Book of Abstracts

The 9th Symposium on Frequency Standards and Metrology

Kingscliff, NSW, Australia. 16-20 October 2023

The Symposia on Frequency Standards and Metrology

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Program

Time	Sunday 15	Monday 16	Tuesday 17	Wednesday 18	Thursday 19	Friday 20
7:00 am		Breakfast/Registration	Breakfast	Breakfast	Breakfast	Breakfast
		Welcome to Country Keynote **Chair: Michael Tobar**	Lattice Clocks **Chair: Elizabeth Donley**	SI Definition, Clocks and Time Scales **Chair, Michael Wouters**	Microwave Clocks and Oscillators **Chair: Enrico Rubiola**	Compact Clocks **Chair, Erling Riis**
8:30 am		1) Opening and Smoking Ceremony	13) Andrew Ludlow	24) Tetsuya Ido		42) Eric Burt
9:00 am		Keynote Address:	14) Tanya Zelevinsky	25) Jérôme Lodewyck	29) Eugene Ivanov	43) Nan Yu
9:30 am		2) Matthew Bailes	15) Sebastien Bize	26) Helen Margolis	30) Krzysztof Szymaniec	44) Leo Hollberg
10:00 am		3) Jacques Vanier	16) Jun Ye	10:00 am Coffee Break	31) Luigi Cacciapuoti	45) Patrick Gill
10:30 am		Coffee Break	Coffee Break	Nuclear Clocks **Chair, Ian Hill**	Coffee Break	Coffee Break
		Precision Measurements and Fundamental Physics I **Chair: Jacinda Ginges**	SI Definition, Clocks and Time Scales **Chair: Patrizia Tavella**	10:30 am 27) Ekkehard Peik	Compact Optical Clocks **Chair, Yeshpal Singh**	Low Noise Optical Systems **Chair, Michael Tobar**
11:00 am		4) Klaus Blaum	17) Noel Dimarcq	28) Atsushi Yamaguchi	32) Hidetoshi Katori	46) Yanyi Jiang
11:30 am		5) Maxim Goryachev	18) Michel Abgrall	Free	33) John Kitching	47) Uwe Sterr
12:00 pm	**Registration Desk Open**	6) Tara Fortier	19) Thomas Udem	12:00 pm-1:00 pm Lunch	34) Scott Papp	48) Andrey Matsko
12:30 am - 2:00 pm		Lunch	Lunch	1:00 pm-4:30pm Optional Excursion: Tropical Fruit World or Free Time	Lunch	Farewell Lunch and speeches
		Optical Ion Clocks **Chair, Fritz Riehle**	Precision Measurements and Fundamental Physics II **Chair: Franklyn Quinlan**		Precision and Quantum Measurements **Chair, Andrew White**	End of Symposium
2:00 pm		7) Piet Schmidt	20) Dima Budker		35) Mark Kasevich	
2:30 pm		8) Murray Barrett	21) Nils Huntemann		36) Gerard Milburn	
3:00 pm		9) Tanja Mehlstäubler	22) Kurt Gibble		37) Andrey Jarmola	
3:30 pm		Coffee Break	23) Andrei Derevianko		Coffee Break	
		Optical Ion Clocks **Chair: Ting Rei Tan**	Posters + Coffee		Precision Fibre and Free Space Transfer **Chair, Robert Scholten**	
4:00 pm		10) Anne Curtis	Posters Continued + Coffee		38) Jian-Wei Pan	
4:30 pm		11) Chin-wen Chou			39) Anne Amy-Klein	
5:00 pm		12) Yao Huang		Free	40) Sascha Schediwy	
5:30 pm		Posters and Welcome Reception Buffet Dinner Sponsor Speeches			41) Davide Calonico	
6:00 pm				Banquet: Sponsor Speeches Poster Awards CH-SLSC	Free	
6:30 pm			6:30 pm Dinner		6:30 Dinner	
7:00 pm						
7:30 pm			Posters Continued		Free	
8:00 pm						
8:30 pm						
9:00 pm						

Brief Contents

Welcome

Welcome to the 9th Symposium on Frequency Standards and Metrology (9FSM). The Symposium is an event held approximately every seven years as the forum for bringing together international scientists and technologists engaged in the development of precise frequency standards and their applications in metrology, to exchange information on the latest developments in the field, and to point out future directions.

The symposium has been traditionally held in a venue that promotes such an exchange, which in this case is in the resort of Mantra on Salt Beach, located in the isolated Salt Village of South Kingscliff on the Tweed Coast of New South Wales.

The Symposium has a single session approach which includes oral presentations by invitation, poster sessions and keynote talks from internationally recognized speakers, and always includes a published proceedings. The 2023 proceedings will be undertaken in the same way as the 2015 proceedings will appear in the Open Access Journal of Physics: Conference Series (JPCS), which is part of IOP Conference Series.

The first symposium was organized by Jaques Vanier in 1971 in Forét Montmorency in Quebec, Canada. The next ones took place in 1976 in Copper Mountain, USA organized by Helmut Hellwig, 1981 in Aussois, France (Claude Audoin), 1988 in Ancona, Italy (Andrea de Marchi), 1995 in Woods Hole, USA (James Bergquist), 2001 in St Andrews, UK (Patrick Gill), 2008 Pacific Grove, USA (Lute Maleki) and 2015 Potsdam, Germany (Fritz Riehle).

A brief history of the symposium was written by, David Wineland, "The evolution of the Frequency Standards and Metrology symposium and its physics", 2016 *J. Phys.: Conf. Ser.* 723 012001
For further information on the history see:
https://www.qdmlab.com/9fsm2023-history

Details of the Symposium are available at the following webpages:
https://www.qdmlab.com/9fsm2023
https://indico.cern.ch/event/1226483/

Michael Tobar and the Local Organizing Committee, October 2023

Symposium information

The Symposium starts with the registration on Sunday afternoon, October 15 at the Mantra on Salt Beach. The sessions will start in the morning of Monday, October 16 and will end on Friday, October 20 after lunch. There will be one keynote talk and 47 invited talks. Invitations for 104 poster presentations have been accepted. All talks will be held in the Plantation room adjacent to the reception of the hotel. Except for the keynote speaker (1 h) all oral presentations have a slot of 30 minutes including 5 minutes of question time.

Laptop computers (MS PowerPoint, Adobe Acrobat Reader and Keynote) will be provided. All presentations must be pre-loaded via the indico website or directly to the provided laptop at the latest during the break before the session. To avoid software compatibility please also upload a backup PDF version of their presentation (mainly effects power point users).

Poster sessions are on Monday and Tuesday afternoon and evening. The poster boards will be arranged in the foyer identified by the numbers in this book and on the Symposium indico website. Posters should be A0 portrait. Material for putting up the posters will be provided near the poster board or at the registration desk. Posters can be on display from Monday until Thursday night or Friday morning. On Monday evening, there will be a welcome reception combined with the poster session, with canapes and a walk and fork dinner.

Lunches and dinners are included in the conference fee and is served in or close to the conference room. Breakfast is included or not included with your accommodation, depending on how you booked. The excursion to Tropical Fruit World on Wednesday afternoon will start with buses from the Mantra on Salt Beach and come back to the same starting point. The Symposium banquet will take place on Wednesday after the excursions at the Cudgen Headland Surf Life Saving Club in Kingscliff. Busses will shuttle the guests there and back.

Millisecond Radio Pulsars: Nature's clocks in the sky

Matthew Bailes[1]

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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.

Professor Matthew Bailes is the co-discoverer of Fast Radio Bursts and the founder of the Swinburne Centre for Astrophysics and Supercomputing. He has been working on relativistic astrophysics for almost four decades and has a passion for public outreach and building radio astronomy instrumentation. With his team Bailes has discovered many of the millisecond pulsars used in pulsar timing arrays with the Parkes 64m radio telescope. He founded and currently leads the MeerTime collaboration that uses the 64-dish MeerKAT telescope in South Africa to time millisecond pulsars useful for tests of general relativity and hunting for the gravitational waves emitted by pairs of supermassive black hole binaries. In 2023 Bailes was awarded the Shaw Prize in Astronomy for his role in the discovery of Fast Radio Bursts. Since 2017 Bailes has led the Australian Research Council Centre of Excellence for Gravitational Wave Discovery.

Atomic frequency standards, physical constants, and metrology

Jacques Vanier

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When we started this series of symposia on frequency standards in 1971, Helmut Hellwig and I were wandering what title we should give to it. There was another series under the control of the US Army Electronics Command, called *Annual Frequency Control Symposium*. It was and is still held yearly In 1983, IEEE became a co-sponsor. We wanted to have some independence in content relative to sponsors. Furthermore, the second, a base unit of time in the International System of Units, the SI, had just been defined in terms of the Cs ground state hyperfine frequency (1967). It was implemented by means of the Cs beam atomic frequency standard, becoming the first practical, accurate, reliable atomic clock. Length was already defined in terms of a wavelength in the krypton spectrum, and we thought that those definitions were steps opening the door to the use of frequency standards in *metrology* at large. In those days we thought also that when a measurement of a phenomenon was planned, a gain in accuracy would result if it could be transformed into a frequency or time measurement. Consequently, we associated the name frequency standards to metrology in the title. The idea went much further. It did spread to the quantity length, and in 1982, the metre was redefined in terms of the speed of light, *c*, making it a unit that depends on the base unit of time, the second. The speed of light is of course defined in terms of two other physical constants, the vacuum magnetic and electrical constants, μ_o and ε_o. A deep interest in implementing other SI base units in terms of physical constants arose. The other base SI quantities involved are mass (kilogram, kg), electric current (ampere, A), temperature (kelvin, K), light intensity (candela, cd), quantity of matter, (mole, mol). Could we not extend the idea to those other units in particular the kilogram, which was defined in terms of an artefact, a metal cylinder stored under three bell jars at BIPM? A basic discovery had been made earlier, the Josephson effect, coupling the derived unit *volt* to Planck's constant, *h*, the charge of the electron, *e,* and the second. Another discovery was later made, the quantum Hall effect, studied by von Klitzing, coupling the derived unit *ohm*, to the two same constants *h* and *e*. It made possible the determination of the ampere in terms of those constants through ohm's law. However, there was a need to couple this to the original definition of the ampere in terms of a force between two infinite wires. The unique and direct approach to do that was the use of a so-called ampere balance and the kilogram artefact in the earth's gravitational field as base standard. However, the implementation of such an instrument faces major geometrical difficulties. This was resolved by means of the so-called Kibble balance that leads to a connection of the kg artefact to Plank's constant. The presentation will outline the steps that were accomplished, which led to the determination of *h* in terms of the kilogram standard. That accomplishment led in turn to the new 2019 International System of Units, in which all the units are now defined in terms of physical constants*. Except for the mole, all SI units depend now on the unit of time defined by means of the hyperfine frequency of the ground state of Cs, thus completing the original task associated to the goal of the present symposia series, coupling frequency standards and metrology at a level we did not expect in those days.

**The presentation is based on various articles and reports, in particular those of the International Bureau of Weights and Measures, BIPM, available in open literature.*

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

Klaus Blaum[1]

1. Max-Planck-Institut für Kernphysik, Heidelberg, Germany

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 ultraviolet (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.

Low Loss Acoustic Cavities: from Frequency Control to Fundamental Physics

Maxim Goryachev[1], William Campbell, Michael Tobar

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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 measurement 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. Moreover, 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.

Frequency combs for differential spectroscopy of atomic clocks

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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 using a differential measurement technique, Figure 1. In this technique, the single ion $^{27}Al^+$ clock near and the ^{171}Yb lattice clock shared a common local oscillator using the phase coherent wavelength conversion 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 $^{27}Al^+$ clock quantum projection noise by increasing its probe time by mitigating laser-atomic decoherence [7].

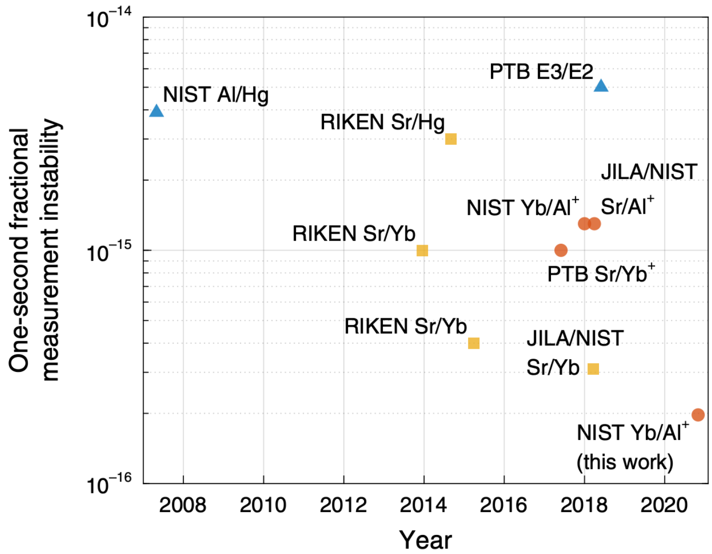

Figure 1. One-second instability of various interspecies optical clock comparisons plotted by their measurement date.

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An Optical Atomic Clock Based on a Highly Charged Ion

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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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Frequency reference validation with $^{176}Lu^+$

K. J. Arnold[1,2], S. Bustabad[3], Zhao Qi[1], Qin Qichen[1], Zhiqiang Zhang[1], Zhang Zhao[1], M. D. Barrett[1,2,3]

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Singly ionized lutetium ($^{176}Lu^+$) has a unique level structure that provides multiple clock transitions [1]. In combination with hyperfine averaging [1], two of these transitions ($^1S_0 – {}^3D_1$ & $^1S_0 – {}^3D_2$) present both a long lifetime and low sensitivity to the electromagnetic environment, which allows high performance clock operation on both transitions [2]. Recently we have demonstrated clock comparison on the $^1S_0 – {}^3D_1$ at the low 10^{-18} level limited by clock stability, with an error budget that supports the capability to go well beyond 10^{-18} [3].

Clock assessment is nothing more than the measurement of atomic properties that define the sensitivity of the atomic reference to its electromagnetic environment, an assessment of that environment, and an account of relativistic shifts. When a frequency ratio is measured within the one apparatus, relativistic shifts drop out and both transitions experience the same electromagnetic environment. Consequently, the error budget for the frequency ratio is practically identical to the individual error budgets for the two transitions. Since motional effects are easily quantifiable and typically very small for a heavy ion, the frequency ratio measured in situ provides a well-defined metric to compare the performance of remotely located systems. If the frequency ratios disagree, we can be certain at least one of the clock assessments is incorrect. If they agree, clock comparison on the $^1S_0 – {}^3D_1$ (primary) transition would only differ by the gravitational red shift between them, which may be confirmed by comparison on the $^1S_0 – {}^3D_2$ (secondary) transition.

Provided the zero-temperature frequency ratio is established, the above idea can be extended to include temperature assessment for room temperature systems. The frequency ratio would provide a measurement of the system temperature, and a comparison on the primary would provide the gravitational red-shift with a minor correction for temperature. Subsequent comparison on the secondary must give a frequency difference consistent with the inferred temperature and redshift.

References

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

Tanja Mehlstäubler [1]

1. Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

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.

$^{171}Yb^+$ optical clock at NPL for frequency metrology and tests of fundamental physics

E.A. Curtis, A.O. Parsons, B.I. Robertson, A. Tofful, M. Schioppo, D.B.A. Tran, J. Tunesi, H.S. Margolis and R.M. Godun

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The accuracy and stability of atom-based optical frequency standards make them an ideal metrological tool, with numerous applications in areas requiring precise position, navigation and timing. In isolation, the accuracy of an optical clock is difficult to fully assess. Performing measurements of optical frequency ratios via optical frequency comb systems - whether locally or utilising clocks in different laboratories or countries via interconnected fibre networks - can enable a direct exploration of clock performance at the part-in-10^{17} level and below. Repeatability of the results year on year gives added confidence in how well the clock system and its long-term behaviour are understood - an essential step for redefining the SI second in terms of an optical frequency. The culture of sharing increasingly long-term measurement data has also enabled analysis of clock frequency data on a variety of different timescales, which has great potential for testing fundamental physics theories [1,2].

The electronic structure of the $^{171}Yb^+$ ion provides two clock transitions that are used for optical frequency metrology at NPL: the ultra-narrow electric octupole transition (E3), and the broader electric quadrupole transition (E2), which is additionally utilised as a more sensitive probe of several systematic effects. During clock operation a single $^{171}Yb^+$ ion is held in an endcap trap designed for minimised ion heating rate and symmetric rf delivery to the endcap electrodes [3]. To improve the overall performance of our clock system we have implemented an ARTIQ [4] infrastructure for experimental control of the clock operation and systematics evaluation. Within this new control framework, ion loading, minimisation of ion micromotion in the trap, and magnetic field calibration routines are completely automated and can be scheduled at appropriate intervals during a frequency measurement campaign. Additionally, improved monitoring of experimental parameters such as ion fluorescence and laser wavelengths enables more robust operation (e.g., enabling automatic steering of laser frequencies and the implementation of an ion-recovery algorithm). This helps to maximise the uptime of the frequency measurement process, which exceeded 90% over a 2-week period in a recent measurement campaign. Recent advances in on-the-fly assessment of systematics have enabled near real-time correction of the E3 optical clock output frequency, and this has been used to explore and test future methods for steering the UTC(NPL) time scale.

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 [2,5].

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Quantum state control and precision spectroscopy of single molecular ions

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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 prepared 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 spectroscopic precision. The project builds on laser cooling and trapping techniques, frequency comb technology, and quantum-logic spectroscopy protocols nowadays routinely employed in cold-atom research and trapped ion optical clocks. That enables demonstrations, on single molecular ions, of coherent 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 structure 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.

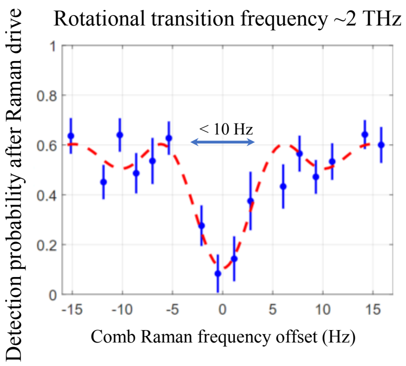

Fig.1. High-resolution rotational spectrum of CaH^+.

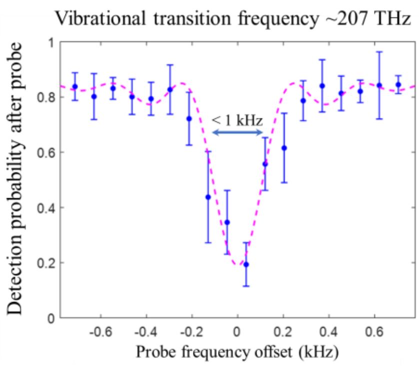

Fig.2. High-resolution vibrational spectrum of CaH^+.

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Ca^+ Optical clocks with Systematic Uncertainties at the 10^{-18} level

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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 10^{-18} level [1,2]; recently with a low 10^{-16} level stability clock laser, the clock stability has been improved to ~ $1 \times 10^{-15}/\sqrt{\tau}$, about another factor of 2 improvement and about an order of magnitude smaller than that in 2016 [3]. 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 3.0×10^{-18} [4]. Thirdly, the Ca^+ clock at room temperature is also improved. The systematic uncertainty of the room temperature clock was at the 10^{-17} level [3], 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 [5], 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 4.6×10^{-18}, then the overall systematic uncertainty of the room temperature clock is evaluated as 4.9×10^{-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 10^{-18} level after the systematic shift corrections: With the systematic shift corrections, the frequency difference between the two clocks is measured as $1.8(7.5) \times 10^{-18}$, the overall uncertainty includes a statistic uncertainty of 4.9×10^{-18} and a systematic uncertainty of 5.7×10^{-18}.

Besides the laboratory clocks mentioned above, a transportable Ca^+ ion clock is also built, with an uncertainty of 1.3×10^{-17} and an uptime rate of > 75% [6]. 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 5.6×10^{-16} [6], about 5 times smaller than our previous result [3]. 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 3.2×10^{-16}, which is another factor of 1.7 improvement.

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Towards the next-generation of optical lattice clocks

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In the last several years, optical lattice clocks based on ytterbium have realized 10^{-18} levels (or better) in the key figures of merit of total systematic uncertainty, stability, and reproducibility [1]. Benefiting from this performance, these clocks have been deployed in optical frequency ratio measurements approaching the $5x10^{-18}$ accuracy level [2], and have been used in multi-ensemble interrogation protocols to realize new levels of frequency stability [3,4]. They have also been used to provide calibrations of International Atomic Time or other time scales, and to sensitively probe for new physics [2,5,6].

As the international community looks ahead to an optical re-definition of the SI second, it's natural to wonder how far optical clock performance will continue to improve. Here we consider techniques, strategies, and recent efforts toward realizing next-generation optical clock uncertainty and stability. The systematic uncertainty of lattice clocks is typically dominated by the BBR Stark shift or lattice light shifts, and can also be significantly impacted by ultracold collisions. Towards improved control of lattice light shifts, we report two sub-recoil cooling techniques using the narrowband clock transition. The resulting sub-uK temperatures facilitate reduced light shifts through shallow lattices, as well as a more precise determination of high-order light shift effects. Towards improved control of the BBR Stark effect, we describe a cryogenic shield with dynamic actuation, aimed at reducing the BBR shift at or below the 10^{-19} level. To mitigate pernicious ultracold collisions in the optical lattice while still allowing high atom numbers for reduced quantum projection noise, we report two techniques for realizing spatially-extended 1D optical lattices. One approach uses coherent delocalization via lattice tunneling, while the other exploits spatially-selective lattice loading using the metastable clock state. Towards improved clock stability and laser coherence, we also highlight recent efforts at laser stabilization using cryogenic sapphire optical cavities for reduced thermal noise.

Finally, if state-of-the-art optical clock performance can be realized beyond the lab, it has long been anticipated that new applications like relativistic geodesy become feasible. Alternatively, more optical frequency ratios at high accuracy can be realized, as metrologically-required for re-definition of the second. Towards these goals, we report on the construction of a transportable Yb optical lattice clock, including first measurements beyond NIST.

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Vibrational Molecular Lattice Clock

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The techniques of manipulating laser-cooled atoms can be successfully applied to create samples of ultracold molecules. These samples can be held in optical traps and be fully state-controlled.

Moreover, molecules provide physical degrees of freedom that atoms lack. For example, diatomic molecules feature vibrational dynamics, and vibrational quantum states are typically separated by terahertz frequencies. They possess very long natural lifetimes in nonpolar molecules as well as very low sensitivities to external fields.

We have fully evaluated the systematic shifts of a clock based on the largest vibrational interval in ground-state Sr_2 molecules, reaching a total systematic uncertainty $<5\times10^{-14}$ that is limited by two-photon interactions with the trapping light (Fig. 1) [1]. We have also evaluated the absolute frequency of this 32 THz transition.

Paths forward include reducing decoherence and nonlinear frequency shifts induced by the lattice environment, and applying the clock to a novel set of vibrational isotope shifts measurements for fundamental tests of mass-dependent physical forces.

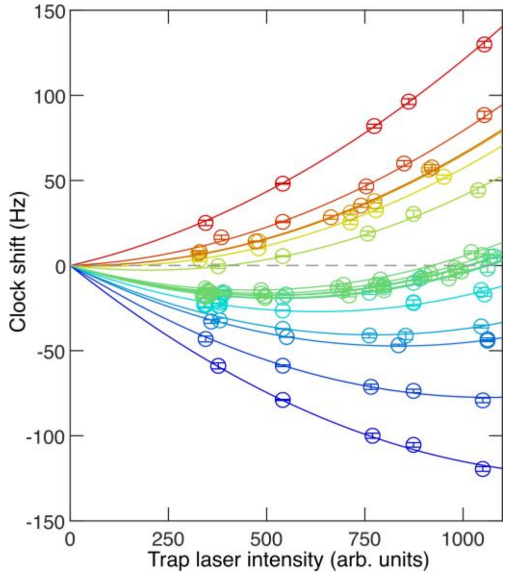

Fig.1. Hertz-level shifts of the Sr_2 vibrational clock for a range of nearby optical lattice wavelengths near 1005 nm, exhibiting scalar polarizabilities and hyperpolarizabilities.

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Developments to improve the stability of optical lattice clocks

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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 report on our work done with the ^{199}Hg fermionic isotope to improve uncertainty, stability and reliability [1][2], noting that managing the required deep UV wavelength remains a significant experimental challenge. We will also report on a series of frequency ratio measurements with ^{87}Sr and other species, as allowed by the optical fiber network in Europe, including the REFIMEVE infrastructure in France [3]. The excited clock state $^3P_0$ in ^{199}Hg 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 probing 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 environment [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 stabilization 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.

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Engineered Hamiltonian for high clock precision and accuracy

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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 1×10^{-18} for an optical lattice clock. On the front of clock precision, the use of microscopic imaging and cavity-QED-based nondemolition measurement have allow us to measure gravitation time dilation across a few hundred micrometers, and demonstrate spin squeezing-enabled metrological gain for clock comparison.

The roadmap to the redefinition of the SI second

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on behalf of the CCTF task force on the redefinition of the second [1]

In the last 10 years Optical Frequency Standards (OFS) has shown a consolidated capacity to ensure a relative accuracy at the level of 10^{-18}, one hundred times better than the current frequency standard realizations based on the cesium atom. The debate on a possible redefinition of the second is very much alive.

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 representing the CCTF countries, with some additional experts.

The Task Force was organized with three subgroups:

A. Requests from user communities, National Metrology Institutes and Liaisons

B. Atomic frequency standards, and possible redefinition approaches

C. Time and Frequency dissemination and time scales.

that gathered feedback on the redefinition of the second through a global consultation of concerned communities and stakeholders through an online survey from December 2020 to January 2021. The needs and possible impacts of a new definition was evaluated, not just scientific and technological, but also regulatory and legislative.

The debate is largely dedicated to the choice of the new definition which could be based on three options:

1. choosing another atomic transition to replace the Cs hyperfine transition,
2. creating an ensemble definition by the weighted geometrical mean of the frequencies of an ensemble of chosen transitions,
3. fixing the numerical value of one more fundamental constant, in addition to c, h and e, as for example the electron mass or the Rydberg frequency.

The CCTF has updated mandatory criteria and conditions that quantify the status of the developments and their maturity for a redefinition. The main achievements and the open challenges related to the status of the optical frequency standards, their contribution to time scales and UTC, the possibility of their comparison and the knowledge of the Earth's gravitational potential at the necessary level of uncertainty are considered (fig 1).

The fulfillment level of those mandatory criteria is annually evaluated by the CCTF. At the last General Conference on Weights and Measures (CGPM) in Nov 2022, the fulfillment level was presented (fig 2) and a resolution has been adopted [3] aiming to encourage the NMIs and research laboratories to pursue the goal of the roadmap and bring proposals to the CGPM (2026) about the further steps that must be taken for a new definition to be adopted by the CGPM (2030).

	Mandatory criteria	Ancillary conditions	Criteria and conditions
Frequency standards, including the contribution of OFS to time scales	X		I.1 - Accuracy budgets of optical frequency standards
	X		I.2 - Validation of Optical Frequency Standard accuracy budgets – Frequency ratios
	X		I.3 - Continuity with the definition based on Cs
	X		I.4 - Regular contributions of optical frequency standards to TAI (as secondary representations of the second)
		X	I.5 - High reliability of OFS
		X	I.6 - Regular contributions of optical frequency standards to UTC(*k*)
TF links for comparison or dissemination	X		II.1 – Availability of sustainable techniques for Optical Frequency Standards comparisons
	X		II.2 – Knowledge of the local geopotential with an adequate uncertainty level
		X	II.3 – High reliability of ultra-high stability TF links
Acceptability of the new definition	X		III.1 - Definition allowing more accurate realizations in the future
	X		III.2 – Access to the realization of the new definition
		X	III-3 - Continuous improvement of the realization and of time scales after redefinition
		X	III.4 - Availability of commercial optical frequency standards
		X	III.5 - Improved quality of the dissemination towards users

Fig 1: Mandatory criteria and ancillary conditions to ensure the benefit and the acceptability of a new definition.

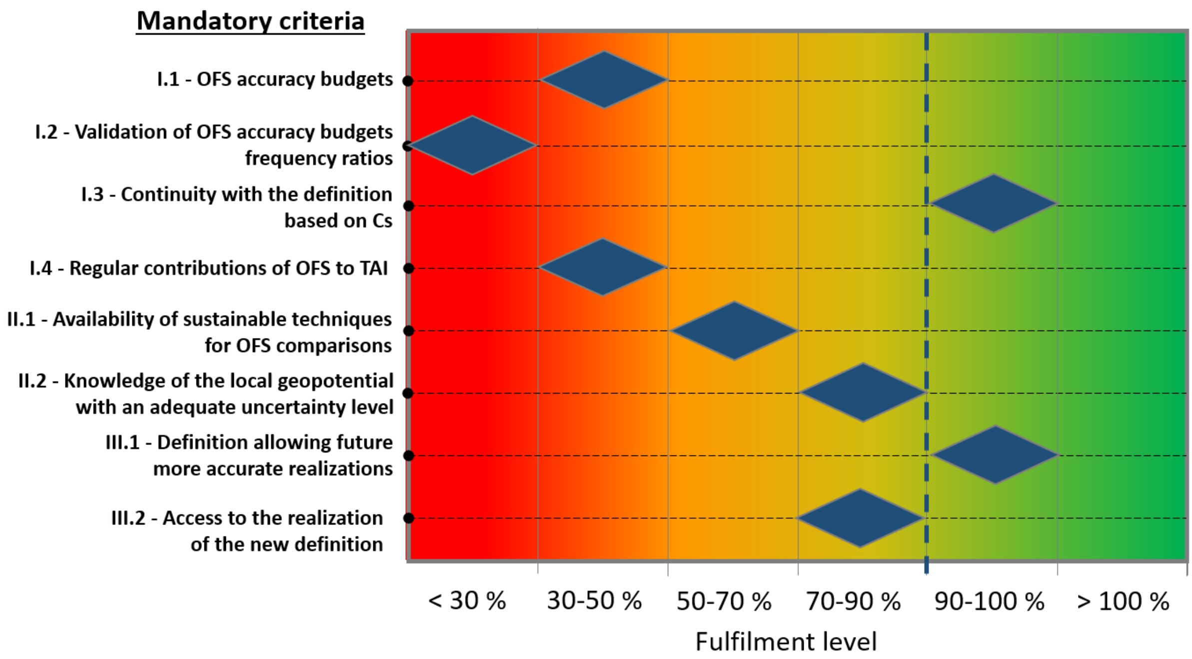

Figure 2: Fulfilment levels of mandatory criteria in 2022

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Invited Talk

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

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Optical frequency standards (OFS) under development in many institutions worldwide have demonstrated impressive progress in terms of accuracy and stability [1-5], surpassing the performances of atomic fountain microwave frequency standards by two orders of magnitude. In the frame of the redefinition of the second in the international system of units (SI) [6], several OFS currently considered as secondary representations of the SI second already contribute to the steering of International Atomic Time (TAI), calculated monthly by the Bureau International des Poids et Mesures (BIPM). Local time scales maintained by National Metrology Institutes will also benefit in the near future from the accuracy and stability of OFS with an expected time offset from Coordinated Universal Time (UTC) maintained in the 100 ps range or lower [7-10].

In this paper, we will present real-time optically steered timescales generated at the same time at OP and NPL. In this experiment, performed during the Robust Optical Clocks for International Timescales (ROCIT) project funded by the European Metrology Programme For Innovation and Research (EMPIR), independent experimental time scales UTCx(*k*) were generated for one month in both laboratories in parallel to the local UTC(*k*) time scales. The UTCx(*k*) time scales were based on hydrogen masers whose frequency was calibrated by the local OFS (SYRTE-SrB and SYRTE-Sr2 optical lattice clocks [11] at OP, NPL-Sr1 [12] and NPL-Yb^+E3 [13] OFS at NPL) via frequency combs. From these frequency calibrations, steering corrections were updated hourly via frequency offset generators fed by the hydrogen masers, to better compensate for the real time maser frequency fluctuations. 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. We will show that the two optically steered time scales remained less than 4 ns away one from each other, which is better than the corresponding UTC(*k*) over the same period. To our knowledge, this is the first-ever comparison of two independent 'optical time scale' prototypes, and the results demonstrate the capacity of optical clocks to produce operational timescales.

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A computable Hydrogen optical lattice Clock

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Defining the values of physical constants is the best method to set up a system of units. With this method the definition gets separated from the realization. Therefore, progress in technology that allow new methods for realization of the unit does not require a new definition. The 2018 definition of the value of Planck constant is an example where two methods for realization currently yield comparable accuracies. Another advantage of fixing the values of constants, is that different realization can operate on vastly different scales. Whereas with the kg artifact it was very difficult to bridge the gap to particle masses, one can readily realize masses at the photon energy scale with the new definition.

With the reform of the SI system in 2018, all but one of the units are now based on defined constants. The only remaining (natural) object is the cesium atom that is used to define **and** realize the SI second. It is interesting to note that one can remove the last object from the system of units, that then seem to have no relation to the real physical world. However, this is not so because the realization of the units still requires physical objects. The definition simply does no longer say which.

Any atomic or molecular transition frequency can be expressed through the Rydberg constant multiplied with a dimensionless number obtained from theory. Defining the value of the Rydberg constant would remove the last object from the SI. While for hydrogen-like systems this theory expression is known with the best accuracy, the cesium ground state hyperfine splitting cannot be computed from first principles with sufficient accuracy. What is a sufficient accuracy of course depends on the demands. The best optical lattice clocks are now sensitive to variations of the gravitational redshift within the atomic cloud. Going below this level essentially means to measure elevation not time. In future the hydrogen like systems may also reach this level if experimental techniques are improved. To use it for a new definition of the SI second also requires progress of the underlying theory.

Here we are proposing a new spectrometer that may reach this level with atomic hydrogen. We want to set up an optical lattice clock for atomic hydrogen that is not more complex than a usual optical atomic clocks. It is based on a magic wavelength optical dipole trap, similar to the current most accurate optical clocks. The trap can be loaded without Doppler cooling which avoids an extremely difficult 121nm cooling laser. The 1S−2S transition with a natural linewidth of 1.3Hz would be the clock transition driven in a Doppler-free manner. Hence, only moderate temperature and no Doppler cooling are required. Even without operating it as a clock, such a setup can be used to improve hydrogen spectroscopic data to test QED. In the long run other hydrogen like systems like He^+ could be envisioned for realizing a new SI second.

Fast oscillating fundamental “constants”

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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.

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

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The $^{171}Yb^+$ ion is widely used in ion-based optical clocks and quantum technology. Long trapping lifetimes exceeding months have been observed and reliable laser sources for Doppler cooling and interrogation of the clock transitions are readily available. We employ transitions from the $^2S_{1/2}$ (F=0) ground state to the first excited states for the realization of optical clocks: an electric octupole (E3) transition to $^2F_{7/2}$ (F=3) state and an electric quadrupole (E2) transition to $^2D_{3/2}$ (F=2) state. Interrogating both transitions in an alternating fashion allows us to employ the E2 transition to characterize residual fields on a magnified scale and correct the corresponding shifts for the E3 transition with low uncertainty because the relative sensitivities have been determined.

In this work, we report on results from long-term operation of the Yb1 optical clock of PTB, where we have obtained uptimes exceeding 80% over typical TAI reporting intervals of 30 days. The measurement instability of the E3/E2 frequency ratio obtained over the last two years is compatible with pure white frequency noise as expected from the quantum projection noise on the E2 transition, reaching the mid 10^{-18} level for averaging periods of 5×10^6 s. This result is consistent with the expected reproducibility of the E2 transition frequency of 4×10^{18}. 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 as well as temporal drifts of the fine structure constant and its potential dependence on the gravitational field [1]. Interestingly, the same optical clock comparison data can also be used to probe UDM-nuclear couplings and provides competitive sensitivity [2].

To further improve systematic uncertainties and increase the coherent interrogation time of the Yb^+ E3 clock transition which features an excited state lifetime of 1.6 years, we have started to investigate the use of $^{88}Sr^+$ as co-trapped ancillary ion. Its well-characterized differential polarizability has enabled a direct measurement of the thermal field perturbing the ion during clock operation and a small uncertainty for the ratio of the $^{171}Yb^+$ E3 and $^{88}Sr^+$ clock transition frequencies [3]. Our measurement provides vital information for resolving the tension found between other $^{88}Sr^+$ clock frequency measurements [4,5]. Further investigation of both species in one trap will enable us to improve the performance of $^{171}Yb^+$ clocks by reducing the so-far limiting uncertainty in the sensitivity to thermal radiation and increasing the frequency stability by extending the coherent interrogation time via sympathetic cooling.

Finally, we will shortly report on our efforts to employ a transportable optical clock based on the E2 transition for contributions to TAI and frequency measurements at other institutes in Europe.

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

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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. Its moderate nuclear size is expected to yield small contributions from nuclear deformations to its isotope shifts.

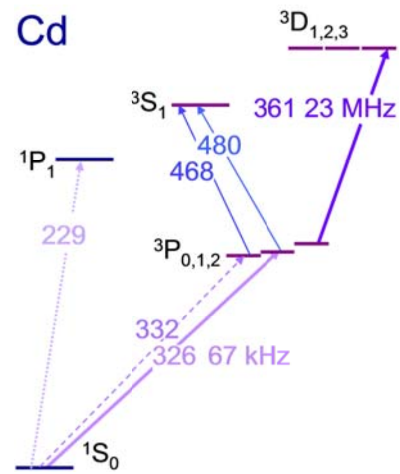

Fig.1. Cadmium transition wavelengths (nm). Using no 229 nm singlet excitations, we first capture thermal atoms using only the 326 nm intercombination transition. Large numbers of atoms are subsequently trapped using the high loading rate of the 361 nm $^3P_2$-$^3D_3$ transition.

Cadmium has been trapped and laser-cooled to 5.6 µK using its broad UVB 229 nm singlet resonance line and its narrow 67 kHz wide UVA intercombination line at 326 nm [1]. Without using 229 nm light, 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 $^3P_2$-$^3D_3$ transition (Fig. 1.), trapping ~10^7 ^{114}Cd atoms. We trap the 6 bosonic isotopes and show that the cadmium hyperfine structure allows the fermionic isotopes to be efficiently trapped with no additional lasers or frequency modulation. The UVA and blue laser light are generated from the first and second harmonics of a 1083 nm fiber amplifier via sum frequency generation with 820 nm to 863 nm semiconductor lasers. The laser system is automatically locked with a custom FPGA controller.

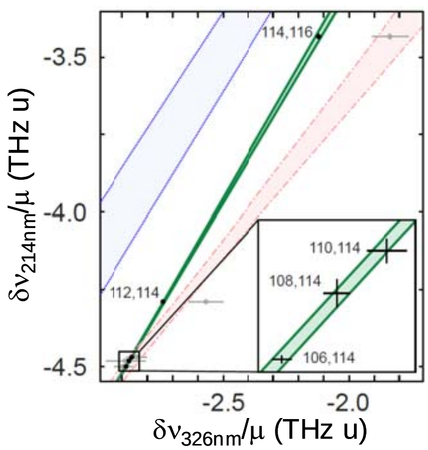

Fig.2. King Plot for the Cd$^+$ D2 [3] and Cd intercombination transitions [2]. The gray points are from [4] and others [2], and the blue calculation is from [5].

