growth and substrate-transfer processes. Previously, our GaAs/AlGaAs multilayers exhibited typical excess losses (scatter + absorption) at the ~20 ppm level. With a focused effort on minimizing the background impurity level of the constituent films, we can now achieve an optical absorption level below 1 ppm in the near infrared, between 1000-1600 nm. Most recently, by improving the quality of the substrate-transfer process, we have minimized optical scatter losses, reaching limiting levels of ~3 ppm in the same wavelength range.

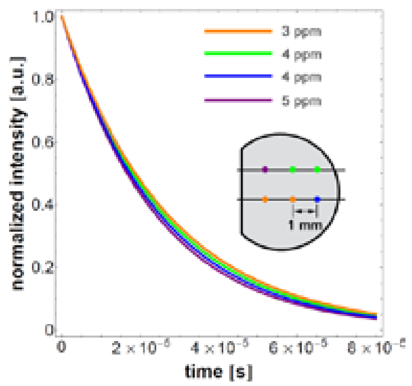

Fig. 1: Position-dependent ringdown of a 1550 nm crystalline coating. Six discrete positions are probed in a 75-mm cavity with a dielectric reflector, yielding excess losses ≤ 5 ppm.

Here, we present the optical performance of crystalline-coated cavity end mirrors, consisting of 38.5-period (9.50-µm thick) AlGaAs multilayers, with a center wavelength of 1550 nm, directly-bonded to super-polished fused silica substrates. Position-dependent optical ringdown yields excess loss levels in the best samples below 5 ppm (Fig. 1). With a nominal transmission of 10 ppm, these coatings are capable of finesse values exceeding 2×10^{5}, while a reduction in transmission to 5 ppm would enable a cavity finesse exceeding 3×10^{5}. These results represent a significant enhancement in optical quality and enable crystalline coatings with finesse values on par with those achieved with high quality IBS coatings.

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Progress of the ACES/PHARAO Space Clock Mission

<u>C. Salomon</u>[1], P. Laurent[2], L. Cacciapuoti[3], D. Massonnet[4]

1: Laboratoire Kastler Brossel, ENS-PSL Research University, CNRS, UPMC, Collège de France,
24 rue Lhomond, 75005, Paris, France
2: SYRTE, CNRS UMR 8630, Observatoire de Paris, LNE, UPMC,
61 Av. de l'Observatoire, 75014, Paris, France
3: European Space Agency, ESTEC, Noordwijk, ZH 2200 AG, the Netherlands
4: CNES, Centre Spatial de Toulouse, 18 Avenue Edouard Belin, 31401, Toulouse, France

Proposed in 1997, the ACES/PHARAO experiment is a space mission in fundamental physics with two atomic clocks on the International Space Station, a network of ultra-stable clocks on the ground, and space-to-ground time transfer systems. The mission objectives include the test of a laser cooled atomic clock designed for microgravity operation, an improved test of the gravitational red shift, a search for time variations of fundamental constants through distant clock frequency comparisons, and worldwide time and frequency metrology. The ACES flight instruments are near completion and launch in space is planned for the first half of 2017 for a mission duration of three years. The microgravity cold atom clock PHARAO is operating with laser-cooled cesium atoms and is a key element of the satellite payload. We will first report on the design and tests of the PHARAO flight model, which is now completed and ready for launch [1]. We will also present the development status of the other ACES instruments, the Space Hydrogen Maser (SHM), the microwave time-transfer system (MWL), and the laser time transfer (ELT).

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Perspectives of T&F Transfer via Satellite

W. Schäfer[1], T. Feldmann[1]
1. TimeTech GmbH, D-70563 Stuttgart, Germany
E-mail: wolfgang.schäfer@timetech.de

Bi-directional time and frequency transfer via satellite (TWSTFT) is in regular use since the early 1980s, mostly using a modem which has originally been developed at TU-Berlin [1]. During its introduction, its stability and accuracy was roughly 1...2 orders of magnitude better than existing clocks, whereas its current status lacks performance by few orders. This is due to the dramatic improvement of fountains and optical clocks over the last decade.

Standard TWSTFT between remote ground clocks and timescales uses bend-pipe communication transponders, for which the bandwidth has to be paid for. Partly due to this, the current modem is hardly explored to full extent. The main advantage of TWSTFT is however still seen in the capability to cover intercontinental distances and being a true alternative to GNSS based links. Although ground optical fibers have a promising perspective, they are currently limited to continental distances.

The best current link hardware has been developed for the ACES mission [2], i.e. ACES-MWL. Hardware test results show that the link performance can be largely scaled to user requirements. In particular, the suitability of ACES-MWL hardware can be demonstrated for high performance ground-to-ground time- and frequency transfer links over intercontinental baselines.

The presentation reviews key characteristics and requirements for TWSTFT links. The outline and perspective of two concepts will be described:

1. The classical bend-pipe transponder, without special equipment on board, with the potential of 1E-17 / day frequency transfer uncertainty, using advanced modulation.
2. The ACES-MWL like active on-board equipment, with the potential down to few 1E-19 / day, using both high-rate modulation and carrier-phase. The latest results of relevant tests will be presented.

Advanced technologies are about to be introduced, which have the capability to overcome limitations of existing satellite systems, using wide modulation and carriers at new high frequency bands, but still providing tolerance to fog and clouds [3,4]. Link and performance budgets will be provided for these candidate configurations. Finally, an outlook is given for optical free-space communication links [5,6], which are currently explored in satellite-to-satellite configuration as well as for space-to-ground. The latter is still limited to good weather conditions.

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Optical clock synchronization over free-space links

Nathan R. Newbury[1], Jean-Daniel Deschênes[2], Laura C. Sinclair[1], Fabrizio R. Giorgetta[1], William C. Swann[1], Esther Baumann[1], Hugo Bergeron[1], Michael Cermak[1], and Ian Coddington[1]
1. National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305
2. Université Laval, 2375 rue de la Terrasse, Québec, Québec, Canada, G1V 0A6
E-mail: nnewbury@boulder.nist.gov

Optical oscillators/clocks can now reach timing stabilities of femtoseconds with absolute accuracies approaching 10^{-18} [1–4]. A physical network of linked optical clocks and oscillators could enable dramatic improvements in precision navigation, tests of special and general relativity, clock-based geodesy, and other applications. However, current rf-based techniques cannot support an optical clock network since these techniques do not fully correct for the variable time delay between sites leading to uncontrolled Doppler shifts and time offsets. Optical fiber-based techniques can reach the levels of performance needed for optical clocks, but require a dedicated bidirectional fiber link between clock sites. In contrast, optical free-space links between clocks will be needed for future precision navigation and timing, regional geodesy, and satellite-based relativity or dark matter searches. Here we discuss an optical two-way time-frequency (TWTFT) method for real-time time comparison and synchronization between optical clocks that are connected by a free-space link.

The system synchronizes the relative time of a slave clock, comprised of a frequency comb phase-locked to a cavity-stabilized cw laser, to the time of a master clock, comprised of a second frequency comb phase-locked to a second cavity-stabilized cw laser. (Eventually, the master oscillator would comprise a full atomic clock.) The time synchronization is defined by overlap of master and slave frequency comb pulses at a reference plane with sub-femtosecond agreement over short times and < 20 fs wander over days. These results are achieved despite turbulence-induced piston noise, turbulence-induced fading, intermittent physical obstructions across the link, and even active manual adjustment of the link from 0 to 4 km. To achieve this synchronization, three systems run in parallel: a coherent single-mode optical link with a pseudo-random binary sequence (PRBS) modulation for "coarse" ambiguity-free synchronization to <1 ns, a two-way coherent exchange of optical frequency comb pulses for fine synchronization to a few fs with a $1/2f_r$ = 2.5 ns ambiguity[5], and a coherent optical communication link to send data between the sites.

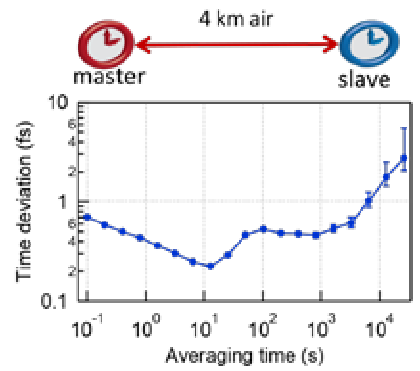

Figure 1: The system synchronizes the time between a master and slave optical clock. The lower figure shows the measured time deviation between the arrival of the master and slave comb pulses at a common reference plane.

We will discuss the latest performance and expected limitations of this optical TWTFT approach for time comparison/synchronization between remote optical clocks.

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Poster sessions

The poster sessions will take place in the ECC-Foyer from 4:30 pm to 9:30 pm on Monday, October 12 and Tuesday, October 13. There will be a dinner-break at 6:30 pm. The Foyer is close to the registration desk.

Boards will be available for presenters to put up their posters. The recommended format is A0 portrait: 84.1 cm × 118.9 cm (33.1 inch × 46.8 inch). Posters will be attached with provided tape. Please do only use the conference tape! Do not fix the posters with different elements like pins or own tape.

The posters' numbers will be noted on each board in accordance with the corresponding number which is shown on the following pages.

Please make sure to be present at your poster reasonably often during the sessions.

Poster sessions - Overview

Microwave clocks

Optical clocks

Oscillators and Noise

Frequency Combs and Applications

Time and Frequency Transfer

Test of Fundamental Physics with Clocks

Novel Concepts and Applications

Advanced Timekeeping with Atomic Fountains

M. Abgrall, S. Bize, B. Chupin , J. Guéna, Ph. Laurent, P. Rosenbusch, G. D. Rovera
LNE-SYRTE, Observatoire de Paris – LNE- CNRS –UPMC, Paris, France
E-mail: michel.abgrall@obspm.fr

The accuracy and the reliability of atomic fountains have dramatically improved the performances of national and international time references over the past ten years. At SYRTE, we have developed an ensemble of 3 fountains, the Cs fountain FO1, the mobile Cs fountain FOM and the dual fountain FO2 that is operated simultaneously with Cs and Rb. These fountains share the same reference frequency that is based on an ultra-stable cryogenic sapphire oscillator (CSO) phase locked to a hydrogen maser with a time constant of ~ 1000 s, in order to take advantage of the ultra-low phase noise of the CSO and of the low frequency drift of the hydrogen maser. Thanks to this system, the fountains can be operated at their fundamental limit, the quantum projection noise, demonstrating a record stability of $1.6 \times 10^{-14}\ \tau^{-1/2}$ and routine stabilities between 4 and $8 \times 10^{-14}\ \tau^{-1/2}$ in fully accuracy mode. This low instability enables us to reduce the accuracy evaluation time. Among the latest systematic effects that have been studied, the characterization of the residual distributed cavity phase shift and the modeling of the microwave lensing, allow to reach an accuracy between 2.3 and 6×10^{-16} depending on the set-up.

Thanks to their performances and their reliability, the SYRTE primary standards have provided the largest number of contributions in steering the International Atomic Time (TAI) and to the definition of the SI second, corresponding to 40 to 50% of the contributions of the about ten atomic fountains in operation worldwide. Also, the Rb part of FO2 was the first secondary representation of the second to be included in this steering. The implemented process illustrates what could be done in the future in view of a possible redefinition of the SI second based optical clocks. The SYRTE fountains also allowed a drastic improvement of the French time scale UTC(OP). Since about two years, this time reference is based on a hydrogen maser steered using daily frequency calibrations by the fountains. With this new method, UTC(OP) is one of the real time realizations of UTC the closest to UTC (within a few ns). Moreover, the SYRTE fountains serve for the absolute calibration of transition frequency in optical clocks down to the low 10^{-16}, either at SYRTE with the Sr and Hg optical lattice clocks under development, or in distant laboratories using the mobile fountain FOM for the Ca+ ion clock in University of Innsbruck, Austria and for the H 1S-2S transition at the Max Planck Institut für Quantenoptik, Garching, Germany. These experiments allow to perform stringent fundamental physics tests on the stability of the fundamental constants α and $\mu=m_e/m_p$ over time. The SYRTE clock ensemble including the atomic fountains, the optical clocks, the time reference UTC(OP) and the dedicated signal distribution and comparison tools will play an important role in the frame of the space mission ACES, that will fly onboard the international space station in 2017.

Status of the atomic fountain clock at the National Research Council Canada

S. Beattie[1], **J. Alcock**[1], **B. Jian**[1,2], **M. Gertsvolf**[1], **and J. Bernard**[1]
1. Measurement Science and Standards Portfolio, National Research Council Canada, Ottawa, Ontario, Canada
2. Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
E-mail: Scott.Beattie@nrc-cnrc.gc.ca

There are plans at the National Research Council (NRC) to replace our current caesium fountain clock FCs1 [1], which uses a horizontal C-field, with a new fountain of more-conventional design, FCs2. In preparation, several improvements have been made to the laser, microwave, and data acquisition systems, as well as to the operation of the current fountain. These improvements will be applied to the redesigned physics package of FCs2.

A new laser system, which uses two semi-conductor tapered amplifiers, has replaced the previous system which depended on four injection-locked slave diodes. This has resulted in more robust performance and higher output power (over 1.5 W). The master laser lock system has been simplified to have feedback to the laser piezo come directly from a cesium saturated absorption error signal. In contrast, the master laser had previously been locked to a Fabry-Perot cavity, which was in turn locked to a saturated absorption error signal. The lasers will now stay locked for several days.

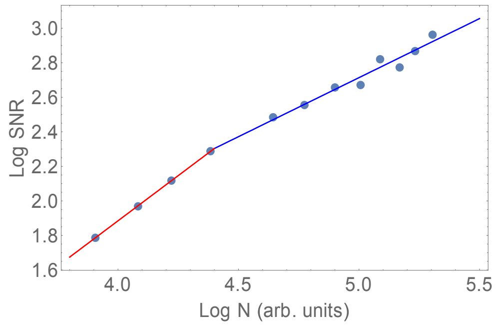

Fig. 1: Log of signal to noise ratio vs. log of atom number measured in arbitrary units. The reduction in slope at high atom numbers is indicative of being limited by the quantum projection noise.

In addition, new fountain control software has been developed to provide better flexibility in the equipment control. Considerable improvement to the atom number has been achieved through an optical pumping stage which prepares the atoms in the $|F=4, m_f=0\rangle$ state with linear polarized light tuned to the $|F=4\rangle \rightarrow |F'=4\rangle$ transition. This has increased the detected atom number by over a factor of 6 and has led to an increase in the signal to noise, such that it is now limited by quantum projection noise and the short term stability is limited by the local oscillator at $\sigma(1s) \sim 4\times10^{-13}$.

We will present details of the improvements to FCs1 and our work towards implementing a local oscillator derived from a microwave source locked to an ultra-stable laser [2]. This could potentially improve the short term stability of the fountain by an order of magnitude. Features of the physics package for NRC FCs2, such as MOT geometry and detection region, will be presented along with the current status of NRC FCs1.

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Operation of NIM5 fountain with 1.5×10^{-15} uncertainty and design of new NIM6 in NIM

F. Fang, W. Chen, K. Liu, N. Liu, R. Suo and T. Li
Time and frequency division, National Institute of Metrology, Beijing, China
E-mail: fangf@nim.ac.cn

The cesium fountain primary frequency standard NIM5 was developed at the National Institute of Metrology (NIM) China. It started to operate since 2008 and seven evaluations were reported to BIPM in 2014 and 2015 with a typical fractional frequency stability of 3×10^{-13} $(\tau/s)^{-1/2}$ and Type B uncertainty of 1.4×10^{-15}, which was dominated by the microwave-related frequency shifts. The standard deviation of the measured frequency from UTC in these 7 evaluations is 1.0×10^{-15}.

The design of NIM5 was briefly introduced in the last FSMS in 1998 [1] and its detailed operation and evaluations reported in another paper [2]. Since its first operation, NIM5 underwent a serious of improvements, including laser locking, adding an microwave interferometric switch and monitoring the transit phase in real time, reducing the microwave leakage effect by selecting atom signals in certain range, and so on [2, 3]. The major constrains of NIM5 now is a relatively larger background signal at the detection and microwave leakages.

We have been building a new cesium fountain NIM6 since 2014. It is going to collect more atoms in shorter period of time from a 3D MOT loading optical molasses (OM) as shown in figure 1. The atom distribution is expected to be more uniform compared with a 2D MOT loading OM. The diameter of the cloud could be adjusted by the intensity and detuning of the 3D MOT lights. A heat pipe around the fly tube is expected to further uniformize the temperature distributions in the interrogation range to reduce the black body radiation shift uncertainty. The atom number is expected to be further increased by a new de-pumping - optical pumping technique to pump atoms to the $|F=3, m_F=0\rangle$ state. With a new cryogenic sapphire oscillator (CSO) based frequency synthesizer, NIM6 is aiming to reach its quantum projection noise. In addition to the modifications mentioned above, some improvements on the vacuum system, magnetic shield, Ramsey cavity and microwave synthesizer is going to be made in NIM6 to reduce its Type B uncertainty further.

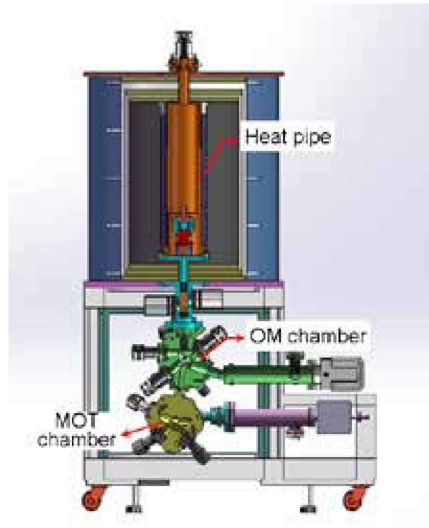

Fig. 1 Schematic of NIM6 physical package

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Status and Prospect of the Swiss Continuous Cs Fountain FOCS-2

A. Jallageas[1], **L. Devenoges**[2], **J. Morel**[2], **M. Petersen**[1], **L.-G. Bernier**[2], **T. Südmeyer**[1]
[1] Laboratoire Temps-Fréquence, Université de Neuchâtel, Neuchâtel, Switzerland
[2] Federal Institute of Metrology METAS, Bern, Switzerland
Email: antoine.jallageas@unine.ch

METAS FOCS-2 is the only Cs fountain clock worldwide taking advantage of a continuous atomic beam. This characteristic brings a series of remarkable advantages compared to the classical pulsed fountains. For instance, a frequency stability below the standard Dick limit has been demonstrated using a commercial synthesizer [1] and the low density of the cold atomic beam maintains the collisional shift at a minimum [2]. Furthermore, the fundamentally different principle of operation positively contributes to the metrological diversity.

Several upgrades of the original design have been implemented in the last few years, such as the design and the implementation of a new Ramsey microwave cavity with reduced phase gradients [3]. These improvements recently led us to focus on the evaluation of electromagnetic leakage in the system and on its effects on the clock frequency.

We observed that microwave leaks occurring on the top of the vacuum chamber and surface currents propagating along the coaxial cable shields were responsible for an uncontrolled frequency offset. Different solutions to remove this effect were evaluated. An original approach to avoid microwave leakage consists in using an optical fiber link instead of coaxial cables to deliver the microwave signal to the Ramsey cavity. The microwave is generated by two fast photodiodes (PD) directly imbedded in the cavity microwave feeds. These PDs receive a modulated infrared laser signal at 1550 nm. The modulation at 9.192631770 GHz is done using an optical Mach-Zehnder Modulator driven by a low noise microwave frequency synthesizer.

To prevent a degradation of the clock performance, the optical microwave transfer system has to preserve the low phase noise and spectral purity of the high performance local oscillator. Preliminary measurements performed on a test bench have demonstrated that the additional phase noise due to the optical link does not affect the short term stability of the clock, which would still be limited by the atomic shot noise ($6 \cdot 10^{-14}\,\tau^{-1/2}$). Moreover, a first phase stability measurement showed no drift above 10 µrad/s for one hour integration time. Given a transition time of 0.5 s this phase variation produces a relative frequency shift lower than $1.5 \cdot 10^{-16}$.

In this conference, we will present the current status of the FOCS-2 continuous fountain, together with an overview of the improvements implemented during the recent years, and the first measurements towards a microwave cavity powered with an optical link will be discussed.

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Toward the full evaluation of the cesium fountain NMIJ-F2

A. Takamizawa[1], **S. Yanagimachi**[1], **K. Hagimoto**[1], **I. Hirano**[1], **K. Watabe**[1], **T. Ikegami**[1], **and J. G. Hartnett**[2]
1. National Metrology Institute of Japan, AIST, Tsukuba, Ibaraki 305-8563, Japan
2. The Institute of Photonics and Advanced Sensing, and the School of Physical Sciences, the University of Adelaide, Adelaide 5005, South Australia, Australia
E-mail: akifumi.takamizawa@aist.go.jp

We have been developing the cesium fountain primary frequency standard NMIJ-F2, and its uncertainty is now estimated to be 1.1×10^{-15} except for a microwave power dependence shift [1]. Now the power dependence shift is being investigated. In NMIJ-F2, because the feedthroughs into the microwave cavities are outside of the vacuum chamber, the influence of the microwave leakage from the feedthrough on the atoms can be suppressed. On the other hand, because the Ramsey cavity and the state-selection cavity are connected to each other with the cutoff tube, microwave leakage from the Ramsey cavity is likely to enter the state-selection cavity and be enhanced. Therefore, the power dependence shift due to the so-called after-Ramsey interaction is large and clearly observed.

Figure 1 shows the fractional frequency difference as a function of n, where the pulse area of the microwave for the Ramsey interrogation is given by $n\pi/2$. The experimental data are fitted well to the theoretical model $An\sin(n\pi/2)$, where A is a free parameter. The frequency correction for the power dependence shift is determined from the parameter $A = (-5.2\pm0.5)\times10^{-15}$. This value is much larger than those in other fountains, where the power dependence shift is usually evaluated to have no biases and an uncertainty at the low 10^{-16} level. Adding the large correction for the power dependence shift to all the other corrections, we obtain y(NMIJ-F2) – y(TAI) = $+0.5\times10^{-15}$ during MJD 57094-57109. We are now preparing an interference switch for the microwave signal to remove the after-Ramsey interaction. Thus the power dependence shift with its uncertainty will be reduced.

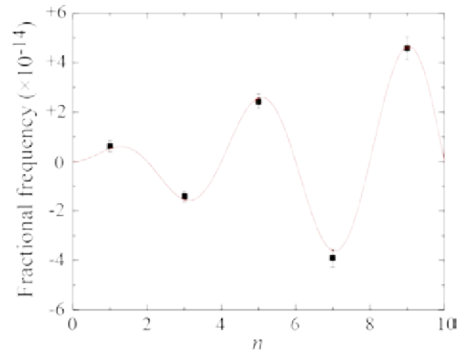

Fig. 1. Squares: the power dependence of the frequency. Red line: the fitted line.

As for the collisional shift, we plan to evaluate it not using alternation of the atom number during normal operation but simply by taking the coefficient between the atom number and the collisional shift obtained from the previous measurement, since in the alternation mode the effective frequency-stability is degraded. In the non-alternation mode, variation in the coefficient over the long term might not be negligible. So far, the Allan deviation of the fractional frequency of NMIJ-F2 against a hydrogen maser has reached $(7.6\pm5.6)\times10^{-16}$ for an averaging time of 4 days. This shows that variation in the coefficient does not affect the uncertainty at the 1×10^{-15} level. In the near future, we will obtain the Allan deviation of the relative frequency difference of NMIJ-F2 against TAI to confirm that there are no problems at the 10^{-16} level.

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Discussion on the practical correction of some biases in primary and secondary frequency standards

F. Levi[1] and S.R. Jefferts[2]

1. Physical Metrology Division, INRIM, Torino
2. Time and Frequency Division, NIST, Boulder (Co)

E-mail: f.levi@inrim.it

In this work we discuss how some frequency corrections are evaluated and applied to primary and secondary frequency standards (PFS, SFS) , that are reporting accuracy evaluations to BIPM. We present some suggestions on how we can achieve a more rigorous and uniform reporting system.

Among the various corrections routinely applied to frequency standards some are based on measurements that depend only of the particular standard, for example the density shift. Others are based on measurements performed within the standard and then corrected using a theory, for example some microwave related shifts. Finally other corrections are based on measurements of some environmental parameters and the correction is applied to the standard using some externally derived coefficient, this is the case e.g. of the Zeeman effect or the Blackbody radiation shift.

In the latter case, while the physics behind the shift is quite well understood and not generally questioned the best value of the coefficient derived from all available data is not generally known, thus leaving to each group the choice of the coefficient to be used. In the case of the Blackbody radiation frequency shift for example, several experimental and theoretical values are reported in the literature, with satisfying consistency, however, all PFS reporting to BIPM use only one experimental value. We think that a statistical analysis of the various measurements reported in the literature, along with a calculated "best value" for the coefficient, should result in a more rigorous evaluation of this shift.

In the paper we discuss the issue and present possible guidelines to address this problem.

Recent progress in optically-detected cesium beam clock

C. Liu, S. Zhou, S. Wang, Y. Wang

Institute of Quantum Electronics, school of Electronic Engineering and Computer Science,
Peking University, Beijing, China
E-mail: wnagyanhui@pku.edu.cn

To achieve a compact long-life and drift-free clock, we establish a thermal cesium beam clock where we detect the magnetically deflected cesium beam with a laser. The schematic is shown in Fig. 1. The tube is baked and sealed. A small ion pump maintains the pressure around 1E-6 Pa. Magnet A generates inhomogeneous magnetic field that bends the atom trajectories. The microwave cavity has two 1-cm-long interaction regions and a microwave-free distance of 17cm. A commercial diode laser is frequency-locked on (F=4-F'=5) transition of cesium D2 line with the saturated absorption spectroscopy. Atoms that pass through the cavity are exited and fluorescence is collected as the signal. The frequency of the local oscillator is locked to the center of Ramsey spectral line. The Allan deviation of the output frequency is measured against an H-maser, plotted in Fig. 2.

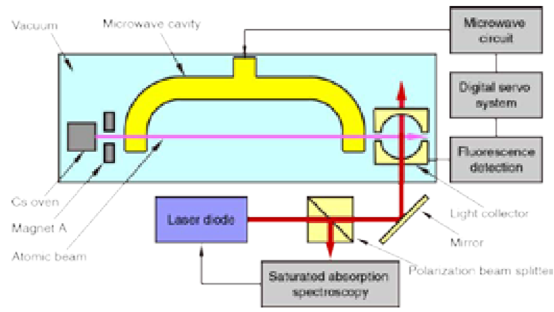

Fig. 1: the schematic of the clock

As we previously showed, the short-term stability is mainly determined by the atomic shot noise and laser frequency noise [1]. Methods to reduce the laser frequency noise are on trial.

The stabilizations of microwave power, C-field and oven temperature improves the long-term stability, with the help of a digital servo system based on field-programmable gate array (FPGA) [2]. We discuss the stabilization methods in detail.

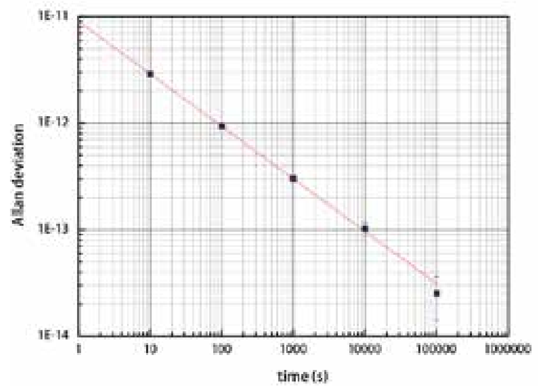

Fig. 2: The Allan deviation of the output frequency against an H-maser.

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Improving statistical and systematic uncertainties of PTB's caesium fountain clocks

V. Gerginov[1], G. Dobrev[1], M. Kazda[1], B. Lipphardt[1], K. Gibble[2], S. Weyers[1]

1. Time and Frequency Department, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
2. Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA

E-mail: vladislav.gerginov@ptb.de

Since about two decades the most accurate realization of the SI-second is obtained from caesium fountain clocks. Nowadays the best of these instruments offer uncertainties at the low 10^{-16} level, while at the same time their instability allows for reaching statistical uncertainties at the same level after averaging times of ~10000 s only [1]. For many years PTB's fountain clocks CSF1 and CSF2 are utilized as primary frequency standards for TAI (Temps Atomique International) steering contributions, optical frequency measurements and the steering of UTC(PTB), the basis for legal time in Germany. At the same time there is an ongoing process of improving the statistical and systematic uncertainty contributions of the PTB fountains.

Recently particular attention has been concentrated on a more rigorous evaluation of frequency shifting effects due to the distributed cavity phase (DCP), cold collisions and Ramsey pulling with the goal to obtain a better understanding of these effects and to reduce the related uncertainties. Because the necessary measurements for such evaluations strongly benefit from an improved frequency stability (and corresponding statistical resolution), an optically stabilized microwave source has been developed at PTB [2]. For CSF2, a significant improvement of the loaded and detected atom number, resulting in a significant signal-to-noise ratio enhancement, has been achieved recently by loading atoms from a cold atom beam from a Low Velocity Intense Source (LVIS, [3]).

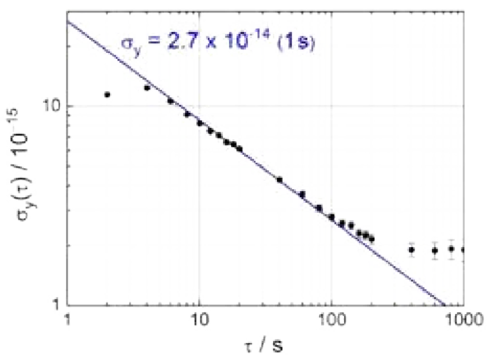

Fig. 1: Fractional frequency instability of the fountain CSF2 using a modified LVIS setup for atom loading and a microwave oscillator stabilized to an optical cavity (linear drift removed).

We will report details of this setup and describe a simple modification of the original LVIS design which results in another factor ~2 enhancement of the useful atomic flux, and a frequency instability (Fig.1) that is at the same level as the best instabilities reported so far for fountain clocks [1]. New results of DCP evaluations for both PTB fountains will be presented together with updates on their uncertainty budget.

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High stability double-modulation CPT cesium compact clock

P. Yun[1], S. Mejri[1], F. Tricot[1], M. Abdel Hafiz[2], R. Boudot[2], E. De Clercq[1], **S. Guérandel[1]**

[1]LNE-SYRTE, Observatoire de Paris, 61 av. de l'observatoire 75014 Paris

[2]FEMTO-ST, CNRS and UFC, 26 chemin de l'épitaphe 25030 Besançon

E-mail: stephane.guerandel@obspm.fr

A double-modulation CPT clock project is presented. The coherent population trapping states are prepared by alternating opposite circularly polarized bichromatic laser. Contrary to the push-pull scheme using a Michelson type setup that separates and recombines the laser beams [1, 2], our setup uses only one EO amplitude modulator as a polarization switch [3]. This simple and robust scheme may be integrated in a single linear light guide to finally get a compact laser bench.

In this scheme, the polarization of a bichromatic laser beam is modulated between two opposite circular polarizations to avoid trapping the atomic populations in the extreme Zeeman sublevels [4]. Meanwhile, an appropriate modulation of the phase between the two components of the bichromatic laser beam, the so-called Raman phase, is applied synchronously. The two CPT dark states, produced successively by the alternate polarizations, add constructively. Owing to this additional Raman phase modulation, the common dark state is decoupled from the laser at all times. For these two reasons, i.e., the atomic population accumulated to the clock states and the constructive enhance of two CPT dark states, a high contrast CPT signal of the clock transition is observed. The advantages of this scheme are following. There is no $\Delta m_F=2$ spurious CPT transitions and without the requirement of spectral resolved the excited hyperfine splitting states [5]. Moreover, our scheme provides compact and robust system for CPT atomic clock, in which only one-laser system is utilized, the sideband modulator can be removed by directly modulating the laser diode and the polarization switch is vibration insensitive.

Several experimental parameters are investigated, e.g., modulation frequency, detected time and laser intensity. An optimal modulation frequency bandwidth is found for high contrast of clock transition. Ramsey fringes with high contrast and narrow linewidth have been observed. The SNR has been evaluated, leading to an estimation of the short term frequency stability. The dominant noise source is the laser intensity noise. The latest frequency stability measurement will be reported at the conference.

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A CPT-based Cs vapor cell atomic clock with a short-term fractional frequency stability of 3 10^{-13} $\tau^{-1/2}$

M. Abdel Hafiz[1], X. Liu[1*], S. Guérandel[2], E. De Clercq[2] and **R. Boudot[1]**
[1]FEMTO-ST, CNRS, UFC, 26 chemin de l'épitaphe 25030 Besançon
*now in NIST, Time-Frequency division, 325 Broadway, Boulder, Colorado.
[2]LNE-SYRTE, UPMC, Observatoire de Paris, 77 av. Denfert-Rochereau 75014 Paris
E-mail: rodolphe.boudot@femto-st.fr

Microwave vapor cell atomic clocks, using interactions of light and thermal atoms in a vapor cell, are exciting candidates for numerous timekeeping applications because they combine compactness, a modest power consumption and excellent fractional frequency stability at the level of a few 10^{-13} $\tau^{-1/2}$. In the frame of the MClocks JRP project funded by EURAMET, we report a Cs vapor cell atomic clock based on coherent population trapping (CPT) with a preliminary short-term fractional frequency stability at the level of 3 10^{-13} $\tau^{-1/2}$ up to averaging times of 100 s. These performances are close to those of best laboratory-prototype double-resonance Rb clocks [1,2], about two orders of magnitude better than commercially-available Rb clocks and among the best performances ever reported for a CPT-based clock [3]. The optics part of our clock combines a distributed feedback (DFB) diode laser resonant on the Cs D_1 line at 894 nm, a pigtailed Mach-Zehnder electro-optic modulator driven at 4.596 GHz, an acousto-optic modulator (AOM) for laser power stabilization and a Michelson-based delay line and polarization orthogonalizer system. The laser is frequency-stabilized on an annex Cs vapor cell using a bi-color saturated absorption scheme. The optics ensemble allows to produce the so-called push-pull optical pumping (PPOP) scheme [4] leading to the detection of high-contrast CPT resonances on the clock transition [5]. CPT interaction occurs in a 2-cm diameter and 5-cm long Cs vapor cell filled with a N_2-Ar buffer gas mixture of total pressure 15 Torr. The typical clock resonance signal exhibits a contrast of about 25% and a linewidth of 400 Hz. The noise budget is mainly currently limited by laser intensity effects. The mid-term frequency stability is currently limited at the level of 3 10^{-14} by laser intensity light-shift effects. Different potential solutions will be investigated to improve performances of the clock. Proposals are to perform a Ramsey-like interrogation scheme of the clock transition for reduced sensitivity of the clock frequency to laser intensity variations or to use a Cs vapor cell with optimized buffer gas mixture. Latest results will be presented at the conference.

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Cold-atom coherent population trapping clock

X. Liu, E. A. Donley, and J. Kitching
Time-Frequency Division, National Institute of Standards and Technology, Boulder, Colorado, USA
E-mail: elizabeth.donley@nist.gov

We report a detailed study of a cold-atom coherent population trapping (CPT) clock [1]. The clock combines the techniques of laser-cooled atoms and CPT to demonstrate a ^{87}Rb atomic clock with the lin‖lin configuration [2] probed with the time-separated Ramsey method [3]. The clock achieves a short-term frequency stability of $4\times10^{-11}/\sqrt{\tau}$, limited by frequency noise on the phase-locked interrogation lasers. The light shift in this lin‖lin configuration clock was characterized in [4].

In microwave vapor-cell atomic clocks, a narrow transition linewidth is achieved by using a high-pressure buffer gas to confine the alkali atoms to the Lamb-Dicke regime [5]. However, the buffer gas introduces large pressure shifts. Laser-cooling techniques remove this shift, but at the expense of potentially re-introducing a Doppler shift. With balanced CPT interrogation with counter propagating beams, the reintroduced Doppler shifts can be substantially reduced.

We have previously characterized the Doppler shift in our system with the interrogation beams aligned parallel to the direction of gravity where the shift is largest [1]. Currently, we are operating the system with the interrogation beams propagating horizontally. We still observe a Doppler shift under horizontal interrogation if the beams are misaligned or imbalanced.

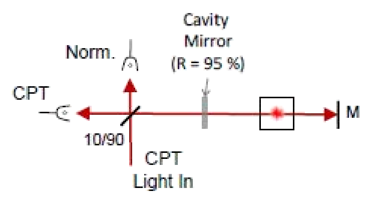

Fig. 1: Simple cavity excitation scheme to minimize Doppler effects.

Biases to the Doppler shift can be estimated by measuring clock shifts as a function of the position of the retroreflecting mirror, which simulates changes of the atoms' initial position that can arise from thermal and mechanical drift. In our current system, we estimate that a change in 10 μm for the initial atom position would cause a fractional frequency shift of 1×10^{-13}. This sensitivity to the Doppler shift can be improved by using more balanced counterpropagating beams. We propose a simple cavity around the atoms (Fig. 1) that would force the counterpropagating beams to be more in balance and less sensitive to the beam alignment.

The latest measurement results of the Doppler shift and also the achieved frequency stability of the clock will be presented at the conference.

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Atomic clock using coherent population trapping in a cesium cell: Frequency stability and limitations

Sinda Mejri, François Tricot, Jean-Marie Danet, Peter Yun, Emeric de Clercq, and Stéphane Guérandel
LNE-SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, 61 avenue de l'Observatoire, 75014 Paris, France
E-mail: Sinda.mejri@obspm.fr

Compact and stable frequency standards are needed in many applications such as GPS or Galileo, the European GNSS. Double resonance alkali-metal vapor-cell atomic clocks are currently used for this purpose. Toward to the next generations of compact atomic clocks, clocks based on Coherent Population Trapping (CPT) phenomenon offer a very interesting alternative [1]. In fact thanks to their simple scheme and high performance stability they represent a promising candidates for on-board applications [2].

The laboratory prototype pulsed clock presented here intends to explore what could be the ultimate stability of a CPT based clock. In order to do so our clock combine a double Λ optical scheme and a pulsed interrogation Ramsey technique to get a good compromise between contrast and linewidth. In our clock the two lasers fields are generated by two phase-locked extended cavity diode laser (ECDL) tuned to the Cs D1 line transmission. A great deal of work has been done to investigate the two mains frequency noise source [3]: laser intensity noise and the local oscillator noise. It led to a state-of-the art stability measurement at the level of $3.2x10^{-13}$ at 1s (Fig.1).

In this presentation we will point out our current limitations in term of short-term and mid-term stability. For the short term stability we are aiming to improve the signal-to-noise ratio and optimize the time sequence and the parameters of our clock. A new frequency chain build with collaboration of INRIM FEMTO-ST (EMRP project INDSS clock) will be used in order to minimize further the contribution of the Dick effect, originates from the down-conversion of the local oscillator intrinsic frequency noise. For the long-term stability, a careful study is conduct on the influence of the laser power and the magnetic field on the clock frequency.

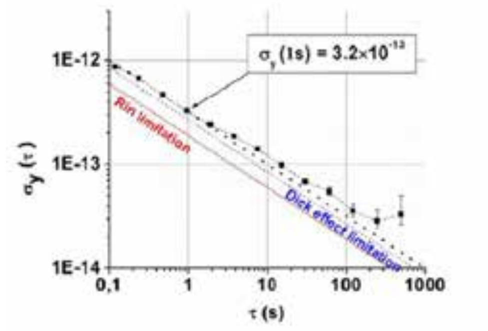

Fig.1 Short term frequency stability. Black dots: Measurement. Black dashed lines: Asymptotic behavior of the measurements: $3.2 \times 10^{-13}\ \tau^{-1/2}$

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Relaxation times and stability studies for a compact pulsed optically pumped vapor cell clock

C. Affolderbach[1], S. Kang[1], M. Gharavipour[1], F. Gruet[1], G. Mileti[1]
1. Laboratoire Temps-Fréquence, Institut de Physique, Université de Neuchâtel, Neuchâtel, Switzerland.
E-mail: Christoph.affolderbach@unine.ch

We are reporting on our studies towards a very compact realization of a high-performance pulsed optically pumped (POP) Rb vapor-cell frequency standard, in view of novel frequency standards for industrial applications (EMRP project IND55, Mclocks). This clock approach is based on pulsed optical and microwave interrogation in the Ramsey scheme applied to a Rb vapor cell, shown to enable clock stabilities on the level of $\approx 1\times10^{-13}\ \tau^{-1/2}$ down to below 10^{-14} level at one day integration time [1]. In view of a rugged clock realization, our clock physics package is based on a 25 mm diameter Rb vapor cell held inside a compact magnetron-type microwave cavity resonator of 45 mm^3 external volume only [2]. When combined with a frequency-stabilized laser head with integrated acousto-optical modulator for switching of the laser light, the overall physics package of this clock can be significantly smaller than ≈ 5 liter overall volume.

