9th Symposium on Frequency Standards and Metrology

Report of Contributions

Contribution ID: **8** Type: **Invited Oral**

An Optical Atomic Clock Based on a Highly Charged Ion

Monday 16 October 2023 14:00 (30 minutes)

Optical atomic clocks are the most precise and accurate measurement devices ever constructed, reaching fractional systematic uncertainties below one part in 10^{-18} [1]. Their exceptional performance opens up a wide range of applications in fundamental science and technology. The extreme properties of highly charged ions (HCI) make them highly sensitive probes for tests of fundamental physical theories [2, 3]. Furthermore, these properties make them significantly less sensitive to some of the leading systematic perturbations that affect state-of-the-art optical clocks, making them exciting candidates for next-generation clocks [4, 2]. The technical challenges that hindered the development of such clocks have now all been overcome, starting with their extraction from a hot plasma and sympathetic cooling in a linear Paul trap [5], readout of their internal state via quantum logic spectroscopy [6], and finally the preparation of the HCI in the ground state of motion of the trap [7], which allows levels of measurement accuracy to be reached that were previously limited to singly-charged and neutral atoms. Here, we present the first operation of an atomic clock based on an HCI (Ar^{13+} in our case) and a full evaluation of systematic frequency shifts [8]. The achieved uncertainty is almost eight orders of magnitude lower than any previous frequency measurements using HCI. Measurements of some key atomic parameters confirm the theoretical predictions of the favorable properties of HCIs for use in clocks. The comparison to the $^{171}Yb^+$ E3 optical clock [9] places the frequency of this transition among the most accurately measured of all time. Furthermore, by comparing the isotope shift between $^{36}Ar^{13+}$ and $^{40}Ar^{13+}$ to improved atomic structure calculations, we were able for the first time to resolve the largely unexplored QED nuclear recoil effects. Finally, prospects for 5th force tests based on isotope shift spectroscopy of Ca^+/Ca^{14+} isotopes and the high-sensitivity search for a variation of the fine-structure constant using HCI will be presented. This demonstrates the suitability of HCI as references for high-accuracy optical clocks and to probe for physics beyond the standard model.

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[9] Lange, R. *et al.*, Phys. Rev. Lett. **126**, 011102 (2021).

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Presenter: Prof. SCHMIDT, Piet (Physikalisch-Technische Bundesanstalt and Leibniz University Hannover)

Session Classification: Optical Ion Clocks I

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **9** Type: **Invited Oral**

Atomic frequency standards, physical constants and metrology

Monday 16 October 2023 10:00 (30 minutes)

The paper highlights the importance of the time unit definition,by means of the atomic Cs frequency standard, in the definition of the base units of the International System of units (SI).

Author: VANIER, Jacques (Universite de Montreal Canada)

Presenter: VANIER, Jacques (Universite de Montreal Canada)

Session Classification: Smoking Ceremony and Opening Plenary Session

Track Classification: SI definition, Clocks and Time Scales

Contribution ID: **10** Type: **Invited Poster**

High bandwidth linewidth reduction of a cateye laser using a lithium niobate wafer as output coupler and intracavity modulator

Laser linewidth narrowing is critical to advances in frequency standards and metrology, including optical clocks, trapped ion qubit manipulation, gravity wave detection, and quantum sensing. Common feedback actuator mechanisms include piezoelectric transducers and laser diode injection current, but non-linear crystal electro-optic modulators (EOMs) are preferred for their higher bandwidth and reduced secondary effects such as amplitude modulation. Nevertheless, they have seen little application to tunable external cavity diode lasers (ECDLs), due to high cost and high voltage driver complexity, and the difficulty of incorporating a bulk crystal into an ECDL which usually has a short cavity to minimize mode-hopping.

We show that an intracavity modulator can easily be incorporated into a cateye laser; that is, an ECDL with an intracavity filter for wavelength tuning, and optical feedback from a cat's-eye reflector [1]. We use a small chip from a lithium niobate (LN) wafer as the partially reflective output coupler at the focus of the cat's-eye. Gold electrodes allow modulation of the refractive index and thus optical cavity length and lasing frequency. The electrodes can be closely spaced because of the tight cateye focus, and thus the frequency modulation sensitivity is relatively high, in our example 1 MHz/V. The ECDL free-running linewidth is typically of order 50 kHz, so that feedback voltages of below 1 V are sufficient to compensate for the fluctuations of the free-running laser, removing the need for a high-voltage driver. We measured the −3 dB modulation bandwidth to be 25 MHz without any attempt at impedance matching, a closed-loop bandwidth of 5 MHz, and final laser linewidth below 1 Hz [2].

References

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Authors: SCHOLTEN, Robert (The University of Melbourne); Ms PALMER, Sonya (RMIT University)

Co-authors: Mr STEINER, Alex (University of Innsbruck); Dr BOES, Andreas (The University of Adelaide); Prof. MITCHELL, Arnan (RMIT University); Dr MARCINIAK, Christian (University of Innsbruck); Dr REN, Guanghui (RMIT University); Dr NGUYEN, Thach (RMIT University); Prof. MONZ, Thomas (University of Innsbruck)

Presenter: SCHOLTEN, Robert (The University of Melbourne)

Track Classification: Precision and Low Noise Signal Generation and Techniques

Contribution ID: **12** Type: **Invited Poster**

Collapse Phenomenon in Phase Noise Curve of E5052B

In the experiment of a 10MHz low phase noise crystal oscillator, a collapse phenomenon was observed in the phase noise curve when testing with Agilent E5052B. It was believed that this was caused by the instrument's background noise. The numerical relationship of this phenomenon was estimated, and a solution was proposed.

Authors: HUANG, Xianhe (University of Electronic Science and Technology of China); Ms FU, Wei (University of Electronic Science and Technology of China)

Presenter: HUANG, Xianhe (University of Electronic Science and Technology of China)

Track Classification: Precision and Low Noise Signal Generation and Techniques

Contribution ID: **13** Type: **Invited Oral**

Ca+ Optical clocks with Systematic Uncertainties at the 10(-18) level

Monday 16 October 2023 17:00 (30 minutes)

Here our progress on the Ca+ ion optical clocks for the last few years will be reported, including both the laboratory clocks and the transportable clock.
First of all, the clock stability is greatly improved, with long term stability reaches the E-18 level; recently with a low E-16 level stability clock laser, the clock stability has been improved to ~ 1E-15/$\sqrt{\tau}$, about another factor of 2 improvement and about an order of magnitude smaller than that in 2016.
Secondly, a cryogenic Ca+ clock at the liquid nitrogen environment is built, with the blackbody radiation (BBR) shift uncertainty greatly suppressed, and improvements made with other systematic uncertainties, the overall systematic uncertainty of the clock is evaluated as 3.0E-18. Thirdly, the Ca+ clock at room temperature is also improved. The systematic uncertainty of the room temperature clock was at the E-17 level, limited by the BBR shift uncertainty. To lower the BBR shift uncertainty, the precise measurement of the differential scalar polarizability through of the clock transition is taken, and the active liquid-cooling scheme is adopted, combined with the precise temperature measurement with 13 temperature sensors. The BBR field temperature uncertainty is then evaluated as 0.4 K, corresponding to a BBR shift uncertainty of 4.6E-18, then the overall systematic uncertainty of the room temperature clock is evaluated as 4.9E-18. Clock frequency comparison between the room temperature clock and the cryogenic clock is taken for testing the systematic shift uncertainty evaluations, and the two clocks show an agreement at the E-18 level after the systematic shift corrections: With the systematic shift corrections, the frequency difference between the two clocks is measured as 1.8(7.5)E-18, the overall uncertainty includes a statistic uncertainty of 4.9E-18 and a systematic uncertainty of 5.7E-18.
Besides the laboratory clocks mentioned above, a transportable Ca+ ion clock is also built, with an uncertainty of 1.3E-17 and an uptime rate of > 75%. With the comparison between the transportable clock and the laboratory clock, a demonstration of geopotential measurement with clocks has been made. The clock is then transported for > 1200 km to another institute, the absolute frequency measurement is made there with an uncertainty of 5.6E-16, about 5 times smaller than our previous result. Recently, a new round, 35-day-long absolute frequency measurement is taken, with improvements made such as the increase of the uptime rate to 91.3 %, the reduced statistical uncertainty of the comparison between the optical clock and hydrogen maser, and the use of longer measurement times to reduce the uncertainty of the frequency traceability link. The uncertainty of the absolute frequency measurement is further reduced to 3.2E-16, which is another factor of 1.7 improvement.

Authors: HUANG, Yao (Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences); Dr GUAN, Hua (Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences); Dr GAO, Kelin (Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences)

Presenter: HUANG, Yao (Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences)

Session Classification: Optical Ion Clocks II

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **14** Type: **Invited Poster**

Phase-Noise to Amplitude-Noise Conversion in Quantum Devices: Recent Advances in its Understanding and Mitigation

Laser phase-noise (PM) to detected intensity-noise (AM) conversion is fundamental to the field/matter interaction: it cannot be avoided, only mitigated. It occurs when laser light passes through a resonant atomic vapor in atomic clocks, magnetometers, and rf-sensors, and it occurs when laser-induced-fluorescence is detected from an atomic or molecular beam. More specifically, it is a tall-pole noise source in many next-generation vapor-cell atomic clocks. In this presentation the origin of PM-to-AM conversion will briefly be reviewed with attention to recent experiments aimed at better understanding the phenomenon and developing mitigation strategies.

Author: CAMPARO, James (The Aerospace Corporation)

Presenter: CAMPARO, James (The Aerospace Corporation)

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **15** Type: **Invited Oral**

Vibrational Molecular Lattice Clocks

Tuesday 17 October 2023 09:00 (30 minutes)

This talk will discuss a vibrational molecular lattice clock based on ultracold strontium dimers, its systematic evaluation at the 14th decimal digit, the current limitations, and paths forward.

Author: ZELEVINSKY, Tanya

Presenter: ZELEVINSKY, Tanya

Session Classification: Lattice Clocks

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **16** Type: **Invited Poster**

Ultralow Phase Noise Optoelectronic Oscillator

In this article, we have been using a high-power low-RIN laser, a long fiber loop, and an ultra-low noise optical connection to generate an OEO with a phase noise of -162.5dBc/Hz@10kHz at a frequency of 10 GHz to investigate the optoelectronic oscillator's single-loop structure, meanwhile, more significant factors on OEO have been explored.

Authors: Mr YAN, Dongliang; Ms GE, Jun; LIU, Dan

Presenter: Mr YAN, Dongliang

Track Classification: Precision and Low Noise Signal Generation and Techniques

Contribution ID: **19** Type: **Invited Poster**

Progress on cadmium-ion and ytterbium-ion Microwave Frequency Standards at Tsinghua University

The laser-cooled cadmium-ion microwave frequency standard has been developed at Tsinghua University for thirteen years. Recently, the ground-state hyperfine splitting frequency of $^{113}\mathrm{Cd}^+$ was determined to be 15199862855.02799(27) Hz, and the fractional frequency instability was measured to be $4.2 \times 10^{-13}/\sqrt{\tau}$. The result was consistent with previously reported values, but the measurement precision was four times better than the best result obtained to date. In addition, using sympathetic cooling technology, we have developed a high-performance cadmium-ion microwave frequency standard with $^{40}\mathrm{Ca}^+$ as coolant ions. The short-term frequency instability reached $3.48 \times 10^{-13}/\sqrt{\tau}$, which is comparable to that of the mercury ion frequency standard. It is worth mentioning that a microwave frequency standard based on laser-cooled $^{171}\mathrm{Yb}^+$ ions has also been developed in our laboratory since 2021. Recently, the short-term frequency instability was measured to be $8.5 \times 10^{-13}/\sqrt{\tau}$. The ground-state hyperfine splitting frequency of $^{171}\mathrm{Yb}^+$ was determined to be 12642812118.4674(8) Hz.

Authors: Mr MIAO, Shengnan (Tsinghua University); Mr QIN, Haoran (Tsinghua University); Mr XIN, Nongchao (Tsinghua University); Mr ZHANG, Jianwei (Tsinghua University); Mr WANG, Lijun (Tsinghua University)

Co-authors: Ms CHEN, Yiting (Tsinghua University); Ms ZHENG, Ying (Tsinghua University); Mr HAN, Jize (Tsinghua University); Ms SHI, Wenxin (Tsinghua University); Mr ZHAO, Tiangang (Tsinghua University)

Presenter: Mr ZHANG, Jianwei (Tsinghua University)

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **20** Type: **Invited Poster**

High Temperature Chip Scale Atomic Clock

We present the development of alkali-alloy-based vapor cells for operating Chip-Scale Atomic Clocks (CSAC) at ambient temperatures up to 105 ℃. Potassium is chosen for a better miscibility as compared with gold for the designed operating temperature. The caesium vapor density is reduced as predicted by the Raoult's law through mixing a controlled amount of potassium metal in the vapor cell. We have demonstrated vapor pressure suppression equivalent to 20 ℃. We have measured the collisional broadening due to potassium-caesium collisions and concluded it to be negligible. We will present experimental data demonstrating short- and long-term clock frequency performance as well as temperature sensitivity.

Author: HA, Lichung (Microchip)

Co-authors: NEWELL, Bruce (Microchip); NOBLE, Jay (Microchip); LUTWAK, Robert (Microchip)

Presenter: HA, Lichung (Microchip)

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **21** Type: **Invited Poster**

Cesium and Rubidium fountains at NTSC

Cesium atomic fountain primary frequency standards(PFS) and Rubidium fountain clocks are building to produce more accurate and stable local atomic time UTC(NTSC). The abstract presents 2 Cesium fountain PFS and 2 Rubidium at National Time Service Center, Chinese Academy of Sciences (NTSC).

Author: RUAN, Jun

Co-authors: Ms LIU, Dan-dan; Mr ZHANG, Hui; SHI, Jun-Ru; HAO, Qiang; ZHAO, Shu-Hong; NIE, Shuai; FAN, Si-Chen; WU, Wen-Jun; Mr WANG, Xin-Liang; BAI, Yang; Mr GUAN, Yong

Presenter: RUAN, Jun

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **26** Type: **Invited Poster**

Re-evaluation of the NRC-FCs2 Fountain Clock

At the National Research Council Canada, we are re-evaluating the NRC-FCs2 caesium fountain clock. The systematic uncertainty has been dominated by four contributions: cold collisions, the distributed cavity phase (DCP) shift, microwave leakage, and synchronous phase transients. We have significantly reduced all but the DCP shift, which is currently being characterized. We will discuss the methods, results, and impact of the re-evaluation.

Author: BEATTIE, Scott (National Research Council Canada)

Co-authors: JIAN, Bin (National Research Council Canada); GERTSVOLF, Marina (National Research Council Canada)

Presenter: BEATTIE, Scott (National Research Council Canada)

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **27** Type: **Invited Poster**

Fringes and Light Shift in CPT-Ramsey Spectroscopy

Up to now, the mechanism and light shift in CPT-Ramsey have not yet been clarified theoretically. Using the time evolution of the Bloch vector after the steady-state condition is achieved at the first excitation pulse, we derived an expression of CPT-Ramsey fringes and formulized the light shift in CPT-Ramsey connecting to the ordinal light shift due to Rabi-pulling, which are suitable to explain the experimental results. We discuss a method of higher reduction of the light shift in CPT-Ramsey.

Author: MORINAGA, Atsuo

Co-author: YANAGIMACHI, Shinya

Presenter: MORINAGA, Atsuo

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **28** Type: **Invited Poster**

Portable Dual-Wavelength Optical Atomic Rubidium Clock

We report progress on the development and out-of-lab demonstrations of a next-generation optical timing reference based on the dual-wavelength excitation of the $5S_{1/2} \rightarrow 5D_{5/2}$ two-photon transition of rubidium-87.

We make use of the robustness of mature laser telecommunications technologies, FPGA-based control systems and automation, and a compact optical frequency comb to generate stable clock outputs in the optical (778nm, 385THz) and radio frequency (1GHz) domains for interfacing with both optical systems and conventional electronics. We have measured fractional frequency instability of the rubidium clock of 1.5×10^{-13} at 1s, integrating down at $1/\sqrt{\tau}$ to 3×10^{-15} at 8,000s.

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Presenter: SCHOLTEN, Sarah (Institute for Photonics and Advanced Sensing, University of Adelaide)

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **29** Type: **Invited Poster**

Stable RF transmission using PLL over long-distance optical fiber

Stable frequency standards have important applications in gravitational wave detection, precise navigation timing, and verification of relativity principles. Effectively utilizing the present fiber network resource to construct the stable radio frequency (RF) transfer system has been explored by many researchers. As the transmission distance is extended, the noise induced by the fiber link affects the frequency stability of the receiver signal. Phase-locked loop (PLL) is an efficient method to filter out noise and obtain the synchronous frequency signal at the receiver. In this paper, we test the performance of the frequency transfer system over long-distance optical fiber link and compare the effect of PLL on the frequency stability.
As shown in Fig.1, the experiment is carried out on a 480 km optical fiber link constructed from the cascade of 80 km fiber spools. The transmitter and receiver of the transfer system are placed at ei-ther end of the link, and bi-directional erbium-doped fiber amplifiers (Bi-EDFAs) are placed at the fiber link. The experimental results are shown in Fig. 2, when the PLL is turned off, the frequency stability of the transfer system is 4.65E-14@ 1 s and 4.66E-17@ 10,000 s. When the PLL is turned off, the frequency stability of the transfer system is 1.54E-13@ 1 s and 1.17E-16@ 10,000 s. Experimental results show that the frequency stability of the transfer system is significantly im-proved by the PLL for long-distance frequency transmission. The frequency stability of the synchronous frequency signal recovered from the receiver is better than that of the cesium clock, which meets the demand of long-distance frequency transmission.

Authors: GAO, Hao (Beijing University of Posts and Telecommunications School of Optoelectronic Information); Prof. LUO, Bin (Beijing University of Posts and Telecommunications School of Optoelectronic Information)

Co-authors: Ms LIU, Chenxia (North China Electric Power University); Prof. SHANG, Jianming (Beijing University of Posts and Telecommunications School of Optoelectronic Information); Prof. CHEN, Ziyang (Peking University); Prof. YU, Song (Beijing University of Posts and Telecommunications School of Optoelectronic Information); Prof. GUO, Hong (Peking University)

Presenter: GAO, Hao (Beijing University of Posts and Telecommunications School of Optoelectronic Information)

Track Classification: Time and Frequency Transfer

Contribution ID: **30** Type: **Invited Poster**

Reduction of the blackbody radiation and lattice light shift uncertainty of strontium lattice clocks

We present recent improvements of the systematic lattice light shift in our strontium lattice clock, reaching a fractional uncertainty on the order of 1×10^{-18}. A series of independent determinations of the E2-M1 polarisability $\Delta\alpha_{\mathrm{qm}}$ by different groups, including our own experimental measurement, has narrowed down the limits for the correct value of $\Delta\alpha_{\mathrm{qm}}$. The reduced fractional uncertainty of the lattice light shift benefits the strontium lattice clocks in the community. Further improvements of our system are planned by operating at cryogenic temperature of about 80 K. The fractional uncertainty from blackbody radiation is estimated to be reduced below the level of 2×10^{-19} by this procedure.

Author: Mr KLOSE, Joshua

Co-authors: Mr LISDAT, Christian; Mr DÖRSCHER, Sören

Presenter: Mr KLOSE, Joshua

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **31** Type: **Invited Oral**

Atomic Clock Ensemble in Space

Thursday 19 October 2023 10:00 (30 minutes)

The Atomic Clock Ensemble in Space (ACES) mission is developing high performance clocks and links for space to test Einstein's theory of general relativity. From the International Space Station, the ACES payload will distribute a clock signal with fractional frequency instability and inaccuracy of 1×10^{-16} establishing a worldwide network to compare clocks in space and on ground. ACES will provide an absolute measurement of Einstein's gravitational redshift, it will search for time variations of fundamental constants, contribute to tests of topological dark matter models, and perform Standard Model Extension tests. The network of ground clocks participating to the ACES mission will additionally be used to compare clocks over different continents and measure geopotential dif-ferences at the clock locations.
After some technical delays, the ACES flight model is now approaching its completion. System tests involving the laser-cooled Cs clock PHARAO, the active H-maser SHM and the on-board frequency comparator (FCDP) have measured the performance of the clock signal delivered by ACES. The ACES microwave link MWL is currently under test. The single-photon avalanche detector of the ACES optical link ELT has been tested and will now be integrated in the ACES payload.
The ACES mission concept, its scientific objectives, and the recent test results will be presented together with the major milestones that will lead us to the ACES launch.

Authors: CACCIAPUOTI, Luigi (European Space Agency); LAURENT, Philippe (SYRTE, Observatoire de Paris-PSL, CNRS, Sorbonne Université, LNE); SALOMON, Christophe (Laboratoire Kastler Brossel, ENS-PSL, CNRS)

Presenter: CACCIAPUOTI, Luigi (European Space Agency)

Session Classification: Microwave Clocks and Oscillators

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **34** Type: **Invited Oral**

Robust Design and Performance of NPL Cs Fountain Clocks

Thursday 19 October 2023 09:30 (30 minutes)

Atomic fountain clocks have become ubiquitous in maintaining the most stable national time scales within nanoseconds of UTC. After three decades of development, they offer accuracy of about 1 part in 10ˆ16. Recent efforts have been aiming at increased reliability and robust commercial design. We present the distinctive design approach and performance of the NPL built fountains, as well as current work to miniaturise the device and prospects for new applications.

Author: SZYMANIEC, Krzysztof

Co-authors: Mr WILSON, Andrew; Prof. FOOT, Christopher; Dr WHALE, Joshua; Dr HENDRICKS, Richard; Mr WALBY, Samuel

Presenter: SZYMANIEC, Krzysztof

Session Classification: Microwave Clocks and Oscillators

Track Classification: SI definition, Clocks and Time Scales

Contribution ID: **35** Type: **Invited Oral**

Nuclear-spin-based rotation sensing with diamond

Thursday 19 October 2023 15:00 (30 minutes)

A nuclear-spin-based rotation sensor is implemented based on simultaneous measurements with two nitrogen isotopes intrinsic to nitrogen-vacancy centers in diamond, employing a microwave-free technique with optical addressing of nuclear spins. Differential measurements suppress systematics related to magnetic-field and temperature variations.