We use both MOT's to measure the isotope shifts of the 326 nm intercombination transition (Fig. 2), and the 480 nm $^3P_1$-$^3S_1$ and $^3P_2$-$^3D_3$ transitions [2]. These clarify a long-standing discrepancy for the nuclear charge radius [4], give the isotope shifts of the clock transition, and suggest that precise measurements of cadmium isotope shifts can provide 100 times higher sensitivity in tests of fundamental physics [2].

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Atomic clocks as exotic field telescopes in multi-messenger astronomy

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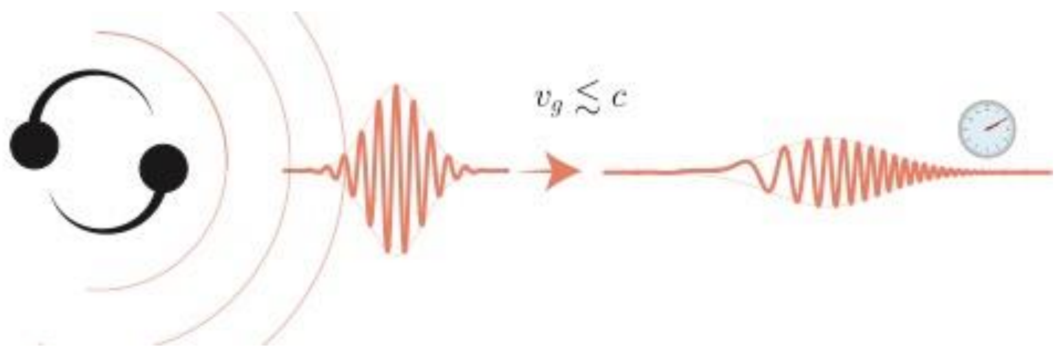
Since the initial discovery of gravitational waves (GW) by LIGO in 2015, there were multiple observations of GW arrivals at the Earth. Most of these GW result from mergers of a pair of black holes. However, on August 17, 2017, a new class of GW events was discovered: the binary neutron star merger GW170817. That was the first astrophysical source detected in both gravitational waves and multiwavelength electromagnetic radiation. This event has generated a considerable excitement in the astrophysics community, ushering the era of 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 mergers. This approach must be contrasted with *indirect* detection strategies, e.g., based on minute exotic-physics induced changes in GW spectral features. While the progenitors are 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 sensors and (ii) because of the enormous amounts of energy released in the mergers.

Figure summarizes our idea. A merger emits both the GW and an exotic low-mass fields (ELFs) bursts. Since the ELF is massive, the ELF burst propagates at a group velocity smaller than the speed of light. Thereby, the ELF pulse lags behind the GW burst. Because of the intrinsic dispersion for massive particles, the ELF burst tends to spread out as it travels. More energetic components of the ELF wave-packet travel faster, imprinting a universal anti-chirp signature in the atomic clock data. We present a detailed analysis of the anticipated signature.

As to the exotic, beyond the standard model, physics modality, we focus on ultralight (yet non-zero mass) bosonic fields as the messenger. Such ultralight bosons are ubiquitous in various new physics scenarios. There is a wide variety of speculative scenarios for ELF production, enumerated in our original publication; these range from the scalar-tensor gravity to stripping away boson clouds coherently built up around black holes (BH). My favorite is due to quantum gravity of BH singularities. Much of the underlying physics of coalescing singularities in BH mergers remains unexplored as it requires understanding of the yet unknown theory of quantum gravity. Then the ELF burst would emerge from the merger as a quantum gravity messenger. Then atomic clocks offer an intriguing opportunity to measure the messengers of quantum gravity unchained by the BH mergers.



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

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UTC (Coordinated Universal Time) is a so-called paper clock timescale derived from the weighted average of more than 400 clocks worldwide, providing an extremely robust foundation to the time infrastructure of modern society. Thus, most countries base their national time on UTC, typically with a time zone correction of an integer or half-integer number of hours. National standard time is a real signal and needs to be disseminated without interruptions, but since UTC is determined with a latency of one month, each time and frequency laboratory "*k*" operates its own clocks to generate a real-time signal UTC(*k*) maintained as close as possible to UTC. Traditionally, standard time has been generated using microwave frequency standards such as cesium atomic clocks or hydrogen masers, but to take advantage of the improved performance of optical clocks and in preparation for the future redefinition of the second, it is desirable to determine the scale interval of standard time by such an optical clock. However, continuous operation of optical clocks is not yet easy and redundancy of clocks is difficult to attain since commercial optical clocks are not yet available.

NICT has been studying methods to generate real time signals with a scale interval based on an optical clock. In 2016 a timescale TA(Sr) was first generated [1], using a single hydrogen maser (HM) with an output signal that was steered by reference to an ^{87}Sr optical lattice clock. Further increased stability can be achieved by considering a larger HM ensemble [2]. But with no redundancy in the source oscillator or the Sr system, it is difficult to use such a system as a source of UTC(*k*). In contrast, the Japan Standard Time (JST) system generates a numerically calculated ensemble timescale from more than 15 Cs atomic clocks, and obtain three real time signals (for redudancy) by steering three HMs independently to this product with a certain offset frequency f_{offset}.

A method for incorporating an optical clock is then to adjust f_{offset} to compensate for the difference between UTC(NICT) and TA(Sr). If any problem affects the generation of TA(Sr), effects on UTC(NICT) can be avoided by suspending the steering to TA(Sr) and reverting the steering to the ensemble of radio frequency clocks. NICT has been generating UTC(NICT) and JST in this way since August 2021. Since then, |UTC−UTC(NICT)| has been reduced from 20 ns to 5 ns as shown in Fig. 1(a). As shown in Fig. 1(b), however, the stability of UTC(NICT) over the period between measurements remains limited by the performance of the Cs ensemble. For this reason, we are investigating adding hydrogen masers to the clock ensemble and modifying the algorithm to incorporate clocks with predictable frequency drifts [3]. We will also present preliminary results of this improved scheme.

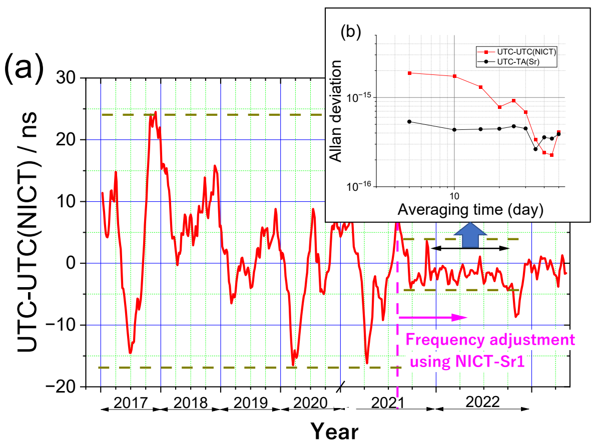

Fig.1 (a) Record of UTC−UTC(NICT) (b)Allan deviation of UTC(NICT) and TA(Sr) obtained in the operation of ten months (black arrow)

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A definition of the SI second based on several optical transitions

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As the performances of optical frequency standards now overcome the cesium primary frequency standards by several orders of magnitude, the question of a redefinition of the SI second based on these optical transitions is topical. A road-map crafted by the CCTF and its working groups indicates a possible redefinition in 2030 [1]. However, in the current context where many competing optical frequency standards present performances that quickly evolve, finding a good candidate for the new definition, and ensuring that this choice will remain relevant over several decades is a difficult task.

Three options are currently considered for the redefinition of the SI second : in option 1, the Cs transition would be replaced by a single optical transition, yet to be chosen ; option 2 rather proposes to define the second based on the weighted geometric mean of several transitions [2]; in option 3, the numerical value of a fundamental constant (e.g. the Rydberg constant or the electron mass) would be fixed, in the spirit of the 2018 revision of the SI, but with the showstopper that the realization would be limited to about 10^{-12}.

In this paper, we present the theoretical concepts underpinning option 2, including the reason for choosing the geometric mean, how the concept of primary and secondary frequency are integrated in this definition, and the role of frequency ratios measurements in the realization of the unit.

Then, we discuss how gradually changing the weights of the various transitions composing the unit, and introducing new transitions to the pool of transitions composing the unit can be used to adapt to new developments in optical frequency standards. We show that these updates can provide a smooth and convergent process towards a constant value for the SI second, as compared to option 1, for which adapting to new frequency standards requires to abruptly change the transition used to define the second.

We also present how option 2 would be practically implemented and realized, using as input the set of recommended frequency ratios between optical transitions [3], as currently published by the CCTF. For this purpose, we simulate the implementation of option 2 based on the recommended frequency ratios published at the 2021 CCTF. We also describe a systematic method to determine the weights of the various transitions composing the unit.

Finally, we propose an analysis of the strengths and weaknesses of option 2, and compare how options 1 and 2 would satisfy a possible set of requirements for the redefinition of the SI second.

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Robust Optical Clocks for International Timescales (ROCIT)

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The recently concluded collaborative European project "Robust optical clocks for international timescales" (ROCIT) [2] 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 (TAI) as secondary representations of the second.

Improvements to optical clock robustness and reductions to data latency are key enablers for their use in time scales. Advances were made in the robustness of both trapped ion optical clocks and neutral atom optical lattice clocks, with the focus on the systems that were known to require most frequent user intervention. Developments included new approaches for automatic long-term control of laser systems and for automated adjustment of optical setups, and enabled unattended optical clock uptimes exceeding 80 % over 2 weeks to be achieved in several laboratories.

Two coordinated programmes of frequency comparisons were carried out to verify the international consistency of optical clocks. The second of these involved 11 optical clocks in seven different countries, including one outside Europe (^{171}Yb at NMIJ). Both optical fibre links and satellite-based techniques were used to compare clocks in different locations, maximizing participation and enabling results obtained by different techniques to be compared. The remote comparisons were supplemented by local optical frequency comparisons, including the measurement of several optical frequency ratios that had never been determined directly before. Traceability to the present definition of the second was ensured by including caesium primary frequency standards in the comparison programme.

Methods were developed for on-the-fly evaluation and correction of systematic frequency shifts, and for real-time validation of data provided by optical clocks, preparing the way for steering of UTC(*k*) time scales. Steering algorithms able to handle low uptimes and periods of data unavailability were also developed. Building on these developments, NPL and LNE-SYRTE independently and simultaneously demonstrated prototype optically steered time scales, termed UTCx(NPL) and UTCx(OP) respectively, based on data from one or more optical clocks with high uptimes. These time scales were directly compared using a GPS PPP link, and their offset was observed to remain smaller than the offset between the corresponding operational UTC(*k*) time scales over the same period.

When optical clocks contribute to TAI, they do so with the uncertainty of the recommended frequency value for the secondary representation of the second, as approved by the Consultative Committee for Time and Frequency (CCTF). The most recent (2021) update to these values was influenced by our work showing the importance of including correlations between frequency ratio measurements in the analysis. During the ROCIT project, twelve optical clocks within the consortium were used to evaluate the frequency of a hydrogen maser contributing to the computation of TAI, over a total of 55 periods ranging from 5 to 35 days. Three of these optical clocks (SYRTE-Sr2, IT-Yb1 and NPL-Sr1) have been approved by the CCTF Working Group on Primary and Secondary Frequency Standards and are contributing data to the BIPM for TAI steering, whilst others will be submitted for approval pending updated uncertainty budgets and peer-reviewed publications.

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[1] The ROCIT project (18SIB05) received funding from the European Metrology Programme for Innovation and Research (EMPIR), which is co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme. It involved numerous contributors from national metrology institutes NPL, CMI, GUM, INRIM, LNE-SYRTE, PTB and VTT MIKES, as well as from the Astrogeodynamical Observatory in Borowiec (Poland), Ben-Gurion University (Israel), CNRS (France), Leibniz University Hannover (Germany), Nicolaus Copernicus University (Poland) and the Politecnico di Torino (Italy).

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

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There is strong interest in optical spectroscopy of ^{229}Th because of the unique low-energy (8.3 eV) isomer that exists in this nucleus [1]. With a transition energy in the range that is typical for resonances of the valence electrons and that is accessible for laser excitation, this nuclear resonance is attractive as the reference of an optical clock that combines high accuracy with a strong sensitivity for hypothetical effects of new physics that may be sought in frequency comparisons with atomic clocks [2]. Since direct laser excitation of the ^{229}Th nucleus has not yet been achieved, experimental studies of properties of the isomer so far have relied on its population in nuclear decay, like in the recent observation of the nuclear optical emission from ^{229}Th implanted in fluoride crystals [3].

As a step towards laser excitation of ^{229}Th we have developed a tunable vacuum-ultraviolet (VUV) laser source based on four-wave frequency mixing in xenon. Using seed radiation from two continuous-wave lasers, the system allows for precise control of the VUV frequency. Tunable in the wavelength range 149-155 nm, the source produces pulses of 6-10 ns duration with up to 40 µJ energy and is coupled via a vacuum beamline to a linear radiofrequency ion trap. In a first implementation of VUV laser spectroscopy of trapped Th^+ ions we excite three previously unknown resonance lines to electronic levels in the range of the ^{229}Th isomer energy. An analysis of the lineshape is used to estimate the linewidth of the VUV radiation to be about 6 GHz, dominated by phase noise that is enhanced in harmonic generation and in the four-wave mixing process. The use of the system in nuclear laser spectroscopy of ^{229}Th as trapped atomic ions or as dopants in calcium fluoride crystals prepared by our cooperation partners from TU Wien [4] will be discussed.

Trapping of ^{229}Th ions in charge states 1+, 2+ and 3+ has been demonstrated with the ions produced in laser ablation from solid ^{229}Th targets [5,6], but the efficiency of the method decreases substantially with increasing charge. In preparation of an optical clock with laser-cooled trapped $^{229}Th^{3+}$ ions we have developed an apparatus for the trapping of Th^{3+} recoil ions from the alpha decay of ^{233}U. The ion source in a helium buffer gas cell is linked to a linear radiofrequency trap in ultrahigh vacuum, where the ions are cooled sympathetically by laser cooled $^{88}Sr^+$ ions. $^{88}Sr^+$ has been selected as the coolant ion because of its convenient laser cooling transitions and because its charge to mass ratio is similar to that of $^{229}Th^{3+}$, so that Coulomb crystals are produced where the two ion species are closely coupled.

This work has been funded by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant Agreement No. 856415), the Deutsche Forschungsgemeinschaft (DFG) – SFB 1227 - Project-ID 274200144 (Project B04) and by the Max-Planck-RIKEN-PTB-Center for Time, Constants and Fundamental Symmetries.

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

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The nuclear isomer of ^{229}Th (^{229m}Th) attracts attention for its extremely low energy [1, 2]. The energy of ^{229m}Th was determined to be about 8.3 eV (corresponding to wavelength 149 nm) by internal conversion electron spectroscopy [3], γ-ray spectroscopy [4-6], and, more recently, vacuum-ultraviolet spectroscopy of ^{229m}Th [7]. The nuclear transition between the nuclear ground state and the isomer state of ^{229}Th offers a unique opportunity for laser spectroscopy of an atomic nucleus. One of the applications is a high-precision optical nuclear clock: an atomic clock based on this nuclear transition [8].

As a platform of the ^{229}Th nuclear clock, an ion trap with triply charged ^{229}Th ($^{229}Th^{3+}$) is suitable because $^{229}Th^{3+}$ possesses electronic transitions that enable laser cooling. In a previous study laser cooling and laser spectroscopic studies of $^{229}Th^{3+}$ ions in the nuclear ground state ($^{229g}Th^{3+}$) were demonstrated [9]. For the operation of the nuclear clock, properties of $^{229m}Th^{3+}$ also need to be known. For example, hyperfine structures of $^{229m}Th^{3+}$ should be known to confirm nuclear excitation via selective detection of $^{229g}Th^{3+}$ and $^{229m}Th^{3+}$. However, since the trapping of $^{229m}Th^{3+}$ ions has not been demonstrated yet, detailed properties of $^{229m}Th^{3+}$ remained uninvestigated.

In this study, we performed laser spectroscopy of trapped $^{229m}Th^{3+}$ ions. 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.

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Low-phase Noise Sapphire Oscillators with Improved Frequency Stability

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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 $2\ 10^{-13}$ 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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Robust Design and Performance of NPL Cs Fountain Clocks

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Atomic fountain clocks have become ubiquitous in maintaining the most stable national time scales within nanoseconds of UTC in the short- and long-term. After three decades of development their design has reached a level of maturity offering accuracy of about 1 part in 10^{16}. Recent efforts have been aiming towards increased reliability and a robust commercial design.

At NPL we have pursued a distinctive design approach offering the highest short-term stability and accuracy, yet with relatively simple construction and operation. The physics package is based on a single-stage vapour-loaded magneto-optical trap as the source of cold atoms, an easy to align (0,0,1) optical configuration, and efficient time-of-flight detection with large solid angle of fluorescence collection. The cold atom signal is further boosted by accumulation of the $m_F = 0$ clock state sublevel population via optical pumping. High detection signal-to-noise ratio and short-term stability below 3×10^{-14} (1 s) have been achieved for a sufficiently low-noise local oscillator [1]. Despite the high atom number and density, a leading systematic effect, the cold collision frequency shift, can be controlled at parts in 10^{17} thanks to a cancellation mechanism and manipulation of the atom cloud parameters [2]. To limit the uncertainty of another potentially dominant systematic, the distributed cavity phase effect, to the 10^{-17} level, we have elaborated on a technique to precisely determine the position of the cloud of atoms in the microwave cavity [3].

The complete system consists of a physics package, which can be transported assembled by road or air, and just two full height 19-inch racks for control electronics, microwave generation and optics. The optical package is entirely mounted in one of the racks. Incorporating a distributed Bragg reflector (DBR) type diode laser for cooling and detection enables months of operation without any unintentional stoppages.

The system has been designed in compliance with the latest engineering standards and delivered to customers under the rigour of commercial contracts. Our customer base includes national measurement institutes, as well as large scientific facilities and providers of telecommunication and financial services. In order to support flexibility of timing infrastructure design and its resilience we have demonstrated operation of the fountain with a reference maser installed in a lab several hundred kilometres away. The maser was linked by an optical fibre connection and no deterioration of the fountain's short-term stability was observed [4].

Despite rapid progress in the development of other ultra-precise frequency standards, atomic fountains are likely to remain widely used in time scales as well as in experiments on the stability of fundamental constants and symmetries. Our current efforts are concentrated on developing a miniaturised version of the fountain with only a modest sacrifice of performance. We are building a prototype physics package 20 times smaller in volume and an all-in-fibre optics module that is also significantly reduced in size. From a different perspective, the nearly continuous uptime may enable the operation of time scales without the necessity of using a hydrogen maser as flywheel.

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Atomic Clock Ensemble in Space

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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 $1\text{x}10^{-16}$ 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 differences at the clock locations.

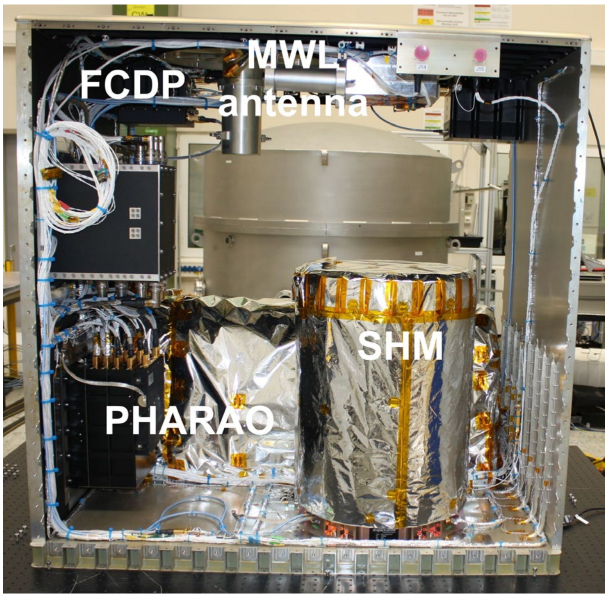

Fig. 1: Flight model of the ACES payload before system tests.

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.

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Development of transportable optical lattice clocks and applications

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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.

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Next-Generation Chip-Scale Atomic Clocks

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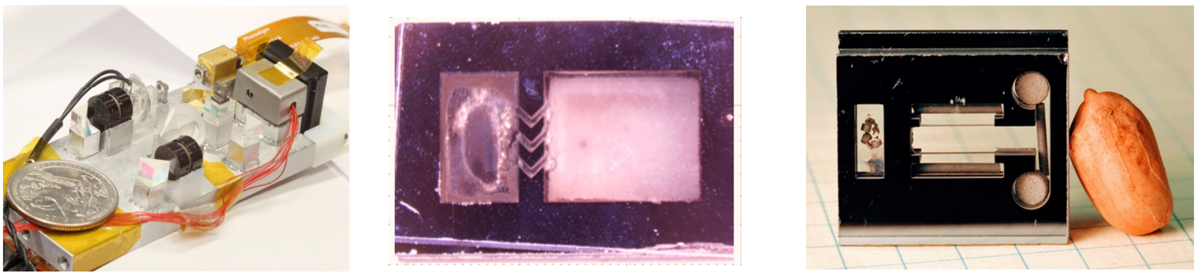
Since the demonstration of the first chip-scale atomic clock physics package in 2003 [1], remarkable progress has been made worldwide to advance this technology and its offshoots. Over 95,000 commercial chip-scale atomic clocks have been deployed in the field over the last twelve years [2] and chip-scale atomic magnetometers [3] are now a commercial reality [4]. New devices and instruments continue to be developed for broader application spaces and higher performance.

At the 2014 Symposium on Frequency Standards and Metrology, some ideas were proposed [5] on how to develop a broad class of SI-traceable chip-scale standards using atomic spectroscopy, silicon micromachining and photonics. Such chips, if successfully developed and manufactured, would revolutionize the way calibrations are carried out by allowing SI-traceability to be inexpensively deployed on the manufacturing floor or internal to measurement instruments themselves. In this talk, we present progress toward this goal carried out in our group over the last decade. We describe the development of compact optical clocks and wavelength references based on 2-photon transitions in Rb [6-8] and narrow optical transitions in Sr [9], both implemented using microfabricated vapor cells. We also describe the development of chip-scale atomic beam clock physics packages (see Fig. 1c). Such clocks may pave the way for accurate realization of time and frequency in a compact, low-power format.



(a) (b) (c)

Fig. 1. (a) A compact Rb 2-photon wavelength reference (from Ref. [7]); (b) a microfabricated Sr vapor cell (from Ref.[9]); and (c) a chip-scale atomic beam clock physics package (from Ref. [10]).

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Scalable infrastructure for Sr optical clocks with integrated photonics

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Optical-lattice clocks with alkaline-earth metal vapors are among the most stable and precise sensing platforms in all of physics [1]. Moreover, their ultranarrow atomic transitions provide quantum calibration of not only timing signals, but they can be converted to calibrate numerous physical observables and as a basis for quantum information. Disrupting the photonics, laser, and systems technologies required for optical-lattice clocks with scalable and manufacturable integrated-photonics is a universally acknowledged goal [2]. The critical step of transitioning from complicated, hand-assembled, free-space optics to integrated photonics will pay dividends not just for advanced quantum sensors but throughout quantum information science, advanced computing architectures, and high-capacity, secured data links.

We demonstrate laser cooling and trapping in a novel, fully integrated metasurface (MS) optics platform, engineered to support both broad-line and narrow-line cooling of strontium. Metasurface optics offer complete control of free-space propagation and co-integration, hence we realize the aligned configuration required for magneto-optical trapping (MOT) upon assembly. Furthermore, we phase-lock the lasers needed for broad-line and narrow-line cooling of strontium by use of supercontinuum generated with fiber-coupled, tantalum-pentoxide nonlinear waveguide modules. The supercontinuum modules transform a low-power Er-fiber comb to Sr reference combs at 690 nm, 780 nm, 813 nm, and 922 nm.

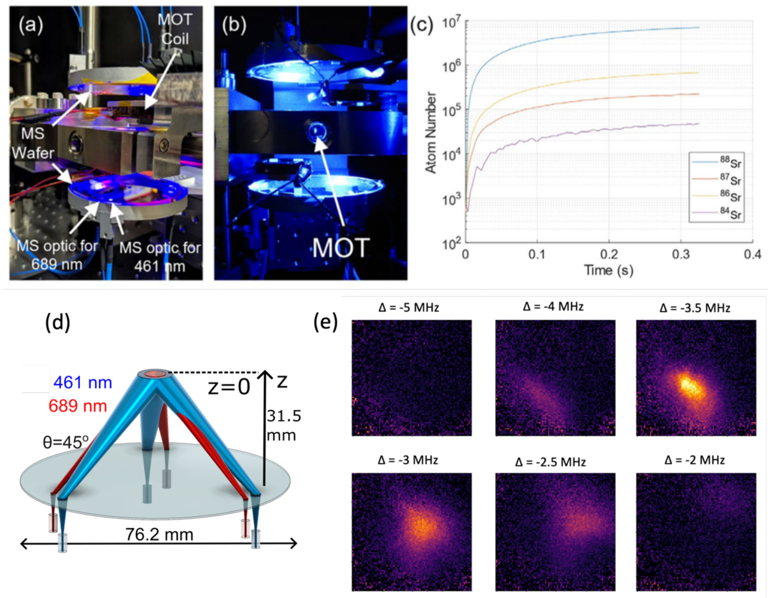

Fig.1. Magneto-optical trapping on the 461 nm and 689 nm transition of strontium with laser beams generated from twelve metasurface optics integrated on a fused silica wafer. (a) Image of the compact Sr apparatus with three-inch metasurface optics wafers for scale. (b) Sr MOT on the 461 nm transition. (c) Demonstration of Sr 461 nm MOT loading for the four most abundant isotopes. (d) Schematic arrangement of the metasurface optics system with optical fiber illumination at 461 nm and 689 nm. (e) Exploring a metasurface optics Sr MOT on the 689 nm transition.

Figure 1 shows an image of our compact and scalable Sr system with metasurface optics to generate the broad- and narrow-line MOTs. This talk will explore integrated photonics technologies for robustly reconfigurable use in atomic physics systems and the development of our scalable Sr lattice clock system. We use a low-power Sr beam oven and a counterpropagating 461 nm beam to assist MOT capture. With this MOT beam configuration generated from metasurfaces, we have the capability to trap four Sr isotopes in their isotopic abundances, demonstrating robust, 3D, polarization diverse optical configurations. Our system further enables laser cooling to microkelvin temperature on the 689 nm transition.

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Distributed quantum sensing with networks of entangled atomic ensembles

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The noise performance of atomic sensor networks can improve with non-local entanglement protocols. Here we show how a modified quantum non-demolition spin squeezing protocol improves two node atomic clock and atomic interferometer networks [1]. These protocols can be directly applied to recently demonstrated gravity gradient atomic interferometer configurations. Applications of such networks range from satellite geodesy to gravitational wave and ultra-light dark matter detection. We will discuss recent work to extend these methods to atomic Sr.

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Stochastic quantum thermodynamics of clocks

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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.

Nuclear-spin-based rotation sensing with diamond

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Recently, we demonstrated a solid-state rotation sensor based on ^{14}N nuclear spins intrinsic to nitrogen-vacancy (NV) centers in diamond [1]. This type of sensor detects rotation by measuring the shift in the precession rate of nuclear spins, analogous to vapor-based NMR devices. The sensor employs direct optical polarization and readout of the ^{14}N nuclear spins and a radio-frequency double-quantum pulse protocol that monitors ^{14}N nuclear spin precession, and it does not require microwave pulses resonant with the NV electron spin transitions. However, nuclear-spin-based rotation sensors are inherently sensitive to variations in the magnetic field, which produce changes in the precession rate similar to those produced by rotation, limiting the long-term stability of the device. This issue can be overcome by simultaneously measuring the precession of two spin species with different gyromagnetic ratios, which can be combined to obtain the rotation rate while canceling the contribution from magnetic field fluctuations.

In this work we implement this idea using a diamond containing two isotopes of nitrogen (^{14}N and ^{15}N) and simultaneously measure the precession rates of NV nuclear spins of both isotopes. We found that we were able to suppress the magnetic sensitivity of the rotation sensor by several orders of magnitude. Its performance is limited in part by the temperature dependence of nuclear spin transitions, which we have recently measured to be on the order of ~0.1 Hz/K [2]. This dependence can be canceled by monitoring temperature using the nuclear quadrupole splitting of the NV centers containing ^{14}N.

The nuclear spin interferometric technique developed in this work may find application in solid-state frequency references and in extending tests of fundamental interactions at micro- and nanoscale to those involving nuclear spins. With further improvements, it may also find use in practical devices such as miniature diamond gyroscopes for navigational applications.

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Time and frequency dissemination over 113 km free-space

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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 10^{-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 10^{-19}.

Here, we report time–frequency dissemination with an offset of $6.3 \times 10^{-20} \pm 3.4 \times 10^{-19}$ and an instability of less than 4×10^{-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.

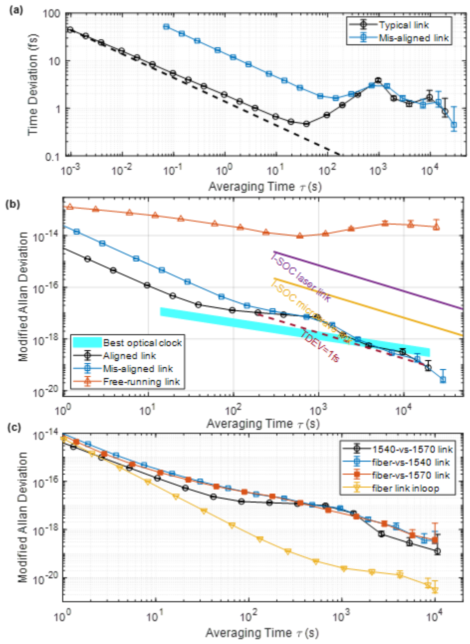

Fig.1. Experimental results of time–frequency transfer. a, The TDEV of one free-space link. b, The fractional frequency instability of links. c, Time comparison among the fibre link and two free-space links.

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 multiplexing 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 terminals 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.

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REFIMEVE frequency and time network and applications

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REFIMEVE is a national research infrastructure of optical fiber links which disseminates time and frequency reference signals generated at LNE-SYRTE to more than 30 research labs all over France. It uses mainly the optical fiber backbone of RENATER, the French National Research and Education Network. It is currently providing an optical frequency reference to around 15 labs and to connection points to Germany, UK, Italy and Switzerland, as depicted on Fig. 1. For that purpose, the network is equipped with industrial-grade Repeater Laser Stations (RLS) [1] and with Multibranch Laser Stations [2] allowing multiple coherent outputs for the dissemination to several links and the simultaneous real-time supervision of all the links. In Paris suburban, the frequency signal is dropped using Extraction Stations along a main link using a ring topology [3]. An embedded supervision system enables us to control and assess the network operation and performances [4] and enables to characterize the signal received by each user labs.

We have recently developed a new link to CERN in Switzerland and we have also extended the network in Paris region for both frequency and time reference signals. The residual frequency fluctuations of the optical links for 1-s measurement time range from a few 10^{-17} to a few 10^{-15} depending on the length and noise of each links, and the uptime of the links is between 70% and 90%. We checked that there is no bias of the frequency transfer with an uncertainty typically below 10^{-19}. Thanks to these performances, the REFIMEVE network has been used for the precise comparison of primary and optical clocks in Europe, especially for the ROCIT project [5]. In France, the REFIMEVE signals are currently exploited by user labs for photonics, laser stabilisation or control, atomic and molecular spectroscopy [6-7]. At LPL for instance a Quantum Cascade Laser is stabilized to the optical reference enabling high precision spectroscopy of methanol and other molecules of interest for atmospheric and astrophysics studies [7].

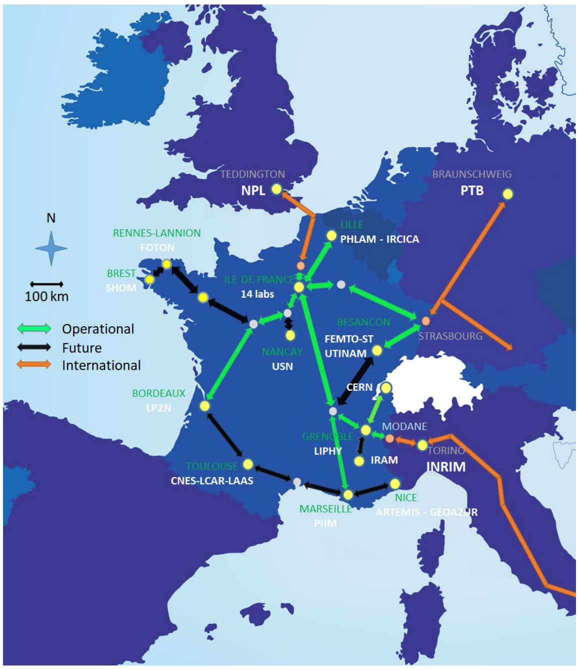

Fig.1. schematic of the REFIMEVE network, with its European Connections.

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

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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 [1]. Ultra-stable frequency comparison has already been demonstrated over fixed-point, free-space links with residual instabilities below 1×10^{-20} at 300 s integration [2]; over extremely long-distance links [3-4]; and even over links via relatively slow-moving drones [5-6]. However, the applications mentioned above will require frequency comparison over free-space links to and from fast-moving vehicles.

For example, direct laser links between stationary and moving clocks can be used to test Special Relativity; relay links via aircraft can be used to map the gravitational potential for geoscience and resource exploration applications, and also deliver secure, over-the-horizon time synchronisation and precise positioning; and ground-to-space links can test General Relativity, and provide the global timescale comparison required for the redefinition of the SI second [1]. However, none of the laser link technologies outlined above can operate in a high-Doppler-shift regime, with the current record for optical frequency comparison set at 24 m/s [5]. For comparison, typical cruising speeds for light aircraft start at around 60 m/s, and satellite orbital velocities are typically hundreds of times greater.

Here, we report on our work to demonstrate a low size, weight, and power, continuous-wave laser technology that is well suited for transportable terrestrial and space applications. We have demonstrated this technology over point-to-point links [7]; over links with equivalent turbulence as a link to space, while setting the record for most-stable frequency transfer [2]; and over links via slow-moving drones [6]. Furthermore, we report on our work to establish links via light aircraft, where we validate our technology for dealing with large point-ahead angles [8]; the inclusion of ranging [9]; and dealing with large Doppler shifts. Follow-up work will include demonstrations of terrestrial aircraft relay links, and integration of this technology in our optical ground station [10] to enable the first ultra-stable optical frequency comparison between ground and space.

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Applications of time and frequency signals on the fiber

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In the last 10 years, time and frequency transfer techniques over optical fibres have demonstrated results beyond time and frequency community, opening new venues for innovation and science.
Coherent laser interferometry over fibre enables to compare optical clocks beyond their accuracy [1].
In Europe, Italy, France, Germany, UK, Check Republic, and Poland developed coherent optical links with hauls even longer than 2000 km. Italy, France, Germany, and UK implemented the first continental optical and microwave clocks comparisons [2, 3], enabling the first demonstrations of chronometric levelling in real filed [2, 4].
In Italy, INRIM realized a multi-purpose research optical fibre infrastructure, the Italian Quantum Backbone, 1850 km long, connecting the main towns and labs all over the country [5]. Coherent frequency and time transfer coexist, the latter uses the White Rabbit technique.
INRIM explored the use of laser interferometry over fibre for new applications, not only in time and frequency. We demonstrated the use of ultrastable lasers and T/F methods for geophysics [6], for Earthquakes detection in submarine and terrestrial cables [7]. The use of submarine cables proved the feasibility of intercontinental clock comparisons, and a transatlantic optical link was realized [8]. The dissemination of frequency references via fibre was used in radioastronomy, for better measurements [5], demonstrating also new methods for intercontinental clock comparisons [9].
Last, coherent interferometry and phase noise control demonstrated to be useful in quantum communication, e.g. in effective Twin Field Quantum Key Distribution [10].
Time and Frequency Distribution, Clock Comparisons, Geophysics sensing and geodesy, Quantum communication can be all implemented at the same time on the Italian Quantum Backbone, thanks to its architecture, designed for multiapplication purposes, exploiting both T/F and single photon methods. Indeed, the Italian Quantum Backbone is the core of the QUID (Quantum Italy Deployment), the Italian realization of the initiative European Quantum Communication Infrastructure. At the Symposium, all this results will be shown and the forthcoming perspectives will be presented.

Fig.1. The Italian Quantum Backbone fibre research infrastructure for quantum technologies

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

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The methods of trapping and cooling of atoms and ions have been transformative for atomic clocks due to the reduction and in some cases elimination of major systematic frequency shifts [1], [2], [3]. Trapped atom/ion optical clocks have achieved orders of magnitude improvements in performance over their predecessors and have become a key component in national metrology laboratory research programs [4], [5]. Continuously operating atomic clocks based on trapped ions have existed for decades but have until now been restricted to terrestrial applications [6]. Here we report on NASA's Deep Space Atomic Clock (DSAC), which was launched in 2019 and became the first trapped ion atomic clock to operate in space [7]. The DSAC design did not include cryogenics, a sensitive microwave cavity, nor lasers. Instead, it operated at near room temperature, used simple travelling wave microwave components, and used a plasma discharge deep UV light source. The high maturity and robust operability of each of these enabled launch into and operation in space. On the ground, DSAC demonstrated a short-term fractional frequency stability of $1.5x10^{-13}/t^{1/2}$ [8]. In space it operated for 2 years where it achieved a fractional frequency stability of $1.5x10^{-13}$ at one second, a long-term stability of $3x10^{-15}$ for averaging times greater than a day, a time deviation of only 4 ns at 23 days (no drift removal), and an estimated drift of $3.0(0.7)x10^{-16}$ per day. Among the most stable space clocks currently in use, each of these established a new space clock performance standard by at least an order of magnitude [9], [10], [11]. The DSAC clock was also amenable to the space environment, due to low sensitivities to variations in radiation, temperature, and magnetic fields. It is expected that this level of space clock performance will enable one-way navigation whereby signal delay times are measured in-situ making near-real-time deep space probe navigation possible [12]. In this paper we will describe the DSAC performance in space along with its environmental sensitivities, the primary applications of this technology, and future directions.

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

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As communication and navigation systems increasingly rely on precise timing signals from atomic clocks, the interest for 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 stubborn trade-off [1]. Improving clock stability means higher number of atoms, better vacuum conditions, higher laser powers, and more complex system control, all of which inevitably result in larger size 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 as shown in Figure 1 [2].

M2TIC adopts the traditional trapped mercury ion microwave clock approach as it was demonstrated NASA Deep Space Atomic Clock [3]. To significantly reduce SWaP while maintain its high frequency stability capability, we have developed miniature vacuum trap tubes with field-emitter-arrays electron sources, 194-nm micro plasma lamps, and 40.5-GHz CMOS-based microwave synthesizers. We integrated these new technologies into the M2TIC clock prototypes, which demonstrated stability at the 10^{-14} level within a day, while packaged in a 1.1-liter standalone box and consuming less than 6 watts of DC power. This stability level is comparable to the widely used Microchip 5071A cesium frequency standard, which is much larger and consumes more power. The prototypes have also been shipped across North America intact to a government laboratory where they were independently tested and verified. One of the prototypes were able to run over 40 days with a drift less than any vapor-cell based atomic clocks in use. The successful demonstration of the M2TIC opens possibilities for high-performance clocks in terrestrial and space applications.