For characterization of the clock physics package, we employ Rabi oscillations and a microwave field imaging technique to assess the homogeneity or the microwave field in the cavity, to assure well-realized π/2 pulses over a large part of the vapor-cell volume. Franzen's technique is used to measure the T1 relaxation time, and Spin echo yields a T2 time of 3 ms, in agreement with theoretical expectations for the cell used. The observed Ramsey signals (see Fig.1) show a contrast of up to 35% with a linewidth of 160 Hz (limited by the 3 ms Ramsey time). With such signals, we measure a typical short-term clock stability of $2.1\times10^{-13}\ \tau^{-1/2}$, currently mainly limited by the detection noise [3]. Measurements of systematic shifts such as light shifts, microwave power shifts, etc. indicate that a clock stability of $< 10^{-14}$ at 1 day should be feasible with our compact clock system.

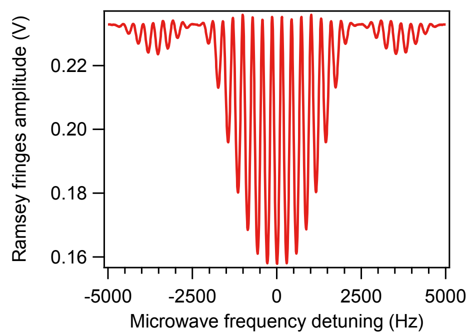

Fig. 1:High-contrast Ramsey fringes observed with the compact POP clock atomic resonator package.

This work was supported by the Swiss National Science Foundation (SNSF grant no. 140712) and the European Metrology Research Programme (EMRP project IND55-Mclocks). The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union. We also acknowledge previous support from the European Space Agency (ESA) and the Swiss Space Office (Swiss Confederation). We thank C. Calosso (INRIM) for providing the microwave local oscillator.

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Pulsed Optically Pumped Rb clock

F. Levi[1], **C. E. Calosso**[1] , **A. Godone**[1], **B. François**[1], **S. Micalizio**[1], **R. Boudot**[2], **C. Affololderbach**[3], **S. Kang**[3], **M. Gharavipour**[3], **F. Gruet**[3], **G. Mileti**[3]

[1]Physical Metrology Division, INRIM, Torino
E-mail: f.levi@inrim.it

[2]Femto-St, CNRS, UFC, Université de Franche Comté, Besançon, France
rodolphe.boudot@femto-st.fr

[3]Laboratoire Temps Fréquence, Université de Neuchâtel, Neuchâtel, Switzerland
christoph.affolderbach@unine.ch

Development of high stability, low consumption, compact clocks is an important challenge for today's technology, both for space and for ground applications. Several different approaches have been pursued in the last years with interesting results on the short term stability. The pulsed Optically Pumped Rb Clock (POP), with the possibility to separate in time optical pumping and microwave interrogation, is one of the most promising technique. In fact, other than reducing by several order of magnitude the light shift, the pulsed scheme allows to optimize both the microwave amplitude and the detection laser power thus achieving better S/N ratio. While several different approaches have demonstrated good short term stabilities in 10^{-13} range at 1s, to our knowledge the only approach that could tame at the same time also the long term drift is the POP.

The first prototype of the POP was developed at INRIM under an ESA contract aimed at identifying possible candidates to replace the passive H-maser currently used for on board Galileo GNSS satellites. The results of this system are reported in fig 1: a short term stability $\sigma_y(\tau)= 1.7\times10^{-13}\ \tau^{-1/2}$ and a long term drift of 7×10^{-15}/day were obtained [1]. Aiming to a further improvement of the clock performances, a new system is being developed taking in particular care the design of the microwave synthesis chain, the thermal stability and uniformity of the Rb cell. Another issue is the overall size of the clock; in this regard, a very compact laser head source has been developed and characterized and a magnetron cavity will be tested in the physics package.

In the presentation, together with the most recent results achieved by our new prototype, we will discuss the major causes of noise that affect the short and long term stability of the cell clocks, showing how these effects are mitigated in the POP approach.

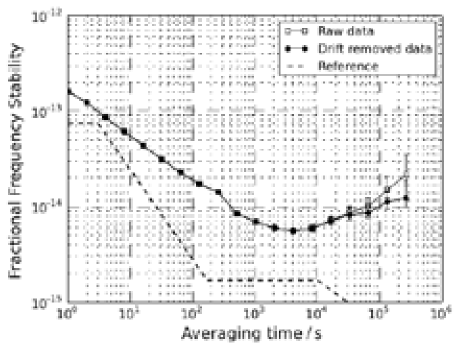

Fig. 1: Stability of the POP prototype.

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Metrological characterization of the pulsed Rb clock with optical detection, Metrologia, **49**, 425-436 (2012).

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Features of adjustment of the magnetic field in the quantum frequency standard on the atoms of caesium-133

A. Petrov, **V. Davydov**
Peter the Great Saint-Petersburg Polytechnical University
E-mail: Alexandrpetrov.spb@yandex.ru

Currently caesium atomic clocks are the main devices allowing the formation and reproduction with the high accuracy of physical unit of time and frequency. High-precision atomic clocks have a high importance in science and technology and a vast area of their application. The greatest difficulty in ensuring stable operation of quantum frequency standards arise when they are used in a variety of aircrafts. Especially, when the aircrafts move with the high speed and etc.

The design of modern aircrafts is constantly changing and new requirements for their parameters are produced to them. This leads constantly upgrade existing and develop new models of quantum atomic clocks. For this aims it is reasonable to carry out research, develop new methods and find a new design solutions based on the latest appearing electronic components and discovered physical phenomena. Development of new models of frequency standards is a complex task for the implementation, which needs a lot of time. Therefore, applied research in this field, in contrast to the fundamental, aimed at solving problems of improving and modernization existing designs of frequency standards.

In present work one of the directions of modernization of the cesium atomic clock is considered. A new implementation of a digital frequency synthesizer and a magnetic field control unit for atomic clocks are presented. In designs of these blocks various overloads and influences which will arise in aircraft at the fast movement and change of its direction are considered.

In difficult operation conditions it is necessary to provide big resolution of frequency of 12,631 MHz directly influences to the accuracy of obtaining resonant frequency of nuclear transition. New scheme of the frequency synthesizer is designed using method of direct digital synthesis. Experimental study of frequency synthesizer showed improvement parameters of the microwave-excitation signal, such as the step of frequency tuning, time of the frequency tuning, range of generated frequencies and spectral characteristics.

A range of generated output frequencies is expanded, and the possibility of detuning the frequency of the neighboring resonance of spectral line that makes it possible to adjust the C-field in quantum frequency standard is implemented. This feature gave us the opportunities to close the ring-locked loop frequency oscillator on the neighboring resonance transition. By alternately locking ring-locked loop at the central and the neighboring transition resonance the frequency of the quartz generator adjusts to the frequency of the atomic transition, and the value of the magnetic field inside the atomic beam tube remains constant. In this case the effects associated with changes in the magnetic field are excluded.(for example, long-term drift of the current source, the temperature dependence, the influence of an external magnetic field, etc.)

Experimental research of the metrological characteristics of the quantum frequency standard on the atoms of caesium - 133 with new scheme of the frequency synthesizer and the magnetic field control unit showed improvement in daily frequency stability on 1.2×10^{-14} at variable load conditions that may occur during the operation of aircraft.

Self-generating magnetometer with laser pumping employment in "end resonance" wall coated vapor cell atomic clocks.

A. Baranov, S. Ermak, E. Sagitov, R. Smolin , V. Semenov
Department of Quantum Electronics, St. Petersburg Polytechnic University, St. Petersburg, Russia
E-mail: Vladimir_semenov@mail.ru

In this report we present the results of two vapor cell magnetometers with a single optical trunk simultaneous operation ability in atomic clocks based on the "end" microwave transition. The first magnetometer is a spin generator, while the second is based on a passive radio spectroscope scheme with resonance frequency auto tuning to one of an alkali atom ground state "end" transitions.

A semiconductor laser tuned to Rb^{87} D_2 line was used as source of optical pumping. The joint trunk demonstrated high degree of correlation between observing signals and minimum inaccuracy during data processing was reached.

An anti relaxation wall coated small size vapor cell (1 cm^3) was placed in the center of Helmholtz coils, which created working magnetic field of 100 nT at an 45° angle to the light propagation of the laboratory setup. External magnetic fields were weakened by magnetic shield with a shielding factor 100.

The difference of two magnetometers signals was processed to determine Allan variance of the dual scheme. In wall coated cells this property significantly depends on circular polarization sign because of the possibility of the vector and scalar light shift components mutual compensation [2]. This effect has principle restriction and cannot be observed in a buffer gas vapor cell [1].

The dual scheme with the reference "end" transition demonstrates better stability for 100+ seconds averaging times in comparison to 0-0 transition. Workability of this scheme can be realized on long-wave component of the electro-dipole transition only, when maximum amount of atoms interacts with optical field. Due to low atoms concentration on the short wave component of the D2 line, self generating requirement cannot be fulfilled.

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On the possibility of achieving higher metrological characteristics of the atomic clock with the ^{87}Rb-absorption cell (wall coating + buffer gas)

Evgeny Pestov

The Fed. State Scient./Prod. Ent. "Geologorazvedka", 19/1 Knipovich str., St.-Petersburg 192019
The Russian Institute of Radionavigation and Time, RIRT, 2 Rastrelli sq., St.-Petersburg 191124, Russia
E-mail: *infra-balt@peterlink.ru*

It is known that short-, medium- and long-term frequency stability are the main metrological characteristics of atomic clock.

In this work the author represents investigation results of several principle parameters of atomic frequency discriminator (AFD) that make it possible to obtain maximum stability of atomic clock in the regime with continuous laser pumping of ^{87}Rb absorption cell with two anti-relaxation (AR) components (wall coating + buffer gas) [1,2].

It is known that basic AFD parameters such as signal value (S), resonance width ($\Delta\nu_{0-0}$), light shift of resonance frequency $\delta\nu_{0-0}(I)$ depending on laser pump intensity I, additional noise from laser radiation (N_{LAS}) [3], temperature frequency coefficient (TFC) [1,2] and variable in time shift of resonance center $\delta\omega^{(1)}_{p\text{-}ch} = (\gamma\cdot H_1\cdot z/a)\cdot\cos\theta$ [4] define the stability in time of atomic clock. Frequency shift $\delta\omega^{(1)}_{p\text{-}ch}$ is the first correction of mcw fiefd amplitude H_1 to 0-0 resonance frequency.
This work represents the results of research for the last three parameters (N_{LAS}, TFC, $\delta\omega^{(1)}_{p\text{-}ch}$).

1. In particular, for reducing *short-term* clock instability $\sigma_y(\tau)$ the principle question is the problem of decreasing additional amplitude noise N_{LAS} which arises from the frequency fluctuations of laser radiation. One of the solutions to this problem is represented in [3]. We offer a more effective method of noise reduction to extremely low values, even to "zeroing" of these noise from laser source.

2. Investigation results in achieving maximum low TFC value in ^{87}Rb cells with two AR-components are represented [2]. In the experiment the possibility of achieving TFC value at the level of < $1\cdot10^{-13}$/ deg. at cell temperature t° ~ 57°C is shown that significantly increases the *medium-term* stability of atomic clock.

3. The principle question for realization of high *long-term* stability of atomic clock is reducing to zero of a drift varying-in-time shift of resonance frequency, $\delta\omega^{(1)}_{p\text{-}ch}$. The first correction $\delta\omega^{(1)}_{p\text{-}ch}$ to resonance frequency is a source of regular long-period drift of 0-0 resonance center, ν_{0-0}, with a very long period - from units to ten days and more. Solutions of this problem are found-out.

Conclusion

In solving the examined physical and technical problems the ^{87}Rb atomic clocks can actually have the metrological characteristics comparable to the hydrogen frequency standards (or above).

The author extends appreciation to Dr. G. Mileti and Dr. J. Delporte for stimulation the investigation concerning ^{87}Rb absorption cells with AR-Coating.

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Next Generation JPL Ultra-Stable Compensated Multipole Trapped Ion Atomic Clock

Eric Burt, Lin Yi, and Robert Tjoelker

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

Email: eric.a.burt@jpl.nasa.gov

Over the past two decades, the long-term stability of trapped ion atomic clocks developed at the Jet Propulsion Laboratory (JPL) has improved dramatically. The first improvement resulted from the implementation of a quadrupole linear ion trap [1], the second resulted from the introduction of multi-pole traps [2], and a third key improvement resulted from the introduction of a magnetically compensated multi-pole ion trap [3]. At the 2008 Frequency Standards and Metrology conference we presented results demonstrating an order of magnitude improvement in long-term stability using magnetic compensation in the JPL multi-pole trapped ion standard, LITS-9 [4]. In this paper we will present the design and results from two new ultra-stable trapped ion clocks that use this compensation technique.

The two new identical clocks, build on the LITS-9 experience by incorporating magnetic compensation into the design with a goal of improving the exceptionally low drift of less than 3×10^{-17}/day [5] to below 1×10^{-17}/day. The significant reduction in the second-order Doppler shift enabled by magnetic compensation leaves background gas collisions as the largest residual systematic effect in these clocks. We will present improvements in the design of the vacuum chamber that are expected to give further performance improvements. The first of these clocks, designated L10, has been delivered to the Naval Research Lab, while the second, and eventually a third and fourth, will be retained as in-house standards at JPL.

L10 during delivery to NRL.

The excellent long-term stability of LITS-9, and the anticipated equivalent or better performance of the new clocks, has both engineering and scientific applications. It will be invaluable for characterizing the performance of flight clocks both at JPL and at NRL, as well as that of clocks being delivered to, and operated in NASA's Deep Space Network. In addition, the new standard at JPL will be used as a reference for an ACES ground station [6] at JPL when the ACES laser-cooled atomic clock becomes operational on the International Space Station in the 2017 time frame. We will describe the ensemble of clocks that we will use as the reference for the ACES Ground Terminal located at JPL.

Finally, in 2008 we reported on ideas for implementing a new trapped ion clock based on a different isotope of mercury. All trapped mercury ion clocks use $^{199}Hg^+$, however $^{201}Hg^+$ is also stable and had received little study. In this conference we will report on implementation of a $^{201}Hg^+$ clock, initial results, and scientific measurements including a new measurement of the hyperfine anomaly in mercury [7]

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Miniature Trapped-Ion Frequency Standard with $^{171}Yb^+$

Peter D. D. Schwindt[1], Yuan-Yu Jau[1], Heather Partner[1], Jeffery Hunker[1], Darwin Serkland[1], Adrian Casias[1], Ronald Manginell[1], Matthew Moorman[1], John Prestage[2], Nan Yu[2], Igor Kosvin[3], Dan Boschen[3], David Scherer[3], David Mailoux[3]

1. Sandia National Laboratories, Albuquerque, NM/USA
2. Jet Propulsion Laboratory, Pasadena, CA/USA
3. Microsemi, Inc., Beverly, MA/USA

E-mail: pschwin@sandia.gov

We are developing a highly miniaturized trapped-ion clock by probing the 12.6 GHz hyperfine transition in the $^{171}Yb^+$ ion. Our goal is to achieve long-term frequency stability in the 10^{-14} range in a package that is as small as and consumes as little power as possible. Trapped ion systems are an excellent candidate for such extreme miniaturization because ions are well isolated from the environment independently of the size of the trap. Significant miniaturization has already been demonstrated with the $^{199}Hg^+$ trapped ion clock developed at the Jet Propulsion Laboratory [1].

We will discuss the development of the ion trap physics package [2] and its integration with other key elements of the frequency standard, including miniaturized laser sources at 369 and 935 nm, a local oscillator, control electronics, and a microfabricated Yb source for trap loading. We have recently demonstrated operation of the 1 cm^3 ion trap vacuum package. The package is made from titanium with sapphire windows. The ion trap is built up on a high temperature co-fired ceramic (HTCC) substrate to which Ti trap electrodes and microfabricated Yb sources are brazed. The package is evacuated through a copper tube, and once the appropriate vacuum conditions are achieved in package, the copper tube is crimped to form a cold weld seal. Vacuum conditions are maintained by an internal non-evaporable getter. We implemented the vacuum package in an atomic clock and demonstrated $2 \times 10^{-11}/\tau^{1/2}$ performance. In addition, we will show results of using a methane buffer gas to quench the low-lying $^2F_{7/2}$ state in ^{171}Yb. In our small sealed vacuum packages as many as 95% of the ions are in th F-state during clock operation, and we show the viability of collisionally quenching the F-state, limiting the F-state population to < 10%.

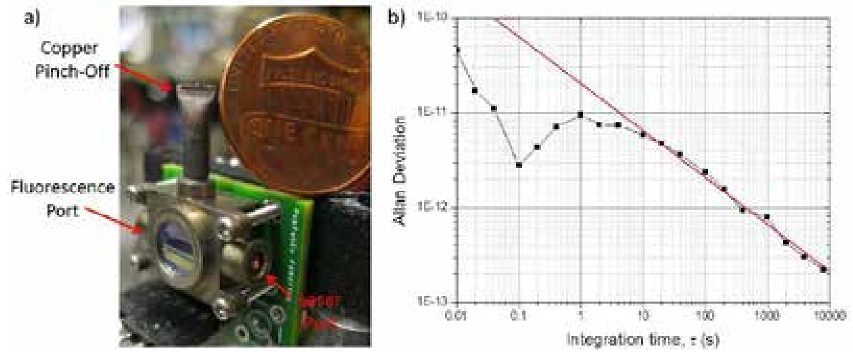

Fig. 1.(a) Picture of the 1 cm^3 vacuum package. (b) Performance of the vacuum package in an atomic clock.

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Low He Permeation Cells for CSACs

A. Dellis, S. Knappe, E.A. Donley, J. Kitching
National Institute of Standards and Technology, Boulder, Colorado 80305, USA
E-mail: argyrios.dellis@nist.gov

Chip Scale Atomic Clocks (CSACs) [1] have been successfully used as low cost and low power frequency standards for about a decade. Their long-term stability is affected, among other parameters, by changes in the buffer gas pressure. Usually the windows of CSAC cells are made of Pyrex, a material known to be permeable to Helium. It can be estimated that atmospheric Helium can diffuse through the Pyrex, causing a drift in the clock frequency of about 10^{-12}/day. This result is consistent with the observed drift in CSACs after several years of operation. Replacing Pyrex with a low permeation rate material such as alumino-silicate glass (ASG) may solve the problem and improve the stability of the clock.

We have identified a suitable source of ASG that is fabricated in wafer form and can be anodically bonded to silicon. Moreover we have successfully fabricated micro-machined alkali vapor cells using this type of glass for the optical windows and we have developed a method for measuring the permeation rate. We have measured the permeation rate of ASG in our microfabricated cells and it was found to be about a factor of 100 lower than that of Pyrex at 90^{o}C. This result suggests that alumino-silicate glass can be used to suppress Helium permeation in microfabricated cells and thus can improve the long-term stability of chip scale atomic clocks.

In the future, alumino-silicate glass windows could be used in combination with passive pumping techniques, such as non-evaporable getters, in order to completely replace large vacuum pumps. In this way they could contribute to the miniaturization of instruments and sensors based on laser-cooled atoms [2].

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A Sr Optical Lattice Clock at NPL for both ^{87}Sr and ^{88}Sr

I.R. Hill[1], R. Hobson [1, 2], W. Bowden[1, 2], M. Menchetti [1, 3], E.A. Curtis[1], R. Williams[1], P. E. G. Baird[1, 2], K. Bongs[1, 3], P.Gill[1]
1. Time and Frequency, National Physical Laboratory, Teddington, UK
2. Clarendon Laboratory, Oxford University, Oxford, UK
3. School of Physics and Astronomy, University of Birmingham, Birmingham, UK
E-mail: ian.hill@npl.co.uk

Optical lattice clocks with fermionic ^{87}Sr have recently demonstrated exceptional accuracy and stability [1], progressing toward the 10^{-18} level of total clock uncertainty. We outline the current status of the strontium lattice clock at the NPL, including results from the Euramet International Timescales with Optical Clocks (ITOC) campaign. We present an absolute frequency measurement of the $^1S_0 – {}^3P_0$ transition in ^{87}Sr, along with a corresponding uncertainty budget. The linear Zeeman shift and the vector lattice shift are cancelled by locking the clock laser to alternating hyperfine stretched states, and other shifts are evaluated with extrapolation techniques. The addition of a beat-note lock of the clock laser to a 'universal synthesizer' helps suppress short-term cavity noise, facilitating improved Dick-limited clock instability. We ensure reliable long-term clock operation as well as low shot-to-shot atom number fluctuations (<5%) by stabilizing the intensity and frequency of all cooling and state-manipulation lasers, which are referenced through a transfer cavity to the clock laser frequency.

We also report on our first frequency measurement of the $^1S_0 – {}^3P_0$ clock transition in ^{88}Sr in a 1D magic-wavelength optical lattice using magnetically induced spectroscopy (MIS) [2]. The bosonic ^{88}Sr presents several advantages compared to ^{87}Sr, e.g. no vector or tensor lattice Stark shifts, no first-order Zeeman shift, ten times higher natural abundance, and a simpler cooling sequence. However, these advantages come at a cost: The ultra-forbidden clock transition in bosons is not easily accessible, and s-wave atomic interactions cause large collisional decoherence and shifts [3]. Interactions may be suppressed in a system containing one or fewer atoms per lattice site [4], or potentially using a higher-dimensional optical lattice to spectrally resolve the collisional energy shift [5]. To address the large ac-Stark and quadratic Zeeman shifts associated with MIS we plan to implement Hyper-Ramsey spectroscopy [6].

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Tranportable optical frequency standard at $1\cdot10^{-15}$ uncertainty

S.B. Koller, St. Vogt, J. Grotti, S. Häfner, S. Herbers, U. Sterr, Ch. Lisdat

Physikalisch-Technische Bundesanstalt, Bundesallee 100, Braunschweig, Germany
E-mail: silvio.koller@PTB.de

Optical lattice frequency standards have now reached a performance exceeding the Cs clock uncertainty and its stability by 2 orders of magnitude [1]. The stability of the neutral atom optical lattice clocks is superior to ion clocks due to the fact that many atoms can be interrogated at the same time. To transfer the high precision in time and frequency over large distances, transmission via global navigation satellite systems (GNSS) has become insufficient. Therefore, transportable frequency standards or stabilized optical fiber links are necessary [2]. Further, transportable optical lattice frequency standards allow for relativistic geodesy (height measurement) [3] at the decimeter and in future centimeter level between arbitrary far points limited by the fiber length connecting the two points.

We present our first results and characterization of the PTB transportable ^{87}Sr frequency standard. This consists of a physics package, several compact laser breadboards, and a transportable high finesse cavity to lock the clock laser. We have successfully tested the parts of our system for transportability. We have compared the transportable system with our stationary optical lattice clock in fall 2014. Our preliminary results show an uncertainty of $1\cdot10^{-15}$ and an instability of $2.2\cdot10^{-15}\sqrt{s/\tau}$. The uncertainty was limited by the free running optical lattice near the magic wavelength. The stability is limited by the transportable clock laser system. We are currently improving of our transportable system to reach an uncertainty at or below 10^{-17} level limited by the uncertainty in black body radiation.

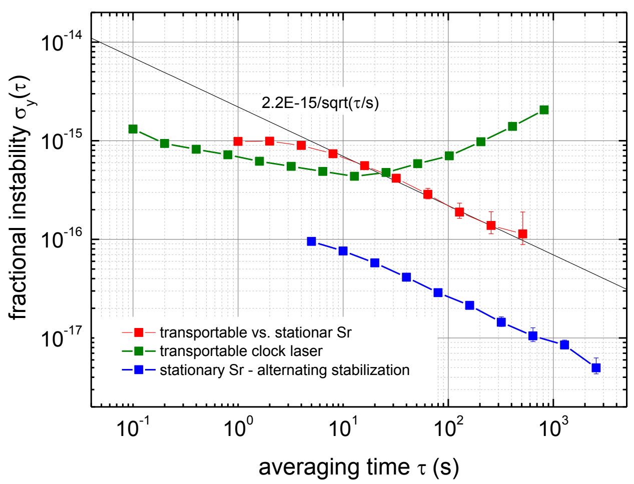

Fig. 1: Plot of the Allan deviation for transportable clock laser (green) and comparison with stationary system (red) $(2\cdot10^{-16}\sqrt{\ \ \tau})$. Additionally, the instability of the stationary system is shown (blue).

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Development of a strontium optical lattice clock for the Space Optical Clocks mission on the ISS

Y. Singh[1], L. Smith[1], S. Origlia[2], W. He[1], D. Świerad[1], J. Hughes[1], O. Kock[1], S. Alighanbari[2], S. Schiller[2], K. Bongs[1], S. Vogt[3], U. Sterr[3], C. Lisdat[3], R. Le Targat[4], J. Lodewyck[4], D. Holleville[4], B. Venon[4], S. Bize[4], G. P Barwood[5], P. Gill[5], I.R. Hill[5], Y.B. Ovchinnikov[5], N. Poli[6], G. M Tino[6], J. Stuhler[7], W. Kaenders[7], E.M. Rasel[8], *and the SOC2 team* [9]

[1]*Department of Physics and Astronomy, University of Birmingham, Edgbaston Park Road, Birmingham B15 2TT, UK*
[2]*Heinrich- Heine-Universität Düsseldorf, Germany*
[3]*Physikalisch-Technische-Bundesanstalt,Germany*
[4]*Observatoire de Paris, France;*
[5]*National Physical Laboratory Teddington, the United Kingdom ;*
[6]*Universita' di Firenze;*
[7]*TOPTICA Photonics AG, Germany;*
[8]*Leibniz Universität Hannover, Germany;*
[9]*EADS Astrium Friedrichshafen, Germany;*
[9]*Menlo Systems GmbH, Germany;*
[9]*Kayser-Threde GmbH, Germany;*
[9]*Kayser Italia S.r.l.,Italy*
[9]*Centre Suisse d'Electronique et de Microtechnique SA, Switzerland ;*
[9]*Université de Neuchâtel, Switzerland ;*
[9]*Ecoles Polytechniques Fédérales Lausanne, Switzerland;*
[9]*Istituto Nazionale di Ricerca Metrologica, Italy*
E-mail: y.singh.1@bham.ac.uk

Within an European Space Agency (ESA) program, the "Space Optical Clocks" (SOC) project aims to install and to operate an optical lattice clock on the International Space Station (ISS) towards the end of this decade. It would be a natural follow-on to the ACES mission, improving its performance by at least one order of magnitude. The payload is planned to include a strontium optical lattice clock, as well as a frequency comb, a microwave link, and an optical link for comparisons of the ISS clock with ground clocks located in several countries and continents.

Within the EU-FP7-SPACE-2010-1 project No. 263500, we have developed a novel Sr lattice clock apparatus of modular design and consisting of compact subunits [1-3]. The goal performance is a fractional frequency instability below $1\times10^{-15}\tau^{-1/2}$ and a fractional inaccuracy below 5×10^{-17}. At present, the apparatus can reliably trap atoms in the first-stage and single-frequency second-stage MOTs.

Currently, we are working on trapping atoms in the optical lattice, after which the apparatus will be transferred to PTB in the summer 2015 for further optimization and characterization with respect to stationary optical clocks. We will present the most recent results of the Sr optical clock in SOC2, its novel compact design features, new methods employed and outlook.

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Measuring the Yb/Sr clock frequency ratio with cryogenic optical lattice clocks

N. Nemitz[1], **T. Ohkubo**[1,2,3], **M. Takamoto**[1,2,4], **I. Ushijima**[1,2,4], **M. Das**[1,2,4], **N. Ohmae**[1,2,3], **H. Katori**[1,2,3,4]

1. Quantum Metrology Laboratory, RIKEN, Wako, Saitama, Japan
2. Innovative Space-Time Project, ERATO, Japan Science and Technology Agency, Tokyo, Japan
3. Dep. of Applied Physics, Graduate School of Engineering, The University of Tokyo, Tokyo, Japan
4. RIKEN Center for Advanced Photonics, Wako, Saitama, Japan

E-mail: Nils.Nemitz@riken.jp

Optical lattice clocks now approach an overall fractional uncertainty of 10^{-18} [1,2,3]. RIKEN operates multiple optical lattice clocks utilizing Sr, Yb and Hg atoms [4], and the results of comparing clocks interrogating different atomic species can not only provide constraints on the variation of fundamental constants, but also demonstrate performance and reproducibility of optical clocks: As the resulting ratios are simple dimensionless numbers, they are easily transferred and can be tested by an laboratory with access to the same combination of clocks.

Two of the clocks at RIKEN interrogate atoms in a cryogenic environment to suppress blackbody radiation shifts to below 10^{-16} and have been designed for operation with both Sr and Yb. In the experiments presented, one clock measures the Sr clock frequency with an overall uncertainty of 7×10^{-18} [3], while the second interrogates Yb atoms. Using a frequency comb with high control bandwidth to derive the stability of the Yb clock laser from the Sr clock laser [5], a significant fraction of the residual phase noise is common between both and can be suppressed by the technique of synchronous interrogation [6].

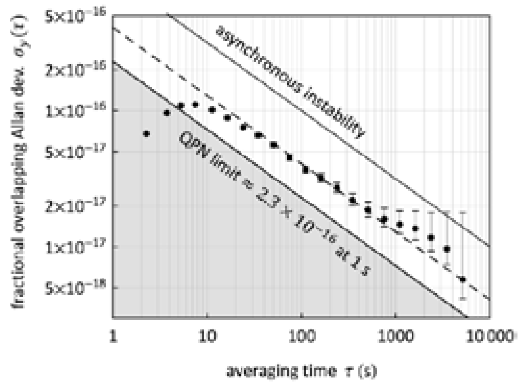

Fig. 1: Fractional instability of a ratio measurement.

Ratio measurements show an instability below 10^{-17} for one hour of averaging time, corresponding to $\sigma_y(\tau) \leq 5\times10^{-16}\,(\tau/s)^{-1/2}$ [Fig. 1]. A preliminary characterization of the Yb clock yields a systematic uncertainty of 2.3×10^{-17}, which will enable frequency ratio measurements with an uncertainty below 3×10^{-17}. We will present the current uncertainty budget of the Yb clock and our latest work to measure the Yb/Sr frequency ratio beyond the limit of the current definition of the SI second.

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Two independent ^{88}Sr optical lattice clocks at KL FAMO

P. Morzyński[1], **M. Bober**[1], **A. Cygan**[1], **D. Lisak**[1], **J. Zachorowski**[2], **P. Masłowski**[1], **F. Ozimek**[3], **M. Prymaczek**[1], **M. Piotrowski**[2], **P. Wcisło**[1], **P. Ablewski**[1], **M. Piwiński**[1], **S. Wójtewicz**[1], **K. Bielska**[1], **D. Bartoszek-Bober**[1], **M. Zawada**[1], **R. Ciuryło**[1], **W. Gawlik**[2], **C. Radzewicz**[3]

1. Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziądzka 5, PL-87-100, Toruń, Poland
2. M. Smoluchowski Institute of Physics, Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University, St. Łojasiewicza 11, PL-30-348, Kraków, Poland
3. Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Hoża 69, PL-00-681 Warsaw, Poland

E-mail:pmorzynski@fizyka.umk.pl

We report a system of two independent bosonic strontium optical lattice standards with ^{88}Sr probed with a single shared ultra-narrow laser [1]. We achieve frequency stability (frequency difference between two standards) of $3*10^{-16}$ after 2500 s of averaging (Fig. 1). All best present realizations of the strontium optical clocks are made with fermionic strontium isotope ^{87}Sr since the bosonic isotopes are expected to have larger collisional effects on the clock transition. Additionally, the bosonic isotopes require at least one extra field to induce the clock transition, which implies careful control of this field and its respective field shift. On the other hand, the bosonic lattice clocks have some advantages over their fermionic counterpart: no first order Zeeman shift, no vector or tensor lattice Stark shifts and much higher isotopic abundance. In our system the low collisional shift is ensured thanks to large waist of the lattice and only a few atoms per lattice site in a trap.

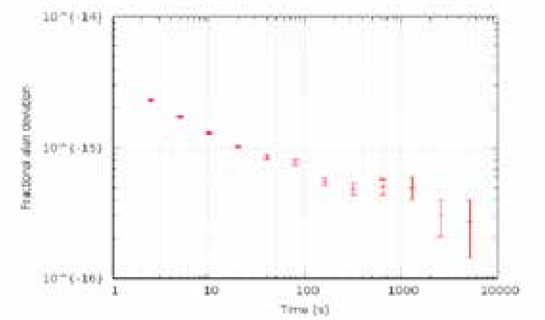

Fig. 1: The measured frequency stability (frequency difference between two standards) in fractional units represented by the Allan standard deviation.

The absolute frequency of the clock transition can be measured by the use of a frequency-doubled Er:fiber polarization-mode-locked optical frequency comb referenced either to the GPS-disciplined Rb frequency standard or for higher accuracy to the UTC(AOS) and UTC(PL) [2,3] via the 330 km long distance stabilized fiber optic link of the OPTIME network [4].

We present current status of the KL FAMO optical lattice clocks, including their frequency stability, the uncertainty budget and the measured absolute frequency of the clock line.

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Development of optical clocks based on strontium atoms: dipole trap.

S. Strelkin[1], A.Galyshev[1], O.Berdasov[1], A.Gribov[1], K.Khabarova[1,2], N.Kolachevsky[1,2], S.Slyusarev[1].

1.Russian Research Institute of Physical, Technical and Radiotechnical Measurements (FSUE "VNIIFTRI"),Mendeleevo, Moscow, 141570, Russia
2.P.N.Lebedev Physical Institute of the Russian Academy of Sciences
53, Leninskiy Prospekt, Moscow, 119991, Russia
E-mail: sergstrelkin@gmail.com

Currently, an optical clock based on cold strontium atoms, captured in an optical lattice, is being developed in the laboratory of FSUE VNIIFTRI. The prospect of such work is confirmed in a number of experiments conducted in various laboratories around the world. Among the numerous candidates for the role of optical clocks, Sr has magic wavelength of optical lattice[1] and energy levels, which allow conducting an effective 2-stage cooling down to the temperature of several μK.

On the first stage of cooling ("blue" MOT) transition $^1S_0$-$^1P_1$ with the wave length of 461 nm is used, which allows to cool atoms down to the temperature of about 1mK. In our experiments, the real final temperature after "blue" MOT is 6 mK due to the necessity of maintaining the balance between the number of atoms and their temperature. The temperature is determined by the thermal expansion of atomic cloud on a series of images from CCD.

Also, a second stage cooling ("red" MOT) on the transition $^1S_0$-$^3P_1$ was implemented. In the second cooling stage, the requirements to the spectral characteristics of the cooling-laser radiation are very stringent. A laser system with a narrow generation line based on ULE cavity has been developed and investigated.[2,3] "Red" MOT consists of two stages: broadband frequency MOT and single frequency MOT. Broadband frequency cooling permits to reload about 30% of cooled in a "blue" MOT atoms into a "red" MOT. Single frequency allows decreasing the final temperature down to 3 μK. Such significant decrease in the temperature of atoms has made implementation of dipole trap on magic wavelength of 813 nm possible. For these purposes, a commercial laser TOPTICA with outgoing radiation power of 1.5W was used. Laser's radiation is directed into the polarization-maintaining fiber and is focused into a cloud, with a beam waist radius about 30 microns. The described configuration allows obtaining about 1% of atoms in the dipole trap.

At the moment, research and optimization of dipole trap are performed. Also, a system for magnetic field-induced spectroscopy of forbidden optical transition $^1S_0$-$^3P_0$ has been prepared.

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Magic Wavelength Measurement of the Strontium Optical Lattice Clock at NIM

Y. Lin[1], Q. Wang[1,2], Y. Li[1,2], B. Lin[1,2], F. Meng[1], E. Zang[1], T. Li[1], Z. Fang[1]

1. Time and Frequency Division, National Institute of Metrology, Beijing, China
2. Department of Precision Instruments and Mechanology, Tsinghua University, Beijing, China

E-mail: linyige@nim.ac.cn

An optical lattice clock based on ^{87}Sr is being built at NIM. The strontium atoms experience a two-stage laser cooling process[1]. After the first stage 461 nm broadband laser cooling, the atoms are further cooled down to less than 3 μK with the second stage narrow line laser cooling at 689 nm. More than 10,000 atoms are then loaded into a horizontal 1-dimensional optical lattice. The lattice laser is a Ti:Sapphire laser (Coherent MBR110 pumped by a Verdi-10) which has much less spectral background than semiconductor tapered amplifier lasers. After passing an acousto-optic modulator (AOM) which is used to modulate its power, the laser is delivered to the atoms by a piece of single mode polarization-maintaining fiber. The laser at the output end of the fiber is focused to the center of the magneto-optic trap (MOT) and then retro-reflected to build the lattice. The frequency of the lattice laser is locked to a high finesse cavity held in a temperature controlled vacuum chamber and monitored by a wavemeter. In order to probe the narrow clock transition, a 698 nm clock laser is locked to a high finesse reference cavity to suppress its linewidth[2]. The reference cavity (finesse is ~200,000) is a notched cylindrical cavity supported horizontally in a vacuum chamber. The support structure is optimized to be insensitive to vibrations. The vacuum chamber is held in a copper box winded with heating wires to control the temperature.

In order to evaluate the magic wavelength of the optical lattice, we change the frequency of the lattice laser by locking to a series of reference cavity modes. At one single frequency, the power of the lattice is modulated by the AOM and interleaved locks to the atoms are done with high power and low power. The frequency difference between these loops can be used to extract the frequency shift at a special power I_0 at that lattice frequency. The measured data points are showed in Fig. 1. The zero shift point is 368.5541(1)THz. The data needs to be corrected by density shifts because when the lattice power is modulated, the atomic density is modulated too. The density shift is evaluated by alternatively locking to different atomic densities by changing the blue MOT loading time. The density shift is under evaluation.

After the systematic evaluations, the absolute frequency of the strontium optical clock will be measured by the NIM5 cesium fountain.

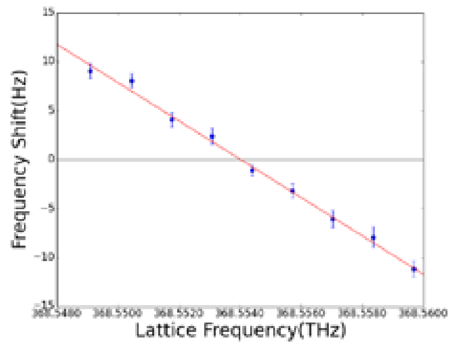

Fig. 1: Evaluation of the magic wavelength.

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Precision measurement and control of Stark shifts in a Yb optical lattice clock

K. Beloy[1], N. Hinkley[1,2], T. H. Yoon[1,3], M. Schioppo[1], R. C. Brown[1], W. F. McGrew[1,2], N. B. Phillips[1,4], J. A. Sherman[1], C. W. Oates[1], and A. D. Ludlow[1]

1. Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado USA
2. Department of Physics, University of Colorado, Boulder, Colorado USA
3. Department of Physics, Korea University, Seoul, Korea
4. Stable Laser Systems, Boulder, Colorado USA

E-mail: kyle.beloy@nist.gov

In an optical lattice clock, the measured transition frequency must be corrected for systematic frequency shifts, including Stark shifts attributed to blackbody radiation (BBR), stray static charge in the system, and the lattice trapping light. Here we describe in detail our strategies to control these Stark shifts and present their resulting contributions to the clock uncertainty budget.