Author: JARMOLA, Andrey (UC Berkeley)

Co-authors: LOURETTE, Sean (UC Berkeley); ACOSTA, Victor (University of New Mexico); BIRDWELL, Glen (DEVCOM Army Research Laboratory); BLÜMLER, Peter (Johannes Gutenberg-Universität Mainz); BUDKER, DMITRY (Helmholtz Institute Mainz and UC Berkeley); IVANOV, Tony (DEVCOM Army Research Laboratory); MALINOVSKY, Vladimir (DEVCOM Army Research Laboratory)

Presenter: JARMOLA, Andrey (UC Berkeley)

Session Classification: Precision and Quantum Measurements

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **37** Type: **Invited Poster**

The development and future of the Faraday laser

This paper introduces the development of the Faraday laser, which is a novel external cavity diode laser that uses the Faraday anomalous dispersion optical filter as the frequency selective element based on the quantum technology. This paper also demonstrates the advantages of the Faraday laser compared to the traditional ECDLs which are usually based on gratings, Fabry-Pérot etalons and interference filters. The Faraday lasers are immune to the fluctuations of current and temperature of the laser diode, and the output wavelength can automatically correspond to the atomic lines. This paper also shows the recent researching results in frequency locking, quantum precision measurement, and gives a research planning of future.

Authors: WANG, Zhiyang (Peking University); Dr SHI, Hangbo (Peking University); Dr LIU, Zijie (Peking University); Dr MIAO, Jianxiang (Peking University); Dr SHI, Tiantian (Peking University); Prof. CHEN, Jingbiao (Peking University)

Presenter: WANG, Zhiyang (Peking University)

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **38** Type: **Invited Poster**

Active Optical Clock: Seventeen Years of Progress and Next Steps

The concept of the active optical clock (AOC) [1] was proposed seventeen years ago by prof. Jingbiao Chen. After early calculations and experiments that demonstrated the advantages of "cavity-pulling suppression"and "narrower linewidth", the development of AOCs soon became an active competition involving many research groups that proposed schemes based on different atomic gain mediums, and different energy-level structures. The AOC has great promise for applications in quantum metrology, as it can overcome the thermal noise of the reference cavity that limits conventional lasers, making AOC a promising candidate for future atomic clocks.

Due to the significant advantages, the AOC has received extensive attention from international colleagues, and dozens of institutes such as NIST, JILA, Niels Bohr Institute, and University of Hamburg, etc., have conducted research on AOCs. Current experimental schemes include AOCs based on thermal atomic vapor cell, thermal atomic beam, laser slowed atomic beam, optical lattice, and magneto-optical trap (MOT) trapped atoms. The Niels Bohr Institute used ^{88}Sr atoms imprisoned in a MOT operating in bad-cavity region as a quantum reference to achieve a quasi-continuous superradiant lasing through cavity-enhanced atomic interactions with a linewidth of 820 Hz. JILA [2] has reduced the frequency stability of AOC to 6×10^{-16} @ 1 s with a linewidth of narrower than 2 Hz.

Peking University has recently conducted research around Cs four-level AOC [3], mainly including: 1) A continuous wave (cw) 1470 nm AOC with a linewidth of 53 Hz was realized based on the dual-wavelength good-bad-cavity technique. 2) We proposed a laser referenced on a version of velocity-grating Ramsey-Bordé atom interferometry with greatly improved atom utilization, which can generate optical Ramsey fringes with an amplitude enhanced by 1000-fold or more. 3) An inhibited laser was innovatively proposed, expanding the working regime of the classical AOC from the resonant cavity condition to the far off-resonance condition. It is proved that the suppressed cavity-pulling effect of the inhibited laser is further enhanced by a factor of $(\frac{2\mathcal{F}}{\pi})^2$ compared with the resonant state-of-the-art superradiant laser. 4) An exact expression for the FWHM of the Fabry-Pérot (FP) cavity Airy distribution was derived, which solves the problem of inapplicability under ultra-low reflectivity conditions in the conventional formula. 5) We achieved the first continuously operating extremely bad-cavity laser with a cavity finesse close to the limit of 2 (corresponding to a reflectivity of 0.5%). Experimentally, we obtained a cavity-pulling coefficient that is nearly 70 times less sensitive to cavity thermal and technical noise than conventional good-cavity lasers.

The AOC uses the stimulated radiation signal of atoms directly as an optical frequency standard and operates in the deep bad-cavity region. The gain linewidth is much narrower than the cavity mode linewidth, so the laser frequency depends mainly on the quantum transition rather than the cavity-mode center frequency. Currently, one of the major directions in the development of AOCs is cw operation. Peking University has carried out cold-atom four-level AOC with simultaneous cooling, repumping, and pumping, which are expected to realize cold-atom-based AOC operating continuously with linewidths of the order of Hz. JILA, RIKEN, and the European Union are also conducting AOC superradiant experiments based on moving optical lattices, and have now achieved the use of optical lattices to transport atoms into resonant cavities. In the near future, we believe that continuously operating AOC superradiant lasers based on moving optical lattices will be realized.

References

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Authors: ZHANG, Jia (Peking University); MIAO, Jianxiang; Prof. CHEN, Jingbiao; SHI, Tiantian (Peking University); GUAN, Xiaolei (Peking University); GAO, Xun

Presenter: SHI, Tiantian (Peking University)

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **40** Type: **Invited Poster**

Testing novel high-reflectivity mirror technologies from room-temperature to 4 K

We are presenting a low-vibration closed-cycle cryostat setup for the characterization of mirror coatings performance and direct Brownian thermal noise measurements from room-temperature to 4 K.

Using a high-finesse optical resonator as well as multiple techniques to circumvent technical noise sources related to vibration and temperature fluctuations this facility will enable the investigation of the optical behavior of crystalline AlGaAs/GaAs multilayer coatings across a broad temperature range, which in turn can help understanding the source of an observed novel excess noise. The same system will also offer the possibility to verify thermal noise estimates and ruling out yet unknown noise sources in other novel high-reflectivity mirror designs such as nanostructured meta-etalons and amorphous-Si multilayer coatings.

Author: Ms KEMPKES, Mona (PTB Germany)

Co-authors: Dr NICOLODI, Daniele (PTB Germany); Dr LEGERO, Thomas (PTB Germany); Dr STERR, Uwe (PTB Germany)

Presenter: Ms KEMPKES, Mona (PTB Germany)

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **41** Type: **Invited Poster**

Frequency comb for 88Sr+ clock frequency comparison with Cs fountain clock at the NRC

We present the portable saturable absorber-based fibre combs made for the 88Sr+ single ion clock measurement campaign against NRC-FCs2 Caesium fountain clock. We also present the setup that we intend to use for this clock comparison.

Authors: Dr MARCEAU, Claude (National Research Council Canada); Dr GERTSVOLF, Marina (National Research Council Canada); Dr BEATTIE, Scott (National Research Council Canada); Mr PAKULSKI, Wojciech (National Research Council Canada)

Presenter: Dr MARCEAU, Claude (National Research Council Canada)

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **42** Type: **Invited Poster**

The Optimization of Cold Atom Microwave Clocks

The cold atom microwave clocks play important roles in the field of primary frequency standards, space exploration, satellite navigation, time keeping and fundamental physics, in which the microwave local oscillator drives the transitions between two well-defined cold atomic states using a Ramsey microwave interrogation sequence. Through decades of both theoretical and experimental exploration, many scientific experiments and engineering tests have been initially performed. However, there is still a vast optimization space to improve the performance for atom fountain clock and integrating sphere cold atom clock.
In this paper, after a simple review, we will mainly present the most recent original research progresses for the optimization of atom fountain clock and integrating sphere cold atom clock to improve their frequency stability, including optical path, physical structure, operation time sequence, etc.
The first part focuses on the 87Rb atom fountain clock to solve the problem of the laser frequency stability and limited free evolution time. As shown in Fig.1(a), an ECDL and a DFB laser are applied to build the optical path, whose laser frequency are stabilized by modulation transfer spectrum and saturated absorption spectrum respectively. The designed optical lattice along the gravity in physical structure will be discussed in detail.
The second part emphases on the 133Cs integrating sphere cold atom clock to solve the problem of the laser frequency stability and limited cold atom number in Ramsey interrogation. The experimental scheme of optical path is shown in Fig.1(b) and a new integrated multifunctional microwave cavity in physical structure is proposed, which will be discussed in detail.
The cold atom microwave clocks with the presented optimization are expected to open a range of exciting possibilities for higher frequency stability and better operation ability. The future development of cold atom microwave clocks is also discussed.

Authors: Ms WANG, Danyang (Beijing Institute of Radio Measurement and Metrology); Mr LLIU, Guodong (Beijing Institute of Radio Measurement and Metrology); Mr CHEN, Jingbiao (Peking University); Mr WANG, Liang (Beijing Institute of Radio Measurement and Metrology); Mr GAO, Lianshan (Beijing Institute of Radio Measurement and Metrology); Mr LIU, Shuo (Beijing Institute of Radio Measurement and Metrology); Mr ZHOU, Tiezhong (Beijing Institute of Radio Measurement and Metrology); Ms WANG, Weili (Beijing Institute of Radio Measurement and Metrology); Ms ZHU, Xi (Beijing Institute of Radio Measurement and Metrology); WANG, Xiumei; Ms WANG, Yifei (Beijing Institute of Radio Measurement and Metrology); Mr LI, Yuebao (Beijing Institute of Radio Measurement and Metrology); Mr WANG, Yunjia (Beijing Institute of Radio Measurement and Metrology)

Presenter: WANG, Xiumei

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **43** Type: **Invited Poster**

Field-deployable Interferometric Fiber Link terminals with very low temperature sensitivity

In this work, we present a novel optical setup for interferometric fiber links with an inherently very low temperature sensitivity, based on standard fiber and components, in a topology free of uncompensated optical paths. The terminals are designed to be deployed outside of well-controlled labs, for example for chronometric levelling with transportable optical clocks. We setup two terminals and put the optical setup from the second terminal into a climate chamber and ramp the temperature be-tween 10℃ and 40℃. We observe phase shifts of less than 0.4 rad (0.3 fs at 194.4 THz) from the temperature ramping.

Authors: KUHL, Alexander (Physikalisch-Technische Bundesanstalt, Braunschweig, Germany); Mr KRONJÄGER, Jochen (Physikalisch-Technische Bundesanstalt, Braunschweig, Germany)

Presenter: KUHL, Alexander (Physikalisch-Technische Bundesanstalt, Braunschweig, Germany)

Track Classification: Time and Frequency Transfer

Contribution ID: **44** Type: **Invited Poster**

Sr Optical Lattice Clock and Precision Optical Frequency Measurement at NIM

Two Sr optical lattice clocks are being built at NIM. The systematic shift uncertainty of Sr1 is 2.9E-17, and 7.2E-18 for Sr2. A comparison between these two clocks is in progress. The absolute frequency measurements of optical clocks have been carried out at NIM referenced to both the local cesium fountains and the PSFS in Circular T bulletin through a satellite link.

Author: LIN, Yige (National Institue of Metrology, China)

Co-authors: Dr LIN, Baike (National Institue of Metrology, China); Mr LU, Bingkun (Tsinghua University, Beijing, PRC); Dr FANG, Fang (National Institue of Metrology, China); Mr MENG, Fei (National Institue of Metrology, China); Ms ZHU, Lin (Tsinghua University, Beijing, PRC); Dr WANG, Qiang (National Institue of Metrology, China); Mr LIAO, Tangyin (Tsinghua University, Beijing, PRC); Dr YANG, Tao (National Institue of Metrology, China); Dr LI, Ye (National Institue of Metrology, China); Dr WANG, Yuzhuo (National Institue of Metrology, China); Dr FANG, Zhanjun (National Institue of Metrology, China)

Presenters: LIN, Yige (National Institue of Metrology, China); Dr FANG, Zhanjun (National Institue of Metrology, China)

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **45** Type: **Invited Poster**

Progress on the optically detected magnetic-state-selected cesium beam clock

We present the recent progress on the optically detected magnetic-state-selected cesium beam clock (OMCC). The stability of the compact prototype reaches 4.0E-13@100s, 4.5E-14@10000s and 2.2E-14@1d. We use beam optics to increase SNR to obtain better short-term stability. We propose detuned light detection method and pulsed light detection method to suppress the light shift. To further optimize the stability, we develop a new type of OMCC, which has a narrower linewidth and higher SNR. The stability of this new type reaches 2.94E-12 tauˆ-1/2 on the laboratory platform.

Authors: Prof. WANG, Yanhui (Peking University); LI, Yuanhao (Peking University)

Co-authors: Mr LI, Chaojie (Peking University); Mr LIU, Chen (Peking University); Mr FAN, Lifeng (Peking University); Mr CHEN, Sifei (Peking University)

Presenter: Prof. WANG, Yanhui (Peking University)

Track Classification: SI definition, Clocks and Time Scales

Contribution ID: **46** Type: **Invited Poster**

Status Report on Yb optical lattice clocks at KRISS

Status report is given on the Yb optical lattice clocks developed at KRISS. KRISS-Yb1 is being operated regularly to contribute to International Atomic Time (TAI). KRISS-Yb2 was developed to reach the 10ˆ-18 uncertainty level overcoming the BBR shift uncertainty of KRISS-Yb1. Preliminary uncertainty evaluation results of KRISS-Yb2 will be presented at the conference.

Author: Dr LEE, Won-Kyu (KRISS)

Co-authors: Dr YU, Dai-Hyuk (KRISS); Dr KIM, Huidong (KRISS); Dr PARK, Chang Yong (KRISS); Dr HEO, Myoung-Sun (KRISS)

Presenter: Dr LEE, Won-Kyu (KRISS)

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **47** Type: **Invited Poster**

Test of local Lorentz invariance in the phonon sector using quartz BAW oscillators

In this work, we will present the test of local Lorentz invariance using the precision measurements of oscillation masses of particles (phonons). The experiment utilizes two ultra-stable Bulk Acoustic Wave (BAW) quartz oscillators placed orthogonally to each other on a turntable and search for LIV by comparing their relative frequency shift. The resonant frequency of mechanical resonators including BAW oscillators depends on the mode effective mass, which not only depend on the external load-ings but also on the intrinsic mass, i.e. inertial masses of composing particles of the device. Thus, the modulations of inertial masses can be converted to the modulations of phonon resonant frequencies and can be detected precisely with frequency measurement techniques. In SME theory, the modulations of the inertial masses depend on the direction and boost velocity in space. In this case, the LIV test is reduced to the measurements of frequency stabilities of mechanical resonators as a function of direction and boost velocity in space. The overall sensitivity of such an experimental scheme is limited by the frequency stabilities of resonators or oscillators at time periods twice of the rotation period rather than the long-term performance of the oscillators. The best sensitivity is achieved by limiting the integration time low and in this experiment the rotating period of the turntable is optimized at 1 second. Quartz BAW oscillators provide the best frequency stability below 10-13 between 1 and 10 seconds in integration time and low sensitivity to other effects such as temperature, vibration, acceleration and aging. The stability of the oscillators has an order of magnitude improvement than the one used in the previous version of the experiment. Data analysis is done by using the two-stage demodulated least square (DLS) method. The fractional frequency difference is demodulated into DLS parameters and linked to SME neutron c coefficients to obtain the sensitivity.

Author: Dr ZHAO, Zijun C. (Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia.)

Co-authors: Dr GORYACHEV, Maxim (Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia.); Prof. IVANOV, Eugene N. (Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia.); Prof. TOBAR, Michael E. (Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia.)

Presenter: Dr ZHAO, Zijun C. (Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia.)

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **48** Type: **Invited Poster**

High Performance Transportable Optical Frequency References Based on a Dual-Axis Cubic Cavity (DACC) Configuration

We present high performance, transportable, dual-axis optical frequency references based upon NPL's patented cubic cavity design. These cavities have demonstrated leading insensitivity to micro-vibrational perturbations and are pushing fractional frequency instability performance beyond the mid 10-15 level at 1 s. These characteristics led themselves to many applications including spaced-based gravitational wave detection, low phase noise microwave generation and laser stabilisation requirements in transportable optical lattice clocks.

Author: ALLEN, Ben (National Physical Laboratory)

Co-authors: Dr SPAMPINATO, Alessio (National Physical Laboratory); Dr BARWOOD, Geoffrey (National Physical Laboratory); Dr HILL, Ian (National Physical Laboratory); Dr STACEY, Jonathan (National Physical Laboratory); GILL, Patrick (National Physical Laboratory); Mr TSOULOS, Peter (National Physical Laboratory)

Presenter: ALLEN, Ben (National Physical Laboratory)

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **49** Type: **Invited Poster**

Primary and secondary frequency standards and the Coordinated Universal Time

Contribution of primary and secondary frequency standards to UTC and the support from BIPM to the redefintion of the second and accurate time and frequency metrology

Author: TAVELLA, Patrizia

Co-authors: HARMEGNIES, AURELIE; MEYNADIER, FREDERIC; PANFILO, GIANNA; TAGLIAFERRO, GIULIO; TISSERAND, LAURENT

Presenter: TAVELLA, Patrizia

Track Classification: SI definition, Clocks and Time Scales

Contribution ID: **50** Type: **Invited Oral**

Robust Optical Clocks for International Timescales (ROCIT)

Wednesday 18 October 2023 09:30 (30 minutes)

The recently concluded collaborative European project "Robust optical clocks for international timescales" (ROCIT) tackled some of the key challenges on the roadmap towards a redefinition of the second. The overall aim was to bring European optical clocks to the stage where they can contribute regularly to International Atomic Time as secondary representations of the second.

Author: MARGOLIS, Helen

Presenter: MARGOLIS, Helen

Session Classification: SI Definition, Clocks and Time Scales II

Track Classification: SI definition, Clocks and Time Scales

Contribution ID: **51** Type: **Invited Oral**

Laser-Cooling Cadmium with only Triplet Excitations and Cadmium Isotope Shift Measurements

Tuesday 17 October 2023 15:00 (30 minutes)

Cadmium is attractive for optical lattice clocks and for searches for Dark Matter and beyond-Standard-Model physics via isotope shift measurements. The cadmium clock transition has a small sensitivity to blackbody radiation and it has 8 stable isotopes, 6 spin 0 bosonic isotopes, and 2 spin ½ fermionic isotopes. Without using 229 nm light to drive the singlet transition, we capture thermal Cd atoms directly into a 326 nm narrow-line MOT. We then increase the loading rate by capturing atoms using the 361 nm $^3P_2 \rightarrow {}^3D_3$ transition. We measure the isotope shifts of the 326 nm intercombination transition, and the 480 nm $^3P_1 \rightarrow {}^3S_1$ and $^3P_2 \rightarrow {}^3D_3$ transitions. These clarify a discrepancy of the nuclear charge radius and suggest that cadmium isotope shifts can sensitively test beyond standard model physics.

Author: GIBBLE, Kurt (The Pennsylvania State University)

Presenter: GIBBLE, Kurt (The Pennsylvania State University)

Session Classification: Precision Measurements and Fundamental Physics II

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **52** Type: **Invited Poster**

PTB's Second-Generation Transportable Strontium Lattice Clock

Due to the gravitational redshift, clocks can be utilized for height determination in geodesy. To become geodetically relevant, fractional clock frequency differences of about 1×10^{-18} need to be resolvable. Our second-generation transportable strontium lattice clock represents our recent efforts in reaching the required level of accuracy with an in-field deployable device. These include a single-beam pyramid magneto-optical trap for robust cooling and trapping of strontium-87 atoms, a blackbody radiation (BBR) shield for fractional BBR shift uncertainties below 1×10^{-18} and a transportable clock laser with an instability in modified Allan deviation of down to 1.6×10^{-16}.

Author: LÜCKE, Tim (Physikalisch-Technische Bundesanstalt)

Co-authors: VISHWAKARMA, Chetan (Physikalisch-Technische Bundesanstalt); LISDAT, Christian (Physikalisch-Technische Bundesanstalt); NOSSKE, Ingo (Physikalisch-Technische Bundesanstalt); HERBERS, Sofia (Physikalisch-Technische Bundesanstalt)

Presenter: LÜCKE, Tim (Physikalisch-Technische Bundesanstalt)

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **53** Type: **Invited Poster**

Development of a laser stabilized on an ultra-stable silicon cryogenic Fabry-Pérot cavity for dark matter detection

Ultra-stable Fabry-Pérot cavities are ideal tools for ultra-light dark matter detection, since the fluctuations of length of the cavity can be detected on the frequency of the laser stabilized on the cavity. At FEMTO-ST, we dispose of an ultra-stable silicon cavity suitable for a test of detection of ultra-light dark matter in an energy range close to 10^{-10} eV.c^{-2}. We present the status of the development of our ultra-stable laser and the mechanical response of the cavity in presence of ultra-light dark matter, strongly enhanced by the mechanical quality factor of silicon compared to ULE glass or fused silica.

Authors: Mrs HARIRI, Yara (FEMTO-ST); Dr LACROÛTE, Clément (FEMTO-ST); Dr MILLO, Jacques (FEMTO-ST); Dr BARBARAT, Joannès (FEMTO-ST); Prof. KERSALÉ, Yann (FEMTO-ST); Prof. GILLOT, Jonathan (FEMTO-ST)

Presenters: Mrs HARIRI, Yara (FEMTO-ST); Prof. GILLOT, Jonathan (FEMTO-ST)

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **54** Type: **Invited Oral**

Frequency reference validation with 176Lu+

Monday 16 October 2023 14:30 (30 minutes)

We discuss some of the many advantages that lutetium offers as an optical frequency reference. We illustrate the ease at which a comparison at the level of 1e-18 can be achieved and we show how the use of two available clock transitions can be used to verify clock performance between two systems.

Author: BARRETT, Murray (Center for Quantum Technology)

Presenter: BARRETT, Murray (Center for Quantum Technology)

Session Classification: Optical Ion Clocks I

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **55** Type: **Invited Oral**

Resonant photonic oscillators and regenerative frequency dividers

Friday 20 October 2023 12:00 (30 minutes)

Mode-locked Kerr frequency combs generated in nonlinear resonators pumped with coherent monochromatic light have attracted significant attention because of their practical importance associated with their applications in optical and microwave frequency generation, signal synthesis, clocks and others. Dichromatic resonant continuous wave pumping of a nonlinear optical resonator can result in generation of broad microcombs at low power levels as well as other comb structures different from the usual Kerr combs. These frequency combs can be fully stabilized by means of pump harmonics and the repetition rate of the microcombs can be significantly smaller than the frequency difference between the pump frequencies. These combs can be considered as realizations of large order discrete time crystals and can be used as regenerative photonic frequency dividers. In this presentation we will discuss properties and applications of the optical frequency combs generated in cavities by means of dichromatic light.