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

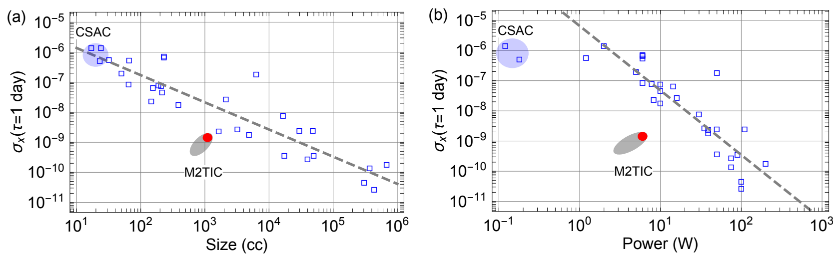

Fig.1. Time deviation after a day vs. size (a) and power (b) of some of the state-of-the-art compact atomic clocks. Existing compact atomic clock data (blue markers) are taken from Ref.1. The solid red dot indicates the current M2TIC prototypes, and the gray shaded area indicates possible further improvements. Figure from Ref. [2].

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

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GNSS satellites provide accurate: Time (w/ epoch uncertainty ≈ 10 ns), frequency (w/ fractional unc. ≈10^{-13}) and position (unc. ≈10 cm) worldwide at low cost. Those incredible systems meet or exceed most. In contrast, much of the Earth is covered by salt water and hence has no GNSS signals, but Position Navigation and Timing (PNT) information is required for many undersea applications (e.g. active and passive seismic monitoring, temperature profiles, ocean-geo science, navigation). We are exploring approaches for atomic clocks for undersea applications with objectives of < 1 ms timing uncertainty at 1 year in harsh ocean conditions, and with low power consumption (< 100 mW).

Quartz crystals and Chip Scale Atomic Clocks (CSAC) play critical roles in undersea timing. Commercial CSACs perform exceptionally well on only 120 mW, operate over a wide temperature range (-20 C to +70C). They represent a significant market (>10^5 sold as of 2019*) with diverse applications (GNSS receivers, instruments...) and achieving microsecond timing for days). [1-2] However, these fantastic low-power clocks were not optimized for undersea and very long duration timing.

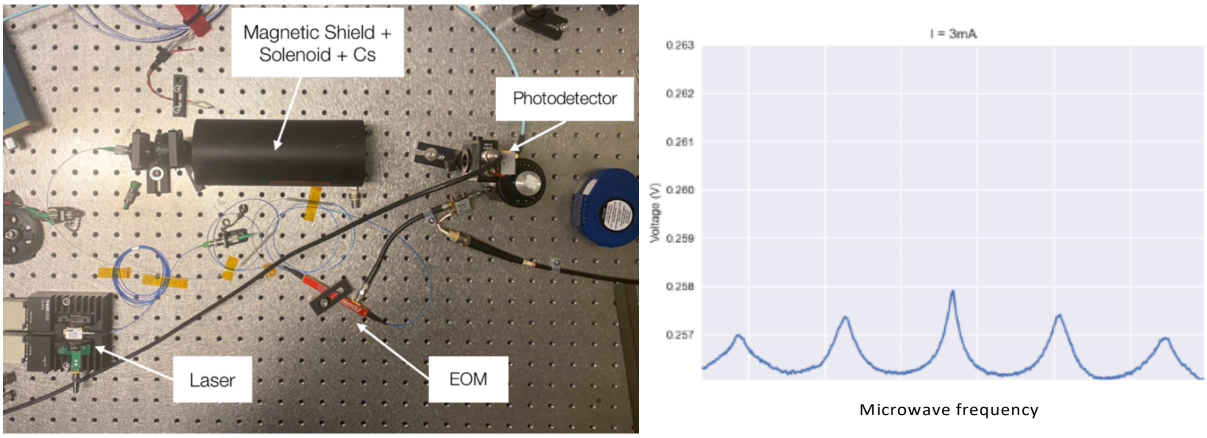

Fig.1. Image of our simple experimental test-bed for undersea atomic clocks. On the right are CPT signals verses microwave frequency (at 4.6 GHz). The multiple peaks illustrate the Zeeman structure for a small DC magnetic field. The resonance width of the magnetically "insensitive" central (m=0 to m=0) component is about 10 kHz FWHM. The other components could serve as an atomic magnetometer.

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 timing over durations of greater than one year. The approach is based on the same principles used in CSACs (laser-pumped Coherent Population Trapping (CPT) but operating in a very different range of the parameter space (Fig 1.). The initial results look promising, and we believe that it will be possible to improve the long-term timing performance relative to other low-power alternatives for the undersea environment.

The range of undersea applications of clocks is surprising, including, seismic monitoring of many types and even ocean water temperature profiles measured precisely by accurate timing of acoustic signals. This is particularly challenging in polar regions under ice, but the data is critical for climate modeling.[3]

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Compact clocks & cavities for space and ground applications

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This presentation addresses the problem of near-total reliance on global navigation satellite systems (GNSS) of multiple sectors and organisations across commerce, industry, defence and critical national infrastructure, and the difficulties arising for position, navigation & timing due to GNSS denial (e.g., constellation clock failures, orchestrated denial or solar storm activity). Current microwave GNSS satellite clocks and best-in-class commercial microwave clocks can provide holdover for short periods (e.g., hours to few days) in situations where GNSS disciplining is lost. Compact laser-cooled ion clocks, both microwave and optical, that could challenge or out-perform commercial maser capability but with smaller size, weight and power (SWaP), are being developed at NPL and elsewhere. NPL systems include a portable laser-cooled trapped $^{171}Yb^+$ multi-ion microwave system [1], as well as a portable laser-cooled single $^{88}Sr^+$ ion optical clock that employs a multi-wavelength dual-axis cubic cavity-stabilised clock control unit [2,3] suitable for space or ground deployment. The $^{88}Sr^+$ physics package and cavity sub-system are subjects of ESA studies for future space clocks and ultra-stable lasers for Earth observation and space science, as well as offering future resilient long-holdover times for ground segment portable clocks.

Our laser-cooled multi-ion $^{171}Yb^+$ 12.6 GHz microwave clock [1] operates on the ions' magnetically-insensitive Zeeman transition of the hyperfine ground state. Ions created by photo-ionisation of a weak thermal Yb atomic beam are confined within a linear 4-rod trap and laser-cooled with 369 nm light. Light at 935 nm repumps ions leaking from the cooling cycle. Progress on a compact package trapping thousands of ions in a cold crystal will be described, targeting a low-SWaP 3U or 4U complete rack-mountable system.

The laser-cooled $^{88}Sr^+$ strontium ion optical clock has a relatively simple energy level scheme, with some of the cooling and auxiliary transitions in the visible & near IR accessible by DFB lasers. The $^{88}Sr^+$ ion $^2S_{1/2} - {}^2D_{5/2}$ transition frequency is an internationally accepted optical secondary representation of the second. An early trap design achieved frequency agreement of 4×10^{-17} between two Sr^+ single ion systems. Our enhanced end-cap trap design [4] provides reduced frequency sensitivities to black body radiation and phonon heating rates. Activity is underway to increase robustness and reduce SWaP of the $^{88}Sr^+$ physics package to a 3U rack system. Central to the clock is a dual-axis 50-mm cubic spacer optical reference cavity [2], for pre-stabilising both clock laser and all cooling and auxiliary lasers to run an $^{88}Sr^+$ ion clock [3]. The spacer is an evacuated ultra-low-expansion glass cube with zero expansivity near room temperature, with mirrors optically contacted to opposite cube faces, achieving finesse ~ 200,000 on one axis. It has demonstrated vibration-insensitivities below $2.5\times10^{-11}g^{-1}$ for all axes. A single-axis cavity version has been subject to vibration/shock and irradiation testing, and thus suitable for both space and mobile ground deployment, providing an opto-electronic clock control unit with reduced footprint and avoiding the need for multiple cavities.

Applications such as the Kepler navigation idea, the next generation gravity mission (NGGM) and the LISA gravitational wave detector will be briefly discussed.

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Low-noise optical frequency divider for precision measurement

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Nowadays, the frequency uncertainties of optical atomic clocks achieve ~1×10^{-18}, and the uncertainties induced by optical frequency combs in optical frequency ratio measurement approach to 1.4×10^{-21}[1]. These impressive advances in optical frequency metrology have drawn wide attentions since many precision measurements succeed in gaining higher sensitivity or accuracy by transforming other quantities into a frequency. Among them, search for dark matter, tests of relativity, and detection of gravitational wave anticipate even more precise optical frequency ratio measurement.

Here we report an optical frequency divider (OFD), which can realize optical frequency ratio measurement and optical frequency division to other desired frequencies. The core of the OFD is an optical frequency comb based on a Ti:Sapphire mode-locked laser, which is stabilized to a maser or a rubidium clock for long-term continuous operation. The comb frequency noise in optical frequency division is subtracted via the transfer oscillator scheme [2]. An optically-referenced RF time-base [1], i.e. f_t in Fig. 1(a), is introduced for fine setting of the divisor and low division noise. Moreover, we demonstrate the transportability, long-term operation and multi-channel division of the OFD.

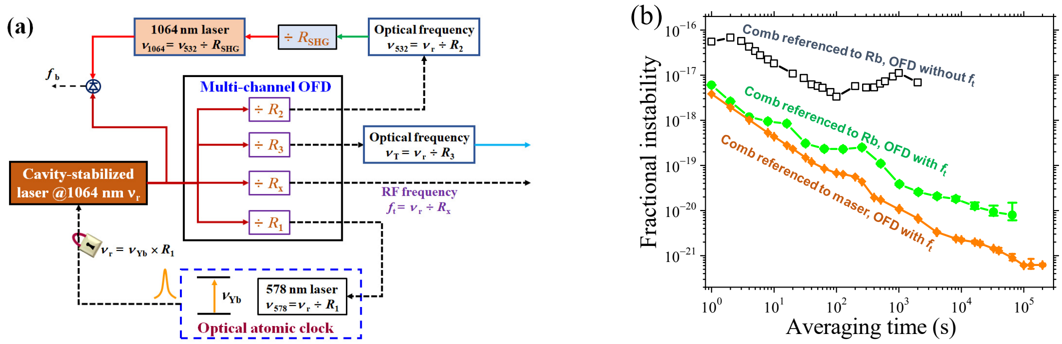

Fig.1. (a) Experimental diagram. We realize a multi-channel OFD, which can be referenced to an ytterbium clock. (b) The division noise induced by the OFD.

Using the OFD when the comb is frequency-stabilized to a maser, we divide the frequency of a cavity-stabilized laser at 1064 nm (ν_r) to 532 nm, $\nu_{532} = \nu_r/R_2$ in Fig. 1(a), while ν_{532} is the second harmonic of an independent 1064 nm laser, $\nu_{1064} = \nu_{532}/R_{SHG}$. By counting the beating frequency between ν_r and ν_{1064}, we measure R_{SHG} to be 2 with a fractional uncertainty of 3×10^{-22}, nearly five times better than previous results [1]. The statistical noise contributed by both the OFD and the second harmonic generation is 4×10^{-18} at 1 s in Fig. 1(b), 10 times smaller than that of the state-of-the-art optical clocks.

To make precision measurement with optical atomic clocks, we also realize an optical frequency synthesizer (OFS) referenced to an ytterbium optical clock [3]. The coherence of a portable cavity-stabilized 1064 nm laser with a frequency instability of 6×10^{-16} at 1 s (as local oscillator) is accurately transferred to a 578 nm laser with the OFD. Despite of megahertz-linewidth comb lines, hertz-level-linewidth ytterbium (Yb) clock transition is resolved, which is then used to faithfully reference the OFS to the ytterbium optical clock by regulating ν_r. Thereby, the output of the OFS is referenced to the Yb optical clock as $\nu_T = \nu_{Yb}\times R_1/R_3$.

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Ultrastable Lasers – New Developments and Challenges

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Lasers with long coherence time and narrow linewidth are an essential tool for quantum sensors and clocks. State-of-the-art optical oscillators employing cryogenic reference cavities with highly reflective dielectric coatings reach now instabilities of 4×10^{-17} for averaging times from seconds to hundreds of seconds [1,2]. This performance is limited by the Brownian thermal noise associated with the mechanical dissipation of the dielectric Ta_2O_5/SiO_2 mirror coatings.

Recently, crystalline AlGaAs/GaAs Bragg reflectors have emerged as a promising candidate for reducing coating thermal noise due to their low mechanical loss [3,4]. We present measurements of the frequency noise of fully crystalline cryogenic reference cavities with $Al_{0.92}Ga_{0.08}As/GaAs$ optical coatings applied to silicon substrates which are contacted to silicon spacers at 4 K, 16 K and 124 K. We have confirmed the reduced Brownian noise as expected from the low mechanical loss, however novel noise sources were identified that have so far prevented the expected improvements [5,6]. One contribution appears as fluctuations of the coating's intrinsic birefringence, while the other one appears as fluctuations with large-scale spatial correlations after averaging away the birefringent noise. To gain more insight into the physical mechanisms that may be related to the semiconductor properties of AlGaAs/GaAs, we are now investigating the non-thermal response of the coatings to changes in intracavity power, and to broadband illumination over a broader temperature range.

We will also report on alternatives for improving the stability, like nanostructured materials [7] or increased mode sizes. Finally, we will 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.

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Resonant photonic oscillators and regenerative frequency dividers

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Mode-locked Kerr frequency combs generated in nonlinear microresonators pumped with coherent monochromatic light [1] 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 [2] as well as other comb structures different from the usual Kerr combs [3-5]. 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 [3] and can be used as regenerative photonic frequency dividers.

Dichromatically pumped nonlinear cavities can generate frequency combs just because of the thresholdless frequency mixing process. The optical nonlinearity can be utilized to lock repetition rates of two frequency combs having nonoverlapping spectra or generated at orthogonal polarizations [6] in the same cavity. A Kerr comb can be injection-locked to a low power reference light coupled to the nonlinear cavity [7]. A higher power pump also leads to generation of frequency combs resulting from the time symmetry breaking in the cavity [3-5]. Stability of these unique comb states depends on the optimization of the dispersion of the nonlinear cavity.

The dichromatically pumped frequency comb fully locked to the pump light is a periodic in frequency structure in which two harmonics coincide with the pump frequencies. In the case the dichromatically pumped frequency comb becomes an ideal regenerative radio-frequency (RF) divider realized by pure optical means. Demodulation of the frequency comb on a fast photodiode results in generation of an RF beat note characterized with better spectral purity than the original pumping light can provide. In this presentation we will discuss properties and applications of the optical frequency combs generated in cavities by means of dichromatic light.

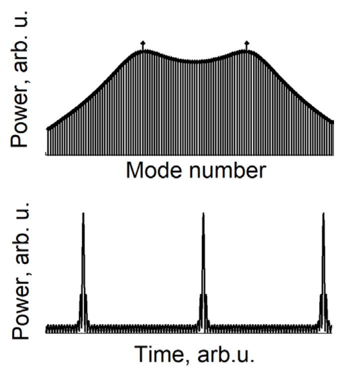

Fig.1. An example of a Kerr frequency comb and corresponding pulses generated in a nonlinear microcavity coherently pumped with dichromatic coherent light.

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

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The laser-cooled cadmium-ion microwave frequency standard has been developed at Tsinghua University for thirteen years. In 2013, we measured the ground-state hyperfine splitting frequency of $^{113}Cd^{+}$, and the precision was 5.7×10^{-13} [1]. In addition, we obtained preliminary short-term frequency instability to approximately $1.0 \times 10^{-12}/\sqrt{\tau}$ [2]. In 2015, the precision was further improved to 6.6×10^{-14}, and the short-term frequency instability was measured to be $6.1 \times 10^{-13}/\sqrt{\tau}$ [3]. In 2021, the performance of our cadmium-ion microwave frequency standard was improved once again. The second-order Zeeman frequency shift and its uncertainty was determined to be $1.05720(3) \times 10^{-10}$ due to the better magnetic shielding design, which is the most important factor among all factors that affect the performance of the $^{113}Cd^{+}$ clock. Finally, the ground-state hyperfine splitting frequency of $^{113}Cd^{+}$ was determined to be 15199862855.02799(27) Hz with a fractional frequency uncertainty of 1.8×10^{-14}, and the fractional frequency instability was measured to be $4.2 \times 10^{-13}/\sqrt{\tau}$ [4], which is close to the short-term instability limit estimated from the Dick effect. The result was consistent with previously reported values, but the measurement precision was four times better than the best result obtained to date.

To overcome the limits suffering from the Dick effect because of the dead time in the laser-cooling process and second-order Doppler frequency shift introduced by the ions rising temperature during interrogation, the sympathetic cooling technology was applied. In 2022, using laser-cooled $^{40}Ca^{+}$ as coolant ions, we developed a high-performance cadmium-ion microwave frequency standard. During the experiment, the $^{113}Cd^{+}$ ion crystal is cooled to below 100 mK and has a coherence lifetime of over 40 s. The short-term frequency instability reached $3.48 \times 10^{-13}/\sqrt{\tau}$ [5], which is comparable to that of the mercury ion frequency standard [6]. Its uncertainty was reduced to 1.5×10^{-14}, which was better than that of directly laser-cooled cadmium-ion microwave frequency standard.

Moreover, a microwave frequency standard based on laser-cooled $^{171}Yb^{+}$ ions has also been developed in our laboratory since 2021. More than 10^{5} $^{171}Yb^{+}$ ions were stably trapped for over 40 hours. The short-term frequency instability of our system was measured to be $8.5 \times 10^{-13}/\sqrt{\tau}$. The ground-state hyperfine splitting frequency of $^{171}Yb^{+}$ was determined to be 12642812118.4674(8) Hz with a fractional frequency uncertainty of 6.33×10^{-14} [7]. Our work is in a continuous line with that of other scholars, while the short-term instability is promoted into a new record level.

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Cesium and Rubidium fountains at NTSC

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The National Time Service Center, Chinese Academy of Sciences (NTSC), generates and maintains the UTC (NTSC), which connects BeiDou Navigation Satellite System Time (BDT) to UTC, and broadcasts the time signal to users through BPM, BPC and BPL systems, networks and telephones, etc. Cesium atomic fountain primary frequency standards(PFS) and Rubidium fountain clocks are building to produce more accurate and stable local atomic time UTC(NTSC).

NTSC-CsF2 is operating to calibrate hydrogen maser as PFS. A cold atom beam source produced by 2D MOT is used to increase the loading rate. Microwave leakage is confirmed below 130dB before and after assembling the physical package in the free drift zone and around the detection zone. The type A and combined type B uncertainties of NTSC-CsF2 is exhibited at 3×10^{-16} and 4.2×10^{-16} in 30 days period . Frequency comparison between NTSC-CsF2 and the SI second show the rate difference of $3.9(4.5) \times 10^{-16}$ over six months through GNSS link with reduced chi-square of $\chi 2 = 1.1$. This indicates NTSC-CsF2 is consistent with that of the other fountains within the uncertainty.

NTSC-CsF3 is under building to operate at cryogenic temperature near 85 K. The microwave cavity[1] have been tested to install in physical package. A zero-evaporation liquid nitrogen Dewar device maintains a continuous cryogenic environment for free drift zone. Preliminary operation indicates blackbody radiation frequency shift is 9.05×10^{-17}, and the uncertainty is 2.68×10^{-18}.

Rubidium fountain clock NTSC-RbF1 is developed as a continuous clock (^{87}RFCC) like commercial cesium clocks. A frequency doubled C-band telecom fiber laser is lock to the ^{87}Rb D2 line by modulation transfer spectroscopy in pulse mode. In this way, the frequency is decreased to 150MHz red detuned during post-cooling stage and remain locking during other stage. The fountain generates 5 MHz or 1 PPS signal by the phase and frequency offset generator with maser input which exhibited a frequency stability of $1.91\times10^{-13}\tau^{-1/2}$, reaching 4.7×10^{-16} at 200000 s [2]. Since May 2022, the NTSC-RbF1 has demonstrated frequency drift of E-18/d level and they have regularly received weight in the TAI timescale.

NTSC-RbF2 has similar structure except the laser setup, which is made of all fiber component including fiber laser, AOM, shutter and splitter. An ultra stable oscillator HSO14 is lock to Ramsey fringe directly, which is shown frequency stability $3\times10^{-13}\tau^{-1/2}$(1-10000s). A cyro sapphire oscillator is an alternative to improve the stability down to $5\times10^{-14}\tau^{-1/2}$.

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Re-evaluation of the NRC-FCs2 Fountain Clock

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We will describe the re-evaluation of the NRC-FCs2 fountain clock, which was first evaluated in 2019 [1]. Since that time, it has demonstrated both accuracy and robustness and has contributed regularly to the steering of International Atomic Time (TAI) through monthly submissions to the BIPM. It is also currently used to steer UTC(NRC), Canada's official timescale.

A typical monthly error budget for NRC-FCs2 is shown in Table 1. The systematic uncertainty is slightly higher than the 2.3 x 10^{-16} reported in [1]. The higher uncertainty is due to cold collisions, which can vary from month to month. We have recently undertaken a re-evaluation of the systemic biases in NRC-FCs2, with the goal of reducing the systematic uncertainty by a factor of ~2. The uncertainty is dominated by 4 contributions: cold collisions, distributed cavity phase shift (DCP), microwave leakage, and synchronous phase transients. Of these effects, we have significantly reduced the uncertainty contribution of all but DCP, for which the re-evaluation is ongoing. Notably, the uncertainty in the cold collision frequency bias (previously the largest contribution to the systematic effect) has been reduced by an order of magnitude by using absorption imaging to better characterize the effect [2].

The re-evaluation of the NRC-FCs2 fountain clock will be beneficial in several areas. It reduces the uncertainty of the contributed data for the steering of TAI, as well as for the steering of UTC(NRC). Additionally, we are preparing for an absolute frequency measurement using the NRC $^{88}Sr^+$ optical clock, which will be limited by the uncertainty of the fountain clock. The reduction in the systematic uncertainty from the re-evaluation will allow for the most precise absolute measurement of the NRC $^{88}Sr^+$ optical clock by a factor of 2 [3].

Physical effect	**Bias [10^{-16}]**	**Uncertainty [10^{-16}]**
Zeeman effect	724.92	0.2
Blackbody radiation	-162.61	0.7
Gravitational redshift	104.52	0.03
Cold collisions	-	**2.25 (0.2)**
DCP m=0	0.07	0.4
DCP m=1	**-0.71**	**1.3**
DCP m=2	0.04	0.2
Microwave lensing	0.60	0.2
Microwave leakage	**0.10**	**1.0 (0.3)**
Synchronous phase transients	-	**0.8 (0.5)**
Total	666.9	3.05 **(1.7)**

Table.1. Contributions to type B uncertainty for NRC-FCs2 for BIPM reporting period MJD 59819 - 59849. The largest contributions to the uncertainty are in bold, with the re-evaluated uncertainties shown in parentheses. Biases and uncertainties are given in fractional frequency.

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Fringes and Light Shift in CPT-Ramsey Spectroscopy

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The long-term frequency stability of CPT (Coherent population trapping)-based atomic clocks is limited by the light shift of the excitation lights [1]. To reduce the light shift, Ramsey's method based on two separated excitation pulses were used as so-called CPT-Ramsey [2]. Furthermore, auto balanced Ramsey methods were developed to remove them perfectly, but the complicated process leads to reduce the size of fringes [3]. Up to now, the mechanism of CPT-Ramsey was often explained by the idea of the Raman Ramsey [4] and the observed light shift has not yet been clarified theoretically. Recently, Micalizio and Godone solved the time evolution of the Bloch vector after the steady-state condition is achieved at the first pulse and derived that there are a detection-dependent light shift and a Rabi-pulling induced light shift, based on the light shift of CPT maser [5]. According to their idea, we could derive an expression of CPT-Ramsey fringes and formulized the light shift in CPT-Ramsey Δ_{CPT-R} from the ordinal light shift Δ_{LS} , as follows,

$$\Delta_{CPT-R} = \Delta_{LS}\left(\frac{\tau_2}{T} + \frac{1}{1+(\gamma_c+2\Gamma_p)T}\right), \quad (1)$$

where T is a free evolution time, τ_2 is detection time, γ_c is the coherence between ground states, and Γ_p is the excitation rate. Typical calculated fringes are in good accordance with the experimental results as shown in Fig. 1. Eq. (1) confirms the experimental results as a function of free evolution time, as shown in Fig. 2. It should be noted that Δ_{CPT-R} becomes constant, although Δ_{LS} increases as the excitation rate increases.

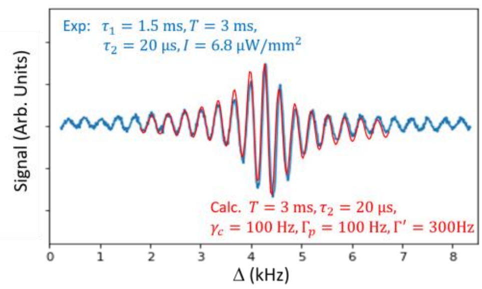

Fig.1. Typical CPT-Ramsey fringes. Experiment (blue) and calculation (red).

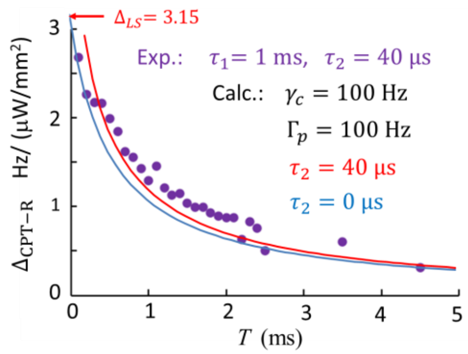

Fig.2. Light shift in CPT-Ramsey versus free evolution time T. Experiment (dot) and calculation (solid lines).

We would like to discuss a method of further reduction of the light shift in the CPT-Ramsey.

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

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To accurately control frequency shifts of the clock transition (5s5p) $^3P_0$ – (5s^2) $^1S_0$ in neutral strontium and operate a clock at a fractional uncertainty below 10^{-17}, detailed understanding of the lattice light shift and the blackbody radiation (BBR) shift is necessary. The fractional frequency correction of the BBR shift with respect to the clock transition frequency is in the order of 10^{-15} at room temperature, and therefore the largest correction in most strontium lattice clocks. In order to shield the atoms from BBR and to operate at cryogenic temperature, we designed and installed a dual layer copper heat shield. Currently, apertures to inject an atomic beam still cause a direct line of sight from the atoms to the external environment, which causes a fractional uncertainty of our clock at 1×10^{-18} for operation at 80 K. Blocking the atomic beam holes during the interrogation is planned by installing additional beam shutters. This modification is estimated to reduce the uncertainty to less than 2×10^{-19}.

Regarding the lattice light shift, one must consider not only electric-dipole (E1) interactions, but also higher-order multipole contributions, such as electric-quadrupole (E2) and magnetic-dipole (M1) interactions, between the optical lattice and the atoms. However, previous experimental and theoretical results [1-3] exhibited large discrepancies in the values of the E2-M1 polarisability $\Delta\alpha_{qm}$. Corrections of the light shift using the values reported in [1] and [2], respectively, deviate by up to 1×10^{-17} from each other for typical operation conditions. This renders light shift correction with a fractional uncertainty at the 10^{-18} level impossible. In an independent experimental determination of the $\Delta\alpha_{qm}$ coefficient, where we measured the differential lattice light shift for different motional state distributions, we found $\Delta\alpha_{qm} = -987^{+174}_{-32}$ μHz [4]. This result is in very good agreement with the experimental value reported by Ushijima *et al.* Two recent publications, one experimental by Kim *et al.* [5] and one theoretical by Wu *et al.* [6], corroborate the conclusion that previous theoretical results are incorrect. Discarding those theoretical values lowers the fractional uncertainty of the lattice light shift to 1×10^{-18} and better for trap depths around 70 E_{rec}.

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The development and future of the Faraday laser

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External cavity diode lasers (ECDLs) are very important in a lot of areas. Specifically, the ECDLs that can correspond to the atomic transition lines are extremely significant in many applications. Traditionally, the main frequency selective methods for ECDLs are gratings, Fabry-Pérot etalons and interference filters. The ECDLs based on those methods always have excellent performance in tunability, output wavelength stability, and these methods are commonly used in commercial products. However, the output wavelength of those ECDLs mentioned above cannot automatically correspond to the atomic lines, and is easily affected by fluctuations in the temperature and current of the laser diode. The ECDLs using the Faraday anomalous dispersion optical filter (FADOF) as the frequency selectivity element, which was first named as "Faraday laser" by Peking University [1], have extremely good performance. The Faraday lasers have immunity to the fluctuations of laser diodes' temperature and current [1,2], and its output wavelength directly correspond to the vicinity of the atomic transition lines immediately as soon as it is turned on. The basic principle of the FADOF's frequency selection is that, the Faraday anomalous dispersion effect only occurs when the frequency of the incident light is near the resonant transition frequency of the atoms. As a result, the FADOF can limit the laser frequency to the atomic Doppler-broadened line, and leads to the fantastic phenomena.

Moreover, we have proposed some methods to solve the mode hopping problem caused by the inner mode of laser diode. In 2011, based on the first creative use of the anti-reflection coated laser diode [2], Peking University achieved an ECDL with rubidium FADOF operating at 780 nm that is immune to the fluctuations of current and temperature of the laser diode. In the past dozen years, we have made a lot of great efforts. The excited-state rubidium FADOF at 775.9 nm without any additional frequency-stabilized pump laser, the ultranarrow-bandwidth FADOF at 455 nm based on the combination of Faraday effect and saturation effect, the high transmittance FADOF with single peak or working at side wings, the cold atom FADOF with the narrowest transmission bandwidth as well as high figure of merit, and a great deal of other breakthroughs have been achieved to optimize the Faraday laser. Besides, the excited-state Faraday laser based on the electrodeless discharge vapor lamp, the free running 852 nm Faraday laser, the frequency stabilization of the Faraday laser to atomic lines have been achieved step by step. We always focus on improving the Faraday laser and try to create a new generation for ECDLs through quantum technologies. After the realization of frequency locking of Faraday laser, the fractional frequency Allan deviation of the residual error signal is down to $5.8 \times 10^{-15}/\sqrt{\tau}$ [3], and it can be further improved.

In addition, we also achieved the Voigt laser, whose wavelength fluctuation is less than ±0.5 pm when the diode current is changed between 73 mA and 150 mA. We believe the Voigt laser is also a promising type of laser for future applications in quantum technology. We also use a corner-cube reflector as the cavity mirror to improve the environmental adaptability of Faraday laser. Furthermore, the Faraday lasers are applied to the optically-pumped cesium atomic clock and the cesium fountain clock to improve the performance of atomic clocks, and they can also be applied to atomic magnetometers, atomic gravimeters, and other quantum precision measurements in the future.

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Active Optical Clock: Seventeen Years of Progress and Next Steps

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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.

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Frequency comb for $^{88}Sr^{+}$ clock frequency comparison with Cs fountain clock at the NRC

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The redefinition of the SI second in terms of optical atomic transitions is expected to happen within the next few years. The CIPM has issued requirements for candidate clocks to be considered in the redefinition [1-3]. Among these requirements is continuity: the candidate clock frequencies need to be measured against current primary frequency standards and the measurements need to be mainly limited by the systematic uncertainty of the Cs clock. NRC has recently commissioned its Cs fountain clock NRC-FCs2 [4]. NRC also has a candidate clock for the redefinition, the $^{88}Sr^{+}$ single ion clock, which was used to make an absolute frequency measurement with an uncertainty of 4.3×10^{-16} [5].

In this work, we present the portable saturable absorber-based fibre combs made for this clock comparison [6-7]. We also present the setup that we intend to use for the $^{88}Sr^{+}$ single ion clock measurement campaign against NRC-FCs2. The ultrastable probe laser [8] of the $^{88}Sr^{+}$ clock at 674 nm will serve as the local oscillator of both clocks. The stability of the Cs fountain clock operating with two different local oscillators can be seen in Fig.1. The fractional frequency uncertainty averages down as $\sigma_y = 2.9\times10^{-14}/\sqrt{\tau}$ when using the ultrastable laser as its local oscillator through the comb, while it is averaging as $\sigma_y = 10.5\times10^{-14}/\sqrt{\tau}$ using NRC's best active hydrogen maser. The departure from a $\sigma_y \propto \tau^{-1/2}$ dependence fails at τ ~ 100 s due to the drift of the ultrastable probe laser not being perfectly removed. As soon as the slow laser drift correction is properly implemented, we should see nearly a factor ten reduction in averaging time, essentially reaching the systematic uncertainty of NRC-FCs2 in one day. This scheme will also be used to facilitate the re-evaluation of the systematic biases of NRC-FCs2.

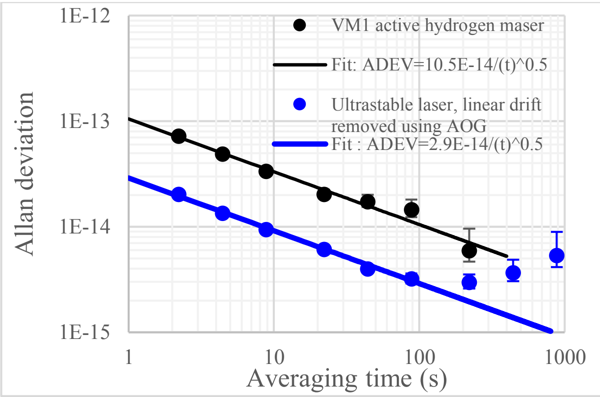

Fig.1. Stability of the NRC-FCs2 fountain clock using two different local oscillators. Black: active hydrogen maser. Blue: ultrastable laser through comb. Fit for τ <100 s.

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The Optimization of Cold Atom Microwave Clocks

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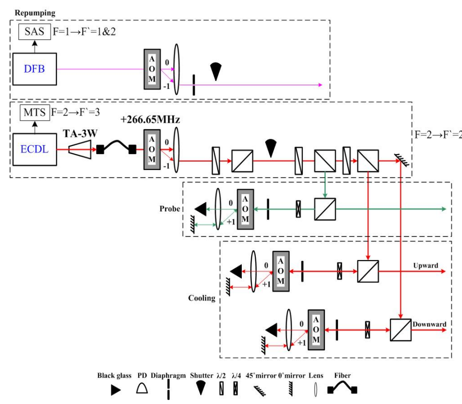
The cold atom microwave clocks play important roles in the field of primary frequency standards[1], space exploration[2], satellite navigation[3][4], time keeping and fundamental physics, in which the microwave local oscillator drives the transitions between two well-defined cold atomic states using 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[1] and integrating sphere cold atom clock[3][4].

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.

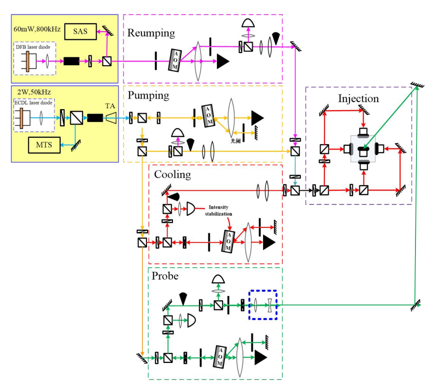
The first part focuses on the ^{87}Rb atom fountain clock to solve the problem of the laser frequency stability and limited free evolution time. As shown in Fig.1(a), an ECDL and a DFB laser are applied to build the optical path, whose laser frequency are stabilized by modulation transfer spectrum and 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 ^{133}Cs 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.



(a)



(b)

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Sr Optical Lattice Clock and Precision Optical Frequency Measurement at NIM

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Two Sr optical lattice clocks are being built at NIM. Sr1 was built on NIM's Hepingli Campus. It was first evaluated in 2015 and improved later on.[1] In 2021, the systematic shift uncertainty of Sr1 was evaluated to be 2.9E-17. Sr2 was started to be built on NIM's Changping Campus in 2017. Many improvements have been made in the design of Sr2, like black body radiation control, 30 cm long reference cavity based clock laser, cooling and lattice laser frequency stabilization, etc. The systematic shift uncertainty of Sr2 was evaluated to be 7.2E-18 in 2022.[2] In order to compare these two Sr clocks, an optical frequency transfer fiber link with a length of 54 km was established between these two clocks.

NIM has two cesium fountains, which can be used as the local references to measure the absolute frequencies of optical clocks.[3] The remote method to measure the absolute frequencies of optical clocks through a satellite link was also adopted, with reference to the ensemble of primary and secondary frequency standards published in the circular T bulletin by BIPM. With the remote method, the absolute frequency of Sr1 was measured with an uncertainty of 3.1E-16[1]. The same method were applied to 3 other optical clocks in China, with the measurement uncertainties at the level of E-16.

Preliminary study of generating a local time scale with Sr1 has been carried out at NIM.[4] The time scale generated by post-processing of the comparison data between Sr1 and a H-maser demonstrated a better stability than the time scale that steered by UTC.

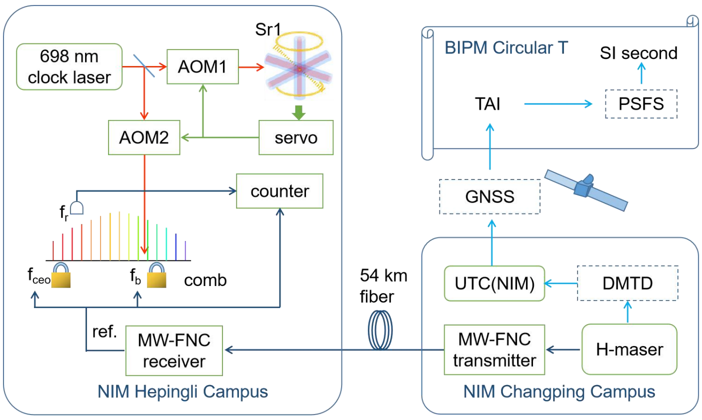

Fig.1. Remote method to measure the absolute frequency of Sr1 with a satellite link.

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Status Report on Yb optical lattice clocks at KRISS

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Optical lattice clocks based on Yb atoms have been developed at KRISS since 2002. The absolute frequency of the first Yb optical lattice clock at KRISS (KRISS-Yb1) has been reported in 2013 [1], in 2017 [2], and in 2021 [3], contributing to the determination of the BIPM recommended values of standard frequencies. KRISS-Yb1 is now being operated regularly to contribute to International Atomic Time (TAI) as one of the most contributing optical clocks worldwide. The total systematic uncertainty of KRISS-Yb1 has been gradually improved and it now reached 1.7×10^{-17}, however, further improvement was considered to be impossible. This uncertainty limit was mainly caused by the blackbody radiation (BBR) shift uncertainty due to the temperature inhomogeneity of the stainless steel vacuum chamber of KRISS-Yb1.