To control the BBR shift, we have constructed a "shield" that furnishes the lattice-trapped atoms with a highly-uniform, room temperature environment. Several precision sensors on the shield monitor its temperature in real-time, allowing an accurate determination of the BBR shift. By activating heaters on the shield, we were able to experimentally demonstrate consistency between our evaluated BBR environment and the expected atomic response over a range of temperatures. We further discuss improvements in the shield design to achieve BBR environmental uncertainty at the low 10^{-19} level.

To mitigate the build-up of stray static charge, we were careful to employ conductive materials on our aforementioned shield, resulting in an effective Faraday cage surrounding the atoms. Nevertheless, the absence of stray fields must be verified. To this end, we introduced a static field at the atoms by applying high voltage to isolated portions of the shield, while keeping the remainder electrically grounded. Reversing polarity of the applied voltage results in a clock signal that is sensitive to a stray field in the direction of the applied field. Using this method, we probed for stray fields along three mutually orthogonal axes, leading to an uncertainty at the 10^{-19} level for the electrically grounded configuration.

In a lowest order approximation, operation of the lattice at the "magic" wavelength yields identical trapping potentials for both clock states, resulting in zero net lattice-light shift. However, higher order interactions with the lattice light—including hyperpolarizability, magnetic dipole, and electric quadrupole interactions—have non-negligible effects on the trapping potentials. We have constructed a build-up cavity for our lattice laser, which allows us to operate with lattice trap depths beyond $1000E_R$ (E_R = photon recoil energy). Exploiting this flexibility, we have measured clock frequencies over a large range of trap depths using a number of different lattice wavelengths. By simultaneously accounting for other important effects using both experimental data and theoretical modeling, including axial and transverse motional state distributions, we have found an optimal operational condition (lattice depth and wavelength) so as to minimize uncertainty in the lattice-light shift. We also discuss theoretical calculations of the lattice-light shift parameters for different optical lattice clock species.

The SOC2 ^{171}Yb optical lattice clock

G. Mura, T. Franzen, C. Abou-Jaoudeh, D. Sutyrin, A. Görlitz, H. Luckmann, I. Ernsting, A. Nevsky, S. Schiller and the SOC2 Team

Institut für Experimentalphysik, Heinrich-Heine Universität, Düsseldorf, Germany

E-mail: denis.sutyrin@hhu.de

Optical lattice clocks are suitable instruments for next-generation time-and-frequency standards. Transportable optical clocks (TOCs) open up the possibility of implementing a new geophysical measurement concept, relativistic geodesy. The development of TOCs also supports the development of space optical clock instruments, which can be used for improved tests of fundamental physics [1]. In the framework of the ESA candidate mission "Space Optical Clock", an optical lattice clock is foreseen to be operated on the ISS around the year 2018. As part of technology development towards that goal, TOC demonstrators using Sr and Yb are being developed in an EU FP7 project [2, 3, 4].

The Yb TOC system [4] is based on compact diode lasers (399 nm, 759 nm), a waveguide-doubled fiber laser at 556 nm developed by Menlo Systems, and a commercial DFB laser at 1388 nm. The apparatus features an in-vacuum enhancement resonator to form a 1D optical lattice using moderate laser power. The atom source setup occupies an optical table of 2 m × 1 m for the optical and vacuum setup; the clock laser is a commercial ECDL frequency-doubled and stabilized to 1-Hertz linewidth using a highly stable ULE cavity. This subsystem occupies a 90 cm × 120 cm breadboard [5].

We have obtained a linewidth of the $^1S_0 \rightarrow {}^3P_0$ clock transition at 578 nm of 12 Hz and determined a value for the magic wavelength in agreement with the results from Ref. [6]. We performed a first measurement of the TOCs medium-term frequency stability (below 2×10^{-14} after 1000 s) and transported it by van from Düsseldorf (Germany) to the Italian National Metrology Institute (INRIM) in Torino (Italy), where is will be compared with the Cs primary frequency standard and with a stationary Yb optical lattice clock.

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Yb optical lattice clock and fiber frequency transfer researches at KRISS

D. -H. Yu[1], C. Y. Park[1], W. -K. Lee[1], M. –S. Heo[1], H. Kim[1], S. Lee[2]
1. Division of Physical Metrology, Korea Research Institute of Standards and Science, Daejeon, Rep. of Korea
2. Agency for Defense Development, Daejeon, Rep. of Korea
E-mail: dhyu@kriss.re.kr

The development of an Yb optical lattice clock at the Korea Research Institute of Standards and Science (KRISS) will be presented with the current results of an accuracy evaluation. A highly stable clock laser at 578 nm was developed with the current short-term linewidth of 3.5 Hz. The laser was locked to the clock transition and the fractional frequency stability was 2.0×10^{-15} at 4 s. We are currently developing a build-up cavity to make a large volume optical lattice potential with enhanced depth for a given lattice laser intensity.

We also analyzed the collisional frequency shift in an optical lattice clock interrogated by a Rabi pulse. For the perturbative regime in which most optical lattice clocks are operated, the analytical solution was also obtained. It provides convenient expressions to explore the collisional shift and can be used to extract collision interaction energies in Rabi spectroscopy. Based on our analysis, we propose that an over-π pulse combined with a small inhomogeneity enables the cancellation of the total collisional frequency shift. This shows the potential for an optical lattice clock with a 10^{-18} uncertainty level with Rabi spectroscopy [1].

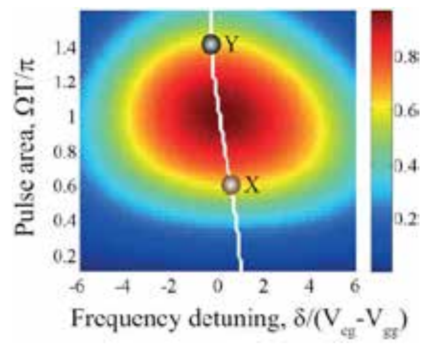

Fig. 1: Excited population at the end of the Rabi pulse as a function of the normalized laser frequency detuning and pulse area, obtained by projecting the singlet and triplet populations onto the single-atom basis(Veg and Vgg correspond to the frequencies characterizing the p-wave collision shifts of the triplet states, respectively). The white solid line depicts the peak of the transition spectrum.

We have implemented a fiber-optic dissemination system inside the KRISS. 1 GHz RF frequency, which is locked to 5 MHz from H-maser, was transferred over 23 km fiber spool. The stability of the remote signal was 10^{-14} at 1 s integration time and 8×10^{-17} at 10000 s. We are currently building up a time and frequency transfer system over urban fiber data network from Daejeon to Seoul over 150 km.

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Study on the ytterbium optical lattice clocks

M. Zhou, X. Zhang, N. Chen, Q. Gao, C. Han, P. Xu, Y. Yao, Y. Xu, S. Li, L. Ma, X. Xu
State Key Laboratory of Precision Spectroscopy and Department of Physics, East China Normal University, Shanghai, China
E-mail: xyxu@phy.ecnu.edu.cn

The optical lattice clocks with the unprecedented accuracy and precision have enabled for studying the fundamental physics, such as measuring time variation of the fine-structure constant and searching for the dark matter, and realistic applications, such as the global navigation and positioning systems. Since the ytterbium lattice clock is one of promising optical clocks, we have studied the ytterbium optical lattice clocks theoretically and experimentally.

We have analyzed the collisional frequency shift caused by the inhomogeneous excitation in a ^{171}Yb optical lattice clock [1]. The fractional collision frequency shifts as the function of the ground state fraction with various atom temperatures and numbers and trap depths have been calculated numerically. We have found that in order to suppress such kind of the frequency shifts, we need to make the atom temperature as low as possible, and the atom number as small as possible, and the lattice-trap depth as deep as possible. We think, further lowering the ytterbium atom temperature will be a more effective way to decrease such a frequency shift. And the temperature of the cold ytterbium atoms could be below 1 μK by using the sideband cooling. We have carried out the experiments for obtained the ultralow temperature of ytterbium atoms in the optical lattices by optimizing the parameters of the cooling and lattice lasers and so on. Recently, we have made the ytterbium atom temperature being below the Doppler limit. We believe that the collisional frequency shift and uncertainty resulted from the inhomogeneous excitation can be down to the 10^{-19} level or even below with certain experimental parameters.

We have also studied the clock-transition spectrum of cold ^{171}Yb ytterbium atoms in detail [2]. The dependence of the linewidth on the clock-laser power is investigated. By compensating the stray magnetic field, the Zeeman broadening effect is cancelled out, and a 16-Hz linewidth clock-transition spectrum with the 60-ms interrogation time is observed, which is already close to the Fourier-limited linewidth. Furthermore, a 6-Hz linewidth clock-transition spectrum is obtained by increasing the interrogation time to 150 ms. By adjusting the magnetic field, we can observe all or partial clock-transition spectra. By spin-polarizing atoms in the Zeeman sublevels with a 556-nm laser pulse, we can increase the excitation fraction of each π transition. The findings here will be very useful for obtaining the narrow-linewidth clock-transition spectrum with the high signal-to-noise ratio, and very helpful for developing the high-precision and high-accuracy optical lattice clocks.

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Recent progress of neutral mercury lattice clock in SIOM

R.C. Zhao[1,2,3], X.H. Fu[1,2,3], K.K. Liu[1,2,3], W. Gou[1,2,3], J.F. Sun[1,2], Z. Xu[1,2,4], and Y.Z. Wang[1,2,4]

1. Key Laboratory of Quantum Optics, Chinese Academy of Sciences, Shanghai 201800, China
2. Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China
3. University of Chinese Academy of Sciences, Beijing 100049, China
4. Center of Cold atom physics, Chinese Academy of Sciences, Shanghai 201800, China

E-mail: xuzhen@siom.ac.cn

Neutral mercury atom is one of good candidates of optical lattice clock [1]. Due to its large atomic number, mercury atom is insensitive to black body radiation [2], which is the severe limitation for the development of optical clocks. It is also a good candidate in the search for variation of natural constants because of its high sensitivity to variations of the fine structure constant α [3]. However, the challenge of neutral mercury lattice clock is the requirement of high power deep-UV laser sources for both the cooling laser and the lattice laser. Here we report the recent progress of neutral mercury lattice clock in SIOM, including the development for laser cooling of mercury atom and the cooling laser system with fiber laser amplifier.

An ultra-high vacuum system was built to produce ultracold mercury atoms with a single chamber and a mercury source which cooled to about -70°C. The frequency quadrupled semiconductor deep-UV laser is locked on $^1S_0$-$^3P_1$ transition (253.7 nm) by sub-Doppler frequency modulation spectroscopy. The ultracold mercury atoms were produced by the folded beam configuration magneto-optical trap (MOT) because of the shortage of laser power, and observed by fluorescence detection [4]. The temperature was measured by time of flight method. All of six rich abundant isotopes have been observed, and the atom number is about 4.6×10^5 with density of 1.1×10^9 /cm^3 for ^{202}Hg and 1.0×10^5 for ^{199}Hg. The temperature is about 400 μK for ^{202}Hg and 120 μK for ^{199}Hg.

To enhance the power of cooling laser, a room temperature 1014.8 nm fiber laser amplifier was developed [5]. After two stages of frequency doubling, about 75 mW of 253.7 nm UV laser were generated at IR fundamental input power of 4 W, and the saturated absorption spectroscopy of mercury atom was also observed. Now we have designed a new efficient frequency doubling cavity to enhance the UV power. More power of UV cooling laser could help us to trap more atoms in the future.

These works laid a good foundation to realize the mercury lattice clock in SIOM.

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Hg optical lattice clock at LNE-SYRTE: status and perspectives

L. De Sarlo[1], M. Favier[1], R. Tyumenev[1], S. Bize[1]

1. LNE-SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, 61 avenue de l'Observatoire, 75014 Paris, France

Email: luigi.de-sarlo@obspm.fr

Among the different atomic species considered for optical clocks, neutral mercury has several favorable atomic properties that reduce the impact of systematic effects currently limiting the accuracy of optical lattice clocks. The $^1S_0 - {}^3P_0$ clock transition in Hg is weakly coupled to thermal radiation and to static electric fields. For instance blackbody radiation sensitivity in Hg is a factor of ~30 less than in Sr. Mercury has a high vapor pressure at room temperature, which allows eliminating large temperature gradients in the experimental setup due to heating systems. Furthermore the isotope 199 has a spin ½ which suppresses several systematic effects related to the lattice trap. Finally Hg atoms can be laser-cooled to rather low temperature of 30 μK with a single stage magneto optical trap (MOT), performed directly on $^1S_0 - {}^3P_1$ intercombination transition, and then straightforwardly loaded in the optical lattice.

The biggest challenge for operating an optical lattice clock based on Mercury is that the three relevant transitions for cooling, trapping and interrogation lie in the deep UV part of the spectrum (253.7 nm, 362.5 nm, and 265.6 nm respectively).

In this poster we will present the detail of our experimental setup with a particular emphasis on the laser system. We show how the technical limitations to the full exploitation of the advantages of mercury outlined above are now being eliminated. We will also outline the recent progress of our experiment in particular for the improvement of the short-term stability and on the control of the biggest systematic shift, namely trap-related light shift. Confidence in our understanding of the clock physics is obtained by comparisons with both Cs and Rb atomic fountains and Sr optical lattice clocks which will also be presented.

We will finally discuss how these improvements pave the way for using mercury in its 7 naturally occurring isotopes for atomic physics studies and for applications in fundamental physics tests, including the search for a variation of the fine-structure constant α, for which mercury has a fairly high sensitivity.

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On the strategy of deep laser cooling of magnesium atoms

<u>D.V. Brazhnikov</u>[1,2], O.N. Prudnikov[2], A.V. Taichenachev[1,2], V.I. Yudin[1-4], A.E. Bonert[1], R.Ya. Ilenkov[1], A.N. Goncharov[1-3]

1. Institute of Laser Physics SB RAS, Novosibirsk, Russia
2. Novosibirsk State University, Novosibirsk, Russia
3. Novosibirsk State Technical University, Novosibirsk, Russia
4. Russian Quantum Center, Skolkovo, Moscow region, Russia

E-mail: brazhnikov@laser.nsc.ru

Laser cooling of ^{24}Mg atoms has special importance for quantum metrology. In contrast to the other main candidates (Yb, Sr, Hg, Ca), deep laser cooling of ^{24}Mg close to recoil energy limit is the intricate problem. At the same time, ^{24}Mg has some advantages over the other candidates. In the recent experiments [1] researches managed to cool magnesium down to 1.3 μK, but effective evaporative cooling technique was applied immediately after the magneto-optical trap stage (MOT), what led to dramatic loss in number of atoms. Also, laser cooling in MOT, involved $3^3P_2 \rightarrow 3^3D_3$ dipole transition, did not show desirable result ($T \geq 1$ mK, while $T_{rec} \approx 5$ μK). Therefore, the problem of magnesium cooling by means of laser radiation is still relevant.

Here we have tried to solve the magnesium problem by theoretical examination of $3^3P_2 \rightarrow 3^3D_3$ dipole transition in details out of limits of many widely used approximations (semiclassical, slow atoms, weak field, etc.). Our theory based on quantum treatment of the problem with full account for the recoil effect. We assume cooling field to be one-dimensional. The noticeable differences between the results of semiclassical and quantum treatments have been obtained for the atoms in MOT (compare black lines at Fig.1). The latter treatment shows the temperature just a little bit lower than the Doppler limit for the transition considered ($E_D^{kin} \approx 87.5 \times E_{rec}$, where E_{rec} is the recoil energy). This result could explain the existing difficulties of laser cooling of magnesium atoms in MOT: sub-Doppler mechanism has appeared to be not effective enough in this case. As the second sub-Doppler cooling stage we suggest using optical molasses composed of two counterpropagating beams with orthogonal linear polarizations. This configuration is known as more effective in many cases for laser cooling of atoms. Indeed, Fig.1 shows (red line) that kinetic energy as low as $16 \times E_{rec}$ can be obtained ($T_{eff} \approx 80$ μK). We have also found the optimal parameters of laser field for achieving maximal fraction of ultracold atoms in a cloud: $\delta \approx -2\pi \times 130$ MHz and $I \approx 200$ mW/cm^2. The regime of ultracold-fraction maximization is especially important for further evaporative cooling stage, which can bring much more productive result only after the realization of suggested two-stage strategy of laser cooling. The work was partially supported by the Russian Ministry of Education and Science (gov. order #2014/139, project #825), and by the grants of RFBR (nos. 15-02-06087, 15-32-20330, 14-02-00806, 14-02-00712, 14-02-00939) and Presidential Grants (MK-4680.2014.2 and NSh-4096.2014.2).

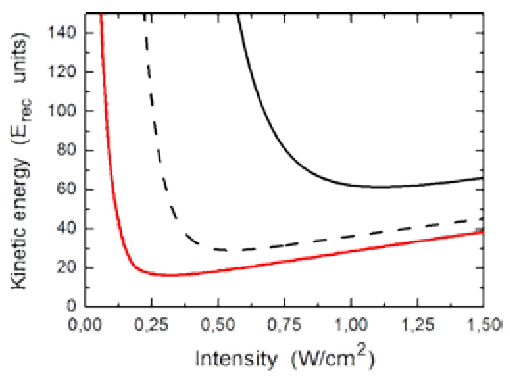

Fig. 1: Average kinetic energy of an atom under $\sigma^+\sigma^-$ (black lines) and *lin*⊥*lin* (red line) laser-field configurations. Detuning equals to –130 MHz. Dashed line is the result of semiclassical approach, while the solid ones are for quantum treatment.

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Quantum projection noise limited stability of a ^{88}Sr$^+$ atomic clock

<u>B. Jian</u>[1,2], P. Dubé[1], and A.A. Madej[1,2]

1. Measurement Science and Standards Portfolio, National Research Council Canada, Ottawa, ON, Canada
2. Department of Physics and Astronomy, York University, Toronto, ON, Canada

E-mail: Bin.Jian@nrc-cnrc.gc.ca

Optical atomic clocks based on single trapped ions have witnessed a dramatic development during the last few years [1-4]. At the National Research Council of Canada, we have developed an atomic clock referenced to the 5s $^2S_{1/2} \rightarrow$ 4d $^2D_{5/2}$ transition of ^{88}Sr$^+$ at 445 THz [3-5]. The fractional frequency uncertainty of the clock has reached 1.2×10^{-17} by using several methods to reduce uncertainties. For example, the electric quadrupole shift and the tensor Stark shift are cancelled by probing several pairs of Zeeman components. The micromotion shifts are reduced to the 10^{-19} level by minimizing ion micromotion [3,4] and by using the accurately known value of the differential scalar polarizability of the clock transition, $\Delta\alpha_0$, to tune the trap frequency such that the time dilation and scalar Stark shifts cancel each other to a factor of about 200 [5]. Furthermore, the accurate knowledge of $\Delta\alpha_0$ has also reduced the uncertainty associated with the blackbody radiation shift [5].

Besides evaluated uncertainty, the other critical parameter for the practical use of a high-performance clock is its stability which will determine how long the signals from two similar clocks have to be compared to reach a given level of uncertainty. The optimum stability of an ion clock requires that its initial state must be prepared such that the ion is ready to interact with the clock laser light at each probe cycle. For the ^{88}Sr$^+$ clock transition, the ion must be prepared in one of the two ground state magnetic sublevels. To achieve this goal, a clearout laser at 1033 nm is used as an initialization step to transfer rapidly the ion from the metastable $^2D_{5/2}$ state to the ground state following a successful excitation by the probe laser. Then a state preparation step optically pumps the ion to the desired ground magnetic sublevel. The state preparation is achieved by illuminating the ion with circularly polarized cooling light at 422 nm with the magnetic field aligned in the direction of laser propagation. The obtained clock stability is on the order of $4 \times 10^{-15}/\sqrt{\tau}$, comparable to the quantum projection limit for a 100 ms pulse [6].

Given the current evaluated uncertainty and stability of our frequency reference, we are preparing to explore the gravitational red shift effect in the laboratory by comparing the frequency shift between two similar clocks. One of the clocks will be positioned at different heights using a vertical translation stage under construction for this purpose.

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Trapped-ion $^{88}Sr^+$ optical clock systematic uncertainties

GP Barwood, G Huang, SA King, HA Klein and P Gill
National Physical Laboratory, Teddington Middlesex TW11 0LW U.K.
E-mail: hugh.klein@npl.co.uk

A comparison between two trapped-ion $^{88}Sr^+$ optical clocks at NPL has demonstrated agreement to 4 parts in 10^{17} [1]. One of the major uncertainty contributions to the optical clock absolute frequency arises from the blackbody shift which in turn depends on uncertainty in the knowledge of the differential polarizability. Measurements of the scalar contribution to AC Stark shifts at a number of wavelengths will be reported; they complement a recent NRC measurement of the DC shift [2]. The estimated optical clock AC Stark shift as a function of wavelength is shown in figure 1. Preliminary results using a fibre laser at 1064 nm agree with calculated values to within ~3%. Measurements at other wavelengths are also planned and current progress will be reported.

The Stark shift is observed by two-trap comparison. An extra laser source directed through one of the traps causes scalar, tensor and vector Stark shifts. The vector Stark shift depends on the magnetic quantum number m and so behaves in the same way as the Zeeman effect whereas the tensor Stark shift depends only on m^2 as does the quadrupole shift. By averaging over a set of different Zeeman components, both the tensor and vector Stark shifts are cancelled, leaving a measurement of the scalar Stark coefficient required for determination of the blackbody shift.

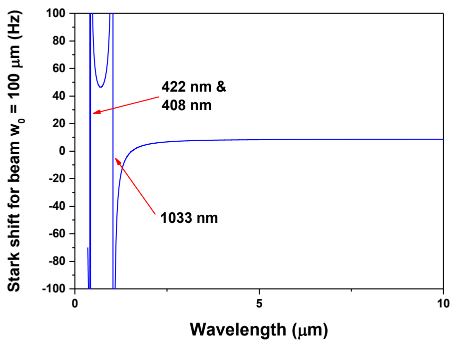

Fig. 1: Calculated Stark shifts for a beam fo-cused to a 1/e amplitude radius of 100 μm and wavelengths between 350 nm and 10 μm.

The effect of magnetic field noise on the frequency stability of our optical clock has also been modelled [3]. The 674 nm clock transition linear Zeeman shift is nominally cancelled by interrogating components symmetrically placed around line centre, but even with two layers of mumetal shielding, magnetic field noise can degrade the frequency stability. The software controlling the frequency servo to the ion probes the higher and lower frequency Zeeman components alternately. These two components have the same field sensitivity, but opposite sign. Sensing the magnetic field differentially in this way alters the noise characteristic from random walk to white frequency noise [3]. The contribution of magnetic field noise to the observed two-trap frequency instability will also be discussed.

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Broadband, unpolarized repumping and clearout light sources for alkaline-earth-metal single-ion clocks

T. Lindvall[1], T. Fordell[1], P. Dubé[2], A. A. Madej[2], A. E. Wallin[1], and M. Merimaa[1]
1. Centre for Metrology MIKES, VTT Technical Research Centre of Finland Ltd, Espoo, Finland
2. Frequency and Time Group, Measurement Science and Standards Portfolio, National Research Council of Canada, Ottawa, Canada
E-mail: thomas.lindvall@vtt.fi

Due to the gravitational redshift, comparisons of optical clocks at the lowest uncertainty level must be carried out locally. Transportable clocks are therefore needed for comparisons between different institutes. This sets stringent requirements on the compactness and robustness of all parts of the clock, among them the light sources.

Ions with low-lying, metastable D states, such as Ca^+, Sr^+, and Ba^+, require a repumper light source to provide optical pumping out of the $^2D_{3/2}$ state during Doppler cooling. In the low magnetic fields required in ion clocks, this leads to the formation of dark states [1], which can be destabilized by modulating the laser polarization. We have proposed using broadband, unpolarized repumper light sources based on amplified spontaneous emission (ASE) [2]. These offer several advantages compared to laser repumpers: dark states are prevented without external polarization modulation, no frequency stabilization is required due to the broad linewidth, and the sources can be turned on and off electronically, requiring no external shutters.

We have demonstrated 1092-nm repumper and 1033-nm clearout light sources for $^{88}Sr^+$ based on ASE in Yb-doped fibers. The sources were recently characterized and compared against the 1092-nm and 1033-nm lasers used in the Sr^+ clock at NRC in Canada [3]. The ASE repumper gave scattering rates a few tens of percent lower than the laser repumper, but also slightly lower temperatures of 1–1.5 mK, close to the Doppler limit. The clearout source showed 100 % clearout efficiency. The clock-transition light shifts caused by the two light sources were characterized, demonstrating that fractional light shifts of 10^{-19} during the probe pulse can be achieved with electronic modulation. Similar repumper light sources could be made for Ca^+ (866 nm) and Ba^+ (650 nm) using semiconductor gain media.

The ASE sources will be used with the MIKES Sr^+ clock. Here, trapping of single ions was first achieved in late 2013. The clock laser, stabilized to a 30-cm ULE cavity, is now nearly completed and a new, compact and transportable physics package with improved control of the blackbody radiation field seen by the ion is also being developed.

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Optical frequency ratios with the $^{171}Yb^+$ frequency standard

C. F. A. Baynham[1,2], R. M. Godun[1], J. M. Jones[1,3], S. A. King[1], P. B. R. Nisbet-Jones[1], F. Baynes[1], H. S. Margolis[1], A. Rolland[1], P. E. G. Baird[2], K. Bongs[3], and P. Gill[1]
1. National Physical Laboratory, Teddington, TW11 0LW, UK
2. Clarendon Laboratory, University of Oxford, Oxford, OX1 3PU, UK
3. School of Physics and Astronomy, University of Birmingham, Birmingham, B15 2TT, UK
E-mail: rachel.godun@npl.co.uk

Optical frequency standards have demonstrated accuracies two orders of magnitude better than existing primary frequency standards, and require much shorter averaging times to reach a given uncertainty. A redefinition of the SI second in terms of an optical transition frequency thus appears likely in the near future. Before such a redefinition can take place, further measurements of optical frequencies against cesium primary standards are required in order to establish optimized absolute values that would link the new SI second to the existing definition. It is also important to establish agreement at the highest level between optical frequencies at different institutions, and therefore a large campaign of direct optical comparisons is also being undertaken, without reference to cesium standards that would degrade the measurement accuracy.

The ytterbium ion optical frequency standard at the UK's National Physical Laboratory is currently operating with a systematic uncertainty at the mid 10^{-17} level. This standard is contributing to both local and international frequency comparison campaigns, targeting comparison uncertainties at the 10^{-16} level. $^{171}Yb^+$ has the added advantage that the octupole transition (E3: $^2S_{1/2} - {}^2F_{7/2}$) is not only an optical clock candidate but is also highly sensitive to changes in the fine structure constant. Frequency ratios involving this transition can therefore be measured periodically to reveal any present-day variation in this fundamental constant.

We will present our latest results from local comparisons of the ytterbium ion frequency against other optical frequency standards. We will also summarize our measurement of the direct optical frequency ratio of the octupole (E3) and quadrupole (E2: $^2S_{1/2} - {}^2D_{3/2}$) transitions within $^{171}Yb^+$, as depicted in Fig. 1. The history of absolute frequency measurements in ytterbium and other optical standards also enabled us to place constraints on the present-day level of time variation of the fine structure constant and proton-to-electron mass ratio [1].

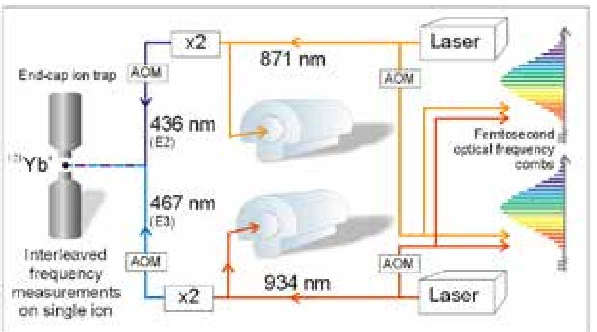

Fig. 1: Yb^+ optical standard with interleaved measurements to allow two different clock lasers to be simultaneously stabilized to their respective atomic transitions. The ratio of the stabilized frequencies is then measured directly with optical frequency combs.

Further measurements of frequency ratios with $^{171}Yb^+$ will thus continue to contribute to fundamental physics as well as advancing the efforts towards an optical redefinition of the SI second.

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A compact optical clock based on trapped Yb^+

C. Lacroûte, M. Souidi, J. Millo, K. Saleh, E. Bigler, R. Boudot, V. Giordano, Y. Kersalé
FEMTO-ST, TF Dpt., UMR 6174 CNRS-ENSMM-UFC-UTBM, Besançon, France
E-mail: clement.lacroute@femto-st.fr

Today's most accurate frequency standards are realized by optical transitions in trapped atoms or ions. Laboratory setups have now reached relative frequency uncertainties down to the 10^{-18} level [1, 2]. In parallel to the effort towards the ultimate performance, there is an academic as well as industrial need for compact atomic clocks with good frequency stabilities: observatories, very-long baseline interferometry, particle accelerators, GPS, telecommunications, all require a stable frequency reference for timekeeping purposes. Today's best compact atomic clocks are liter-sized microwave clocks with a relative frequency stability at the level of 10^{-13} at 1 s [3]. There will be a strong need for even better clocks in the future [4].

We are currently designing a compact system for single ion trapping and cooling. It aims to be the core of an optical atomic clock with a frequency stability of $10^{-14}\ \tau^{-1/2}$ and a targeted volume of order 100 liters. The quadrupole transition of Yb^+ at 435.5 nm will be used as the clock transition. The trap will be based on a micro-fabricated circuit, with surface electrodes (SE) generating a trapping potential to localize the ions a few hundreds µm from the chip.

The setup will be a testbed for SE traps-based atomic clocks, as SE traps have so far not been used in a metrological apparatus. A compact vacuum chamber will be designed, as well as an optical bench allowing the ionization, cooling, and spectroscopy of the ions. An extended cavity diode laser (ECDL) at 369.5 nm will be used for cooling. A commercial spectrometer will be used for frequency stabilization of the cooling beam (see Fig. 1). The clock beam at 435.5 nm will be generated using a fibered non-linear waveguide for second harmonic generation, and will be stabilized to an ultra-stable cavity.

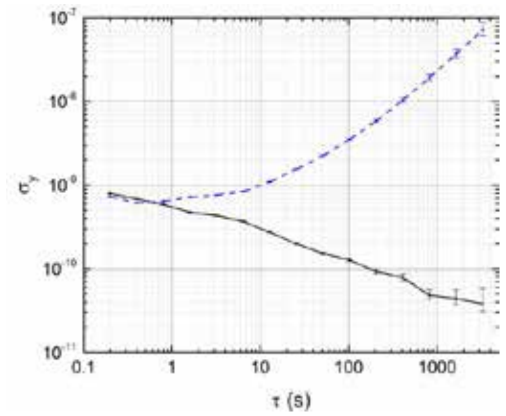

Fig. 1: 370 nm ECDL stabilized to a commercial spectrometer. *Dashed line*: free-running laser relative frequency stability. *Solid line*: in-loop stabilized laser frequency stability.

We will present the status of the clock design, with an emphasis on the optical setup.

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Developments towards miniature optical clock

N. Yu

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA. USA
E-mail: nan.yu@jpl.nasa.gov

The advent of high performance optical clocks over the past two decades has revolutionized frequency metrology due to their unprecedented stability and accuracy. Recently there has been more interest in taking these instruments out of the laboratory and into the real world including space-based applications. In this paper, we describe our investigations on developing towards a miniature optical clock of shoebox size. The main approach uses single trapped ions as the atomic reference standard and high Q crystalline resonators for the optical frequency comb and the reference cavity for laser stabilization.

The miniature optical clock consists of an atomic reference, the associated laser cooling/detection system, a stabilized clock laser and an optical frequency divider. The atomic reference will be based on a single Yb+ ion in a completely sealed trap vacuum enclosure. Recent development of micro ion clocks and its vacuum packages [1] suggests that similar vacuum enclosure can be used for a laser cooled single ion system. The use of single ions helps to reduce the laser power requirements and thus overall size and power consumption of the clock.

The approach to the miniature optical clock will take the advantage of some of the unique properties of high Q crystalline micro resonators. Crystalline whispering gallery mode (WGM) resonators are small and structurally monolithic, yet capable of ultra-high quality factors and dramatically enhanced optical nonlinearities. These properties are being exploited for stabilized laser systems as the optical local oscillator and for wide-span optical frequency comb as the optical frequency divider. One the one hand, we have studied various ways to frequency stabilize micro resonators as laser reference cavities [2] and show that a properly stabilized resonator can be used for stabilizing the clock laser. On the other hand, we also investigated the ways to efficiently generate octave combs through spectral and dispersion engineering of the crystalline resonators [3] and are highly encouraged by our recent results.

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The PTB aluminium-ion clock

N. Scharnhorst[1], S. Hannig[1], K. Jakobsen[1], J. Kramer[1], I. D. Leroux[1,2], P. O. Schmidt[1,3]

1. QUEST Institut für Experimentelle Quantenmetrologie, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
2. idleroux@quantummetrology.de
3. Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany

We report on recent progress at the PTB in constructing a transportable optical frequency standard based on a trapped $^{27}Al^+$ ion. Thanks to the exceptionally low differential polarizability of the intercombination line in aluminium [1] and to a trap design optimised for thermal conductivity and temperature homogeneity, the blackbody radiation shift makes only a negligible contribution to the inaccuracy of the standard [2]. Instead, the uncertainty budget is dominated by frequency shifts associated with the motion of the ion. We discuss measures taken to improve our control of this motion, including a novel multi-wavelength laser cooling scheme, double-EIT cooling [3], made possible by our choice of $^{40}Ca^+$ as a sympathetic coolant ion [4] and by the high-bandwidth phase-locking of all cooling lasers to a single reference through an optical frequency comb [5].

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Development of $^{27}Al^{+}$ optical clock at HUST

Z. T. Xu, X. Y. Zeng, W. H. Yuan, H. Che, X. H. Shi, K. Deng, J. Zhang, and Z. H. Lu
MOE Key Laboratory of Fundamental Quantities Measurement, School of Physics,
Huazhong University of Science and Technology, Wuhan 430074, China
E-mail: zehuanglu@mail.hust.edu.cn

The $^{27}Al^{+}$ optical clock is a strong candidate for new definition of the SI "second". It is first realized through quantum logic spectroscopy (QLS) by NIST [1]. Here we give a progress report of $^{27}Al^{+}$ ion optical clock that is under development at Huazhong University of Science and Technology (HUST). $^{25}Mg^{+}$ ions are chosen to be the "logic" ions for sympathetic cooling and internal state detection of the $^{27}Al^{+}$ ion. Single Mg ions have been successfully trapped in a linear Paul trap. The fluorescence collection efficiency is 0.87%. Through micromotion compensation and trapping parameters optimization, the temperature of Mg ions is lowered to around Doppler limit of 2 mK.

We have measured two hyperfine ground states splitting of $^{25}Mg^{+}$ ion with an uncertainty of 2 kHz. This value is limited by the magnetic field fluctuations. With this measurement, we are able to compensate the background magnetic field. The heating rate of our trap is measured to be 3.3 quantum/ms. In order to perform QLS, we have to Raman sideband cool Mg ions. Precision measurement of Raman beams light shift has been carried out, and Raman spectrum has been obtained. An efficient Raman sideband cooling strategy has been designed. With that, an average vibrational quantum number $<n>$ much less than 1 can be obtained. Two-photon ionization is used to obtain $^{27}Al^{+}$ ions, which are sympathetically cooled by Mg ions. The presence of Al ions was confirmed by observing the secular motion frequency shift of Mg ions.

$^{27}Al^{+}$ clock transition requires an ultra-narrow linewidth laser as a clock laser with sub-hertz linewidth. To develop the first generation clock laser, two diode lasers with a wavelength of 1070 nm are phase stabilized to two independent 10 cm long all ULE cavities through Pound-Drever-Hall (PDH) locking technique. A beat note with a linewidth of 0.88 Hz is obtained between the two lasers, indicating an absolute linewidth of 0.6 Hz for one single laser. The Allan deviation of the beat note is 1.2×10^{-15} at 1s, which is close to the thermal noise limit of the cavities. In order to develop better ultrastable lasers that can reach a level of 10^{-16} or even 10^{-17}, noise contributions due to temperature fluctuation, residual amplitude modulation, intensity fluctuation, seismic noise, pressure fluctuation, and electronic noise are analyzed to give an error budget for the future work.

For our second generation clock laser, the diode lasers will be locked to 30 cm long ULE cavities with fused silica mirrors to reach a stability of 1×10^{-16} at 1s. One of the cavities is a commercial product with a sandwich structure. The other cavity is home-made with a re-entrant structure which can have a wide tuning range of the zero crossing temperature of CTE to reach room temperature [2]. For a third generation clock laser, the laser will be locked to a 6 cm long cryogenic silicon cavity with sapphire mirrors to reach a stability of 2×10^{-17} at 1s. Our designed square shape cavity will be maintained at 4 K so that the CTE of the cavity (4×10^{-11} /K) and the slope of CTE (3×10^{-11} /K^2) are all quite small. A pulse tube cryostat is under development using finite-element analysis with a goal of achieving high performance vibration isolation.

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Towards Optical Clocks based on Ion Coulomb Crystals

T.E. Mehlstäubler, J. Keller, T. Burgermeister, J. Kiethe, D. Kalincev
Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany
E-mail: tanja.mehlstaeubler@ptb.de

In order to exploit their full potential and to resolve frequencies with a fractional frequency instability of 10^{-18} and below, optical ion clocks need to integrate over many days to weeks. For the characterisation of systematic shifts of the clock, as well as for applications, such as relativistic geodesy, the long averaging time scales pose severe limits. Scaling up the number of ions for optical clock spectroscopy is a natural way to significantly reduce integration times, but was hindered so far by the poor control of the dynamics of coupled many body systems, on-axis micromotion and systematic shifts due to interacting ions. However, ion species, such as Yb^{+}, In^{+} or Al^{+}, with low or zero quadrupole moments of the clock states are interesting candidates for frequency standards based on multiple ions [1,2,3].

We will detail on how a fractional inaccuracy of 10^{-18} can be reached in such systems. We implement linear chains of Yb^{+} and In^{+} ions for a first evaluation for optical clock operation and detail on the expected uncertainties. We will present a first evaluation of the expected uncertainty in scalable ion traps.

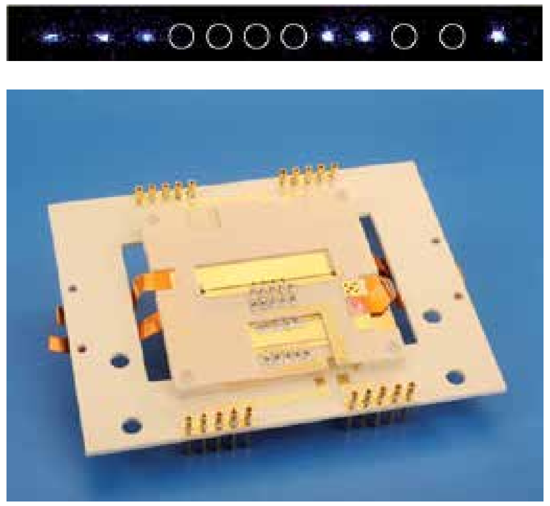

Fig. 1: $^{115}In^{+}$ ions sympathetically cooled in a linear $^{172}Yb^{+}$ ion crystal (top) inside a scalable ion trap for precision spectroscopy (bottom).