Author: Dr MATSKO, Andrey (Jet Propulsion Laboratory, California Institute of Technology)

Presenter: Dr MATSKO, Andrey (Jet Propulsion Laboratory, California Institute of Technology)

Session Classification: Low Noise Optical Systems

Track Classification: Precision and Low Noise Signal Generation and Techniques

Contribution ID: **56** Type: **Invited Oral**

Atomic clocks as exotic field telescopes in multi-messenger astronomy

Our work [Dailey et al., Nature Astronomy 5, 150 (2021)] extends the gravitational and electromagnetic modalities of multi-messenger astronomy to exotic (beyond the Standard Model of elementary particles) fields. We are interested in a direct detection of exotic fields emitted by the powerful astrophysical events such as binary black hole mergers. While the progenitors can be located in another galaxy, we demonstrate that modern atomic clocks are sensitive to exotic fields plausibly emitted in the mergers due to (i) the exquisite sensitivity of atomic clocks and (ii) because of the enormous amounts of energy released in the mergers.

Author: Dr DEREVIANKO, Andrei (University of Nevada, Reno)

Presenter: Dr DEREVIANKO, Andrei (University of Nevada, Reno)

Session Classification: Null

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **57** Type: **Invited Poster**

Developing a Free-Space Quantum-Secured Time Transfer System

We will present our latest results towards implementing a free-space optical quantum time transfer system. We compare experiments using correlated photon pairs over a 100 m free-space link with a theoretical model we have developed to determine the fundamental limits of our system.

Author: SLIMANI, Sabrina

Co-authors: YUEN, Nicole (Defence Science and Technology Group); BAYNES, Fred (QuantX Labs); GRANT, Ken (Defence Science and Technology Group); LUITEN, Andre (Institute for Photonics and Advanced Sensing, University of Adelaide); SPARKES, Ben (Defence Science and Technology Group)

Presenter: SLIMANI, Sabrina

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **58** Type: **Invited Oral**

Free-space laser links for frequency comparison between fast-moving optical clocks

Thursday 19 October 2023 17:00 (30 minutes)

Frequency comparison using ultra-stable, free-space laser links between transportable optical atomic clocks will result in globally significant advancements in applications spanning from fundamental physics, to outputs with immediate societal impact. Here, we report on our work to demonstrate a low size, weight, and power, continuous-wave laser technology that is capable of free-space frequency comparison between fast-moving optical clocks.

Author: SCHEDIWY, Sascha (University of Western Australia)

Co-authors: Dr DIX-MATTHEWS, Benjamin (University of Western Australia); Mr FROST, Alex (University of Western Australia); Dr GOZZARD, David (University of Western Australia); Mr KARPATHAKIS, Skevos (University of Western Australia); Mr MCCANN, Ayden (University of Western Australia); Mr MCSORLEY, Shawn (University of Western Australia); Dr WALSH, Shane (University of Western Australia)

Presenter: SCHEDIWY, Sascha (University of Western Australia)

Session Classification: Precision Fibre and Free Space Transfer

Track Classification: Time and Frequency Transfer

Contribution ID: **59** Type: **Invited Poster**

Phase stabilised microwave frequency dissemination across a 200 node, 3000 km optical fibre network

We present the industrial mass manufacturing processes that has enabled us to develop the Frequency Distribution System for the mid-frequency Square Kilometre Array radio telescope. The system performs microwave frequency dissemination across an optical fibre network, encompassing 197 modular receive-transmit nodes and a total fibre link of > 3000 km, with individual segments up to 173 km in length. The system is designed to be cost effective, have a > 99.9% up time, and disseminate microwave-frequency signals with residual instability below 10^{-16}.

Author: Dr KRIELE, Michael (University of Western Australia)

Co-authors: Mr GRAVESTOCK, Charles (University of Western Australia); Dr GLUSZAK, Edward (University of Western Australia); Mr CHOUNG, Kevin (University of Western Australia); Mrs THOMAS, Neethu (University of Western Australia); SCHEDIWY, Sascha (University of Western Australia)

Presenter: Dr KRIELE, Michael (University of Western Australia)

Track Classification: Time and Frequency Transfer

Contribution ID: **60** Type: **Invited Poster**

Miniaturized Optical Clock using Rb Two-Photon Transition

We introduce our research in developing a miniaturized optical clock at KRISS using 87Rb two-photon 5S1/2 to 5D5/2 transition in a chip-scale vapor cell. This transition provides a narrow spectral linewidth with potential applications in deployable optical clocks. We obtain a resonance spectrum of the two-photon transition with a chip-scale rubidium vapor cell with a size of 4×7×2.6 mm. The chip cell is made by 5-layer-wafer bonding procedure for longer interaction lengths with the atoms. The wafer is dichroic-coated to reflect 778.1 nm while transmitting the fluorescence signal of 420 nm. The spectral signal is used for locking the laser frequency. The error signal is processed by a
FPGA and is fed into the driving current of laser to construct a frequency servo. Preliminary stability without optimization shows 2×10ˆ-11@1 s and is expected to be improved in the future. By further miniaturizing the two-photon spectroscopy apparatus, we plan to develop a mobile optical frequency synthesizer platform combined with microcomb and photonic pre-stabilization technique for field applications.

Author: YU, Dai-Hyuk (Korea Research Institute of Standards and Science)

Co-authors: Dr SEO, Meungho (Korea Research Institute of Standards and Science); Dr LEE, Jae Hoon (Korea Research Institute of Standards and Science); Dr HONG, Hyun-Gue (Korea Research Institute of Standards and Science); Dr PARK, Jongcheol (National NanoFab Center)

Presenter: YU, Dai-Hyuk (Korea Research Institute of Standards and Science)

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **61** Type: **Invited Oral**

171Yb+ optical clock at NPL for frequency metrology and tests of fundamental physics

Monday 16 October 2023 16:00 (30 minutes)

We will report on absolute E3 frequency measurements and E3/E2 optical frequency ratio measurements in $^{171}Yb^{+}$, local $^{171}Yb^{+}$/ ^{87}Sr clock frequency ratios, related uncertainty budgets, and improvements in automation and robust operation of the $^{171}Yb^{+}$ clock system at NPL. We will also show how these measurement results have been used to constrain temporal variation of the fine structure constant and exclude regions of parameter space in theories beyond the Standard Model, such as those which include ultralight scalar dark matter.

Authors: PARSONS, Adam (NPL); TOFFUL, Alexandra (NPL); TRAN, An (NPL); CURTIS, Anne; ROBERTSON, Billy (NPL); MARGOLIS, Helen (NPL); TUNESI, Jacob (NPL); SCHIOPPO, Marco (NPL); GODUN, Rachel (NPL)

Presenter: CURTIS, Anne

Session Classification: Optical Ion Clocks II

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **62** Type: **Invited Poster**

Towards practical quantum secure time transfer

Quantum Secure Time Transfer (QSTT) ensures the authenticity of time signals and offers protection against spoofing attacks. This project aims to create a portable QSTT system to establish a two-way free-space quantum connection between two mobile transceivers spanning 10 km. The system consists of multiple beacon lasers, a single-photon source, and adaptive fast-steering optical mirrors, all working together seamlessly to achieve quantum-secured timing accuracy at a level of a few hundred picoseconds. Pathfinder QSTT missions will involve deploying quantum light sources, initially utilizing compact BB84-type single photon sources and later transitioning to entangled photon pair sources based on bulk crystals.

Authors: Prof. PERUZZO, Alberto (RMIT); VILLASENOR, Eduardo (CSIRO); Dr QUACH, James (CSIRO); Dr SHIMIZU, Kenji (CSIRO); Dr CHANDRASEKARA, Rakhitha (CSIRO); Dr GENSEMER, Stephen (CSIRO)

Presenter: VILLASENOR, Eduardo (CSIRO)

Track Classification: Time and Frequency Transfer

Contribution ID: **63** Type: **Invited Poster**

A compact cold atom cavity clock

A sample of laser cooled atoms are created inside an additively manufactured loop-gap microwave cavity using a grating magneto-optic trap. Using a Ramsey excitation scheme with free evolution times of up to 10 ms and based on the 87Rb ground-state clock transition we demonstrate this setup as a viable route forward for a miniaturised atomic clock.

Authors: Mr BREGAZZI, Alan (University of Strathclyde); AFFOLDERBACH, Christoph; RIIS, Erling (University of Strathclyde); Mr BATORI, Etienne (University of Neuchâtel); MILETI, Gaetano (University of Neuchâtel); Dr GRIFFIN, Paul (University of Strathclyde)

Presenter: RIIS, Erling (University of Strathclyde)

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **64** Type: **Invited Poster**

Optical rotation of CPT dark states

Optical Raman excitation is used to investigate the ground-state clock transition in laser cooled Rb atoms. The initial state preparation in a Ramsey-type scheme is achieved by coherent population trapping whereas the second pulse is a Raman π/2 pulse allowing the evolution of the coherence to be mapped back onto the bare atomic states. This allows for a significant increase in detected signal compared with a conventional CPT detection scheme.

Authors: Dr LEWIS, Ben (University of Strathclyde); RIIS, Erling (University of Strathclyde); Dr GRIFFIN, Paul (University of Strathclyde); Dr ELVIN, Rachel (University of Strathclyde)

Presenter: RIIS, Erling (University of Strathclyde)

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **65** Type: **Invited Poster**

Towards an atomic gravimeter with the accuracy of below 10 nm/s2; overcoming the current uncertainty of KRISS-AGRb-1

We report the uncertainty evaluation of the atomic gravimeter KRISS-AGRb-1 developed at KRISS with the total uncertainty of below 30 nm/sˆ2 which is mainly limited by a wavefront distortion, and we present the way to overcome the uncertainty limited by the wavefront distortion and reach the accuracy of below 10 nm/sˆ2, by combining adjusting beam size of a detection laser and compensating the bias by the direct measurement of the wavefront distortions induced by all optical elements

Author: LEE, Sang-Bum (Korea Research Institute of Standard and Science)

Co-authors: Dr LEE, Hyun Gyung (Korea Research Institute of Standard and Science); Dr HONG, Hyun-Gue (Korea Research Institute of Standard and Science); Dr LEE, Jae Hoon (Korea Research Institute of Standard and Science); Dr SEO, Meung Ho (Korea Research Institute of Standard and Science); Dr PARK, Sang Eon (Korea Research Institute of Standard and Science); Mr LEE, Sang Lok (Korea Research Institute of Standard and Science); Dr SEO, Sangwon (Korea Research Institute of Standard and Science); Dr KANG, Seji (Korea Research Institute of Standard and Science); Dr KWON, Taeg Yong (Korea Research Institute of Standard and Science); Dr PARK, Young-Ho (Korea Research Institute of Standard and Science)

Presenter: LEE, Sang-Bum (Korea Research Institute of Standard and Science)

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **66** Type: **Invited Poster**

Study on Stabilizing the Laser Frequency in 10^-14 Level by Optimizing Modulation Transfer Spectroscopy on the 87Rb D2 Line

In this study, we present a high-performance laser frequency stabilization method that utilizes modulation transfer spectroscopy (MTS) on the rubidium 87 D_2 transition line. The frequency instability is evaluated with beating signal of two frequency-locked external cavity diode lasers (ECDL), and reached a short-term stability of $4.5\times10^{-14}/\sqrt{\tau}$ and did not exceed 2×10^{-12} until 10^5 s. To the best of our knowledge, this is the best performance reported with the rubidium 87 D_2 transition.

Author: LEE, SangLok (Korea Research Institute of Standards and Science)

Co-authors: Prof. MOON, Geol (Chonnam National University); Dr PARK, Sang Eon (Korea Research Institute of Standards and Science); HONG, Hyun-Gue (Korea Research Institute of Standards and Science); LEE, Jae Hoon (Korea Research Institute of Standards and Science); Dr SEO, Sangwon (Korea Research Institute of Standards and Science); Dr KWON, Taeg Young (Korea Research Institute of Standards and Science); Dr LEE, Sang-Bum (Korea Research Institute of Standards and Science)

Presenter: LEE, SangLok (Korea Research Institute of Standards and Science)

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **67** Type: **Invited Poster**

A compact laser-cooled atomic clock with a loop-gap cavity

We introduce a compact atomic clock based on laser-cooled atoms trapped inside a loop-gap microwave cavity. The cavity occupies a volume eight times smaller than conventional cylindrical cavities with ten apertures required for optical manipulation of cold atoms. The measured linewidth of the central Ramsey spectrum was 19.6 Hz. The corresponding frequency instability was $4.5{\times}10^{-13-1/2}$, which could be further improved by optimizing experimental parameters. We expect this type of physics package to be utilized for various portable applications of atomic clocks including onboard atomic clocks for navigation satellite.

Author: PARK, Sang Eon (Korea Research Institute of Standards and Science)

Co-authors: Dr CHOI, Gyeong Won (Korea Research Institute of Standards and Science); Dr HONG, Hyun-Gue (Korea Research Institute of Standards and Science); LEE, Jae Hoon (Korea Research Institute of Standards and Science); Dr HEO, Myoung-Sun (Korea Research Institute of Standards and Science); Dr LEE, Sang-Bum (Korea Research Institute of Standards and Science); Dr LEE, Sangmin (Korea Research Institute of Standards and Science); SEO, Sangwon (Korea Research Institute of Standard and Science); KANG, Seji (Korea Research Institute of Standard and Science); Dr KWON, Taeg Yong (Korea Research Institute of Standards and Science); Dr PARK, Young-Ho (Korea Research Institute of Standards and Science)

Presenter: PARK, Sang Eon (Korea Research Institute of Standards and Science)

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **68** Type: **Invited Poster**

A chip-scale atomic beam clock

We have demonstrated a chip-scale atomic beam clock based on a new chip-scale atomic beam platform. The chip-scale beam clock presents a pathway for exceeding the long-term stability of existing chip-scale atomic clocks while maintaining compact and low-power operation.

Author: MCGEHEE, William (National Institute of Standards and Technology)

Co-authors: Ms MARTINEZ, Gabriela (NIST, CU); Dr LI, Chao (Georgia Tech); Mr STARON, Alexander (NIST, CU); Dr RAMAN, Chandra (Georgia Tech); Dr KITCHING, John (NIST)

Presenter: MCGEHEE, William (National Institute of Standards and Technology)

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **69** Type: **Invited Poster**

Light shift suppression in rubidium two-photon optical references

We demonstrate a method for suppression of the light shift in rubidium two-photon spectroscopy based on digital signal processing of the fluorescence signal to generate an error signal with lock point independent of probe power.

Authors: KITCHING, John ((National Institute of Standards and Technology); HUMMON, Matthew (National Institute of Standards and Technology); ANDEWEG, Yorick (NIST and University of Colorado, Boulder)

Presenter: HUMMON, Matthew (National Institute of Standards and Technology)

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **70** Type: **Invited Poster**

A Laser-Cooled Optical Beam Clock

We have recently demonstrated a laser-cooled optical beam clock based on the 10mHz-wide 1S0-3P0 transition in neutral ytterbium. Our goal is to combine the robust architecture of a beam clock with the improved performance offered by optical transitions to produce a device that can provide high-performance timing capabilities outside of the lab.

Author: OFFER, Rachel (Institute for Photonics and Advanced Sensing, University of Adelaide)

Co-authors: STRATHEARN, Aidan (Institute for Photonics and Advanced Sensing, University of Adelaide); LUITEN, Andre (Institute for Photonics and Advanced Sensing, University of Adelaide); HILTON, Ashby (Institute for Photonics and Advanced Sensing, University of Adelaide); WHITE, Benjamin (Institute for Photonics and Advanced Sensing, University of Adelaide); KLANTSATAYA, Elizaveta (Institute for Photonics and Advanced Sensing, University of Adelaide); BOURBEAU HÉBERT, Nicolas (Institute for Photonics and Advanced Sensing, University of Adelaide)

Presenter: OFFER, Rachel (Institute for Photonics and Advanced Sensing, University of Adelaide)

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **71** Type: **Invited Poster**

Precise Atomic Calculations for Low-Energy Searches for Physics Beyond the Standard Model

Precision atomic metrology gives us an extraordinary probe of physics beyond the Standard Model, but also necessitates accurate calculations of these systems for planning and supporting experiments, as well as to interpret the results as limits on new physics. Calculations in open-shell systems currently used or proposed for these experiments pose a challenge for atomic structure theory. I will present some motivations, methods, and results of calculations using the particle-hole CI+MBPT method implemented in the AMBiT code. All-order coupling of selected core shells allows the method to have accuracy comparable to coupled-cluster methods while being applicable across the entire periodic table.

Author: BERENGUT, Julian (University of New South Wales)

Presenter: BERENGUT, Julian (University of New South Wales)

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **72** Type: **Invited Poster**

Synergetic Repetition Frequency Locking of an Optical Frequency Comb

In order to make optical comb work for long time under severe temperature changes environment, meeting some needs that require using optical comb under harsh environment, this paper proposes a scheme for repetition-rate locking of optical frequency combs based on delay line, temperature control and PZT.

Authors: Mr JIN, Ziyi (State Key Laboratory of Information Photonics and Optical Communications); Mr YU, Dongrui (State Key Laboratory of Information Photonics and Optical Communications); Mr CHEN, Ziyang (State Key Laboratory of Advanced Optical Communication Systems and Networks, School of Electronics, and Center for Quantum Information Technology); Mr GUO, Hong (State Key Laboratory of Advanced Optical Communication Systems and Networks, School of Electronics, and Center for Quantum Information Technology)

Presenter: Mr JIN, Ziyi (State Key Laboratory of Information Photonics and Optical Communications)

Track Classification: Time and Frequency Transfer

Contribution ID: **73** Type: **Invited Poster**

Three-Corner Hat Comparison Between Dissimilar Optical Atomic Clocks at an International Naval Exercise

We report on a recent international collaboration in which three emerging optical clock technologies were trialed at sea as part of an international naval exercise.
Each system included an integrated optical frequency comb for synthesis of microwave clock signals, and three-cornered hat measurements were made of both optical and microwave outputs over more than six weeks of operation.
This is a powerful demonstration that optical clocks with integrated optical frequency combs are ready for use outside of the lab.

Author: Dr HILTON, Ashby (Institute for Photonics and Advanced Sensing, University of Adelaide)

Co-authors: LUITEN, Andre (Institute for Photonics and Advanced Sensing, University of Adelaide); WHITE, Benjamin (Institute for Photonics and Advanced Sensing, University of Adelaide); PERRELLA, Chris (University of Adelaide); BILLINGTON, Christopher (Institute for Photonics and Advanced Sensing, University of Adelaide); LOCKE, Clayton (QuantX Labs); KLANTSATAYA, Elizaveta (Institute for Photonics and Advanced Sensing, University of Adelaide); AHERN, Emily; ALLISON, Jack (Institute for Photonics and Advanced Sensing, University of Adelaide); Dr ELGIN, John (United States Space Force, Quantum Sensing and Timing); MARTIN, Kyle (Blue Halo); NELLIGAN, Montana (Institute for Photonics and Advanced Sensing, University of Adelaide); BOURBEAU HÉBERT, Nicolas (Institute for Photonics and Advanced Sensing, University of Adelaide); OFFER, Rachel (Institute for Photonics and Advanced Sensing, University of Adelaide); Mr BEARD, River (Blue Halo); SCHOLTEN, Sarah (Institute for Photonics and Advanced Sensing, University of Adelaide)

Presenter: Dr HILTON, Ashby (Institute for Photonics and Advanced Sensing, University of Adelaide)

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **74** Type: **Invited Poster**

Demonstration of a Field-Deployable Ytterbium Cell Clock - a Robust Optical Atomic Clock for Real World Applications

We present an optical atomic clock based on spectroscopy of the relatively narrow $^1S_0$ $^3P_1$ intercombination line in neutral ytterbium. We show that this system is not only able to achieve short- and medium-term frequency instability better than 10-14 but is also compact and robust. We demonstrate the potential of this system by performing extensive field testing of the clock with an integrated optical frequency comb in a harsh maritime environment.

Author: Dr HILTON, Ashby (University of Adelaide)

Co-authors: LUITEN, Andre (Institute for Photonics and Advanced Sensing, University of Adelaide); WHITE, Benjamin (Institute for Photonics and Advanced Sensing, University of Adelaide); BILLINGTON, Christopher (Institute for Photonics and Advanced Sensing, University of Adelaide); KLANTSATAYA, Elizaveta (Institute for Photonics and Advanced Sensing, University of Adelaide); ALLISON, Jack (Institute for Photonics and Advanced Sensing, University of Adelaide); NELLIGAN, Montana (Institute for Photonics and Advanced Sensing, University of Adelaide); BOURBEAU HÉBERT, Nicolas (Institute for Photonics and Advanced Sensing, University of Adelaide); OFFER, Rachel (Institute for Photonics and Advanced Sensing, University of Adelaide); SCHOLTEN, Sarah (Institute for Photonics and Advanced Sensing, University of Adelaide)

Presenter: Dr HILTON, Ashby (University of Adelaide)

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **75** Type: **Invited Poster**

A new resilient time and frequency infrastructure for UTC(NPL)

A Resilient Enhanced Time Scale Infrastructure (RETSI) is being built by the National Physical Laboratory (NPL) as part of the UK National Timing Centre programme. RETSI will comprise four geographically distributed time scale laboratories at sites located across the UK, which will support the generation of the national time scale, UTC(NPL). The purpose of RETSI is to improve the resilience of UTC(NPL) and to reduce the UK's reliance on timing signals from GNSS.

The attached abstract briefly outlines the design concept of RETSI, the distribution of time and frequency signals from its laboratories, its incorporation of primary frequency standards, progress on RETSI's hardware and software infrastructure and RETSI as a platform to help facilitate the future inclusion of optical clocks in the UK's national time scale.