We developed the second Yb optical lattice clock (KRISS-Yb2) to reach the 10^{-18} uncertainty level overcoming this BBR shift uncertainty. KRISS-Yb2 introduced a copper BBR shield for more homogeneous thermal environment. After the temperature stabilization of the BBR shield, the temperature at the atom trap site was determined with an uncertainty of 13 mK. The total uncertainty of the BBR shift including the atomic response was evaluated as 9.5×10^{-19} [4]. Also, six electrodes were installed in the BBR shield to evaluate the DC Stark shift along three axes. We expect that the total systematic uncertainty of KRISS-Yb2 would be improved to be less than 5×10^{-18} with these upgrades. Preliminary uncertainty evaluation results will be presented at the conference.

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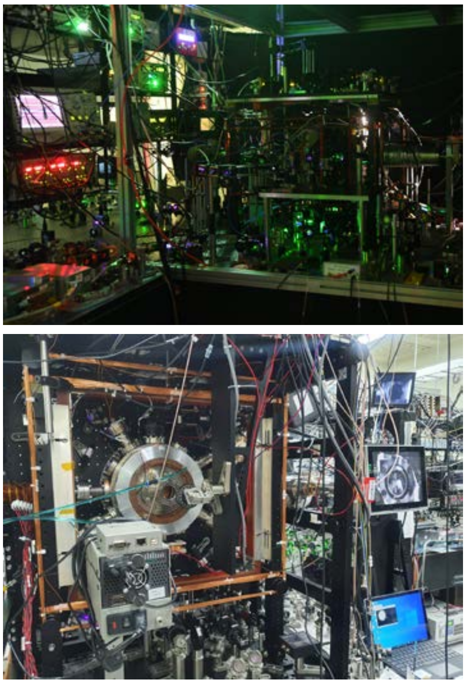

Fig.1. Photo of KRISS-Yb1 (upper) and KRISS-Yb2 (lower).

PTB's Second-Generation Transportable Strontium Lattice Clock

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According to general relativity, the difference in the gravitational potential seen by two clocks directly influences their frequency ratio. Highly accurate clocks are therefore promising tools to map the geopotential. To become geodetically relevant, fractional clock frequency differences of about 1×10^{-18}, corresponding to geopotential differences of $0.1\ m^2\ s^{-2}$ or 1 cm height differences near the Earth's surface, need to be resolvable. Although state-of-the-art laboratory optical atomic clocks have reached this level of accuracy, their usage for geodesy is limited by their lack of portability [1,2]. Here we present our recent efforts in making these complex devices in-field deployable: our second-generation transportable strontium lattice clock.

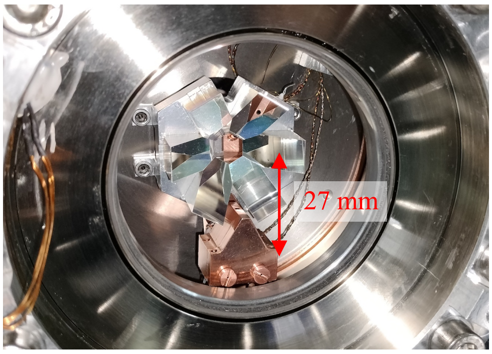

Fig.1. The pyramid MOT mirrors and the BBR shield.

For robust cooling and trapping of ^{87}Sr atoms, a single-beam pyramid magneto-optical trap (MOT) is used (Fig. 1). It consists of six silver-coated copper-substrate mirrors and one CaF_2 prism [3].

After laser-cooling and trapping of atoms in the MOT, they are transferred into an optical lattice, generated by two opposing laser beams. A frequency chirp on one of the beams is then used to move the atoms into a blackbody radiation (BBR) shield for clock interrogation and another to move them back for state readout [4]. The shield is made from copper and connected to a pulse tube refrigerator, allowing operating temperatures below 170 K and thus, together with a high-emissivity coating on the inside, enabling fractional BBR shift uncertainties below 1×10^{-18} [5].

Other improvements upon our old setup [6] include a better vacuum with a pressure in the low 10^{-11} mbar range for a reduced background gas collision shift and a mu-metal shield for a stable magnetic field environment.

To achieve a higher clock stability, the setup is equipped with a new, frequency-doubled, transportable clock laser based on a 20 cm long, ultra-stable resonator with crystalline AlGaAs mirror coatings. Operating at 1.4 µm, the laser system reaches an instability in modified Allan deviation of down to 1.6×10^{-16} [7].

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Light shift suppression in rubidium two-photon optical references

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Optical frequency references (OFR) based on two-photon spectroscopy of warm rubidium vapors offer performance with instabilities at or below 10^{-13} at 1 s and longer [1,2] with a potential for low operating size, weight, and power [3]. Optical clocks based on this technology offer performance approaching maser level instability, which can enable applications such as distributed coherent sensing. Overall performance of two-photon OFRs is often a trade-off between improving short-term performance by enhancing the signal-to-noise ratio by increasing probe beam power at the expense of degraded long-term stability due to increased ac light shift [1,2].

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. The experimental setup for implementing this hybrid error signal is shown in Fig. 1 (a). As described in reference [4], by scaling the standard error signal by a factor proportional to P^{-3}, where P is the probe laser power, the resulting error signal has a power independent lock-point corresponding to the zero-light-shift point (Fig 1. (b)). The hybrid error signal is generated using demodulation with a reference signal that has an envelope with a $(1/P_{mod})^3$ scaling. Figure 1 (c) shows preliminary measurements of laser stabilization using the hybrid error signal. The total power is changed at about 600 s and 1500 s. We observe a light shift of about 2 kHz for the standard error signal, while the hybrid error signal suppresses the light shift to below 100 Hz.

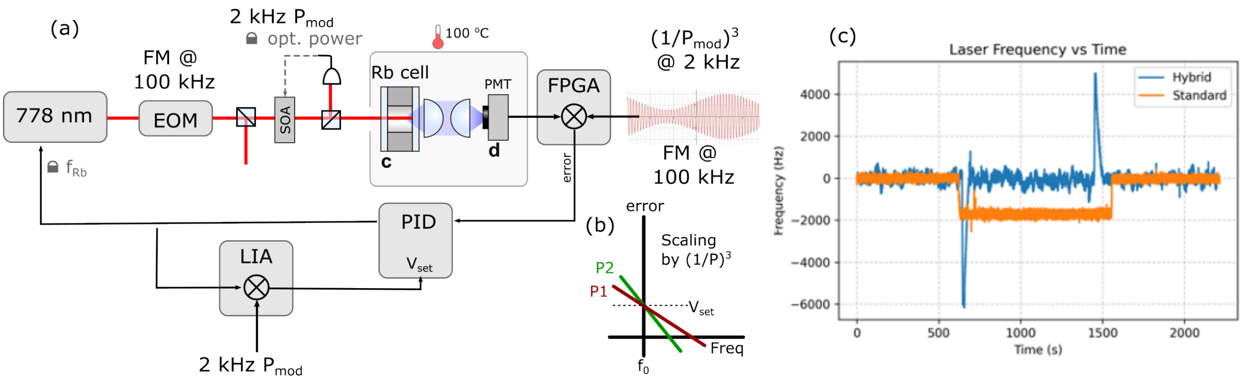

Fig. 1. Light shift suppression for Rb two-photon spectroscopy. (a) Probe power modulation (P_{mod}) is applied using a semiconductor optical amplifier at 2 kHz. The hybrid error signal is generated using demodulation with a reference signal that has an envelope with a $(1/P_{mod})^3$ scaling. The offset for the frequency lock point is determined by detecting residual modulation at 2 kHz in the correction signal for the probe laser. (b) Hybrid error signal with zero-light-shift lock point at V_{set}. (c) Preliminary measurements comparing laser stabilization using the hybrid and standard error signal. The total power is changed at about 600 s and 1500 s.

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Compact and Robust Laser System for Transportable Strontium Optical Lattice Clock

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An optical lattice clock [1] realizes a fractional frequency uncertainty of 10^{-18} level [2] and is a promising candidate for a redefinition of the SI second. Furthermore, it is expected to be used for geodesy [3] and fundamental physics [4]. Most of optical lattice clocks have been developed as stationary systems in laboratories because of complexity of system containing multiple lasers and control electronics. On the other hand, for use outside laboratories, clocks need to be compact and to operate continuously over a long period. In our previous work, a transportable optical lattice clock with a volume of 920 L were developed to test the gravitational redshift at Tokyo Skytree [5, 6].

One of our goals is to make optical lattice clocks easier to use in various applications. We are downsizing the clock while improving robustness and maintainability. The optics were fixed by laser welding to prevent misalignment during transportation and operation. The volume of the laser system was reduced by removing adjustable mechanisms and integrating multi-function electronics. To facilitate maintenance, the laser system was divided into modules that can be easily replaced. By utilizing the developed laser system, an optical lattice clock with a volume of 250 L was realized as shown in Fig. 1.

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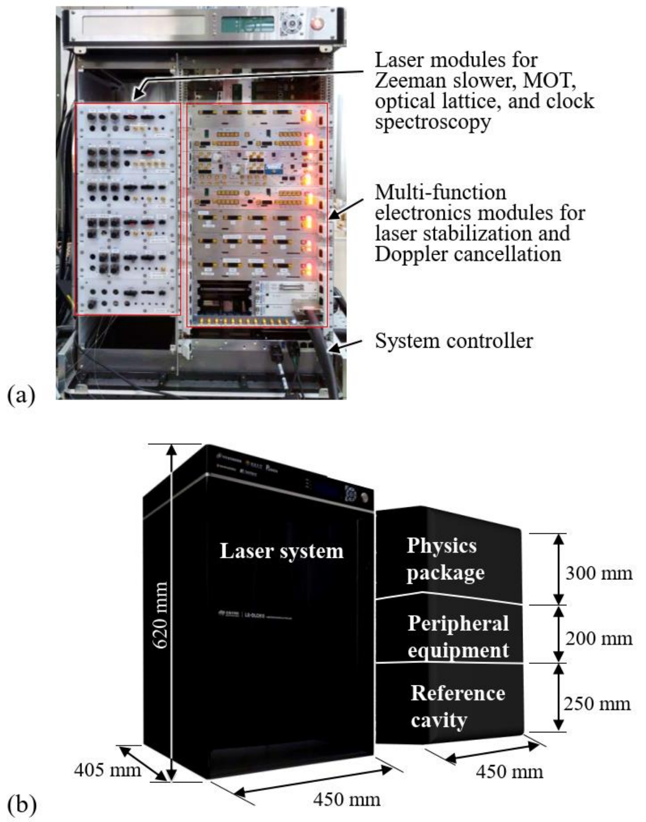

Fig. 1 Developed laser system and optical lattice clock. (a) Front view of the laser system. (b) Overview of an optical lattice clock composed of the developed laser system, a physics package and a reference cavity.

Cavity Design Simulation for an Atomic Fountain Clock KRISS-F2

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A cesium atomic fountain clock KRISS-F1 [1-3] and an optical lattice clock KRISS-Yb1 [4] 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 as shown in Fig. 1. 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. By using a bimetal (Ti + Cu) structure, Fasong Zheng *et al*. [5] reported achieving df/dT value 150 times smaller than that of typical microwave cavities with uni-metal (copper) material. 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.

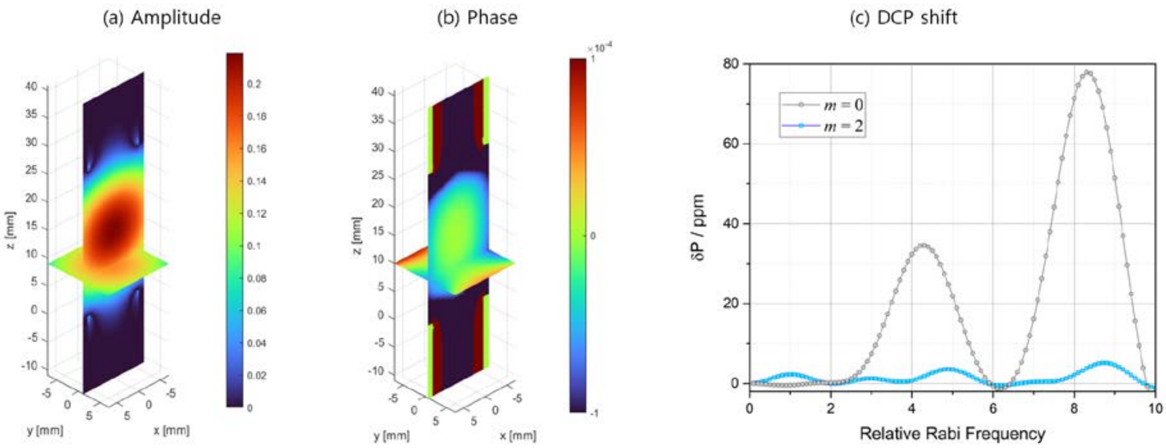

Fig. 1 . Example of a DCP shift calculation with the Monte-Carlo method. (a) Amplitude and (b) phase of *z*-component of the magnetic field inside a normal cylindrical cavity calculated from FEM simulation code (COMSOL). (c) Difference of the transition probability at the two sides of the central Ramsey fringe due to the DCP variation of $\boldsymbol{m} = \boldsymbol{0}$ and $\boldsymbol{m} = \boldsymbol{2}$ azimuthal modes when 10^6 atoms are launched and probed by a Gaussian laser beam.

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

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The blackbody radiation (BBR) Stark shift constitutes the leading uncertainty in the state-of-the-art optical lattice clocks [1,2]. Several approaches to control the shift have been reported that utilize radiation shields at room [3] or cryogenic temperatures [4,5]. The former approach has been limited by the knowledge of higher-order dynamic corrections to the BBR shift estimation in room temperature shields, whereas the latter confronts challenges in truly isolating the atoms from leaking room temperature radiation. In either case, the BBR uncertainty typically lies at 10^{-18} fractional frequency level.

We report on the design and construction of an in-vacuum cryogenic radiation shield that enables controlling the BBR shift uncertainty *below* the 10^{-19} level. By mechanically actuating the shield internal structure during spectroscopy time of each clock cycle, the shield *completely* encloses the atomic sample with highly emissive cryogenic surfaces, blocking atoms' direct line of sight to the external environment but allowing a small optical access through thick cryogenic BBR-blocking windows for the optical lattice and spectroscopy beam.

Separately, we report a novel lattice loading scheme that enables arbitrary atomic sample distribution over more than 5 mm along the lattice. Using a combination of the MOT cloud position control and shelving to the metastable clock transition, we demonstrate loading flat-top samples and spatially resolved atomic ensembles with control over each ensemble atom number. The scheme reproduces cloud distributions that are stable shot to shot, and avoids lattice complexities such as movable optical lattices [6]

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The Optical Clock with $^{176}Lu^+$

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Singly ionized lutetium ($^{176}Lu^+$) 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, demonstrated 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 investigate this through high accuracy measurements of differential quadrupole moments and g-factors [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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Development of commercial fountain clocks in NIM

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While Cs fountain clocks have achieved a typical Type B uncertainties of a few parts in 10^{16}, and are employed as the primary frequency standards to realize the definition of the second [1-7], 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 $1.49\times10^{-13}/\sqrt{\tau}$ 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 3.5×10^{-16} was obtained compared with NIM5 Cs fountain clock as shown in figure 1. The instability after 4 days didn't drop as $\tau^{-1/2}$ is under study.

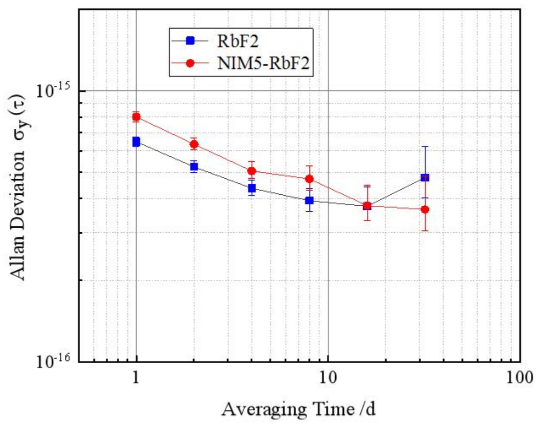

Fig.1.The measured instability of Rb fountain clock. The blue squares are compared to a H-maser, and its long term instability drifts up due to the H-maser. The red dots are compared with NIM5 fountain clock.

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

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Ultra-stable lasers are important for high-resolution spectroscopy and optical atomic clocks [1]. Laser frequency noise limits precision in measurement and bounds frequency standards. It affects not only the resolvability and interaction times with optical-atomic transitions but also degrades clock stability through the optical 'Dick effect' [2]. To achieve high stability a laser is typically locked with feedback control to an optical cavity resonator using the Pound-Drever-Hall technique [3]. The inherent length stability of an optical cavity is imparted upon a laser's frequency. Optical cavities are bounded in their ultimate stability by the random 1/√f thermal motion in their reflective coatings. Reducing or mitigating this fundamental thermodynamic bound is an important area of research for the science of precision measurement and optical time standards.

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 multiple higher order modes, the effective sampling area of mirrors increases. This improves the averaging of thermal motion, thereby lowering the overall length noise. We propose a scheme where a top-hat like beam is effectively synthesized from a weighted combination of signals fed back to a laser. We will present results of a theoretical study into this new scheme and progress and plans for an experimental implementation.

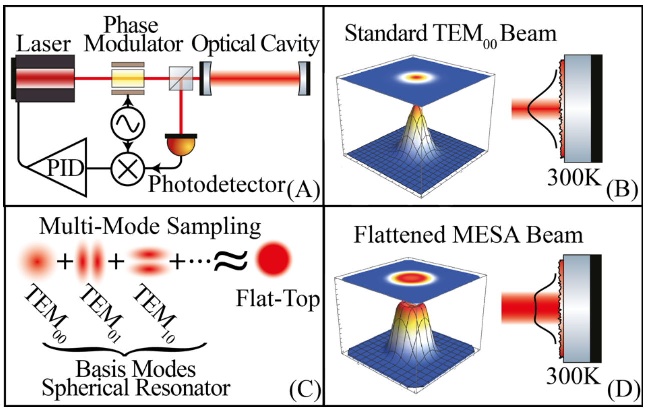

Fig.1. Figure 1:(A) Classic Pound-Drever-Hall locking typically implements a (B) TEM00 Gaussian Beam that is strongly weighted to the center reducing the averaging potential of beams incident on mirrors. By combining the basis set of Hermite Gaussian Modes (C) a Flat-top beam can be synthesized similar to the diffraction limited 'MESA' beam (D) that maximizes the spread of laser light on mirrors while steeply cutting off at the edges to avoid clipping.

We will show that an experimentally feasible implementation of a three-mode lock – combining modes TEM_{00}, TEM_{02}, and TEM_{20} – can reduce overall coating thermal noise by a factor of 1.6, equivalent to cooling the mirrors to 120 K. Such improvements are multiplicative with advancements in materials, cryogenics, and cavity lengthening approaches.

We will also outline the achievable bounds on thermal noise improvements for many higher order modes (more than three) and prospects for implementation in in the laboratory.

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Superradiance on ytterbium clock transition for frequency metrology

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The most accurate timekeepers available today are passive optical atomic clocks [1], which rely on frequency stabilization of an external optical local oscillator on an atomic transition. In passive clock schemes, the intermittent interrogation of atoms gives rise to the Dick effect, which is, along with cavity instabilities, the limiting factor for state-of-the-art passive optical clocks.

To circumvent the issues related to the local oscillator frequency instability, a promising idea is to directly collect fluorescence emitted by an atomic ensemble on a narrow optical transition and to use it as an ultra-stable frequency reference for the clock laser. Nonetheless, the anticipated optical powers achievable with a feasible number of atoms are insufficient for practical applications. To enhance atomic emission, an appealing idea is to exploit the superradiant emission of the atoms to generate a signal, the optical power of which scales as the number of atoms squared [2]. Furthermore, another advantage of superradiance lies in the nature of the optical signal, as it relies on coherent spontaneous emission rather than the overall atomic population. In this work, we present the development of a cold atom active optical clock designed to leverage superradiant emission on the forbidden $^1S_0 \rightarrow {}^3P_0$ narrow-linewidth transition in ^{171}Yb. Contrary to strontium, which is another candidate of interest for superradiant experiments [3], Yb's simple hyperfine structure does not degrade repumping efficiency.

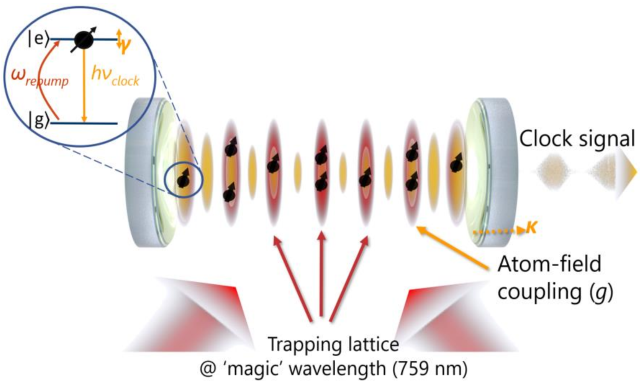

Fig. 1 Scheme of a superradiant laser.

In our experiment, a collimated thermal beam of Yb atoms generated in an oven is decelerated using a Zeeman slower. At the final capture velocity at ~10 ms^{-1}, the atoms can then be trapped in a conventional three-dimensional magneto-optical trap operating on the $^1S_0 \rightarrow {}^3P_1$ transition (Γ = 182 kHz), and cooled down to a Doppler-limited temperature of 4 μK. From here, the atoms will be transported using an optical conveyor belt over a distance of ~ 40 cm to an ultra-stable tunable cavity, where a dipole trap will ensure an efficient coupling with the cavity mode. Finally, the atoms will be prepared to generate superradiant pulses on the narrow (Γ = 7 mHz) $^1S_0 \rightarrow {}^3P_0$ clock transition at 578 nm. Operating in the "bad-cavity" regime, these pulses can exit the cavity and be employed to stabilize the frequency of the clock laser. To achieve the ultimate goal of continuous superradiance, one crucial factor is the continuous reloading of atoms into the cavity. A two-site loading of the cold atomic ensembles has been designed to achieve this objective.

With this design, we expect the initial fractional frequency stability of the system to be on the order of 10^{-13}. Active optical clocks in principle have the potential to reach stabilities in the 10^{-18} level.

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Demonstration of A Calcium Atomic Beam Optical Clock

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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 $^1S_0$-$^3P_1$ 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 $^1S_0$-$^1P_1$ 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.

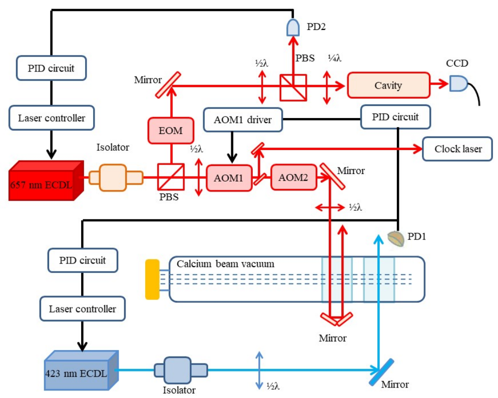

Fig. 1. The schematic of the calcium beam frequency standard.

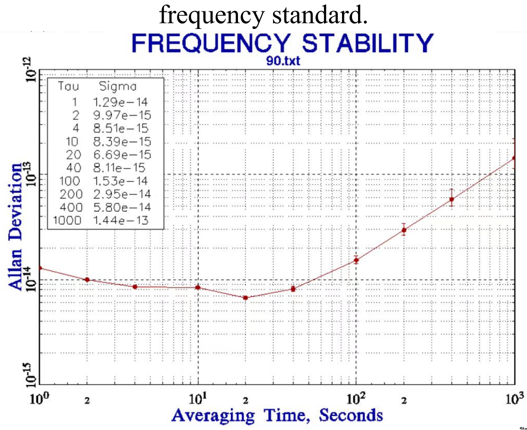

Fig. 2. The Allan Deviation results.

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Optical Lattice Clocks at NPL

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In the two decades since its inception, the optical lattice clock [1, 2] has been established as a leading platform for optical frequency metrology with multiple examples evaluated at close to 1×10^{-18} total systematic fractional frequency uncertainty [3-5]. Several high-uptime systems, including NPL-Sr1 [6], now regularly contribute to TAI, highlighting the progress of the technology for adoption in critical timing infrastructure and propelling the case for a redefinition of the SI second. Exploiting the low quantum projection noise offered by the many-atom system has relied heavily on a complementary effort to develop ultrastable lasers [7-10], mitigating to an extent the problematic Dick-effect and enabling record single clock instabilities approaching $1 \times 10^{-16}\tau^{-1/2}$ [3, 11, 12]. Through synchronous comparisons of clocks sharing the same local oscillator, relative clock instabilities approaching one order of magnitude below this figure have been observed, both between distinct clocks at NPL and others [12], and across neighbouring ensembles that share a similar environment. This has allowed for measurements of gravity at the mm-scale [13, 14] and highlights the promise of a new realm of precision space-time measurement.

We present our contribution to the state-of-the-art including the evaluation of NPL-Sr1 targeting $< 5 \times 10^{-18}$ total systematic uncertainty, and the systems in place to achieve high-uptime near-autonomous operation and validation for contribution to timescale steering, both locally synthesised and in on-time contributions to the BIPM for determination of TAI. Framed by the goal of improving the precision of the NPL $^{171}Yb^{+}$(E3)/^{87}Sr frequency ratio which offers a favourable sensitivity to variations in the fine structure constant, we will present composite clock schemes similar to ref. [15] to extend local oscillator coherence for reduced Yb^{+} QPN-limited instability. The schemes entail both dynamical decoupling [16] in near zero-deadtime operation of two Sr clocks, where 50% duty cycle [17] cannot be trivially reached, and the exploitation of quantum non-demolition readout schemes for repeated successive measurement of laser phase [18]. Finally, progress of a new Yb optical lattice clock with focus on low measurement deadtime, and fully autonomous operation will be presented.

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Development of Transportable Optical Lattice Clock.

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A laboratory-based optical lattice clock resolves a millimeter height difference of atoms trapped in an optical lattice by the gravitational redshift [1]. Chronometric leveling, which relies on the gravitational redshift of two remote clocks, is one of the most promising applications of optical lattice clocks, allowing real-time monitoring of seismic and volcanic activities underground [2,3]. Field deployable clocks have been developed worldwide [4-10], some of which resolve a few centimeters height difference [7,8].

We developed our 2nd generation transportable optical lattice clock (Figure 1). Its physics package fits in the volume of less than 50 L, which is 16% of that of our 1st generation transportable system [8]. The physics package was operated by modularized lasers and electronics. We successfully demonstrated clock operation using ^{87}Sr.

By sharing an ultra-stable clock laser, we synchronously compared the 1st and 2nd generation transportable clocks to achieve clock stability of low 10^{-18} after averaging 10^4 s (Figure 2). The systematic frequency shifts and their uncertainties are under evaluation. This work was supported by the JST-Mirai Program "Space-time information platform with a cloud of optical lattice clocks" (JPMJMI18A1).

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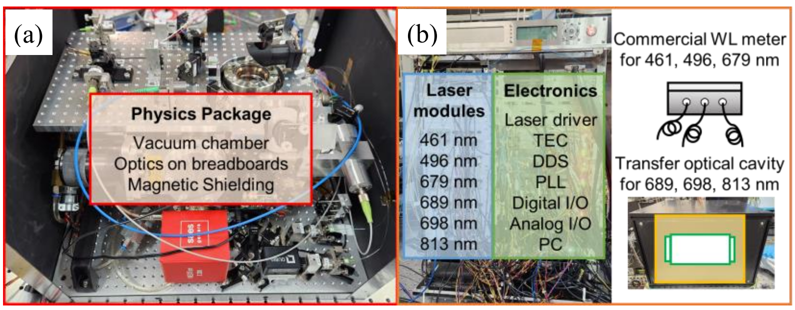

Figure 1: A transportable optical lattice clock.
(a) Cooling, trapping and clock spectroscopy of ^{87}Sr were conducted in the physics package. (b) Laser and electronics modules to operate the physics package.

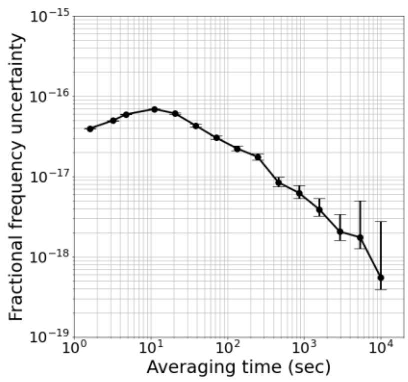

Figure 2: Overlapping Allan deviation of synchronous frequency comparison. Statistical uncertainty reached low 10^{-18} in 10^4 s of averaging.

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

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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.

The entire system is shown in Fig. 1. The single $^{171}Yb^{+}$ ion is trapped in a linear Paul trap which consists of six electrodes. Four cylindrical electrodes act as radio frequency (RF) electrodes for radial confinement; two tapered electrodes act as endcap (EC) electrodes for axial confinement; two extra cylindrical electrodes act as compensate (CMP) electrodes for the compensation of stay electric field and reducing micromotion of ion.

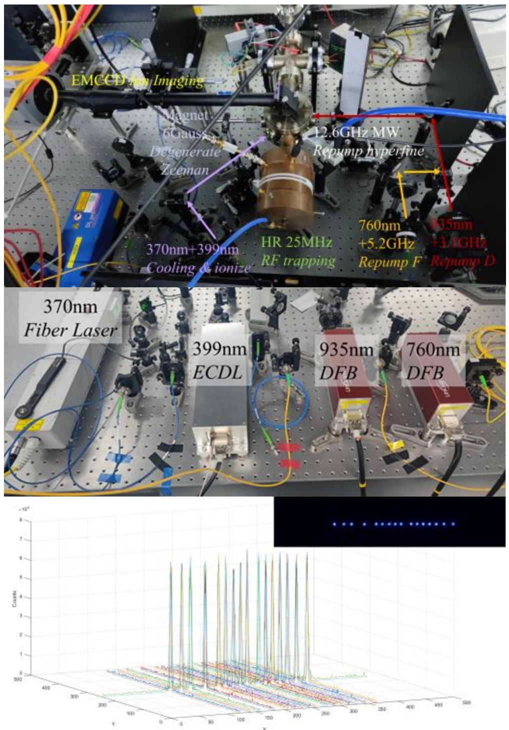

Fig.1. System, Lasers & $^{171}Yb^{+}$ ion crystal.

Lasers are fully made in China. The 370 nm laser beam is used for Doppler cooling the $^{171}Yb^{+}$ ion. Two repump laser beams of wavelengths 935-nm and 760-nm are used to repump the $^{171}Yb^{+}$ ion from the $^{2}D_{3/2}$ and $^{2}F_{7/2}$ dark states. A 3.06-GHz and 5.2-GHz microwave sidebands are applied to the 935-nm and 760-nm laser beams by fiber electro-optic modulator (EOM) to eliminate the hyperfine dark state of the $^{2}D_{3/2}$ and $^{2}F_{7/2}$ level, respectively. Laser beam output from the fiber collimators is focused on the $^{171}Yb^{+}$ ion through lenses installed on translation stages. The waists of the focused laser beams are around 50 μm. The frequencies of laser beams are stabilized to a high-precision wavelength meter (HighFinesse WS8-2) by a proportional–integral–derivative controller. The wavelength meter can further be calibrated using an ultra-stable "clock laser".

The temperature of the single $^{171}Yb^{+}$ ion is estimated through the EMCCD image. The image of ion is the convolution of the point-spread function (PSF) and the fluorescence of the ion [1,2]. The temperature of the single $^{171}Yb^{+}$ ion is estimated to be around 0.8 mK which close to its Doppler cooling limit. The temperature of multi $^{171}Yb^{+}$ ions is also estimated to be below 1 mK, which indicate a low heating rate of our ion trap. A low temperature of ion aiding a suppression of the second-order Doppler shift of uncertainty.

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

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The self-consistent fundamental theory of standard model (SM) is successful in classifying the elementary particles and describing interactions between fundamental forces, but it left some questions unanswered in its incompatibility with General Relativity (GR). The search of new physics beyond SM and GR will help answer those questions. The possibility that the Local Lorentz Invariance Violations (LIV) might exist motivates a variety of precision measurements. Test models are well described in the Standard Model Extension (SME) by introducing anisotropies into different sectors of SM and GR [1, 2]. SME coefficients are thus grouped into different sectors including light, matter, neutrinos and gravity.

In this work, we will present the test of local Lorentz invariance using the precision measurements of oscillation masses of particles (phonons) [3, 4]. 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 loadings 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 [5] and low sensitivity to other effects such as temperature, vibration, acceleration and aging [6]. 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.

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

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Astrophysical observations [1] suggest the existence of an unknown kind of matter in the Universe, in the frame of the ΛCDM model. The research field of dark matter covers an energy scale going from massive objects to ultra-light scalar fields [2], on which we focus in the present work. It is supposed that ultra-light scalar fields couple with several fundamental constants of physics, including the fine structure constant α and the electron mass m_e, and induce an oscillation of those constants that depends on the coupling parameters d_e and d_{m_e}. As a consequence, the length of objects also changes due to Bohr radius oscillations, but the speed of light stays unchanged. This makes ultra-stable Fabry-Pérot cavities ideal tools for ultra-light dark matter detection [3-4], 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}. Our 14 cm cavity is composed of two mirrors optically bonded to an ultra-rigid spacer, with each element made in a single crystal of silicon, and cooled at 17 K in order to cancel the thermal expansion coefficient of the silicon spacer. The state of the art aimed frequency stability of the laser is $\sigma_y = 3 \times 10^{-17}$, limitated by the thermal noise of the cavity, and in particular the reflective coatings [5]. In order to reach this remarkable stability, several effects have to be sufficiently controlled to be under the thermal noise limit. While the contribution of the residual amplitude modulation is now smaller than the thermal noise [6], we are currently implementing a laser power lock [7] with residual fluctuations lower than $\Delta P = 60$ pW and a piezo servo loop to actively reduce the vibration noise that has to be inferior to -110 dB/(m.s^{-2})^2 at 1 Hz.

Here, we present both 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.

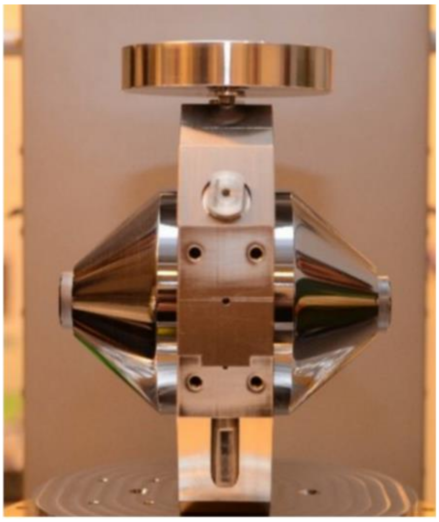

Fig.1. 17 K cryogenic single crystal silicon cavity at FEMTO-ST, in its mount.

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

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Precision atomic metrology gives us an extraordinary probe of physics beyond the Standard Model, enabling searches for new particles, dark matter, variations of fundamental constants, and violations of fundamental symmetries (see, e.g., review [1]). Many of the most sensitive probes extract limits on new physics from differential measurements of heavy atoms with complicated open-shell spectra. This necessitates accurate calculations of these systems for planning and supporting experiments, as well as to interpret the results as limits on new physics.

As an example, recent measurements of the isotope shift of Yb and Yb^+ have seen strong deviation from theory (the 'King plot nonlinearity' [2]), which could be interpreted as evidence for a new force-carrying boson that couples electrons and neutrons [3-5]. However, atomic theory is required to quantify (or remove) systematic nuclear effects that might also create the observed deviations, such as quadratic field shifts. Calculations in open-shell atomic systems like Yb^+ are notoriously difficult to perform with high accuracy.

Novel clocks based on highly charged ions promise significant gains in sensitivity to new physics effects, while simultaneously improving frequency precision [6]. The required accuracy of calculation for these systems increases with ionization stage because of the strong cancellation of binding energies in an optical transition, posing a challenge for atomic structure theory.

I will present some motivations, methods, and results of calculations using the particle-hole CI+MBPT method [7] implemented in the AMBiT code [8]. All-order coupling of selected core shells allows the method to have accuracy comparable to coupled-cluster methods (Fig. 1) while being applicable across the entire periodic table.

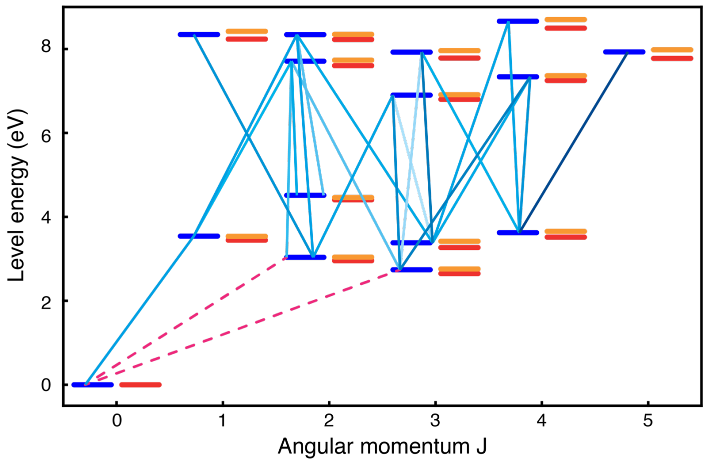

Fig.1. Grotrian diagram at the 5p – 4f orbital crossing in Pr^{9+} [9]. Blue: experiment; Red: CI+MBPT calculations using AMBiT; Orange: Fock-space coupled-cluster calculations.

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Development of a molecular Hg_2 clock to investigate fundamental physics

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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 [1, 2], with the ultimate goal of constructing a Hg_2 optical molecular clock [3, 4]. This tool has the potential to push limits for fundamental research by achieving unprecedented advancements in terms of precision and accuracy.

To experimentally investigate new hadron-hadron interactions, we will employ Hg_2, one of the heaviest two-atom molecule. The interatomic potential of Hg-Hg is relatively well-characterized [5], especially compared to other heavy molecules like Yb_2. Nonetheless, to mitigate the impact of theoretical imperfections, we will leverage quantum defect theory [6] and measure rovibronic bound states near the dissociation threshold within the ground electronic configuration [7]. This approach has recently emerged as a promising method for probing new interactions [8].

The spectroscopy of Hg_2 will be conducted in gas samples cooled to microkelvin temperatures within a dipole trap. Experimental results from one- and two-color photoassociations involving various isotopologues of Hg_2 will provide essential insights into quantum defects that describe near-threshold bound states, with and without electron excitation. Mapping these bound states within the Hg_2 system will allow us to select the appropriate isotopologue for realization of the optical molecular clock [8]. To achieve the electronic ground state of Hg_2, a two-stage experiment will be employed. Firstly, a weakly bound state of Hg_2^* (near the molecule dissociation limit) will be created through photoassociation. Subsequently, the electronic ground-state molecule will be formed via stimulated Raman adiabatic passage (STIRAP). The realization of an optical molecular clock will be pursued based on proposed scenarios outlined in Ref. [3]. The photoassociation spectra will be referenced to optical atomic frequency standards, aiming for sub-kHz level accuracy. The formation of ultra-cold Hg_2 molecules through photoassociation represents a significant advancement in our understanding of fundamental physics.