For optimum control of the ion motion and lowest frequency shifts due to micromotion and excess heating rates we have developed a new segmented ion trap with on trap filter boards and a protected spectroscopy segment [4]. The operating prototype trap with minimized axial micromotion allows us to trap and cool large ion Coulomb crystals with lowest heating rates. To reduce systematic shifts due to blackbody radiation, this trap design is transferred to an AlN based chip trap. We will present an evaluation of the uncertainty of relative frequency shifts stemming from the ion trap at the level of 10^{-20}.

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Different Ways to Active Optical Frequency Standards

Jingbiao CHEN
State Key Laboratory of Advanced Optical Communication System and Network, School of Electronics Engineering and Computer Science, Peking University, Beijing 100871,China.
E-mail: jbchen@pku.edu.cn

The concept of active optical clock was conceived ten years ago [1, 2], and some preliminary considerations [1-3] presented in the 7th Symposium on Frequency Standards and Metrology [4] have since then triggered wider interests on different ways [5-11] to the creation of active optical frequency standards with unique techniques and elegant ideas[5-8].

Different ways with atoms at 2-level, 3-level, 4-level structures with thermal and laser cooled and trapped configurations [4-5], Raman laser [6], sequential coupling [7] and moving optical lattice configuration [9] have been investigated recently. To make continuous-wave active optical frequency standards, one has to apply sequential coupling technique [7,8], or synchronization between two ensembles of 3-level atoms [8]. The bad-cavity Rb Raman laser has been investigated with very beautiful results [6].

The way of 4-level active optical frequency standard has been proposed to avoid the sensitivity of light shift due to pumping laser. Recently, in this way, the Cs four-level active optical frequency standards have made a progress experimentally reach a linewidth of 380 Hz [9,10]. For alkali atoms like Cs, and Rb , the available diode lasers and techniques of laser cooling and trapping will be helpful in the way of active optical frequency standards based on alkali atoms.

However, in all above mentioned ways [1-10] to the active optical frequency standards, the quantum refer-ence of optical frequency standard and the stimulated optical emission of gain medium are from the same atomic transition of the same atoms. This requirement strongly limits available quantum system. The active Faraday optical frequency standard, as demonstrated by a recent experiment reach a linewidth of 281 Hz [11], spatially separates the quantum reference of frequency standard and the stimulated emission of gain medium. Here [11], a narrow linewidth Faraday atomic filter, which can be a very general 2-level atomic transition, is used as quantum reference of optical frequency standard, while the stimulated emission of gain medium can be provided by Ti: sapphire and dye, besides semiconductor diode materials[11]. In this way, the Faraday effect found 170 years ago, starts to play a quantum reference role in modern optical clocks. This unique way of active optical frequency standard opens the door for various atomic transitions and alternative gain media to optical clocks.

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Ultra compact reference ULE cavity

A. Didier[1], J. Millo[1], C. Lacroûte[1], V. Giordano[1], E. Rubiola[1], Y. Kersalé[1]
1. FEMTO-ST Institute, TF Dpt., UMR 6174 CNRS-ENSMM-UFC-UTBM, Besançon, France
E-mail: ykersale@femto-st.fr

Cavity stabilized lasers are promising devices that could overcome the fractional frequency stability limits of current secondary frequency references. Some ultra-stable lasers already display fractional frequency stabilities in the range of 10^{-16} at short term for cavity lengths superior or equal to 10 cm [1,2] and for cryogenic cavities [3]. This very good performance is obtained at the expense of a total set-up volume around 1 m^3.

We are using the high frequency stability offered by this technology in order to build a compact and transportable ultra-stable laser with a relative frequency stability that overcomes the current performances of the best quartz crystal oscillators. For that purpose we have built a compact ULE cavity with 2.5 cm length. The cavity fits in a set-up with a total volume of 1.1 L. Mechanical and thermal simulations led to a new spacer geometry (cf. Fig. 1) with acceleration sensitivity lower than $10^{-12}/(m.s^{-2})$ in all directions and a thermal expansion coefficient annulation around 11°C. The thermal noise of this cavity has been calculated to be 1.2 x 10^{-15}, which would make it a valuable challenger for the current most stable quartz oscillator.

To reach this low thermal noise with a short cavity, we have used fused silica mirror substrates, ULE compensation rings and crystalline reflective coatings [4]. We measured a finesse above 70 000 with such coatings, which should be high enough to reach the desired performances. The liter-sized, custom-designed vacuum chamber includes a breadboard for optical coupling to the cavity, and frequency modulation and control for the Pound-Drever-Hall stabilization is all-fibered.

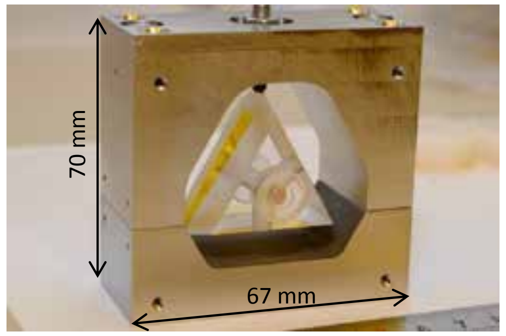

Fig. 1: Ultra-compact ULE cavity. The cavity length is 2.5 cm. The double tetrahedron spacer and three-point holder ensure low acceleration sensitivity.

We will present the cavity, thermal shielding and vacuum chamber designs as well as our most recent experimental results.

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Conceptual Design of an Optical Local Oscillator for Space Applications

P. Gill[1], S.A. Webster[1*], A. Wicht[2], R. Le Goff[3], S. Schilt[4], M. Chwalla[5], Ch. Stenzel[5]
1. National Physical Laboratory, Teddington, TW11 0LW, UK
2. Ferdinand-Braun-Institute, Berlin
3. Sodern, France
4. Laboratoire Temps-Fréquence, Université de Neuchatel, Switzerland
5. Airbus DS GmbH, Immenstaad, Germany
E-mail: christian.stenzel@airbus.com

In the frame of an ESA-funded study, a conceptual design for the overall layout and the single components of an Optical Local Oscillator (OLO) for space applications has been accomplished. Whilst the OLO is an essential sub-component of a space optical atomic clock, it can be employed also as an ultra-low phase noise source for optical-to-microwave down-conversion for navigation and radar, or for laser interferometry and ranging applications such as next generation gravity missions. The design is focussed on a local oscillator for a single Sr+ ion clock with a stable frequency in the optical domain (674 nm for Sr+) as well as for a Sr lattice clock (698 nm), stabilised by means of a Pound-Drever-Hall control loop. Challenging performance requirements to reach a narrow laser linewidth below 1 Hz on time scales of 1 to few 10 seconds in a potentially hostile space environment underline its criticality in optical clock applications.

Particular challenges for the OLO optical reference cavity, apart from the laser source technology, are the need for a robust mechanical suspension that provides for vibration insensitivity of the cavity but is also capable of ensuring that the cavity will survive space launch and deployment, precision thermal control of the reference cavity once deployed, and automatic relock of the laser to the correct cavity mode if stabilisation is lost. Critical OLO design issues concerning space-compatibility have been addressed, with consideration of payload volume, mass and power constraints on the spacecraft, without significant loss of performance with respect to a laboratory-based version. Emphasis is given to the thermo-mechanical interaction between components and resulting impact on optical performance. Key elements of the OLO design are addressed below.

- The 674 nm clock laser is an extended cavity diode laser (ECDL) developed by FBH, with free-running linewidth output of less than 100 kHz, micro-integrated using a state-of-the-art hybrid technology. Output is coupled directly into polarisation maintaining fibre, followed by an isolator to protect against optical feedback. A version of the laser operating at a different wavelength has been tested within the Bremen drop tower and recently during a sounding rocket mission.
- The OLO high stability and narrow linewidth is derived from a portable ultra-low-expansion optical cavity with finesse > 200,000, previously developed by NPL [1]. The baseline-design comprises a cubic cavity spacer with optimized immunity against mechanical and thermal distortions via a mounting frame that symmetrically supports the cavity tetrahedrally at four of the cavity vertices. The cavity mounting frame within the vacuum chamber provides both vibration and thermal isolation from the environment. Analysis by Sodern shows that a combination of active thermal control of the vacuum housing at the 10 mK level, and the passive thermal shield of the mounting frame should reduce frequency drift on a time scale between 1 and 100 s to the order of 1 Hz.

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* Now at M Squared Lasers Ltd, Glasgow, Scotland

Towards an improved measurement of the 2S-4P transition in atomic hydrogen

L. Maisenbacher[1], A. Beyer[1], A. Matveev[1], K. Khabarova[1,2], R. Pohl[1], N. Kolachevsky[1,2], T. W. Hänsch[1,3] and Th. Udem[1]
1. *Max Planck Institute of Quantum Optics, Garching, Germany*
2. *P. N. Lebedev Physical Institute, Moscow, Russia*
3. *Ludwig Maximilians University, Munich, Germany*
E-Mail: lothar.maisenbacher@mpq.mpg.de

Precision measurements of atomic hydrogen have long been successfully used to extract fundamental constants and test bound-state QED. The extraction of the Rydberg constant R_∞, one of the most precisely determined physical constants, from hydrogen spectroscopy is currently limited by the measurements of hydrogen lines other than the very precisely known 1S-2S transition [1]. We are currently working towards a new and improved measurement of the 2S-4P transition to address this limitation. This will also allow for a more precise extraction of the proton r.m.s. charge radius r_p from electronic hydrogen, which currently disagrees by 4σ with the much more precise value extracted from muonic hydrogen spectroscopy [2].

To reach our accuracy goal for the transition frequency in the low kHz range, we implement for the first time a cryogenic beam of hydrogen atoms optically excited to the initial 2S state [3]. This strongly suppresses the first order Doppler shift of the one-photon 2S-4P transition, which is further suppressed by actively stabilized counter-propagating laser beams and time-of-flight resolved detection. Important, but often overlooked in high-precision experiments, quantum interference arising from spontaneous emission, or cross-damping [4], is a leading systematic effect in our measurement. We have theoretically studied and experimentally characterized this effect and the resulting line distortions using a segmented detector to spatially resolve the emission pattern (Fig. 1). Finally, we show an experimental scheme to suppress the quantum interference shift and extract the unperturbed transition frequency.

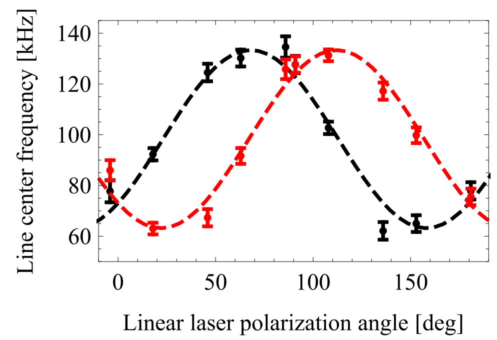

Fig. 1: Signature of cross-damping for the $2S-4P_{1/2}$ transition. Experimental data for the two detectors is shown (black squares and red dots, with arbitrary frequency offset) along with simulation results (dashed lines).

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Low Noise Oscillators

Jeremy Everard
Department of Electronics, University of York, Heslington, York, YO105DD, UK
jeremy.everard@york.ac.uk

The Electronic oscillator is used to set the reference frequency and time accuracy in most electronic systems. These include mobile and fixed communication, RADAR and satellite navigation systems as well as computers and general consumer products. They are also used as flywheel oscillators in atomic clocks. The performance of these oscillators has improved significantly recently.

This paper will describe the key theories and topologies used in electronic oscillators which offer the very best state of the art performance. The key design rules, including some common design techniques, for oscillators operating from 5MHz to 16GHz will be shown. These oscillators are used in professional products, the most advanced multi-national radar demonstrator systems and high performance atomic clocks. Oscillator types utilizing LC, helical, crystal, dielectric, and Bragg resonators have been developed. The highest performance (crystal and dielectric) will be illustrated.

It will be shown that linearized theories using transfer function techniques at the operating frequency (rather than at baseband) enable highly accurate prediction of the ultimate performance and enable feedback and negative impedance oscillators operating at the theoretical limit to be produced.

The oscillators are designed by independently optimizing all the individual elements of the oscillator for the lowest residual phase noise performance the lowest noise figure and the highest operating power. The elements include amplifiers, resonators, varactor based tunable phase shifter networks, output couplers and spurious oscillation rejection filters.

Tuning and it's effect on phase noise will be shown and methods for narrow band tuning with negligible phase noise degradation (< 1dB) will be described. Techniques for tuning high Q (>80,000) resonators at 10GHz over > 1% tuning range (with a large spurious free range) will be presented.

A number of recent results are shown in table 1. Further improvements will occur in the very near future.

Frequency	Oscillator	Phase Noise dBc/Hz At 10kHz	NoiseFloor dBc/Hz	Elec tuning	Mod BW
10MHz	SC cut Xtal	−123dBc/Hz at 1Hz −149dBc/Hz at 10Hz	< −163	~3Hz, ~0.5Hz/V	>20Hz
1.25GHz	DRO	−173	<−185	20kHz	
1.5GHz	CRO	−127	<−165	3MHz	>2MHz
4.5GHz	DRO	−153	<−180	200kHz	>200kHz
10GHz	DRO	−135	<−170		>200kHz
10GHz	BRAGG	-153	<−175		

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Laser frequency stabilization based on steady-state spectral-hole burning in $Eu^{3+}:Y_2SiO_5$*

S. Cook[1], T. Rosenband[1], D.R. Leibrandt[1]
1. National Institute of Standards and Technology, Boulder, CO, USA
E-mail: shon.cook@nist.gov

Frequency stable laser local oscillators (LLOs) are key tools in the field of metrology. Applications of such LLOs include tests of general relativity, searches for variation of fundamental constants, relativistic geodesy, and optical atomic clocks. The best lasers to date are stabilized to Fabry- Pérot reference cavities, and their stability is intrinsically limited by thermomechanical length fluctuations of the cavity.

Spectral holes in cryogenically cooled $Eu^{3+}:Y_2SiO_5$ are a promising alternative to the use of a mechanical frequency reference for laser frequency stabilization. At 4 K, this material supports spectral holes at 580 nm with linewidths as narrow as 122 Hz and lifetimes of 10^6 s. The frequency shifts due to fluctuations in the magnetic and electric fields, temperature, pressure, optical probe power, and acceleration are all small enough to allow laser frequency stability at the 10^{-17} fractional frequency level [1, 2]. However, prior laser frequency stabilization experiments with $Eu^{3+}:Y_2SiO_5$ have been limited to run times of a few thousand seconds due to degradation of the spectral holes caused by the probe laser [3].

In this work, we demonstrate laser frequency stabilization to a steady-state pattern of spectral holes in $Eu^{3+}:Y_2SiO_5$. This pattern consists of three sets of spectral holes spaced in frequency by 42.6 MHz and 36.4 MHz, corresponding to the ground-state hyperfine splittings of $^{151}Eu^{3+}$. The Eu^{3+} population reaches steady-state as the spectral holes are burned, and additional interleaved probing does not modify the absorption spectrum. Using this spectral-hole pattern, laser frequency stabilization experiments can run indefinitely. We measure the frequency stability of a laser locked to such a steady-state spectral hole pattern relative to an independent cavity-stabilized laser and a Yb optical lattice clock, demonstrating a spectral-hole stability of $1.0\times10^{-15}\ \tau^{-1/2}$ for 0.01 s < τ < 20 s, which averages to 8.5×10^{-17} at τ = 73 s.

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Development of cryogenic sapphire oscillators using cryocoolers at NMIJ

T. Ikegami[1], **K. Watabe**[1], **S.Yanagimachi1**[1], **A. Takamizawa**[1], **and J.G. Hartnett**[2]
1. Time Standards Group, National Metrology Institute of Japan (NMIJ), AIST, Tsukuba, Ibaraki, Japan
2. Institute of Photonics and Advanced Sensing, and, the School of Physical Sciences, University of Adelaide, Adelaide, Australia
E-mail: t.ikegami@aist.go.jp

A cryogenic sapphire oscillator (CSO) using a cryocooler has been constructed at NMIJ, which has a frequency stability better than 10^{-15} at the averaging time of 3 s to 3000 s and has been operating continuously for about 2 years.

The accuracy of the International Atomic Time (TAI) has been determined by a combination of the frequency stabilities of cesium primary frequency standards, time comparison methods, and local oscillators to the value of 3×10^{-16}. On the other hand, the performance of optical clocks has been improving year by year, and could soon reach the 10^{-18} region. After any future redefinition of the second, a more stable oscillator than a hydrogen maser will be required for better timekeeping. One of the candidates for such an oscillator is a CSO, because of its good short-to-mid-term frequency stability. However, it has been difficult to use the CSOs for this purpose, due to the high maintenance cost of regular liquid helium refills and the phase jumps occurring in the output signal during refilling of the liquid cryogen every 3 weeks. In order to overcome these problems, a low-vibration cryostat has been developed using a pulse-tube-cryocooler [1]. It has been applied to cryogenic sapphire oscillators and the frequency stability of the resulting cryocooled CSOs (cryoCSO) have been demonstrated to be better than that of the liquid helium CSOs [2].

In NMIJ, one of the liquid helium cooled CSOs has been converted into a cryocooled oscillator and its frequency stability evaluated.

Fig. 1 shows the estimated Allan deviation of the cryoCSO. The short term frequency stability was evaluated against a liquid helium cooled CSO, and the medium and long term stability against a hydrogen maser. The frequency stability between 1s and 10000 s is worse than that of the best data [2] by a factor of 2. This is considered to be due to the worse temperature stability due to technical issues with the thermal design of the converted cryoCSO.

Our second cryoCSO is currently under development, by which evaluation and improvement of the frequency stability of both cryoCSO will be made easier.

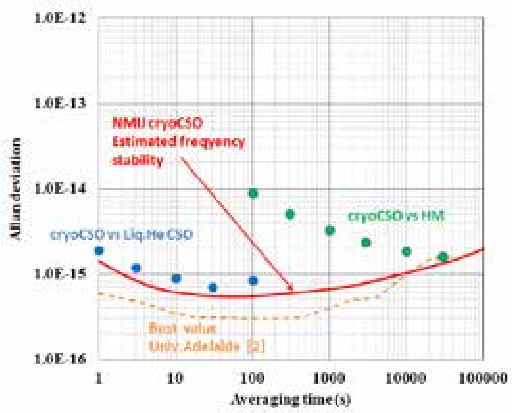

Fig. 1: The estimated frequency stability of the NMIJ cryoCSO using a liquid helium CSO and a hydrogen maser.

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Cryogenic Quartz BAW Resonator Technology

M. Goryachev[1]
1. ARC EQUS School of Physics, University of Western Australia, Crawley 6009, WA, Australia
E-mail: maxim.goryachev@uwa.edu.au

The photonics technology has become extremely successful in many areas of modern science and engineering from everyday appliances to advanced tests of frontier physics. The possibility to achieve extremely high Q factors of photonics devices has made photons an irreplaceable tool for high stability frequency generation (such as cryogenic sapphire resonators and Fabry Perot cavities) and probing the laws of physics. On the other hand, phonons, quanta of mechanical vibration, could be as valuable as quanta of light. Representing collecting motion of real particles, phonons give possibility to generate high frequency stability and to test forces and violations to which photons are not directly sensitive to. Moreover, phonons could be as long lived as photons, that has been demonstrated with cryogenic Quartz Bulk Acoustic Wave (BAW) Resonators, acoustic versions of Fabry-Perot cavities, exhibiting Q-factors of up to 10^{10} for frequencies approaching 1GHz [1,2] due to the electrodless technology and effective phonon trapping [3].

Phonon cavities, whose parameters depend on matter properties, may be used to test for Lorentz invariance violations (LIV) in the matter sector [6]. For this purpose, in collaboration with UC Berkeley, two room temperature oscillators with orthogonally oriented BAW cavities were rotated to search for such violations based on commercial room temperature quartz oscillators of frequency stability 10^{-12} at one second. Frequency resolution of 10^{-15} was achieved providing orders of magnitude lower limits on LIV. The sensitivity could be augmented by 3-4 orders of magnitude with a cryogenic implementation based on a SQUID amplifier in the oscillator loop due to Q factor and noise improvement. In this presentation we will show the required road map to the realisation of ultra-stable frequency sources, which would not only realise an important new technological tool, but also allow search for LIV with frequency resolution of order 10^{-19} in the matter sector.

Furthermore, we show phonon cavities are directly sensitive to the space-time metric, and may serve as gravitational wave antenna for various cosmological sources[4]. These antennas provide natural coupling due to the piezoelectric effect, quantum limit self noise, compactness and possibility to create arrays, low price and extremely high Q factors. Quartz BAW devices has been already used to demonstrate Nyqvist noise of acoustic modes at cryogenic condition[5]. This experiment may be improved to the quantum level sensitivity with the advanced milli-Kelvin SQUID amplifiers such as those used for the dark matter search.

Ultra-cryogenic gram scale phonon BAW may simultaneously exhibit quantum properties and feel significant influence of relativistic phenomena. Thus, by measuring coherence properties of quantum states of such devices one may come to relativistic corrections of the quantum mechanical commutation relationships[2].

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Ultra low phase noise micro- to sub-millimeter wave optical synthesis: preliminary results

F. Bondu[1], G. Danion[1], G. Loas[1], L. Frein[1], C. Hamel[1], A. Carre[1], M. Alouini[1], A. Brillet[2], J.-P. Coulon[2], F. Cleva[2], M. Merzougui[2], A. Beck[3], G. Ducournau[3], J.-F. Lampin[3], M. Zaknoune[3], C. Coinon[3], X. Wallart[3], E. Peytavit[3], T. Akalin[3], G. Pillet[4], L. Morvan[4], G. Baili[4], J. Bourderionnet[4]

1. Institut de Physique de Rennes, Université Rennes 1, Rennes, France
2. ARTEMIS, observatoire de la côte d'azur, Nice, France
3. IEMN, Université de Lille CNRS, Villeneuve d'Ascq, France
4. Thales Research and Technology, Palaiseau, France

E-mail: francois.bondu@univ-rennes1.fr

We have designed and realized two setups to synthetize ultra low phase noise micro-waves, millimeter and submillimeter waves at -150 dBc/Hz at 10 kHz offset frequency. One setup consists in a dual frequency dual polarization home made laser at 1.5 µm, a hybrid amplifier, an optical frequency reference cavity, a polarizer and a fast photodiode. The electrical output of the two setups (measurements planned at 10 GHz, 100 GHz and 300 GHz) will be mixed and down-converted to a RF frequency range for phase noise characterization.

The principle of the setup is to stabilize two optical waves, with a frequency separation equal to the desired output electrical frequency, in one stable ULE spacer cavity. The waves are cross polarized so that the intensity of the light in the cavity is constant at the beat note frequency. Each optical wave is resonant in the cavity: the accessible frequency range at the output is a multiple of the 1.5 GHz free spectral range. When taking into account cavity spacer thermal noise, optical shot noise level (12 mW per polarization), amplitude-to-phase noise conversion due to absorption, performance of frequency and amplitude stabilizations, -150 dBc/Hz stability at 10 kHz carrier offset ought to be independent of the generated electrical carrier frequency. This will be state of the art at microwave frequencies, and should be much better than state of the art at millimeter and submillimeter frequencies.

The 800 Hz linewidth (1 µs timescale) laser source is a solid state laser with a Er:Yb gain medium, with one electro-optic crystal per polarization to drive the frequency with electro-optic and thermo-optic effects [1]. The separation of the two frequencies is tunable from DC to 850 GHz. The amplifier noise factor is optimized with one EDFA and one SOA per polarization axis; the laser amplitude at relaxation oscillation frequency is reduced, and the SOA are actuators for the stabilization of the beam amplitudes at the cavity output [2]. We have demonstrated an out of loop relative intensity noise of -150 dBc/Hz at 3 Hz offset frequency.

The laser frequency is stabilized on the cavity with a Pound-Drever-Hall scheme, with 1 MHz unity gain frequency and four low frequency integrators. The modulation frequency was at 10 MHz, applied on the intra laser cavity crystals. We then measured the phase noise of one setup with a PN9000; we measured -110 dBc/Hz (resp. -130 dBc/Hz) at 10 kHz offset frequency on a 9 GHz (resp. 1.5 GHz) carrier, limited by the phase noise measurement apparatus noise floor. The low-frequency was due to residual amplitude noise. We are mitigating this noise source with new modulators.

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Precision Optical Metrology with Alkali-Atom Isoclinic Points

Nathan Wells, Travis Driskell, and James Camparo

Physical Sciences Laboratories, The Aerospace Corporation, El Segundo, CA/USA

E-mail: james.c.camparo@aero.org

Vapor-phase spectroscopy rarely involves transitions between well-isolated quantum states. Routinely, the spectra comprise overlapped Doppler/pressure-broadened resonances, and this overlap leads to "pulling" of the spectral peaks from their true, underlying, atomic resonance frequencies. Moreover, as vapor temperature, T_{vap}, fluctuates, the Doppler-broadened widths vary, which in turn leads to more or less spectral overlap. Consequently, the spectral lines are endowed with a systematic, usually time varying, and routinely non-negligible, temperature-dependent frequency shift. Though sub-Doppler spectroscopy is one way to deal with the problem, it is not always a viable solution: it can be problematic if microphonics are of concern (*e.g.*, in chip-scale optical clocks), and it may be untenable when collisional interactions are present (*e.g.*, pressure shifts). Here, we discuss the use of isoclinic points in precision spectroscopy: spectral features whose frequency is insensitive to spectral overlap, and hence insensitive to the systematic temperature shifts that arise from Doppler/pressure-broadening.

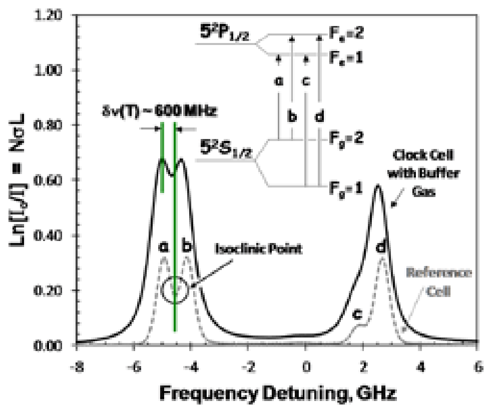

Fig. 1: The midpoint between the a and b transitions is an isoclinic point; the resonance-to-isoclinic difference has a temperature sensitivity of ~ 1 MHz/°C.

According to the IUPAC Compendium of Chemical Terminology, an isoclinic point is "a wavelength, wavenumber, or frequency at which the first derivative of an absorption spectrum of a sample does not change upon a chemical reaction or physical change of the sample." If we take this to include changes in state variables (*e.g.*, temperature and pressure), then the D_1 spectra of I=3/2 alkalies contain isoclinic points. Here, we first discuss our experiments demonstrating the isoclinic point in ^{87}Rb's D_1 absorption spectrum [1], which has a *measured* temperature sensitivity of zero ± 10^{-12}/°C. We then discuss experiments using the isoclinic point to measure the energy dependence of the D_1 collision shift for Kr [2] and most recently for Xe. To date, this energy dependence has not been well studied, due in part to the overlapped lineshape problem mentioned above. Finally, we discuss our recent efforts turning the problem around. If a laser sideband is locked to the (temperature independent) isoclinic point, while the laser's center frequency is locked to a (temperature dependent) absorption resonance, then their beat frequency becomes a measure of T_{vap}. One advantage to this optical temperature "sensor," is that it provides a measure of T_{vap} *over the spectroscopic signal volume*. This is in contrast to more conventional "point" measures, which are made on the outside surface of a glass cell. Isoclinic-point temperature sensing may prove useful for laser-pumped Rb clocks, where temperature and temperature-gradient fluctuations limit the device's long-term stability [3].

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QCL frequency stabilization and measurement with 100 Hz - level linewidth, drift and inaccuracy, using an upconversion technique

M. Hansen, E. Magoulakis, Q.-F. Chen, I. Ernsting, S. Schiller

Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany

The mid-infrared (MIR) spectral range (λ > 4.5 µm) is of interest in both applied and fundamental spectroscopy, for diverse applications such as trace gas detection and molecular frequency metrology. Approaches currently pursued for enabling MIR spectroscopy with accurate frequency control are based on generating the desired radiation by down-conversion, either of frequency combs or of cw near-infrared (NIR) sources. Such downconverted sources, however, typically have low power per frequency interval.

Upconversion of the MIR radiation to the NIR range in principle provides a way to take advantage of the frequency measurement capabilities of the standard Erbium-fiber frequency comb. In previous work, the spectral ranges λ < 4.5 µm (Muecke et al. (2004), Borri et al (2010), Gatti et al (2011)) and λ > 9.1 µm (Amy-Klein et al. (2004, 2005), Mills et al. (2012)) were covered, by using periodically poled $LiNbO_3$ and $AgGaS_2$, respectively.

In this work [1], we demonstrate for the first time to our knowledge a cw quantum cascade laser (QCL) stabilized to a ULE cavity and referenced to an optical frequency comb, improving on our previous work by several orders of magnitude [2]. The principle is shown in Fig. 1 (left): The MIR laser wave (5.4 *µ*m) is upconverted to 1.2 *µ*m by sum-frequency generation in an orientation-patterned GaAs crystal with the output of a standard high-power cw 1.5 *µ*m fiber laser and subsequent amplification of the sum-frequency wave.

A standard Er:fiber based frequency comb is phase-locked to an ultra-stable reference laser [3], resulting in comb nodes with a linewidth at the Hz level. The 1.5 *µ*m laser is phase-locked to the comb. The upconverted light at 1.2 *µ*m is stabilized to a high-finesse ULE cavity by feed-back control of the QCL's frequency. Locking of the QCL to the ULE cavity leads to a linewidth reduction of the QCL from 1.2 MHz to below 100 Hz. Fig. 1 (right) shows the beat-note between the 1.2 µm and the frequency comb, with an FWHM linewidth of 11 Hz. The true linewidth of the QCL, however, is on the order of 100 Hz, due to fiber broadening of the 1.5 µm light. In the future, a fiber stabilization can remove this effect.

The frequency of the 1.5 µm laser can be freely adjusted by changing the offset frequency of the phase lock to the frequency comb. Therefore the frequency of the MIR laser is not limited to resonance frequencies of the ULE cavity. Tuning of the 1.5 µm laser can also be used to compensate long-term drifts of the ULE cavity. The absolute frequency of the QCL is measureable with 30 Hz inaccuracy relative to a H-maser and is stable at the 5 Hz level (after drift removal).

The implementation of the method is robust and relatively simple. All components except the OP-GaAs crystal are standard. Due to the large transmission window of OP-GaAs crystals, with this method the entire range of 5 µm to 12 µm can in principle be covered with a multigrating GaAs crystal containing ten QPM periods [2]. This type of spectrometer is suitable, e.g. for precision measurements on cold trapped molecules.

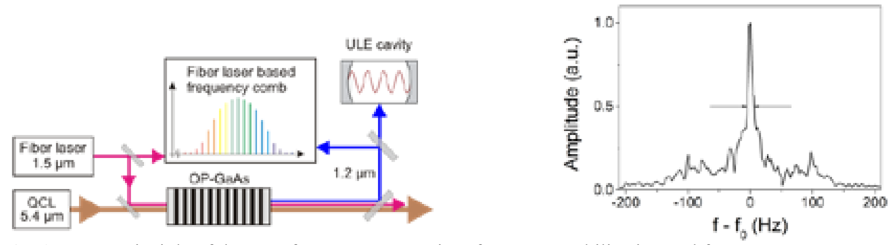

Fig. 1 LEFT: Principle of the sum-frequency generation, frequency stabilization and frequency measurement. RIGHT: Beat note of the 1.2 µm light with the frequency comb. Arrows: FWHM linewidth of 11 Hz.

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Frequency stability and long-term drift of a crystalline silicon cryogenic optical resonator at 1.5 Kelvin

E. Wiens, A. Nevsky, S. Schiller

Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany

E-mail: step.schiller@hhu.de

Optical resonators with low sensitivity to temperature and mechanical forces are of significant importance for precision measurements in the optical and microwave frequency domain. Cryogenic operation of a resonator lowers the thermal noise limit of length fluctuations and also significantly reduces the length drift.

Silicon, a machineable optical material, is available with high purity and large size. It possesses two zero crossings of the coefficient of thermal expansion (CTE), at 17 K and 124 K, an ultralow CTE below 4 K, high stiffness, high thermal diffusivity, and low mechanical dissipation. Recently, ultra-high frequency stability and an extremely low long-term drift of a silicon resonator operated at 124 K have been demonstrated [1]. We have demonstrated a silicon resonator at temperatures as low as 1.4 K. The resonator is 25 cm long and exhibits a finesse of 2×10^5 at 1.5 µm. The basic properties of the silicon resonator were already described [2]. The measured CTE is < 1×10^{-12}/K at 1.5 K. The calculated Brownian noise instability limit is 5×10^{-18} at 1.5 K.

We operate the resonator inside a pulse-tube cooler (PTC) cryostat equipped with a Joule-Thomson low-temperature stage. A 1.5 µm semiconductor laser is frequency-stabilized to the resonator using the Pound-Drever-Hall technique. The laser power transmitted through the resonator is actively stabilized. The absolute frequency is obtained by a frequency comb with respect to a GPS-stabilized hydrogen maser. In order to reduce the noise level of this measurement, the frequency comb is phase-locked to an ultra-stable 1064 nm laser, or to one of the silicon resonators.

The absolute frequency of the resonator was measured by the frequency comb and the maser. The frequency instability derived from this measurement, Fig. 1 (left), represents the combined instability of resonator and maser together. It drops to approx. 2×10^{-15} at 10 000 s integration time. This is at the same level as the instability specification of the hydrogen maser itself. Thus, the absolute frequency instability of the silicon resonator is at least as low as that of the maser.

We have also measured the absolute resonator frequency over three weeks; the result is given in Fig. 1 (right). A long-term drift occurs, with value approx. -2 mHz/s. The origin of this effect could not be determined so far; it may be caused by relaxation in the copper/steel support structure of the resonator [2], which may have some residual influence on the resonator length.

In current work, we are characterizing in fine detail various residual disturbances such as residual amplitude modulation, vibrations, alignment variations, and will implement corresponding correction systems.

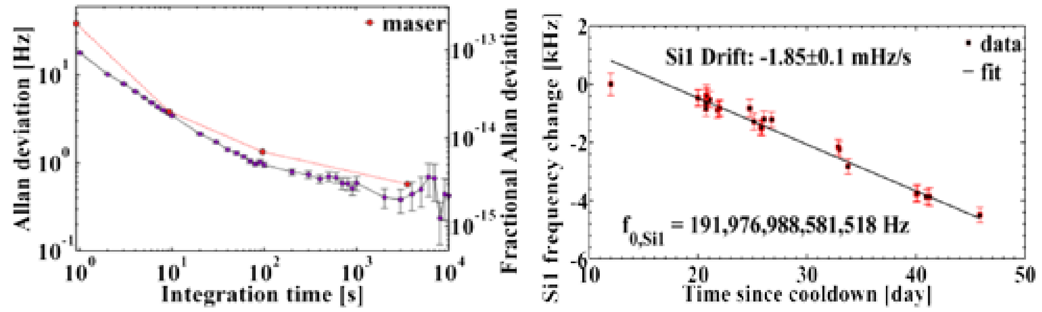

Fig. 1. LEFT: frequency instability of a silicon resonator at 1.5 K with respect to a maser. Linear drift was subtracted from the data. Red line: specified maser frequency instability. RIGHT: long-term drift of the frequency of the resonator, measured with respect to GPS-delivered atomic time. Monitoring of the drift was implemented 12 days after beginning of the cool-down of the cryostat from the room temperature.

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Micro-integrated semiconductor laser system operating in the UV for deployment in a portable optical atomic clock

A. Bawamia[1], M. Krüger[1], Ch. Kürbis[1], W. Lewoczko-Adamczyk[1], A. Wicht[1], G. Erbert[1], G. Tränkle[1], and S. Hannig[2], P. O. Schmidt[2,3], and A. Peters[1,4]

1. Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Berlin, Germany
2. QUEST Institut, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
3. Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany
4. Humboldt-Universität zu Berlin, Berlin, Germany

As part of the effort to realize portable and space qualified optical atomic clocks, a miniaturized laser system that suits the requirements for deployment in an optical atomic clock is being developed. Designed for an operating wavelength around 267 nm, the laser system consists of a diode-based local oscillator emitting in the NIR and two cascaded frequency doubling stages, with the last one based on a resonant cavity. Each stage is built into a packaged module with a maximum volume of 125 x 75 x 22.5 mm³ and is connected to the next stage via an optical fiber.

The local oscillator is built around a master oscillator (MO) power amplifier (PA) laser with an extended cavity diode laser (ECDL) as MO and a ridge-waveguide amplifier (RWA) as PA. Results of the optimization of the ECDL are presented, whereby intrinsic linewidths < 1 kHz and a side mode suppression ratio > 50 dB over a complete mode-hop free tuning range > 5 GHz are achieved. With the RWA as PA, output powers of the MOPA in excess of 1 W prior to fiber coupling are expected. Moreover, the micro-integration of the MOPA laser into a hermetically sealed package with a footprint of 125 x 75 mm², including low frequency (LF) and high frequency (HF) electrical interfaces, fiber optical interface and integrated thermal management, shall be presented. All materials and processes used for the local oscillator laser are either already space qualified or space compatible.

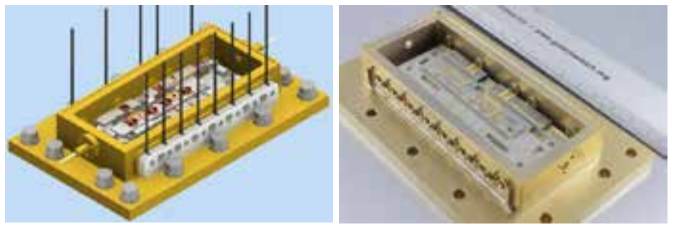

Fig. 1: CAD-model of a fully integrated laser module (left); laser module package prior to integration of optics (right)

The optical output of the local oscillator is fed into a first frequency doubling module for frequency conversion into the visible range. For this stage, a commercially available module based on single pass second harmonic generation (SHG) is used. The visible light is then fed via optical fiber into a second frequency doubling module (under development), this time based on resonant SHG. The optical design of the resonant cavity, built around a BBO-crystal, is presented, as well as simulation results that predict an optical-to-optical conversion efficiency of 2.5% at an input power of the visible light of approximately 150 mW.

One of the main challenges in the micro-integration of the resonant SHG cavity lies in the control of the positions and angles of the optical components, the stress-free fixation of the BBO-crystal and its thermal management. The design of the micro-integrated resonant cavity will be presented, with an emphasis on mitigation strategies for the above-mentioned constraints.

Cryogenic Sapphire Optical Cavities

Moritz Nagel, Klaus Döringshoff, Sana A. Pyka, Sylvia Schikora, Evgeny V. Kovalchuk, and Achim Peters
Institut für Physik, Humboldt-Universität zu Berlin, Berlin, Germany

The performance of cavity stabilized lasers is typically limited by thermal noise in the glass ceramic optical resonators at room temperature. Cryogenic operation can lower the thermal noise limit by more than one order of magnitude, but cannot be easily adopted for conventional cavity materials and designs. Well suited for cryogenic operation are resonators made of crystalline materials due to their favorable low-temperature material properties.

We present the status of our work on an optical cavity made of sapphire (Fig. 1a) specifically designed for cryogenic operation, and on a suitable cryogenic experimental setup (Fig. 1b). More than one order of magnitude improvement in the short- and long-term stability compared to room temperature resonators of the same length is expected with a thermal noise limited minimal fractional frequency instability of a few 10^{-17} (Fig. 1c). We are also preparing to replace the "standard" high finesse mirrors (Ta_2O_5/SiO_2 multilayer coating) with crystalline high finesse mirrors ($Al_xGa_{1-x}As$ DBRs [1]) which will further reduce the thermal noise limit by at least one order of magnitude (Fig. 1c). Ultimately, these cavities will be used in a high-precision experiment to test Lorentz invariance with more than two orders of magnitude improvement within the 10^{-20} to 10^{-21} regime.