Author: Mr JONES, Douglas

Co-authors: SHEPPARD, Adam; ASHKHASI, Ali; WILSON, Andrew; EGLIN, Belinda; EVERETT, Ben; DEVINE, Bob; WILSON, Charles; SMYTH, Chris; LANGHAM, Conway; GALBRAITH, Daniel; WESTON, Daniela; MARGOLIS, Helen; OWEN, Huw; DAVIS, John; NEWTON-GRIFFITHS, Jonathan; WHALE, Josh; KHATRY, Kathryn; SZYMANIEC, Krzysztof; AIKOMO, Mayokun; WHIBBERLEY, Peter; LEWIS, Rebecca; HENDRICKS, Rich; FOOT, Rob; WALBY, Sam; SHEMAR, Setnam; ASHFORD, Simon

Presenter: Mr JONES, Douglas

Track Classification: SI definition, Clocks and Time Scales

Contribution ID: **76** Type: **Invited Oral**

Compact clocks & cavities for space and ground applications

Compact robust atomic clocks are being developed as remote timing references with extended holdover to mitigate difficulties arising from loss of disciplining during periods when GNSS satellite constellations are unavailable. This paper describes progress on two NPL low SWaP trapped ion atomic clock systems, namely the ytterbium multi-ion 12.6 GHz microwave clock and the strontium single ion 445 THz optical clock, together with potential applications.

Author: GILL, Patrick (National Physical Laboratory)

Co-authors: SPAMPINATO, Alessio (National Physical Laboratory); ALLEN, Ben (National Physical Laboratory); HOCKLEY, Gary (National Physical Laboratory); BARWOOD, Geoffrey (National Physical Laboratory); HUANG, Guilong (National Physical Laboratory); KLEIN, Hugh (National Physical Laboratory); HILL, Ian (National Physical Laboratory); SILVER, Jonathan (National Physical Laboratory); STACEY, Jonathan (National Physical Laboratory); HAJI, Mohsin (National Physical Laboratory); TSOULOS, Peter (National Physical Laboratory); MULHOLLAND, Sean (National Physical Laboratory)

Presenter: GILL, Patrick (National Physical Laboratory)

Session Classification: Null

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **77** Type: **Invited Poster**

Towards Compact, Robust and Highly Stable Optical Frequency References for Space Applications

While in terrestrial applications optical frequency references are already being established in many fields, the situation is different for space applications. Here, reliability, size, weight, and power budgets are key considerations in addition to the performance. We will present the ongoing development of two different types of optical frequency references towards space compatibility. This includes on the one hand an optical cavity setup, and on the other a broad outline of the evolution of the iodine technology towards the COMPASSO project. Finally, a brief overview of a hybrid lock will complete this presentation.

Author: WEGEHAUPT, Timm (German Aerospace Center (DLR))

Co-authors: GOHLKE, Martin (German Aerospace Center (DLR)); Dr KUSCHWESKI, Frederik (German Aerospace Center (DLR)); OSWALD, Markus (German Aerospace Center (DLR)); ABICH, Klaus (German Aerospace Center (DLR)); Dr ALAM, Tasmim (German Aerospace Center (DLR)); BLOMBERG, Tim (German Aerospace Center (DLR)); BISCHOF, Jonas (German Aerospace Center (DLR)); BOAC, Alex (German Aerospace Center (DLR)); BUSSMEIER, Andre (German Aerospace Center (DLR)); RÖDER, Niklas (German Aerospace Center (DLR)); WÜST, Jan Martin; Dr SANJUAN, Jose (German Aerospace Center (DLR)); Dr SCHULDT, Thilo (German Aerospace Center (DLR)); Prof. BRAXMAIER, Claus (German Aerospace Center (DLR))

Presenter: WEGEHAUPT, Timm (German Aerospace Center (DLR))

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **78** Type: **Invited Poster**

Toward a sub-kelvin cryogenic Fabry-Perot silicon cavity

We report the current development of a sub-kelvin Fabry-Perot silicon cavity. This devel-opment aims to reduce thermal noise-limited frequency instability and by this way address the cur-rent limitations of ultrastable lasers, aiming to set the ground for the next generation of these devic-es with frequency instabilities below 1×10-17 [1]. However, silicon cavities with crystalline mirror coatings at cryogenic temperatures have shown birefringence correlated frequency fluctuations [2], [3].

Our cavity (Fig. 1) is based on a spacer made from a monocrystalline silicon with optical axis aligned to the [111] axis. The size of the cylindrical spacer is about 18 cm in length and 20 cm in diameter. Mirrors with silicon substrates and Al0.92Ga0.08As/GaAs crystalline coatings are optically contacted [4]. We measured a room-temperature finesse of 220 000 and a TEM00 mode splitting due to the birefringence of the coatings of about 250 kHz. (Fig. 2)
To operate our cavity at sub-kelvin temperatures, we use a dilution cryostat able to reach 12 mK in unloaded operation with optical windows. Calculations based on the Stefan-Boltzmann law indicate that cooling by radiation alone would take excessive times with our spacer design, of order a year. To circumvent that, we propose to decouple the mechanical support and thermal management.
We propose to measure optical characteristics of our silicon cavity with crystalline AlGaAs coatings at sub-kelvin temperatures, as well as the sensitivity of our cavity to residual temperature fluctuations in the cryostat. We will also investigate the efficiency of our cavity cooling at sub-kelvin.

Authors: Dr BARBARAT, Joannes (FEMTO-ST, CNRS, Université Bourgogne-Franche-Comté, ENSMM); GILLOT, Jonathan (FEMTO-ST / ENSMM); MILLO, Jacques (FEMTO-ST); LACROUTE, Clément; GIORDANO, Vincent (FEMTO-ST, CNRS, Université Bourgogne-Franche-Comté, ENSMM); KERSALÉ, Yann (FEMTO-ST)

Presenters: Dr BARBARAT, Joannes (FEMTO-ST, CNRS, Université Bourgogne-Franche-Comté, ENSMM); GILLOT, Jonathan (FEMTO-ST / ENSMM)

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **79** Type: **Invited Poster**

Pure frequency-based dispersive spectroscopy

We explore applicability of several variations of pure frequency-based spectroscopic techniques to molecular systems and their metrology. In these techniques we take advantage from linear phenom-enon well-known as mode pushing in an optical cavity with an absorbing medium and intrinsic physical connection between absorption and dispersion. It was demonstrated that mode frequency shifts measurements allow to obtain molecular spectra with exceptional accuracy and precision.

Author: CIURYŁO, Roman (Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Toruń)

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Presenter: CIURYŁO, Roman (Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Toruń)

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **80** Type: **Invited Poster**

Development of a molecular Hg_2 clock to investigate fundamental physics

We introduce a novel molecular sensor designed for the study of fundamental interactions, focusing on clock transitions within a Hg-Hg system. Our project implements optical Feshbach resonances in systems involving Hg_2 or Hg-alkali systems, with the ultimate goal of constructing a Hg_2 optical molecular clock. This tool has the potential to push limits for fundamental research by achieving unprecedented advancements in terms of precision and accuracy.

Author: CIURYŁO, Roman (Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Toruń)

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Presenter: CIURYŁO, Roman (Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Toruń)

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **81** Type: **Invited Oral**

The Deep Space Atomic Clock: Demonstration of a Trapped Ion Atomic Clock in Space

Friday 20 October 2023 08:30 (30 minutes)

Research on room-temperature trapped ion atomic clocks at the Jet Propulsion Laboratory recently culminated in the launch of NASA's Deep Space Atomic Clock (DSAC) mission in 2019. Operating in space for 2 years, DSAC achieved a new level of performance among the most stable space clocks now in use and is expected to enable new space clock applications that require both high stability and autonomy. In this paper we will describe the DSAC mission and results, applications, and future directions.

Authors: BURT, Eric (Jet Propulsion Laboratory); PRESTAGE, John (Jet Propulsion Laboratyr); TJOELKER, Robert (Jet Propulsion Laboratory); ENZER, Daphna (Jet Propulsion Laboratory); KUANG, Da (Jet Propulsion Laboratory); MURPHY, Dave (Jet Propulsion Laboratory); ROBISON, David (Jet Propulsion Laboratory); SEUBERT, Jill (Jet Propulsion Laboratory); WANG, Rabi (Jet Propulsion Laboratory); ELY, Todd (Jet Propulsion Laboratory)

Presenter: BURT, Eric (Jet Propulsion Laboratory)

Session Classification: Compact Clocks

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **82** Type: **Invited Poster**

Compact and Robust Laser System for Transportable Strontium Optical Lattice Clock

Downsizing and improving robustness of the laser system was performed to realize an transportable optical lattice clock with a volume of 250 L.

Author: Mr MURAMATSU, Takashi (Shimadzu Corporation)

Co-authors: Prof. KATORI, Hidetoshi (The University of Tokyo); Mr TOJO, Koji (Shimadzu Corporation); Dr TAKAMOTO, Masao (RIKEN); Mr UNO, Shingo (Shimadzu Corporation); Dr FURUMIYA, Tetsuo (Shimadzu Corporation); Mr HIROKI, Tomoyuki (Shimadzu Corporation); Dr HISAI, Yusuke (Shimadzu Corporation); Mr SAKAI, Yuya (Shimadzu Corporation)

Presenter: Mr MURAMATSU, Takashi (Shimadzu Corporation)

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **83** Type: **Invited Poster**

Cavity Design Simulation for an Atomic Fountain Clock KRISS-F2

A cesium atomic fountain clock KRISS-F1 and an optical lattice clock KRISS-Yb1 share their duty of steering a hydrogen maser that generates local time scale in Korea. In order to secure the redundancy of primary frequency standards, we plan to build another fountain clock named KRISS-F2. Since the performance of a fountain clock depends largely on the microwave cavity, we make efforts on the cavity design estimating the distributed cavity phase (DCP) and cavity pulling effects by calculating field distribution using the finite element method (FEM). We have built a Monte-Carlo simulation code using MATLAB that calculates DCP shifts from the field distribution inside the cavity. Another effort we make on the cavity design is to reduce the rate of change of the cavity resonance frequency against temperature variation (df/dT) for the robust operation under loosely temperature-controlled environment. We find that a bimetal cavity with around 10-cm long aluminum caps plus a copper cylinder tube exhibits fairly reduced df/dT value with only a small loss of Q. In this symposium, we present our cavity design and the estimated shifts and uncertainties of cavity-related effects like DCP and cavity pulling under temperature changes.

Author: Dr PARK, Young-Ho (Korea Research Institute of Standards and Science)

Co-authors: PARK, Sang Eon (Korea Research Institute of Standards and Science); HONG, Hyun-Gue (Korea Research Institute of Standards and Science); LEE, Sang-Bum (Korea Research Institute of Standard and Science); LEE, Jae Hoon (Korea Research Institute of Standards and Science); KANG, Seji (Korea Research Institute of Standard and Science); SEO, Sangwon (Korea Research Institute of Standard and Science); KWON, Taeg Yong (Korea Research Institute of Standard and Science)

Presenter: Dr PARK, Young-Ho (Korea Research Institute of Standards and Science)

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **84** Type: **Invited Poster**

A Novel Laser Power Measurement Scheme Using Rubidium Clock

Precise measurements of weak laser power are necessary, while few methods can meet this requirement. To realize the measurement of weak laser power down to microwatt and nanowatt, we adopt an atomic clock to measure the laser power, which is traceable to the output frequency of the atomic clock. A 795 nm semiconductor laser and a Rb atomic clock are utilized. The laser is incident into the cell of the rubidium clock and the frequency of atomic clock varies with the laser power. The affect of 795 nm laser power, wavelength on frequency of Rb atomic clock is analyzed. The experimental results show that the output frequency of Rb clock changes with the laser wavelength and power. At a wavelength of 794.99 nm, 2 μW laser power leads to a frequency shift of 0.13 mHz@10MHz, and the frequency shift of the atomic clock increases with the laser power increasing.
In summary, a novel method to measure the weak laser power is proposed. The experiment is carried out to realize the quantum measurement of weak laser power. It provides a new way to trace laser power to atomic frequency. Moreover, the experimental setup can be further improved to stabilize laser power.

Author: JI, Qianqian

Co-authors: Ms HAN, Lei; Mr SU, Yabei; Mr XUE, Xiaobo; Mr ZHANG, Shengkang; Ms GE, Jun

Presenter: JI, Qianqian

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **85** Type: **Invited Poster**

Advancing electric-field sensing through near-ground state cooling and beam position optimization in a Penning trap

We describe a novel method to search for ultra-light, wave-like dark matter by sensing ultra-weak electric fields using trapped ions. We present technical advancement in our system for near-ground state laser cooling and laser beam delievery to increase our spin-motion and spin-spin entanglement.

Author: PHAM, Joseph (Quantum Control Laboratory)

Co-authors: JEE, Julian; Prof. BIERCUK, Michael; WOLF, Robert (The University of Sydney)

Presenter: PHAM, Joseph (Quantum Control Laboratory)

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **86** Type: **Invited Poster**

Single ion addressing and read out of dynamic 2D ion crystals for quantum simulations in a Penning trap

We propose a method for performing complex quantum simulations utilising 2D ion crystals in a Penning trap through engineered spin-spin interactions. This has potential applications in the study of computationally intractable condensed-matter phenomena such as two-dimensional superconductivity.

Author: JEE, Julian (Quantum Control Lab)

Co-authors: PHAM, Joseph (Quantum Control Laboratory); WOLF, Robert (The University of Sydney); Prof. BIERCUK, Michael (Quantum Control Laboratory)

Presenter: JEE, Julian (Quantum Control Lab)

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **87** Type: **Invited Oral**

Low-noise optical frequency divider for precision measurement

Friday 20 October 2023 11:00 (30 minutes)

Here we report an optical frequency divider (OFD), which can realize optical frequency ratio measurement as well as optical frequency division to other desired frequencies. Using the OFD, we measure the frequency ratio between the fundamental and its second harmonic with an uncertainty of 3E-22. Meanwhile, we also demonstrate an optical frequency synthesizer referenced to a Yb optical clock. Moreover, we demonstrate the transportability, long-term operation and multi-channel division of the OFD.

Author: JIANG, Yanyi

Co-authors: Dr SHI, Haosen (East China Normal University); Dr YAO, Yuan (East China Normal University); Mrs YU, Hongfu (East China Normal University); Prof. MA, Longsheng (East China Normal University)

Presenter: JIANG, Yanyi

Session Classification: Low Noise Optical Systems

Track Classification: Precision and Low Noise Signal Generation and Techniques

Contribution ID: **88** Type: **Invited Poster**

Improving a trapped-ion quantum computer with a cryogenic sapphire oscillator

We describe an agile microwave synthesis system devised of an ultra-low phase-noise cryogenic sapphire oscillator (CSO) that serves as a master clock for a ytterbium ion (Yb+) qubit. We report a 10X improvement of qubit coherence time from 0.9 to 8.7 seconds and single-qubit quantum gates with errors of 1.6e-6 achieved with the synthesis system. Using a filter function approach [1], we find evidence that the precious coherence of 0.9 seconds was limited by the phase noise of a precision-grade commercially off-the-shelve microwave synthesizer [1]. Furthermore, we also leverage the agility of the microwave synthesis system to demonstrate a Bayesian learning algorithm that can autonomously design informationally-optimised control pulses to identify and calibrate quantitative dynamical models to characterize a trapped-ion system. We experimentally demonstrate that the new algorithm exceeds the precision of conventional calibration methods with few samples [2].

References:
[1] H. Ball, W. Oliver, M. Biercuk. (2016). The role of master clock stability in quantum information processing npj Quantum Information 2(1), 16033. https://dx.doi.org/10.1038/npjqi.2016.33
[2] T. M. Stace, J. Chen, L. Li, V. S. Perunicic, A. R. R. Carvalho, M. R. Hush, C. H. Valahu, T. R. Tan, M. J. Biercuk. (2022). Optimised Bayesian system identification in quantum devices. arXiv:2211.09090. https://arxiv.org/abs/2211.09090

Author: TAN, Tingrei

Presenter: TAN, Tingrei

Track Classification: Precision and Low Noise Signal Generation and Techniques

Contribution ID: **89** Type: **Invited Poster**

Reconfigurable Brillouin laser for line width narrowing and microwave-spaced frequency combs

Reconfigurable Brillouin laser for line width narrowing and microwave-spaced frequency combs

Author: SHARP, Adam

Presenter: SHARP, Adam

Track Classification: Precision and Low Noise Signal Generation and Techniques

Contribution ID: **90** Type: **Invited Oral**

Laser Spectroscopy of Triply Charged Thorium-229 Isomer Toward a Nuclear Clock

Wednesday 18 October 2023 11:00 (30 minutes)

Toward a ^{229}Th nuclear clock, we performed laser spectroscopy of the triply charged ^{229}Th isomer ($^{229m}Th^{3+}$) in an ion trap. The $^{229m}Th^{3+}$ ions were obtained as a decay product of ^{233}U. We determined the hyperfine constants of the electronic state of $^{229m}Th^{3+}$ and derived the magnetic dipole and electric quadrupole moments of ^{229m}Th. We also investigated the nuclear decay lifetime of $^{229m}Th^{3+}$ which was a key parameter to estimate the performance of a $^{229}Th^{3+}$ nuclear clock.

Author: YAMAGUCHI, Atsushi

Co-authors: SHIGEKAWA, Yudai (RIKEN); HABA, Hiromitsu (RIKEN); Prof. WADA, Michiharu; KATORI, Hidetoshi (The University of Tokyo)

Presenter: YAMAGUCHI, Atsushi

Session Classification: Nuclear Clocks

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **91** Type: **Invited Poster**

Dynamic cryogenic radiation shield for controlling blackbody radiation shift in optical lattice clocks

Design and construction of an in-vacuum cryogenic radiation shield that enables controlling the BBR shift uncertainty *below* the 10^{-19} level
Novel scheme that enables loading arbitrary atomic sample distributions over more than 5 mm in 1D optical lattices

Author: HASSAN, Youssef S. (National Institute of Standards and Technology; University of Colorado, Boulder)

Co-authors: BELOY, Kyle (National Institute of Standards and Technology); CHEN, Chun-Chia (National Institute of Standards and Technology; University of Colorado, Boulder); GIBBLE, Kurt (Department of Physics, The Pennsylvania State University); SIEGEL, Jacob L. (National Institute of Standards and Technology; University of Colorado, Boulder); GROGAN, Tanner (National Institute of Standards and Technology; University of Colorado, Boulder); HUNT, Benjamin D. (National Institute of Standards and Technology; University of Colorado, Boulder); LUDLOW, Andrew D. (National Institute of Standards and Technology; University of Colorado, Boulder)

Presenter: HASSAN, Youssef S. (National Institute of Standards and Technology; University of Colorado, Boulder)

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **92** Type: **Invited Poster**

Absolute laser frequency reference for next generation inter-satellite laser interferometry

We demonstrate the absolute frequency calibration of a laser against a GPS disciplined OCXO using a free spectral range cavity readout designed for next generation geodesy missions.

Author: REES, Emily Rose

Co-authors: WADE, Andrew (The Australian National University); SUTTON, Andrew (Australian National University); MCKENZIE, Kirk (Australian National University)

Presenter: REES, Emily Rose

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **93** Type: **Invited Poster**

A Thermal-noise-limited Fibre Frequency Reference with 0.1 Hz/√Hz Stability

We describe a passive, fibre-optic frequency reference with a state-of-the-art short-timescale stability of 0.1 Hz/$\sqrt{\text{Hz}}$. We model and compute limiting noise sources, including Double Rayleigh scattering and intrinsic fibre thermal noise.

Author: ZHANG, Ya (Australian National University)

Co-authors: BANDUTUNGA, Chathura; Prof. CHOW, Jong (Australian National University); Dr GRAY, Malcolm (Australian National University); Dr MCRAE, Terry (Australian National University)

Presenter: ZHANG, Ya (Australian National University)

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **94** Type: **Invited Poster**

The Optical Clock with 176Lu+

Singly ionized lutetium (176Lu+) is a unique clock candidate with several attractive features for clock applications [1-6]. It provides three independent clock transitions allowing consistency checks of error budgets through frequency comparisons within the one system [6]. Recently, the systematic uncertainties of two lutetium frequency references have been calibrated to the mid 10-19 fractionally on the 848-nm transition. Subsequent comparison via correlation spectroscopy, demon-strated inaccuracy to low 10-18 level limited by statistical uncertainty [1]. The absolute frequency measurement of 848-nm clock transition has been measured with a fractional uncertainty of 1.8×10−15 limited by our available realization of the second.

To realize the full potential lutetium has to offer requires an assessment of the 804-nm clock transition to a comparable level as the 848-nm transition. The two most challenging aspects of this are the blackbody radiation (BBR) shift and the residual quadrupole moment. The larger BBR shift of the 804-nm transition requires inaccuracy of the scalar differential polarizability at the 1% level. We plan to achieve this through comparison measurement with Ba+ as proposed in [7], for which the required measurements have been made [8]. The residual quadrupole moment arises from coupling between fine-structure levels resulting in imperfect cancellation via hyperfine averaging [9]. The effect is expected to give a shift at the low 10-19 as for the 848-nm transition and we plan to in-vestigate this through high accuracy measurements of differential quadrupole moments and g-fac-tors [9,10].

Absolute frequency accuracy requires an assessment of the system temperature, and this requires temperature calibration at the level of a few degrees for the 804-nm transition. However, for applications requiring only a comparison, such as height referencing, it is only a temperature difference that matters. For lutetium this can be assessed through measurement of the frequency ratio between the 804-nm and 848-nm transitions within each apparatus.

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Authors: ARNOLD, Kyle (National University of Singapore); BARRETT, Murray (Center for Quantum Technology); ZHAO, Qi; QIN, Qichen (National University of Singapore); ZHANG, Zhao (Centre for Quantum Technologies, National University of Singapore); Dr ZHANG, Zhiqiang (National University of Singapore)

Presenter: ZHAO, Qi

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **95** Type: **Invited Poster**

Engineering a 2-Colour Compact Rubidium Optical Clock for Space

The physics and parts of the design of a 2-colour rubidium optical clock for application in space is presented. The design targets a size weight and power of 20 L, 20 kg and 100 W. The clock aims to meet performance requirements necessary for operation in global navigation satellite systems.