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Precision Laser Spectroscopy for Antiprotonic Helium

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Metastable antiprotonic helium is an exotic atom composed of a helium nucleus, an electron, and an antiproton in a Rydberg state. By measuring the transition frequencies of this atom by sub Doppler two-photon laser spectroscopy, the antiproton-to-electron mass ratio can be determined to high precision which can then be compared to the proton value [1]. Any deviation, however small, would indicate that this fundamental symmetry of nature is broken.

The ASACUSA collaboration at CERN will utilize the new ELENA storage ring [2] that has the potential to carry out these measurements at an improved level. The experiment synthesizes samples of antiprotonic helium by utilizing a pulsed beam of antiprotons that arrive from ELENA every 2 minutes; once formed, some of the long-lived states of the atom contain antiprotons for up to 10 µs, in the course of which they are probed by two Ti:Sapphire lasers. For proper spectroscopy, during the microsecond lifetime, it is necessary that the lasers have a frequency uncertainty as low as possible: at the level of 10^{-11} or better. This requirement, quite relaxed at first sight, is very stringent, since it corresponds to a time fluctuation of a few tens of attoseconds.

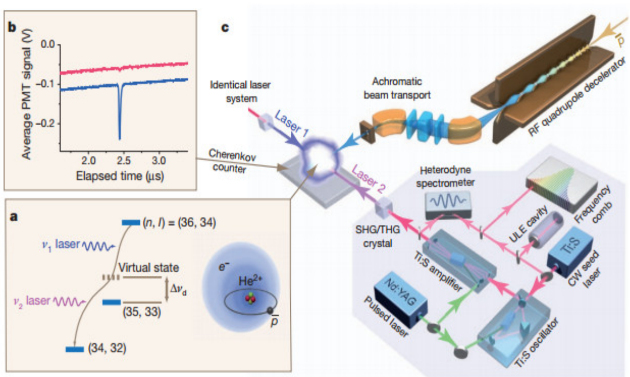

Fig.1. Frequency chain that is used to refer the probing lasers to a primary frequency standard. A Nd:YAG laser pumps the Ti:Sa laser; the ultrastable ULE cavity acts as flywheel and the frequency comb closes the gap with the local RF reference. The latter is disciplined by GNSS. The figure is from [1].

In this work, we will show how to approach this problem, how to analyze the frequency chain reported in Figure 1 and how to calculate its contribution to the frequency uncertainty. We will consider the role of the hard sampling induced by the very short lifetime together with the long repetition period; we will discuss which estimator between Allan and classical variances is more suitable; we will derive the formulae for calculating the contribution of each term in the polynomial-law model of the noise. Finally, we will use these tools to provide a noise budget for different configurations in order to understand which one is better for present and future needs.

The authors acknowledge Davide Calonico, Ronald Holzwarth and Enrico Rubiola for fruitful discussions.

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Optical atomic clocks for fundamental physics research

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Optical atomic clocks have recently played an important role in the exploration of fundamental physics. In these studies, optical clocks, optical cavities, as well as networks composed of these components in various configurations can be utilized. As the reliability of optical clocks increases and international clocks campaigns can be performed for several weeks almost continuously, a growing volume of data becomes available for analysis [1]. We outline our calculation methods geared towards utilizing these data to search for fundamental constant variations which may originate from scalar fields that oscillate in time or takes the form of topological domains with topological defects between them [2].

Despite predictions by cosmological theories, the characteristics of these variations remain largely uncharacterized. In this context, our study aims to shed light on the distinct sensitivity variations between active and passive optical atomic clocks with respect to transient effects. We explain how the operation of an optical atomic clock in an active mode can augment its sensitivity for the detection of very short transient effects.

While pulsed superradiant emission [3] from a clock transition in an ensemble of atoms in a bad-cavity regime has been reported [4], continuous operation is still under development. A continuously operating active clock based on the phenomenon of superradiance could overcome passive clock limitations deriving from thermal noise and mechanical vibrations within the clock laser cavity [5]. Theoretically, it is suggested that even quasi-continuous operation of such an active clock would lead to the exceedingly stable phase/frequency output. We present the current state of an experimental setup developed for conducting superradiance tests at the clock transition $^1S_0$-$^3P_0$ in strontium atoms.

We also propose to use a cryogenic ultra-stable cavity made from present-day components as a resonant-mass gravitational-wave detector [7]. Its sensitivity superior to other bar-like detectors in the kHz frequency regime, enabling detection of gravitational signals from neutron stars mergers and subsolar-mass black holes mergers as well as ultralight bosons formed through a black hole superradiance.

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Fundamental physics with an Optical Clock Orbiting in Space: FOCOS

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Precise time and frequency comparisons of high-stability optical lattice clocks via high-performance free-space optical links can dramatically improve tests of fundamental physics and searches for physics beyond the standard model. The FOCOS mission concept consists of an optical lattice clock in an elliptical Earth orbit and an optical link to ground clocks [1]. The elliptical 8 hour orbit in Fig. 1 has a $\delta\nu/\nu = 2.4\times10^{-10}$ modulation of the Earth's gravitational redshift, and enables a frequency comparison of the orbiting clock at periapsis and apoapsis with the same ground clock every 12 hours. This utilizes the high frequency stability of the clocks [2] for a measurement of the gravitational redshift at the ppb level, an improvement of a factor of 30,000 over the recent result from Galileo [3] (see Fig. 2).

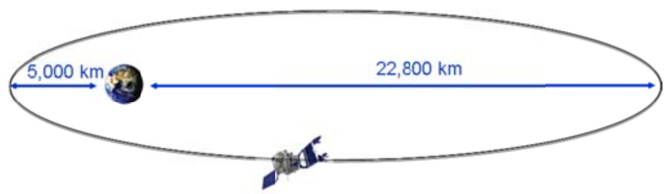

Fig.1. The FOCOS mission will perform precise time and frequency comparisons between a high-stability orbiting optical clock and ground optical clocks. An elliptical 8-hour orbit allows large variations in the gravitational redshift to be observed every 12 hours from the same ground station.

The orbiting FOCOS clock may also serve as a primary frequency standard, free from gravitational tidal perturbations on Earth, and provide world-wide high performance links between ground clocks. A network of ground clocks will allow precise frequency comparisons and can extend searches for dark matter and time variations of fundamental constants.

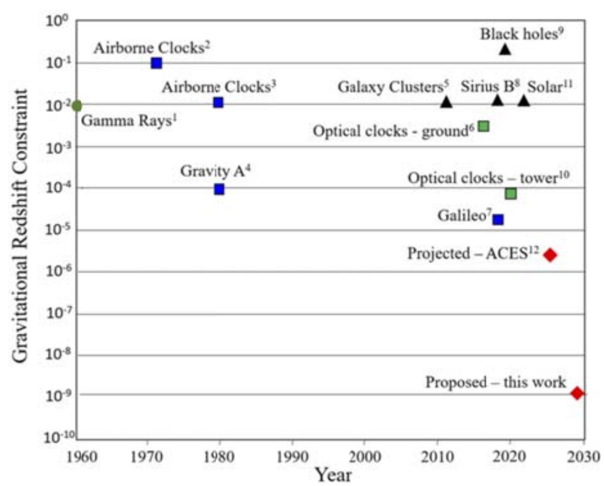

Fig.2. Tests of the gravitational redshift, from [1]. The high-stability or an orbiting optical clock may improve the best tests of the redshift by a factor of 30,000, to an uncertainty of 1 ppb.

The 8-hour orbit requires a telescope for the optical link with a modest SWaP, size, weight and power. Further SWaP development, especially for the orbiting lattice clock, may reduce the estimated FOCOS power requirement of 250 W.

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Quantum clock precision studied with a superconducting circuit

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We theoretically and experimentally study the precision of a quantum clock near zero temperature, explicitly accounting for the effect of continuous measurement. The clock is created by a superconducting transmon qubit dispersively coupled to an open co-planar resonator. The cavity and qubit are driven by coherent fields, and the cavity output is monitored with a quantum noise-limited amplifier. When the continuous measurement is weak, it induces persistent coherent oscillations (with fluctuating periods) in the conditional moments of the qubit, which are manifest in the output of the resonator. On the other hand, strong continuous measurement leads to an incoherent cycle of quantum jumps. 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 a kinetic uncertainty relation for the precision, and experimentally verify that this quantum clock obeys the kinetic uncertainty relation for the precision, thus making an explicit link between the (kinetic) thermodynamic behaviour of the clock and its precision, thus achieving the first experimental test of a kinetic uncertainty relation in the quantum domain.

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

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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 [1,2], 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 [3].

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. Examples include precision tests of the Standard Model at low energy [9], studies of atomic polarisabilities for the development of optical atomic clocks [8], searching for dark matter [4,6], and searching for variation of fundamental constants, including in the extreme gravitational environment around the super-massive black hole at the centre of our galaxy [5].

Motivated by recent measurements of several properties of alkali metal atoms and alkali-like ions, 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. Using the all-orders correlation potential method, we perform high-precision calculations of E1 transition amplitudes between the lowest s, p, and d states of the above systems. We perform a robust error analysis, and compare our calculations to 43 amplitudes which have high-precision experimental determina-tions. We find excellent agreement, with accuracies at the level of 0.1% or better [7].

Half our calculated amplitudes are *within the experimental uncertainties*, demonstrating unprecedented theoretical accuracy for many-body atoms, and setting a new precedent for atomic theory precision. Further, 95% of our calculated amplitudes are within 1σ combined (theory + experimental) uncertainties, much better than statistically expected, demonstrating our theory uncertainties are con-servative. Together, this demonstrates that the atomic theory is at the same level as most atomic ex-periment for transition amplitudes, and that theoretical uncertainties can be determined robustly. We also compare our results to other theoretical evaluations, and discuss the implications for uncertainty analyses of theoretical methods. In particular, we observed that in many cases there is a large discrepancy between various calculations using coupled-cluster methods, possibly indicative of the sensitivity of such methods to basis choices and the details of the inclusion of triple excitations. Our method, which is based on an exact summa-tion of screening diagrams using a Feynman diagram and Green's function technique, does not suffer from these issues.

Finally, by combining highly accurate calculations of branching ratios with recent experimental data, we extract new high-precision values for several E1 amplitudes of Ca^+, Sr^+, Cs, Fr, and Ra^+.

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QED radiative corrections to electric dipole amplitudes in heavy atoms

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In the last years, increasing attention has been given to the role of quantum electrodynamic (QED) radiative corrections in high-precision studies of heavy many-electron atoms and ions. The ability to theoretically describe electric dipole (E1) transition matrix elements with high precision is important in a number of different areas, both fundamental and applied, including atomic parity violation studies, atomic polarizabilities, and atomic clocks. The account of QED corrections was critical in the interpretation of the atomic parity violation measurement in cesium [1].

We report on the first detailed study [2] 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; see also Ref. [3].

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Dark matter detection via atomic interactions

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The mystery of dark matter (DM) is a long-standing issue in physics, with numerous dedicated experiments returning no confirmed detections. As many direct detection experiments rely on catching a signal of nuclear recoil, these types of experiments are not applicable to many DM models.

Instead, we can utilise the precision that atomic physics allows to search for potential interactions between atomic systems and DM, with possibilities spanning a large mass range. If we have a DM particle with masses just above electrons, then we can search for signals of atomic ionisation [1, 2]. If we move to masses just below electrons, then we look to absorption of DM on atomic electrons [3].

Moving much further down to where DM begins to behave like a classical field, then we can measure the effects with atomic systems, such as those in atomic clocks and variations in fundamental constants [4]. Additionally, interactions such as these many be possible to detect with current and upcoming detection experiments.

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.

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The hyperfine anomaly and precision atomic searches for new physics

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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 studies, and for maximising the impact on particle physics discovery.

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The ORGAN Experiment: Phase 1 results

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Precise cosmological measurements provide strong evidence for the existence of dark matter and estimate that it accounts for 85% of all the matter in our Universe. Axions are hypothetical, massive, spin-0 particles that were first postulated as an elegant solution to the strong CP problem in quantum chromodynamics. The weakly interacting nature of axions simultaneously makes them a popular dark matter candidate which can be searched for in experiments known as "haloscopes", which exploit a putative axion-photon coupling.

The ORGAN (Oscillating Resonant Group AxioN) experiment in Perth, Australia is a microwave cavity axion haloscope that aims to search for axion dark matter particles within the mass range of 50 to 200 micro–electron volts predicted by the standard model axion seesaw Higgs portal inflation (SMASH) model [1]. The experiment's initial phase 1a scan sets an upper limit on the coupling of the axion to two photons of $g_{a\gamma\gamma} \leq 3 \times 10^{-12}$ GeV^{-1} over the mass range of 63.2 to 67.1 micro–electron volts with a 95% confidence interval. This highly sensitive result is sufficient to exclude the well-motivated axion-like particle (ALP) cogenesis model for dark matter in the searched region. We also present the most recent results from the phase 1b search, which also excludes the ALP cogenesis model between 107.4 and 111.9 micro–electron volts [2].

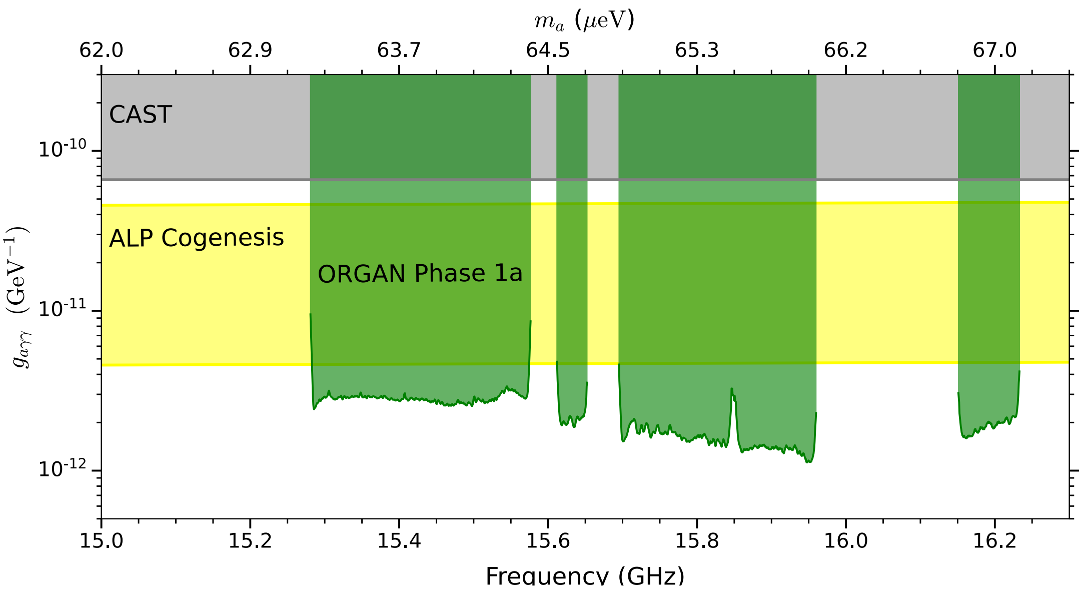

Fig.1. Our 95% confidence exclusion limits on the axion mass coupling parameter space

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Implementation of the Wide Band Josephson Parametric Amplifier in ORGAN Q

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The Quantum Technology and Dark Matter group (QDM) at the University of Western Australia is currently undertaking the Oscillating Resonant Group AxioN (ORGAN) experiment. ORGAN will search for invisible axions in the frequency range 15 GHz to 50 GHz with sensitivity levels that will cover the KSVZ and DFSZ QCD axion models [1]. ORGAN consists of different experimental stages and the 2nd stage aims to achieve the KSVZ/DFSZ sensitivity levels [1]. Quantum-limited amplifiers such as the Josephson Parametric Amplifier (JPA) can be used as the first stage for a microwave cavity axion haloscope in order to achieve this. JPAs have standard quantum limit noise temperature with relatively high gain which makes them ideal for optimising the signal to noise ratio (SNR) in axion haloscopes [2].

The ORGAN Q experiment is an important steppingstone for the ORGAN experiment. While it will perform an axion haloscope search at the lower frequencies of 6.1 GHz – 6.4 GHz, the experiment will also test the viability and feasibility of the use of JPAs in axion haloscopes. Thus, a successful run of ORGAN Q will pave the way for axion haloscopes at higher frequencies (such as ORGAN) using quantum-limited amplifiers with similar designs. Figure 1 shows the photon-axion exclusion plot for ORGAN Q and mass-sensitivity ranges for QCD axion models (as a reference).

The Wide-Band Josephson Parametric Amplifier (JPA) by Raytheon BBN is used in the characterisation experiment for 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 readjusted while performing the input frequency sweep.

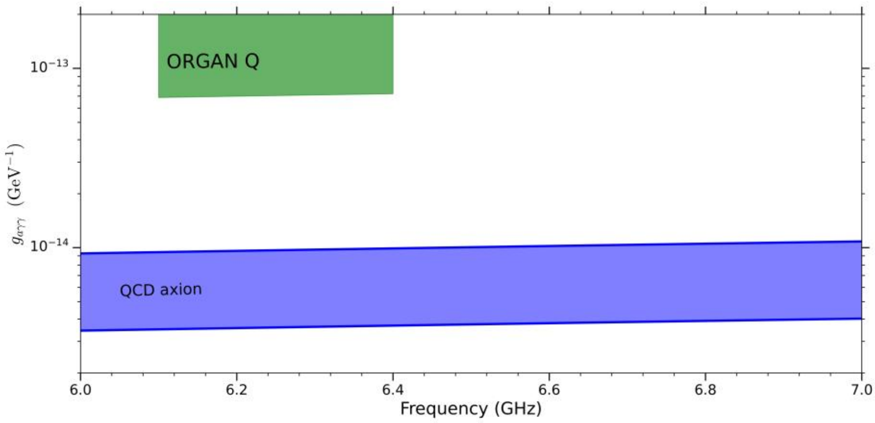

Fig.1. Axion exclusion plot for ORGAN Q [3]

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Introducing the Multimode Acoustic Gravitational Wave Detection Experiment: MAGE

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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 $6 \times 10^{-21} \frac{[strain]}{\sqrt{Hz}}$in 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

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Ground and space-based laser interferometry for precision metrology

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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.

Quantum science and precision measurements in space

- Fundamental Physics Program in NASA and at JPL

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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.

The future direction of the FP program at NASA is anticipated to be strongly influenced by the findings of the upcoming National Academy decadal survey [1], which is expected to be published before the symposium. High-performance clocks are likely to play a crucial role as sensors for testing fundamental laws of physics and exploring unknown phenomena.

This paper will provide an overview of the current BPS Fundamental Physics program, including its quantum pivot missions and research activities at JPL. Additionally, it will discuss the implications of the decadal survey report, provided it is published in time.

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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

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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].

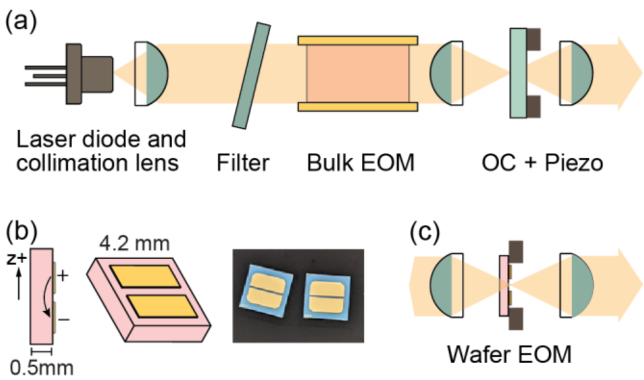

Fig. 1. (a) Schematic of cateye external cavity laser showing placement of an intra-cavity bulk crystal electro-optic modulator. OC: output coupler. (b) Schematic and photograph of wafer-based lithium niobate intra-cavity modulator with rectangular gold electrodes. The gap spacing of the electrodes varied from 0.1 to 0.5 mm. An arrow between the electrodes indicates the electric field. (c) Modified cateye external cavity laser configuration with LN intra-cavity modulator. The inside surface is anti-reflection (AR) coated for 729 nm; the exit surface is uncoated, with Fresnel reflectivity of 15%.

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Collapse Phenomenon in Phase Noise Curve of E5052B

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Phenomenon: To improve the close-to-carrier phase noise of a crystal oscillator, the main technical is to increase the loaded Q_L. In our experiment, we first used an AT-cut 10 MHz overtone crystal resonator, whose unloaded Q was above 1000K. We planned to use this AT-cut crystal to test the circuit state first, and then replace it with an SC-cut high-precision crystal resonator.

The circuit prototype used a Pierce oscillator circuit with good frequency stability. Larger C_1 was selected to obtain a larger loaded Q_L [1]. The phase noise curve tested by Agilent E5052B is shown in Fig.1. Due to the lack of anti-interference measures such as shielding in the experimental circuit board, the interference in the curve is relatively large. However, the key issue is that a segment of the noise curve offset from the carrier frequency at around 1 Hz to 10 Hz directly collapsed, which is a strange phenomenon.

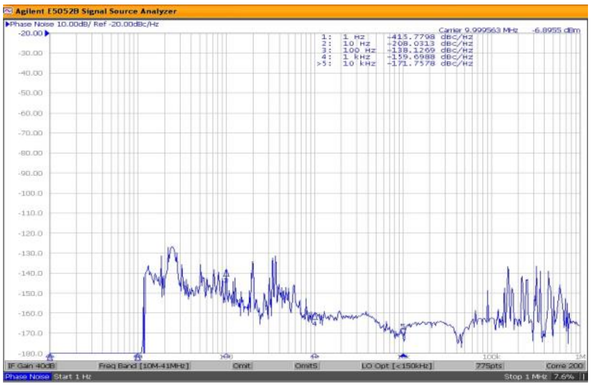

Fig. 1. The collapsed phase noise curve.

Explanation: A) First, due to the use of an AT-cut crystal, the excitation power cannot be too strong. At the same time, in order to improve the near-carrier noise, it is often necessary to further reduce the excitation power [2]. Therefore, the output power in the experiment was only about -7 dBm, so $(F*K*T)/(2*P)$ is not less than -170 dBc/Hz. Therefore, it is impossible for the noise curve to be lower than -170 dBc/Hz.

B) Why did the curve collapse? We consulted the technical manual of Agilent E5052B[3], and its correct testing capability under specific conditions is shown in Table 1. From Table 1, it can be seen that under the given conditions in the table, the typical values of the sensitivity of a 10 MHz signal at 1 Hz and 10 Hz offset from the carrier are -74 dBc/Hz and -114 dBc/Hz, respectively, which are caused by the background noise of the testing system.

Table 1. SSB Phase Noise Sensitivity (Standard, < 150 kHz optim., Measurement quality = Normal, correlation = l, +5 dBm input, start frequency = l Hz, measurement time = 17.7 sec)

Input Frequency		Offset from carrier (Hz)								
		1	10	100	1k	10k	100k	1M	10M	40M
10 MHz	Spec.				-148.5	-156.5	-166.5	-168.5	-	-
	typ.	-74.0	-114.0	-144.5	-152.5	-160.5	-170.5	-172.5	-	-

However, the E5052B (and other similar phase noise testing systems) uses a correlation algorithm, and the true sensitivity after using the correlation algorithm can be estimated using eq. (1):

$$Noise_{meas} = Noise_{DUT} + \frac{Noise_{Ins}}{\sqrt{M}} \tag{1}$$

where M is the number of calibration times. It can be seen that when M = 10000 (the maximum number of calibrations for the E5052B), the instrument noise can be optimized by 20 dB, which means that the typical value of the sensitivity at this time can reach -134 dBc/Hz@10Hz.

The testing time with M=10000 is difficult to tolerate for experiments. As shown in Fig .1, the value of M used in this experiment is 200, which can optimize the instrument noise by 13 dB, and the typical value of the sensitivity can reach -127 dBc/Hz@10Hz. In fact, the typical value provided by the instrument has a margin. In this experiment, we were able to measure above -130 dBc/Hz@10Hz with M=200. It can be seen from Fig. 1 that the noise level is approximately -135dBc/Hz@10Hz, which is much lower than the calibrated instrument noise, resulting in a collapse.

Suggestion:

A) If the extremely long testing time can be tolerated, M can be appropriately increased.

B) A better solution is to use an extremely low-noise 10 MHz crystal oscillator as an external standard for the instrument.

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Ultralow Phase Noise Optoelectronic Oscillator

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The optoelectronic oscillator(OEO)'s main technological advantage over the traditional microwave oscillator is its ultra-low phase noise property. 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. More significant factors on OEO have been explored in this work, including residual phase noise of the optoelectronic link, linear operating state of the optical link, optical power input to the photodetector, and photodetector bias voltage.

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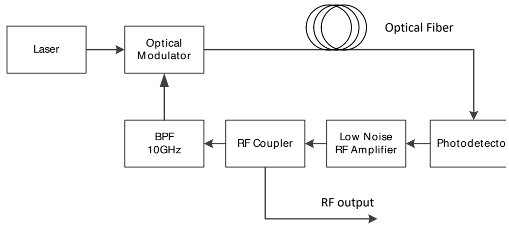

Fig.1. Block diagram of the single-loop OEO.

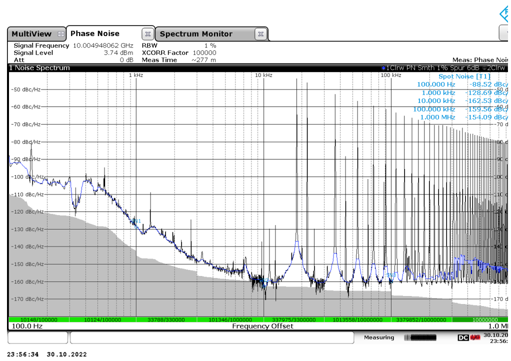

Fig.2. Ultra-low phase noise opto-oscillator phase noise.

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

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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].

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Reconfigurable Brillouin laser for linewidth narrowing and microwave-spaced frequency combs

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Narrow-linewidth frequency-stable sources are of interest for a diverse range of applications such as quantum computing and sensing, high-bandwidth communications, precision timekeeping and high-frequency (>10 GHz) radar. Brillouin lasers are promising practical sources of extremely narrow linewidths due to their narrow gain spectrum and ability to dissipate pump phase noise [1]. Though remarkable performance has been reported in terms of linewidth and power [1,2], progress in Brillouin lasers has been hampered by a lack of control of power into higher Stokes orders. Such control is an important requirement depending on applications for single narrow-linewidth output for coherent laser applications or Brillouin frequency combs for use in microwave photonics.

Here we report a novel approach to Brillouin laser design that enables reconfigurable operation between single-frequency narrow-linewidth and Brillouin comb output. The cavity length is tuned to either enhance or suppress second and higher-order Stokes. Shown in Fig. 1(a), the design uses a temperature-stabilized etalon with a transmission peak tuned to the pump frequency. In combination with the high gain Brillouin crystal paratellurite [3], laser action is achieved for singly- and multiply-resonant alignment of the cavity modes with the Brillouin gain peaks (Modes 1 and 2 in Fig. 1(a)).

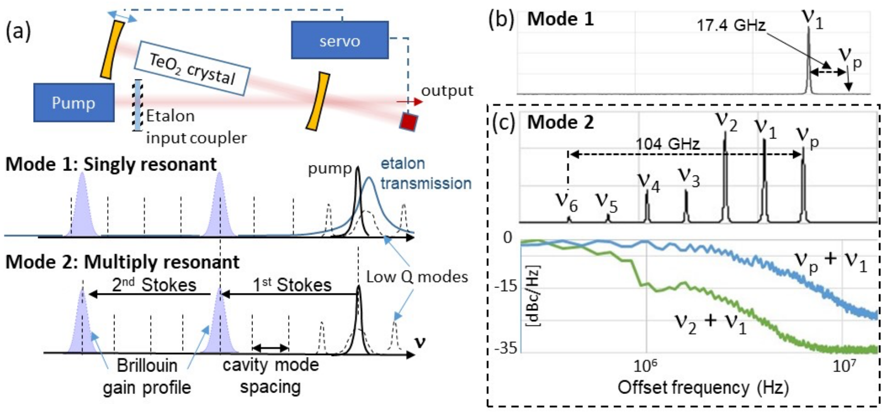

Fig. 1. (a) Layout of the Brillouin laser layout along with cavity resonance conditions for single Stokes (Mode 1) and Brillouin comb output (Mode 2). (b) Mode 1 output spectrum. (c) Mode 2 spectrum with measured frequency noise spectra for heterodyne signals of the pump with the first Stokes (ν_p+ν_1) and the first with second Stokes (ν_1+ν_2). Spectra measured using a 1-GHz resolution spectrometer (Light Machinery, Hyperfine).

Spectra obtained for Mode 1 and 2 resonance configurations using a 1064 nm pump laser of 2 MHz linewidth show the transition from single Stokes to frequency comb output (Figs. 1(b) and (c)). For single wavelength output, the threshold for laser action was 10 W with a maximum output beam power of 0.25 W at a frequency shift of 17.4 GHz and a measured reduction in the Lorentzian linewidth by a factor of 3. For comb output, we obtained up to 6 Stokes orders spanning frequencies over 104 GHz, with a combined output power of 0.4 W. Comparison of first and second Stokes photo-mixed signals on a 25 GHz detector showed an 18 dB reduction in phase noise at offset frequencies above 1 MHz compared with the pump and first Stokes photo-mixed signal (Fig 1(c)). We believe the design is amenable to a wide range of power, generation of ultra-narrow linewidths and synthesis of low-noise microwave and mm-Wave frequencies.

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Status of the Low-AC-Power Cryogenic Sapphire Oscillators

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The cryogenic sapphire oscillator (CSO) is a highly specialized oscillator delivering a microwave signal exhibiting extremely low instability. The Allan deviation $\sigma_y(\tau)$ 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 early American and Australian experiments in liquid-He bath [1,2], we demonstrated the use of a closed-cycle refrigerator at no cost in terms of stability. Prototypes #0 to #3 required 6-7 kW 3-phase AC power. The first codenamed ELISA [3], was delivered to the ESA station in Malargüe, Argentina, and #1-#3 were built for Oscillator IMP, our platform of metrology. The second generation, called ULISS 2G, came in 2015 starting from prototype #4. We used a new refrigerator requiring only 3 kW single phase AC, which can be powered from a regular 230 V, 16 A outlet.

After the results shown at the 8th Frequency Standard and Metrology Symposium [4], 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. Recent results are available in [5].

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 nonprofit 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.

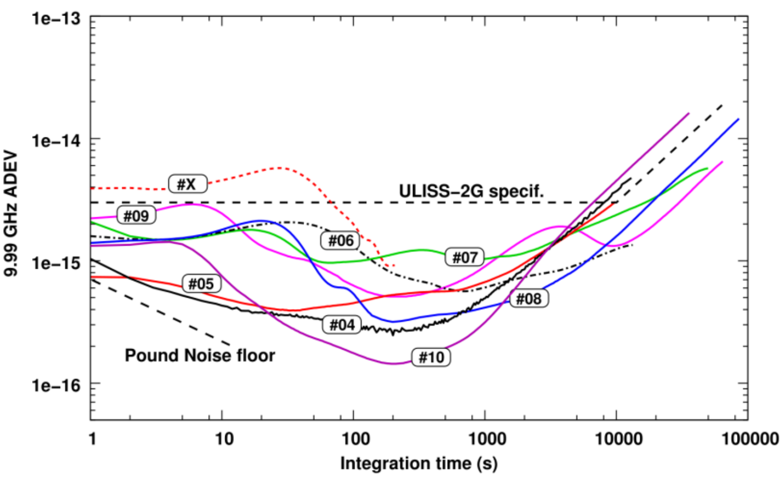

Fig.1. Allan deviation of the low-power (3 kW, single-phase AC) CSOs implemented and tested in Besancon. The sapphire resonator of #X is out of specs. Drift is not removed.
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Techniques on Crystal Oscillator Vibration Compensation

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An Oven Controlled Crystal Oscillator (OCXO) is a precision timing circuit based on a high Q quartz resonator enclosed in an oven to provide 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, short-term stability of reference is combined with 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 Microsemi 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.

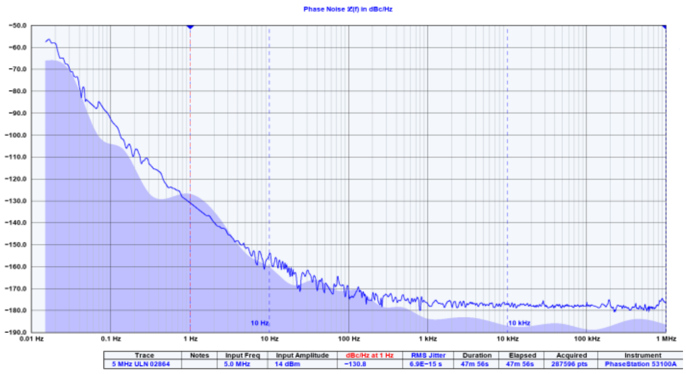

Fig.1. SSB Phase Noise of Bluetop ULN

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 the effect.

This technical note covers various vibration compensation techniques developed at Wenzel to reduce vibration induced phase noise errors in crystal-based oscillators.

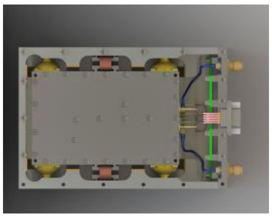
Fig.2. Model of the vibration compensation oscillator (VXO)

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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Excitation of a Microwave Cavity Resonators using an Interferometric Dipole Probe

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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].

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

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In the optically detected magnetic-state-selected cesium clock (OMCC) [1,2], the cesium atoms in $6S_{1/2}$ F=3 are selected by a non-uniform magnetic field and the state detection is realized by using laser that resonates with D_2 line F=4→F'=5. Fig. 1 shows the structure. The magnetic state selection brings a slower atomic velocity, but it also reduces the atomic utilization. The magnetic state selection also causes the mixing of atoms with F=4, mf=-4 in the F=3 atoms. These can bring about a deterioration of the signal-to-noise ratio (SNR). Optical detection avoids the use of the electron multiplier, but introduces the light shift.

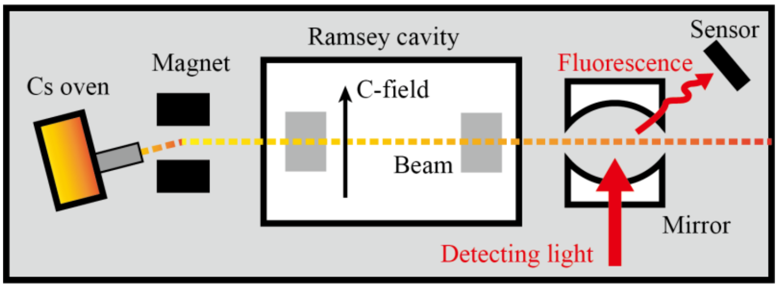

Fig.1. The diagram of the optically detected magnetic-state-selected cesium beam clock

The size of the OMCC prototype is 4U (456*561*177 mm), weight is less than 40 kg and the operating power is less than 50 W. Fig. 2 shows the stability of our prototype. The clock reaches 4.0E-13@100 s, 4.5E-14@10000 s and 2.2E-14@1 d.

We use beam optics to increase SNR to obtain better short-term stability [3]. For light shift, we propose detuned light detection method [4] and pulsed light detection method [5] to suppress the light shift. To further optimize the stability, we develop a new type of OMCC (Reversed OMCC), which selects atoms in F=4 and detects atoms with D_2 F=3→F'=2 line (3-2 line) [6]. This scheme has a narrower linewidth and higher SNR, but requires an additional magnetic field in the detection region to remove the coherence in ground states when using 3-2 line. The stability reaches 2.94E-12 τ^-1/2. The Reversed OMCC's prototype is still on process, and the frequency stability (Fig. 2) is from a Reversed OMCC in a laboratory platform.

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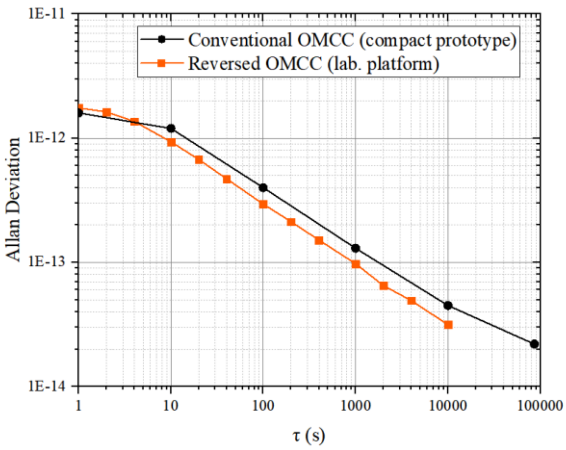

Fig.2. The stability of OMCC. Due to the narrower linewidth and higher SNR, the Reversed OMCC has better frequency stability.

Primary and secondary frequency standards and the Coordinated Universal Time

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The accuracy of the Coordinated Universal Time (UTC) [1] is based on the contribution of primary and secondary frequency standards (PSFS) operated by time laboratories all over the world and regularly reported to the BIPM, based on the rules set by the CCTF and its working groups.

The regular contribution is fundamental for ensuring the accuracy and long-term stability of UTC and to allow UTC to act as reliable reference for the measurement of other potential frequency standards.

The BIPM is publishing the results of the measures concerning PSFS and the accuracy of UTC in the monthly circular T, in a database accessible from the web, and also on a custom-configurable plot (Fig 1). The regularity of the presence of PSFS in UTC is monitored by one of the criteria for the redefinition of the second [2]. This is also automatically evaluated, and a plot is available (Fig 2)

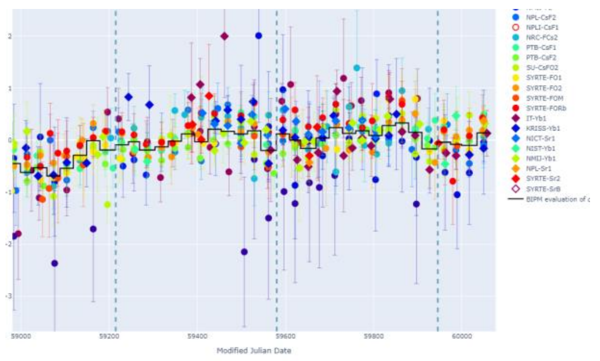

Fig.1. measurement of the fractional deviation of the UTC scale interval by PSFS, (● for microvawe, ♦ for optical frequency standards), https://webtai.bipm.org/database/d_plot.html

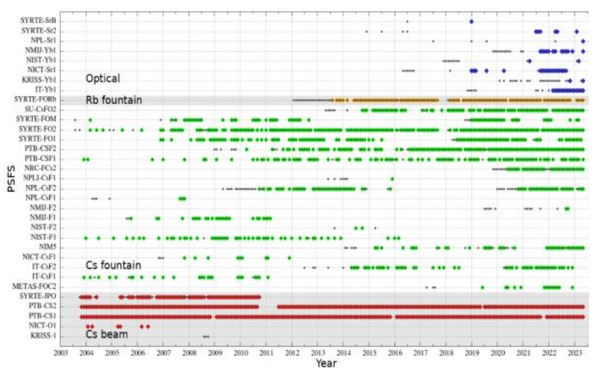

Fig.2. PSFS contributing to UTC since 2003 (enhanced colors indicate evaluations reported timely for the monthly UTC computation, https://webtai.bipm.org/database/show_psfs.html

The value of the frequencies that are accepted by the CCTF as secondary representations of the second (https://www.bipm.org/en/publications/mises-en-pratique/standard-frequencies) [3], together with related information as supporting measures, uncertainty, and correlation coefficients, are stored in a data base that can be automatically accessed on the web by a dedicated prototype API currently under test.