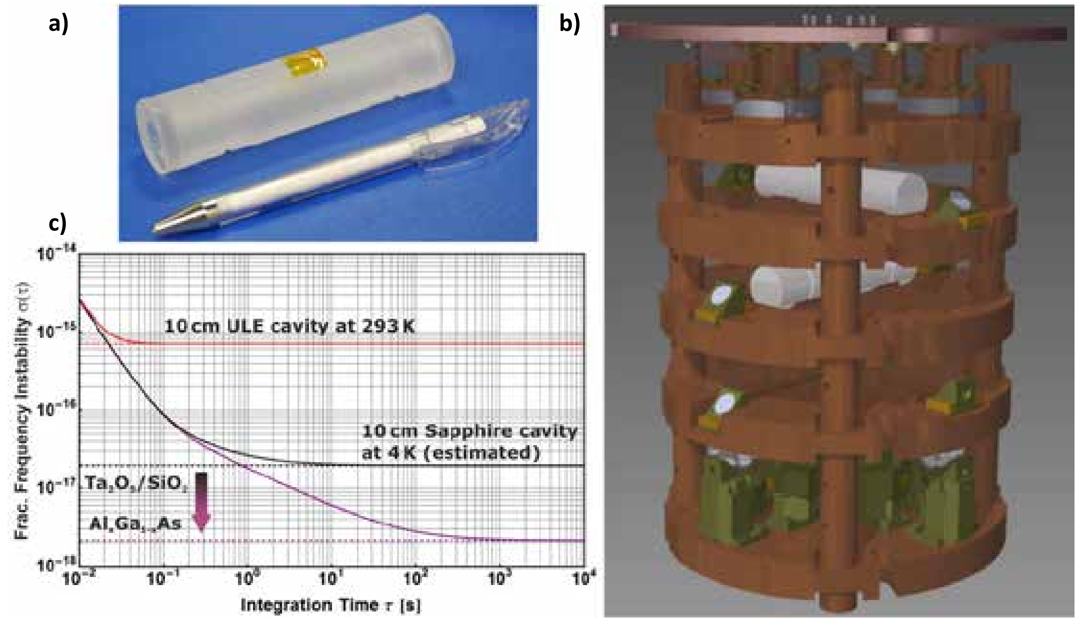

Fig. 1: a) 10 cm sapphire cavity with high finesse mirrors. All cavity parts were machined out of one high-purity mono-crystal. b) CAD drawing of the cryogenic setup, which is installed in a closed-cycle cryogenic cooler for testing two sapphire cavities simultaneously. c) Comparison of the estimated ADEV of a laser locked to the cryogenic optical sapphire cavity operated at 4 Kelvin (black line: standard coating, purple line: crystalline coating) with the ADEV of a laser locked to an ULE room temperature cavity with the same length and locking performance (red line). The dashed lines indicate the theoretical thermal noise limits at the operating temperatures.

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Metrology-Optimized Spectrally Pure Diode Lasers

L. Maleki, W. Liang, E. Dale, D. Eliyahu, A. Savchenkov, V. Ilchenko, A. Matsko
OEwaves Inc., 465 N. Halstead Str., Pasadena, CA 91107, U.S.A.
E-mail: andrey.matsko@oewaves.com

Optical clock applications typically require sub-Hz, ultra-stable lasers. Diode lasers, with small size and low power requirement, would be highly desirable for these applications, but they typically have linewidth exceeding several MHz. Furthermore, their relative long-term frequency stability is typically limited to 10^{-8} at one day. So, conventional diode lasers are usually stabilized with an external stable cavity to increase their stability and reduce their linewidth. For ultra-stable operation, the cavity must be held in an evacuated chamber and must be thermally stabilized. Consequently, the ultra-stable laser becomes bulky and power inefficient. The large size of the assembly leads to low mechanical frequencies of the structure leading to significant acceleration sensitivity of the whole system. In this paper we report on the development of compact, stable, and low noise diode lasers for optical frequency metrology and optical atomic clocks.

Two types of semiconductor lasers, distributed feedback and Fabry-Perot, were demonstrated by coupling them to high-quality (Q) factor monolithic whispering-gallery-mode (WGM) resonators as external cavities. The resonators support high quality factor within their transparency windows that range from UV to infrared wavelength. We demonstrated lasers operating at various wavelengths ranging from 532 nm to 4.5 μm.

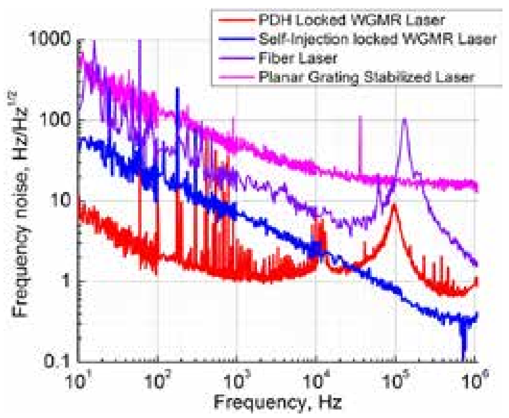

Fig. 1: Frequency noise spectra of WGM-stabilized diode lasers (red and blue lines) compared with frequency noise of a generic fiber laser (purple line) and a planar grating stabilized fiber laser (magenta line).

The miniature external cavity lasers are also tunable, and can be frequency modulated. Modulation and dithering of the laser frequency were produced by altering the frequency of the WGM resonator via changing its temperature, as well as by applying stress with a piezoelectric transducer (PZT) actuator. In some version electro-optically tunable resonators were used.

The best spectral purity of the lasers so far was achieved at telecommunication band. As shown in Fig. 1, the phase noise of the WGM-based lasers is much better than the frequency noise of the fiber lasers. To demonstrate suitability of the lasers for atomic clock applications, a frequency modulatable 795 nm semiconductor laser was built based on self-injection to the resonator. The laser is characterized by residual amplitude modulation below −80 dB and frequency noise better than 300 Hz/Hz$^{1/2}$ at offset frequencies ranging from 100 Hz to 10 MHz. The frequency modulation speed and span of the laser exceed 1 MHz and 4 GHz, respectively. Locking of the laser to the Doppler-free saturated absorption resonance of the ^{87}Rb D_1 line was demonstrated and Allan Deviation of better than 10^{-12} was measured for integration time spanning from 1 s to 1 day. The architecture demonstrated in this study is suitable for realization of frequency modulatable lasers at any wavelength for which a semiconductor diode is available.

Effect of anti-correlation on cross-spectrum measurements of thermally limited oscillators

Archita Hati, Craig W. Nelson and David. A. Howe

Time and Frequency Division
National Institute of Standards and Technology
Boulder, CO/USA
E-mail: archita.hati@nist.gov

While the cross-spectrum technique is widely used to improve the sensitivity of a noise measurement system it has several newly discovered drawbacks. Recently, a set of conditions were demonstrated and explained in [1], [2] where the detection of a desired signal in cross-spectral analysis fails partially or entirely. If two time series, each composed of the summation of two fully independent signals, are correlated in the first time signal and anti-correlated (phase inverted) in the second, and have the same average spectral magnitude, the cross-spectrum power density between two time series collapses to zero. These conditions may occur only at localized offset frequencies or over a wide range of frequency of the cross-spectrum. Such interfering signals can either be correlated to the DUT or completely uncorrelated. More recently a different source of anti-correlation in a cross-spectrum measurement has been identified; the origin is from the common-mode power splitter (Wilkinson, Resistive 2-R, 3-R). The thermal noise of the common-mode power splitter appears equally but in opposite phase in two channels of the cross-spectrum system. In this paper, we will discuss the influence of anti-correlated thermal noise of the power splitter on the thermally limited oscillator noise measurements. We will provide theory, simulation and experimental results and also discuss solutions to overcome this problem.

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Rb-stabilized compact optical laser source at arbitrary frequency in the 1.55-μm spectral region

R. Matthey, F. Gruet, W. Moreno, S. Schilt, G. Mileti
Laboratoire Temps-Fréquence, Institut de Physique, Université de Neuchâtel, Neuchâtel, Switzerland
E-mail: renaud.matthey-de-lendroit@unine.ch

Applications like differential absorption light detection and ranging (DIAL) often require a frequency-stable laser source operating at a precise and stable wavelength where no direct suitable molecular or atomic reference transition exists. One reason is the weakness of the considered transition linestrength that would require long optical pathlengths to get a sufficient absorption signal for laser stabilization, leading to a frequency stability that is then degraded or limited by etalon-induced optical interference fringes. In other cases, the laser must precisely emit at a frequency lying on the wing of an absorption line, at a detuning of up to several GHz from the line center, or even out of any absorption line.

To respond to these needs and in view of a reliable transportable system with reduced volume, consumption and weight, we have developed a compact laser system that can emit single-mode frequency-stable radiation with several mW output power at any wavelength within a minimum spectral interval ranging from 1545 nm to 1575 nm. A 1560-nm DFB laser acts as a master laser source, which is frequency-doubled in a PPLN waveguide and stabilized onto an Rb transition at 780 nm in a saturated absorption scheme using a home-made cm-scale vapor cell (Fig. 1). Part of the stabilized 1560-nm light feeds an optical frequency comb (OFC) generator, which consists of a waveguide electro-optics modulator (EOM) enclosed in a Fabry-Perot cavity. The OFC covers the interval from 1540 to 1580 nm, with a line spacing of 10 GHz equal to the EOM carrier frequency. A slave DFB laser is finally offset-locked to a line of the OFC using a combination of high-pass and low-pass filters [1]. The comb line and the offset frequency are selected so that the slave laser emits at the desired wavelength.

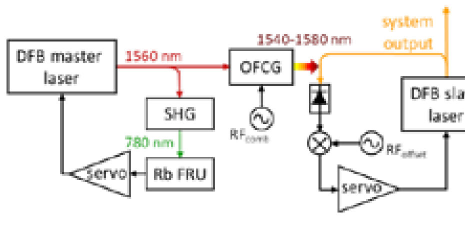

Fig. 1: Schematics of the laser system. OFCG: OFC generator; SHG: second harmonic generator; Rb FRU: rubidium frequency reference unit.

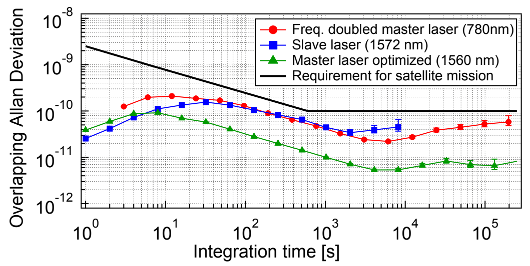

Fig. 2: Fractional frequency stabilities of the slave laser and of the frequency-doubled master laser as measured simultaneously. The stability at 1560 nm was obtained in a separate measurement with optimized master laser settings.

In view of a possible lidar satellite mission to monitor atmospheric CO_2, we have stabilized a slave laser in the wing of the CO_2 R20 transition at 1572 nm, close to the targeted wavelength. Heterodyne measurements with a self-referenced OFC and a reference laser head at 780 nm demonstrate that the frequency stability of the Rb-referenced light is transferred with high fidelity to the slave laser (Fig. 2). In the applied locking scheme, the slave laser frequency is not dithered, so its short-term stability surpasses that of the master laser.

This work is funded by ESA and the Swiss National Research Foundation.

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Self-referencing an electro-optic modulation frequency comb

Scott Papp[1], Katja Beha[1], Daniel Cole[1], Pascal Del'Haye, Fred Baynes[1], Scott Diddams[1]
1. Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO USA
E-mail: scott.papp@nist.gov

A self-referenced frequency comb provides a cycle-by-cycle link between lightwave and microwave frequencies, which has enabled myriad applications from optical clocks to precisely calibrated spectroscopy to quantum information. To date, such experiments use modelocked-laser combs, which feature typically sub-GHz repetition rates and <100 fs pulses.

Frequency combs are also generated via electro-optic modulation (EOM) of CW laser phase and intensity with a microwave source [1]. The 10's of GHz repetition frequency and the offset frequency of such an EOM comb are widely tunable to match a fuller range of comb applications in communications, molecular spectroscopy, arbitrary waveform generation, and metrology. Moreover, the EOM comb's spectral phase is predetermined by the modulation scheme, which can be optimized to yield unique optical pulse shapes [2].

Despite these advantages, two drawbacks have prevented the use of EOM combs for absolute optical frequency metrology: (1) low bandwidth that reduces spectral broadening efficiency; and (2) the conversion of electronic phase noise associated with the microwave source to the frequency noise of the optical comb. Importantly, the frequency noise power scales as N^2, where N~19,340 is the sideband order for octave bandwidth. Here we report the solution of these challenges with an EOM comb system that employs dual-stage spectral broadening with <200 fs pulses and a 10 MHz linewidth optical filter to truncate the electronic noise. This approach has enabled us for the first time to create a coherent, octave supercontinuum from an EOM comb, and detect the EOM comb's offset frequency and use it for precision metrology.

Fig 1 shows the apparatus we use for comb generation, broadening, and frequency metrology. A CW laser at 1550 nm is connected to a series of three EOMs. The laser's linewidth is ~1 Hz via a Fabry-Perot reference. Spectral broadening occurs in two stages; the second contains a pulse-picker gate and dispersion decreasing HNLF. The spectrum after broadening the 10 GHz (2.5 GHz) comb is shown in Fig. 1a (1b). We detect the offset frequency of these combs following second-harmonic generation from 2140 nm; the offset frequency heterodyne (noise floor) is shown in Fig. 1c by the black (gray) trace. Fig. 1d is a one-hour record of the offset frequency, which directly characterizes the CW laser frequency with respect to N times the maser-referenced 10 GHz comb repetition rate.

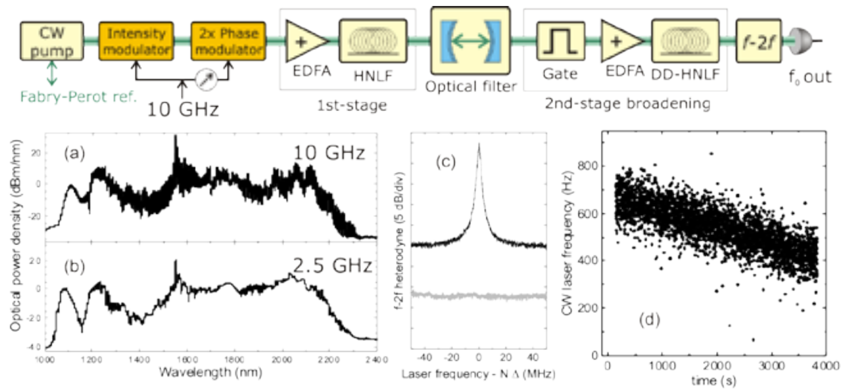

Figure 1: EOM comb setup, including nonlinear spectral broadening and optical filter. (a-b) Supercontinuum at 2.5 GHz and 10 GHz repetition rates. (c) Detection of EOM comb offset frequency with 25 dB signal to noise. (d) CW-laser frequency (minus 193 397 278 336 Hz) vs. time with respect to the maser-referenced 10 GHz.

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High fidelity optical frequency division for ultrastable microwaves

F. Quinlan[1], **F. N. Baynes**[1], **T. M. Fortier**[1], **A. Beling**[2], **J. C. Campbell**[2], **S. A. Diddams**[1]
1. Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO USA
2. Department of Computer and Electrical Engineering, University of Virginia, Charlottesville, VA USA
E-mail: fquinlan@boulder.nist.gov

The highest frequency stability is now produced optically, with optical atomic clocks approaching instabilities of 10^{-18} at 10^4 s [1-2], and passive optical cavities of 1×10^{-16} at 1 s [3]. Both the short and long-term stability provided by optical references could find new utility if faithfully transferred to the microwave domain. Examples include precision microwave spectroscopy, navigation and radar systems, displacement metrology, and an optical clock-based redefinition of the SI second. Depending on the application, the timescale of interest could range from sub-microsecond to hours or days. High fidelity frequency division from an optical reference at 100s of THz to the electronic domain at RF, microwave, and millimeter-wave frequencies is performed by locking an optical frequency comb (OFC) to the optical reference, followed by photodetection of the OFC pulse train. Here we discuss practical and fundamental limits to the frequency-division performance of the OFC and photodetection for current and next-generation optical frequency references.

Figure 1 shows the noise added in frequency-dividing an optical frequency reference down to a 10 GHz carrier. Recently we demonstrated phase noise in photodetection >10 dB below state-of-the-art optical references close-to-carrier. While the photodiode noise would impact the performance for offset frequencies greater than ~50 Hz, the noise remains well below that of the best microwave sources. For offset frequencies from ~5kHz to 1 MHz, residual noise in the frequency comb becomes dominant. Past 1 MHz, the phase noise floor is limited by noise in photocarrier transport [5]. At longer timescales, the frequency instability added by the OFC and photodetector are comparable, with 1 s instability near 1×10^{-17}, averaging down to 1×10^{-19} at 10^3 s [4]. With current optical references, this allows for the generation of microwaves with higher stability than any other source.

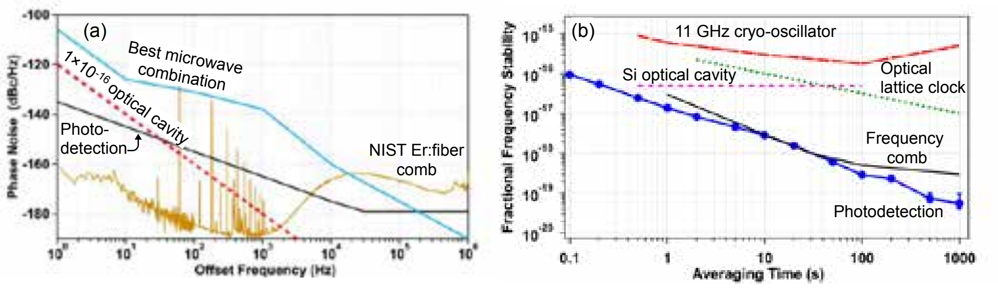

Fig. 1: (a) phase noise and (b) frequency instability added in optical frequency division, compared with the performance of state-of-the-art optical and microwave frequency references.

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Turn-key 1 GHz Ti:sapphire frequency comb with enhanced offset locking bandwidth

M. Beck, **A. Cox, T. Plötzing, M. Indlekofer, T. Mandhyani, P. Leiprecht, A. Bartels**
Laser Quantum GmbH, Konstanz, Germany
E-mail: abartels@laserquantum.com

In the early days of the frequency comb mode-locked Ti:sapphire lasers were the dominant light sources serving this ground-breaking technology [1-3]. Amongst them, those with a repetition rate (f_R) around 1 GHz were often favored over systems nearer 100 MHz due to their larger mode spacing, higher average power coherent super-continuum output and consequently higher power per mode [2,3]. With maturing fiber laser technology, Ti:sapphire lasers were later rivaled by mode-locked Er or Yb doped fiber lasers offering more user-friendliness with less need for frequent intervention. Although fiber lasers are not generally available at f_R>250 MHz, their turn-key functionality made them the preferred choice in many applications more recently.

To combine the benefits of maintenance-free long-term operation with those of having a high repetition rate and high power at 800 nm (i.e. nearer the visible range), we have developed a new 1 GHz turn-key Ti:sapphire laser. It has a hermetically sealed housing and is capable of continuous operation for many thousands of hours delivering more than 2W of average output power. To demonstrate frequency comb generation, about 0.7 W is split off to generate an octave-spanning spectrum and enter a standard f-2f interferometer. A beat at the carrier-envelope offset frequency f_0 with 50 dB signal to noise ratio is obtained in 300 kHz bandwidth, sufficient for long-term phase-locking. The free-running beat is long-term stable within ±3 MHz. It can be tuned via either housing temperature (14 MHz/K) or the 532 nm pump power (98MHz/W) with an operating range of 22-28°C and 10-10.6 W, respectively showing that the laser has the capability to stay locked for indefinite times. The remaining 1.3 W of output power can drive further super-continuum spectra tailored to the application.

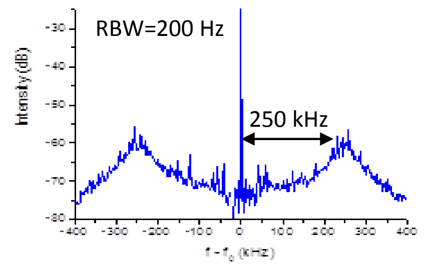

Fig. 1: Locked carrier-envelope offset beat of 1 GHz Ti:sapphire laser using direct pump current modulation.

To lock the comb, the f_0 signal enters a digital phase detector to generate an error signal against a reference synthesizer. Phase-locking is achieved by directly feeding back to the current for the pump diodes of the 532 nm solid-state pump laser. This novel mechanism is simpler than conventionally used AOMs and has much higher bandwidth. For the offset frequency feedback loop, we have achieved a bandwidth of ~250 kHz, about a factor 3-5 higher than AOMs can obtain (Fig. 1). This enhanced performance is expected to have significant impact on the generation of sub-Hertz linewidth combs and the derivation of ultra-stable microwave signals from optical standards.

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Characterization of the carrier-envelope offset in an optical frequency comb without direct detection

P. Brochard, S. Schilt, T. Südmeyer
Laboratoire Temps-Fréquence, Institut de Physique, Université de Neuchâtel, Neuchâtel, Switzerland
E-mail: pierre.brochard@unine.ch

The self-referencing of an optical frequency comb from a modelocked laser is a crucial requirement in many applications in time and frequency metrology. The ability to achieve a tight phase-lock of the carrier-envelope offset (CEO) frequency f_{CEO} strongly depends on the frequency noise of the free-running beat and on the capability to modulate f_{CEO} using a proper actuator with a sufficient bandwidth. Novel laser sources are being developed for future frequency comb systems, such as semiconductor modelocked lasers or Kerr-combs, in which the generation of a CEO beat using the standard f-to-$2f$ interferometry method remains challenging. For such systems, first assessments about the general characteristics of f_{CEO}, such as its free-running noise and modulation bandwidth, would be very valuable even before being able to generate such a CEO beat.

In this work, we suggest and validate a new method to characterize the CEO beat, which does not require a coherent octave-spanning spectra and an f-to-$2f$ interferometer, but makes use instead of a judicious combination of different signals. These signals are combined so that the contribution of the comb repetition rate f_{rep} cancels out (Fig. 1a), following a similar approach as for the transfer oscillator method proposed in [1]. As a proof-of-principle demonstration, we implemented the method with a commercial Er:fibre frequency comb and compared the assessed CEO noise and modulation response with the characteristics directly measured from the CEO beat generated using a standard f-to-$2f$ interferometer for validation.

For this, we combined a high harmonic $N_1 = 60$ of $f_{rep} \approx 250$ MHz with the heterodyne beat between a narrow-linewidth laser and a comb mode N (with $N = N_1 \cdot N_2$), subsequently frequency-divided by a large number N_2 (12'800 in the present case). The resulting signal contains the contribution of f_{CEO}/N_2, which was analyzed with a phase noise analyzer in terms of noise or demodulated with a frequency discriminator and a lock-in amplifier for transfer function measurements. An excellent agreement was obtained between the experimental results of the proposed scheme and the direct measurement of f_{CEO} (Fig. 1b and 1c), which demonstrates the suitability of the proposed method and paves the way to using it for the characterization of modelocked lasers in which a CEO beat has not yet been detected.

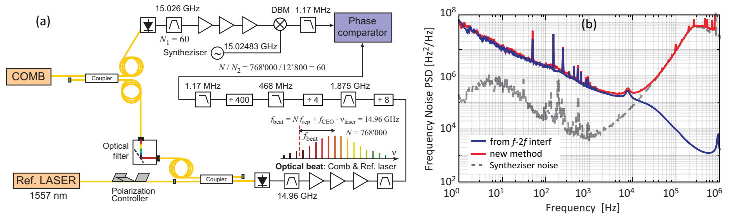

Fig. 1: (a) Basic principle of the proposed scheme to assess the noise of f_{CEO} without direct detection of the CEO beat. The noise of a high harmonic N_1 of the repetition rate (upper branch) is mixed with the heterodyne beat with a cw laser, frequency-divided by N_2 (lower branch), to produce a signal that is exempt of the contribution of $f$rep. (b, c) Comparison between the CEO properties assessed with the new proposed method (red lines) and measured directly on the CEO beat at the output of an f-to-$2f$ interferometer (blue lines): (b) frequency noise spectrum of the free-running CEO; (c) transfer function of f_{CEO} (in amplitude and phase) for a modulation of the pump current.

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Optical frequency combs from diode-pumped solid-state lasers

S. Schilt, M. Hoffmann, K. Gürel, V.J. Wittwer, T. Südmeyer
Laboratoire Temps-Fréquence, Université de Neuchâtel, CH-2000 Neuchâtel, Switzerland
E-mail: thomas.sudmeyer@unine.ch

Modelocked diode-pumped solid state lasers (DPSSL) are a competitive alternative to fibre lasers and Ti:Sa lasers for the generation of low-noise stable optical frequency combs. DPSSLs offer a low intrinsic noise owing to their high-Q cavities with low residual losses and can access substantially higher average power levels than unamplified femtosecond fiber oscillators. They can be built in very compact configurations enabling frequency combs with high repetition rates in the GHz or multi-GHz range to be achieved [1], which remains very challenging with fibre-lasers. In this contribution, we will present an overview on novel DPSSL comb systems studied at University of Neuchatel and present our latest research results in this area.

The starting point is a SESAM-modelocked Er:Yb:glass oscillator that demonstrated the benefit of the DPSSL technology for low phase-noise operation of the comb carrier-envelop offset (CEO) beat [2]. The importance of the dynamics of the CEO beat frequency f_{CEO} for the comb self-referencing was studied with this laser, giving some guidelines about the self-referencability of modelocked lasers using the standard method of feedback to the current of the pump diode [3].

We also introduced an alternative and powerful method for CEO control and stabilization, which overcomes the bandwidth limitation of the common pump modulation of the gain material (a few kHz only in Er-doped materials) using opto-optical modulation (OOM) realized by optically-pumping the intra-cavity SESAM with a cw laser [4]. The OOM stabilization led to an a residual integrated CEO phase noise of 63 mrad, and an improvement by more than one order of magnitude in the CEO control bandwidth (in the 100-kHz range) resulting in a 4-fold reduction in the CEO frequency instability. Besides its initial demonstration in a 75-MHz DPSSL, the method has a high potential for the stabilization of frequency combs from GHz DPSSL, as well as for high-power oscillators such as thin-disk lasers [5] with several hundred watts of output power that we are developing to produce XUV frequency combs by high harmonic generation. We also investigated first steps towards the use of the SESAM-OOM as a fast actuator for the stabilization of the comb repetition rate to an optical reference [6].

Finally, we will report the latest status of a project in which we target the realization of frequency combs from directly green diode-pumped Ti:Sapphire lasers. Very recently, we achieved 350 mW in 39 fs pulses from an air-cooled Kerr-lens-modelocked Ti:Sapphire laser pumped with 3 W from two 520-nm diodes [7]. The key application area for green laser diodes is the projection display market, this will ultimately lead to extremely low prices (projectors with more than ten 1-W blue laser diodes are today sold for less than 1 kUSD). This will pave the way towards a generation of compact and extremely cost-efficient Ti:Sapphire combs.

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Characterization of a passively carrier envelope phase stable frequency comb

Russell Kliese, Alexander Sell, Nazanin Hoghooghi, Thomas Puppe, Axel Friedenauer, Robert Herda, Armin Zach, Felix Rohde, Jürgen Stuhler, Wilhelm G. Kaenders

TOPTICA Photonics AG, Lochhamer Schlag 19, 82166 Gräfelfing, Germany
E-mail: felix.rohde@toptica.com

Optical frequency combs provide a greatly simplified clockwork to link the optical and RF or microwave frequency domain [1]. A comb spectrum generated from a short pulse mode-locked laser is defined by the repetition rate frep, and the carrier envelope offset frequency fceo. The repetition rate is typically monitored by a photodiode and phase-locked to an RF or optical oscillator.

Several methods for stabilizing the fceo have been demonstrated. Instead of stabilizing the fceo, it can be fundamentally removed from the comb output using difference frequency generation (DFG), as has been previously realized with pulsed Ti:Sa lasers [2]. The DFG process has the advantages of an intrinsically high bandwidth for fceo removal and, because the DFG process is a passive optical process, and a phase-noise performance that is not limited by electronic noise.

By broadening an Erbium doped fiber comb such that the DFG results in emission at again 1550 nm [3] we have realized a technologically elegant solution [4]. The resulting offset-free comb can be amplified, broadened or wavelength converted to cover a range of 420-2200nm.

Another advantage of the DFG method is that the offset stabilization is very reliable and rigid. Fig. 1 shows a spectrogram of a spectral interferometry obtained from our DFG comb. Here, light from the long wavelength end of a supercontinuum is frequency-doubled and interfered with the short wavelength part of the same supercontinuum. An out of loop phase stability of < 280mrad over 10 h (limited by the detection interferometer) can be derived from the interference pattern.

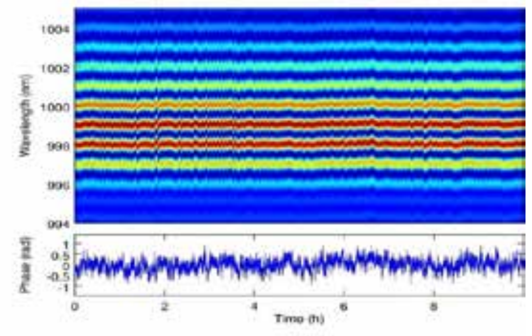

Fig. 1: Spectrogram of the spectral interferometry obtained from an offset-free DFG comb.

By phase locking a single comb line to a narrow linewidth laser at 1162nm stabilized to a high finesse cavity, an optical linewidth on the Hz level is achieved. This is shown by beating another comb line with a second narrow linewidth laser at 1152nm and a phase noise measurement.

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Noise characterization and optical frequency measurement with an optical parametric oscillator frequency comb

S. Schilt[1], K. Balskus[2], V.J. Wittwer[1], P. Brochard[1], T. Ploetzing[3], N. Jornod[1], R.A. McCracken[2], Z. Zhang[2], A. Bartels[3], D.T. Reid[2], T. Südmeyer[1]

1. Laboratoire Temps-Fréquence, Université de Neuchâtel, CH-2000 Neuchâtel, Switzerland
2. Institute of Photonics and Quantum Sciences, SUPA, Heriot-Watt University, Edinburgh, EH14 4AS, UK
3. Laser Quantum GmbH, D-78467 Konstanz, Germany

E-mail: Stephane.schilt@unine.ch

A 333 MHz Ti:Sa pump laser at 800 nm was used to synchronously pump a 4-mirror ring optical parametric oscillator (OPO). Full frequency comb stabilization of the OPO was achieved by stabilizing both the repetition rate f_{rep} of the Ti:Sa pump laser and the carrier-envelope-offset (CEO) frequency f_{CEO} of the signal pulses. The 3th harmonic of f_{rep} was phase-compared to a 1 GHz reference signal from a frequency synthesizer phase-locked to an active H-maser for f_{rep} stabilization via feedback to a combination of fast and slow piezoelectric transducers (PZT) in the pump laser cavity [1]. A feedback bandwidth of about 1 kHz was thus achieved for f_{rep} stabilization, which was limited by some sharp resonances in the PZT observed in the measured f_{rep} transfer function. CEO stabilization of the signal pulses was achieved by heterodyning coherent pump supercontinuum light at 529 nm with a non-phase matched pump-signal sum-frequency component of the OPO [2], with feedback applied to a PZT in the OPO cavity

The OPO operates at a signal wavelength of 1.56 µm, which overlaps with half the frequency of the Rb D_2 transition. Phase noise and fractional frequency stability of the OPO have been fully characterized for f_{rep}, f_{CEO} and for an optical comb line at 1557 nm obtained from the heterodyne beat f_{beat} with a narrow linewidth laser. A tight CEO lock with an in-loop residual integrated phase noise of around 300 mrad was achieved using only a slow PZT in the OPO cavity with a locking bandwidth in the kilohertz range. The measured frequency noise power spectral density (PSD) of a comb line at 1557 nm leads to a comb mode optical linewidth of ~70 kHz and a fractional frequency stability in the $2\cdot10^{-12}$ range at 1 s assessed from measurements with a dead-time-free Λ-type counter. These results are currently limited in the low-frequency range by the multiplied phase noise of the RF reference used for f_{rep} stabilization (see Fig. 1) and a contribution of the CEO frequency noise is observed at ~28 kHz in the noise of the optical comb line, which originates from the pump laser.

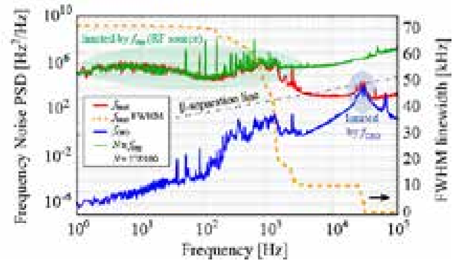

Fig. 1: OPO frequency noise PSD measured for $N\cdot f_{rep}$, f_{CEO} and a comb line at 1557 nm and corresponding optical linewidth (right axis) as a function of the observation time (inverse cut-off frequency).

As a first metrology application, we used the OPO to measure the optical frequency of the ^{87}Rb D2 F=2→3 transition, by counting f_{rep}, f_{CEO} and f_{beat} when heterodyning the OPO with a 1560 nm laser, frequency-doubled and locked to a Rb cell in a saturated spectroscopy setup [3]. A frequency of 384,228,115.347±0.015 MHz has been determined, which is in good agreement with the value retrieved using a commercial Er:fibre comb, and limited by etalon fringes in the all-fibered stabilization scheme of the cw laser.

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Compact and robust wavelength-stabilized laser at the 1.5 micron region

Atsushi Onae,[1,3] Satoshi Hatano,[2] Hajime Inaba,[1,3] Feng-Lei Hong,[1,3] Kaoru Minoshima[3]

1. National Metrology Institute of Japan (NMIJ), National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Umezono, Tsukuba, Ibaraki 305-8563, Japan
2. Neoark Corp., 2062-21 Nakanomachi, Hachioji-shi, Tokyo, 192-0015, Japan
3. JST, ERATO, MINOSHIMA Intelligent Optical Synthesizer Project, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8563, Japan

E-mail: a-onae@aist.go.jp

Wavelength stabilized lasers using absorption transitions of atoms or molecules are utilized at various fields such as wavelength management at telecom system, precise measurements and spectroscopy. If we can make these lasers more compact and robust without penalties in linewidth characteristics or long term stability, wider application fields are opened as reliable reference lasers. So far, an extended cavity diode laser (ECDL) with a diffraction grating have been developed as useful laser sources. Recently new method of wavelength selection using optical filter is proposed and many works have been done towards , for example, space mission applications such as ACES etc. [1].

In the report, we are going to apply this new filter method ECDL to saturated absorption spectroscopy of acetylene transitions at the telecom region. Figure 1 shows a beat note signal between a filter type ECDL radiation and one mode of an optical frequency comb. Observed linewidth (3dB) are below 300 kHz which is very similar as a usual grating type ECDL.

We also use a high power chip as a light source and we have 50 mW output power from our ECDL. With this relatively high power, we can observe the saturated absorption of the acetylene transition. The figure 2 shows the observed traces with a simple retro-reflect type spectrometer with a low pressure acetylene cell. We are now preparing the frequency measurement of the wavelength stabilized laser.

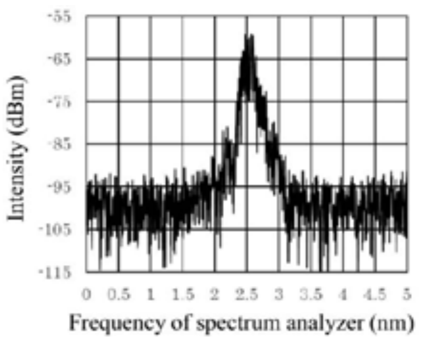

Fig. 1 Linewidth of the developed laser

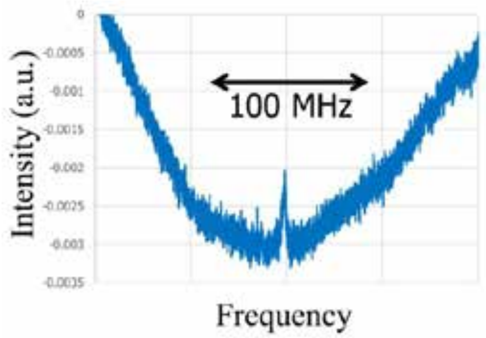

Fig. 2 Observed saturation absorption

We are aiming to use this type of wavelength stabilized laser in the astro-comb system which is recently proposed for the reference of the wavelength marker for the spesctrograph at many astronomy observatories. [2] We are expecting that these wavelength references can make it simple to determine the integer of the comb with the usual relatively low repetition rate.

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Broadband Near-Infrared Dual-Comb Spectroscopy

Sho Okubo,[1,3] Kana Iwakuni,[1,2,3] Hajime Inaba,[1,3] Kazumoto Hosaka,[1,3] Atsushi Onae,[1,3] Hiroyuki Sasada,[2,3] Feng-Lei Hong[1,3,*]

1. National Metrology Institute of Japan (NMIJ), National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Umezono, Tsukuba, Ibaraki 305-8563, Japan
2. Department of Physics, Faculty of Science and Technology, Keio University, 3-14-1, Hiyoshi, Kohoku-ku, Yokohama, Kanagawa 223-8522, Japan
3. JST, ERATO, MINOSHIMA Intelligent Optical Synthesizer Project, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8563, Japan

E-mail: hong-fl@ynu.ac.jp

Dual-comb spectroscopy (DCS) provides a new spectroscopic tool using two optical frequency combs (OFCs) with slightly different repetition rates to record an interferogram of Fourier transform spectroscopy [1]. It takes the advantages of the coherent property, wide spectral bandwidth, and frequency accuracy of OFCs, which enable high resolution and broad spectral bandwidth concurrently at a short measurement time compared with a conventional FT-IR. Recently some different schemes of DCS are demonstrated and applied to real-time gas sensing [2], and Raman microscope [3].

In this work, we extend the spectral bandwidth of dual-comb spectrometer using Er-fiber-based OFCs with wide servo bandwidth and observe absorption spectrum of acetylene, methane, and atmospheric water. Two combs are tightly phase-locked to each other with reference to a common CW laser and their relative linewidth are less than 1 Hz. Therefore, frequency difference of the repetition rate can be a few Hz, which allows us to record an extensive spectrum of 176 to 290 THz.

Figure 1 shows observed DCS spectra. The Δf_{rep} is 7 Hz therefore the one shot measurement time is about 140 ms. The interferogram is averaged 400,000 times in real time, and the spectrum is obtained from it by the Fourier transformation. The horizontal axis is scaled by the absolute frequency.

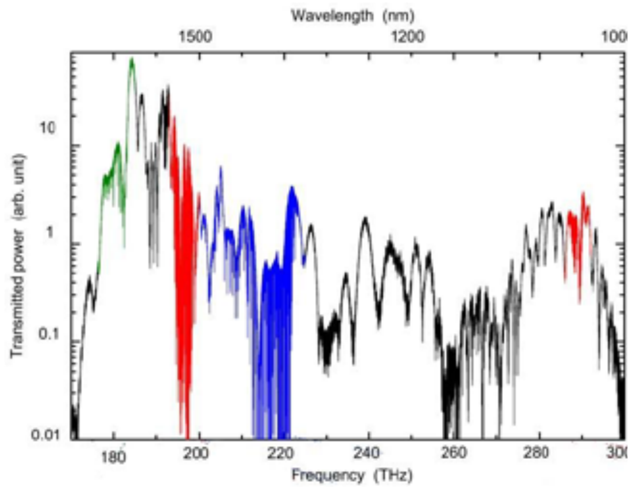

Fig. 1: Observed whole DCS spectrum from 1.0 to 1.7 µm, including $^{12}CH_4$ $2\nu_3$ band at 1.67 µm, $^{12}C_2H_2$ $\nu_1+\nu_3$ band at 1.52 µm, H_2O $2\nu_2+\nu_3$ band at 1.38 µm, and $^{12}C_2H_2$ $3\nu_3$ band at 1.04 µm.