Author: SCARABEL, Jordan (QuantX Labs)

Co-authors: LUITEN, Andre (Institute for Photonics and Advanced Sensing, University of Adelaide); PERRELLA, Chris (University of Adelaide); LOCKE, Clayton (QuantX Labs); AHERN, Emily; Mr HARRIS, Geoff (QuantX Labs); Mr GRAY, James (QuantX Labs); O'CONNOR, Martin (QuantX Labs); Mr BURNS, Matthew (QuantX Labs); BOURBEAU HÉBERT, Nicolas (Institute for Photonics and Advanced Sensing, University of Adelaide); SCHOLTEN, Sarah (Institute for Photonics and Advanced Sensing, University of Adelaide); NG, Sebastian (QuantX Labs); Dr NGUYEN, Thanh-Long (QuantX Labs); Mr OOI, Yong (QuantX Labs)

Presenter: SCARABEL, Jordan (QuantX Labs)

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **96** Type: **Invited Oral**

Low Loss Acoustic Cavities: from Frequency Control to Fundamental Physics

Monday 16 October 2023 11:30 (30 minutes)

Phonons, quanta of Acoustic vibration, have much in common with photons, elementary excitation of Electro-Magnetic fields. Despite the fact that photonic devices have dominated physics and engineering for at least a century, and the acoustical systems have almost been forgotten. One of the main reasons for that is much lower energy losses exhibited by well designed photonic systems, e.g. optical cavities. The situation started to change over the last decade when practical implementation of extremely low loss resonant acoustical systems at low temperatures was demonstrated. This was achieved due to exceptional engineering of phonon trapping Quartz Bulk Acoustic Wave (BAW) devices that have much in common with optical Fabry-Perot cavities. Initially used in frequency control devices, BAW resonators demonstrated that at low temperatures their performance is only limited by fundamental phonon-phonon interaction as well as two level systems. With Quality factors well exceeding 10^9 in many modes, BAW cavities often outperform many photonic counterparts and open new possibilities in physics and engineering. Started from a systematic measurements of losses in a solid state, this research lead to a discovery of a physical platform that can answer some fundamental questions about our Universe such as validity of fundamental symmetries postulated in all current theories, existence of Dark Matter, Quantum Gravity, variation of fundamental constants and primordial gravitational waves. More over, many research groups started to use such acoustic systems as a building block of Quantum Hybrid systems, a future base for quantum computing, measurement and control.

Authors: Dr GORYACHEV, Maxim (UWA); Prof. TOBAR, Michael (UWA); Mr CAMPBELL, William (UWA)

Presenter: Dr GORYACHEV, Maxim (UWA)

Session Classification: Precision Measurements and Fundamental Physics I

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **97** Type: **Invited Poster**

Extension of REFIMEVE with a White Rabbit network

T-REFIMEVE is a new project funding the infrastructure REFIMEVE, in which one of the objectives is the deployment of a White Rabbit network at the French national scale. Here we report on our current status of the deployment of a White Rabbit network disseminating UTC(OP) to five academic users over a maximum distance of 40 km. We report loop-back measurements and compare results obtained with time transfer and frequency transfer, and discuss the results.

Authors: POTTIE, Paul-Éric (Observatoire de Paris-PSL, CNRS, SU, LNE); Dr LIM, Caroline B. (Observatoire de Paris-PSL, CNRS, SU, LNE); Dr FRANK, Florian (Observatoire de Paris-PSL, CNRS, SU, LNE); Mr CHUPIN, Baptiste (Observatoire de Paris-PSL, CNRS, SU, LNE); Mr CHIU, Olivier (Observatoire de Paris-PSL, CNRS, SU, LNE); Dr ABGRALL, Michel (Observatoire de Paris-PSL, CNRS, SU, LNE); Dr TUCKEY, Philip (Observatoire de Paris-PSL, CNRS, SU, LNE); Dr CANTIN, Etienne (USPN, CNRS); Dr CHARDONNET, Christian (USPN, CNRS); AMY-KLEIN, Anne (USPN, CNRS)

Presenter: POTTIE, Paul-Éric (Observatoire de Paris-PSL, CNRS, SU, LNE)

Track Classification: Time and Frequency Transfer

Contribution ID: **98** Type: **Invited Poster**

Development of commercial fountain clocks in NIM

While Cs fountain clocks have achieved a typical Type B uncertainties of a few parts in E16, and are employed as the primary frequency standards to realize the definition of the second, Rb fountain clock has also been studied. Due to its low collisional shift and more robust cooling lasers, a Rb fountain clock is easier to operate and more suitable be to a commercial clock. A new Rb fountain clock has been built in NIM aiming to operate semi-continuously and achieve an excellent long-term instability for time keeping. While the basic design is adopted from our Cs fountain clocks, some new features are included for a better performance. A double metal interrogation microwave cavity with a thermal expansion self-compensating mechanism is used to reduce the clock sensitivity to ambient temperature fluctuations. The cylindrical tube of the cavity is made from titanium (Ti), and two end caps are made from oxygen-free copper (OFC). A Thin layer of copper is coated inside the Ti- tube to ensure reaching a high Q-factor of about 10000. With an optimized design, the thermal-coefficient of the resonance frequency is reduced to less than 10 kHz/℃, more than an order improvement compared with a copper cavity. The optical system with two independent frequency stabilized laser sources with automatic re-locking system is located on a 400×600 mm optical breadboard with special designed optical mounts to ensure stable output light powers. All light powers are varied less than 10% with a environment temperature increasing 7℃. A similar design Cs fountain clock resume operating without any realignment of optical path after being transported to another lab 40 km away.
A short term instability of was obtained for this Rb fountain clock. After optimization, the clock has been operated for more a year without any failure. A long term instability of 3.5E-16 was obtained compared with NIM5 Cs fountain clock as shown in figure 1. The instability after 4 days didn't drop as τ-1/2 is under study.

Author: FANG, Fang (National institute of metrology)

Co-author: Mr CHEN, Weiliang (National institute of metrology)

Presenter: FANG, Fang (National institute of metrology)

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **99** Type: **Invited Oral**

A definition of the SI second based on several optical transitions

Wednesday 18 October 2023 09:00 (30 minutes)

In this paper, we discuss the possibility to redefine the SI second using the geometric mean of several optical clock transitions. This definition would allow to take advantage of the many high performance optical frequency standards currently available.
Here, we describe the fundamental properties of this definition and its practical implementation. Finally, we discuss its strengths and weakness, as compared to a definition involving a single transition.

Author: LODEWYCK, Jérôme (LNE-SYRTE Observatoire de Paris)

Presenter: LODEWYCK, Jérôme (LNE-SYRTE Observatoire de Paris)

Session Classification: SI Definition, Clocks and Time Scales II

Track Classification: SI definition, Clocks and Time Scales

Contribution ID: **100** Type: **Invited Poster**

Microfabricated surface-electrode ion trap for frequency metrology

With outstanding systematic uncertainties at the 10^{-18} level or below optical atomic clocks surpass the best cesium clocks that currently define the time unit. With the related impact on various applications, a growing number of laboratories around the world are developing transportable optical clocks. We are developing a single-ion optical clock targeting a total volume well below 500 L. The core of the experiment is a surface-electrode trap that operated with $^{171}Yb^{+}$ ions on the quadrupole transition at 435.5 nm. We have developed a custom micro-fabricated trap and a custom resonant RF circuit with a high quality factor for optimal trapping and electric field noise filtering. We will present our trap design and characterization, our RF circuit design and test results as well as our latest experimental results.

Authors: Mrs MADUNIC, Josipa (FEMTO-ST); Dr ABDEL HAFIZ, Moustafa (FEMTO-ST); KERSALÉ, Yann (FEMTO-ST); LACROUTE, Clément

Presenter: Mrs MADUNIC, Josipa (FEMTO-ST)

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **101** Type: **Invited Poster**

Photonics integrated trap for a 176Lu+ optical clock

Singly ionized lutetium (176Lu+) is both attractive for high accuracy clock applications [3,4] and well suited for integrated photonics. With the exception of one repump laser at 350-nm, all other laser wavelengths are within the transparency window of silicon nitride (SiN). Leveraging commercially available SiN microfabrication processes, we have designed and fabricated an ion trap with integrated light delivery of the 848-nm clock laser and 646-nm cooling laser. Here we present evaluation of the fabricated photonics structures and progress towards establishing an operational clock on a surface trap. This platform will be used to measure the key environmental factors to characterize clock performance in a chip-based system.

Author: Dr ARNOLD, Kyle (National University of Singapore)

Co-authors: Dr WEST, Gavin (Massachusetts Institute of Technology); Prof. RAM, Rajeev (Massachusetts Institute of Technology); Prof. BARRETT, Murray (National University of Singapore)

Presenter: Dr ARNOLD, Kyle (National University of Singapore)

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **102** Type: **Invited Poster**

Precision clockwork for optical clock operation at the 1E-19-level accuracy

Optical frequency standards have achieved fractional stabilities of a few parts in 1E19 [1], with accuracies approaching and soon reaching the same level [2]. Furthermore, extraordinary progresses have been made on rendering these complex apparatuses transportable [3,4], such to enable their use as quantum sensors for testing fundamental physics and General Relativity [5].
In order to construct atomic clocks and generate timescales with optical frequency standards, we have contributed in advancing the spectral purity, stability and relative accuracy of optical frequency combs and the extraction of the lowest phase noise photonic microwave signals demonstrated so far [6]–[8]. These advances aim to support the comparisons via frequency ratio measurements of 18-digit accurate optical frequency standards [9]. Additionally, these achievements allow to construct accurate clockworks capable of porting exquisite optical fidelity down to the microwave domain. The phase-coherent transfer of the optical frequency standard´s precision and accuracy to the electrical signals is necessary to permit access to these fidelities by conventional electronics.
We will cover the path towards the realization of these ultra-low noise clockworks, and illustrate their engineering, now allowing us to demonstrate 1E-19-level stability and relative accuracy also on transportable systems. These achievements are key for constructing practical optical clocks and quantum sensors which are now conceived as deployable measurement tools, and paving the way to an optical SI-second redefinition.

Authors: Dr FISCHER, Marc (Menlo Systems GmbH); GIUNTA, Michele (Menlo Systems GmbH); Dr HOLZWARTH, Ronald (Menlo Systems GmbH); Dr HÄNSEL, Wolfgang (Menlo Systems GmbH)

Presenter: GIUNTA, Michele (Menlo Systems GmbH)

Track Classification: SI definition, Clocks and Time Scales

Contribution ID: **103** Type: **Invited Poster**

Lower Laser Noise with Multi-Higher Order Mode Locking to Re-duced Brownian Thermal Noise

We will outline a new approach to mitigating fundamental Brownian coating thermal noise in optical cavities using multiple higher order TEM gaussian modes [4]. By blending the readout signals of mul-tiple higher order modes, the effective sampling area of mirrors increases. This improves the averag-ing of thermal motion, thereby lowering the overall length noise. Reducing or mitigating this fundamental thermodynamic bound is an important area of research for the science of precision measurement and optical time standards.

Author: WADE, Andrew (The Australian National University)

Co-authors: CHABBRA, Namisha (The Australian National University); Dr ZHANG, Jue (The Australian National University); MCKENZIE, Kirk (The Australian National University)

Presenter: WADE, Andrew (The Australian National University)

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **104** Type: **Invited Poster**

Superradiance on ytterbium clock transition for frequency metrology

Today's unsurpassed timekeepers are passive optical atomic clocks, which rely on frequency stabilization of an external optical local oscillator on an atomic transition. However, overcoming their technical limitations, such as the Dick effect and cavity instabilities, is a challenging task.
To circumvent the issues related to the local oscillator frequency instability, a promising idea is to use fluorescence emitted by an atomic ensemble on a narrow optical transition directly as a frequency reference for the clock laser.
We present here the development of a cold atom active optical clock designed to leverage superradiant emission on the forbidden narrow-linewidth transition in fermionic 171 ytterbium.

Author: MATUSKO, Martina (Université de Franche-Comté, SUPMICROTECH, CNRS, FEMTO-ST)

Co-authors: PONCIANO OJEDA, Francisco Sebastian (Université de Franche-Comté, SUPMICROTECH, CNRS, FEMTO-ST); EL BADAWI, Jana (Université de Franche-Comté, SUPMICROTECH, CNRS, FEMTO-ST); HAUDEN, Martin (Université de Franche-Comté, SUPMICROTECH, CNRS, FEMTO-ST); DELEHAYE, Marion (Université de Franche-Comté, SUPMICROTECH, CNRS, FEMTO-ST)

Presenter: MATUSKO, Martina (Université de Franche-Comté, SUPMICROTECH, CNRS, FEMTO-ST)

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **105** Type: **Invited Poster**

Dual-atom-interferometric gyroscope with continuous cold atomic beams

In this work, we demonstrated a dual-atom-interferometric gyroscope based on two contin-uous cold 87Rb beams, which can decouple the rotation rate and acceleration from interference phase shifts.

Authors: YAN, Peiqiang (Tsinghua University); WANG, Shengzhe (Tsinghua University); FENG, Yanying (Tsinghua University); Dr MENG, Zhixin (Tsinghua University)

Presenter: WANG, Shengzhe (Tsinghua University)

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **106** Type: **Invited Poster**

Dual-species atomic interferometric sensor for simultaneous inertial measurement and clock operation

In this paper, we propose a scheme utilizing dual-species atoms that integrates atomic interferometric inertial sensors and the atomic clock into a unified system. The preliminary experimental results have confirmed the system's capability to perform subsequent inertial measurements, thus establishing a foundation for further experiments.

Authors: YAN, PEIQIANG (Tsinghua University); WANG, SHENGZHE (Tsinghua University); JIA, WEICHEN (Tsinghua University); FENG, YANYING (Tsinghua University)

Presenter: YAN, PEIQIANG (Tsinghua University)

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **107** Type: **Invited Poster**

Precision Laser Spectroscopy for Antiprotonic Helium

The ASACUSA collaboration at CERN aims to measure the antiproton-to-electron mass ratio with high precision using sub Doppler two-photon laser spectroscopy of metastable antiprotonic helium. Any deviation from the proton value would indicate a broken fundamental symmetry of nature. The new ELENA storage ring is used to synthesize samples of antiprotonic helium and the experiment relies on lasers with a very low frequency uncertainty to perform proper spectroscopy during the microsecond lifetime of the atom. This presents a very stringent requirement due to time fluctuations of just a few tens of attoseconds. The authors of this work demonstrate how to approach this problem, analyze the frequency chain, and provide a noise budget for different scenarios to identify which is best for present and future needs.

Authors: CALOSSO, Claudio (Istituto Nazionale di Ricerca Metrologica and Istituto Nazionale di Fisica Nucleare); HORI, Masaki (Imperial College London and Max-Planck-Institut für Quantenoptik); Dr GIUNTA, Michele (Menlo Systems GmbH and Max-Planck-Institut für Quantenoptik)

Presenter: CALOSSO, Claudio (Istituto Nazionale di Ricerca Metrologica and Istituto Nazionale di Fisica Nucleare)

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **108** Type: **Invited Poster**

Demonstration of A Calcium Atomic Beam Optical Clock

With the development of quantum frequency standard at optical frequency [1], the robust and portable optical beam clocks have attracted a lot of attention [2,3]. The calcium atomic beam clock is one promising scheme due to its relatively simple interrogating and detecting schemes, which can be used for time-keeping, satellite navigation and space exploration [4].
Here we demonstrate an optical atomic clock based on spectroscopy of the 1S0-3P1 clock transition of calcium. The scheme of the calcium beam frequency standard is shown in Fig. 1. Only two narrow- linewidth lasers are needed in the calcium beam optical clock system and they are commercially available. The 423 nm laser is locked to the 1S0-1P1 transition which is used as the readout laser. The 657 nm external cavity diode laser (ECDL) laser is used as the interrogation laser and it is locked to a ULE cavity through the Pound-Drever-Hall (PDH) method. The saturated absorption spectrum is used to stabilize the clock laser by feedback the frequency deviation to the AOM1. This stability is evaluated by comparing with the other PDH-locked laser. The experimental results are shown in Fig. 2. The Allan deviation at 1s is ˜1.3E-14.
The work demonstrates a calcium atomic beam optical clock. The short-term stability can be further improved with the use of the Ramsey spectrum. And the long-term downward trend of the stability can be optimized with careful control of temperature and the fluorescence stability of 423 nm laser and so on. Developing a second calcium frequency standard to measure the stability is also needed.

Author: SU, yabei

Co-authors: PAN, duo; ZHAO, huan; CHEN, jingbiao; GE, jun; HAN, lei; ZHANG, lu; ZHANG, shengkang; SHEN, tong; XUE, xiaobo; CHEN, yu; DING, yudong

Presenter: SU, yabei

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **109** Type: **Invited Poster**

Space Optical Frequency Combs

We have developed a frequency comb for future long-term missions in space having a volume of 6.5l, a weight of 7.5kg and a power intake of 30-55W, depending on mission and application. The system will be part of the COMPASSO mission by the German space arospace center (DLR), testing future optical clock and quantum technologies on the BARTOLOMEO platform located outside of the ISS. After finalization of the Engineering Model we start now building a Protoflight Model system from qualified components, with an expected launch date for the COMPASSO experiment in 2026.

Author: LEZIUS, Matthias

Co-authors: Dr BÖHLE, Frederik; Dr HOLZWARTH, Ronald

Presenter: LEZIUS, Matthias

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **110** Type: **Invited Poster**

Contributions of the Optical Lattice Clock NICT-Sr1 to TAI Calibration and UTC(NICT) steering

Our efforts with the optical lattice clock NICT-Sr1 are now focused on contribution to both the international and the local timescale. Since 2018, NICT-Sr1 has been recognized as a secondary frequency standard and contributed to TAI calibration. Since August 2021 it serves as a reference for the generation of UTC(NICT), which now deviates from UTC by only few nanoseconds.

Author: HACHISU, Hidekazu (NICT)

Co-authors: Dr NEMITZ, Nils (NICT); Dr TØNNES, Mads (NICT); Dr ITO, Hiroyuki (NICT); Dr OHTSUBO, Nozomi (NICT); Ms MIYAUCHI, Yuka (NICT); Mr MORIKAWA, Masaki (NICT); Dr MATSUBARA, Kensuke (NICT); Dr GOTOH, Tadahiro (NICT); Dr IDO, Tetsuya (NICT)

Presenter: HACHISU, Hidekazu (NICT)

Track Classification: SI definition, Clocks and Time Scales

Contribution ID: **111** Type: **Invited Oral**

Ultrastable Lasers –New Developments and Challenges

Friday 20 October 2023 11:30 (30 minutes)

Lasers with long coherence time and narrow linewidth are an essential tool for quantum sensors and clocks. We will report on the progress using low thermal noise crystalline mirror coatings with cryogenic silicon cavities, discuss alternatives for improving the stability, and give an outlook for more reliable, maintenance free and robust cryogenic silicon cavity setups that will enable also transportable optical clocks to benefit from their performance.

Author: STERR, Uwe (PTB)

Co-authors: YU, Jialiang (PTB); LEGERO, Thomas (PTB); HERBERS, Sofia; NICOLODI, Daniele (PTB); KEMPKES, Mona (PTB); MA, Chun Yu (PTB); RIEHLE, Fritz (PTB); ROBINSON, John M. (JILA/NIST); KEDAR, Dhruv (JILA/NIST); YE, Jun (JILA/NIST)

Presenter: STERR, Uwe (PTB)

Session Classification: Low Noise Optical Systems

Track Classification: Precision and Low Noise Signal Generation and Techniques

Contribution ID: **112** Type: **Invited Poster**

Hydrogen Maser Flywheels for Optical Clocks

Hydrogen masers remain the best available option for a flywheel oscillator that can bridge both accidental and intentional gaps in the operation of an optical frequency standard. Our poster will show applications and statistical evaluation of such measurements spanning optical and radio-frequency domains.

Author: NEMITZ, Nils (NICT)

Co-authors: HACHISU, Hidekazu (NICT, Japan); ITO, Hiroyuki (NICT, Japan); MATSUBARA, Kensuke (NICT, Japan); MORIKAWA, Masaki (NICT, Japan); OHTSUBO, Nozomi (NICT, Japan); IDO, Tetsuya (NICT, Japan); MIYAUCHI, Yuka (NICT, Japan)

Presenter: NEMITZ, Nils (NICT)

Track Classification: SI definition, Clocks and Time Scales

Contribution ID: **113** Type: **Invited Poster**

Optical atomic clocks for fundamental physics research

Optical atomic clocks have become essential for exploring fundamental physics, providing valuable data for analysis. Our research focuses on using this data to search for variations in fundamental constants. We aim to understand the sensitivity differences between active and passive optical atomic clocks when detecting transient effects. Additionally, we propose using a cryogenic ultra-stable cavity as a highly sensitive gravitational-wave detector.

Author: Dr MORZYŃSKI, Piotr (Institute of Physics, Nicolaus Copernicus University in Torun, Poland)

Co-authors: Dr BOBER, Marcin (Institute of Physics, Nicolaus Copernicus University in Torun, Poland); Dr WITKOWSKI, Marcin (Institute of Physics, Nicolaus Copernicus University in Torun, Poland); Mr NAROŻNIK, Mateusz (Institute of Physics, Nicolaus Copernicus University in Torun, Poland); Prof. ZAWADA, Michał (Institute of Physics, Nicolaus Copernicus University in Torun, Poland); Prof. WCISŁO, Piotr (Institute of Physics, Nicolaus Copernicus University in Torun, Poland); Dr BILICKI, Sławomir (Institute of Physics, Nicolaus Copernicus University in Torun, Poland)

Presenter: Dr MORZYŃSKI, Piotr (Institute of Physics, Nicolaus Copernicus University in Torun, Poland)

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **114** Type: **Invited Oral**

REFIMEVE optical link network and applications

Thursday 19 October 2023 16:30 (30 minutes)

REFIMEVE is a national metrological network for time and frequency dissemination using the academic fiber network. It enables the coherent dissemination of time and/or frequency reference signals from LNE-SYRTE to around 15 labs and more than 30 in the future. We will show the latest extensions of the network in the Paris urban area and all over France, the architecture required for such a network, and the progress in terms of robustness and uptime. We will also present some applications to precision measurements, in particular ultra-high-resolution molecular spectroscopy in the mid-infrared spectral range.