The BIPM aims to ensure the best possible level of UTC accuracy ($3*10^{-16}$ in the last years), to provide support to the CCTF along the roadmap to the redefinition of the second, and to serve the time and frequency community by providing complete and FAIR data with the relevant information to all applications of high accuracy time and frequency metrology.

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

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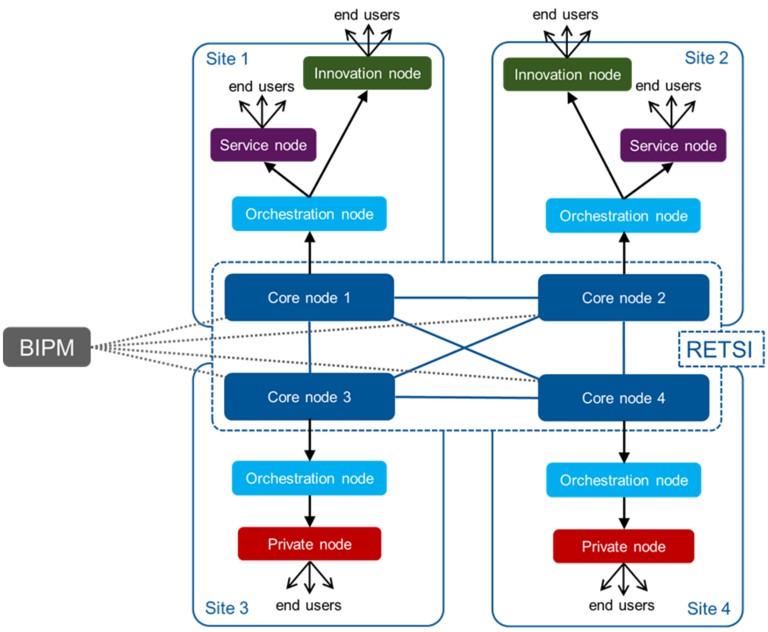

Fig.1. The design of RETSI, showing the four interconnected sites, the interfaces to the BIPM and illustrative examples of "user access nodes" which include service, private and innovation nodes, that disseminate RETSI's time and frequency signals to end users.

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) (Fig.1). The purpose of RETSI is to improve the resilience of UTC(NPL) and to reduce the UK's reliance on timing signals from GNSS [1]. Each site will produce multiple time scale realisations, although only one of the realisations at any time from a single RETSI site will be chosen as the source of UTC(NPL), which will be steered to UTC. The site generating UTC(NPL) may be changed through a switching process. Time and frequency transfer between the sites (comprising GNSS, Two-Way Satellite Time and Frequency Transfer (TWSTFT) and optical fibre links) will allow for the time scales at the other sites to be steered to UTC(NPL).

Work is underway to develop access and distribution points (nodes) for RETSI's time and frequency signals. These signals are distributed from the time scale realisations (at core nodes) through "orchestration nodes", which are used to secure the interface to RETSI. End users can then access these signals through "user access nodes" for use in business, industry or academia, to help reduce their reliance on time and frequency signals from GNSS.

RETSI will include caesium fountain primary frequency standards at some of the sites, which will support the objective of maintaining 95% of published values of UTC – UTC(NPL) being kept within ±5 ns over any five-year period. RETSI will be monitored in real time and will use secure methods for transferring data between sites.

An initial RETSI site at NPL in Teddington has had its equipment installed, and a second site will be ready for installation of equipment in late 2023. Software developed for RETSI so far includes phase and time-interval data-logging, system monitoring, a graphical user interface and an automated software scheduler. TWSTFT and optical fibre links between sites are being procured. The optical links will provide a platform that will facilitate the future incorporation of optical clocks into the UK's national time scale and allow for the comparison of optical frequency standards between RETSI sites.

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Precision clockwork for optical clock operation at the 10^{-19}-level accuracy

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Optical frequency standards have achieved fractional stabilities of a few parts in 10^{19} [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 10^{-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.

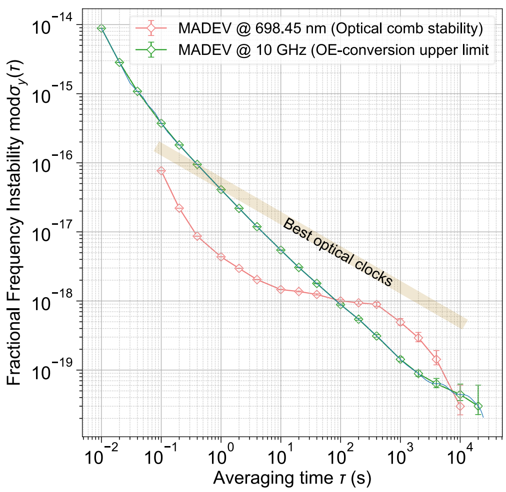

Fig.1. Optical and microwave fractional frequency stability of a rack-mounted transportable clockwork system.

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

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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 frequently contributed to BIPM's monthly calibration of the rate of the international atomic time TAI. This fulfills one of the criteria that the Consultative Committee for Time and Frequency CCTF set for the redefinition of the SI second.

The same criteria also require contribution of an optical clock to the generation of a local timescale UTC(*k*), which has recently gained significant attention [1-5]. NICT-Sr1 began contributing to the generation of Japan Standard Time JST in August 2021. To this end, NICT-Sr1 intermittently evaluates the frequency and drift rate of a hydrogen maser (H-maser) to steer its frequency and generate a timescale signal TA(Sr). We demonstrated this optically steered timescale in 2016 [6] and resumed its generation in July 2021.

NICT generates and provides the local timescale UTC(NICT), from which JST is derived by adding +9 hours. UTC(NICT) is originally generated by adjusting a H-maser source frequency to the calculated local ensemble time derived from 18 commercial cesium atomic clocks. Since August 2021, we add an additional twice weekly steering of the conventionally generated UTC(NICT) to compensate the timing drift between UTC(NICT) and TA(Sr). The peak-to-peak variation of the deviation of UTC(NICT) from UTC has subsequently improved from approximately 40 ns to 11 ns as shown in Fig. 1.

We believe that these contributions to the international and the nationally distributed timescale help demonstrate the suitability of optical clocks as the basis for a redefined SI second.

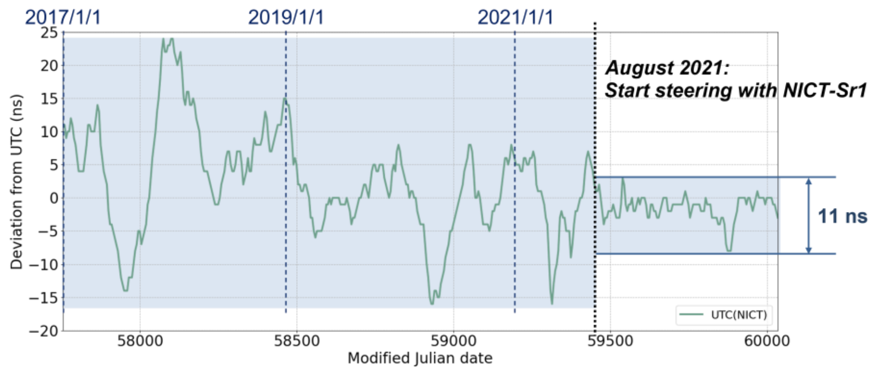

Fig.1. Deviation of UTC(NICT) from UTC since 2017, where steering of UTC(NICT) towards TA(Sr) started since August 2021.

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Hydrogen Maser Flywheels for Optical Clocks

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Until long-term frequency stable optical references [1] reach the robustness needed to operate as signal sources free from interruptions, hydrogen masers (HM) 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. NICT's approach of operating its strontium optical lattice clock NICT-Sr1 only intermittently [2] is designed around the stability of the hydrogen masers operated for the generation of Japan Standard Time (JST) [3].

From October 29, 2021 to March 30, 2023, NICT-Sr1 performed 78 frequency evaluations of hydrogen maser JST-HM14, typically to a statistical fractional uncertainty of $2–3\times10^{-16}$. Isolating each evaluation from the full dataset and comparing it to an interpolation of the remainder yields prediction errors with a standard deviation of only 5.0×10^{-16} (Fig. 1), in good agreement with the statistical uncertainty of 5.6×10^{-16} calculated using our previously reported stochastic HM model [4]. The same model yields an uncertainty of 1×10^{-15} or below when extrapolating the HM behavior to the next weekly clock measurement. These uncertainties support that intermittent operation of a precise optical clock, combined with a well-performing hydrogen maser acting as a predictable flywheel oscillator, is sufficient to generate a time scale with excursions at or less than 1 ns over several weeks.

Our poster will show greater detail on this and similar evaluations spanning optical and radio-frequency domains.

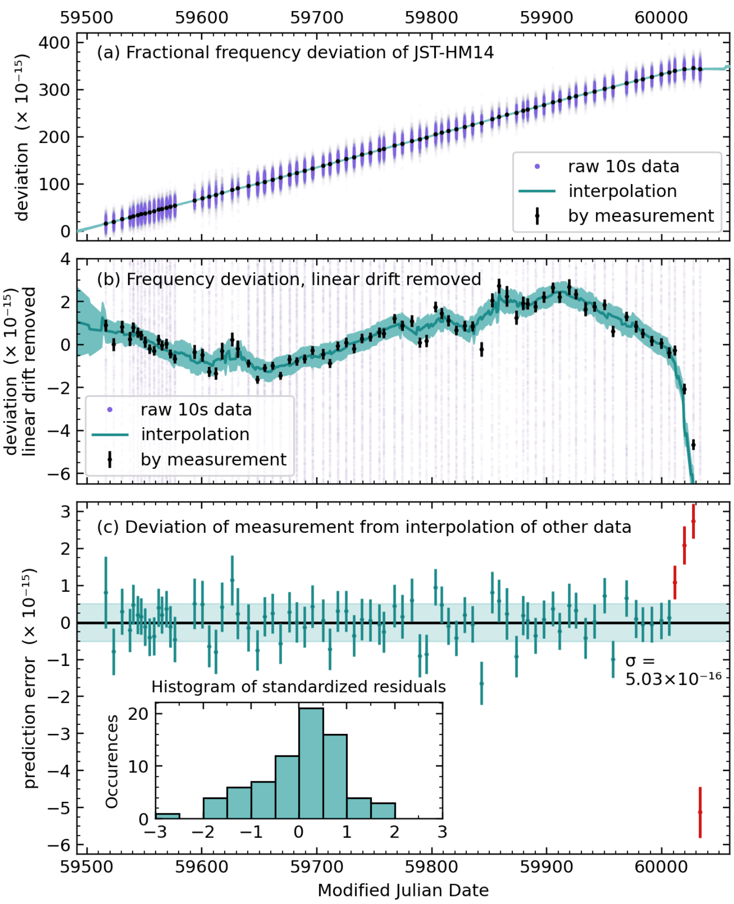

Fig.1.(a, b): Frequency tracking of hydrogen maser JST-HM14 by NICT-Sr1 over more than 500 days. (c) Each measurement is compared to an interpolation of the data taken in other measurements. JST-HM14 depleted its hydrogen reservoir at the end of the measurement, and the last four points were excluded from the statistical evaluation.

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Impact of Low-Noise Digital Technology on Time Scales

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Often, people are so focused on physical signals that they overlook the actual information they are interested in. This mindset comes from the past, where processing was done through analog means and every step required necessarily physical signal regeneration. Even though digital electronics have been established for decades, this way of thinking persists and restricts the full potential of digital electronics and its beneficial effects on time and frequency metrology, particularly in clock composition and time scale generation. The digital approach, which focuses on the information carried by the sinusoids rather than the sinusoids themselves, enables numerical implementation of the functionalities required by clock composition, with significant advantages.

Figure 1 illustrates a general scheme for combining multiple clocks of arbitrary frequencies to generate a composite sinusoid. The analog approach (a) involves frequency synthesizers to match the working frequency of micro-steppers, that in turn align the clocks. The alignment is driven by the algorithm and is based on the measure of the secondary and primary clocks (in the figure a cryogenic fountain), and data from BIPM. The weights of the combiner are also set by the algorithm. Each step is performed by a specific instrument that increases complexity and the total noise.

The digital approach (b), on the other hand, does most of the functionalities numerically on the streaming data of clock measurements. The frequency synthesizers are replaced by multiplications that normalize the phase to phase time; the steering is done by subtracting the deterministic components using parabola generators; the composition of the clock information is done by a weighted average. In this way, most instruments and their functionalities are replaced by the equivalent codes that fit into a digital processor.

We tested this approach by using the Time Processor [1] with state-of-the-art oscillators and facilities at FEMTO-ST [2] and FEMTO-Engineering [3], including classical RF sources (active hydrogen masers, cesium clocks, and ultrastable OCXOs), microwave sources (cryogenic sapphire oscillators), and optical sources via a frequency comb.

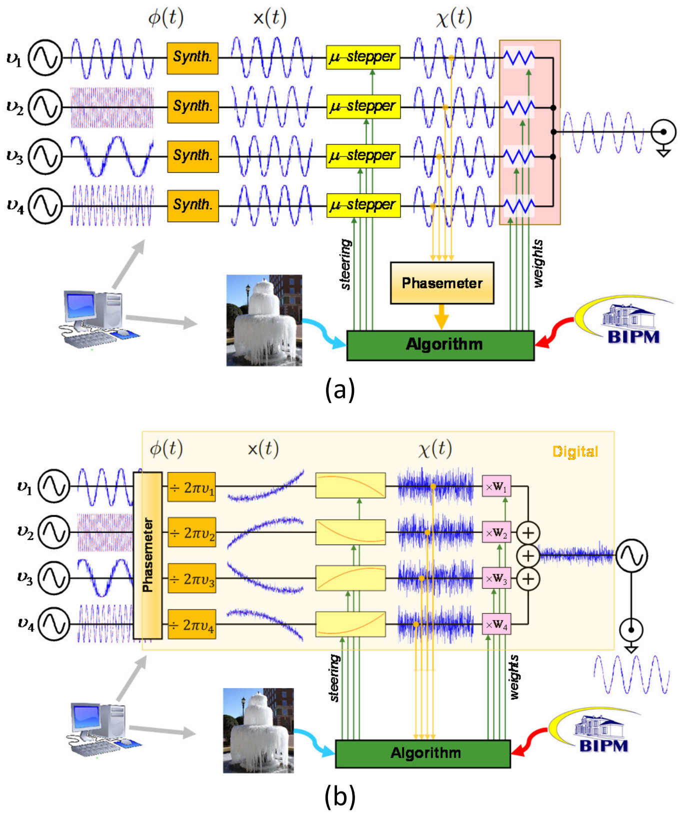

Fig.1. Analog (a) and a digital (b) composite clock. In a), the inputs are frequency converted, steered and combined. In b), the same functionalities implemented numerically: normalization, drift removal, then weighted averaging. The output clock signal is generated only at the end of the process.

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Progress on Optical Clock Technology for Operational Timescales

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Dramatic progress on optical atomic clocks and frequency standards in recent years is having a significant impact on metrology and fundamental science. However, fully integrating optical technology into continuous operations for timing applications and timescale generation remains a significant challenge.

The U.S. Naval Observatory (USNO) produces one of the best realizations of Coordinated Universal Time (UTC) using a large ensemble of operational clocks and disseminates this time throughout the world via various methods, including GPS. The best clocks in the ensemble are rubidium fountains that were designed and built in house in order to meet requirements that could not be met with commercial clocks [1]. To prepare for emerging and future needs, efforts to improve the USNO clock ensemble and supporting technology are ongoing, including several avenues to incorporate optical technology.

While a lattice clock with an anticipated role similar to primary standards elsewhere is under development, we are experimenting with using the optical "front end" (telecom-wavelength-based local oscillator (LO)) as a continuously available clock signal; disciplined to a rubidium fountain, this offers an operational clock with optical-oscillator stability in the short term, with quantum-projection-noise-limited fountain performance in the long term. This may also serve as the basis of a future architecture in which the LO is steered by the optical lattice when online, and by a fountain (with white-frequency noise level of order 5×10^{-14}) at all other times.

Optical atomic clocks intended to run continuously are also under development. A system based on optical spectroscopy on a thermal beam of calcium is far less complicated than an optical lattice and is more compatible with 24/7 operation [2, 3]. Ramey-Borde spectroscopy at a resolution of ~3 kHz supports $<10^{-14}$ stability at 1 s, with the long-term stability achievable in a well regulated environment still being investigated. Laser-beam propagation reversal and optical ensembling of clocks are under consideration for optimizing long-term stability, as is slowing the atomic beam; recent demonstration of Ramsey-Borde spectroscopy on slowed calcium is enabling this avenue to be investigated.

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Stable RF transmission using PLL over long-distance optical fiber

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Stable frequency standards have important applications in gravitational wave detection, precise navigation timing, and verification of relativity principles [1-4]. 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.

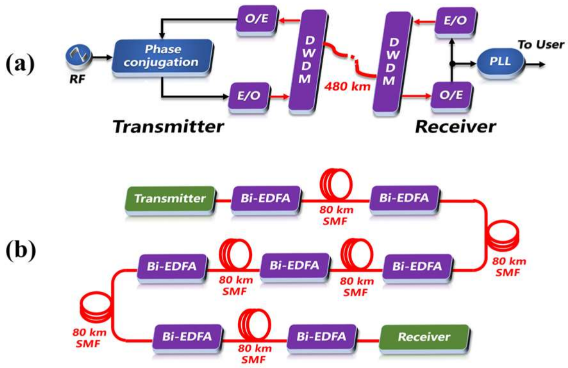

Fig.1. (a) Schematic diagram of the RF transfer system. (b) Schematic diagram of optical fiber link.

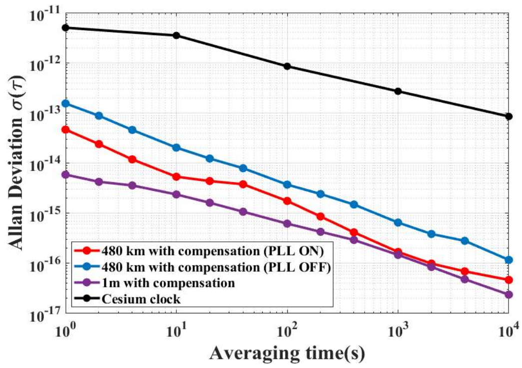

Fig.2. Measured stability of the radio frequency transfer system.

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 either 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 4.65×10^{-14}@ 1 s and 4.66×10^{-17}@ 10,000 s. When the PLL is turned off, the frequency stability of the transfer system is 1.54×10^{-13}@ 1 s and 1.17×10^{-16}@ 10,000 s. Experimental results show that the frequency stability of the transfer system is significantly improved 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.

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

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Long distance optical frequency dissemination via interferometric fiber links (IFLs) reaches fractional instabilities and uncertainties of 10^{-19} and below [1,2]. IFLs enable a wide range of high precision application such as comparison of atomic clocks [2], chronometric leveling, tests of fundamental physics [3] or searches for Dark Matter [4]. However, conventional IFL topologies, including those implemented in commercial equipment [5], generally involve reference arms and other uncompensated paths that need to be passively stable. This is generally achieved by keeping these paths as short as possible, balancing path lengths and placing them in a temperature-stabilized environment.

In this work, we present a novel optical setup for IFLs 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.

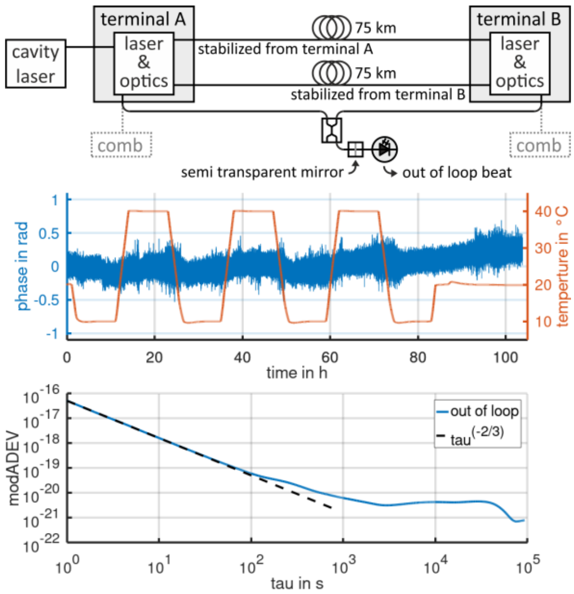

Fig.1. Schematic setup and measured frequency transfer performance of the link terminals.

We setup two terminals for locations A and B (see Fig. 1). Each terminal supports one short and one long IFL. The short IFL is later to be routed to a frequency comb for comparison with an optical clock. The long IFL connects the two terminals. The transfer laser of Terminal A can be pre stabilized to a cavity laser. The transfer laser of terminal B is phase locked to the transferred signal from terminal A. For this proof of concept, we connect terminal A and B via 75 km of fiber spools. The beat note between the short IFLs from terminal A and B provides an out-of-loop measurement of the residual phase error of the long IFL. Furthermore, we put the optical setup of terminal B into a climate chamber and ramp the temperature between 10°C and 40°C. We observe phase shifts of less than 0.4 rad (0.3 fs at 194.4 THz) from the temperature ramping, indicating a temperature sensitivity of less than 0.014 rad/K (11 as/K at 194.4 THz). We also observe a nonlinear drift over the measurement period of 100 hours. Preliminary tests show that this is probably due to polarization changes. Nevertheless, over the measurement duration of 100 hours, including the temperature ramps, the total phase variation is below 1 rad (0.8 fs), corresponding to a fractional frequency error in the low 10^{-21}.

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

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The use of optical fibre networks allows for highly stable and accurate frequency reference dissemination over large distances [1–3]. To achieve this, such networks utilise highly stable lasers and propagation noise correction on these optical fibre links, leading to frequency dissemination with very low residual instability [4]. Subsequently, these links support atomic clock comparison [5], atomic spectroscopy experiments [6], relativistic geodesy [7], and synchronisation of radio astronomy arrays [1]. The largest frequency transfer networks span lengths of 2,200 km [3] and 4,800 km [2] with residual instabilities between 10^{-16} and 10^{-19} with $\leq 94\%$ up time.

To increase the reach of these networks, effort has been placed on combining disparate national fibre infrastructure and multiple hardware technologies; often utilising bespoke laboratory-grade equipment. A more industrial approach is required to efficiently grow these networks to greatly augment the number of nodes and operate over a longer total distance

Here, 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 [8]. 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}. The system's modular nature makes it easily extendible to apply for optical frequencies in addition to different microwave frequencies, potentially serving as steppingstone for large industrial metrological networks and/or novel systems such as the ngVLA [9].

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Towards practical quantum secure time transfer

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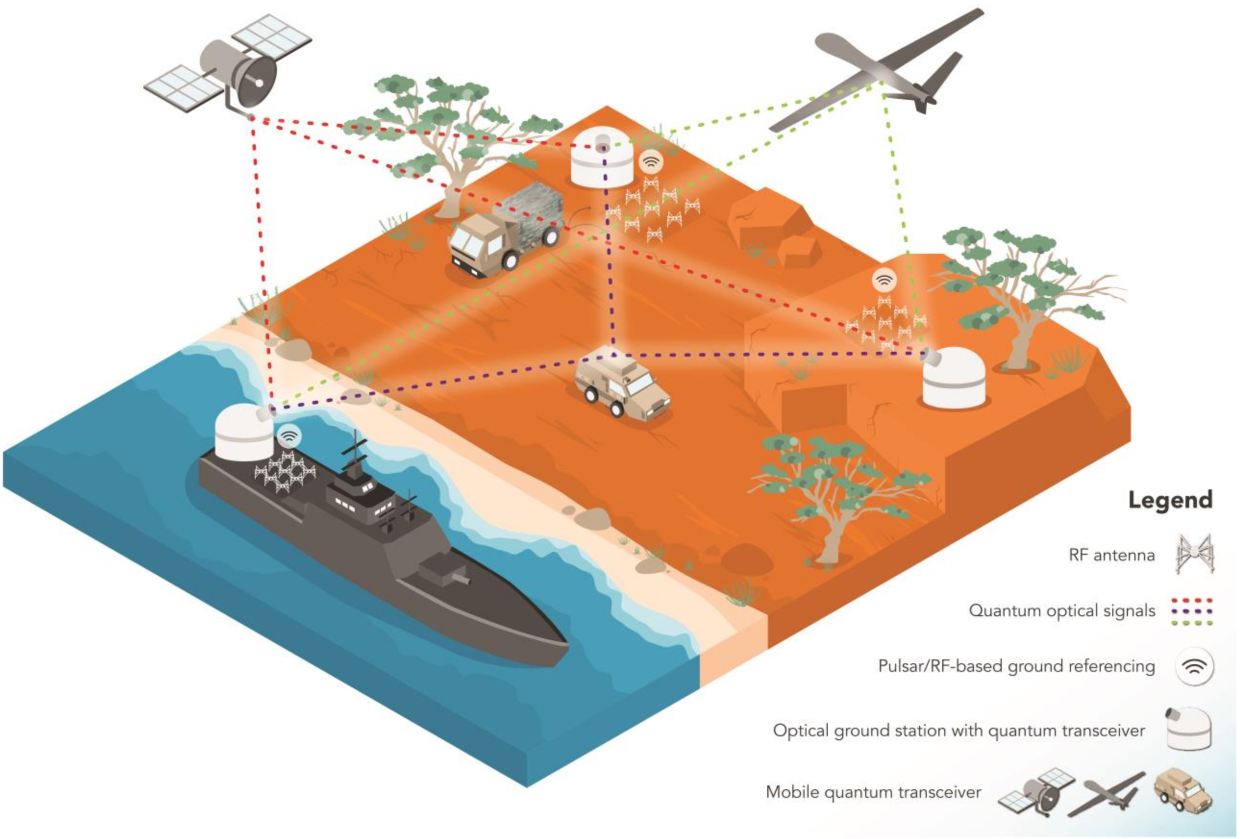
Accurate clock synchronization and time transfer are vital for positioning, navigation, and timing systems. The Global Positioning System (GPS) plays a crucial role in telecommunications, agriculture, and weather forecasting, enhancing productivity and enabling efficient operations. However, the GPS is susceptible to attacks such as spoofing, posing a significant risk. Quantum Secure Time Transfer (QSTT) can address this threat by providing a method to validate the authenticity of the time signals used.

This project aims to develop a portable system for QSTT, capable of maintaining a two-way free-space quantum link between two mobile transceivers over a distance of 10 km. The system comprises several beacon lasers, a single-photon source, and adaptive fast-steering optical mirrors, all working harmoniously to enable quantum-secured timing precision on the order of a few hundred picoseconds. Pathfinder QSTT missions will carry quantum light sources, starting with compact BB84-type single photon sources and eventually using bulk crystals-based entangled photon pair sources. Beyond proof of concept, we strive to deliver a practical solution that could benefit various industries. We cordially invite you to join us in exploring the intricacies of our solution while delving into the persisting challenges encountered during the construction of this system.



Synergetic Repetition Frequency Locking of an Optical Frequency Comb

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In recent years, the new generation of fiber-based optical frequency combs (OFCs) has achieved rapid development [1-4]. There are two common methods for locking the repetition frequency (f_r): using piezoelectric transducers (PZT) [5] or electro-optic modulators (EOM) [6]. Although PZT has a lower feedback bandwidth than EOM, it is sufficient to meet the needs of many OFCs. Moreover, PZT directly adjusts the cavity length, with less dependence on polarization and wavelength. It also has the advantages of small size, fast response, no heat generation, good controllability, low cost and simple structure [7,8]. Consequently, PZTs are widely used in many f_r-controllable OFCs.

The dynamic range of PZTs is limited. In the case of drastic changes in ambient temperature, even if the temperature in the comb's cavity is controlled, the residual effect is enough to make f_r drift beyond the dynamic range of PZT, resulting in locking lost in a short time.

In order to promote the robustness of OFCs under severe temperature changes, we propose a scheme for OFCs' f_r locking utilizing a delay line, a thermoelectric cooler (TEC) and a PZT. With the help of computer devices, the TEC set value and delay line set value are dynamically adjusted according to the PZT control voltage and TEC output voltage, so that three servo feedback control systems work together to achieve long-term locking of OFCs under extreme temperature conditions. Over 1 month stable locking is realized when the room temperature changes over 5 K in a day.

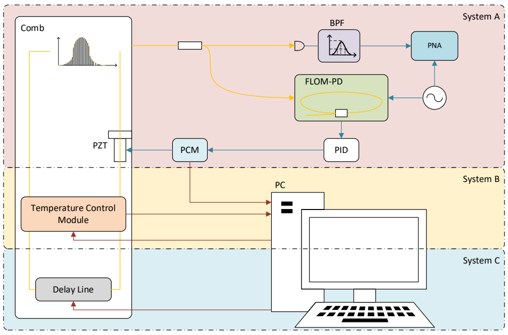

Fig.1. A feedback control system for locking the optical comb with the coordination of PZT, temperature controller and delay line. PCM stands for Piezoelectric Control Module, which amplifies the control signal output by PID. PC stands for Computer, which reads the output voltages of PCM and temperature controller, and dynamically adjusts the set values of temperature controller and delay line.

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Extension of REFIMEVE with a White Rabbit network

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Scientific applications concerned either by improved performance or by redundancy and traceability motivate the growing popularity of time and frequency dissemination techniques over fiber as an alternative to GNSS techniques [1-2]. To be considered as a practical solution at a national scale, the level of maturity of the technologies deployed in-field are crucial, both for the effectiveness of the new service and for its implementation on an existing active telecommunication network beyond the framework of a short-term project.

In France, we built over the last decade a national network to disseminate optical frequencies in parallel to the data traffic of active telecommunication networks, under the research program REFIMEVE+. Consolidation and geographical expansion of the network, together with its extension to radio-frequency and time transfer and to new users, are funded within the ESR+ project T-REFIMEVE.

As one element of T-REFIMEVE, we plan to deploy a long-range White Rabbit (WR) network over a unidirectional telecommunication architecture at national scale using xWDM technology [3-4], following our preliminary studies on fiber spools with a 500 km cascaded architecture [5].

In this paper, we will present the status of deployment of our White Rabbit network. By early 2023 the WR network comprises 11 WR modules, in a cascaded approach and corresponds to approximately 120 km cumulative sum distance. We will present the data acquired for the time signal and the frequency signal and discuss the results. We will show the monitoring and exploitation of these signal by end-user laboratories.

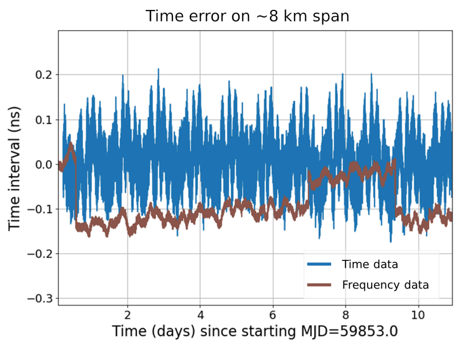

Fig.1. *Time error over 10 consecutive days on an 10-km deployed span, derived from frequency and time data.*

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

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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.

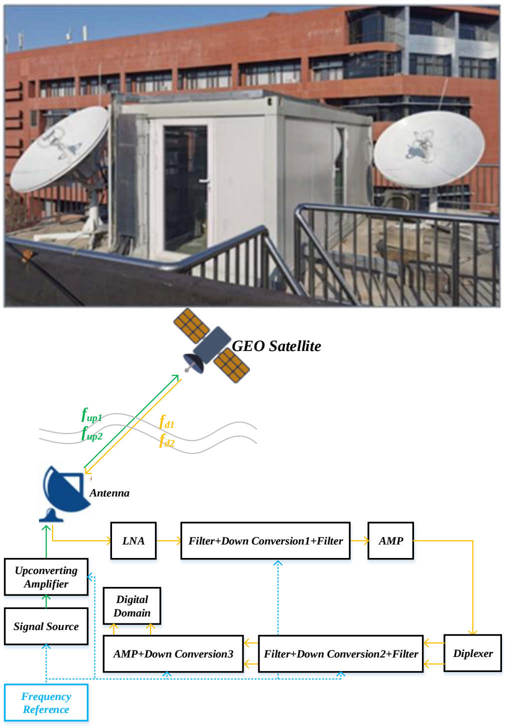

Fig.1. Setup and theoretical diagram of the experimental system.

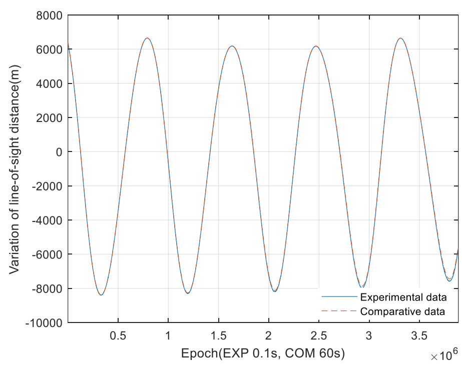

Fig.2. The variation in the line-of-sight distance of the Zhongxing-10 satellite.

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Optical Frequency Transfer and Velocimetry to Rapidly Moving Targets

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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 $1.5/m/s^2$. Fractional frequency stability on the order of 10e-17 is obtained after 10 seconds of integration, along with a noise density of 10e-7 cyc^2/Hz at 10Hz.

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High Temperature Chip Scale Atomic Clock

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We present the development of alkali-alloy-based vapor cells for operating Chip-Scale Atomic Clocks (CSAC) [1-2] at ambient temperatures up to 105 °C. Potassium is chosen for a better miscibility as compared with gold [3-4] 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 °C. We have measured the collisional broadening due to potassium-caesium collisions and concluded it to be negligible [5]. We will present experimental data demonstrating short- and long-term clock frequency performance as well as temperature sensitivity.

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Portable Dual-Wavelength Optical Atomic Rubidium Clock

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Modern society is critically dependent upon stable timing signals typically disseminated by global navigation systems such as GPS, but the highest degree of timing accuracy is afforded by laboratory-based primary frequency standards [1]. The trade-off between clock frequency stability and Size, Weight and Power (SWaP) is the subject of intense research, with high-performance portable clock systems a necessity for a large array of real-world applications and in GPS-denied environments [2].

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 [3, 4]. This work aims to develop a commercial portable frequency reference that has greatly improved frequency stability over the best commercially available technologies. 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 [5]. 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.

Variants of this clock architecture have operated successfully in harsh out-of-lab environments including onboard a moving van and for several weeks operating autonomously on the deck of a large maritime vessel during active sea trials. The clock is currently being developed for space operations.

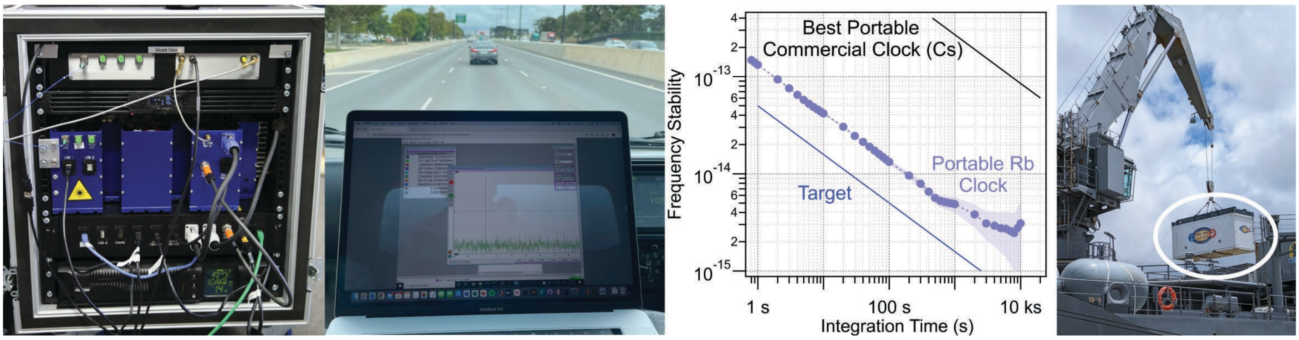

Fig.1. Left to right: 19" rack mounted portable Rb clock held within 11 rack units (11U); readout of clock during operation in vehicle; Clock performance of 1.5×10^{-13} at $\tau = 1$s, integrating down at $1/\sqrt{\tau}$ to 3×10^{-15} at 8,000s, clock loading onto HMNZS Aotearoa (within shipping container, circled) prior to naval exercises.

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

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High resolution cavity-stabilised lasers are playing an increasingly signicant role across many applications in metrology, science and engineering. They contribute to high accuracy time and frequency measurement using optical clocks, as well as offering possibilities for future deep space navigation and seismic sensing. State of the art lab-based systems have demonstrated performance $< 1 \times 10^{-16}$ fractional frequency instability at 1s. Major opportunities for exploitation of these cavity systems lie in developing their transportability - facilitating in situ measurements of physical phenomena beyond the reach of lab constrained systems.

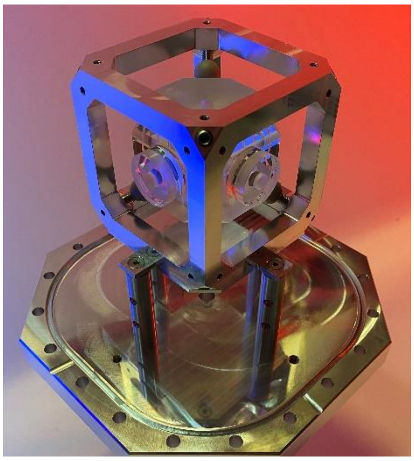
Fig.1. A dual-axis cubic cavity to be deployed in ultra-precise radar systems.

Field deployable systems require compactness, high resilience to environmental perturbations and ideally a minimal reliance on external steering signals from GNSS or fibre networks, without excessive sacrifices in overall performance. At NPL, a cavity technology based upon a patented cubic geometry and force insensitive frame mounting arrangement has been developed [1]. These systems have demonstrated high resilience to mechanical shake and shock while maintaining leading acceleration insensitivity of $< 2 \times 10^{-11}$/g in a 5-cm ULE cavity.

Here, we present an extension of the cubic cavity technology in the form of the dual-axis cubic cavity (DACC) configuration. The use of two optical axes in DACC-stabilised lasers allows exploitation of cavity spacer anisotropy to measure the relative material creep relation between the two axes. This can help compensate for isothermal cavity frequency drift due to the spacer creep in a self-reliant manner. Dual optical axes also allow for the simultaneous stabilisation of multiple optical frequencies required in optical lattice clock operation in a compact, transportable manner.