* Now working at YNU (Department of Physics, Graduate School of Engineering, Yokohama National University, Yokohama 240-8501, Japan) and NMIJ, AIST, Japan

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Fully stabilized ultra-low phase noise Er:fiber frequency comb

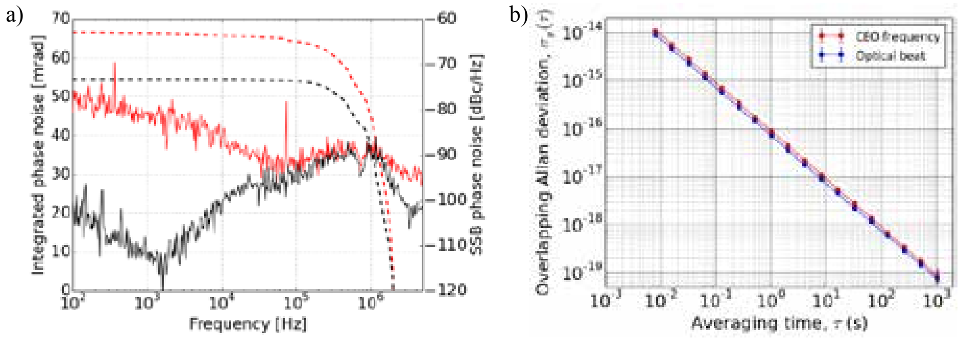
W. Hänsel[1], M. Giunta[1,2], K. Beha[1], M. Fischer[1], R. Holzwarth[1,2]
1. Menlo Systems GmbH, Martinsried, Germany
2. Max-Planck-Institute for Quantum Optics, Garching, Germany

E-mail: w.haensel@menlosystems.com

Ever increasing demand for stability and accuracy of time and frequency signals require improved oscillators and frequency references. Today's best clocks rely on narrowband optical transitions and use a frequency comb as clockwork. As their relative stabilities and accuracies both enter into the range of 10^{-18} [1,2], the frequency comb as clockwork needs to keep pace. A high short-term stability of the frequency comb is required to shorten measurement time and to ease the process of investigating uncertainties and drifts.

Here we present an all polarization-maintaining (PM) and fully phase-locked Er:fiber frequency comb with ultra-high short-term stability. An integrated phase noise below 70 mrad (100 Hz – 2 MHz) is reached for the full frequency comb. The locked beat signals exhibit an Allan variance below 10^{-16} at 1s, averaging down below 10^{-19} at 1000 s. The modified Allan variance even reaches $3 \cdot 10^{-18}$ within 1s which by far surpasses the stability of today's best atomic clocks [1,2].

To demonstrate such high stability, a selected comb line at 1.5 µm is optically phase-locked to a cavity-stabilized reference laser while the carrier-envelope offset (CEO) frequency is stabilized to a radio frequency reference. We use a novel electro-optic control element to actuate on the CEO frequency without affecting the optical beat. In-loop and out-of-loop measurements of the CEO phase noise are provided in fig 1a). The in-loop noise of the optical beat is even lower, yielding an integrated value of 25 mrad (100 Hz – 2 MHz). Fig 1b) shows the stability of both the CEO and optical beat frequencies as inferred from the two locked signals. The obtained stability surpasses the limits set by current state-of-the-art optical clocks, hence the averaging time during systematic comparisons of optical frequency standards would not be constrained by such an optical frequency comb.



a) In-loop (black) and out-of-loop (red) phase noise of the CEO frequency stabilization, solid lines (right scale): power spectral density, dashed lines (left scale): integrated phase noise from 2 MHz down to 100 Hz. b) Overlapping Allan deviation of the CEO and optical beat frequency.

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Broadband, spectrally flattened Frequency Combs for Precision Spectroscopy in Astronomy

Sebastian P. Stark[1], Rafael A. Probst[2], Yuanjie Wu[2], Tilo Steinmetz[1], Theodor W. Hänsch[2], Thomas Udem[2], R. Holzwarth[1,2]
1. Menlo Systems GmbH, Martinsried, Germany
2. Max-Planck-Institute for Quantum Optics, Garching, Germany

E-mail: s.stark@menlosystems.com

In recent years, laser frequency combs (LFCs) have found their way from precision laboratory spectroscopy into astronomy, as calibrators for astronomical spectrographs. Their unparalleled accuracy opens up new pathways, such as the detection of Earth-like extrasolar planets through radial-velocity measurements or the direct observation of the accelerated cosmic expansion. The regularly spaced lines (or modes) of an LFC that are well known and controlled by an atomic clock are ideally suited to calibrate spectrographs, surpassing common thorium-argon calibration lamps in many ways. The comb lines must however be resolved by the spectrograph, which requires large mode spacings of typically 15 - 30 GHz. We therefore synthesize our astronomical LFC from a standard ytterbium-fiber LFC with a mode spacing of 250 MHz in the 1µm spectral range by mode filtering with 3 identical medium finesse Fabry Perot cavities. As a final mode spacing we typically select either 18 or 25 GHz. Further the LFC is broadened in a nonlinear optical fiber, to cover the spectral range of interest, which is here the visible spectral region. In this case we use tapered photonics crystal fibers to reach a broad spectrum despite the very low pulse energy of such high repetition rate pulse trains. To supply the spectrograph with a constant flux of photons per comb line, therefore maximizing the signal-to noise ratio of all calibration lines, we apply a final step of spectral flattening using a spatial light modulator (SLM). The result is shown in Fig. 1. This light can now be coupled to the spectrograph as reference light. Recent successful applications include calibration of the HARPS spectrograph at ESO's La Silla observatory [1,2] and KIS' VTT spectrograph in Tenerife.

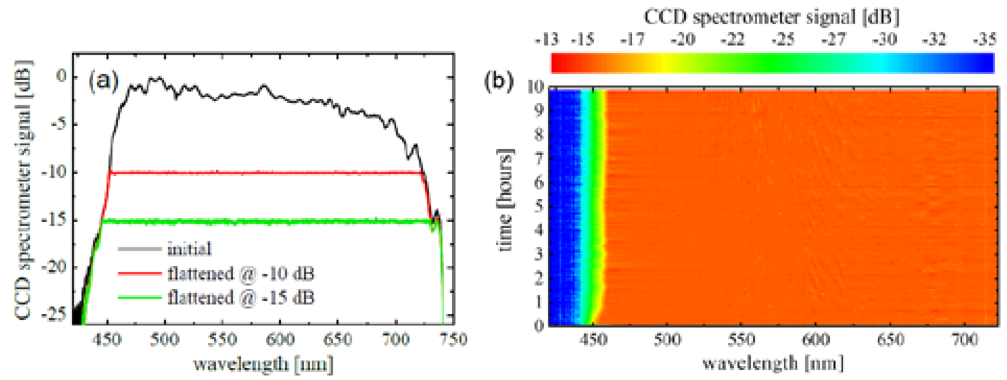

Fig. 1. LFC output spectra at a repetition rate of 25 GHz. (a) Spectra measured with the CCD spectrometer without spectral flattening (black line), and with active spectral flattening at different settings. (b) Temporal evolution of the spectrum over 9.8 h, with the flattening setup truncating the spectrum at -15 dB below its peak. The red area that fills most of the color plot is the flat-top region

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Frequency comb metrology in space

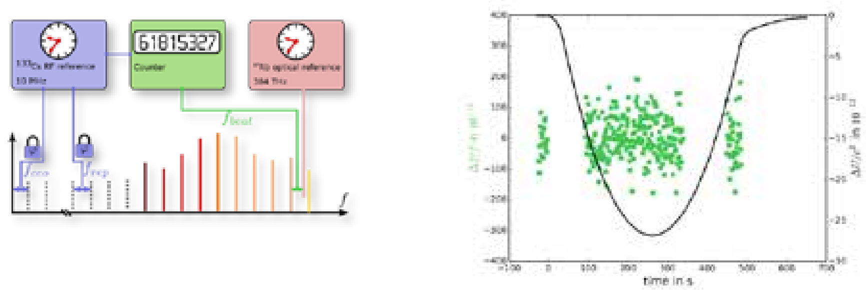
Matthias Lezius[1], Tobias Wilken[1], Christian Deutsch[1], Michele Giunta[1,2], Olaf Mandel[1], Andy Thaller[1], Vladimir Schkolnik[3,4], Max Schiemangk[3,4], Aline Dinkelaker[3], Markus Krutzik[3], Anja Kohfeld[3], Andreas Wicht[3,4], Achim Peters[3,4], Ortwin Hellmig[5], Hannes Duncker[5], Klaus Sengstock[5], Patrick Windpassinger[6], Theodor W. Hänsch[2], and Ronald Holzwarth[1,2]

[1]Menlo Systems GmbH, Martinsried, Am Klopferspitz 19a, D 82153
[2]Max Planck Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D 85741, Garching
[3]Humboldt Universität Berlin, Institut für Physik, Newtonstr. 15 ,D 12489, Berlin
[4]Ferdinand-Braun-Institut, Gustav-Kirchhoff-Str. 4, D 12489 Berlin
[5]Universität Hamburg, Institut für Laserphysik, Luruper Chaussee 149, D 22761 Hamburg
[6]Institut für Physik, Johannes Gutenberg-Universität, D 55099 Mainz
E-mail: m.lezius@menlosystems.com

The German Space Agency's TEXUS 51 sounding rocket has been successfully launched on April 23, 2015 at 09:35 CEST from the ESRANGE space center in Kiruna, Northern Sweden. The flight lasted for approx. 20 min with around 6 min in zero gravity, reaching an altitude of 260km. During the flight, the FOKUS experiment (Faserlaserbasierter Optischer Kammgenerator unter Schwerelosigkeit) on board the rocket was performing a clock comparison of a clock based on an optical transition (Rubidium D_2 line at 384.228 THz) and a RF clock based on the Cs ground state hyperfine splitting (9.2 GHz), coherently linked by a frequency comb based on a Er:fiber femtosecond laser. The comparison was successfully performed during the 0g period, see Fig. b below.

This is the first time that a complete frequency comb system has been operated in space. Since two different species of atomic clocks have been compared with each other, this constitutes a test of local position invariance. The experiment also demonstrates the feasibility to perform frequency comb based precision spectroscopy in space. The superior environmental stability of the flight module containing frequency comb and Rb spectroscopy unit has been achieved in a major collaborative effort between the MPQ, the FBH, HU Berlin, the University Hamburg, and Menlo Systems. The comb technology is based on the recently introduced Fig-9 oscillator technology of Menlo Systems, providing exceptional stability and durability. The DFB laser was mounted on a micro-optical AlN bench developed at the FBH, well suited for future BEC experiments in space. The Rb spectroscopy module by the Univ. Hamburg was based on a Zerodur optical bench technology.

a) b)



a) Scheme of the 0-g based experiment consisting of a frequency comb and two atomic clocks..
b) Frequency deviation of the Rb D line interogation (384,2279817(2) THz) during flight through the gravitational potential.

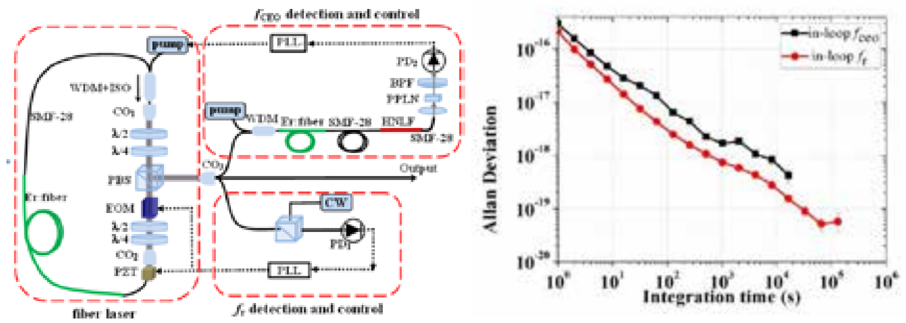
Progress on development of optical frequency combs at NTSC

H.Jiang[1], Y. Zhang[1], L. Yan[1], L. Zhang[1], S. Fan[1, 2], W. Guo[3] and S. Zhang[1]

1. Key Lab. of Time and Freq. Primary Standards, National Time Service Center, Xi'an, China
2. Graduate University of Chinese Academy of Sciences, Beijing, China
3. School of Science, Xi'an Shiyou University, Xi'an, China

E-mail: haifeng.jiang@ntsc.ac.cn

Many researches and applications, including attosecond science, low-noise microwave generation, high-resolution distance measurement, optical clock development and application etc., benefit from the optical frequency combs. Among kinds of optical frequency combs, Er:fiber-based frequency combs are of great interest, because of their compactness, reliability, low power consumption and directly covering telecommunication wavelength. We started to study and develop Er:fiber-based frequency combs at NTSC in 2013. Here, we report some progresses on our work. We have built a few Er:fiber combs with an intra-cavity EOM, enabling fast repetition rate (f_r) control and leading to robust phase lock. The laser cavity of the newest one has a repetition rate of ~232 MHz, and the net dispersion of the ring cavity is estimated to be about -2000 fs^2 at 1550 nm. The direct output is about 180 mW, when two power-combined 976 nm pump lasers are set at 1 A current.



(a) (b)

Figure1: (a)Schematic diagram of the Er:fiber-laser-based frequency comb and (b)In-loop frequency stability of f_r (solid red round) and f_{ceo} (solid black square).

We locked the phase of f_r and the carrier-envelope-offset frequency (f_{ceo}) to a 1550 nm laser and a RF reference frequency respectively. The relative frequency stability of in-loop f_r is ~2.1×10^{-16} at 1 s, and integrates down to the order of 10^{-20} at a day. The relative frequency stability of in-loop f_{ceo} is ~$2.9\times10^{-16}/\tau$ for short terms. Such stabilities are good enough to support our frequency comb system measuring transition frequency of the best optical atomic clocks with frequency stability of ~$3.2\times10^{-16}/\sqrt{\tau}$[1]. Note that, the frequency count in use is a Π-type counter from K&K Inc.; these results are more than one order of magnitude worse that those obtained with Λ-type counter from Agilent, for more high frequency noise contribution observed[2]. We are now studying the relationship between f_{ceo} noise level and ring laser`s parameters, because we observed very different free-running $f_{ceo}$ noise level for a few Er:fiber combs with similar configuration; we are also trying to extend the comb`s coverage to Sr clock transition. Details and more progress will be demonstrated in the formal proceeding.

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Quantum Cascade Laser stabilization at sub-Hz-level by use of a frequency comb and an optical link

B. Argence[1], B. Chanteau[1], O. Lopez[1], D. Nicolodi[2], M. Abgrall[2], C. Chardonnet[1], C. Daussy[1], B. Darquié[1], Y. Le Coq[2], A. Amy-Klein[1]

1. Laboratoire de Physique des Lasers, Université Paris 13, CNRS, Villetaneuse, France
2. LNE-SYRTE, Observatoire de Paris, CNRS, UPMC, Paris, France

E-mail: amy@univ-paris13.fr

With their large mid-infrared (IR) spectral coverage, Quantum Cascade Lasers (QCL) are very promising for probing the molecular fingerprint region. Current applications to high-resolution spectroscopy are mainly limited by their large free-running frequency instability. A lot of efforts have thus been made recently to characterize and improve their spectral properties, especially the emission linewidth and the traceability to frequency standards. Here we demonstrate the frequency stabilization of a QCL emitting at 10 µm onto an optical frequency comb (OFC), itself controlled with a remote near-infrared ultra-stable laser (see Fig. 1) [1]. The latter is transferred from LNE-SYRTE with an optical link of 43 km and its frequency is monitored by primary frequency standards. We demonstrate that the QCL stability is copying the OFC stability, at a level of $2x10^{-15}$ for an averaging time of 1 s. From the OFC stability, one can infer a QCL linewidth of 0.2 Hz. This performance overcome by at least two orders of magnitude what has been demonstrated up to now with a QCL or any laser emitting in the mid-IR spectral range. Moreover the QCL frequency is known with an uncertainty of at most 10^{-14} after 100 s averaging time, thanks to the traceability to primary standards.

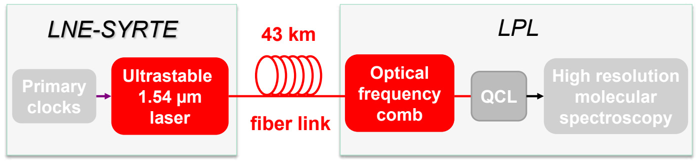

Fig. 1: Principle of the Quantum Cascade Laser stabilisation.

We further demonstrate the continuous tuning of this stabilized QCL and recorded a few OsO_4 molecular absorption lines which cannot be easily probed with gas lasers such as CO_2 lasers. The obtained $8x10^{-13}$ frequency uncertainty is well below what has ever been reported with QCLs.

This stabilization technique can be extended to QCLs emitting in the whole 3-20 µm spectral range, thus giving access to a wide range of molecular rovibrational lines. It opens the way to ultra-high precision measurements with molecules with the same performance than currently achieved with atoms. At LPL, this QCL-based spectrometer will be dedicated to our ongoing project to make the first observation of parity violation by Ramsey interferometry of a beam of chiral molecules [2]. In this project, we aim to measure the difference between vibrational frequencies of two enantiomers, which is predicted to be on the order of 10^{-13}, at most. This requires a very stable, accurate and flexible laser set-up, which will be fully provided by this new QCL spectrometer.

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Cascaded optical link of 1420 km on active telecommunication fiber network

O. Lopez[1], N. Chiodo[1], N. Quintin[1], Fabio Stefani[2,1], F. Wiotte[1], C. Chardonnet[1], G. Santarelli[3], A. Amy-Klein[1], P.-E. Pottie[2]

1. Laboratoire de Physique des Lasers, Université Paris 13, CNRS, Villetaneuse, France
2. Laboratoire National de Métrologie et d'Essais–Système de Références Temps-Espace, Observatoire de Paris, CNRS, UPMC, Paris, France
3. Laboratoire Photonique, Numérique et Nanosciences, Université de Bordeaux 1, Institut d'Optique and CNRS, Talence, France

*E-mail: olivier.lopez@uni-paris13.fr

High-resolution frequency comparisons between remote locations are of major interest for time and frequency metrology and for many applications, such as tests of temporal variation of fundamental constants and relativistic geodesy. Optical fiber links are intensively studied for a decade by several groups for and demonstrate impressive results of ultra-stable and accurate frequency transfer far beyond the GPS capabilities on distances of several hundreds of km [1] with a record of 1850 km [2].

In order to face the issue of the fiber availability, we have extended the technique of optical fiber link to installed telecommunication network, simultaneous used for digital data transfer. We also implement cascaded optical link, where the propagation noise is compensated by successive fiber spans. The optical signal is repeated from one span to the other using a so-called repeater station, as sketched on Fig. 1. Such a station contains a laser source to boost the optical signal injected in the successive span [1]. Part of the light of the remote laser is sent backward to enable the stabilization of the upstream link. The other part of the light is sent forward and allows the stabilization of the following span. With such a technique, we demonstrated a >1420-km cascaded link composed of four sub-links using two parallel fibres between Paris and Strasbourg and back. The complete link uses 5 repeater stations, including the 2 stations at each end. The end-to-end stability is $4x10^{-16}$ at 1-s integration time and reaches $2x10^{-20}$ at less than 10^4 s. This is a major step forward for the REFIMEVE+ project, that aims at disseminating optical frequency standard with repeater stations over 4000 km of public telecommunication fiber network. It also opens the way to an european fiber network for remote clocks' comparison.

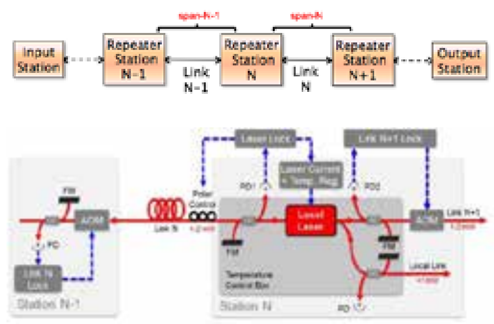

Fig. 1: Principle of a cascaded link and of a repeater station.

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This work was partly funded from Agence Nationale de la Recherche under grant ANR-2011-BS04-009-01 and REFIMEVE+, Action spécifique GRAM, Laboratoire National d'Essai and from the European Metrological Research Programme EMRP under SIB-02 NEAT-FT. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

In-line extraction over a metrological fibre network

A. Bercy[1,2], F. Stefani[2,1], S. Guellati-Khelifa[3], G. Santarelli[4], C. Chardonnet[1], P.-E. Pottie[2], O. Lopez[1] and A. Amy-Klein[1]

1. Laboratoire de Physique des Lasers, Université Paris 13, CNRS, Villetaneuse, France
2. Laboratoire National de Métrologie et d'Essais–Système de Références Temps-Espace, Observatoire de Paris, CNRS, UPMC, Paris, France
3. Laboratoire Kastler-Brossel, UPMC, ENS, CNRS, Paris, France
4. Laboratoire Photonique, Numérique et Nanosciences, Université de Bordeaux 1, Institut d'Optique and CNRS, Talence, France

E-mail: anthony.bercy@univ-paris13.fr

Optical frequency links have been demonstrated on distances up to 1840 km [1,2] and give the possibility to compare future optical clocks in Europe. A key issue consists now in deploying optical links to a number of research laboratories for high sensitivity frequency measurement or remote laser stabilization for instance. A point-to-point transfer scheme is not efficient, especially in a metropolitan area network. Following a proposal by G. Grosche [3] one can extract the ultrastable signal at different points simultaneously along the main link.

We demonstrated the in-line extraction of an ultrastable signal along a 92-km main link consisting of urban telecommunication fibers [4]. The phase noise accumulated along this main link was actively compensated and the in-line extraction tested after 6-km and 86-km. We measured the phase difference between the extraction and the input signals. The resulting fractional frequency stability was found equal or sensibly below the end-to-end stability of 1.3×10^{-15} at 1-s, in agreement with a simple model of noise compensation. At long term, the frequency stability at the extraction end was limited by thermal effect.

To improve this long term stability, we developed a new setup with a compact and thermalized interferometry. Moreover, this setup gives the possibility to phase-lock a laser diode on the extracted signal and to feed a secondary link which phase noise is compensated (see fig. 1). No stable RF local oscillator is required for the noise compensation. By this way, we are able to disseminate the optical reference far away the in-line extraction point.

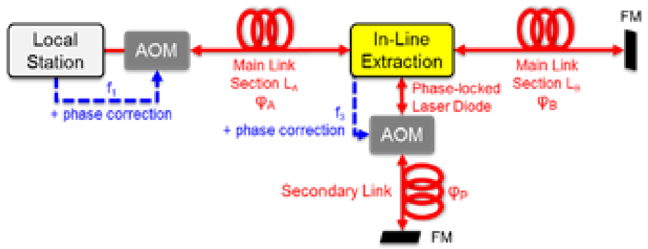

Fig. 1: The phase noise $\phi_A+\phi_B$ accumulated on the main link is detected by the Local Station and compensated using an Acousto-Optic Modulator (AOM). In the Extraction Station, a laser diode is phase-locked to the ultrastable signal, after compensation of the excess noise, and feed a secondary link, which phase noise ϕ_P is corrected using a second AOM. FM : Faraday Mirror.

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Coherent fiber links for radioastronomy and geodesy

D. Calonico, C. E. Calosso, C. Clivati, G. A. Costanzo, M. Frittelli A. Mura, and F. Levi
Physics Metrology Division, Istituto Nazionale di Ricerca Metrologica (INRIM), Torino, Italy
E-mail: d.calonico@inrim.it

Coherent optical fiber links are a unique mean for time and frequency transfer and for optical clocks comparison, allowing also for a network of accurate clocks, e.g. in Europe. They are also beneficial for radioastronomy [1], and for relativistic and space geodesy [2]. In Italy, the Metrological Institute INRIM developed the fiber link LIFT [3], presently connecting INRIM to (i) a radio antenna in Medicina (Bologna, 550 km haul) [4], (ii) the scientific pole in Sesto Fiorentino, Florence (642 km), and (iii) a laboratory in the Frejus tunnel (150 km) [5]. After 642 km, the link stability is 3×10^{-19} (1000 s), the accuracy is 5×10^{-19}. A South extension will connect in 2016 the Space Geodesy Center of the Italian Space Agency in Matera (1750 km haul), to improve space geodesy towards a 1 mm accuracy. At Medicina, the Institute for Radioastronomy of the National Insitute of Astrophysics has two radiotelescopes and participates to VLBI activities. We are investigating the use of fiber links for radioastronomy, to disseminate better frequency references and to synchronize remote antennas by fibers. The link is running and the H-Maser at the radio antenna was compared to the clock ensemble at INRIM. A new campaign scheduled in May 2015 will use INRIM clocks as the reference for radioastronomical measures.

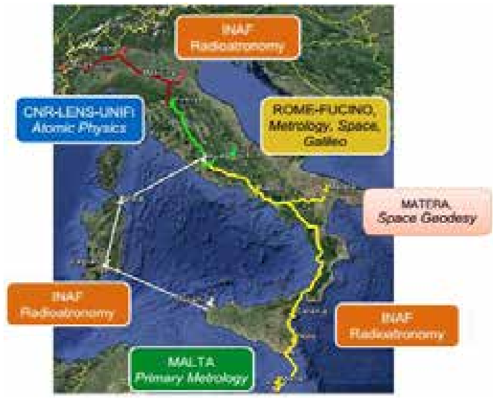

Fig. 1: The LIFT fiber link for radioastronomy, space and relativistic geodesy , atomic physics

At the Symposium, we will present experimental results for the radioastronomical fiber link, the global scenario for this kind of fiber links, together with the possibilities offered for relativistic and space geodesy, focusing on the ongoing activities on the links to the Frejus tunnel and to the Matera Space Geodesy Center.

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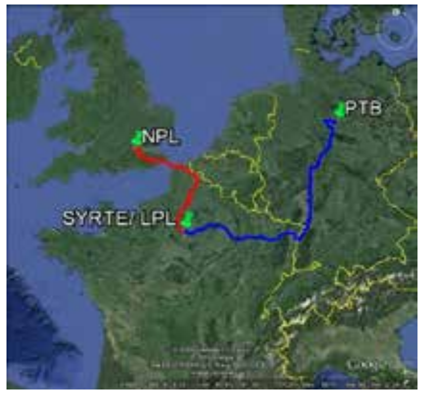
Towards an international optical clock comparison between NPL and SYRTE using an optical fibre network

J. Kronjäger[1], G. Marra[1], W.-K. Lee[2,8], P.-E. Pottie[2], A. Amy-Klein[3], O. Lopez[3], Fatima Spahic[4], D. Calonico[5], G. Roberts[6] and H. Schnatz[7]

1. National Physical Laboratory, Teddington, UK
2. Laboratoire National de Métrologie et d'Essais–Système de Références Temps-Espace, Observatoire de Paris, CNRS, UPMC, Paris, France
3. Laboratoire de Physique des Lasers, Université Paris 13, CNRS, Villetaneuse, France
4. Institut za mjeriteljstvo Bosne i Hercegovine (IMBiH), Sarajevo, Bosnia and Herzegovina
5. Instituto Nazionale di Riserca Metrologica, Torino, Italy
6. GÉANT, City House, Cambridge, UK
7. Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
8. Korea Research Institute of Standards and Science, Daejeon, Korea

E-mail: jochen.kronjaeger@npl.co.uk

Remote optical clock comparisons are an essential step towards a possible redefinition of the second, however traditional satellite-based techniques lack the accuracy and stability needed. Over the last ten years several research groups have explored optical frequency transfer through long haul fibre links. The longest link achieved so far, between PTB and MPQ in Germany, is 1840 km long [1]. The transfer techniques [2, 3] developed under the NEAT-FT project are mature enough to enable the remote optical clock comparison via optical fibre.



Using these techniques, we aim at performing an international comparison of the clocks developed at SYRTE and NPL, by measurement of the frequency ratio of their atomic transitions. The two laboratories are separated by a geographical distance of 340 km and linked by 800 km of optical fibre, mostly provided by the pan-European Research and Education network GÉANT. The total optical loss is about 220 dB and is partially compensated by 9 bi-directional EDFAs and one high-gain narrow-band fibre Brillouin amplifier.

We will present results on the fibre noise cancellation over the London-Paris link and further characterisation by comparing ultrastable lasers between NPL and SYRTE. We also plan to run clock comparisons over the fibre link in parallel to the ITOC campaign of satellite-based clock comparisons in June. Together with the link between France and Germany [4], the London-Paris link will allow to connect three European NMIs and the best clocks in Europe.

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The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7 2007–2013) under Grant Agreement No. 605243 (GN3plus), from Action spécifique GRAM and from the European Metrological Research Programme EMRP under SIB-02 NEAT-FT. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

Strengthening capability of optical fiber link with hybrid solutions

W.-K. Lee[1,3], F. Stefani[1,2], A. Bercy [2,1], O. Lopez[2], A. Amy-Klein[2], P.-E. Pottie[1]

1. Laboratoire National de Métrologie et d'Essais–Système de Références Temps-Espace, Observatoire de Paris, CNRS, UPMC, Paris, France
2. Laboratoire de Physique des Lasers, Université Paris 13, CNRS, Villetaneuse, France
3. Korea Research Institute of Standards and Science, Daejeon 305-340, South Korea

E-mail: won-kyu.lee@obspm.fr

The technique of phase-compensated optical fiber links has been developed rapidly over the last decade enabling the transfer and comparison of optical frequency over the distance exceeding 1000 kilometers. In this report, we present several two-way configurations and active compensation techniques, their comparisons, and their combinations, as a set of tools that can work together and performs ultimate frequency transfer [1, 2]. By comparing several methods, the ultimate performance of the frequency transfer and comparison is discussed. We also show that the combination of these tools can help to build an efficient dissemination of optical frequency standards, especially in urban area.

The experiments are done using a fiber pair of 43 km dedicated urban fiber network, which links SYRTE and LPL. We use one fiber to transfer ultra-stable laser light from SYRTE to LPL with an active noise cancellation set up. The second fibre is used to check the transferred stability on the first fiber, realizing a cascaded hybrid scheme. We obtain excellent frequency instability and robust operation as shown on Fig. 2. We show that the local two-way scheme is particularly suitable for the SYRTE-LPL-NPL link, as it relaxes the need of counter synchronization between SYRTE and LPL. This link will be used as a part of the Paris-London link for international optical clock comparison between SYRTE and NPL.

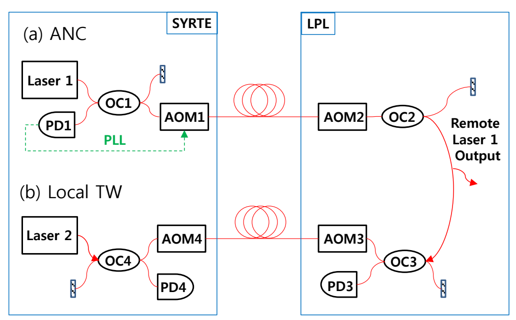

Fig. 1: Experimental setups (a) for active noise compensation, and (b) for local two-way comparison.

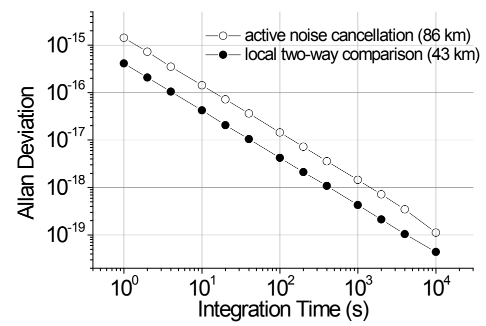

Fig. 2: Fractional frequency instabilities in terms of Allan deviation with Π–type counter in active noise compensation scheme and local two-way comparison.

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This work was partly funded from the EC's Seventh Framework Programme (FP7 2007–2013) under Grant Agreement No. 605243 (GN3plus), Action spécifique GRAM, and from the European Metrological Research Programme EMRP under SIB-02 NEAT-FT. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

Ultra-stable frequency transfer between SP and Chalmers

M. Zelan[1], S. C. Ebenhag[1], P. O. Hedekvist[1], M. Karlsson[2] and B. Josefsson[3]

1. Department of Measurement Technologies, SP Technical Research Institute of Sweden, Borås, Sweden
2. Photonics Laboratory, Chalmers University of Technology, Göteborg, Sweden
3. Swedish University Computer Network, Stockholm, Sweden

E-mail: martin.zelan@sp.se

SP Technical Research Institute of Sweden is the National Metrology Institute (NMI) responsible for the national frequency and time as well as the development and distribution of these to users within Sweden. Within this role an experimental fiber link suitable for ultra-stable frequency transfers is currently being established between SP Borås and Chalmers University of Gothenburg in Sweden, see Fig 1. The one way fiber length is about 60 km and implemented in SUNET (Swedish University Network). The network connection is DWDM-based (Dense Wavelength Division Multiplexing) and connects the network routers in a central node with the client network, where each channel can be configured with terminal equipment based on user needs.

Fig. 1: Map over the southern part of Sweden, indicating the location of SP and Chalmers.

At the sender-site at SP an ultra-stable laser and an optical frequency comb have been installed and will be the basis of the frequency transfer setup. For the frequency transfer, the experiment uses a channel in the DWDM with the wavelength of 1542.14 nm which also is the wavelength of our ultra-stable laser. This wavelength is within the C-band and is therefore compatible with common Erbium doped amplifiers in this network. The experiment uses a fiber pair, i.e. one fiber for transmission from east to west and another, parallel fiber from west to east. This will introduce an asymmetry that will be monitored and evaluated.

Within the project the signal quality when sending a stable optical coherent frequency utilizing a wavelength in a DWDM system fiber pair, will be evaluated. Another aim of the system is to be ultra-stable which corresponds to a stability of 10-13 for $\tau = 1$ sec (Overlapping Allan Variance), as well as providing the ability to distribute monitored ultra-stable frequency with a future traceability to UTC (SP) (National realization of Universal Time Coordinated within Sweden) to multiple users within the future network.

This presentation will describe the implemented technique in more detail, as well as the current status and results from the frequency transfer between SP and Chalmers. We will also present our future plans within the field of ultra-stable frequency transfers in Sweden.

Developing fibre link instrumentation for long-distance frequency transfer with 10^{-20} frequency uncertainty

S. Koke, S.M.F. Raupach, A. Kuhl, A. Koczwara, G. Grosche

Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, D-38116 Braunschweig, Gernany

E-mail: Sebastian .Koke@ptb.de

Optical fibre links enable the comparison of remote optical atomic clocks via the transfer of the ultrastable frequency of their clock laser. In order to cope with the fast advancement of optical atomic clocks, long-distance fibre links with instabilities and accuracies below the currently demonstrated 5×10^{-19} level are required [1,2]. In this contribution, we present our recent 1000 km scale frequency transfer results with a fibre link employing fibre Brillouin amplification (FBA) for signal recovery [3].

We developed field-able bidirectional FBA stages and cascaded three on a link connecting PTB and the Université de Strasbourg. The interferometrically stabilised link consists of a pair of telecommunication fibres patched together in Strasbourg to form a loop of 1400 km length. We characterize the performance of the frequency transfer [3], using a separately housed interferometer at the remote end in a climatised laboratory at PTB.

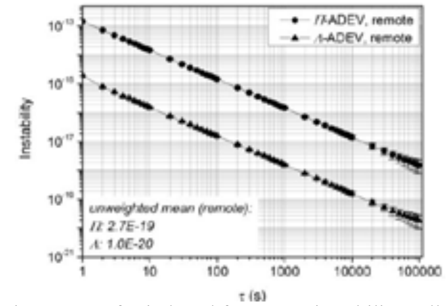

Fig. 1: Transfer-induced frequency instability. Allan deviation of the frequency offset counted in Π-mode (circles) and in Λ-mode (triangles) at 1s report time.

Figure 1 shows the instability of the optical frequency transfer. The Allan deviation of data collected in both Π and Λ counter mode reaches 1.5×10^{-18} and 1.9×10^{-20} (at 10^5s) respectively. The unweighted mean of the transfer-induced frequency offset resolved by the remote interferometer is 2.7×10^{-19} and 1.0×10^{-20}, respectively. Both values lie below the values of the respective Allan deviation: no significant frequency offset is observed. In a three week campaign, we performed 13 continuous measurement runs with 1.3 million seconds of data in total. The frequency offsets of these runs scatter over a range $< \pm3\times10^{-20}$ with a weighted mean of $(1.1\pm0.4)\times10^{-21}$. Possible causes for these offsets include out-of-loop processes in the remote interferometer, overcorrection of link frequency fluctuations due to the different optical frequencies in the forward and backward direction [4], limited noise suppression due to the delay limit, and non-reciprocal phase fluctuations introduced by FBA. The latter we characterise to contribute less than 10^{-8} of the free-running fibre frequency fluctuations, resulting in an uncertainty contribution below 5×10^{-21} for our stabilized link set-up.

In conclusion, the fibre link's instability is two orders of magnitude below that of the world's best optical clocks, and the narrowband FBA supports 1×10^{-20} uncertainty.

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An optical fibre link as reference for a 450-km-baseline GPS carrier phase link

C. Grebing[1], S. Droste[2], J. Leute[1], S. M. F. Raupach[1], A. Matveev[2], A. Bauch[1], R. Holzwarth[2], G. Grosche[1]
1. Physikalisch-Technische Bundesanstalt (PTB), 38116 Braunschweig, Germany
2. Max Planck Institute of Quantum Optics (MPQ), 85748 Garching, Germany
E-mail: christian.grebing@ptb.de

Sophisticated technology is used to compare distant atomic clocks by reception of Global Navigation Satellite System (GNSS) signals, or by sending signals in the microwave region from one location to another through geo-stationary satellites [1]. Further improvements will be required to support comparisons of optical atomic clocks, with their intrinsic fractional frequency uncertainty approaching 10^{-18}. To test and improve GNSS links, active hydrogen masers are useful tools, but for a fractional frequency instability below a few 10^{-15} they are insufficient.

Here we use a 920 km optical fibre link, which we characterised before [2] at an uncertainty level below 10^{-18}, as a reference link for characterising a GPS (i.e. the most common GNSS system) carrier phase (CP) link. We simultaneously compare two active H-masers, via the fibre link and via GPS, over a baseline of 450 km [3]. The masers are located at the endpoints MPQ in Garching and PTB in Braunschweig, see Fig.1. The GPS data is processed using the NRCan Precise Point Positioning (PPP) software. Note, that very recent investigations indicate improvements on this PPP software [4].

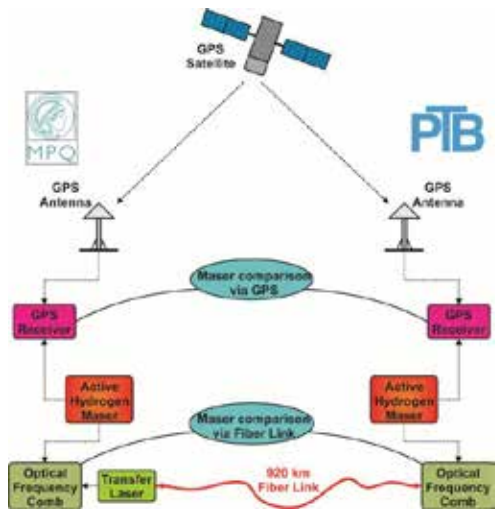

Fig. 1: Experimental set-up. Two hydrogen masers are compared via a reference fibre link, transferring a highly stable optical carrier frequency from MPQ in Garching to PTB in Braunschweig. Optical frequency combs on both sides connect optical and microwave frequencies. Simultaneously, the two masers are compared via a GPS CP link.

In two measurement campaigns (660 h duration in total), the *difference* between GPS link and fibre link data is not affected by frequency fluctuations of the two masers and thus characterises the properties of the GPS link in good approximation, due to negligible contributions from the fibre link: this difference showed a statistically limited mean of $(1.3 \pm 3) \times 10^{-16}$.

This measurement confirms that the well established GPS satellite network supports frequency comparisons at the level of the very best microwave atomic clocks without unveiling any systematic limitation.