Authors: CANTIN, Etienne (LPL - CNRS - USPN); LOPEZ, Olivier (LPL - CNRS and USPN); CAHUZAC, Nicolas (LPL - CNRS and USPN); LIU, Yuhao (LPL - CNRS and USPN); MANCEAU, Mathieu (LPL - USPN - CNRS); DARQUIÉ, Benoît (LPL - CNRS and USPN); CHARDONNET, Christian (LPL - CNRS and USPN); AMY KLEIN, Anne (LPL - USPN - CNRS); RABAULT, Martin (Exail Quantum Sensors); COGET, Grégoire (Exail Quantum Sensors); ROSENBUSCH, Peter (Exail Quantum Sensors); MÉNORET, Vincent (Exail Quantum Sensors); QUINTIN, Nicolas (RENATER); TØNNES, Mads (LNE-SYRTE); POINTARD, Benjamin (LNE-SYRTE); MAZOUTH, Maxime (LNE-SYRTE); ALVAREZ-MARTINEZ, Hector (LNE-SYRTE); LIM, Caroline (LNE-SYRTE); TUCKEY, Philip (LNE-SYRTE); ABGRALL, Michel (LNE-SYRTE); LE TARGAT, Rodolphe (LNE-SYRTE); POTTIE, Paul-Eric (LNE-SYRTE)

Presenter: AMY KLEIN, Anne (LPL - USPN - CNRS)

Session Classification: Precision Fibre and Free Space Transfer

Track Classification: Time and Frequency Transfer

Contribution ID: **115** Type: **Invited Oral**

High-Accuracy Yb+-Ion Clocks for Test of Fundamental Principles and Robust Long-Term Operation

Tuesday 17 October 2023 14:30 (30 minutes)

We report on results from long-term operation of the Yb1 ion optical clock of PTB, where we have obtained uptimes exceeding 80% over typical TAI reporting intervals of 30 days. Using these data and the special electronic structure of Yb+ allows us to improve searches for a coupling of ultra-light dark matter (UDM) to photons, temporal drifts of the fine structure constant and its potential dependence on the gravitational field. Interestingly, the same optical clock comparison data can also be used to probe UDM-nuclear couplings and provides competitive sensitivity.
We will also report on a composite system with Yb+ and Sr+ ions and on our efforts to employ a transportable optical clock based on the 171Yb+ E2 transition for contributions to TAI and frequency measurements at other institutes in Europe.

Author: HUNTEMANN, Nils (Physikalisch-Technische Bundesanstalt (PTB))

Co-authors: Dr PEIK, Ekkehard (PTB); Dr JIANG, Jian (Physikalisch-Technische Bundesanstalt (PTB)); STEINEL, Martin; Ms FILZINGER, Melina (Physikalisch-Technische Bundesanstalt (PTB)); Dr LINDVALL, Thomas (VTT Technical Research Centre of Finland Ltd, National Metrology Institute VTT MIKES)

Presenter: HUNTEMANN, Nils (Physikalisch-Technische Bundesanstalt (PTB))

Session Classification: Precision Measurements and Fundamental Physics II

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **116** Type: **Invited Oral**

Compact and Manufacturable Ultrastable Optical Reference Cavities: 10ˆ-14 Stability in Less Than 10 mL Volume

Friday 20 October 2023 09:30 (30 minutes)

We have developed several sub-10 mL vacuum-gap Fabry-Perot cavities that provide ˜10^{-14} factional frequency stability and ultralow phase noise, using scalable lithographic techniques to fabricate million-finesse mirrors.

Authors: MCLEMORE, Charles; QUINLAN, Franklyn (National Institute of Standards and Technology); KELLEHER, Megan (University of Colorado, Boulder); JIN, Naijun; RAKICH, Peter (Yale University); DIDDAMS, Scott (NIST and Univ. of Colorado)

Presenter: QUINLAN, Franklyn (National Institute of Standards and Technology)

Session Classification: Compact Clocks

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **117** Type: **Invited Oral**

Towards laser excitation of the low-energy nuclear transition in 229Th

Wednesday 18 October 2023 10:30 (30 minutes)

We describe our experiments towards the resonant laser excitation of the 8.3 eV nuclear transition in 229Th with the motivation to develop a highly accurate nuclear optical clock for metrology and tests of fundamental physics.

Author: Dr PEIK, Ekkehard (PTB)

Presenter: Dr PEIK, Ekkehard (PTB)

Session Classification: Nuclear Clocks

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **118** Type: **Invited Oral**

Developments to improve the stability of optical lattice clocks

Tuesday 17 October 2023 09:30 (30 minutes)

We will present the progress of our Hg optical lattice clock. This work is motivated, in particular, by the low sensitivity of Hg to blackbody radiation and stray electric fields and by the possibility to use ratio between Hg and other optical transitions for fundamental physics and metrology. We re-port on our work done with the 199Hg fermionic isotope to improve uncertainty, stability and relia-bility [1][2], noting that managing the required deep UV wavelength remains a significant experi-mental challenge. We will also report on a series of frequency ratio measurements with 87Sr and other species, as allowed by the optical fiber network in Europe, including the REFIMEVE infra-structure in France [3]. The excited clock state 3P0 in 199Hg has a rather short spontaneous decay time compared to other species, which can become a limit to exploit the most recent ultra-stable lasers. Bosonic isotopes can circumvent this limit. We will describe our on-going work to develop a Hg clock based on bosonic isotopes and making use of the quenching method [4] and of hyper-Ramsey interrogation [5][6].

We are also developing a non-destructive detection scheme adapted to Sr optical lattice clocks. The scheme is based on a differential heterodyne measurement of the dispersive properties the atomic sample, enhanced by a high finesse cavity. A first implementation demonstrated how to implement the scheme in a technically robust manner and clarified the path to achieve the quantum non-destructive regime [7]. We will report on our new implementation, on its characterization it terms of quantum noise and destructivity, and on its practical potential to improve optical lattice clocks [8].

Finally, we will report on our investigation of laser stabilization using spectral hole burning in rare-earth doped crystals at ultra-low temperature. We have developed agile heterodyne dispersive prob-ing methods based digital signal generation, modulation and demodulation that gives low detection noise, slow fading of the spectral hole and immunity to perturbations present in the cryogenic envi-ronment [9]. We will report on our investigation of properties of spectral holes at 1.4 K [10] and at cryogenic dilution temperature of a few 100 mK, at which favorable conditions to realize laser sta-bilization at 10-17 or better.

These advances, individually or combined for example with spectral purity transfer with combs and composite clock approaches, shall bring significant progress in clock stability and accuracy.

Authors: FANG, Bess (LNE-SYRTE, Observatoire de Paris - PSL, CNRS, Sorbonne Université); LODEWYCK, Jérôme (LNE-SYRTE, Observatoire de Paris - PSL, CNRS, Sorbonne Université); POTTIE, Paul-Eric (LNE-SYRTE, Observatoire de Paris - PSL, CNRS, Sorbonne Université); LE TARGAT, Rodolphe (LNE-SYRTE, Observatoire de Paris - PSL, CNRS, Sorbonne Université); BIZE, Sébastien (LNE-SYRTE, Observatoire de Paris - PSL, CNRS, Sorbonne Université); LE COQ, Yann (LNE-SYRTE, Observatoire de Paris - PSL, CNRS, Sorbonne Université)

Presenter: BIZE, Sébastien (LNE-SYRTE, Observatoire de Paris - PSL, CNRS, Sorbonne Université)

Session Classification: Lattice Clocks

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **119** Type: **Invited Poster**

Optical Lattice Clocks at NPL

Friday 20 October 2023 10:00 (30 minutes)

We present an overview of the latest activities relating to optical lattice clocks at NPL inlcuding: contributions to the BIPM for steering TAI, a full systematic evaluation of NPL-Sr1 with a target uncertainty below 5e-18, composite clock schemes making use of quantum non-demolition readout to improve the precision of clock comparisons, and the outlook for a new Yb optical lattice clock with emphasis on low measurement deadtime and high autonomy.

Author: HILL, Ian

Co-authors: Dr FENG, Chen-Hao (NPL); Dr JOHNSON, Matthew (NPL); Mr BUTUC-MAYER, Filip (NPL); ALLEN, Ben (National Physical Laboratory); Dr FAVIER, Maxime (NPL); Dr SCHIOPPO, Marco (NPL); Dr TUNESI, Jacob (NPL); MARGOLIS, Helen (NPL)

Presenter: HILL, Ian

Session Classification: Compact Clocks

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **120** Type: **Invited Poster**

Impact of Low-Noise Digital Technology on Time Scales

This work discusses how a traditional focus on physical signals in clock composition and time scale generation can limit the potential benefits of digital electronics. The paper presents a digital approach that emphasizes the information carried by sinusoids, rather than the sinusoids themselves, to enable numerical implementation of clock composition functionalities. The work compares an analog approach, involving frequency synthesizers and complex instruments, with a simpler digital approach that uses code to replace most instruments. The work also describes testing of this digital approach at FEMTO-ST and FEMTO-Engineering using state-of-the-art oscillators and facilities.

Authors: CALOSSO, Claudio (Istituto Nazionale di Ricerca Metrologica and Istituto Nazionale di Fisica Nucleare); Prof. RUBIOLA, Enrico (CNRS FEMTO-ST Institute, and INRiM)

Presenter: CALOSSO, Claudio (Istituto Nazionale di Ricerca Metrologica and Istituto Nazionale di Fisica Nucleare)

Track Classification: SI definition, Clocks and Time Scales

Contribution ID: **121** Type: **Invited Poster**

Development of Transportable Optical Lattice Clock

We developed our 2nd generation transportable optical lattice clock. Clock operation of this system was demonstrated. Its performance was evaluated by synchronous frequency comparison to our 1st generation transportable system.

Author: YANG, Hiutat Antony (Department of Applied Physics, Graduate School of Engineering, The University of Tokyo)

Presenter: YANG, Hiutat Antony (Department of Applied Physics, Graduate School of Engineering, The University of Tokyo)

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **122** Type: **Invited Poster**

Progress on Optical Clock Technology for Operational Timescales

We present efforts at the US Naval Observatory to integrate optical-clock technology into our clock ensemble. Emphasis will be on our use of an optical local oscillator disciplined to an atomic fountain, measured directly in the clock measurement, as well as on our calcium-beam clock development.

Authors: PEIL, S.; TOBIAS, W.; WHALEN, J.; HEMINGWAY, B.; AKIN, T.

Presenter: PEIL, S.

Track Classification: SI definition, Clocks and Time Scales

Contribution ID: **123** Type: **Invited Oral**

Next-Generation Chip-Scale Atomic Clocks

Thursday 19 October 2023 11:30 (30 minutes)

We describe work at NIST to develop next-generation chip-scale atomic clocks based on optical transitions in vapor cells and thermal beams.

Author: KITCHING, John

Co-authors: HUMMON, Matthew (National Institute of Standards and Technology); MCGEHEE, William (NIST); WANG, Ying-Ju (NIST); SCHIMA, Susan (NIST)

Presenter: KITCHING, John

Session Classification: Compact Optical Clocks

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **124** Type: **Invited Poster**

Fundamental physics with an Optical Clock Orbiting in Space: FOCOS

The FOCOS mission will perform precise time and frequency comparisons between a high-stability optical clock in an elliptical orbit and ground optical clocks via a high-performance free-space optical link. The high frequency stability of an orbiting clock allows an improved measurement of the gravitational redshift by a factor of 30,000, precise worldwide time transfer, and searches for dark matter and time variations of fundamental constants with a global network of clocks.

Authors: DEREVIANKO, Andrei (University of Nevada, Reno); GIBBLE, Kurt (The Pennsylvania State University); HOLLBERG, Leo; Dr NEWBURY, Nathan (NIST); Prof. SAFRONOVA, Marianna (U. of Delaware); Dr SINCLAIR, Laura (NIST); Dr YU, Nan (JPL, CalTech)

Presenter: DEREVIANKO, Andrei (University of Nevada, Reno)

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **125** Type: **Invited Poster**

Status of the Low-AC-Power Cryogenic Sapphire Oscillators

The cryogenic sapphire oscillator (CSO) is a highly specialized oscillator delivering a microwave signal exhibiting extremely low instability. The Allan deviation $_y()$ is of parts in 10^{-15} at 1 s, with a flicker floor of parts in 10^{-16}, and some drift beyond a few hours.
After the results shown at the 8th Frequency Standard and Metrology Symposium, we spent a significant effort in understanding and engineering the oscillator. We gathered data about resonators of different manufacturers, including the spread of Q and temperature turning point, related to the frequency stability; and about the long-term operation, faults, interruptions, etc. Unlike optical FP etalons, no lock fault has been detected in the CSO.
The current version of the CSO can run continuously, requiring only one in-field maintenance (1 H manpower of a trained engineer) every 2nd year. Drift, in most cases $< 10^{-14}$/day, proved to be extremely regular, and easy to model and remove. The CSO is now a semicommercial product available to qualified users from Franche Comté Innov, a non-profit Company owned by the University of Franche Comté, in turn a French Gov institution.
Finally, the CSO outperforms the optical FP in terms of reliability and drift, and exhibits the most desirable characteristics for use as the flywheel of atomic frequency standards. It deserves consideration for a maser-free time scale.

Authors: Dr DUBOIS, Benoit (France Comté Innov); Dr FLUHR, Christophe (France Comté Innov); Prof. RUBIOLA, Enrico (FEMTO-ST Institute); Mr LE TETU, Guillaume (FEMTO-ST Institute); Dr PARIS, Julien (My Cryo Firm); Ms SOUMANN, Valerie (FEMTO-ST Institute); GIORDANO, Vincent (FEMTO-ST Institute, CNRS)

Presenter: Prof. RUBIOLA, Enrico (FEMTO-ST Institute)

Track Classification: Precision and Low Noise Signal Generation and Techniques

Contribution ID: **126** Type: **Invited Oral**

Towards the next-generation of optical lattice clocks

Tuesday 17 October 2023 08:30 (30 minutes)

We describe recent techniques, strategies, and efforts toward realizing next-generation optical clock uncertainty and stability with the NIST Yb optical lattice clock.

Author: LUDLOW, Andrew (National Institute of Standards and Technology)

Presenter: LUDLOW, Andrew (National Institute of Standards and Technology)

Session Classification: Lattice Clocks

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **127** Type: **Invited Oral**

UTC(k) steered by intermittent operation of an optical clock

Wednesday 18 October 2023 08:30 (30 minutes)

Since August 2021, NICT has been generating UTC(NICT) with its scale interval calibrated by the intermittent operation of a Sr lattice clock . The improvement in the deviation of UTC-UTC(NICT) as well as the current limitation will be discussed.

Author: IDO, Tetsuya (NICT)

Co-authors: Dr ITO, HIroyuki (NICT); Dr HACHISU, Hidekazu (NICT); Dr MATSUBARA, Kensuke (NICT); Dr TONNES, Mads (NICT); Mr MORIKAWA, Masaki (NICT); Dr NEMITZ, Nils (NICT, Japan); Dr OHTSUBO, Nozomi (NICT); GOTOH, Tadahiro (NICT); Ms MIYAUCHI, Yuka (NICT); HANADO, Yuko (NICT)

Presenter: IDO, Tetsuya (NICT)

Session Classification: SI Definition, Clocks and Time Scales II

Track Classification: SI definition, Clocks and Time Scales

Contribution ID: **128** Type: **Invited Oral**

Atomic Clock for the "GPS-Denied" Environment – Undersea

We are testing concepts and evaluating performance of Cs atomic vapor-cell clocks designed specifically for undersea applications (constrained by power consumption, low temperatures (-10 to +10 C), harsh environment) that require reliable atomic timing over durations of greater than one year. Initial results look very promising relative to alternatives.

Author: HOLLBERG, Leo

Co-authors: NGUYEN, Tuan; KOLNER, Brian

Presenter: HOLLBERG, Leo

Session Classification: Null

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **129** Type: **Invited Oral**

Fast oscillating fundamental "constants"

Tuesday 17 October 2023 14:00 (30 minutes)

Background ultralight scalar fields that are considered as a viable candidate for galactic dark matter may manifest themselves in apparent variation of fundamental constants, see, for example, [1,2].

In this talk, we will discuss some of the recent work of our group and collaborators, for example [3- 6], where we search for oscillating dark matter with Compton frequencies from near DC up to 100 MHz.

References
[1] A Arvanitaki, J Huang, and K Van Tilburg, "Searching for dilaton dark matter with atomic clocks,"Phys. Rev. D 91, 015015, 2015
[2] D Antypas, D Budker, VV Flambaum, MG Kozlov, G Perez, and J Ye, "Fast apparent oscillations of fundamental constants,"ANNALEN DER PHYSIK 2020, 1900566; arXiv:1912.01335
[3] A Banerjee, D Budker, M Filzinger, N Huntemann, G Paz, G Perez, S Porsev, and M Safronova, "Oscillating nuclear charge radii as sensors for ultralight dark matter,"arXiv:2301.10784 (2023)
[4] I.M. Bloch, D. Budker, V.V. Flambaum, I.B. Samsonov, A.O. Sushkov, and O. Tretiak, "Scalar dark matter induced oscillation of permanent-magnet field,"Phys. Rev. D 107, 075033 (2023), arXiv:2301.08514
[5] X Zhang, A Banerjee, M Leyser, G Perez, S Schiller, D Budker, and D Antypas, "Search for ultralight dark matter with spectroscopy of radio-frequency atomic transitions,"arXiv:2212.04413 (2022)
[6] O Tretiak, X Zhang, NL Figueroa, D Antypas, A Brogna, A Banerjee, G Perez, and D Budker, "Improved bounds on ultralight scalar dark matter in the radio-frequency range,"Phys. Rev. Lett. 129, 031301 (2022); arXiv:2201.02042

Author: BUDKER, DMITRY (Helmholtz Institute Mainz and UC Berkeley)

Presenter: BUDKER, DMITRY (Helmholtz Institute Mainz and UC Berkeley)

Session Classification: Precision Measurements and Fundamental Physics II

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **131** Type: **Invited Oral**

Precision Penning-Trap Mass Measurements on Light Nuclei and Highly Charged Heavy Ions

Monday 16 October 2023 11:00 (30 minutes)

Masses of light nuclei provide a network of essential parameters used for the fundamental nature description. For example, the mass difference of tritium and helium-3 allows for an independent check of the limit on the electron-antineutrino mass.
The most precise mass measurements of the lightest nuclei, including helium-3, revealed considerable inconsistencies between the values reported by different experiments. In order to provide an independent cross-check, we have performed the most precise measurements of the atomic masses of the proton, the deuteron and the HD+ molecular ion using the multi-Penning trap mass spectrometer LIONTRAP.
PENTATRAP allows for ultra-precise mass measurements on highly charged heavy ions with relative uncertainties in the low 1E-12 region. Among others the excitation energies of low-lying metastable electronic states could be measured by their mass differences to the ground states. Thus, possible new clock transitions in the extreme ultraviolett (XUV) regime could be detected.
The most recent intriguing results by LIONTRAP and PENTATRAP as well as possible applications of these ultra-precise mass data will be presented.

Author: BLAUM, Klaus (Max Planck Society (DE))

Presenter: BLAUM, Klaus (Max Planck Society (DE))

Session Classification: Precision Measurements and Fundamental Physics I

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **132** Type: **Invited Poster**

Low Temperature Microwave Spectroscopy using High-Q Whispering Gallery Modes in Calcium Tungstate

Single crystal calcium tungstate (CaWO_4) is an important crystal for WIMP dark matter searches and more recently has become an interesting material for microwave quantum electrodynamic experiments that investigate spins in solids. We construct a dielectrically loaded microwave cavity resonator from a cylindrical single crystal of CaWO_4 and perform whispering gallery multi-mode spectroscopy at 30mK in temperature. This study found many high-Q modes of up to O(10ˆ7) in value indicating a low dielectric loss tangent of order O(10ˆ−7). The low-loss at low temperatures enables high sensitivity analysis of photon-spin interactions while the use of multiple high-Q modes allows the measurements of spin g-factors and zero field splittings, allowing identification and characterization of spins. In our sample, spin concentrations of O(10ˆ13) cmˆ−3 were derived from spectroscopic analysis of the crystal. The presence of Gd3+ impurity has been implicated along with other as yet unidentified transition metals.

Author: HARTMAN, Elrina (University of Western Australia)

Co-authors: Dr MCALLISTER, Ben (Swinburne University/University of Western Australia); GORYACHEV, Maxim; TOBAR, Michael

Presenter: HARTMAN, Elrina (University of Western Australia)

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **133** Type: **Invited Poster**

Quantum clock precision studied with a superconducting circuit

We theoretically and experimentally study the precision of a quantum clock near zero temperature, explicitly accounting for the effect of continuous measurement. We theoretically find the precision of the clock in each regime, which reveals that in the coherent regime reveals that the precision can in principle, be arbitrarily large in spite of the presence of measurement backaction. We also derive and experimentally verify an explicit link between the (kinetic) thermodynamic behavior of the clock and its precision, thus achieving the first experimental test of a kinetic uncertainty relation in the quantum domain.

Authors: Dr GANGAT, Adil A. (NTT Research); FEDOROV, Arkady; Prof. MILBURN, Gerard J. (University of Queensland); Dr KEWMING, Michael J. (Trinity College Dublin); Dr PAKKIAM, Prasanna (University of Queensland); HE, Xin (Univeristy of Queensland)

Presenter: FEDOROV, Arkady

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **134** Type: **Invited Oral**

Time and frequency dissemination over 113 km free-space

Thursday 19 October 2023 16:00 (30 minutes)

Networks of optical clocks find applications in precise navigation, in efforts to redefine the fundamental unit of the 'second'and in gravitational tests. As the frequency uncertainty and instability for state-of-the-art optical clocks has reached the 10ˆ−19 level, the vision of a global-scale optical network that achieves comparable performances requires the dissemination of time and frequency over a long-distance free-space link with a similar instability of 10ˆ−19.
Here, we report time–frequency dissemination with an offset of $6.3 \times 10{-}20 \pm 3.4 \times 10{-}19$ and an in-stability of less than $4 \times 10{-}19$ at 10,000 s through a free-space link of 113 km [1]. Key technologies essential to this achievement include the deployment of high-power frequency combs, high-stability and high-efficiency optical transceiver systems and efficient linear optical sampling. We observe that the stability we have reached is retained for channel losses up to 89 dB.
The experiment was performed in Urumqi, Xinjiang Province. Two terminals (A and B) are located at Nanshan and Gaoyazi with a distance of 113 km. Each terminal is equipped with an ultra-stable laser (USL), two 1-W optical frequency combs with different wavelengths centered at 1,545 nm and 1,563 nm, two LOS modules and an optical transceiver telescope. The OFC optical phase locked to the USL is used as the carrier and reference signals of the local sampling [2]. By frequency multi-plexing the common free-space channel, we establish two independent two-way time–frequency transfer links, enabling precise evaluation of the link performance without limitation from the USL. As the two multiplexing channels share the same free-space link, common-mode noise occurs. To better evaluate our system, we also established an independent fibre link connecting the two termi-nals with a distance of 209 km. All links share the same USL at each terminal. Experimental results are shown in Fig. 1.
The work successfully evaluates the possibility of a satellite-based time–frequency dissemination on loss and noise. Next step, we will try to overcome other difficulties such as Doppler effects, link back-forward asymmetry and so on. Hopefully, we can have global optical clock networks in near future.
References
[1] Q. Shen et al., "Free-space dissemination of time and frequency with 10−19 instability over 113 km,"Nature, vol. 610, no. 7933, 661–666, 2022.
[2] FR Giorgetta, WC Swann, LC Sinclair, E Baumann, I Coddington, and NR Newbury, "Optical two-way time and frequency transfer over free space,"Nature Photonics, vol. 7(6), 434–438, 2013.