At NPL, we are currently developing a portfolio of DACC systems for space and terrestrial deployment. A DACC system, in collaboration with the European Space Agency (ESA) is targeted on meeting laser stabilisation requirements for the LISA space-gravitational wave detector and has demonstrated 4×10^{-15} fractional frequency instability at 1 s under lab testing [2]. Another DACC system, in partnership with the UK Sensors & Timing Quantum Hub, aims to fulfil the ultralow phase noise oscillator requirements of radar systems in a fully rackmount, transportable cavity stabilised 1542-nm laser package. This system has demonstrated an acceleration insensitivity $< 5 \times 10^{-11}$/g in the worst performing axis and targets fractional frequency instability below 8×10^{-16} at 1 s. Finally, we present the clock control unit DACC system developed with ESA, demonstrating the proof-of-concept self-reliant cavity frequency drift compensation scheme whilst providing all laser stabilisation requirements for operation of a Sr optical lattice clock. This system has demonstrated drift suppression of a factor $> 10^2$ after 12 hours of operation [3].

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Miniaturized Optical Clock using Rb Two-Photon Transition

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We introduce our research in developing a miniaturized optical clock at KRISS using ^{87}Rb two-photon $5S_{1/2}$ to $5D_{5/2}$ 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-waferbonding 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 2×10^{-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 [1, 2].

Fig.1. Chip-scale vapor cell and Rb two-photon spectroscopy setup.

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A compact cold atom cavity clock

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We present a demonstration of a pulsed optically pumped (POP) cold-atom ^{87}Rb Ramsey clock utilising an additively manufactured loop-gap cavity [1,2] and grating magneto-optical trap [3] (GMOT). The use of additive manufacturing allows for complex cavity structures, more difficult to produce with traditional machining techniques, while the GMOT architecture significantly simplifies the optical system required to trap and cool the atomic sample.

In the current demonstration a single laser is used to trap > 3×10^6 atoms, cool them to around 10 μK, optically pump, and read-out state populations of the atoms after microwave interrogation. A Ramsey-type interrogation scheme is employed with an optimum free evolution time of 10 ms, limited by the loss of signal due to atoms falling out of the read-out beam. Schematic of the experimental setup and results are shown in Fig. 1. We have demonstrated a short-term stability of < $2\times10^{-11}\tau^{-1/2}$ [4], in reasonable agreement with the predicted short-term stability based on the signal to noise ratio of the measured fringes. Excellent field homogeneity of the cavity microwave field is demonstrated though Rabi oscillations, while almost complete optical pumping and good field orientation is demonstrated by Zeeman spectroscopy of the ground hyperfine energy levels. We expect this work will help pave the way towards more compact and portable cold atom microwave clocks with significant potential for further miniaturization of the system and improvements in short- and long-term performance.

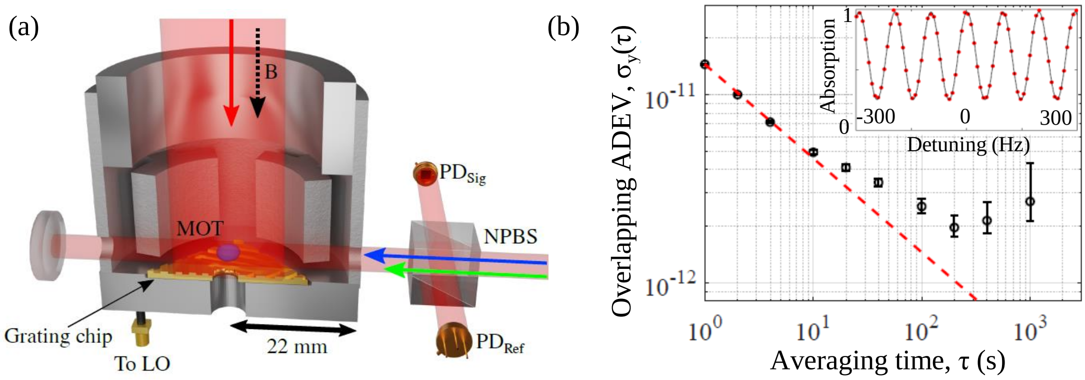

Fig 1. (a) Simplified experimental setup showing cold atoms trapped inside loop-gap cavity. Normalised atomic excitation is detected by absorption of weak probe beam. (b) Overlapping Allan Deviation of local oscillator's stability when locked to atomic signal. The inset shows an example of the central Ramsey fringes taken with a Ramsey time of 10 ms.

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Optical rotation of CPT dark states

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A key technology in the development of robust and miniaturised atomic clocks based on optical interactions is the method of coherent population trapping (CPT). While it has enabled the realisation of chip-scale devices it suffers from probe-induced light shifts and a relatively low signal-to-noise ratio (SNR) caused by a signal limited by only a few scattered photons per atom. Light shifts can mostly be suppressed by using a Raman-Ramsey scheme [1], but mitigating the SNR limit is a more difficult problem to solve. We have demonstrated a variation on the technique whereby a prepared CPT dark state is rotated back onto the bare atomic states using a Raman π/2 pulse. This enables a read-out, that has a potentially significantly improved number of scattered photons and thus SNR.

The experimental setup is based on a grating magneto-optic trap [2,3] (GMOT) operating on the ^{87}Rb D_2 line and is outlined in Fig. 1a. In excess of 10^6 atoms are cooled to ~20 µK in an experiment, that typically runs at a repetition rate of 10 Hz. The CPT/Raman fields are generated from a single laser tuned to the D_1 transition with two frequency components as shown in Fig. 1b. A CPT interaction with the probe close to F'=2 resonance is used for the initial state preparation of a coherent superposition of the ground-state levels. After a free precession time of up to 10 ms a detuned Raman π/2 pulse is applied, rotating the Bloch vector around the beam axis, and mapping the evolved coherent superposition back on the F=1,2 ground levels. These populations are detected by recording the fluorescence as the cooling beam is switched back on. Normalisation with respect to varying atom numbers is obtained by first detecting F=2 atoms and then, after a short pulse or repump light, the entire population. The resulting Ramsey fringes are shown in Fig. 1c for a range of free precession times.

Further investigations of the sources of noise as well as cancellation of probe induced shifts using an auto-balanced Ramsey scheme [4] are required to validate this technique for a possible atomic clock.

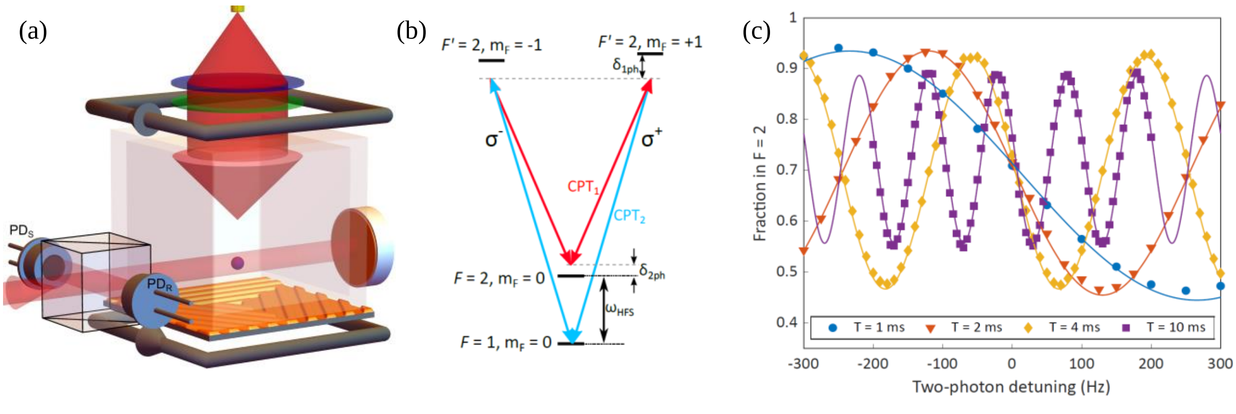

Fig. 1. (a) The experiment is based on atoms prepared in a GMOT and probed optically. (b) The atomic scheme is based on CPT/Raman interactions in a double Λ-system. (c) Ramsey fringes recorded for free precession times from 1 to 10 ms. Note, the signal is asymmetric with respect to the line centre.

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

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The miniaturization of laser-cooled microwave atomic clocks is necessary for more precise compact ground time-keeping instruments replacing bulky hydrogen masers, and ultra-precise navigation satellites. Currently, various laser-cooled atomic clocks are being developed [1, 2], and some have been commercialized [3, 4]. In this presentation, a compact laser-cooled atomic clock in a loop-gap microwave cavity will be introduced [5]. The loop-gap microwave cavity has the advantage of drastically reducing the volume and weight compared to the existing hollow cylinder type microwave resonator, which is advantageous for the miniaturization of laser-cooled atomic clocks, and further opens up the possibility of application as onboard atomic clocks for navigation satellite.

We fabricated a ten-hole loop-gap microwave cavity made of oxygen-free copper based on the FEM simulation results. Figure 1(a) and (b) show the top and side view of the cavity body, respectively. In the cavity body, eight holes with a diameter of 8 mm were symmetrically distributed around the central axis of the cavity. Four ports were for laser cooling and two were monitoring ports. The remaining two ports were used to feed the microwave symmetrically. The cavity occupies a volume eight times smaller than conventional cylindrical cavities. The measured linewidth of the Ramsey spectrum, which is limited by the free-fall distance of the atomic cloud in the cavity, was 19.6 Hz. Figure 1 (d) shows the relative frequency instability relative to that of a hydrogen maser. The frequency instability was measured to be $2.5\times10^{-12}\,\tau^{-1/2}$ [5]. After adopting a low phase noise local oscillator and increasing the number of atoms using an Rb-87 enriched atomic dispenser, the initial short-term stability is improved to $4.5\times10^{-13}\,\tau^{-1/2}$, 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.

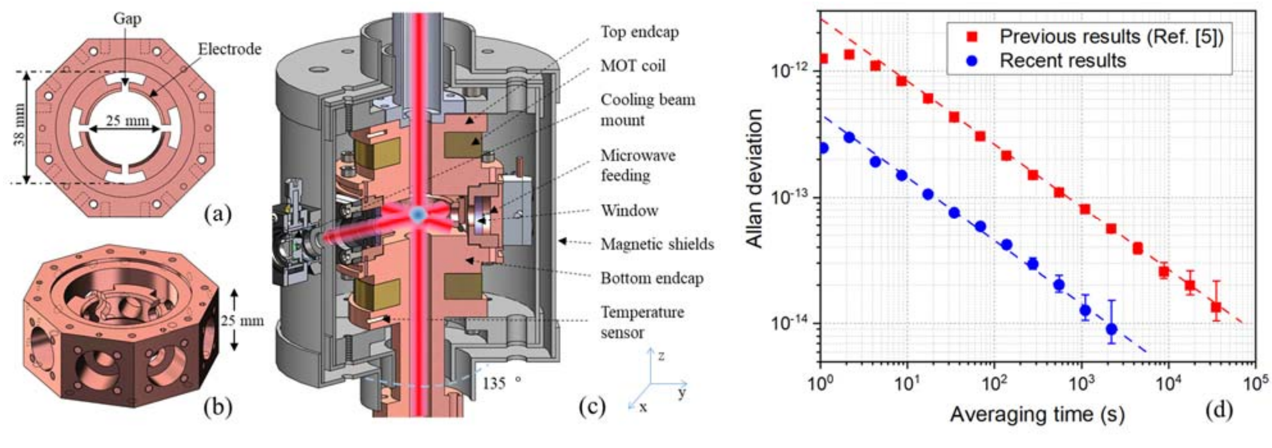

Fig. 1 . (a) Top view of the cavity body. (b) Side view of the cavity body. (c) Cutaway view of the assembled physics package. (d) Allan deviation of the compact cold-atom clock measured relative to a hydrogen maser. The red dashed line (previous results): $\sigma_y(\tau) = 2.5\times10^{-12}\,\tau^{-1/2}$, The blue dashed line (recent results): $\sigma_y(\tau) = 4.5\times10^{-13}\,\tau^{-1/2}$.

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A chip-scale atomic beam clock

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Atomic beams are a longstanding technology for atom-based sensors and clocks with widespread use in commercial frequency standards. Here, we report the development of a chip-scale atomic beam platform and the demonstration of a microwave atomic beam clock built on this platform [1]. The chip-scale beam device consists of a hermetically sealed vacuum package fabricated from an anodically bonded stack of Si and glass wafers with internal components for producing alkali vapor, collimating the atomic beam, and passively maintaining the vacuum environment. Rb vapor is produced in an internal cavity and atomic beams are generated using an array of etched microcapillaries [2,3]. The atomic beams propagate in a 15 mm long drift cavity, and characterization of the atomic flux and divergence indicates a collision-less background vacuum environment < 1 Pa. A microwave atomic beam clock is formed using Ramsey coherent population trapping (CPT) spectroscopy across a 10 mm distance in the drift cavity [4,5], and we have demonstrated an initial fractional frequency stability of $\approx 1.2\times10^{-9}/\sqrt{\tau}$ for integration times, τ, from 1 s to 250 s. Optimized operation of this clock is expected to provide frequency stability at the 10^{-12} level, and there is potential for realizing an integrated atomic beam clock in a compact and low-powered package with long-term stability exceeding that of chip-scale, buffer-gas based clocks.

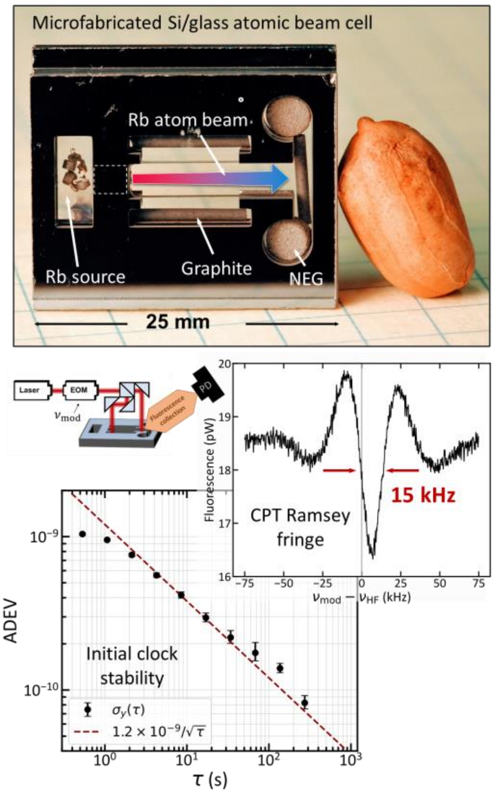

Fig.1. Chip-scale atomic beam cell (peanut for scale), CPT Ramsey fringes, and initial microwave atomic clock stability demonstration.

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A Laser-Cooled Optical Beam Clock

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Microwave beam clocks are found not only in the well-controlled conditions of national laboratories world-wide, but also in GPS satellites and in deployed military environments. At the University of Adelaide, we are investigating the optical analogue of these devices [1,2], and have recently demonstrated an optical beam clock based on the $^1S_0$-$^3P_0$ 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.

Figure 1 (a) and (b) show a schematic and image of the physics package developed for the ytterbium optical beam clock. An in-house designed and constructed oven is used to produce a directional atomic beam, which is then collimated by two transverse cooling stages. A measurement of the 10-mHz wide clock transition is made via Ramsey-Bordé spectroscopy [3] followed by a velocity-selective ground state fluorescence measurement. Figure 1 (c) shows an example clock signal recorded with this physics package (black), with good agreement to our theoretical model (red). Preliminary measurements of the frequency stability of the down-converted [4] 180 MHz clock output show an atom-shot noise limited fractional frequency instability of 10^{-13} at 1s, already competitive with current commercially available portable systems.

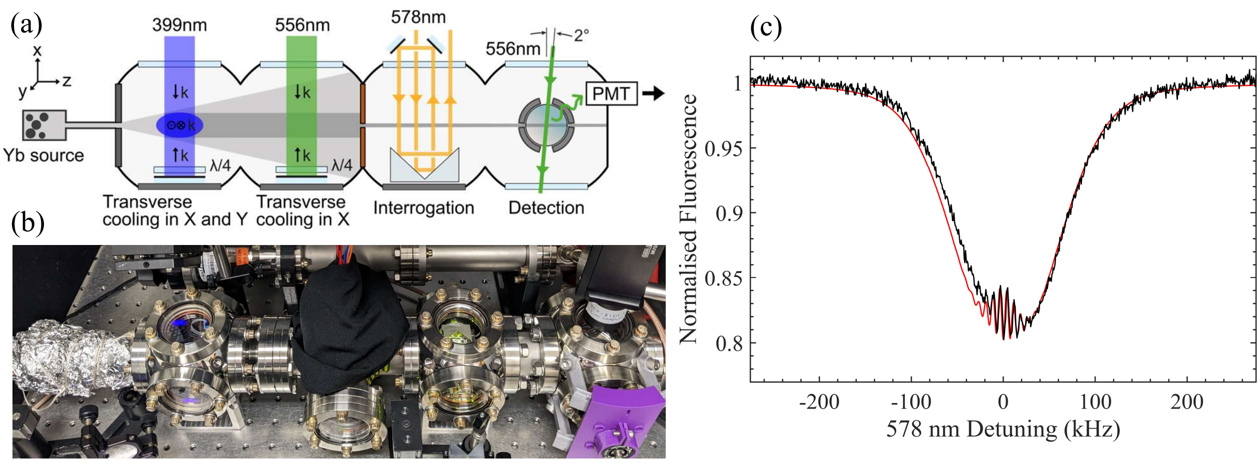

Figure 1: (a) Schematic and (b) image of the atomic beam physics package showing the transverse cooling (first- and second-stage), interrogation and detection stages. (c) Ramsey-Bordé spectroscopy signal (black) and theoretical model (red) for a longitudinal atomic velocity of 95 m/s and rabi frequency of 9 kHz.

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

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Current commercial frequency references utilize microwave transitions in atoms to achieve stabilities on the order of 10^{-11} at 1s. In comparison, the best optical clocks are five orders of magnitude better performing but are currently restricted to laboratories due their size, complexity, and delicacy. The need for high performance timing capabilities in a wide range of harsh and demanding environments has driven the development of a new generation of field-deployable optical atomic clocks. Here we report on a recent international collaboration in which emerging clock technologies were trialed at sea as part of The Technical Cooperation Program (TTCP) Intelligence Surveillance Target Acquisition and Reconnaissance (ISTAR) Group Alternative Position, Navigation and Timing (APNT) action group challenge aboard the HMNZS Aotearoa at the Rim of the Pacific (RIMPAC) exercise out of Pearl Harbor, Hawaii.

Three different optical atomic clocks were tested: University of Adelaide's ytterbium vapor cell clock (UofA Yb) and rubidium 2-photon clock (UofA Rb) [1], and the Air Force Research Laboratory's Optical Rubidium Atomic Frequency Standard (AFRL ORAFS) [2]. Each contained an optical frequency comb for down conversion of the optical frequency stability to the microwave domain to provide useful clock outputs. A complete set of concurrent optical and microwave comparisons were made between devices before and during the sea-trial, covering more than six weeks of operation.

The prototype optical clocks ran autonomously and were stable over weeks at a time during deployment at sea, including heavy sea-states and environmental exposure (Fig.1.a). Using *N*-corner hat techniques we infer the performances of each clock and show that each system achieved orders of magnitude superior stability than the current best-in-class commercial solution (Microchip 5071A) over short and medium timescales (Fig.1.b). This is a powerful demonstration that optical clocks with integrated optical frequency combs are ready for use outside of the lab.

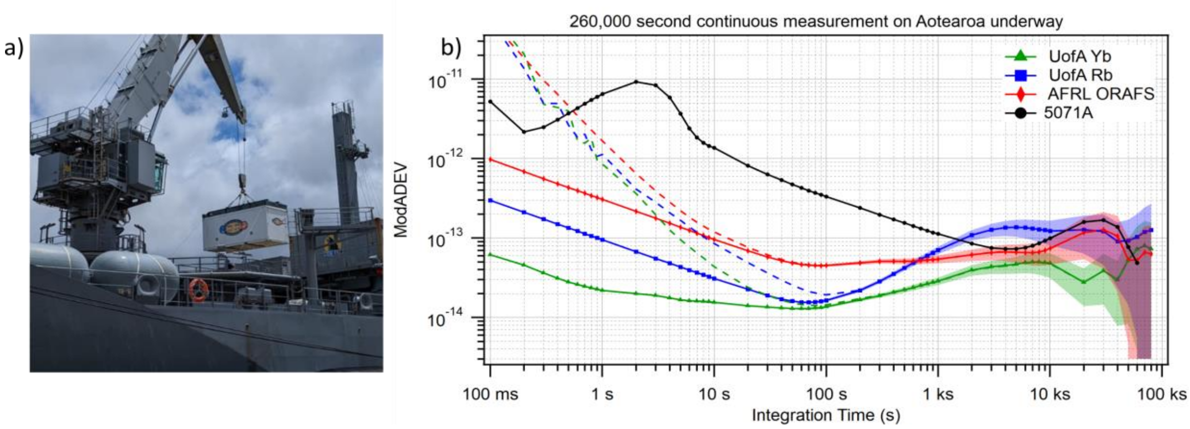

Fig.1. a) Photo of the experiment container being lifted onto the HMNZS Aotearoa, and b) Extracted frequency stability of the optical (solid lines) and microwave (dashed lines) clock outputs during the naval exercise.

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

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Atomic clocks generate an output frequency that is directly connected to an atomic transition which in turn derives its value from the fundamental laws of physics. Given the presumed stability of these laws, atomic clocks deliver the strong foundation of our time and frequency measurement systems. Lab-based optical atomic clocks have demonstrated extremely high performance, reaching fractional frequency instabilities in the 10^{-19} range at long timescales. However, field-deployable commercial clocks offer significantly worse performance around the 10^{-12} range over a second of integration time. Here we present an optical atomic clock based on spectroscopy of the relatively narrow $^1S_0 \leftrightarrow {}^3P_1$ intercombination line in neutral ytterbium that is intended to start to overcome this deficit. We show that this technique 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.

We have developed a complete optical clock system based on the 182kHz wide $^1S_0 \leftrightarrow {}^3P_1$ transition in ^{174}Yb at 556nm, which is interrogated using modulation transfer spectroscopy. The modulation, demodulation, and frequency stabilization processes are all performed using a custom field-programmable gate array (FPGA) suite. The stabilized optical output of the clock is used as the reference for a home built optical frequency comb, which in turn performs the frequency down conversion from the optical to the microwave domain, producing a useful clock output.

We have built two complete optical clocks using this architecture, one prototype for lab-based testing and a second clock that has been ruggedized for field deployment. Direct frequency comparisons have been made between the optical outputs of the two clocks that show a 1s frequency instability of 2×10^{-14}. We have also tested the outputs of these clocks against a separate high-performance deployable optical clock based around a two-photon Rb transition using the frequency comb, as well as making comparisons with best-in-class commercial microwave clocks using the RF outputs of the frequency comb. These comparisons have been made under both controlled laboratory conditions and demanding environments including a moving van travelling on second-class roads around the city, as well as in an unsupervised trial for weeks on the deck of a large maritime vessel over six week. Once fully packaged for deployment the clock has the size, weight, and power of a mini-fridge.

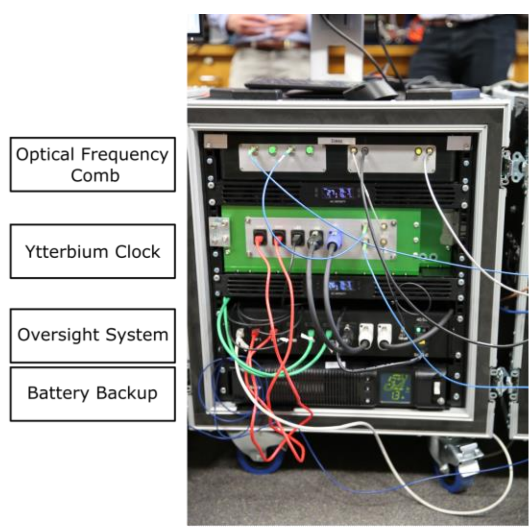

Fig. 1. Fully packaged deployable ytterbium clock including optical frequency comb.

We will present the results from these trials and demonstrate the ability to operate as a turn-key device with stable optical and microwave outputs with frequency instabilities in the 10-15 range over intermediate time-scales.

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

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State-of-the-art optical frequency references like ion clocks have demonstrated frequency stabilities at the 10^{-18} level and below [1]. With these new technologies, many applications will benefit for either time or distance measurements. In terrestrial applications, optical references are already replacing microwave references, but for space applications, optical references are not yet as widely used because reliability, size, weight, and power budgets are key considerations in addition to the performance.

One technology already being used for space missions is optical cavities. Optical cavities can offer high short-term stability, small volumes, low power consumption and comparable low complexity, making them suitable for communication applications or interferometry. With current frequency stabilities at the 10^{-17} level on short timescales for terrestrial applications and 10^{-15} for space applications there is still a need for development. In addition, cavities have the disadvantage of being relative references, which limits their suitability to applications where long-term stability or absolute frequency knowledge is not required. Here, absolute frequency references are the technology of choice, based on the principle that a laser is stabilized to an atomic or molecular transition, resulting in high long-term stability and absolute frequency knowledge, but at the cost of reduced short-term stability and more complex setups.

At the DLR Institute of Quantum Technologies, in cooperation with the Universities of Bremen and Ulm, frequency references covering both, short- and long-term stability are currently under development with a focus on space compatibility. One well known - and compared to ion clocks less complex technology of an absolute reference - is doppler-free spectroscopy of molecular iodine. This technology already demonstrated frequency stabilities at the 10^{-15} level for integration times > 100 s in laboratory experiments, has been flown on a sounding rocket and is currently being further developed to be launched within the COMPASSO project to the ISS Bartolomeo platform in 2025, becoming the first optical clock in space [2]. On the other hand, the further development of a high finesse optical cavity towards space compatibility is ongoing, which should fulfill the requirements of future gravity missions and global navigation satellite systems. Both technologies together can form, in a near future, a so-called hybrid lock, which would offer the advantages of both technologies and would thus be an enrichment for many applications, as a next step [3].

We will present the ongoing development of both, the cavity setup towards space compatibility as well as a broad outline of our evolution of the iodine technology towards the COMPASSO project. Finally, a brief overview of the hybrid lock will complete this presentation.

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

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The Gravity Recovery and Climate Experiment (GRACE) missions rely on inter-satellite interferometry to measure changes in the Earth's local gravity over months and years. These measurements provide a critical tool for understanding large scale mass transport, particularly movement of water and ice.

The next generation of GRACE-like missions are expected to rely on laser interferometry as the primary science measurement, requiring a new technique to provide long term frequency stability over timescales of months and years.

We have previously demonstrated a simple phase modulation scheme that is able to measure changes in laser frequency over long timescales using measurements of the optical cavity's free spectral range. The proposed technique uses hardware that is predominantly already baselined on the mission, requiring minimal changes to existing flight qualified hardware, and enabling tracking of the stability of the cavity free spectral range against a GPS disciplined OCXO for absolute laser frequency knowledge.

The technique has demonstrated performance exceeding the expected mission requirements [1], as well as compatibility with existing flight hardware. We have also calibrated the technique to absolute frequency by comparing with an atomic reference and have validated an approach for on-ground calibration to allow the absolute frequency to be determined in orbit [2].

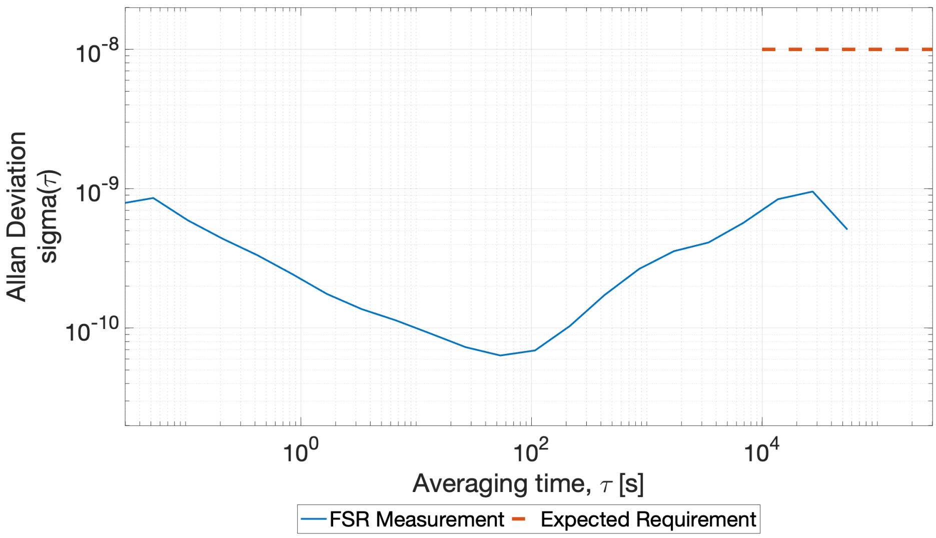

Fig.1. Allan deviation of the FSR measurement. Performance an order of magnitude below the expected requirement has been achieved.

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

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Precision optical metrology relies on the frequency stability of its optical source to reach unprecedented sensitivities. The free-running performance of commercial laser sources often falls short for state-of-theart instruments, necessitating stabilisation to an external reference. At short integration timescales, the standard reference of choice is an ultra-low-expansion (ULE) cavity. While these systems deliver unrivalled short-term stability under controlled laboratory conditions, they become unsuitable for challenging environments such as field deployment and space interferometry.

Optical-fibre-based frequency references present an interesting yet less explored alternative to bulk cavity systems. The intrinsic alignment of optical fibre ensures uninterrupted operation even in hostile environments. Building on the structure of an armlength unbalanced interferometer, a fibre reference is highly frequency agile and can be used to passively remove laser frequency noise in a feedforward arrangement.

In this talk, we present a fibre frequency reference system constructed from two near-identical Mach-Zehnder interferometers with 15 km armlength difference. The two interferometers are deployed to measure the same optical source, allowing a relative stability characterisation through their subtraction. The interferometric readout is handled by Digital Interferometry, a code-multiplexing technique that enables the simplification of optical hardware while providing robust, high dynamic range signal extraction.

To improve the thermal, mechanical and acoustic stability of the system, the differential paths of the interferometers are separately housed in two passive, dual-layer isolation chambers. The thermal time constant of the chambers is modelled and experimentally verified. Sheltered from strong environmental perturbation, the fibre reference reveals a sensitivity of 0.1 Hz/√Hz above 70 Hz Fourier frequency. This performance represents the state-of-the-art sensitivity for fibre references, and reaches parity with room temperature ULE systems. We further model and calculate noise contributions from Double Rayleigh backscattering, and confirm it to be the dominant broadband noise limitation.

Between 0.4 - 2 Hz, the fibre reference reaches the intrinsic fibre thermo-mechanical noise limit [1]. The experimental observation of this fundamental yet less known noise source provides a valuable reference for future scientific endeavours.

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Engineering a 2-Colour Compact Rubidium Optical Clock for Space

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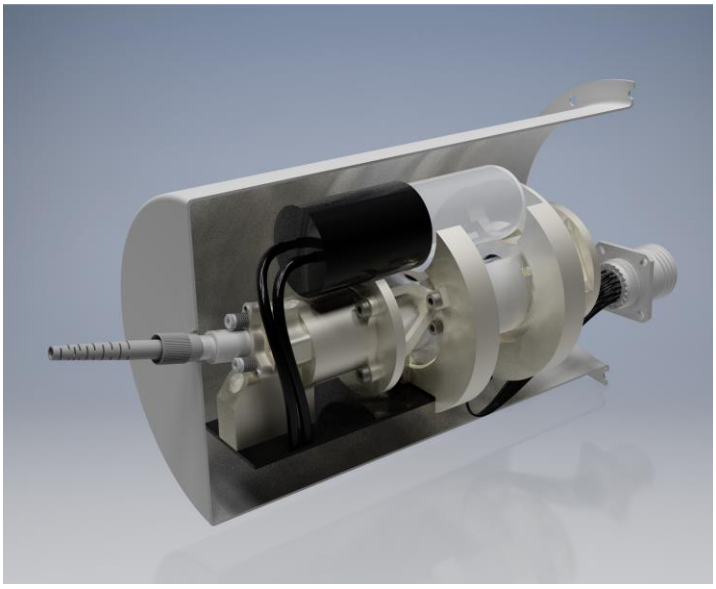
Sovereign Global Navigation Satellite Systems (GNSS) [1,2] are highly desirable for risk mitigation for ensured position, navigation, and timing services, critical to many services of modern society such as power distribution networks, supply chains, and national security. This growing dependence on ensured timing [3] combined with the reduced cost of launching space services has led to an incentive to develop next-generation satellite-enabled technologies. The two-photon $5^2S_{1/2}$-$5^2D_{5/2}$ transition in rubidium offers a frequency reference with a high spectroscopic signal to noise and atomic linewidth suitable for probing without an ultra-stable external reference cavity, from which a low size, weight, and power (SWaP) clock can be developed [4] with potential order of magnitude improvement in performance over existing technology.

The $5^2S_{1/2}$-$5^2D_{5/2}$ transition can be excited using two lasers at 780 nm and 776 nm tuned near the intermediate $5^2P_{3/2}$ state, which allows for much less optical power compared to excitation using a single colour at 778 nm. The two-colour clock, however, requires a more complex control scheme and a lower relative intensity noise on the probing lasers to achieve similar short- and long-term stability. The lower optical power reduces the SWaP requirements by taking advantage of highly engineered telecom industry laser technology to derive the probe light at 780 nm and 776 nm with no post-laser optical amplification.

The pre-flight design presented in this work further develops the portable clock developed by the University of Adelaide for use in a space environment, having a target SWaP of 20 L, 20 kg and 100 W. Some of its considerations are the mitigation of orbit driven thermal fluctuations, improved power efficiency of control logic, and the compact packaging of an optical frequency comb [5].



Conceptual design of the "physics package" of the compact rubidium optical clock.

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Microfabricated surface-electrode ion trap for frequency metrology

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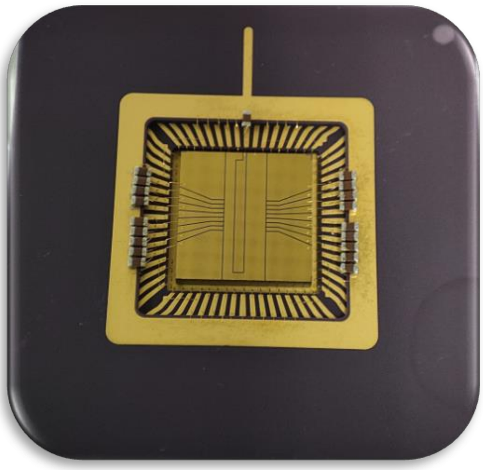
With outstanding systematic uncertainties at the 10^{-18} level or below [1, 2], optical atomic clocks surpass the best cesium clocks that currently define the time unit. With the related impact on various applications such as TF metrology, geodesy, fundamental physics, deep-space navigation and optical atomic clocks networks, a growing number of laboratories around the world are developing transportable optical clocks [3].

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 [4] that we will operate with $^{171}Yb^{+}$ ions on the quadrupole transition at 435.5 nm [5]. We have developed a custom micro-fabricated trap (Fig. 1) based on the 5-wire geometry [6]. The chip has 19 DC electrodes and asymmetric RF electrodes with 600 µm and 1200 µm widths. The electrodes are etched on doped silicon with a 20 µm inter-electrodes distance and a 200 µm depth. The vacuum chamber is described in [7].

Fig.1. 5-wire surface electrode trap microfabricated at FEMTO-ST. The trap is embedded in a commercial, UHV compatible chip carrier. Filter capacitors prevent RF leakage to the DC electrodes.



We have also developed a custom resonant RF circuit with a high quality factor for optimal trapping and electric field noise filtering. With this circuit, we measured a quality factor of 100. Tests were performed under ultra-high vacuum using a testing chip, enabling breakdown voltages measurements as well.

We will present our trap design and characterization, our RF circuit design and test results as well as our latest experimental results.

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Photonics integrated trap for a $^{176}Lu^{+}$ optical clock

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Integrated photonic technologies offer a promising path towards miniaturized and low-cost devices for optical clock applications. In recent years significant progress has been made in developing chip-scale ion traps with integrated light delivery [1] and on-chip detection [2], principally for quantum information applications. These advances are directly applicable to optical ion-based clocks as a clock interrogation can be view as the basic single qubit operation.

Singly ionized lutetium ($^{176}Lu^{+}$) 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.

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Space Optical Frequency Combs

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Future precision metrology in space drives the development and qualification of optical references and optical frequency combs for this environment. Major requirements for such systems are reliability, lifetime, size, weight, power, automation, and remote control. In the past decade Menlo Systems has demonstrated the feasibility of very compact, automated, and robust frequency combs surviving launch, zero-g operation, and reentry under operation in several experimental sounding rocket missions [1, 2]. Consequently, we have now developed a comb for future medium- and long-term space missions. Our comb follows European space ECSS standards and will be built from qualified components. The system exhibits a volume of 6.5 l, a weight of 7.5 kg, and consumes between 30 and 55 W of power, depending on its application and operational modes and is shown in Fig. 1. The comb in its current stage can compare up to four CW reference lasers. As an essential part of an optical clock, it generates highly stable RF clock signal (10MHz) when phase-locked to one of the reference laser's optical frequencies. The comb is based on figure-9 fiber technology built from radiation tolerant fibers. Radiation tolerance exceeds a total dose of 1kGy as shown in irradiation tests, corresponding to over 10yrs at Mid-Earth Orbit [3, 4].

This system will serve as the central hub of the DLR COMPASSO mission, aiming to test future precision optical clock technologies on the Bartolomeo external platform on the ISS [5]. Furthermore, Menlo Systems plans to provide comparable combs to various other satellite-based space missions. Our presently targeted reference laser wavelengths are 532, 689, 780, 1064 and 1542nm, but based on our long-term experience in terrestrial comb applications other wavelengths are well feasible.

The most appealing future applications for combs cover precision atomic clocks, ranging and communication, atmospheric remote sensing, precision gravitational sensing, astronomical spectrometer calibration, and future fundamental physics missions investigating space-time. The authors would like to thank the German Aerospace Center (DLR) for funding and long-term collaboration.

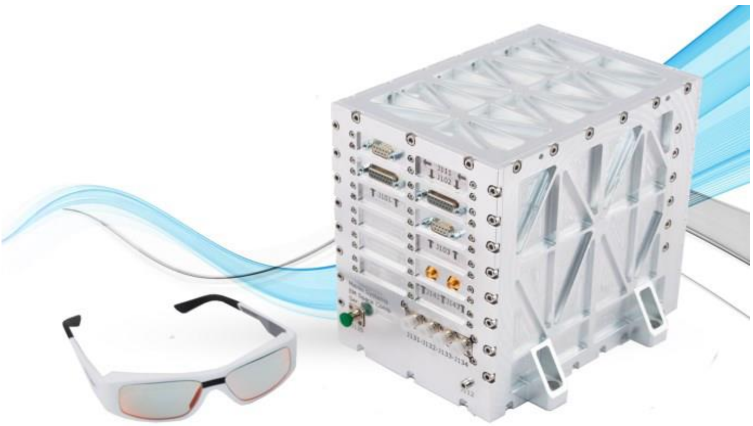

Fig.1. Image of the space qualified frequency comb developed for long-term space operation like the DLR COMPASSO mission.