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Towards international timescales with optical clocks

H.S. Margolis[1], E. Benkler[2], D. Calonico[3], H. Denker[4], P. Delva[5], R. M. Godun[1], C. Lisdat[2], J. Gersl[6], M. Merimaa[7] + members of the ITOC consortium
1. National Physical Laboratory (NPL), Teddington, UK
2. Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany
3. Istituto Nazionale di Ricerca Metrologica (INRIM), Torino, Italy
4. Insitut für Erdmessung (IfE), Gottfried Wilhelm Leibniz Universität, Hannover, Germany
5. LNE-SYRTE / Observatoire de Paris, LNE, CNRS, UPMC, Paris, France
6. Cesky Metrologicky Insitut (CMI), Brno, Czech Republic
7. MIKES Metrology, VTT Technical Research Centre of Finland Ltd, Espoo, Finland
E-mail: helen.margolis@npl.co.uk

Before an optical redefinition of the SI second can occur, optical atomic clocks must be integrated into the international timescales TAI and UTC. For this to happen, a coordinated programme of clock comparisons must be carried out, to validate the uncertainty budgets of the new clocks and to link their frequencies to the present definition of the second, as well as to help establish the leading contenders for a new definition. Such a programme is underway within the EMRP-funded project "International Timescales with Optical Clocks" (ITOC), involving optical clocks in five different laboratories (Fig. 1).

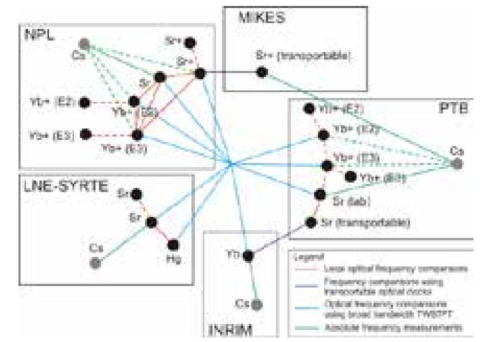

Fig. 1: ITOC clock comparison programme. Dotted lines indicate measurements that are being carried out within other projects, but that will be included in the overall self-consistency analysis.

Optical clocks developed in individual laboratories are being compared either via direct heterodyne beat measurements or by using femtosecond combs to measure optical frequency ratios, and absolute frequency measurements are also being performed. For comparisons between optical clocks developed in different laboratories, we are focusing on two techniques that have the potential to be applied on an intercontinental scale: the use of transportable optical clocks and an enhanced version of two-way satellite time and frequency transfer (TWSTFT) based on an increased chip rate. Several new measurements have already been completed and others are underway. When the programme is complete, the body of data will contain sufficient redundancy for important self-consistency checks to be carried out. The current status of the comparison programme will be reported at the conference.

To support this programme, a complete evaluation is being made of all relativistic effects that influence time and frequency comparisons at the 10^{-18} level of accuracy, including the gravitational redshifts of the clock transition frequencies. Gravity surveys have been carried out at all sites participating in the optical clock comparisons and will feed into the computation of an improved European geoid model.

Within the ITOC project, an experiment is also being prepared to demonstrate the impact that optical atomic clocks could have on the field of geodesy. The aim of this experiment is to measure with high temporal resolution the gravity potential difference between two well-defined locations separated by a long baseline (≈ 90 km) and a height difference of 1000 m.

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

Turbulent phase noise on asymmetric two-way ground-satellite coherent optical links

Robert Clélia, Conan Jean-Marc, Wolf Peter*
DOTA, ONERA - The French Aerospace Lab F-92322 Châtillon, France
*LNE-SYRTE, Observatoire de Paris, CNRS, LNE, UPMC, 61 avenue de l'Observatoire, F-75014 Paris, France
E-mail: peter.wolf@obspm.fr

Bidirectional ground-satellite laser links suffer from turbulence-induced scintillation and phase distortion. Driven by frequency transfer applications, we study how turbulence impacts on coherent detection capacity and on the associated phase noise that limits clock transfer precision. We thus evaluate not only the statistical properties of turbulence effects, but also their temporal evolution. We show an efficient two-way compensation of phase noise that is very promising for time/frequency transfer, and not yet evaluated in the literature to our knowledge. An efficient two-way cancellation of atmospheric effects in such time/frequency links requires reciprocity between up and downlink. This has been studied recently [1-4] on horizontal propagation paths and under conditions of perfect overlap between the two channels. To account for realistic turbulence and wind conditions, the asymmetry of the ground-satellite links, the point-ahead angle and the satellite cinematic, we use wave-optics propagation through turbulence for refined end-to-end simulations with the exact beam geometry. Monte-Carlo simulations allow characterizing the coherent detection in terms of heterodyne efficiency: mean value and statistical distribution. Temporal simulations provide time series and spectral density of the heterodyne efficiency and phase or frequency noises, thanks to translating phase screens following wind profiles and satellite cinematic.

The presentation is twofold: first, we provide statistics on heterodyne efficiency for different turbulence strengths and system parameters. We show that to avoid large fluctuations in signal to noise ratio with frequent extinctions we need to correct at least for tip-tilt. Second, we present examples of temporal phase noise evolution for both up and downlink, like in Fig. 1. Finally, we quantify the two-way partial compensation of the phase noise and its impact on the frequency stability of space to ground clock comparisons in terms of Allan variance.

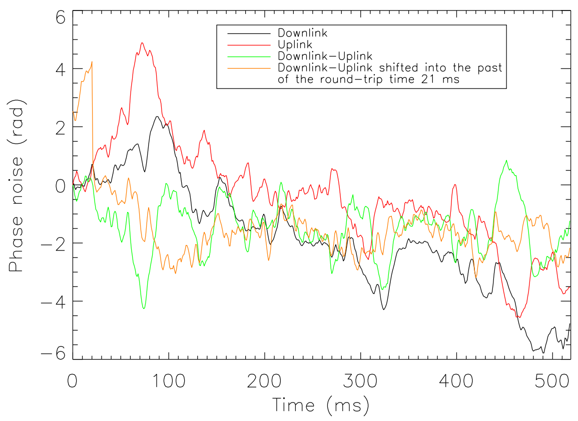

Fig. 1: Example of temporal phase noise evolution for the uplink and downlink, and their difference.

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$1x10^{-16}$ frequency transfer with GNSS or TWTT

G. Petit[1]
1. Time Department, BIPM, 92312 Sèvres, France
E-mail: gpetit@bipm.org

Since many years, GPS phase and code observations have provided reliable time and frequency transfer between stations whatever their location on Earth. The technique of choice is Precise Point Positioning (PPP), with a typical uncertainty for frequency comparisons of order $1x10^{-15}$ at 1-day averaging, a few 10^{-16} at 5 to 10 day averaging and about $1x10^{-16}$ at 30 day averaging. Two-way satellite time and frequency transfer also provides similar performance but requires specific equipment and observation planning.

One approach to overcome the limitations of "classical PPP" is to consider the integer nature of phase ambiguities. Common-view carrier phase with integer ambiguity resolution has been demonstrated several years ago but is limited in distance. We have recently succeeded in applying integer ambiguity resolution to PPP, thus allowing frequency comparison at any distance over long durations. We have shown [1] that this IPPP technique achieves a frequency transfer accuracy of $2x10^{-15}$ at ~5-hour averaging for all links and that an accuracy of $1x10^{-16}$ is reached at ~5-day averaging for regional links (see Fig. 1). A similar performance is likely achievable for long distance links but cannot be proven for lack of an accurate reference.

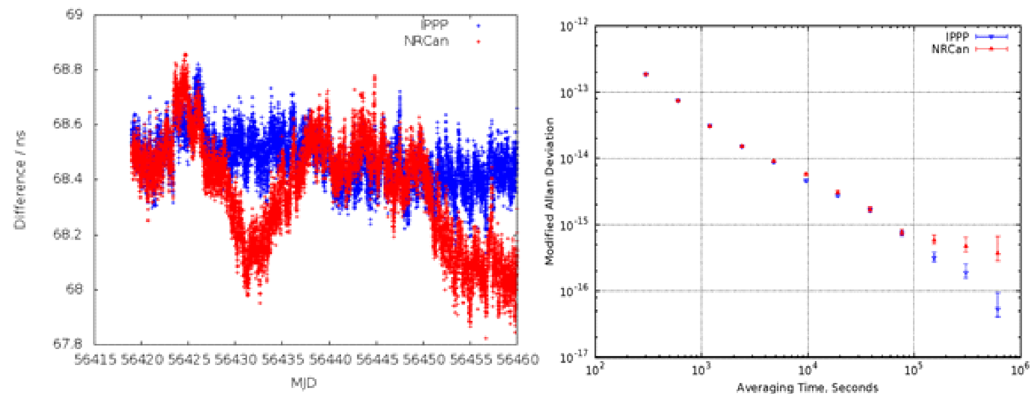

Fig. 1: Comparison between a 420-km optical fibre link and the results obtained with IPPP (blue) and classical PPP (red) over 41 days: Plot of the time differences with arbitrary offset (left), stability analysis (right).

Two-way time transfer using the phase of the carrier would provide still more accurate frequency transfer but it is very difficult to ensure coherent phase continuity over the duration of the frequency comparison. Nevertheless each interval of phase continuity provides one frequency measurement and all such measurements can be averaged to reach the 10^{-16} level.

While regional frequency comparisons will be performed with unprecedented accuracy using fiber links, no perennial technique is on the horizon for long distance links. It is thus important to gain as much as possible from the established GNSS and TW techniques.

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Methods of time series preparation based on UTC and UTCr scales for predicting the corrections for UTC(k)

L. Sobolewski[1], **W. Miczulski**[1]
1. Institute of Electrical Metrology, University of Zielona Gora, Zielona Gora, Poland
E-mail: l.sobolewski@ime.uz.zgora.pl

The problem of maintaining the highest compliance of the UTC(k) with the UTC is due to a complexity and time-consuming process of calculating the UTC based on specific algorithms. This results in a delay of publication by the BIPM of the "Circular T" bulletin, in which around the 10th day of the following month the deviations [UTC - UTC(k)], which define the divergence of the UTC(k) relative to the UTC for the previous month are published. Values of these deviations are designated on MJD dates ending with digits "4" and "9". Correcting these divergences is only possible through predicting the corrections for the UTC(k). Many articles describe methods of predicting corrections for the UTC(k) based on statistical models. Where there is a partial or total lack of knowledge of the rules that describe objects or processes, resulting in a large complexity of problems, neural networks (NN) can be used. A unique feature of the NN is the ability to build models with a method based solely on the analysis of specific examples, i.e., the inductive method. The authors have conducted a series of studies on the application of MLP, RBF, GRNN and GMDH NNs for predicting the corrections for UTC(k). The best results were obtained using GMDH NN [1] and [2].

Predicting the corrections for the UTC(k) in particular requires to obtain the best accuracy of prediction. Therefore for each designated prediction there is a need for proper preparation of the input data (time series) for a NN in the process of its training and predicting. In the NN training process also a selection of its parameters is very important. On the accuracy of predicting the corrections affects also the time interval at which the prediction is made.

In the paper, on the example of UTC(PL) scale and using GMDH NN, the research results in this area will be presented. The first group of times series was built exclusively on the basis of [UTC - UTC(k)] deviations. In this case the first prediction of the correction for the UTC(PL) was practically possible to designate in a given month with time interval of 15 or 20 days in relation to the date of the last known value of the deviation. The second group of times series was built on the basis of [UTC - UTC(k)] and [UTCr - UTC(k)] deviations. The [UTCr - UTC(k)] deviations are determined by the BIPM for each day of the week and published on next Wednesday. In the case of using [UTCr - UTC(k)] deviations for construction the second group of time series the first prediction of the correction for the UTC(PL) scale was practically designated with time interval of 3 days, so at the date of its publication in relation to the date of the last known value of the deviation.

The obtained research results and performed statistical analysis confirmed that the best quality predictions were obtained for the second group of time series. This is due to shorter prediction interval, by using the values of deviations according to the UTCr scale.

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Clock ensembling using Kalman filter – implications of non-observability and causality

M. Peca[1,2]
1. Serenum, a. s., Praha – Letňany, Czech Republic
2. České vysoké učení technické v Praze, Praha, Czech Republic
E-mail: peca@serenum.cz

The goal of clock ensembling is to infer a best estimate of current time, given time measurements and clock models. The key problem of clock ensembling without a master clock is that measured clock phase differences do not allow to fully reconstruct clock phases – the measurement is singular. In effect, a subspace of clock ensemble states is not observable, and a covariance of their estimates grows to infinity. An optimal linear estimator, in its most general form known as Kalman filter (KF), shall be the best possible means of clock ensembling, given currently known stochastic models of clocks. However, the non-observability leading to infinite covariance growth requires a special treatment, which has been originally proposed in seminal and still valid work [1], and later in a different way [2].

To provide better insight, we have decomposed the clock ensemble into an observable and non-observable part, and designed KF for both parts: the observable subsystem is estimated by traditional KF, and the non-observable states are calculated solely out of the observable states. The infinite covariance terms cancel out of the calculations. Although the resulting time estimates are equivalent to [1], our re-formulation allows to use plain KF backed by lots of existing numerical implementations.

Based on this view, we elaborate an important scenario of fixed stochastic models (constant clock covariances over time): the KF converges to a *steady-state*, becoming a simple linear, time-invariant (LTI) filter. This LTI KF can be directly computed by solving a Riccati eqn. (observable part), and Sylvester eqn. (non-observable part). We see, that non-observable states become a linear combination of the observable ones, equivalent to a pseudo-inverse solution of underdetermined system.

An observation of paramount importance is, that in ensemble of distinct clocks, the clock(s) with best long-term stability tend to effectively rule out all other clocks, no matter how good they are in shorter term. This counterintuitive finding has been reported before [2], and most probably helped to divert some researchers towards more empirical and less justified approaches to KF ensembling [2]. To understand this phenomenon, we compare the LTI KF with another formulation of linear estimator, Wiener filter. The key result is, that the unwanted preference of the "long-term stable" clocks is an effect of *causality*, i.e. the demand to obtain the estimates in real time, without any delay. Simply the fact that future is not known leads to such behaviour. Besides the obvious and not always practical treatment by offline (infinite-lag) processing, we look into a possibility how to design slightly sub-optimal, but practically more desirable clock ensemble KF estimators.

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Precision analysis of GPS PPP time transfer with the different IGS products

H. Yuan[1], **L. Yin**[1,2], **W. Guang**[1,2], **LI Wei**[1]

1. National Time Service Center , CAS, BOX 18 Lintong Xi'an Shaanxi, 710600 China
2. University of Chinese Academy of Sciences, No.19A Yuquan Road, Beijing 100049, China

E-mail: yuanhb@ntsc.ac.cn

The GNSS CV, AV and PPP are the high precision time transfer methods based on the satellite navigation system. By calculating the time difference of two stations between the local time and reference time, the time difference between the two stations can be obtained. Take the GPS for an example, for GPS CV and AV the reference time is GPS Time, however for GPS PPP the reference time is IGS Time. There are three types of products which include Ultra-Rapid, Rapid and Final ephemeris and satellite-station clock difference are provided by IGS(International GNSS Service), the different product directly affects the time transfer precision in GPS PPP. In this paper, the real data from the important timekeeping laboratory is used to analyze the precision when the different ephemeris and satellite-station clock difference are used, and the result shows that the different product of ephemeris and satellite-station clock difference really affect the precision of the time transfer in GPS PPP, but no matter which product is used, the precision of GPS PPP time transfer is less than 1ns. Fig1 shows the difference between UTC(NTSC) and UTC(USNO) by using the GPS PPP algorithm with three IGS products.

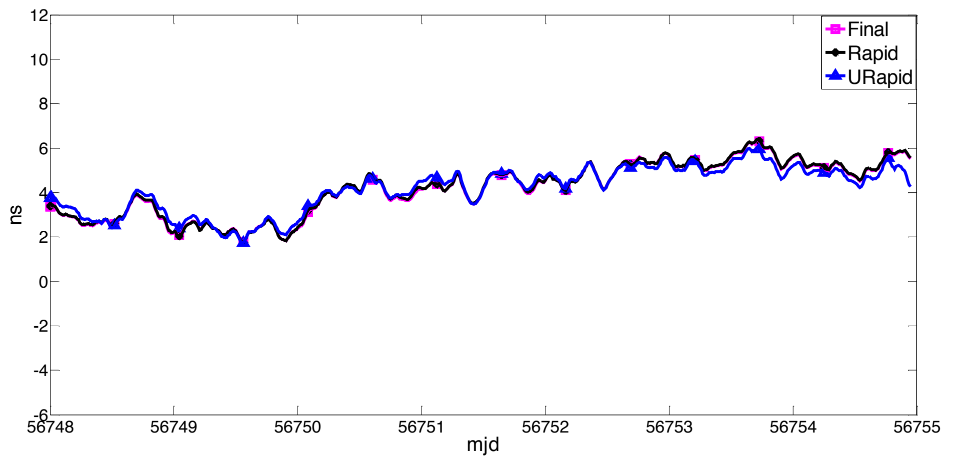

Fig1 UTC(USNO)-UTC(NTSC) with different IGS products

Rapid evaluation of time scale using an optical clock

T. Ido, H. Hachisu, F. Nakagawa, T. Gotoh, H. Ito, M. Kumagai, Y. Hanado

National Institute of Information and Communications Technology, Koganei, Tokyo, Japan

E-mail: ido@nict.go.jp

Optical clocks have made rapid progress for these ten years. Several optical clocks have surpassed the state-of-the-art microwave clocks in the stability as well as accuracy. This fact induces the discussion toward the transfer of clock applications from microwave to optical region. Keeping time scales using optical clocks might be one of them. It is known that some advanced laboratories maintain their local time scale using microwave fountain clocks. The operation of fountains has been matured for twenty years, enabling seamless operation. But it is still not easy to build fountain clocks from scratch. It might be straightforward to build optical clocks and to utilize them to maintain their time scale.

Continuous operation is generally demanded for time scales. However, it is still difficult to operate optical clocks continuously. Particularly in case of lattice clocks, the system consists of not only a clock laser but also various lasers for cooling, lattice, and repumping, whose frequency need to be highly stabilized. Therefore, first step of the application to time scale would be intermittent steering of microwave-based time scale according to the calibration served by an optical clock.

NICT uses hydrogen masers as s a source oscillator of its time scale, UTC(NICT). The stability of the most stable maser reaches 1×10^{-15} at 1000s, and stays at 10^{-16} level until 10^{4}s. The absolute frequency of the Sr lattice clock at NICT [1], on the other hand, was lately evaluated with a reference of a local Cs fountain NICT-CsF1 [2] as well as a frequency link to international atomic time. Both results were consistent with highly accurate measurements performed by SYRTE [3] and PTB [4]. Therefore, 10^{4} s of frequency measurement with a reference to the UTC(NICT) is sufficient to calibrate the time scale with uncertainty of 1×10^{-15} or below, whereas it takes one day for Cs fountain to evaluate the frequency in same level. We operated a Sr lattice clock for more than 10^{4} s per day. Based on the intermittent measurement once in a day, we detected the fluctuation of time scale in short time and estimated the gain or loss of UTC(NICT). The estimation agreed well in sub-ns level with the time difference between UTC(NICT) and UTC, which is available in circular T issued with the latency of one month. The capability of this estimation implies the possible steering of time scale using an optical clock.

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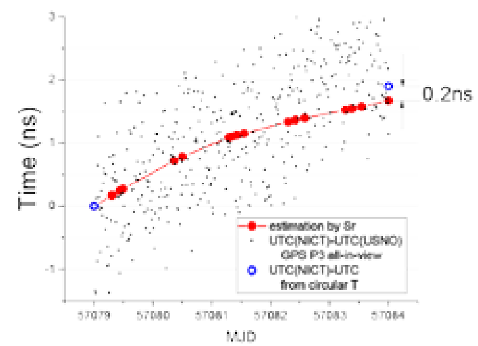

Fig. 1: Estimation of UTC(NICT) based on frequency measurement of the Sr lattice clock .

Minimum uncertainty weighted frequency averaging applied to remote clock comparisons

E. Benkler, C. Lisdat, and U. Sterr
Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
E-mail: erik.benkler@ptb.de

State-of-the-art optical clocks located remotely from each other require improved ways for their comparison. Most promising approaches are fiber links on a continental scale and enhanced satellite links on an intercontinental scale. However, with both fiber and satellite links, white phase noise is the dominant noise type, which even at measurement times of several hours can obscure the performance of the optical clocks [1, 2].

A solution is to determine the average frequency offset between the clocks in a way that suppresses the white phase noise by filtering, without biasing the frequency average. Such filtering is achieved by suitable weighting used for frequency averaging. Prominent examples are equally weighted frequency averaging as performed by Π-counters, and frequency averaging with a Λ-shaped weighting function. There is a connection between the weighting function and the statistical uncertainty of the weighted frequency average, because depending on the weighting function the remaining noise contributes to the average value. Hence, for a given noise condition, an optimum weighting function exists, which optimally filters out the noise, such that the statistical uncertainty of the weighted frequency average is minimized.

A well established tool to characterize the noise properties in an experiment is the Allan variance in case of Π-weighted frequency averaging. This can be generalized to the two-sample variance associated to the weighting function used for frequency averaging, such as the modified Allan variance associated to Λ-weighted frequency averaging. We show how the uncertainty can be determined from the two-sample variance associated to the weighted frequency average and discuss how to find optimum weighting functions, which yield minimum frequency uncertainty under given noise conditions [3]. In the case of white phase noise, we find that a parabolic (Ω-shaped) frequency weighting function corresponding to a linear regression fit to phase data is the optimum approach. Besides offering the minimum uncertainty of the average frequency offset between the optical clocks, this strategy has the benefit to be robust against data gaps, which are usually present on two-way satellite link data.

The advantages of the optimum weighting strategy compared to commonly used, less efficient strategies are presented. Furthermore, the influence of technical disturbances, such as diurnals, is investigated in numerical simulations.

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Absolute frequency measurement at 10^{-16} level based on the international atomic time

H. Hachisu, M. Kumagai, T. Ido
National Institute of Information and Communications Technology, Koganei, Tokyo, Japan
E-mail: hachisu@nict.go.jp

International atomic time (TAI) is a time scale which is generated based on time differences of atomic clocks in worldwide. BIPM calculates the average of ~400 clocks and adjusts its frequency bias referring data from those national laboratories which maintain primary frequency standards. Laboratories send BIPM the clock information of 0:00 UTC every five days. Thus, the TAI is not a real clock but a virtual one that "ticks" once in every five days. Since one second generated by the TAI is maintained with accuracy of 10^{-16} level, it works not only as a time scale but also as a frequency reference, which is particularly convenient for laboratories where primary frequency standards are not always available. Only average frequency of five days is obtainable from the TAI. Therefore, measurements referring TAI has uncertainty due to the limited measurement time as well as that due to satellite-based time link between TAI and local reference.

Absolute frequency measurement of a strontium lattice clock at NICT was for the first time performed in 2012 [1] which had uncertainty of 3.3×10^{-15} predominantly due to the limitation of TAI-based measurement described above. Since the systematic uncertainty related to strontium has been recently reduced to 2×10^{-16} or below, it is crucial to reduce this link uncertainty. While dead-time free measurement for whole five days is ideal to overcome this limitation, we performed frequency measurement for 10^4 s per day on five consecutive days. The measurements partially fill the five days with balanced distribution. The distributed measurements also enable to evaluate the linear drift of local reference (hydrogen maser), allowing better estimation of maser frequency. In addition, repeating the five day experiment has statistically reduced the uncertainty of the time link down to 10^{-16} level. Introducing these ideas, the frequency has resulted in good agreement with that referenced to a local Cs fountain (NICT-CsF1) [2]. The frequency was also consistent with two highly accurate frequency measurements recently performed at SYRTE [3] and PTB [4] with difference below 1×10^{-15}.

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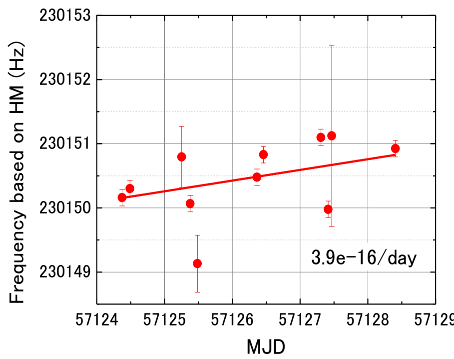
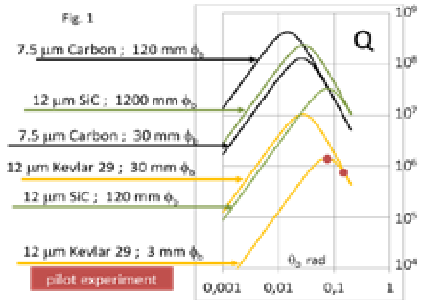


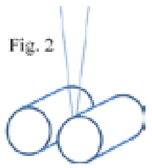
Fig. 1: Frequency measurements with referenced to a local hydrogen maser (HM). The result indicates the drift rate of maser, which mitigates the bias caused by inhomogeneous distribution of measurement time.

A Frequency Metrology approach to Big G determination using a pair of extremely high Q simple pendulums in free decay

A. De Marchi
Dept. of Electronics and Telecommunications, Politecnico di Torino, Torino, Italy
E-mail: andrea.demarchi@polito.it

It is argued that simple pendulums exhibiting Q values in excess of 10^8 can be realized by using high resistance fibers to suspend in vacuum a bob of a few hundred mg mass. In the case of a 1 m long pendulum this leads to a damping time constant of several years, which is long enough to allow experiments in the free decay mode, maximizing in this way the expected short term frequency stability. The experience acquired with the pilot single pendulum Big G experiment [1] carried out at Politecnico di Torino in 2000-2006 supports the theoretical analysis of Q (Fig.1) on the basis of which this argument is made. That experiment was stopped after realizing that ocean waves related angular (Rayleigh) seismic noise was limiting practically achievable Type A uncertainty to the percent level, given the "short" 10 days decay time granted by the measured $2x10^6$ Q value. The confidence recently acquired in much higher Qs is the reason why a new apparatus is now in the works, which common modes angular seismic noise by deploying two pendulums that are alternatively subjected to a gravitational perturbation by the active masses. The relative frequency difference between the two is measured as the rate of time delay change, in a typical high resolution Frequency Metrology technique, and the resulting Type A uncertainty will then improve with power 3/2 of measurement time. The 10^{-12} frequency resolution, necessary for the required $2x10^{-6}$ uncertainty on the $5x10^{-7}$ gravitational effect projected with reasonable cylindrical W active masses (as in Fig.2), will then be achieved in less than two hours when starting from an easily obtainable 10 ns time resolution.





An interesting feature of the pendulum experiment is the fact that, when two active masses are symmetrically positioned around the pendulum, their gravitational effect is first order independent of both lateral and vertical positioning of the low point of the bob's trajectory around a magic point which minimizes it vs horizontal displacements and maximizes it vs vertical ones. The positioning tolerance is about 0.2 mm either side of such center in both directions for an error on G smaller than 10^{-5}. Other Type B uncertainties are all easily below the 10^{-5} mark, including the adiabaticity effect [2], except for the contribution from the distance between active masses, which needs to be known to 100 the order of nm. The use of gauge blocks is projected for this goal.

The experiment is coherent with the need to diversify approaches for the improvement of Big G determination, recognized by the Royal Society in the February 2014 London meeting and by NIST in the October Workshop in Gaithersburg, where it was first presented.

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High-Performance Optical Frequency References for Space

T. Schuldt[1], K. Döringshoff[3], A. Milke[1,2], M. Gohlke[1], E. V. Kovalchuk[3], N. Gürlebeck[2], A. Peters[3], C. Braxmaier[1,2]
1. German Aerospace Center (DLR), Institute of Space Systems, Bremen/Germany
2. Center of Applied Space Technology and Microgravity (ZARM), University Bremen, Bremen/Germany
3. Humboldt-University Berlin, Institute of Physics, Berlin/Germany
E-mail: thilo.schuldt@dlr.de

Optical frequency references have a multitude of possible applications in space, including fundamental physics, geoscience, Earth observation, and navigation and ranging. Examples are the gravitational wave detector eLISA (evolved Laser Interferometer Space Antenna) and missions, dedicated to tests of Special Relativity, e.g., by performing a Kennedy-Thorndike experiment testing the boost dependence of the speed of light.

In this context, we currently develop optical frequency references based on Doppler-free spectroscopy of molecular iodine and an optical resonator, with special emphasis on future operation in space. Compactness and stability are main design criteria. Both frequency references are optimized for long-term frequency stability as for the space-based Kennedy-Thorndike experiment the relevant timescale corresponds to an orbit time of ~90 min.

We realized two setups of an iodine-based frequency reference on elegant breadboard (EBB) and engineering model (EM) level utilizing modulation transfer spectroscopy of molecular iodine near 532 nm (see Fig. 1). A frequency stability of about $1\cdot10^{-14}$ at an integration time of 1 s and below $5\cdot10^{-15}$ at integration times between 10 s and 100 s was achieved. These values are comparable to the currently best laboratory setups.

A cavity-based frequency reference utilizing an NPL cube-shaped resonator [1] is currently developed. A specific sixfold thermal shield has been developed based on analytical methods and numerical calculations to realize the required long-term thermal stability.

Financial support by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant numbers 50 QT 1102, 50 QT 1201 and 50 QT 1401 is highly appreciated.

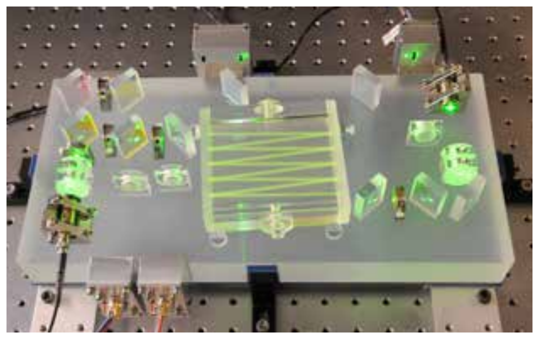

Fig. 1: Ruggedized Iodine spectroscopy unit on EM level, realized on an 18 cm x 38 cm fused silica baseplate.

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Hydrogen molecular ions: new schemes for metrology and fundamental physics tests

J.-Ph. Karr[1,2], **V.Q. Tran**[1], **A. Douillet**[1,2], **J.C.J Koelemeij**[3], **L. Hilico**[1]
[1]Laboratoire Kastler Brossel, UPMC-Sorbonne Universités, CNRS, ENS-PSL Research University, Collège de France, Paris, France
[2]Département de Physique, Université Val d'Essonne, Evry, France
[3]LaserLab and Department of Physics and Astronomy, VU University, Amsterdam, The Netherlands
E-mail: jean-philippe.karr@lkb.upmc.fr

High-resolution spectroscopy of ro-vibrational transitions in the hydrogen molecular ions H_2^+ and HD^+ has emerged as a promising method for the determination of nucleus-to-electron mass ratios [1,2]. In view of the high accuracy reached by theoretical calculations of transition frequencies [3], such measurements could not only improve on the present best determination of m_p/m_e [4] but also play a major role in resolving the current discrepancy on the proton charge radius and Rydberg constant.

Reaching these goals requires experimental accuracies in the 10^{-12} range. While conventional Doppler-free spectroscopy puts many constraints on the experimental setup, we show that two-photon spectroscopy of HD^+ with quasi-degenerate counterpropagating photons is a convenient alternative [5], which may be applicable also to other molecular ions. The transition probability is enhanced by tuning the lasers close to resonance with an intermediate rovibrational level, so that no enhancement cavity is needed, and the residual Doppler broadening is suppressed by a two-photon Lamb-Dicke effect.

Further, H_2^+ and HD^+ are interesting candidates for the realization of optical clocks that would be sensitive to possible variations of m_p/m_e in the 10^{-17}/yr range [6,7]. Among their attractive features are the possibility to calculate very precisely the clock frequency as well as all relevant systematic effects, and the availability of efficient schemes for internal state preparation. The level of performance achievable with different classes of transitions will be discussed in detail.

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Atom interferometers for gravity measurements and fundamental physics tests in space

N. Yu

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA. USA
E-mail: nan.yu@jpl.nasa.gov

Atom interferometers exploit the quantum wave-nature of atomic and quantum gases for precision measurements of inertial forces. Laser-cooled atomic gases in free fall provide ideal, drag free test masses for applications ranging from accelerometers, gyroscopes, gravity gravimeters and gradiometers, to precise testing of fundamental physics. The high stability and sensitivity intrinsic to atom interferometry already demonstrated state-of-the-art performances in sensitivity and accuracy in laboratories. Implementing this new technology in space will provide new opportunities for the next generation global gravity measurements, unprecedented precision in testing fundamental physics, and alternative ways for gravitational wave detection.

We will describe JPL's efforts in the development of atom interferometer technology and investigations of its applications in space. We will first report the results of the development of atom interferometry for Earth gravity mapping. Central to our work is the transportable atom interferometer instrument in operation at JPL, which is designed with a specific configuration for microgravity operation. Our recent advancements have brought the atom interferometer instrument to be competitive with those of the best performances from laboratory experiments reported in literature. We will review the design principle, discuss technical challenges and mitigations, and describe our findings including the laser ranging assisted long-baseline approach.

We will also report findings of the science and engineering feasibility study of Quantum Test of Equivalence Principle and Space Time (QTEST), a concept of dual atomic species interferometer experiment on ISS for precise test of Einstein's equivalence principle. Its primary science objective is a test of Einstein's equivalence principle with two rubidium isotope gases at a precision of better than 10^{-15}. The predicted high measurement precision of QTEST comes from the microgravity environment on ISS, offering extended free fall times in a well-controlled environment, together with a number of systematic reduction techniques including use of one Bragg interferometer laser system for two species, simultaneous k reversal measurements, and most importantly modulation of gravity direction.

This work was carried out at the Jet Propulsion Laboratory under contract with the National Aeronautics and Space Administration.

Compact interferometer based on an expanding ball of atoms

S. Riedl, G. Hoth, B. Pelle, J. Kitching, and E. A. Donley
Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO, USA
E-mail: elizabeth.donley@nist.gov

The intrinsic calibration inherent in atomic sensors gives light-pulse atom interferometry [1] a unique advantage in terms of long-term stability when compared to other sensing technologies. Atom interferometers have the potential to become widely used for applications of inertial navigation and geodesy, but so far, their large size and power consumption have mostly limited their use to laboratory environments.

At the conference, we will present a compact atom interferometer that simultaneously measures rotations and accelerations with a single source of atoms in an active evacuated volume of 5 cubic centimeters. This set up offers a significant simplification compared to typical atom interferometers, which require differential measurements performed with counterpropagating atom samples to distinguish phase shifts from rotation and acceleration [2]. We are able to achieve this simplification by extending the Point Source Interferometry (PSI) technique originally demonstrated in a 10-meter atomic fountain at Stanford [3]. In this technique, a single source of atoms is used in combination with spatially resolved imaging; since the individual atom velocities are correlated with their final positions after the interferometer sequence, rotational phase shifts are observed as interference fringes across the atom cloud.

We employ the PSI method in a regime where the cloud has expanded to only a few times its initial size with a system that is 100× smaller than its previous implementation [3]. Our work illustrates the broad applicability of this technique and explores the possibility of using PSI to sense rotations for portable applications.

In order to characterize our system as a gyroscope, we have simulated two-axis rotations of the interferometer by tilting the Raman axis between light pulses. The spatial PSI fringes have the expected properties, in that they are perpendicular to the axis of rotation, have a wavelength that is inversely proportional to the rotation rate Ω, and decrease in contrast with increasing Ω. We are also able to characterize our system as an accelerometer by measuring the atoms' acceleration due to gravity.

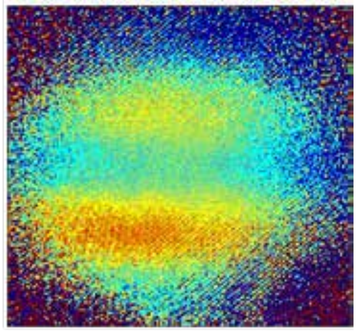

Fig. 1: Spatial interference fringes arising from a rotation rate of Ω=24 mrad/s.

Our near-term efforts will focus on measurements of the gyroscope's scale factor and dynamic range. We will also increase our interaction time, which will enable us to detect the Earth's rotation and characterize the sensitivity of PSI for small phase gradients. In the long term, we hope to characterize our interferometer as an inertial sensor and explore the possibility of developing a truly miniaturized system.

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Atom-chip based quantum gravimetry with Bose-Einstein condensates

J. Matthias[1], S. Abend[1], M. Sahelgozin[1], M. Gebbe[2], M. Gersemann[1], H. Ahlers[1], H. Müntinga[2], W.Herr[1], W. Ertmer[1], C. Lämmerzahl[2], and E.M. Rasel[1]
1. Institut für Quantenoptik, Leibniz Universität Hannover, Germany
2. ZARM, Universität Bremen, Germany
E-mail: matthias@iqo.uni-hannover.de

Today's generation of inertial sensitive atom interferometers typically operate with sources of laser cooled atoms [1],[2] and thus their performance is limited by velocity spread and finite-size effects that impose systematic uncertainties. Ultra-cold sources such as a Bose-Einstein condensate or even delta-kick cooled atomic ensembles with extremely narrow velocity distribution are able to overcome these limitations [3]. Delta-kick cooling has successfully been demonstrated in the drop tower in Bremen [4] and is a valuable prerequisite to obtain high fidelity beam splitters with larger momentum transfer [5]. We show a prototype for such an atom-chip setup capable of reliably generating a BEC and performing delta-kick cooling in combination with Bragg beam splitting. A specialty of this setup is the retro-reflection of the beam splitting light field from the atom-chip itself, serving as inertial reference inside the vacuum. This allows for a compact realization of a quantum gravimeter incorporating a volume of only 1 cm^3 below the atom-chip. With this we were able determining the local gravitational acceleration to $1.4 \cdot 10^{-5}$ *g* in reasonable agreement to the value from the Bundesamt für Kartographie. A step to improve the performance of this sensor is the employment of a state of the art atomic source [6]. We are working on a new system that targets an inaccuracy of below 10^{-9} g by using the demonstrated techniques.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) due to an enactment of the German Bundestag under grant numbers DLR 50 1131-1137 (QUANTUS-III) and by the Deutsche Forschungsgemeinschaft (DFG) in the scope of the SFB 1128 “Relativistic Geodesy and Gravimetry with Quantum Sensors” (geo-Q) .

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Quantum Tests of the Universality of Free Fall

D. Schlippert, H. Albers, H. Heine, C. Meiners, L. L. Richardson, É. Wodey, D. Nath, C. Schubert, W. Ertmer, and E. M. Rasel
Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover
E-mail: schlippert@iqo.uni-hannover.de

In the process of formulating a "theory of everything" that aims to provide a self-contained model of modern physics by unifying all four fundamental interactions, two theoretical frameworks have yielded invaluable contributions: quantum field theory, which explains the nature of physics at the most microscopic length scales, and Einstein's general relativity, that conveys our understanding of gravity over the largest distances across the universe.

Although no theory of "quantum gravity" consistent over all energy scales exists to date, certain modifications enable a reconciliation of quantum mechanics and general relativity. These approaches allow for violations of the universality of free fall (UFF), that among Lorentz invariance and local position invariance constitute Einstein's equivalence principle. The UFF states that all bodies, located at the same space-time point, experience the same acceleration in a gravitational field independently of their composition. Because of its central role in modern physics the UFF has been tested extensively, mostly with macroscopic test masses [1].

Matter wave interferometers resemble a novel test method that differs fundamentally from experiments employing macroscopic test masses. We report on a quantum test of the UFF at a 100 ppb uncertainty using two different chemical elements, ^{39}K and ^{87}Rb [2] (Fig. 1). We show recent improvements of the experiment aiming towards a ppb test, focusing on both, the correlated noise suppression, and reduction of the systematic uncertainty aided by the use of a common optical dipole trap as a source.