Author: Prof. JIANG, Hai-Feng (University of Science and Technology of China)

Co-authors: Prof. PENG, Cheng-Zhi (University of Science and Technology of China); PAN, Jian-Wei; Prof. ZHANG, Qiang (University of Science and Technology of China)

Presenter: PAN, Jian-Wei

Session Classification: Precision Fibre and Free Space Transfer

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **135** Type: **Invited Oral**

Development of transportable optical lattice clocks and applications

Thursday 19 October 2023 11:00 (30 minutes)

An "optical lattice clock"benefits from a low quantum-projection noise (QPN) by simultaneously interrogating many atoms trapped in an optical lattice [1]. The essence of the scheme is an engineered perturbation based on the "magic frequency"protocol, which has been proven successful up to 10-18 uncertainty [2-4]. About a thousand atoms enable such clocks to achieve 10-18 stability in a few hours. This superb stability is especially beneficial for chronometric leveling [5-7], which determines a centimeter-level height difference of the clocks located at remote sites by the gravitational redshift [8].
In transportable clocks [9], the potential stability of the optical lattice clocks is severely limited by the Dick effect [10] caused by the frequency noise of a compact clock laser. We proposed a "longitudinal Ramsey spectroscopy"[11] to improve the clock stability by continuously interrogating the clock transition. Two key ingredients for the continuous clock, continuous loading of atoms into a moving lattice [12] and longitudinal excitation of the clock transition, are reported. In addition, we report our recent development of compact and accurate optical lattice clocks in collaboration with industry partners.

Author: Prof. KATORI, Hidetoshi (The University of Tokyo)

Presenter: Prof. KATORI, Hidetoshi (The University of Tokyo)

Session Classification: Compact Optical Clocks

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **136** Type: **Invited Poster**

The Twisted Anyon Cavity Resonator as a Potential Dark Matter Detector and Sensing Device

The minimum axion mass detectable by existing photonic dark matter searches is set by the detector's frequency and hence size, which places the lower limit around 10^{-7} eV, leaving the ultra-light dark matter (ULDM) parameter space relatively unexplored. In this work, a new class of electromagnetic resonator is described; the Anyon Cavity Resonator, which has the potential to couple to ULDM axions. This is possible due to the existence of a single electromagnetic mode with non-zero helicity, which is generated in vacuo through a pure photonic magneto-electric coupling of a transverse electric (TE) and transverse magnetic (TM) mode. The resonator is based on twisted hollow structures that possess mirror-asymmetry. The origin of these high helicity modes is demonstrated using finite element simulation. It is predicted that these cavities will have the capability to search for dark matter down to 10^{-24} eV with a minimum coupling strength of $10^{-15.8}$ GeV^{-1}; covering a completely unexplored region of parameter space. Further, the generation of a topologically protected Berry phase is successfully measured in Möbius cavities, which are formed by bending the aforementioned twisted hollow structures around on themselves to form a ring.

Authors: PATERSON, Emma (University of Western Australia, QDM labs); BOURHILL, Jeremy; GORYACHEV, Maxim; TOBAR, Michael

Presenter: PATERSON, Emma (University of Western Australia, QDM labs)

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **137** Type: **Invited Poster**

High-precision atomic calculations for fundamental physics applications and the development of atomic clocks

Recent advances in atomic spectroscopy techniques have created a new era of unprecedented precision in the study of atomic phenomena. Atomic physics plays an ever-growing role in fundamental physics studies, including through atomic parity violation and searches for permanent electric dipole moments, as well as for tests of the CPT theorem and Lorentz symmetry, searches for variation of fundamental constants, and detection of dark matter and dark energy.
High precision atomic theory is required both to interpret experimental data in terms of fundamental physics parameters, and to direct experiment by identifying ideal systems for study.
We perform a detailed study of electric dipole (E1) transition amplitudes in K, Ca+, Rb, Sr+, Cs, Ba+, Fr, and Ra+, which are of interest for studies of atomic parity violation, electric dipole moments, polarisabilities, the development of atomic clocks, and for testing atomic structure theory. We demonstrate extraordinary accuracy, and present a robust method for determining theoretical uncertainty.

Author: ROBERTS, Benjamin

Co-authors: GINGES, Jacinda; FAIRHALL, Carter (The University of Queensland)

Presenter: ROBERTS, Benjamin

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **138** Type: **Invited Oral**

Quantum state control and precision spectroscopy of single molecular ions

Monday 16 October 2023 16:30 (30 minutes)

Over the past decades, atoms are trapped and laser cooled to near zero temperature, minimizing the motional effects in spectroscopy. Internal states of atoms can be coherently manipulated and pre-pared in pure quantum states, including entangled states that are impactful in quantum information processing, sensing, and metrology. This talk will describe the effort of the Ion Storage group at NIST in bringing molecular ions to equal footings with atoms in terms of state control and spectro-scopic precision. The project builds on laser cooling and trapping techniques, frequency comb tech-nology, and quantum-logic spectroscopy protocols nowadays routinely employed in cold-atom re-search and trapped ion optical clocks. That enables demonstrations, on single molecular ions, of co-herent quantum state manipulation [1], nondestructive state detection [1-3], rotational [4, 5] and vibrational [6] spectroscopy with better than part-per-trillion resolution, and quantum entanglement [7]. The group is exploring new opportunities in physics and chemistry offered by the richer struc-ture and broader species selections in molecules.
*In collaboration with Alejandra Collopy, Yiheng Lin, Christoph Kurz, Michael E. Harding, Philipp N. Plessow, Tara Fortier, Scott Diddams, Yu Liu, Zhimin Liu, Julian Schmidt, Dalton Chaffee, Baruch Margulis, David R. Leibrandt, and Dietrich Leibfried

Author: Dr CHOU, Chin-wen (NIST)

Presenter: Dr CHOU, Chin-wen (NIST)

Session Classification: Optical Ion Clocks II

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **139** Type: **Invited Poster**

A Photonic Smart Sensor Based on Quantum Memories and Machine Learning

We present a scheme based on the temporal control of single-photon sources and single-photon detectors to learn the parameters of an optical cavity with a nonlinear response. The scheme works by learning the temporal shape of a single-photon pulse reflected from the cavity. This can be achieved using a Raman single-photon detector, a simple quantum memory, with a controllable read-pulse to select particular temporal modes. As an example, we discuss an optomechanical cavity to illustrate how the mechanical frequency and optomechanical coupling rate can be estimated by machine learning.

Authors: GHADIMI, Moji (University of Queensland); Dr MARSHMAN, Ryan (University of Queensland); Prof. MILBURN, Gerard (University of Queensland); Dr SHRAPNEL, Sally (University of Queensland)

Presenter: GHADIMI, Moji (University of Queensland)

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **140** Type: **Invited Oral**

Stochastic quantum thermodynamics of clocks.

Thursday 19 October 2023 14:30 (30 minutes)

The precision of a quantum clock near zero temperature, depends on how it is driven and how it is measured. We investigate both limits to precision using quantum stochastic thermodynamics, and illustrate the results with examples (superconducting and nano mechanical). Of particular relevance is the nature of the measurement as the clock signal ultimately depends on estimating the fluctuations in the period extracted from the measurement signal. We describe precision in terms of a kinetic uncertainty relation, a recently developed method to bound parameter estimation in continuously measured quantum systems.

Author: MILBURN, Gerard

Presenter: MILBURN, Gerard

Session Classification: Precision and Quantum Measurements

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **141** Type: **Invited Poster**

Isotopically Pure Silicon: A Virtual Vacuum for Implanted Ions

Silicon is a common material used in the make up of hybrid quantum systems and semiconductor devices, and is often implemented at low temperatures for quantum technologies, in particular in the isotopically pure form of Si-28. The absence of nuclear spins in such a sample make it an ideal system to realise a multitude of solid state devices based off implanted impurities, including clocks. Electromagnetic diagnostics have been conducted at milliKelvin temperatures, yielding important results for the future development of systems based off this difficult to obtain material. Namely, the importance of surface losses and their removal, the observation of a freeze-out of a conduction mechanism below 1 K and initial observations of narrow bandwidth impurity dopants are reported.

Author: BOURHILL, Jeremy

Co-authors: Dr MCALLISTER, Ben (Swinburne University/University of Western Australia); TOBAR, Michael; Dr GORYACHEV, Maxim (UWA)

Presenter: BOURHILL, Jeremy

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **142** Type: **Invited Poster**

QED radiative corrections to electric dipole amplitudes in heavy atoms

We report on the first detailed study of the interplay between QED and many-body effects in heavy atoms for E1 transition amplitudes. We use the radiative potential method and check its validity by comparing against the results of rigorous QED. We study the effects of core relaxation, polarization of the core by the E1 field, and valence-core correlations for the heavy alkali-metal atoms Rb, Cs, Fr, and alkali-metal-like ions Sr^+, Ba^+, and Ra^+. We identify several transitions in Cs for which the QED contribution exceeds the deviation between atomic theory and experiment.

Authors: ROBERTS, Benjamin; FAIRHALL, Carter (The University of Queensland); GINGES, Jacinda

Presenter: FAIRHALL, Carter (The University of Queensland)

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **143** Type: **Invited Poster**

Dark matter detection via atomic interactions

Despite the abundance of experimental searches for dark matter (DM), there is no confirmed detection to date. However, we can utilise the precision that atomic physics allows to search for interactions between DM and atomic systems. In this work, I will discuss the prospect for DM detection with atomic systems, the tools needed to accurately assess the possibility, and potential implications for experimental searches.

Authors: CADDELL, Ashlee (The University of Queensland); ROBERTS, Benjamin

Presenter: CADDELL, Ashlee (The University of Queensland)

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **144** Type: **Invited Poster**

The hyperfine anomaly and precision atomic searches for new physics

I will discuss the hyperfine anomaly, and its relevance to tests of the standard model and searches for new physics in precision atomic experiments. I will focus on several of our recent works on the topic [1,2,3]. The hyperfine anomaly gives the finite-nuclear-size contribution to the hyperfine structure, and is difficult to quantify at the required level of accuracy from nuclear structure theory. I will describe how —through a combination of atomic theory and atomic and nuclear experiments —the hyperfine anomaly may be determined. An accurate understanding of this effect is needed for reliable tests of atomic structure theory in the nuclear region, and for the development of precision atomic many-body methods. This is important for the error analysis of atomic parity violation stud- ies, and for maximising the impact on particle physics discovery.

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Authors: ROBERTS, Benjamin; SANAMYAN, George; GINGES, Jacinda

Presenter: GINGES, Jacinda

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **145** Type: **Invited Poster**

The Coolest Compass in the Universe

We use phonons in Bose-Einstein condensates to measure rotation.

Authors: GROSZEK, Andrew (The University of Queensland); WOFFINDEN, Charles (University of Queensland); GAUTHIER, Guillaume (The University of Queensland); Prof. RUBINSZTEIN-DUNLOP, Halina (The University of Queensland); Dr BAKER, Mark (Quantum Technologies Group); Prof. DAVIS, Matthew (The University of Queensland); Dr BROMLEY, Micheal (University of Southern Queensland); Mr BRADLEY, Mommers (The University of Queensland); Dr HAINE, Simone (Australian National University); NEELY, Tyler (University of Queensland)

Presenter: GAUTHIER, Guillaume (The University of Queensland)

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **146** Type: **Invited Poster**

The ORGAN Experiment: Phase 1 results

The ORGAN experiment is a microwave cavity axion haloscope that searches for dark matter particles called axions. The experiment's initial phase sets an upper limit on the coupling between axions and photons, excluding a specific axion-like particle model for dark matter within a certain mass range. The recent phase 1b search further excludes the same model within a different mass range.

Author: QUISKAMP, Aaron (The University of Western Australia)

Presenter: QUISKAMP, Aaron (The University of Western Australia)

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **147** Type: **Invited Poster**

LiNbO3 Bulk Acoustic Resonator characterization at liquid helium temperature.

Bulk Acoustic Wave (BAW) resonators utilize the piezoelectric effect in materials like quartz or lithium niobate to generate and detect acoustic waves within a solid medium [1,2]. These devices find applications in filtering and stabilizing radio frequency (RF) signals in communication systems [3,4]. The objective of this research project is to investigate the properties of LiNbO3-BAW resonator mate-rials at both room temperature (RT) and liquid helium temperature (4K). The initial characterization of the crystal has already been conducted at room temperature within the frequency range of 4-25MHz. This characterization is being re-verified at the temperature of 4K. The results show several high-quality modes, having Q-factors on the order of 106 for both longitudinal and shear modes. Crystal modes are studied using the finite element method (FEM) modeling tool COMSOL. It has been observed that there are two types of modes which are longitudinal(A-type) and shear modes present inside the crystal [5,6]. LiNbO3 crystal is of macroscopic dimension. 3A,5A,7A,9A,11A longitudinal modes and 3,5,7,9 shear modes are identified using COMSOL modelling. Q-factor for the identified longitudinal and shear modes are measured at 4K with a high Q-factor of ˜10ˆ6. A re-entrant cavity with the split post of frequency˜5Ghz operating at TM010 mode is designed in COMSOL to further investigate BAW_MWC coupling rates for LiNbO3.[7]

Authors: PARASHAR, Sonali (EQUS); CAMPBELL, William; GORYACHEV, Maxim; TOBAR, Michael; BOURHILL, Jeremy

Presenter: PARASHAR, Sonali (EQUS)

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **148** Type: **Invited Poster**

Implementation of the Wide Band Josephson Parametric Amplifier in ORGAN Q

The Wide-Band Josephson Parametric Amplifier (JPA) by Raytheon BBN is used in the characterisation experiment for its implementation in the ORGAN Q experiment. The JPA was set in a 3-wave mixing configuration: a DC current source provided a tunable resonant frequency while a pump modulator was used to provide parametric amplification of an input signal. Results show that input frequency ranges of 6.1 GHz to 6.75 GHz can give up to 25 dB of gain with 60 MHz of maximum instantaneous bandwidth. Up to 700 MHz of bandwidth can be used if the tuning parameters are re-adjusted while performing the input frequency sweep.

Author: SAMUELS, Steven (Quantum Technology and Dark Matter (QDM), EQUS, CDM)

Co-authors: TOBAR, Michael; FLOWER, Graeme (QDM, EQUS, CDM); QUISKAMP, Aaron (QDM, EQUS, CDM)

Presenter: SAMUELS, Steven (Quantum Technology and Dark Matter (QDM), EQUS, CDM)

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **149** Type: **Invited Oral**

Optically Steered Time Scale Generation at OP and NPL and Remote Comparisons

Tuesday 17 October 2023 11:30 (30 minutes)

We will present real-time optically steered timescales generated at the same time at OP and NPL. After a detailed description of the experimental chains, we will present the implemented algorithms for outlier filtering and frequency steering estimations. We will then analyse the performance of the experimental timescales based on local comparison against the local UTC(k) and remote comparisons performed via UTC and using the GPS Precise Point Positioning (PPP) technique, before presenting strategies for improvement.

Authors: ABGRALL, Michel (LNE-SYRTE, Observatoire de Paris); JOHNSON, Matthew (NPL); MARGOLIS, Helen (N); LE TARGAT, Rodolphe (LNE-SYRTE); GODUN, Rachel; Dr UHRICH, Pierre (LNE); SCHIOPPO, Marco (NPL); Dr LORINI, Luca (LNE-SYRTE, Observatoire de Paris); LODEWYCK, Jérôme (LNE-SYRTE Observatoire de Paris); PARSONS, Adam (National Physical Laboratory); TOFFUL, Alexandra (NPL); TRAN, An (NPL); CURTIS, Anne; CHUPIN, Baptiste (Observatoire de Paris-PSL, CNRS, SU, LNE); POINTARD, Benjamin (LNE-SYRTE); Dr ROBERTSON, Billy (National Physical Laboratory); FENG, Chen-Hao; HILL, Ian (National Physical Laboratory); TUNESI, Jacob (NPL)

Presenter: ABGRALL, Michel (LNE-SYRTE, Observatoire de Paris)

Session Classification: SI Definition, Clocks and Time Scales I

Track Classification: SI definition, Clocks and Time Scales

Contribution ID: **150** Type: **Invited Oral**

A computable Hydrogen optical lattice Clock

Tuesday 17 October 2023 12:00 (30 minutes)

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Authors: Mr TARAY, Derya (Max-Planck Institute for Quantum Optics); Prof. YOST, Dylan (Colorado State University); Dr AMIT, Omer (Max-Planck Institute for Quantum Optics); Prof. HÄNSCH, Theodor (Max-Planck Institute for Quantum Optics); Prof. UDEM, Thomas (Max-Planck Institute for Quantum Optics); Mr WEIS, Vincent (Max-Planck Institute for Quantum Optics); Dr WIRTHL, Vitaly (Max-Planck Institute for Quantum Optics)

Presenter: Prof. UDEM, Thomas (Max-Planck Institute for Quantum Optics)

Session Classification: SI Definition, Clocks and Time Scales I

Track Classification: SI definition, Clocks and Time Scales

Contribution ID: **151** Type: **Invited Oral**

A Multi-ion Clock with In+/Yb+ Coulomb Crystals

Monday 16 October 2023 15:00 (30 minutes)

In 2012, we proposed multi-ion spectroscopy to improve the stability of optical ion clocks which is fundamentally limited by the quantum projection noise of the single ion. Multi-ion clocks will not only improve the stability by exploiting the higher signal to noise of multiple ions or their uncertainty by allowing for sympathetic cooling of clock ions using a separate ion species, but will be the basis for future entangled clocks and cascaded clocks. For the multi-ion approach we have developed and qualified scalable high-precision ion traps, which are already in use in several experiments. A challenge is the high level of control of systematic shifts when scaling up a single trapped ion to a complex many-body system. I will discuss our results in characterizing the shifts in multiple trapped ions and from lessons learned the potential of multi-ion spectroscopy. The multi-ion clock is operated in a recent dedicated experiment, where 115In+ ions are sympathetically cooled by 172Yb+ ions. Here, I will report on the status of clock operation and international clock comparisons. Last but not least, I will briefly discuss new limits we obtained in our work on an improved test of local Lorentz invariance using 172Yb+ ions and the search for new physics using the even Yb+ isotopes.

Author: MEHLSTÄUBLER, Tanja

Presenter: MEHLSTÄUBLER, Tanja

Session Classification: Optical Ion Clocks I

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **152** Type: **Invited Oral**

Engineered Hamiltonian for high clock precision and accuracy

Tuesday 17 October 2023 10:00 (30 minutes)

Precise quantum state engineering, many-body physics, and innovative laser technology are revolutionizing the performance of atomic clocks and metrology, providing opportunities to explore emerging phenomena and probe fundamental physics. A Wannier-Stark optical lattice configuration highlights such an example. Atom-light and atom-atom interactions in the shallow optical lattice are precisely controlled and determined to the 10^{-19} level, representing key steps toward achieving inaccuracy below 10^{-18} for an optical lattice clock. On the front of clock precision, the use of microscopic imaging and cavity-QED-based nondemolition measurement has allowed us to measure gravitation time dilation across a few hundred micrometers, and demonstrate spin squeezing-enabled metrological gain for clock comparison.

Author: Prof. YE, Jun (JILA, National Institute of Standards and Technology and University of Colorado, Boulder)

Presenter: Prof. YE, Jun (JILA, National Institute of Standards and Technology and University of Colorado, Boulder)

Session Classification: Lattice Clocks

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **154** Type: **Invited Poster**

Introducing the Multimode Acoustic Gravitational Wave Detection Experiment: MAGE

Since the advent of gravitational wave (GW) detection in 2015 [1], many such further events have been recorded by the current generation of laser interferometric GW detectors. While highly successful; such detectors possess a limitation in that they are insensitive to potential GWs in the high frequency bands of several hundreds of kHz and above. This has motivated the emergence of a new wave of experiments in the field of high frequency gravitational wave (HFGW) detection [2]. Here, we present a maturing solution [3,4] to the potential detection of HFGWs.
The Multi-mode Acoustic Gravitational wave Experiment (MAGE) is a high frequency gravitational wave detection experiment. In its first stage, the experiment features two near-identical quartz bulk acoustic wave resonators that act as strain antennas with spectral sensitivity as low as 6×10^(-21) ([strain])/√Hzin multiple narrow bands across MHz frequencies. MAGE is the successor to the initial path-finding experiments; GEN 1 and GEN 2. The primary goals of MAGE will be to target signatures arising from objects and/or particles beyond that of the standard model, as well as identifying the source of the rare events seen in the predecessor experiment. The experimental set-up, current status and future directions for MAGE are discussed. Calibration procedures of the detector and signal amplification chain are presented. The sensitivity of MAGE to gravitational waves is estimated from knowledge of the quartz resonators

Author: CAMPBELL, William

Co-authors: GORYACHEV, Maxim; TOBAR, Michael

Presenter: CAMPBELL, William

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **156** Type: **Invited Poster**

Ground and space-based laser interferometry for precision metrology

We trace the evolution of laser metrology from the first laser rangefinders built in 1961 to spectacularly successful science applications: the LIGO gravitational wave detector and the Laser Ranging Interferometer of the Earth-orbiting GRACE Follow-On mission. Methods for reducing imperfections in the apparatus and the effect of fundamental noise sources are described, including laser frequency noise and heterodyne interferometry clock noise.

Author: Dr SPERO, Robert (JPL)

Presenter: Dr SPERO, Robert (JPL)

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **157** Type: **Invited Oral**

Low-phase Noise Sapphire Oscillators with Improved Frequency Stability

Thursday 19 October 2023 09:00 (30 minutes)

We show that low-phase noise and high-frequency stability can be simultaneously achieved in microwave sapphire oscillators. We describe the 9 GHz sapphire oscillator with interferometric signal processing, which was phase-locked to a stable RF reference by controlling microwave power dissipated in the sapphire resonator. The SSB phase noise of the oscillator was measured to be close to -170 dBc/Hz at Fourier frequency F = 10 kHz [1]. The fractional instability of the oscillator frequency was approximately 2x10^{-13} for integration times from 5 to 50 s.