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

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Compact ultrastable laser systems are at the heart of mobile optical atomic clocks, optically derived low phase noise microwaves, and precision environmental sensing using optical fibers. We have developed several sub-10 mL vacuum-gap Fabry-Perot cavities that provide ~10^{-14} factional frequency stability [1-3], an order magnitude better stability than other reference cavities of similar size. Furthermore, to facilitate the move away from individual cavity assembly, we have devised a lithographic technique to define and etch mirror surfaces that enable multiple, million-finesse mirrors to be manufactured onto a single substrate [4].

Figure 1 shows representative cavities, vacuum packaging, as well as phase noise and frequency stability results [1-3]. Figure 1(a) shows a cavity whose volume is ~5 mL. A laser frequency-stabilized to this cavity exhibits phase noise limited by the cavity thermal noise out to ~10 kHz offset, as shown in Fig. 1(b). When paired with an optical frequency comb, the low phase noise of this cavity supports microwave generation with performance comparable to the lowest noise optically derived microwave signals to date for offset frequencies greater than ~100 Hz. This is despite the fact that the cavity volume use here is more than 10x smaller than cavities used in previous microwave generation demonstrations.

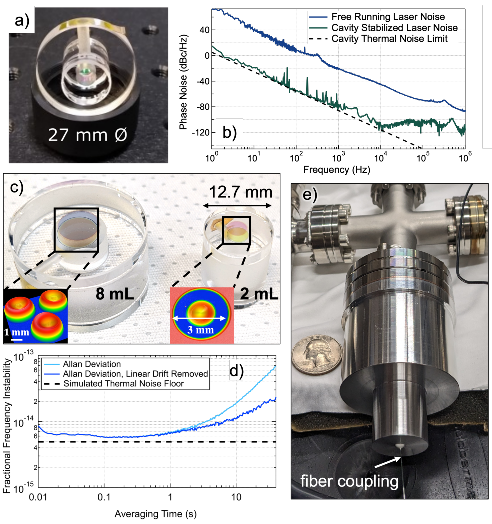

Fig.1. (a) Compact cavity designed for low phase noise, as well as low acceleration and holding force sensitivity. (b) Phase noise of a laser locked to the cavity in (a). (c) 8 mL and 2 mL volume cavities with micro-fabricated mirrors. (d) Allan deviation of a laser locked to the 8 mL micro-fabricated mirror cavity. (e) Compact vacuum enclosure of the 2 mL cavity.

In Fig. 1(c), two cavity structures are shown that are created with micro-fabricated mirrors whose finesse can exceed 1 million at 1550 nm. The 8 mL-volume structure contains 3 micro-fabricated mirrors on one substrate (each with radius of curvature near 1 m), and therefore contains three independent high finesse optical reference cavities. By reducing to a single mirror per substrate, the cavity volume shrinks to only 2 mL, as also shown in Fig. 1(c). The fractional frequency stability of one of the cavities in the 8 mL structure is shown in Fig. 1(d). Here, the instability at 1 second reaches 7×10^{-15}, and stays in the low-10^{-14} range beyond 10 seconds. This is the lowest frequency instability of a laser locked to any optical cavity of similar volume. Fig. 1(e) shows a compact vacuum enclosure containing the 2 mL cavity pictured in Fig. 1(c). The cavity is directly fiber coupled, such that all free-space coupling optics are eliminated. Phase noise and frequency stability measurements for this system are ongoing. The exemplary results from these sub-10 mL cavities demonstrate a path towards compact and mobile ultrastable laser systems that can be manufactured at scale.

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

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At $3\text{x}10^{-13}/\tau^{1/2}$ 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 a 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 $1\text{x}10^{-17}$ 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 the 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 $1\text{x}10^{-14}/\tau^{1/2}$ frequency stability with a stability floor $<1\text{x}10^{-16}$.

From a system engineering perspective, we find that the approach of singly trapped ions will have the most creditable path to minimizing the overall size and power goals. The core of mSOC is an ultra-high vacuum tube that houses nearly perturbation-free laser-cooled and trapped atomic (ion) reference. Currently, we use $^{171}Yb^{+}$, but other ion species are possible. In this paper, we will describe the mSOC concept, discuss the experimental setup, and present results. We will show that we have demonstrated a 16-cc single ion trap tube that is completed sealed off and standalone without any active pump attached (Fig.1). The realization of trapping single ions in a small, sealed package will lead to small sizes and low powers in lasers and optics, and more importantly magnetic and thermal management that will dominate the overall system size and power.

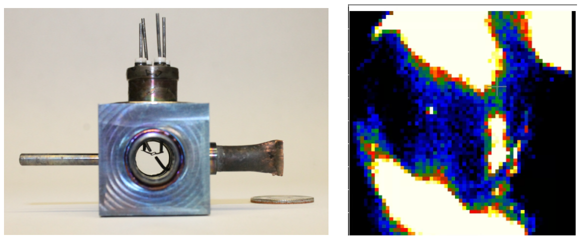

Fig.1. Sealed single ion trap tube of mSOC (left) and a camera image of a single trapped Yb+ (right).

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Sean Mulholland's research was supported by an appointment to the NASA Postdoctoral Program at the NASA Jet Propulsion Laboratory, administered by Universities Space Research Association under contract with NASA.

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Optical terminal for long-distance laser links to moving targets

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Free-space, optical frequency laser links offer high-speed communications between ground and space on the order of terabits per second [1]. 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. To reap the benefits of laser links, optical systems must be designed to overcome these issues.

This work encompasses the design of an optical transceiver terminal for free-space laser links (Figure 1). The terminal is optimised for high power-loss link scenarios, and is ruggedised and compact, making it easily portable. It features tip-tilt control and is compatible with other existing atmospheric stabilisation technologies developed by our research group [2]. Additionally, the terminal easily interfaces with our group's PlaneWave Instruments motorised telescope mounts to provide target tracking well above that required for a low Earth orbit satellite [3].

This terminal is a refined and versatile platform that is intended to support a wide variety of applications outside of communications, including frequency-transfer and velocimetry.

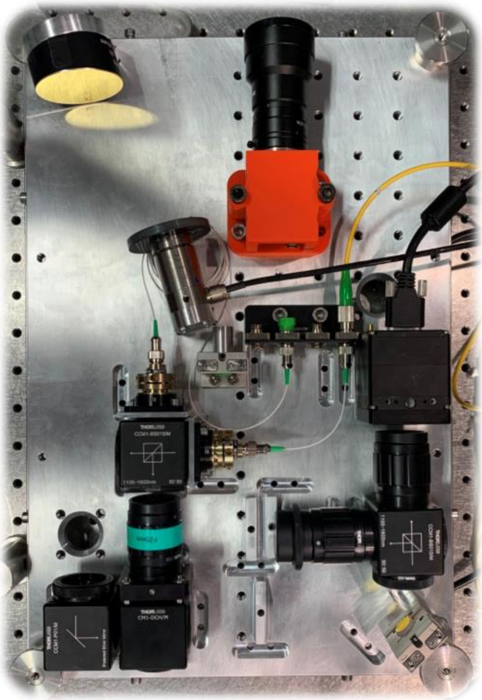

Fig.1. Assembled optical terminal.

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

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Laser phase-noise (PM) to detected intensity-noise (AM) conversion is fundamental to the field/matter interaction: it cannot be avoided, only mitigated [1]. It occurs when laser light passes through a resonant atomic vapor in atomic clocks, magnetometers, and rf-sensors [2-5], and it occurs when laser-induced-fluorescence is detected from an atomic or molecular beam [6]. More specifically, it is a tall-pole noise source in many next-generation vapor-cell atomic clocks [7,8].

Though we imagine the absorption cross-section of an atom to be an intrinsic characteristic of quantum structure, in point of fact the absorption cross-section only arises with the development of a superposition state in the atom or molecule. Anything that causes that superposition state to fluctuate will result in fluctuations of the absorption cross section. Since the superposition state is affected by the phase of the laser that creates the superposition state, laser phase noise will produce random fluctuations in the absorption cross-section: hence laser PM-to-AM conversion.

In this presentation the origin of PM-to-AM conversion will briefly be reviewed. Attention will then turn to recent experiments aimed at better understanding the phenomenon and the development of mitigation strategies. We will discuss experiments aimed at understanding whether or not absorption cross-section fluctuations created by one laser field map onto a statistically independent field. We will show that they do not, which lays the foundation for two PM-to-AM mitigation strategies. In one, a quantum device's signal is created by several statistically independent lasers. In the other, an rf-discharge lamp with intrinsically low PM-to-AM is employed in the LaLI-POP atomic clock [7].

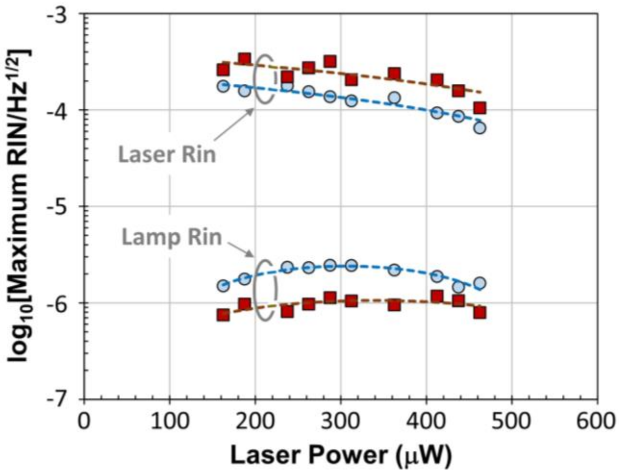

Fig. 1: PM-to-AM Relative Intensity Noise (RIN) in an ^{87}Rb vapor for co-propagating rf-discharge lamp and VCSEL light: squares ⇒ laser tuned to $F_g = 2$ & circles ⇒ $F_g = 1$. There is no PM-to-AM transfer from the laser to the lamp.

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

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Coating thermal noise in high-reflectivity mirror coatings constrains the stability of state-of-the-art optical resonators and hence limits the performance of many precision laser experiments. To get beyond this limitation highly reflective coatings with significantly lower mechanical losses than traditional Ta_2O_5/SiO_2 dielectric coatings are needed. However, only a few promising alternatives have been developed so far.

Crystalline AlGaAs/GaAs multilayer coatings seemed to be a suitable candidate [1] and optical resonators equipped with these coatings demonstrated a performance near the predicted thermal noise floor at room-temperature [2]. Yet, two experiments at 124 K and 4-16 K recently revealed a hitherto unknown noise source which limits the frequency stability far above the expected thermal noise floor at cryogenic temperatures [3, 4]. This not yet identified noise exceeds the thermal noise reduction expected from the low mechanical losses and challenges the potential use of crystalline coatings in next generation cryogenic gravitational wave detectors.

Furthermore, photo-birefringence with very different behavior between room-temperature and cryogenic experiments has been observed in AlGaAs/GaAs multilayer coatings. Thus, one of the most promising mirror coating candidates for ultra-stable optical resonators with fractional frequency stabilities beyond the 10^{-17} level still holds unresolved issues.

We will present 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 analyzing the optical behavior of AlGaAs/GaAs multilayer coatings across a broad temperature range, which in turn helps understanding the source of the observed excess noise and possibly identifying suppression or mitigation strategies.

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 [5, 6] and amorphous-Si multilayer coatings [7] over a temperature range relevant for applications in ultra-stable optical resonators and in next generation gravitational wave detectors.

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Developing a Free-Space Quantum-Secured Time Transfer System

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Accurate time and positioning information is essential for navigation, communication networks and electricity grids. Currently this information is provided by Global Navigation Satellite Systems such as the Global Positioning System (GPS). Unfortunately, transmission of GPS radio frequency signals can be easily spoofed whereby false time and location information is sent to a receiver.

Quantum clock synchronisation protocols using pairs of entangled photons have been proposed as an alternative to GPS that would provide unspoofable and precise time transfer [1]. The most well-known experiment to date, involving the transmission of an optical quantum time transfer signal, was between the *Micius* quantum satellite and a ground station in China in 2020 over a free-space link with 80 dB loss [2]. While a time-transfer signal was transmitted, true single photons were not used in this demonstration nor was the time-transfer signal utilised to discipline clocks. Therefore, many questions remain regarding operational performance of this technique. Here we will present our latest results investigating effects such as loss and noise on a quantum time transfer link using a source of correlated photon pairs.

To date we have utilised the setup illustrated in Figure 1(a), with the corresponding correlation peak, shown in Figure 1(b), to demonstrate the potential performance of free-space time transfer with 1-10 piscosecond resolution. With an integration time of 0.5 seconds, our results show that correlations can still be detected when the noise level is 22 times higher than the signal level. The maximum loss accepted by our system is 38 dB. We will compare our experimental results to a theoretical model we have developed to determine the fundamental limits of free-space optical quantum time transfer. We will also present our latest work towards using polarisation-entangled photons to demonstrate quantum-*secured* time transfer - where the confirmation of entanglement is used to guarantee the authenticity of the signals.

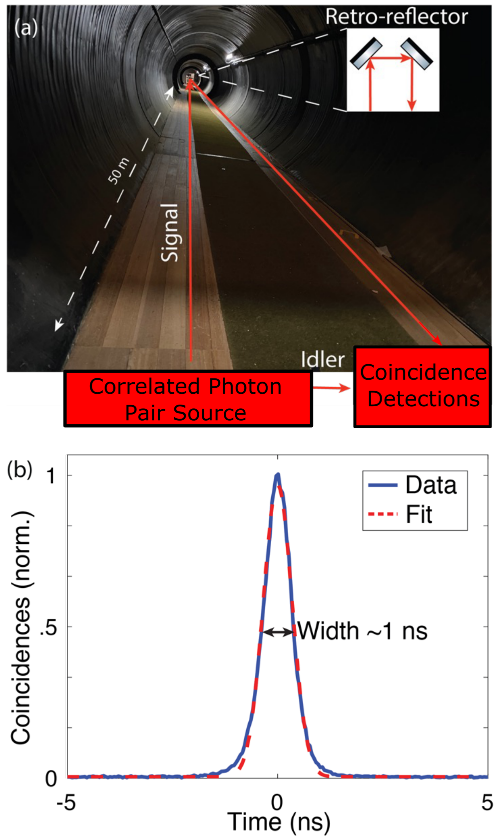

Fig.1. (a) Quantum time-transfer demonstration over a 100 m free-space link. (b) Correlation peak. Full-width-at-half-maximum of the correlation histogram provides an indication of the timing precision of the system.

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Towards an atomic gravimeter with the accuracy of below 10 nm/s^2; overcoming the current uncertainty of KRISS-AGRb-1

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An absolute atomic gravimeter based on an atom interferometer has surpassed the sensitivity of its classical counterpart FG5X by about one order but is still not the case and comparable, with accuracy staying at 30 nm/s^2-50 nm/s^2 [1-4], in terms of the absolute values. The most dominant limit in the accuracy is due to the wavefront distortion of the Raman laser that manipulates the atomic wavepacket to constitute an atom interferometer and also imprints its phase to the phase factor of the atomic wavepacket while manipulating. This effect is related to the ballistic expansion of the atomic source through its motion described as atomic temperature and does not appear at zero atomic temperature. Using ultracold sources such as Bose-Einstein Condensation (BEC) [1,2] or modulating the diameter of a Raman beam can be one candidate for reducing the effect [3]. However, in the former case, the slow repetition rate of measurements caused by preparing the ultra-cold sources degrades the stability, increasing the statistical uncertainty, and in the latter case, the diffraction induced by reducing beam size of Raman laser can increase a systematic uncertainty directly. Here, we report the uncertainty evaluation of the atomic gravimeter KRISS-AGRb-1 (Fig.1) developed at KRISS with the total uncertainty of below 30 nm/s^2 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 below10 nm/s^2, 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.

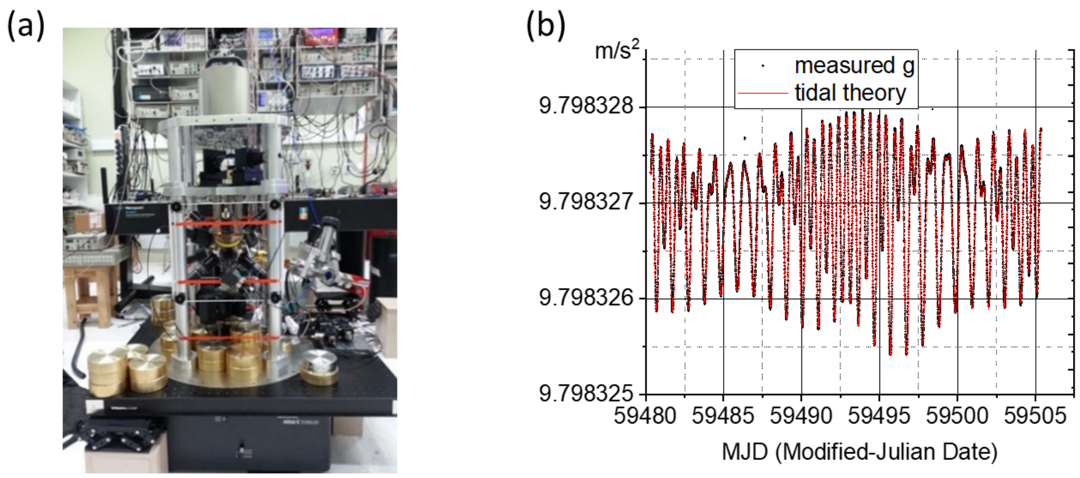

Fig. 1 (a) Photo of the physical package of atomic gravimeter KRISS-AGRB-1, (b) g measured from 23/ 09/2021 to 19/10 2021.

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Study on Stabilizing the Laser Frequency in 10^{-14} Level by Optimizing Modulation Transfer Spectroscopy on the ^{87}Rb D_2 Line

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Stabilizing the laser frequency using the D_2 line of alkali atoms is essential for the implementing high-performance cold atom interferometer. 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 [1, 2]. By optimizing the diameter and intensity settings of the probe and pump beams for the spectroscopy, we achieve a substantial improvement in frequency stability. 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 [1, 2]. However, offset fluctuations induced by residual amplitude modulation (RAM) limit the long-term stability, which is expected to be further improved by reducing the temperature fluctuation. Nevertheless, the current long-term stability is already good enough considering state-of-the-art gravimeters with instability of 5×10^{-11} at 10^5 s [3].

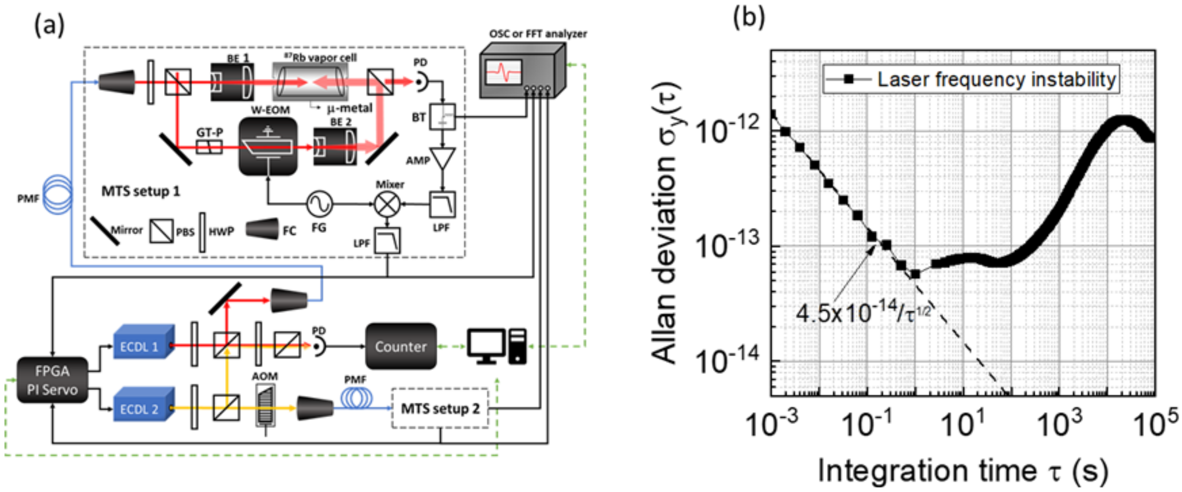

Fig. 1 (a) MTS setup. ^{87}Rb vapor cell; ^{87}Rb enriched wedged vapor cell, FC; fiber collimator, HWP; half-wave plate, BT; Bias-tee, M; mirror, PBS; polarizing beam-splitter, GT-P; Glan-Thompson polarizer, EOM; electro-optic modulator, PD; photodiode, AMP; amplifier, LPF; low-pass filter, Mixer; phase detector, FG; function generator, OSC: Oscilloscope, BE 1&2; beam expander (custom-made). (b) Allan deviation showing laser frequency instability obtained from the beating frequency of two locked external cavity diode lasers.

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Toward a sub-kelvin cryogenic Fabry-Perot silicon cavity

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We report the current development of a sub-kelvin Fabry-Perot silicon cavity. This development aims to reduce thermal noise-limited frequency instability and by this way address the current limitations of ultrastable lasers, aiming to set the ground for the next generation of these devices 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 $Al_{0.92}Ga_{0.08}As/GaAs$ 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)

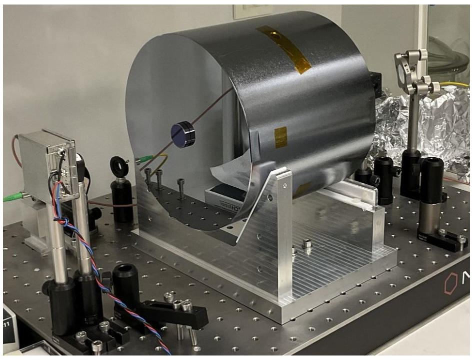

Fig.1. View of the silicon cavity

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.

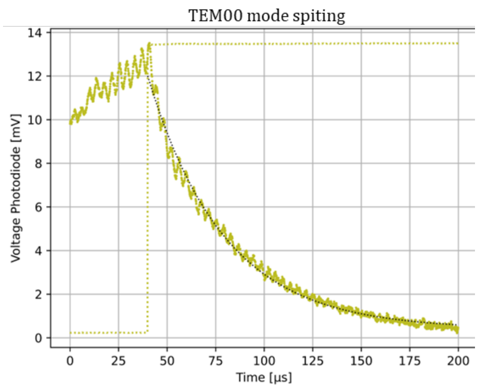

Fig.2. Finesse and TEM00 mode splitting

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.

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Pure frequency-based dispersive spectroscopy

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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 phenomenon 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.

Use of laser tightly PDH-locked to high-finesse cavity filled with absorbing gas allowed scanning of narrow cavity mode resonance and its frequency determination with sub-Hz uncertainties. This technique called cavity mode-dispersion spectroscopy (CMDS), with its primary observable being frequency [1], is immune to bias caused by nonlinearity in the detection of light intensity affecting most commonly used spectroscopic approaches. The CMDS allows molecular transition intensities determination with sub-promille relative uncertainty [2,3] and its traceability to primary frequency standards of the SI. Moreover, CMDS was applied to Doppler-free saturation measurements of weak molecular transitions and appeared to be superior to other techniques [4]. Combination of optical frequency comb as a light source and a Fourier transform spectrometer led to realization of a broadband CMDS [5]. Finally a fast dual-comb detection scheme was implemented to CMDS [6,7]. Even faster realization of these approaches is possible by beating light buildup or decaying from the optical cavity with a local oscillator precisely detuned from the cavity resonance. We demonstrated the cavity buildup dispersion spectroscopy (CBDS) [8] allowing rapid measurement of the mode frequency on a time scale shorter than the cavity decay time and a broadband experiment using dual-comb cavity ring-down spectroscopy (DC-CRDS) [9].

The pure frequency-based dispersive spectroscopy seems to be an attractive alternative to intensity-based measurements of cavity decay rates or light absorption, especially in studies of weak molecular transitions. Applications include reference data for a new generation of spectroscopic databases, studies of fundamental physics, gas metrology and Doppler width thermometry.

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A Novel Laser Power Measurement Scheme Using Rubidium Clock

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Lasers are widely used in basic science research and industry. The laser power is a key parameter. To measure the laser power, many methods are developed, including methods based on photodiode, cryogenic radiometer, photodynamic sensing, integrating sphere. 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. This scheme is mostly based on the light shift effect. 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.

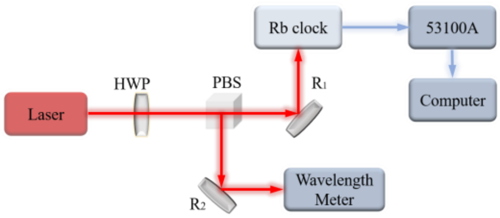

Fig.1.Schematic diagram of the experimental setup. HWP: half wave plate, PBS: polarization splitter, R_1,R_2: reflectors.

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.

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

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Quantum sensing is a rapidly growing field that harnesses the properties of quantum mechanics to develop highly sensitive sensors. This project focuses on developing a Penning-trap-based quantum-sensing system to detecting ultra-weak electric fields. Such a system can potentially search for ultra-light, wave-like dark matter in the mass range of 1-10neV/c^2 [1].

To enhance the sensitivity of our Penning trap [2], we have implemented near-ground-state cooling through electromagnetically induced transparency cooling, ensuring operation within the Lamb-Dicke regime [3].

Furthermore, we have developed a laser beam delivery system based on compact piezo-actuated optical mirrors, which provides efficient beam position tuning. This system allows us to optimise the ratio of spin-spin interaction strength to spontaneous emission, a crucial factor for preparing entangled spin states.

Experimental results demonstrate a linear correlation between the angle of the entangling beam and the interaction strength, with a spin-dependent optical dipole force range of 15yN to 35yN, as seen in figure 1. These findings highlight the potential for further advancements in ion-trap-based quantum sensing and pave the way for developing highly sensitive sensors with applications in various fields, including precision measurements, quantum information processing, and fundamental physics research.

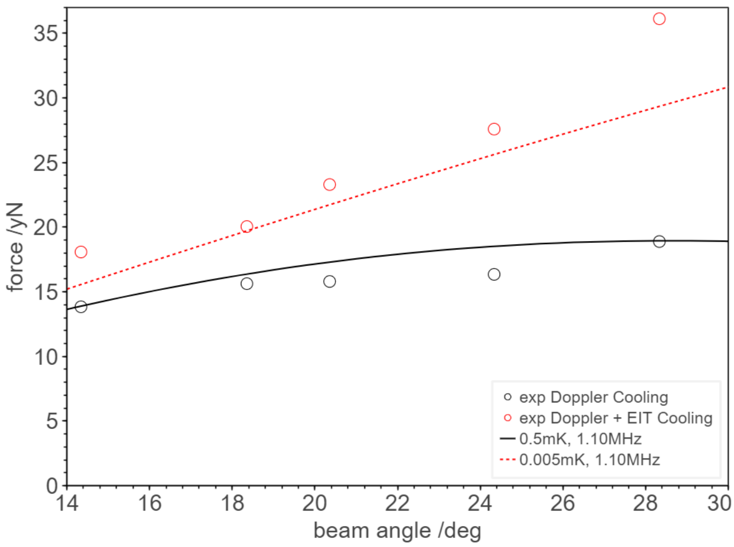

Figure 1: The spin-dependent optical dipole force at different beam angles, with the ions initially cooled with only Doppler or Doppler followed by EIT cooling. The dotted lines are the theoretical curves of the force at those angles and temperatures.

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

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Trapped-ion spins are a strong contender for performing analogue simulations of complex many-body systems that are otherwise computationally intractable [1]. These quantum simulators are a promising tool for feasibly studying condensed-matter phenomena such as quantum magnetism and two-dimensional superconductor behaviour [2]. The Penning trap at the University of Sydney has been specially designed for engineering Ising-type spin-spin interactions with large, two-dimensional Beryllium ion crystals [3]. We propose a setup for targeting single-ion spins using a focussed laser beam to either optically pump to a different spin state or generate an AC Stark shift. The beam position will be controlled using acousto-optic deflectors and strobed with nanosecond precision to achieve selective ion addressing. This will enable more sophisticated quantum states to be initialised and, thus, more complex quantum simulations. Furthermore, we utilise a time-correlated single-photon-counting camera to detect and read out individual ion states efficiently. A neural-network-based object detection algorithm is used to evaluate camera images, allowing for efficient single-site ion detection [4].

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Dual-atom-interferometric gyroscope with continuous cold atomic beams

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Light pulsed atom interferometers have shown their potentials as inertial sensors with high sensitivity and stability, including gyroscopes, gravimeters and gradiometers [1-2]. It is significant to decouple the rotation rate and acceleration from interference phase shifts of a dual-atom-interferometer with three Raman pulses configuration and provide a basic building element for an atom interferometer based inertial measuring unit (IMU) [3].

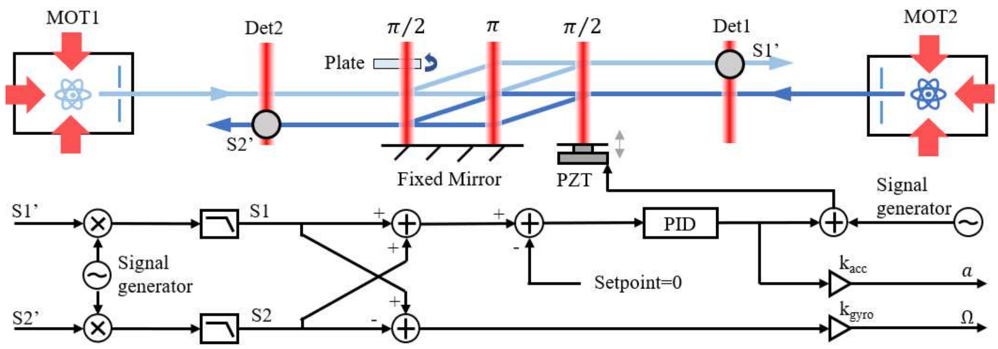

Fig.1. Atom interferometer inertial sensor based on a pair of counter-propagating continuous cold beams from two 2D+ magneto-optical traps (MOT1, MOT2). Raman light beams provide a spatial π/2-π-π/2 sequence.

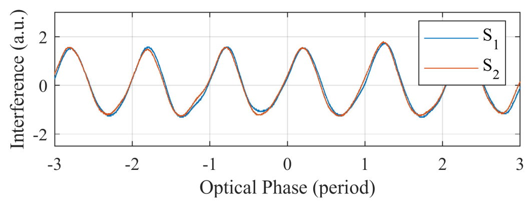

Fig. 2. Interference signal with PZT scanned

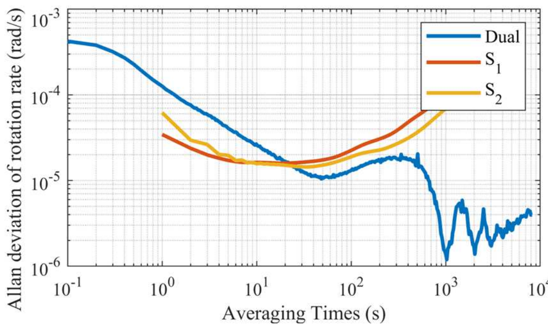

Fig. 3. Allan deviations of rotation measurement from dual-atom-interferometer (blue), S_1 (red), S_2 (yellow).

In this work, we demonstrated a dual-atom-interferometric gyroscope based on two continuous cold ^{87}Rb beams. The decoupled rotation rate phase ϕ_Ω and acceleration phase ϕ_a can be obtained from the sum signal $S_1 + S_2$ and differential signal $S_1 - S_2$ of both atom interferometers.

$$S_1 + S_2 = 2A + 2Bcos(\phi_a - \phi_r)cos(\phi_\Omega - \phi_0) \quad (1)$$

$$S_1 - S_2 = -2Bsin(\phi_a - \phi_r)cos(\phi_\Omega - \phi_0) \quad (2)$$

Closed-loop measurement of rotation rate and acceleration can be realized by controlling the initial optical phase ϕ_0 and the reflection optical phase ϕ_r, which are tuned respectively via the rotation of a glass plate and the movement of retro-reflecting mirror with a piezoelectric-transducer (PZT).

The rotation rate is extracted from the differential signal while ϕ_0 is set to 0° and the sum signal is phase-locked. This operation mode presents a rotation rate measurement stability of $1.19\,\mu rad/s$ with a short interrogation time of only $0.85\,ms$, at an integration time of $2000s$ as shown in Fig.3.

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

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Positioning, navigation and timing technologies play a crucial role in various applications [1]. Quantum devices utilizing atomic interference, including gyroscopes, accelerometers and clocks [2-5], offer notable advantages such as high sensitivity, precision, and independence from external signals, thereby exhibiting substantial potential for PNT applications.

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 counter-propagating atomic beams both comprise two Rubidium isotopes. Specifically, the counter-propagating ^{87}Rb atomic beams enable Mach-Zehnder interference for measuring the rotation rate and acceleration, while the ^{85}Rb atomic beam in one direction serves as the Ramsey clock.

We conducted the Mach-Zehnder interference experiment based on one side of the atomic beam and obtained the interference signal. The atomic beam interacts with three Raman beams, which are spatially separated and can be modulated independently in terms of frequency or phase. By scanning the phase of the first Raman beam, we achieve interference fringes with a contrast of C=0.05, given the spacing of L = 0.27 m between the Raman beams and an interrogation time of T=1.4 ms. The preliminary experimental results have confirmed the system's capability to perform subsequent inertial measurements, thus establishing a foundation for further experiments.

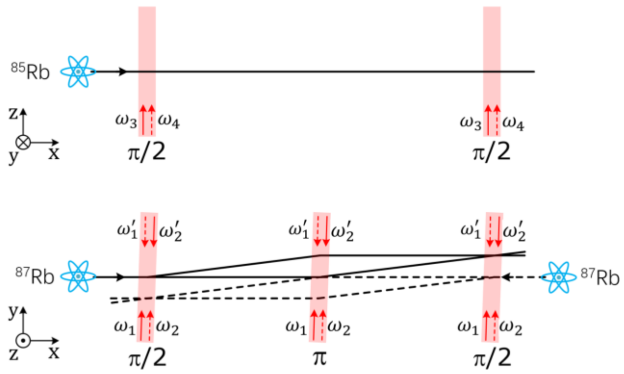

Fig.1. Schematic diagram of the interferometric configuration, including the Ramsey interferometry and the Mach-Zehnder interferometry in two perpendicular planes.

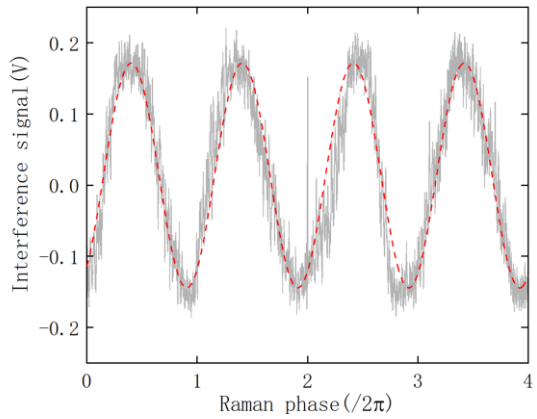

Fig.2. The Mach-Zehnder interference signal obtained by scanning the first Raman beam.

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

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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(10^7) in value indicating a low dielectric loss tangent of order O(10^−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(10^13) cm^−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.

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

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Fig.1. 3D printed twisted triangular waveguide

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 [1], 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 (see Fig. 1), 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 [2]. 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} [2]; 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.

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A Photonic Smart Sensor Based on Quantum Memories and Machine Learning

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Traditional sensors operate in a linear response regime, where changes in signal amplitude are directly proportional to variations in system parameters. However, with the advent of machine learning, sensors can now operate in the non-linear regime [1, 2], leading to the development of "smart sensors". These sensors leverage supervised machine learning methods and labeled data to model the non-linear response of the system to parameter changes. Consequently, they can estimate unknown parameter variations in future experiments.

In our work, we specifically consider an optically probed optomechanical environment, for example, a scenario where a cantilever's mechanical oscillation frequency varies depending on the presence and quantity of impurities in the surrounding air. To capture data, we encode information in the time domain using single-photon pulses. We model this setup as a single-sided optical cavity with a highly reflective output mirror. The reflected pulse's temporal shape, determined by the cavity response function and two parameters (cavity linewidth and detuning), can be used to label the output temporal mode shape.

Our focus is on input pulses prepared with known temporal shapes using Raman schemes [3]. Single photon pulses offer advantages such as enhanced sensitivity to thermal noise compared to coherent pulses with the same average intensity [4]. Additionally, they enable low-power operation, which is highly desirable in biological imaging applications.

To learn the cavity parameters, we drive the cavity with a sequence of identical single-photon pulses and store the amplitude and phase of the reflected signal using a Raman single-photon detector. This data constitutes the nonlinear sensing signal and serves as the training data. By labeling the data with different values of a particular parameter (e.g., mechanical frequency) while holding other parameters constant, a machine learning algorithm can effectively classify the training data based on its dependence on that specific parameter.

In this learning process, a Raman detector utilizes a classical control pulse called the "read" pulse to modify the temporal mode it responds to. By adjusting the read pulse's temporal shape at the Raman detector, the probability of detection can be optimized, minimizing errors. This allows for the implementation of a learning protocol, enabling the sensor to learn the transformation implemented by a single-sided optomechanical cavity. The read pulses are classical and can be modulated using standard techniques, making the approach practical and applicable in various scenarios.

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Isotopically Pure Silicon: A Virtual Vacuum for Implanted Ions

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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 makes it an ideal system to realize 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 [1-3].

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The Coolest Compass in the Universe

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Inertial sensors are critical in navigation systems but are typically reliant on the GPS network. New classes of inertial sensors that exploit quantum effects promise to give enhanced absolute measurements of motion in GPS-denied environments such as in space or underwater. In this work, we demonstrate the use of a ring-shaped Bose-Einstein condensate (BEC) as a rotation sensor by imprinting phase [1] to create low-energy phonon standing wave excitations and then observing the precession of the nodes and antinodes of the excitation in response to rotation. We observe a high-quality factor of up to Q = 27 for the imprinted excitations which, when combined with a relatively large 100 μm ring diameter, realizes a much higher sensitivity than has been demonstrated previously [2,3]. Persistent currents are imprinted into the ring, mimicking slow rotation rates and demonstrating the measurement utility of the scheme. Experimental results are compared with simulations using finite temperature stochastic projected Gross Pitaevskii equation (SPGPE) that reveal the dominant damping mechanisms, furthermore demonstrating the parameter space where the damping can be minimized.

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$LiNbO_3$ Bulk Acoustic Resonator characterization at liquid helium temperature.

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Bulk Acoustic Wave (BAW) resonators utilizes 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 $LiNbO_3$-BAW resonator materials 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 10^6 for both longitudinal and shear modes. Crystal modes are studied using finite element method (FEM) modelling tool COMSOL. It has been observed that there are two type of modes which are longitudinal(A-type) and shear modes present inside the crystal [5,6]. $LiNbO_3$ 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 ~10^6. Re-entrant cavity with split post of frequency~5Ghz operating at TM010 mode is designed in COMSOL to further investigate BAW_MWC coupling rates for $LiNbO_3$.[7]

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

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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 Aharonov-Bohm effect and the AC Stark effect [1].

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Gravitational Aharonov-Bohm Effect

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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 scalar-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, $\Phi_e(t)$ (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.

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