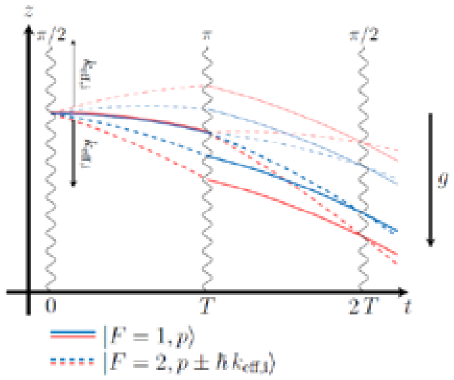

Fig. 1: Space-time diagram of a dual-species (Rb: blue lines, K: red lines) Mach-Zehnder matter wave interferometer based on stimulated Raman transitions in a constant gravitational field.

We furthermore present future strategies for tests of the UFF aiming for accuracies of parts in 10^{13} and beyond. These approaches comprise experiments realizing free fall times on the order of seconds in Very Long Baseline Atom Interferometry [3] (VLBAI) and the use of novel experimental concepts and the alkaline-earth-like element ytterbium.

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Challenges and mitigation strategies for high precision atom interferometers

C. Schubert for the group of W. Ertmer and E. M. Rasel
Institut für Quantenoptik, Leibniz Universität Hannover, Hanover, Germany
E-mail: schubert@iqo.uni-hannover.de

Atom interferometry is widely used for measuring rotations and accelerations with applications in navigation, geophysics/geodesy, and fundamental physics. In our group, an atomic gyroscope measured earth rotation at the percent level [1], a dual species gravimeter resolved the tides [2] and performed a test of the universality of free fall with rubidium and potassium at parts in 10^7 [3].

Aiming for high accuracies imposes challenges which future experiments will have to overcome. The corresponding requirements will be discussed for a test of the universality of free fall based on atom interferometry.

A key component for future experiments is the preparation of atomic ensembles with low expansion rates. This ensures a high contrast and mitigates systematic effects related to the residual effective atomic temperature. Experimentally, this can be engineered by delta kick cooling Bose-Einstein condensates [4]. Moreover, the rapid production of 10^5 ^{87}Rb atoms in a Bose-Einstein condensate per second was demonstrated in an atom chip based setup [5], thus showing the maturity of this technology.

Extending the free fall time in large fountain setups and relying on the low expansion rates of ultra-cold atoms opens the perspective of unprecedented accuracies for quantum tests of the universality of free fall on a competitive level with classical tests [6]. A considerable relief in the remaining requirements for even further improvements could be enabled in a space borne device which offers advantages inaccessible on ground [2,7].

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Frequency shift between coherent superposition states induced by Berry phase

A. Morinaga

Department of Physics, Tokyo University of Science, Noda, Chiba/Japan
E-mail: morinaga_a@rs.tus.ac.jp

It is well known that a resonance frequency between the ground hyperfine levels of the |*F*' = 1, *m*' = −1> state with a negative Landé *g*-factor to the |*F* = 2, *m*=1> state with a positive *g*-factor of an alkaline atom is magnetic-field-insensitive at the magic magnetic field. However, the frequency between two states under the rotation of a magnetic field with constant strength will shift according to the time derivative of the Berry phase evolving in time. The behavior of the frequency shift, including the phase shift, was examined in detail and discussed.

We developed an atom interferometer using the two-photon microwave-radio frequency (MW-rf) transition from the *m*' = −1 to *m* = 1 states (−1-1) of Na atoms at the magic magnetic field of 67.7 ± 1.0 μT and measured the Berry phase using an atom interferometer [1]. The magnetic field was rotated at a frequency f = 400 Hz around a cone of semiangle θ from a rotation axis. The pulse width of the MW-rf was 5 ms and we could obtain the spectrum of −1-1with a width of 200 Hz [2]. The frequency shifts of the −1-1 line were measured for various θ in $0 \le \theta \le \pi$ at interval of 0.05π, as shown in Fig. 1. For the right-handed rotation, the frequency increases in accordance with the function $2f$-$2f\cos\theta$ (solid line). Above $\theta = \pi/3$, the sideband frequency 800 Hz lower than the former peak frequency becomes the peak frequency of the −1-1 line. It then increases as $-2f\cos\theta$, crossing zero at $\theta = \pi/2$. However, it was again replaced by another sideband frequency with a frequency 800 Hz lower than the previous one. Above $\theta = 2\pi/3$, it increases as $-2f - 2f\cos\theta$ and reaches 0 at $\theta = \pi$. For the left-handed rotation, the frequency changes in the opposite manner. The behavior of the frequency shift can be divided into three ranges of θ, namely $0 \le \theta \le \pi/3$, $\pi/3 < \theta < 2\pi/3$, and $2\pi/3 \le \theta \le \pi$.

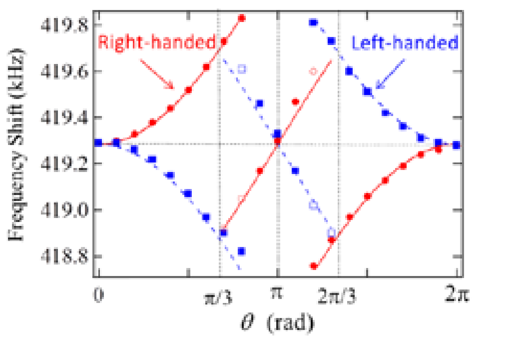

Fig. 1: .Observed frequency shift of spectrum from *m*' = −1 to *m* = 1 states as a function of angle θ from the rotation axis under the rotation frequency of 400 Hz.

In conclusion, the frequency shift is $\nu = 2f - 2f\cos\theta$ for $0 \le \theta \le \pi/3$ and $\nu = -2f - 2f\cos\theta$ for $2\pi/3 \le \theta \le \pi$, which are the time derivative of the Berry phase for a whole rotation. On the other hand, the frequency shift is $-2f\cos\theta$ for $\pi/3 < \theta < 2\pi/3$, which is the time derivative of the phase shift measured by the rotation gauge, because the solid angle subtended by the spherical rectangle measured by the rotation gauge is smaller than that subtended by the spherical triangle measured by the fixed gauge.

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Towards electronic bridge excitation of the low-energy nuclear isomer in Th-229

M. V. Okhapkin, D.-M. Meier, E. Peik

Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
E-mail: *: maksim.okhapkin@ptb.de*

Direct observation of the nuclear transition between the ground state and the isomer in Th-229 is the missing link towards a study of this system as a precise nuclear clock. To excite the isomeric state we use a two-photon laser excitation via electronic bridge processes in Th^+ [1]. The high density of states promises a strongly enhanced nuclear excitation rate [2]. Using laser ablation loading of the ion trap and photodissociation of molecular ions that are formed in reactions of Th^+ with impurities in the buffer gas, we efficiently load and stably store ions of the Th-229 isotope. We have measured the hyperfine structure and isotope shifts of two resonance lines that are suitable as first stages of the electronic bridge excitation and can be used to infer nuclear moments of the isomer.

In addition to an excitation via magnetic dipole hyperfine mixing described in [1], the isomer may also be populated via resonant excitation of higher-lying electronic levels, accompanied by spontaneous emission [3-5]. Doubly ionized thorium is a good candidate for this type of excitation because of its high ionization potential and the presence of *5f8s* electronic configurations in the range of the isomer energy which can provide an efficient isomer excitation because the wave function of the *s*-electron has the greatest overlap with the nucleus. We investigate an optical excitation of trapped Th^{2+} ions for the further search of the isomer energy in addition to our experiments with singly ionized thorium.

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Towards a measurement of the nuclear isomer transition in ^{229}Th

S. Stellmer[1,2], M. Schreitl[1,2], G. Kazakov[1], K. Yoshimura[3], T. Schumm[1,2]

1. Institute for Atomic and Subatomic Physics, TU Vienna, Vienna, Austria
2. Vienna Center for Quantum Science and Technology, Vienna, Austria
3. University of Okayama, Okayama, Japan

E-mail: simon.stellmer@ati.ac.at

The isotope ^{229}Th is believed to possess an extremely low-lying and long-lived excited nuclear state. Latest indirect measurements place the excitation energy at 7.8(5) eV [1], corresponding to a wavelength of 160(10) nm. This nucleus thus offers the unique possibility to transfer well-established methods of optical laser spectroscopy to the realms of nuclear physics. One prominent application could be a "nuclear" optical clock [2], which, given the small size of the nucleus, might be highly immune to external perturbations.

Experiments with ^{229}Th are complicated by the scarcity of ^{229}Th, its radioactivity, and the long lifetime of the excited state. Our group in Vienna follows an approach of embedding ^{229}Th nuclei into VUV-transparent CaF_2 crystals [2]. Such a set-up is extremely robust and allows for simultaneous interrogation of 10^{15} nuclei, a tremendous advantage when searching for the transition. We have produced a number of such crystals, carefully investigated their luminescence properties, and are currently moving towards the optical spectroscopy.

As there are no tunable narrow-linewidth lasers available to perform direct laser spectroscopy yet, various other concepts of populating the isomeric state are under investigation. We follow three different strategies: (1) direct excitation in the VUV, using the MLS synchrotron in Berlin (in collaboration with PTB), (2) excitation of a higher-lying state at 29 keV, followed by spontaneous decay into the isomer (performed at SPring-8, in collaboration with various groups in Japan), and (3) observation of $^{233}U:CaF_2$ crystals, where the ^{233}U nucleus undergoes alpha-decay into ^{229}Th with a significant population of the isomer.

In all of these approaches, the wavelength of the emitted "nuclear" photon is measured with a spectrometer. These experiments are currently ongoing or under preparation, and we will report on the latest results.

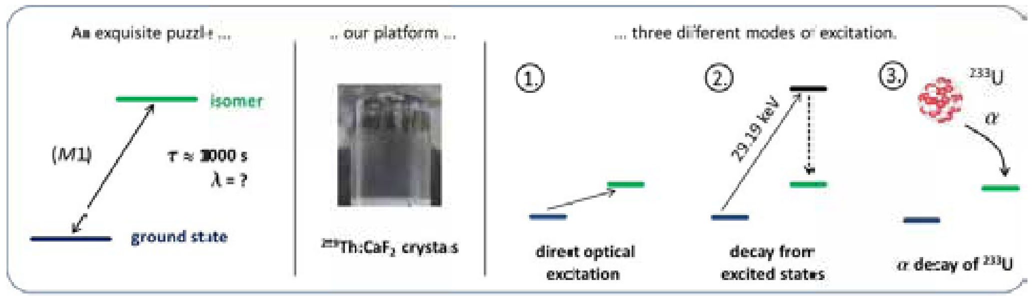

Fig. 1: Our experiments aim to detect the VUV photon emitted by the isomeric state, and to measure its wavelength with a spectrometer. We operate three different experiments: direct excitation at the MLS synchrotron in Berlin, excitation of high-lying nuclear states at SPring-8, and alpha-decay in ^{233}U-doped crystals in Vienna.

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Determining mass ratios of fundamental particles through optical frequency metrology of molecular vibrations

S. Patra[1], J. Biesheuvel[1], J.-Ph. Karr[2,3], L. Hilico[2,3], T.J. Pinkert[1], K.S.E. Eikema[1], W. Ubachs[1], J.C.J. Koelemeij[1]

[1]LaserLaB and Department of Physics and Astronomy, VU University, Amsterdam
[2]Laboratoire Kastler Brossel, Université Pierre et Marie Curie, Paris, France
[3]Département de Physique, Université Val d'Essonne, Evry, France
E-mail: j.c.j.koelemeij@vu.nl

It has long been suggested that vibrational frequency measurements of HD^+ ions can provide an accurate value of μ, the proton-electron mass ratio [1]. Recently, high resolution optical frequency metrology of the $(v, L): (0,2) \rightarrow (8,3)$ vibrational overtone in trapped, laser-cooled HD^+ ions has allowed the first determination of μ from molecular vibrations [2]. The 2.9 ppb relative uncertainty of our result approaches that of the values taken into account in the 2010 CODATA adjustment of μ, and is the smallest of all laser-spectroscopic determinations of μ which do not invoke CPT invariance.

An improved determination is underway using Doppler-free two-photon spectroscopy of the same molecule using the $(v, L): (0,3) \rightarrow (4,2) \rightarrow (9,3)$ transitions, both at 1.44 μm [3]. The wavelengths of the transitions allow us to use diode lasers frequency stabilized to an ultrastable laser using an optical frequency comb as a transfer oscillator [4]. We aim to measure the transition frequency with 1×10^{-12} relative uncertainty, which can be translated to a value of μ with an uncertainty below 0.1 ppb, competing with the current best determination [5]. Besides, this experiment may provide a stringent test of molecular theory (including high-order quantum electrodynamics) at the level of 4×10^{-11} [6] and enable searches for an additional 'fifth force' [7]. Also, this setup is the precursor to the realization of a molecular ion optical clock, suited for searches of a possible time-variation of μ.

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Determination of optimized frequency and frequency ratio values from over-determined sets of clock comparison data

H.S. Margolis, P. Gill
National Physical Laboratory (NPL), Teddington, UK
E-mail: helen.margolis@npl.co.uk

The stability and accuracy of the most advanced optical atomic clocks now significantly surpass the performance of the best caesium primary frequency standards, and a future redefinition of the SI second is anticipated. As a first step in this direction, optical clocks can already be used as secondary representations of the second, with recommended frequencies and uncertainties assigned by the CCL-CCTF Frequency Standards Working Group.

With a single exception, the data considered so far by this group comes from absolute frequency measurements made relative to caesium fountain primary frequency standards, whereas future information about the reproducibility of optical clocks will come mainly from direct optical frequency ratio measurements. For example, a clock comparison programme underway within the EMRP-funded ITOC project [1] will lead to a collection of frequency ratio measurements between all high accuracy optical clocks being developed within European national measurement institutes, as well as caesium-limited absolute frequency measurements. This complete set of measurements will be over-determined, by which we mean that it will be possible to determine some frequency ratios from more than one experiment.

Here we present an approach to analyzing such over-determined sets of clock frequency comparison data to derive optimized values for the frequency ratios between each contributing standard [2]. We use a least-squares adjustment procedure, based on the approach used by CODATA to derive a self-consistent set of values for the fundamental physical constants. The input data are a set of frequency ratio measurements, absolute frequency measurements simply being a special case of frequency ratios involving the caesium primary standard. These measured frequency ratios are expressed as a function of one or more of a set of adjusted frequency ratios, the values of which are optimized in the least-squares adjustment. The value and uncertainty of any other frequency ratio of interest can then be calculated from the adjusted frequency ratios. It is, however, vital to account for correlations between the input data, since these can have a significant effect on the results obtained from the least-squares adjustment. Self-consistency checks are also performed on the body of data to identify any issues with the uncertainty evaluations for each individual clock.

As the number of frequency ratio measurements made without reference to caesium primary standards increases, these techniques can be used to provide valuable information about the relative performance of different candidates for an optical redefinition of the second. They can also be used to determine optimized values and uncertainties for the absolute frequencies of each optical standard relative to the current definition of the second, maximising the potential contribution of optical clocks to international timescales prior to a redefinition.

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Coulomb crystallization of highly charged ions

L. Schmöger[1,2], O. O. Versolato[1,2], M. Schwarz[1,2], M. Kohnen[2], A. Windberger[1], B. Piest[1], S. Feuchtenbeiner[1], J. Pedregosa[3], T. Leopold[2], P. Micke[1,2], A. K. Hansen[4], T. M. Baumann[5], M. Drewsen[4], J. Ullrich[2], P. O. Schmidt[2,6], and J. R. Crespo López-Urrutia[1]
1. Max-Planck-Institut für Kernphysik, Heidelberg, Germany
2. Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
3. Physique des Interactions Ioniques et Moléculaires, Aix-Marseille Université, Marseille, France
4. Department of Physics and Astronomy, Aarhus University, Aarhus, Denmark
5. NSCL, Michigan State University, East Lansing, Michigan, USA
6. Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany
E-mail: lisa.schmoeger@mpi-hd.mpg.de

In highly charged ions (HCIs), the electronic wavefunction is much reduced in size accompanied by an extremely suppressed sensitivity to external field perturbations. Further, electric dipole forbidden optical transitions found near level crossings in HCIs are extremely sensitive to possible drifts in the fine structure constant α [1]. Thus, cold, strongly localized HCIs are of particular interest for metrology (development of novel optical clocks) and the search for α variation [2]. We report on Coulomb crystallization of highly-charged Ar^{13+} ions through sympathetic cooling with co-trapped, laser-cooled Be^+ ions to final translational temperatures of about 200 mK or less [3]. The $^{40}Ar^{13+}$ ions are produced in, and extracted from an electron beam ion trap (EBIT). They are decelerated and pre-cooled by means of two serrated interlaced pulsed drift tubes before they are injected into the cryogenic Paul trap CryPTEx [4]. Subsequently, they are forced to interact multiple times with a Coulomb crystal of laser-cooled $^9Be^+$ ions, thereby losing enough energy to end up implanted as dark structures of spherical shape in the bright fluorescing Be^+ crystal. The combination of an EBIT with a linear Paul trap operating at ~7 K facilitates not only the formation of mixed-species 3D Coulomb crystals, but also of 1D Coulomb crystals down to a single HCI cooled by a single Be^+ ion. This is a necessary step for future quantum logic spectroscopy at a potential 10^{-19} level accuracy. Our preparation technique of cold Ar^{13+} is readily applicable to a broad range of other highly charged elements and is thus a significant step forward for precision spectroscopy of HCIs.

Fig. 1: Left: A single Ar^{13+} ion sympathetically cooled by several Be^+ ions. White scale bar denotes 100 µm. Right: A single Ar^{13+} ion (position marked by cross) sympathetically cooled by a single laser-cooled Be^+ ion. White scale bar denotes 20 µm.

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High-Accuracy Ring Laser Gyroscopes: Earth Rotation Rate and Relativistic Effects

N. Beverini[1,2], A. Di Virgilio[2], J. Belfi[2], A. Ortolan[3], K.U. Schreiber[4], A. Gebauer[4], T. Klügel[5]

1. Department of Physics, Università di Pisa, Pisa, Italy
2. INFN, Sezione di Pisa, Pisa, Italy
3. INFN, Laboratorio Nazionale di Legnaro, Legnaro, Italy
4. Forschungseinrichtung Satellitengeodäsie, Technische Universität München, Germany
5. Bundesamt für Kartographie und Geodäsie, GO Wettzell, Germany

E-mail: beverini@df.unipi.it

Ring laser gyroscopes (RLG) have demonstrated to be the most sensitive devices for testing rotational motions with respect to an inertial frame. The *Gross-Ring* (G), the 16 m^2 ring laser operating at the Geodetic observatory in Wettzell (Bavaria) [1], has continuously improved its performance over the years by more and more accurate control of the environment conditions, finally achieving a rotational sensitivity of the order of 0.7 p-rad/s over 10^4 s. Its short term stability is very near to shot noise limit and the performance is limited by the long-term stability. To further enhancing the sensor sensitivity as well as the stability it would be necessary to increase the dimension of the RLG and to place it in a deep underground location, well isolated from meteorology, hydrologic variability and surface seismic noise. Actually, in this way the laser cavity Q-factor is enhanced, both improving the shot noise limit and reducing the coupling between the two counter-rotating laser beams due to radiation back-scattering on the mirrors, which is so far the dominant source of long-term instability. However, G was constructed from the largest available piece of Zerodur, and is not feasible to scale up its structure. Therefore, the geometry of a larger structure needs to be actively controlled by using a suitable set of diagnostic signals.

GINGER (Gyroscopes IN GEneral Relativity) project [2] will go in this direction, aiming at the observation of the Lense-Thirring effect, arising from the metric deformation induced by a massive rotating body. Einstein's General Relativity theory foresees a 1 ppb correction to the length of the day, when measured in Earth integral laboratory frame with respect to that measured in the cosmic inertial frame by VLBI. The effect has been demonstrated so far only in the contest of satellite experiments. GINGER will be an array of at least three gyroscopes mutually orthogonal of about 6-8 m of side, in order to have a vectorial measure of the rotational speed. It will be mounted in a deep underground location, possibly at the Gran Sasso laboratory under 1000 m of rocks. The goal is to achieve an accuracy up to a few 10^{-10} in the Earth angular velocity. Theoretical and experimental work is in progress. The laser emission dynamics has been analyzed, and Kalman data filtering techniques have been developed to increase the long-term stability [3]. A new RLG is operational in the Pisa INFN laboratory, where the diagnostics and the procedures for a geometric control of the apparatus [4] will be tested. A larger test device (3.60x3.60 m^2) has been installed in Gran Sasso underground laboratory, in order to test the local seismic noise. More information are available at the site: htsps://web2.infn.it/GINGER/index.php/it .

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One-dimensional cavity-mode dispersion spectroscopy

S. Wójtewicz[1], A. Cygan[1], P. Wcisło[1], P. Masłowski[1], J. T. Hodges[2], R. Ciuryło[1], D. Lisak[1]

1. Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziadzka 5, 87-100 Torun, Poland
2. National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, Maryland 20899, USA

E-mail: szymon@fizyka.umk.pl

Recent developments in optical metrology have led to tremendous improvement in precision and accuracy of the horizontal (frequency) axis in measured spectra. However, the vertical (typically absorbance) axis is usually based on the light intensity measurements which are subject to instrumental errors and limit the spectrum accuracy. Here we present the novel frequency-based spectroscopic technique, called one-dimensional cavity-mode dispersion spectroscopy (1D-CMDS), which provides complete information about the dispersive properties of the spectrum by measurements of only the frequencies of high-finesse cavity modes frequencies only [1]. The possibility of the frequency-based measurements of dispersion spectra was mentioned in Ref. [2]. The 1D-CMDS technique depends solely on the measurement of frequencies – the physical quantity that can be measured the best – or their differences. It makes this technique insensitive to instrumental errors of the detection systems based on light intensity measurements. Commonly used absorption techniques rely on two dimensional (2D) measurement of a light intensity versus its frequency. In contrast, here dispersion spectrum is obtained in one dimension from measurement of only one quantity: cavity modes frequency. These spectra can be presented also in more conventional 2D way where the frequency appears on both the horizontal and vertical axes.

We present the experimental results on an example of the line-shape measurements of the CO transition near 1.61 μm. We demonstrate the sub-Hz precision of measurements of the cavity modes relative positions. We compare this technique to two other high-precision cavity-enhanced spectroscopy methods: cavity ring-down spectroscopy (CRDS) and a relatively new cavity mode-width spectroscopy (CMWS) [3, 4]. The dispersion spectra are more sensitive to the choice of line-shape model than absorption spectra thus can be used to verify the influence of various physical effects affecting the line shape [5].

We also present several possible extensions of the 1D-CMDS technique. The broadly tunable offset-locked lasers or Mach-Zehnder single-sideband modulators can be used as frequency shifters instead of the acousto-optic modulator used in our spectrometer. The optical frequency combs can be used in the 1D-CMDS to probe multiple cavity modes at the same time reducing total measurement time and hence minimizing temporal drifts of physical quantities.

The 1D-CMDS technique has the potential to become the most accurate of all absorptive and dispersive spectroscopic methods. We expect that it will have significant impact in fields such as fundamental physics, gas metrology and environmental remote sensing.

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Paper Laser: a step towards a time scale generation from an ensemble of optical clocks

E. de Carlos López[1], C. A. Ortiz Cardona[1, 2], S. López López[1], and J. M. López Romero[1]

[1] Centro Nacional de Metrología, CENAM, Querétaro, México.
[2] Centro de Investigación y de Estudios Avanzados, CINVESTAV, Querétaro, México.
E-mail: mauricio.lopez@cenam.mx

The uncertainty of the SI second best realization has improved by a rate of about one order of magnitude per decade since 1967, reaching a current level of $\sim 2\times10^{-16}$ [1]. During the last two decades the progress on optical clocks has increased their accuracy and stability rapidly, approaching now the lower region of 10^{-18} [2]. A redefinition of the SI second in terms of an optical atomic transition will require, among other conditions, the capability to produce time scales from an ensemble of atomic optical clocks. Measurement of time differences between Cs atomic clocks allows the creation of virtual clocks (also called "paper clocks") [3]. An atomic time scale *TA* can be defined in the most simple way as an average of the reading of the clocks by the relation $TA(t) = \frac{1}{N}\sum_{i=1}^{N} h_i(t)$, where $h_i(t)$ is the reading of the clock *i* at time *t*. However, due to quantities $h_i(t)$ are not available from measurements, the atomic time scale *TA* can be computed from the relation $x_k(t) = \sum_{i=1}^{N}\omega_i(t)x_{ki}(t)$, where $x_k(t)$ is the time difference between clock *k* and the time scale *TA* at time *t*, $x_{ki}(t)$ is the time difference between clock *k* and clock *i* and, $\omega_i(t)$ is the weight of clock *i* at the time *t* obeying the normalization condition $\sum_{i=1}^{N}\omega_i(t) = 1$. Following the well known ideas behind of a paper clock, we have developed and implemented a novelty strategy to produce a virtual optical oscillator called "paper laser". We used an Al*GaAs* laser (852 nm), coupled to an Ultra Low Expansion (*ULE*) optical cavity, as master laser. The laser's light is split in three laser beams with the aim to control the optical frequency of those by three different Acousto-Optic Modulators (*AOM´s*). Each of the laser beam outputs of the *AOMs* is frequency stabilized through a independent but similar polarization spectroscopy to the most probable D_2 Cs-133 transition [$|6^2s_{1/2}$, F = 4> → $|6^2p_{3/2}$, F′= 5>]. Therefore, three independent lasers (optical oscillators) with similar metrological characteristics are obtained. We have measured every second, simultaneously, the optical frequency difference between each pair laser beams. The frequency $\nu_k(t+\tau)$ of the paper laser at the time $t+\tau$ is defined by $\nu_k(t+\tau) = \sum_{j=1}^{N}\omega_j(t)\left[\nu_j(t) - \nu_{jk}(t+\tau)\right]$, where $\omega_j(t)$ represents the weight the laser *j* as function of time *t*. $\nu_j(t)$ is the frequency difference of the laser *j* respect to the paper laser at time *t*. For simplicity and due to the stability of each of the laser beams are similar to each other, we have used weights equal to 1/3 ($\omega_1 = \omega_2 = \omega_3 = 1/3$). The initial optical frequency differences were fixed to zero [$\nu_1(t=0) = \nu_2(t=0) = \nu_3(t=0) = 0\,Hz$]. The term $\nu_{jk}(t+\tau)$ corresponds to the frequency difference between laser *j* and laser *k* at the time $t+\tau$. We have produced a paper laser during hours. Preliminary results are promising; we found that the paper laser frequency stability is superior to the frequency stability of the members of the ensemble. With the aim to produce a time scale from an ensemble of optical clocks, different strategies can be followed to bring adequate metrological characteristics to a paper laser; like stability, accuracy, robustness, and reliability.

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Mode-locked microwave atomic clock laser: A concept

X. Zeng, D. L. Boiko

Centre Suisse d'Électronique et de Microtechnique, Neuchâtel, Switzerland
E-mail: dmitri.boiko@csem.ch

So far, a unique active *push-pull laser atomic oscillator* was demonstrated [1] using a ^{39}K vapour cell in external cavity semiconductor laser. It seemingly behaves like a mode-locked (ML) laser with the cavity length adjusted to hyperfine frequency splitting in ^{39}K atom (462 MHz). However its short-term frequency stability is quite moderate, of $7\times10^{-9}/\tau^{1/2}$ with the floor of 10^{-10}. Apart from using the small hyperfine frequency in potassium atoms as well as mechanically and thermally challenging cavity of 32.5 cm length, this oscillator does not operate in ML regime: Under dual-frequency Λ interrogation with circularly polarized light, the absorption recovery time in ^{39}K cell is set by the spin relaxation time T_S~1 ms. For mode-locking operation, the absorber shall recover faster [2] than the gain (~2 ns for semiconductor QWs) as otherwise, the spontaneous emission noise is not suppressed between pulses.

CPT in Rb vapour cell with intracavity ML pulses was achieved in a Ti:S passively modelocked laser operating at a sub-harmonic of the hyperfine frequency splitting in Rb atoms [3]. Although comb-induced CPT is shown to produce pulling of the pulse repetition rate and being insensitive to the light shift [4], particular realization suffers from using the long cavity and a SESAM saturable absorber mirror for reaching passive ML regime.

In this communication, we report a concept for a passively ML semiconductor laser utilizing Rb vapour cell as a saturable absorber. It has 5 cm long cavity that matches the hyperfine frequency in ^{85}Rb atoms (Fig. 1). We will provide an overview of experimental and theoretical studies on the dynamics of ^{85}Rb vapour cells and show that the Λ interrogation with linearly polarized light enables reaching the absorption recover time of 1.4 ns in a cell containing 200 torr of N_2 buffer. Using Haus-New model in the pulse energy domain [5], we find that passive ML operation is stable in a narrow region of cell temperatures and laser driving current, yielding 3.04 GHz pulse train with the pulse energy 15 fJ and duration 12 ps.

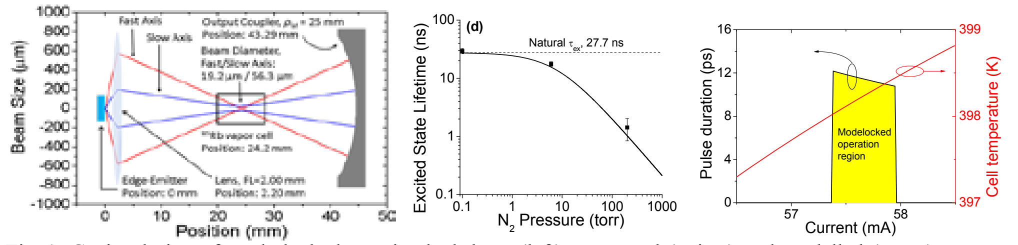

Fig. 1: Cavity design of mode-locked atomic clock laser (left); measured (points) and modelled (curve) recovery time of ^{85}Rb vapour cell absorber *vs* N_2 buffer pressure (middle); and modelled ML pulse width *vs* laser current and cell temperature (right).

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Optical Bloch band spectroscopy using the $^1S_0$ - $^3P_0$ transition in laser cooled magnesium

<u>K. Zipfel</u>[1], A. Kulosa, S. Rühmann, D. Fim, N. Jha, S. Sauer, W. Ertmer and E. Rasel
1. Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany
<u>E-mail</u>: zipfel@iqo.uni-hannover.de

In optical clocks with neutral atoms, narrow transitions are probed on *magic wavelength* lattice-trapped atoms. As in solid-state physics, such periodic optical potentials give rise to band structures caused by tunneling of the delocalized atoms and thus can be used to simulate pure crystalline structures. One common way to deduce the band filling is to map the quasi momentum of the atoms to real space by switching off the lattice and taking an absorption image of the atomic density distribution [1]. Here we report on a direct measurement of the Bloch bands using a narrow optical transition for probing the band shape-corresponding frequency shift (Fig. 1).

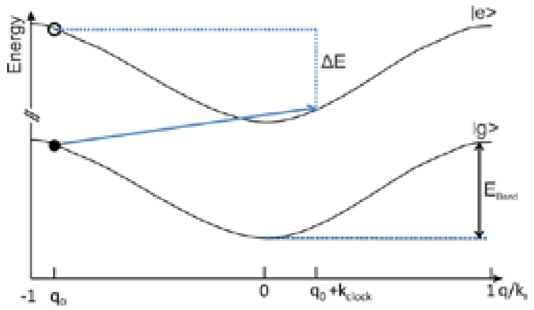

Fig. 1: At shallow trap depths the curvature of the bands introduces a frequency shift ΔE during the clock cycle, depending on the initial quasi momentum q_0.

Optical lattice clocks have recently reached record accuracies and stabilities in the low 10^{-18} regime [2]. In order to suppress the effects of the bands these clocks are normally operated at very deep or even vertical lattices [3]. However, for magnesium the influence of tunneling is more prominent due to its low mass and small magic wavelength which demands for higher power of the lattice for precision spectroscopy, but on the other hand gives access to probe the bands.

By operating the lattice in a regime, where the tunneling rate becomes comparable to the observable linewidth of the narrow transition, the influence of the band structure can be seen in the frequency spectrum. We present the direct observation of Bloch bands by probing the spin-forbidden $^1S_0$ - $^3P_0$ transition of laser cooled magnesium atoms trapped in an optical lattice operated at the magic wavelength. For trap depths below 10 recoil energies (E_r) the band width is larger than the current resolution of the probed transition of 3 kHz. In this regime a shift resulting in a symmetric splitting to a doublet structure in the order of the band width has been observed (Fig 2). When we operate the lattice above or below the *magic wavelength*, an additional asymmetry for the width of the two peaks has been observed. This effect is a consequence of unequal curvature of the bands for the two clock state and can be used to get further information about the *magic wavelength*.

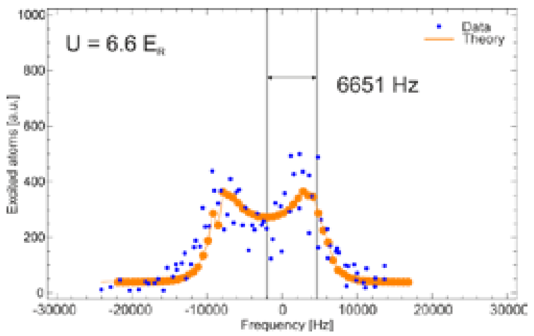

Fig. 2: For shallow lattices (6.6 E_r), the splitting of the carrier transition to a doublet is in the order of the width of the lowest band (6651 Hz). The calculated spectrum according to theory [3] matches the measured data.

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Quantum logic spectroscopy with molecular ions

<u>F. Wolf</u>[1], Y. Wan[1,3], J.-C Heip[1], F. Gebert[1], C. Shi[1], P.O. Schmidt[1,2]
1. QUEST Institut, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
2. Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany
3. Present address: NIST, Boulder, USA
<u>E-mail</u>: Piet.Schmidt@quantummetrology.de

Precision laser spectroscopy of cold and trapped molecular ions is a powerful tool for fundamental physics, including the determination of fundamental constants, the laboratory test for their possible variation, and the search for a possible electric dipole moment of the electron. While the complexity of molecular structure facilitates these applications, the absence of cycling transitions poses a challenge for direct laser cooling, quantum state control, and detection. Previously employed state detection techniques based on photo-dissociation or chemical reactions are destructive. Therefore the molecule has to be reloaded after each interrogation, rendering these techniques inefficient for single-molecule spectroscopy. Here we experimentally demonstrate sympathetic cooling [1] and non-destructive state detection [2] of a single trapped molecular ion through its strong Coulomb coupling to a well-controlled co-trapped atomic ion. For state detection we apply an optical dipole force (ODF) with a laser tuned near a selected transition in the molecular ion. The detuning is small enough to induce an appreciable force if the ion is in the ground state of the selected transition, but large enough to avoid photon scattering. The ODF changes the state of a shared motional mode of the two-ion crystal, which is detected through the atomic ion. There is only a negligible force if the molecule is in any other state. This algorithm implements non-destructive detection of a selected molecular ro-vibrational state. We observe black-body radiation-induced quantum jumps between rotational states of a single molecular ion. Using the detuning dependence of the state detection signal, we implement a variant of quantum logic spectroscopy of a molecular resonance. The technique will unfold its full potential in high precision spectroscopy of narrow transitions using an independent spectroscopy laser. However, while in the present work black-body radiation probabilistically populates the detected state, precision spectroscopy will require efficient state preparation schemes or ro-vibrational cooling techniques. A combination of these powerful tools will enable the realization of optical clocks based on molecular ions, where the underlying clock transitions or a combination of transitions can be sensitive to variations of fundamental constants, an electron electric dipole moment (eEDM) or parity violation in chiral molecules.

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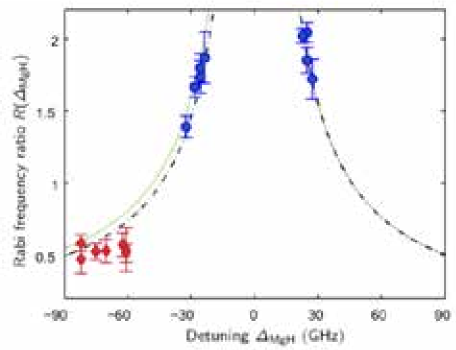

Fig. 1: Quantum logic spectroscopy of a transition in a molecular ions using non-destructive state detection via a co-trapped atomic ion.

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Time Table

	Monday, 12 Oct	Tuesday, 13 Oct	Wednesday, 14 Oct	Thursday, 15 Oct	Friday, 16 Oct	
7:30 am	Breakfast	Breakfast	Breakfast	Breakfast	Breakfast	7:30 am
8:30 am to 10:30 am	Welcome & Opening **Chair:** Fritz Riehle	Optical Clocks I: Lattice Clocks **Chair:** Tetsuya Ido	Optical Frequency Comb **Chair:** Thomas Südmeyer	New Concepts and Novel Applications I **Chair:** Eric Burt	Ultrastable Oscillators: Microwave and Optical **Chair:** Jeremy Everard	8:30 am to 10:30 am
8:30 am	Welcome: Fritz Riehle	Hidetoshi Katori	Scott Diddams	Hao Zhang	John Hartnett	8:30 am
9:00 am	Keynote David Wineland	Andrew Ludlow	Kjeld Eikema	Ekkehard Peik	Vincent Giordano	9:00 am
9:30 am		Sébastien Bize	Long-Shen Ma	Svenia Knappe	Uwe Sterr	9:30 am
10:00 am	Andrei Derevianko	Jun Ye	Lute Maleki	John Kitching	Garrett Cole	10:00 am
10:30 am	Break	Break	Break	Break	Break	10:30 am
11:00 am to 12:30 pm	Tests of Fundamental Physics with Clocks **Chair:** Kurt Gibble	Atom Interferometry **Chair:** Peter Wolf	Towards the Future **Chair:** Salvatore Micalizio	New Concepts and Novel Applications II **Chair:** Lute Maleki	Ground and Space Links **Chair:** Piet Oliver Schmidt	11:00 am to 12:30 pm
11:00 am	Michael Tobar	Mark Kasevich	Jakob Flury	Nan Yu	Christophe Salomon	11:00 am
11:30 am	Magdalena Zych	Arnaud Landragin	José Crespo López-Urrutia	Ernst Rasel	Wolfgang Schäfer	11:30 am
12:00 pm	Isaac Fan	Achim Peters	Patrick Gill	Thomas Zanon-Wilette	Nathan Newbury	12:00 pm
12:30 pm	Lunch	Lunch	Lunch	Lunch	Farewell / Lunch	12:30 pm
2:00 pm to 4:00 pm	Microwave Clocks I: Fountains **Chair:** Christophe Salomon	Optical Clocks II: Ion Clocks **Chair:** Rachel Godun	Free Time	Time and Frequency Transfer **Chair:** Anne Amy-Klein	End of Symposium	2:00 pm to 4:00 pm
2:00 pm	Kurt Gibble	David Leibrandt	Optional Excursions, Sanssouci, Einstein tower, Caputh	Miho Fujieda		2:00 pm
2:30 pm	Krzysztof Szymaniec	Pierre Dubé		Jonathan Hirschauer		2:30 pm
3:00 pm	Steve Peil	Hua Guan		Paul-Eric Pottie		3:00 pm
3:30 pm	Steven Jefferts	Nils Huntemann		Daniele Rovera		3:30 pm
4:00 pm	Break	Break		Break		4:00 pm
4:30 pm to 6:30 pm	Posters **Chair:** Ekkehard Peik	Posters **Chair:** Christian Lisdat		Microwave Clocks II: Miniature Clocks **Chair:** Elizabeth Donley		4:30 pm to 6:30 pm
4:30 pm				Peter Rosenbusch		4:30 pm
5:00 pm				Gaetano Mileti		5:00 pm
5:30 pm				Peng Liu		5:30 pm
6:00 pm				John Prestage		6:00 pm
6:30 pm	Dinner	Dinner		Dinner		6:30 pm
7:00 pm						7:00 pm
7:30 pm	Posters continued	Posters continued	Banquet			7:30 pm
8:00 pm						8:00 pm
8:30 pm						8:30 pm
9:00 pm						9:00 pm