The use of cryogenic sapphire resonators promises significant improvements in the phase noise performance of microwave oscillators [2]. Yet, serious attention must be paid to the noise mechanisms affecting the cryogenic resonators. The vibrations induced by cryocoolers and power-to-frequency conversion in the sapphire resonator are expected to be the leading causes of the oscillator's excess phase noise. In our recent experiments, we measured the power-to-frequency conversion of the cryogenic sapphire resonator as a function of Fourier frequency. We found that the resonator response to the fast variations of dissipated microwave power is similar to the transfer function of the 1st-order low-pass filter with corner frequency close to the resonator's loaded bandwidth [3]. The measurements were performed with three almost identical resonators cooled to 6 K and excited in the same whispering gallery mode with a resonant frequency near 11.2 GHz. Having measured the cryogenic sapphire resonator's power-to-frequency conversion, we predicted the phase noise spectrum of the cryogenic sapphire oscillator.

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3. E. Ivanov and M. Tobar, "Power-to-Frequency Conversion in Cryogenic Sapphire Resonators," Microwave and Wireless Components Letters, page(s): 1-4, Print ISSN: 2771-957X. Online ISSN: 2771-9588, Digital Object Identifier: 10.1109/LMWT.2023.3264975

Author: IVANOV, Eugene N. (Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia.)

Co-author: TOBAR, Michael

Presenter: IVANOV, Eugene N. (Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia.)

Session Classification: Microwave Clocks and Oscillators

Track Classification: Precision and Low Noise Signal Generation and Techniques

Contribution ID: **158** Type: **Invited Oral**

Frequency combs for differential spectroscopy of atomic clocks

Monday 16 October 2023 12:00 (30 minutes)

Over the past 20 years optical frequency combs [1], with atomic clocks [2], have been a powerful and enabling technology in the context of time and frequency measurement [1,2]. Impressively, optical atomic clocks have yielded an 8 order of magnitude improvement in accuracy in the past 30 years. These improvements are fueling a push toward redefinition of the SI second to optical atomic references [3], as well as application of atomic clocks to tests of fundamental physics [4] and as relativistic gravitational sensors [5-6]. Unfortunately, the long measurement times needed to average down clock quantum projection noise and local oscillator noise to reach measurement stabilities at and beyond the 10-18 level, limit the feasibility of next-generation applications.

I will present the improved instability results for an inter-species optical atomic clock comparison us-ing a differential measurement technique, Figure 1. In this technique, the single ion 27Al+ clock near and the 171Yb lattice clock shared a common local oscillator using the phase coherent wavelength con-version with an optical frequency comb. This technique enabled nearly a factor of 10 improvement in 1-s measurement resolution and a 100-time improvement in averaging time to reach a measurement instability of 10-18. Improvements in the measurement stability was achieved via a minimization of laser noise aliasing, and via improvement in the 27Al+ clock quantum projection noise by increasing its probe time by mitigating laser-atomic decoherence [7].

References

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Author: FORTIER, Tara (NIST, Boulder)

Presenter: FORTIER, Tara (NIST, Boulder)

Session Classification: Precision Measurements and Fundamental Physics I

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **159** Type: **Invited Poster**

Techniques on Crystal Oscillator Vibration Compensation

An Oven Controlled Crystal Oscillator (OCXO) is a precision timing circuit based on a high Q quartz resonator enclosed in an oven to provide the best phase noise performance and high short-term stability.
OCXOs provide good short-term stability and clean frequency references for frequency standards, whether Rb [1], Cs, or Hydrogen Maser atomic clocks [2]. By locking the OCXO reference to atomic resonance, the short-term stability of reference is combined with the long-term stability of atomic resonance to enable novel tests of fundamental laws of physics which require extreme levels of precision and accuracy.
In addition, OCXOs are employed for precision timing and synchronization applications, such as telecommunication, instrumentation, and test equipment in today's Commercial, Defense, Military, Space, and LEO markets. Since 1978 Wenzel Associates (now Quantic Wenzel) has been researching and developing high-performance oscillators to provide the lowest phase noise and highest short-term stability in these markets.
Wenzel uses two Wenzel 5MHz BTULN oscillators for measuring ADEV of its high-performance products using Micro- semi 53100A phase noise analyzer with a stability of <3E-13 at τ of 1 sec and phase noise of <-125dBc/Hz at 1Hz frequency offset.
OCXO temperature stabilization and vibration isolation are two critical factors for femtosecond level stability. The OCXO phase noise performance is one of the key parameters considered when used as a reference in highly stable environments. Specifically, dynamic phase noise performance is critical where minute vibrations could affect short-term stability such as from a ground-based rotating platform, an aircraft cruising altitude, or a satellite in orbit.
Reducing OCXO sensitivity begins with crystal selection; low phase noise and low-g sensitive crystals (as low as 0.1 ppb/g) are critical to success. In addition, a further reduction in OCXO g-sensitivity is possible by sensing the vibration affecting the crystal and compensating for the effect. This technical note covers various vibration compensation techniques developed at Wenzel to reduce vibration-induced phase noise errors in crystal-based oscillators. An example of a compact microcontroller-based vibration-compensated OCXO developed at Wenzel will be presented. Such digitally controlled OCXO can also be employed to correct for thermal drift or errors in GPS location when GPS signals are not available in telecom and navigation systems.

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Presenter: Dr MOSS, Mehran (Quantic Wenzel)

Track Classification: Precision and Low Noise Signal Generation and Techniques

Contribution ID: **160** Type: **Invited Poster**

Energy level shift of quantum systems via the electric Aharonov-Bohm effect

A novel version of the electric Aharonov-Bohm effect is proposed where the quantum system which picks up the Aharonov-Bohm phase is confined to a Faraday cage with a time-varying, spatially uniform scalar potential. The electric and magnetic fields in this region are effectively zero for the entire period of the experiment. The observable consequence of this version of the electric Aharonov-Bohmn effect is to shift the energy levels of the quantum system rather than shift the fringes of the 2-slit interference pattern. We show a strong mathematical connection between this version of the scalar electric AB effect and the AC Stark effect.

Author: TOBAR, Michael

Presenter: TOBAR, Michael

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **161** Type: **Invited Poster**

The Decoupling of Geostationary Satellite's Orbit and Clock Offset by Dual-Carrier Differential Method

The coupling of the orbit and the clock offset seriously affects the clock offset measurement of geostationary orbit (GEO) navigation satellites, and even makes the L-band measurement data unusable [1-2]. To solve the coupling problem, we propose a dual-carrier differential method, which is a further utilization of orbit determination by transfer tracking [3-5]. The dual-carrier differential method can obtain the decimeter-level line-of-sight distance variation of GEO satellites in real time.

We conducted an experiment using the Zhongxing-10 communication satellite and verified the feasibility of the dual-carrier differential method. Fig.1 is the setup and theoretical diagram of the system, and Fig.2 shows the variation in the line-of-sight distance of the Zhongxing-10 satellite to the ground station during the experiment period.

Furthermore, we performed an error analysis of the experiment. After the real-time correction of the phase drift of the ground station, the remaining total error can reach the level of 0.3 m/day. This means that when measuring the clock offset of GEO navigation satellites, the periodic effect of the orbit can be effectively reduced in real time.

Through the combination of the dual-carrier differential method and the existing L-band clock offset measurement method, the clock offset measurement of GEO navigation satellites in the future will achieve higher accuracy and stability.

Reference

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Authors: Mr WANG, LiJun (Tsinghua University); Ms WANG, ShiGuang (Tsinghua University); Mr ZHANG, TongBao (Tsinghua University); Ms TANG, XueYi (Tsinghua University)

Presenters: Ms WANG, ShiGuang (Tsinghua University); Mr ZHANG, TongBao (Tsinghua University); Ms TANG, XueYi (Tsinghua University)

Track Classification: Time and Frequency Transfer

Contribution ID: **162** Type: **Invited Oral**

Scalable infrastructure for Sr optical clocks with integrated photonics

Thursday 19 October 2023 12:00 (30 minutes)

We report on development of a strontium optical lattice clock built with integrated photonics. We implement free-space laser beam control of positioning, pointing, shaping, polarization, and integration with metasurface optics, and absolute laser-frequency stabilization with waveguide supercontinuum generators. Such use of integrated photonics can simplify the system integration of Sr clocks. We demonstrate laser cooling to microKelvin temperature with narrow-line cooling, and we will describe ongoing work to probe the clock transition with lattice-trapped atoms.

Author: PAPP, Scott (NIST)

Presenter: PAPP, Scott (NIST)

Session Classification: Compact Optical Clocks

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **163** Type: **Invited Oral**

Micro mercury ion clock with frequency stability performance comparable to that of rack mount Cs frequency standards

Friday 20 October 2023 09:00 (30 minutes)

As communication and navigation systems increasingly rely on precise timing signals from atomic clocks, the interest in smaller and more power-efficient clocks has grown in recent years. However, achieving high performance in clock frequency stabilities while reducing size, weight, and power (SWaP) has proven to be a challenge. Surveying existing atomic clocks in use clearly shows a stubborn trade-off [1]. Improving clock stability means a higher number of atoms, better vacuum conditions, higher laser powers, and more complex system control, all of which inevitably result in larger sizes and higher power consumption. In this paper, we will present the development of micro mercury trapped ion clocks (M2TIC) that clearly broke away from the typical trend.

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Author: YU, Nan (JPL, CalTech)

Presenter: YU, Nan (JPL, CalTech)

Session Classification: Compact Clocks

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **164** Type: **Invited Poster**

Quantum science and precision measurements in space- Fundamental Physics Program in NASA and at JPL

The Biological and Physical Science (BPS) division is the newest addition to the NASA Science Mission Directorate (SMD). The BPS mission is to "enable exploration by expanding the frontiers of knowledge, capability, and opportunity in space, and pioneer scientific discovery in and beyond Low Earth Orbit to drive advances in science, technology, and space exploration to enhance knowledge, education, innovation, and economic vitality."Within the physical sciences, Fundamental Physics

(FP) is a key part of the BPS and Physical Science. FP focuses on leveraging the unique environment of space and microgravity to deepen our comprehension of the fundamental laws of physics. The Jet Propulsion Laboratory (JPL) serves as the NASA center responsible for the FP program, housing the Fundamental Physics Office and supporting the implementation of major flight missions and ground research related to fundamental physics.

Author: YU, Nan (JPL, CalTech)

Presenter: YU, Nan (JPL, CalTech)

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **165** Type: **Invited Poster**

Progress in the miniature trapped ion optical clock development with 16 cc sealed trap tube

At 3x10^(-13)/t^(1/2) and a stability floor at 10^(-15) level, JPL's Deep Space Atomic Clock (DSAC) is the state-of-the-art (SOA) microwave clock of its size, close to the size constraints in deep space applications [1]. To reach frequency stability beyond that of DSAC in a similar size, one will have to take the new approach of the optical clock where the clock ticking rate is at hundreds of terahertz rather than tens of GHz. The high oscillation frequency enables the clock stability and accuracy significantly exceed what today's microwave clocks can achieve, pushing 1x10-17 accuracy and beyond [2]. The challenge is to take advantage of the optical clock performance capability in a small enough size and power to be deployed in deep space platforms. The miniature Space Optical Clock (mSOC) program focuses on studies and development efforts in reducing the size and power of an optical clock while still outperforming any microwave clocks of similar size today by an order of magnitude in all time scales. Specifically, our objective is to develop and demonstrate an mSOC concept that will have 1x10^{-14}/t1^{2} frequency stability with a stability floor <1x10-16.

Author: YU, Nan (JPL, CalTech)

Presenter: YU, Nan (JPL, CalTech)

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **166** Type: **Invited Oral**

Millisecond Radio Pulsars: Nature's clocks in the sky

Monday 16 October 2023 09:00 (1 hour)

In this talk, I will talk about the many different manifestations of neutron stars in our galaxy and the greater cosmos that emit everything from gamma rays to radio waves in either regular pulses or once-off "Fast Radio Bursts".

Normal pulsars die after typically just a few Myr, but some are fortunate to be recycled by material fed to them from a stellar companion. These recycled pulsars offer some amazing scientific opportunities, for both tests of General Relativity and the detection of a stochastic background of gravitational waves from supermassive black holes using an array of millisecond pulsars, nature' s most accurate naturally occurring clocks.

Author: BAILES, Matthew

Presenter: BAILES, Matthew

Session Classification: Smoking Ceremony and Opening Plenary Session

Track Classification: Precision Tests on Fundamental Physics

Contribution ID: **168** Type: **Invited Oral**

Applications of time and frequency signals on the fiber

Thursday 19 October 2023 17:30 (30 minutes)

Applications of time and frequency signals on the fiber.

Author: Dr CALONICO, Davide (Istituto Nazionale di Ricerca Metrologica, INRIM, Turin, Italy)

Presenter: Dr CALONICO, Davide (Istituto Nazionale di Ricerca Metrologica, INRIM, Turin, Italy)

Session Classification: Precision Fibre and Free Space Transfer

Track Classification: Time and Frequency Transfer

Contribution ID: **169** Type: **Invited Poster**

Excitation of a Microwave Cavity Resonators using an Interferometric Dipole Probe

We present a new way to excite a sapphire-loaded cavity resonator based on a balanced microwave dipole probe in a Mach Zehnder interferometric configuration. The probe is constructed from two separate coaxial electric field probes inserted into a cylindrical cavity resonator from opposite sides with a small gap between them, so they act as an active wire dipole antenna. The power into the resonator from the probes is matched with a variable attenuator in one of the arms of the interferometer. To change the phase between the two electric field probes a variable phase shifter is implemented. Following this we show that the probe couples to high-Q cavity modes as well as low-Q background modes associated with the probe, which can be made resonant or anti-resonant with the cavity modes. We show that when the probe modes are in anti-resonance the line shape of the cavity mode can be made symmetric which also optimizes the cavity mode resonant Q-factor. This is a condition required to optimize the phase noise performance of a resonator-oscillator [1].

[1] EN Ivanov, ME Tobar, "Noise Suppression with Cryogenic Resonators," IEEE Microwave and Wireless Components Letters, vol. 31, no. 4, pp. 405-408, 2021.

Authors: IVANOV, Eugene N. (Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia.); BOURHILL, Jeremy; GORYACHEV, Maxim; Mr HATZON, Michael (UWA); TOBAR, Michael

Presenter: Mr HATZON, Michael (UWA)

Track Classification: Precision and Low Noise Signal Generation and Techniques

Contribution ID: **170** Type: **Invited Oral**

The roadmap to the redefinition of the SI second

Tuesday 17 October 2023 11:00 (30 minutes)

The Consultative Committee for Time and Frequency (CCTF) established a Task Force [1] in 2020 to update the roadmap towards the redefinition of the SI second, following a first roadmap agreed in 2016. This paper illustrates the work of the entire task force [2] formed by about 40 people repre-senting the CCTF countries, with some additional experts.

Author: TAVELLA, Patrizia

Presenter: TAVELLA, Patrizia

Session Classification: SI Definition, Clocks and Time Scales I

Track Classification: SI definition, Clocks and Time Scales

Contribution ID: **171** Type: **Invited Poster**

Cooling and crystallization of trapped single 171Yb+ ion for optical frequency standard

By measuring the frequencies emitted as atoms transition between energy levels, atomic frequency standards are among the most advanced devices available for keeping time. Here, we report our recent progress in developing an optical frequency standard based on a single $^{171}Yb^{+}$. With the laser Doppler cooling, a single ytterbium ion is cooled to crystallization and the temperature of the ion crystal is estimated to be below 1 mK. The progress reported in here is the first step of the project and paves the way for future development.

Authors: HAN, Jize (Tsinghua University); Dr ZHENG, Ying (Tsinghua University); Dr MIAO, Shengnan (Tsinghua University); Prof. ZHANG, Jianwei (Tsinghua University); Prof. WANG, Lijun (Tsinghua University)

Presenter: HAN, Jize (Tsinghua University)

Track Classification: Molecular, Atomic, Ion and Nuclear Clocks

Contribution ID: **172** Type: **Invited Oral**

Distributed quantum sensing with networks of entangled atomic ensembles

Thursday 19 October 2023 14:00 (30 minutes)

abstract attached below.

Author: KASEVICH, Mark

Presenter: KASEVICH, Mark

Session Classification: Precision and Quantum Measurements

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **173** Type: **Invited Poster**

Optical Frequency Transfer and Velocimetry to Rapidly Moving Targets

Precise frequency synchronization between distant points is essential for a huge range of scientific measurements. Frequency synchronization to moving targets, such as a satellite in orbit, will provide tests of fundamental physics [1]. Frequency synchronization has been improved with the use of free space optical technology. However, robust optical control systems must be designed to measure and suppress the large Doppler shifts when transfer occurs to rapidly moving targets [2]. The design of an optical control system capable of Doppler velocimetry is described, along with the capability to perform frequency transfer.

The Doppler tracking system has successfully been demonstrated in the laboratory, with maximum tracking rates of 1 MHz/s or 1.5/m/s2. Fractional frequency stability on the order of 10e-17 is obtained after 10 seconds of integration, along with a noise density of 10e-7 cyc2/Hz at 10Hz.

Authors: FROST, Alex (University of Western Australia); MCCANN, Ayden (University of Western Australia); DIX-MATTHEWS, Benjamin Paul (The University of Western Australia); GOZZARD, David (University of Western Australia); SCHEDIWY, Sascha (University of Western Australia); WALSH, Shane (University of Western Australia); MCSORLEY, Shawn (The University of Western Australia)

Presenter: MCSORLEY, Shawn (The University of Western Australia)

Track Classification: Time and Frequency Transfer

Contribution ID: **174** Type: **Invited Poster**

Optical terminal for long-distance laser links to moving targets

Free-space, optical frequency laser links offer high-speed communications between ground and space on the order of terabits per second. However, the atmosphere is a difficult medium for laser propagation. Turbulence causes a beam to deflect and distort as it travels, and also generates large power losses. Additionally, laser links are highly directional and therefore have stringent pointing requirements. Maintaining pointing is particularly important and difficult when one or both terminals is in motion. This work encompasses the design of an optical transceiver terminal to over-come these issues and reap the benefits of free-space laser links, particularly for ground-to-space applications.

Authors: FROST, Alex (The University of Western Australia); DIX-MATTHEWS, Benjamin Paul (The University of Western Australia); MCCANN, Ayden (University of Western Australia); KARPATHAKIS, Skevos (University of Western Australia); WALSH, Shane (University of Western Australia); Mr MC-SORLEY, Shawn (The University of Western Australia); GOZZARD, David (University of Western Australia); SCHEDIWY, Sascha (University of Western Australia)

Presenter: FROST, Alex (The University of Western Australia)

Track Classification: Miniature, Portable and Space Systems

Contribution ID: **175** Type: **Invited Poster**

Gravitational Aharonov-Bohm Effect

The original proposal for the Aharonov-Bohm (AB) effect [1] focused on the scalar and vector potentials of the electromagnetic interaction. In particular, the seminal paper of Aharonov and Bohm [1] focused mostly on the AB effect connected with the vector potential and magnetic field (vector-magnetic AB effect) rather than the scalar potential and electric field (scalar-electric AB effect). Further, the original, experimental set-up for the scalar potential-electric field AB effect involved switching the potential on and off as the electric charges entered and exited metal tubes. These tubes acted as a Faraday shell to shield the charges from the electric field but not from the electric scalar potential. Since the experimental setup for the vector-magnetic AB effect is much easier to realize, there are many experimental tests of the vector-magnetic AB effect, beginning with the first experiments by Chambers [2], to the definitive, loop-free experiments in the mid-1980s [3], and through to the present. In contrast, the best test of the scalar-electric AB effect [5] is not as clean, since it measures both scalar-electric and vector-magnetic effects together, and the charges are not completely shielded from electric fields.
In reference [4] an alternative probe of the scalar-electric AB was proposed. In the standard, ideal sca-lar-electric set-up charges are sent along different paths which had a potential difference between them (but with the charges at all times shielded from the electric fields). The observational signature of the scalar-electric AB effect was to look for a shift in the quantum interference pattern of charges. In contrast, the proposal of reference [4] placed a quantum system (Rubidium atoms) inside a Faraday cage with a time-varying scalar potential, Φe(t) (in [4] V (t) was used for the scalar potential). The observational signature highlighted in [4] was the development of energy sidebands in the spectrum of the quantum system i.e. in this alternative approach one has a shifting of energy levels as compared to a shifting of interference fringes of the standard set-up.
We apply analogously the analysis of [4] to the gravitational AB effect. There has been a recent experimental verification of the gravitational AB effect [6], which follows the standard recipe of splitting matter beams into two paths, with one path experiencing a different gravitational potential, and then looking for a shift in the interference pattern when the beams are recombined. Here we show that it is possible to apply the set-up for the analogous scalar electric AB effect given in [4] gravitational AB effect to get a cleaner confirmation of this effect, in the sense that in our proposal the quantum system will be in free fall and thus screened from the gravitational field via the equivalence principle.

[1] Y. Aharonov and D. Bohm, Phys. Rev. 115, 485 (1959).
[2] R. G. Chambers, Phys. Rev. Lett. 5 3 (1960).
[3] A. Tonomura, N. Osakabe, T. Matsuda, T. Kawasaki, J. Endo, S. Yano, and H. Yamada, Phys. Rev. Lett. 56, 792 (1986).
[4] R. Y. Chiao, H. Hart, M. Scheibner, J. Sharping, N. A. Inan, D. A. Singleton, and M. E. Tobar, Phys. Rev. A 107, 042209 (2023).
[5] Alexander van Oudenaarden, M. H. Devoret, Yu. V. Nazarov, and J. E. Mooij , Nature 391, 768 (1998).
[6] Overstreet et al., Science 375, 226 (2022).

Author: TOBAR, Michael

Presenter: TOBAR, Michael

Track Classification: Precision and Quantum Metrology with Atoms, Photons and Phonons

Contribution ID: **178** Type: **not specified**

Welcome to Country Smoking Cermony

Monday 16 October 2023 08:30 (30 minutes)

Session Classification: Smoking Ceremony and Opening Plenary Session

Contribution ID: **179** Type: **Invited Oral**

Atomic frequency standards, physical constants and metrology

Tuesday 17 October 2023 15:30 (30 minutes)

The paper highlights the importance of the time unit definition,by means of the atomic Cs frequency standard, in the definition of the base units of the International System of units (SI).

Author: VANIER, Jacques (Universite de Montreal Canada)

Presenter: VANIER, Jacques (Universite de Montreal Canada)

Session Classification: Precision Measurements and Fundamental Physics II